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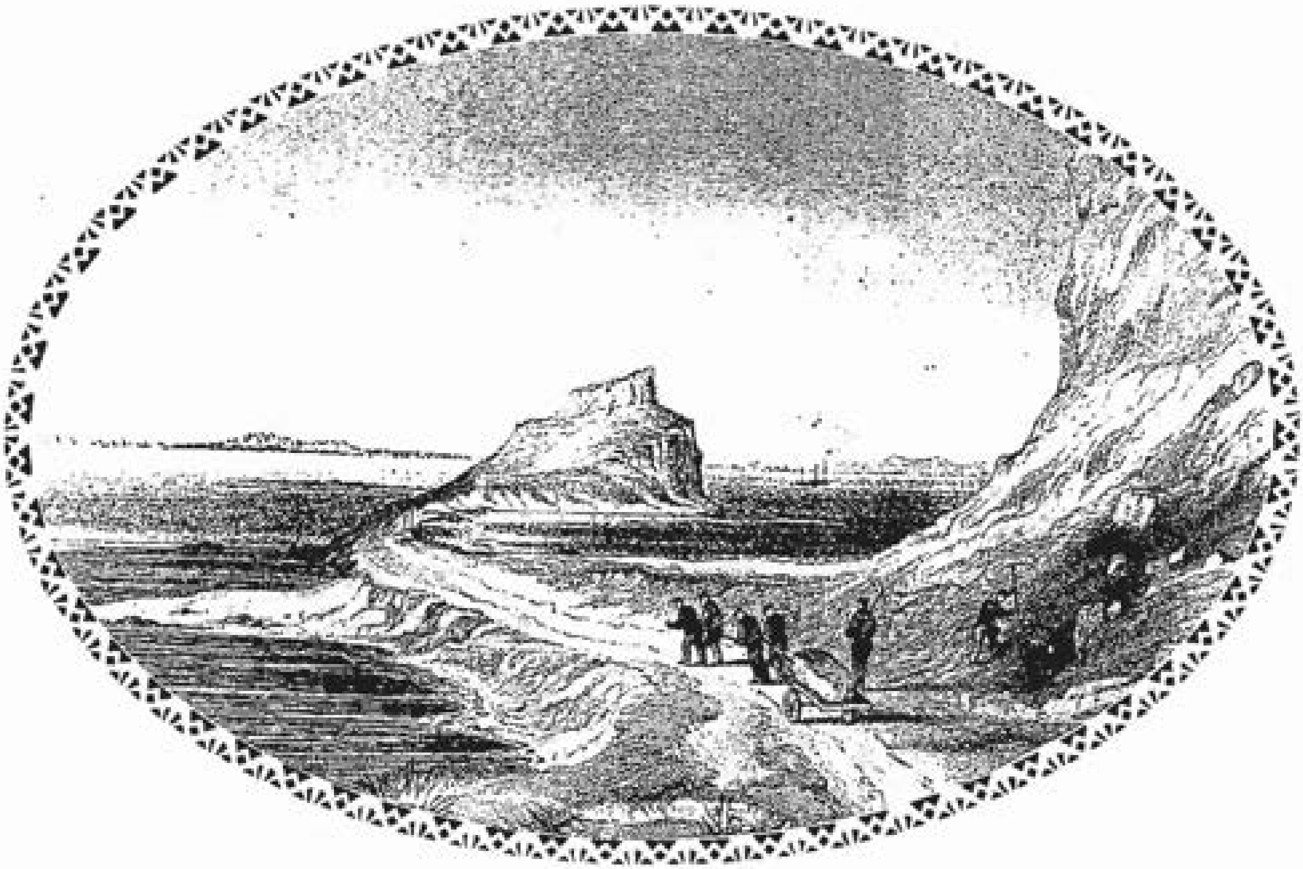
TWENTY EIGHTH NEWCASTLE SYMPOSIUM

on

" *ADVANCES IN THE STUDY OF THE SYDNEY BASIN*"

15th to 17th April, 1994

NEWCASTLE NSW AUSTRALIA



DEPARTMENT OF GEOLOGY, THE UNIVERSITY OF NEWCASTLE, NSW 2308

THE UNIVERSITY OF NEWCASTLE

New South Wales 2308

DEPARTMENT OF GEOLOGY

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COVER : *Old print showing convicts building the breakwater between Nobbys and Fort Scratchley, Newcastle, New South Wales.*

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C.F.K. DIESSEL & R.L. BOYD
CONVENERS

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Note : Acceptance of abstracts and presentation of papers does not necessarily imply acceptance of the ideas and concepts by the organisers of the Newcastle Symposium or The University of Newcastle.

PREFACE

Another year has passed and once again we are looking forward to a Newcastle Symposium weekend filled with interesting lectures, exciting discussions and enjoyable collegiality. The number and scope of the papers presented this year is greater than ever before, which forced us to reduce the time of presentation in some sessions from 30 to 25 minutes and have three parallel sessions on Saturday afternoon as well as on Sunday morning. Future symposia may need to restrict the number of submitted papers due to this increasing popularity.

We did our best to group the oral presentations into consanguineous themes but were constrained in several cases by some of the speakers' limited availability. This and the fact that most participants are interested in more than one subject, might cause the odd agony over the question of which session to attend, but if you cannot make up your mind, read one or two of the posters instead, or visit the trade displays. In any case, you can obtain most of the information you might have missed from the very detailed volume of proceedings.

There have been a number of innovations this year. In addition to the keynote speaker, who is Steven Waller of AMOCO, Australia, several lecturers have been specifically invited to give an overview of key fields they have expert knowledge in. Carl Weber of Pacific Power will complement the keynote address by focussing on a resumè of the exploration activities of Pacific Power in locating coalbed methane in New South Wales, Brad Mullard of the NSW Department of Mineral Resources will give his thoughts on modelling coal deposits, while John Roberts of the University of New South Wales will present a preliminary report on the results of dating the Permian and Carboniferous Systems.

This year will also provide an opportunity to see the introduction of a short course to the symposium program for participants to improve their understanding of the field of "Sequence Stratigraphy and its Application to Coal Geology". Sequence stratigraphy has introduced new concepts of subdividing, correlating and mapping sedimentary rocks, originally as an aid in the search for oil. For this reason, its methods were applied mainly to marine sediments which have been the traditional targets of oil exploration. Lately, sequence stratigraphy has been increasingly applied to coal-bearing strata, which makes the Newcastle Symposium an ideal vehicle to familiarise a wider audience with its concepts and applications.

Not so much an innovation but more a transitional phase is the employment of two conveners for the symposium which has been brought about by the desire of Claus Diessel to have a less direct involvement in the running of the symposium and its associated excursions. However, changes in personnel will not alter the proven formula of the symposium which is the provision of a forum for the exchange of ideas in a friendly and convivial atmosphere. With this in mind we welcome you to the 28th Newcastle Symposium and hope that you will have an enjoyable weekend.

Claus Diessel and Ron Boyd
Conveners

FOREWORD

As planet Earth is dynamic, so too have we seen change in the Department of Geology over the past year. We would like to see more change take place, particularly with regard to the influx of new staff, because the Department finds itself in the position of facing our role of teaching and research in 1994 with the lowest numbers of staff for a couple of decades. We hope to redress that problem during the year.

Robin Offler, who steered the Department's fortunes through the last three years in a very capable fashion has, perhaps not surprisingly, decided not to seek an extension of his term of office as Head of Department. So the buck now stops with me! We are particularly grateful for Robin's leadership during a time when the Department has been under much pressure, culminating in the Review conducted last December.

Happily, I can report that the results of the Review are very favourable to the academic and research efforts of the staff, while recognising the urgent need for more resources and improved facilities. Of particular interest to you, as supporters of our work, is the recommendation that the Chair in Geology be filled as a matter of urgency. Other important recommendations include the need to hire a geophysicist and at least another staff member with 'soft-rock' or hydrogeological skills, and for the Department as a whole to involve itself more in all aspects of basin studies. The next year will see a deal more change as we strive to take up these challenges.

After 36 years of association with the Department, Brian Engel retired at the end of 1993. His contribution to teaching and research in the Department and to his additional more recent roles as Dean and subsequently, Director of the School of Science and Mathematics, will be sorely missed. As with all our recent 'retirees,' Brian has no desire to tear himself away from geology, and will maintain an active research program in the Department.

We were very pleased to have Judy Bailey join the Department mid-way through 1993. Judy, of course, provides the all-important continuity in teaching coal geology, following Claus Diessel's retirement from teaching the previous year. So, with Claus' on-going commitment to research, we are in the fortunate position of having two highly productive people involved in the coal research program.

All staff have been serving the interests of the department nationally and on the international scene over the past year. Phil Seccombe managed to escape to the Czech Republic to discuss his IGCP work on metamorphic gold deposits, Robin Offler made a lightning visit to Chile for an IGCP meeting on low grade metamorphism, Ron Boyd and Claus Diessel presented papers at the 1993 AAPG National Conference in New Orleans and Ron and Claus taught a short course in non-marine sequence stratigraphy at Houston on the same trip.

Judy Bailey, Claus Diessel and Larissa Gammidge visited Crete for the International Commission for Coal Petrology meeting. Bill Collins edited a special issue of Precambrian Research and continued to chair the Specialist Group in Mineralogy, Petrology and Geochemistry for the Geological Society of Australia. Closer to home, all staff were involved in a variety of conferences, on themes which included fluvial sedimentology, new coal technologies, the New England Orogen, economic geology, igneous petrology and crustal evolution. This activity which spans a variety of fields can only enhance the good reputation of the department.

Lastly, I would like to make special mention of the efforts of our two conveners for this year's symposium, Claus Diessel and Ron Boyd in developing the program and the work put in from all members of the Geology Department to ensure the smooth running of yet another Symposium, in particular, Geraldene MacKenzie, Chris Cuthbert and Hope Ruming.

I welcome you all to Newcastle, I hope your stay with us is both productive and enjoyable and I hope that your studies of the Sydney Basin make major advances.

Phil Seccombe
Head of Department

PROGRAM
28th NEWCASTLE SYMPOSIUM

"ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

FRIDAY	**15 APRIL 1994**
09:00 - 17:30 EXCURSION	**HISTORY OF THE BURNING MOUNTAINS, UPPER HUNTER VALLEY** ***LEADERS :*** *David Branagan (University of Sydney) and Claus Diessel (University of Newcastle)* The excursion will visit the Burning Mountains near Wingen, in the Upper Hunter Valley. Depending on travel time, points of geological interest may be visited *en route*, but the main theme of the excursion will be the study of the Burning Mountains. Travel is by bus to the car park at the reserve, followed by a walk of low to moderate difficulty for 2 hours. Firm footwear is recommended. Lunch will be provided. *Because access is restricted, there will be only one bus with a maximum of 53 participants. Please note the earlier start at 09:00.*
18:30 - 23:00	**UNIVERSITY OF NEWCASTLE GEOLOGY GRADUATES' SOCIETY SHEEP ROAST - UNIVERSITY UNION**

SATURDAY	**16 APRIL 1994 — LECTURE THEATRE B**	
08:30 - 09:00	**REGISTRATION** - Foyer of the Geology Department	
09:00 - 09:05 Lecture Theatre B	**WELCOME** by the Head of the Geology Department, Associate Professor Phil Seccombe	
09:05 - 09:10	**OPENING** of the 28th NEWCASTLE SYMPOSIUM by the Vice Chancellor of the University of Newcastle, Professor R.J. Mortley	
TECHNICAL SESSION 1	**LECTURE THEATRE B** **Chair** David Branagan, Sydney University	
09:10 - 09:30	*N. (Victor) Tadros NSW Dept Mineral Resources*	The Gunnedah Basin — Memoir of a last frontier
09:30 - 10:00	*Hervé Théveniaut & Chris Klootwijk et al. AGSO*	Magnetostratigraphy of the Late Permian coal measures, Sydney & Gunnedah Basins : a regional & global correlation tool
10:00 - 10:30 *Invited Lecture*	*John Roberts et al. UNSW*	Permian SHRIMP ages and correlations within eastern Australia
10:30 - 11:00	**MORNING TEA**	in the FOYER OF THE GREAT HALL
11:00 - 11:30 *Invited Lecture*	*Carl Weber Pacific Power*	Coalbed methane exploration by Pacific Power in NSW — the first five years
11:30 - 11:55	*Peter Odins & Malcolm Bocking*	Some variation in methane saturation in the Permian coals of New South Wales
	****** KEYNOTE***	***ADDRESS *****
11:55 - 12:35	*Stephen F. Waller AMOCO Australia*	A comparative study between coalbed methane basins, with a focus on PEL 2, Sydney Basin, Australia
12:35 - 12:40	*CHAIR*	VOTE OF THANKS
12:40 - 13:50	**LUNCH**	in the UNIVERSITY UNION

SATURDAY	**16 APRIL 1994**	
TECHNICAL SESSION 2A	**LECTURE THEATRE E** **Chair Brian Engel, Newcastle University**	
13:50 - 14:15	*David Branagan* *Sydney University*	The Ingleside Cutting, a fault zone and some 'misplaced' dykes
14:15 - 14:45	*Christopher Fergusson* *Wollongong University*	Uplift of the Sydney-Bowen Basin, eastern Australia : comparison with the tectonics of the Colorado Plateau, south-western USA
14:45 - 15:15	*Bill Collins* *Newcastle University*	Escape tectonics & the redistribution of Permian basins in the southern New England Fold Belt
15:15 - 15:45	AFTERNOON TEA	in the Foyer of the GREAT HALL
15:45 - 16:15	*Greg Skilbeck et al.* *NSW UTS*	Sequence & sedimentology in Early Permian sections along the Peel-Manning Fault System
16:15 - 16:45	*Lindsay Elliott* *SANTOS Ltd*	Using the Foreland to interpret the Orogen
16:45 - 17:15	*Michael Vickers* *Sydney University*	Cleavage criteria for distinguishing between deformed strike-slip & rift basins : implications for the Early Permian of southern New England
17:15 - 17:45	*Rick Morante & Chris Herbert* *Macquarie University*	Carbon isotopes & sequence stratigraphy about the Permian/Triassic boundary in the Sydney Basin
17:45 - 17:50	*CHAIR*	VOTE OF THANKS
19:00 FOR 19:30	SYMPOSIUM DINNER	in the UNIVERSITY UNION

SATURDAY	**16 APRIL 1994**	
TECHNICAL SESSION 2B	**LECTURE THEATRE B** **Chair Carl Weber, Pacific Power**	
13:50 - 14:15	*Michael Creech* *Oceanic Coal*	Some aspects of coalbed methane in the Newcastle Coalfield
14:15 - 14:45	*Peter Crosdale & Basil Beamish* *James Cook University*	Methane sorption studies at South Bulli (NSW) and central Queensland collieries using a high pressure microbalance
14:45 - 15:15	*Wolfgang Kalkreuth et al.* *Geological Survey of Canada*	Geological Survey of Canada coalbed methane research – CBM potential of coals from the Western Canada Sedimentary Basins
15:15 - 15:45	AFTERNOON TEA	in the Foyer of the GREAT HALL
15:45 - 16:15	*Chris Herbert* *Macquarie University*	Cyclical sedimentation in the lower Newcastle Coal Measures
16:15 - 16:45	*Michael Hill et al.* *NSW Dept. Mineral Resources*	Tracing the Bulli & Balgownie Seams across the Sydney Basin
16:45 - 17:15	*H. Memarian & C. Fergusson* *Wollongong University*	Fracture pattern of the Illawarra Coal Measures southeastern Sydney Basin
17:15 - 17:45	*John Hanes* *Consultant*	An update on in-seam drilling research in the coal industry
17:45 - 17:50	*CHAIR*	VOTE OF THANKS
19:00 FOR 19:30	SYMPOSIUM DINNER	in the UNIVERSITY UNION

SATURDAY	**16 APRIL 1994**	
TECHNICAL SESSION 2C	**LECTURE THEATRE G04** **Chair** **Ron Boyd, Newcastle University & Peter Roy, Sydney University**	
13:50 - 14:15	*Gavin Birch* *Sydney University*	The Cenozoic evolution of the central NSW continental margin
14:15 - 14:45	*Peter Roy & Ron Boyd* *Sydney University*	Quaternary geology of the lower Hunter Valley
14:45 - 15:15	*Stanler Wallen* *RZM Pty Ltd*	A review of the titanium and zirconium deposits and their geomorphology in the Hunter region
15:15 - 15:45	AFTERNOON TEA	in the Foyer of the GREAT HALL
15:45 - 16:15	*Ron Boyd* *Newcastle University*	Preliminary investigation of the Quaternary seismic stratigraphy, Hunter Valley continental shelf
16:15 - 16:45	*Marie Ferland & Peter Roy* *Sydney University*	Lowstand sedimentation on the central NSW outer shelf : description & implications
16:45 - 17:15	*Colin Murray-Wallace et al.* *Wollongong University*	Aminostratigraphy of Quaternary outer shell sediments, New South Wales
17:15 - 17:45	*Louise Parsons* *Newcastle University*	Port Stephens : Evolution of a Quaternary estuary
17:45 - 17:50	*CHAIR*	VOTE OF THANKS
19:00 FOR 19:30	SYMPOSIUM DINNER	in the UNIVERSITY UNION

SUNDAY	**17 APRIL, 1994**	
TECHNICAL SESSION 3A	**LECTURE THEATRE E** **Chair** **Robin Offler, Newcastle University**	
09:00 - 09:30	*Murray Little* *Newcastle University*	Conglomerate composition & palaeocurrent directions in the Newcastle Coal Measures : Implications for non-marine sequence stratigraphy
09:30 - 09.55	*Christopher Fielding &* *Stuart Tye, Qld University*	Stratigraphy of the Talaterang & Shoalhaven Groups in the southernmost Sydney Basin
09:55 - 10:20	*Stuart Tye &* *Christopher Fielding* *Wollongong University*	Sedimentology of the Talaterang & Shoalhaven Groups in the southernmost Sydney Basin
10:20 - 10:45	*Peter Jorgensen & Chris Fielding* *Queensland University*	Application of facies & architectural analysis to open cut coal mining : the Late Triassic Callide Coal Measures, east-central Queensland
10:45 - 11:15	MORNING TEA	in the Foyer of the GREAT HALL
11:15 - 11:45	*M.H. Dehghani & B.G. Jones* *Wollongong University*	Sedimentology of Coalcliff Sandstone, southeastern Sydney Basin : fluvial interpretation based on bounding surfaces and architectural elements
11:45 - 12:15	*M.H. Dehghani & B.G. Jones* *Wollongong University*	Scarborough Sandstone in the southeastern Sydney Basin : an Early Triassic sandy to gravelly bed-load fluvial deposit
12:15 - 12:45	*Joel Yago et al.* *Queensland University*	Depositional styles of channel & overbank deposits of the middle Jurassic Walloon Coal Measures, Clarence - Moreton Basin, NSW
12:45 - 12:50	*CHAIR*	VOTE OF THANKS
13:00 - 14:30	LUNCH	in the UNIVERSITY UNION

SUNDAY	**17 APRIL, 1994**	
TECHNICAL SESSION 3B	**LECTURE THEATRE B** **Chair Bill Collins, Newcastle University**	
09:00 - 09:30 *Invited Lecture*	*Brad Mullard* *NSW Dept. Mineral Res.*	The mystic art of coal deposit modelling
09:30 - 09.55	*Larissa Gammidge & Claus Diessel* *Newcastle University*	Wavelength optimisation for the microfluorescence intensity measurements of vitrinite & inertinite
09:55 - 10:20	*Phillip Schmidt & M. Lackie* *CSIRO Div. Expl. & Mining*	Determination of stress relaxation axes in drill core using laser micrometry and palaeomagnetism
10:20 - 10:45	*Wayne Stasinowsky & G.R. Poole* *Mining Geophysics Pty Ltd*	Aeromagnetics for mine hazard detection
10:45 - 11:15	**MORNING TEA**	**in the Foyer of the GREAT HALL**
11:15 - 11:45	*Robert Dixon & Peter Hatherly* *CSIRO Div. Expl. & Mining*	Seismic monitoring of longwall extraction at Tahmoor Colliery
11:45 - 12:15	*Barbara Smith* *NSW UTS*	Application of depositional models to potential underground coal extraction at Warkworth Mine, Singleton, NSW
12:15 - 12:45	*L. Walsh & Joan Esterle* *CSIRO Div. Expl. & Mining*	A geological model for the distribution of coal type and quality in the Katoomba Seam, Illawarra Coal Measures, Sydney Basin
12:45 - 12:50	*CHAIR*	VOTE OF THANKS
13:00 - 14:30	LUNCH	in the UNIVERSITY UNION

SUNDAY	**17 APRIL, 1994**	
TECHNICAL SESSION 3C	**LECTURE THEATRE G04** **Chair Phil Seccombe Newcastle University**	
09:00 - 09:30	*Edgar Frankel* *NSW UTS*	Mobility of dumped harbour dredge spoil, Newcastle, NSW
09:30 - 09.55	*Bill Geyl*	Tidal palaeomorphs in and around the Sydney Basin
09:55 - 10:20	*R.A.L. Osborne* *Sydney University*	Caves, dolomite, pyrite, aragonite & gypsum, the karst legacy of the Sydney & Tasmania Basins
10:20 - 10:45	*Mark Taylor* *NSW Dept School Education*	The correlation of the extent of reactive clay soils to their geology in the northern Lake Macquarie & Newcastle region
10:45 - 11:15	**MORNING TEA**	**in the Foyer of the GREAT HALL**
11:15 - 11:45	*John Patterson et al.* *CSIRO Coal & Energy Techn.*	Regional study of carbonate minerals in the Baralaba Coal Measures
11:45 - 12:15	*John Gibson & Phil Seccombe* *Newcastle University*	Mineralisation and controls on gold deposition, Copeland goldfield
12:15 - 12:45	*Harry Hurst et al.* *CSIRO Coal & Energy Techn.*	Viscosity measurements of melts from some NSW coal ashes
12:45 - 12:50	*CHAIR*	VOTE OF THANKS
13:00 - 14:30	LUNCH	in the UNIVERSITY UNION

THE GUNNEDAH BASIN – MEMOIR OF A LAST FRONTIER

N. TADROS
NSW Dept Mineral Resources

INTRODUCTION*

The Gunnedah Basin was one of a few sedimentary basins in New South Wales which remained unexplored until recently.

Since the discovery of coal in the Gunnedah-Curlewis area in 1877, little exploration was carried out for almost 100 years. The area was loosely grouped with other coalfields into the "Main Coal Basin" to the south (figure 1) and named the Gunnedah Coalfield (Stonier 1890, Harper 1926), the "Curlewis Coalfield - a part of the "Western Coalfield" (Carne 1908), the "Northern Coalfield" (Geological Survey of New South Wales 1925), or the "North-Western Coalfield" (Hanlon 1948). Hanlon's definition of the "North-Western Coalfield" incorporated much of the area containing Permian outcrops in the Gunnedah Basin as we know it today.

It was not until 1973, when Bembrick et al. (1973) subdivided the New South Wales portion of the Sydney-Bowen Basin, that the Gunnedah Basin finally acquired its distinct identity and came into focus (figure 2).

RECENT EXPLORATION

Interest in the Gunnedah Basin started in the mid 1970's when it became a main target of coal drilling programmes by the New South Wales Department of Mineral Resources. The decade between 1975 and 1985 was marked by a progressive and significant expansion in exploration activity by the Department in nearly all NSW coalfields, with the highest activity in the early 1980's.

Drilling in the Gunnedah Basin was driven by the need to evaluate the resource potential of the basin. Prior to the drilling the knowledge of the geology of the basin was very limited because outcrop is poor and the basin is mostly concealed by thick Mesozoic and younger cover, and probably also because geologists were more attracted to the Sydney Basin which is relatively richer in outcrops and the centre of coal exploration and mining.

This lack of knowledge and the perceived idea that the basin might be rich in coal resources coupled with a favourable political and economic climate encouraged the investment of several million dollars on exploration and assessment of these resources.

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*For cited references and a comprehensive bibliography on the subject refer to:
Tadros, N.Z. (E.d) 1993. The Gunnedah Basin, New South Wales. *Geological Survey of New South Wales, Memoir* Geology 12, 649pp.

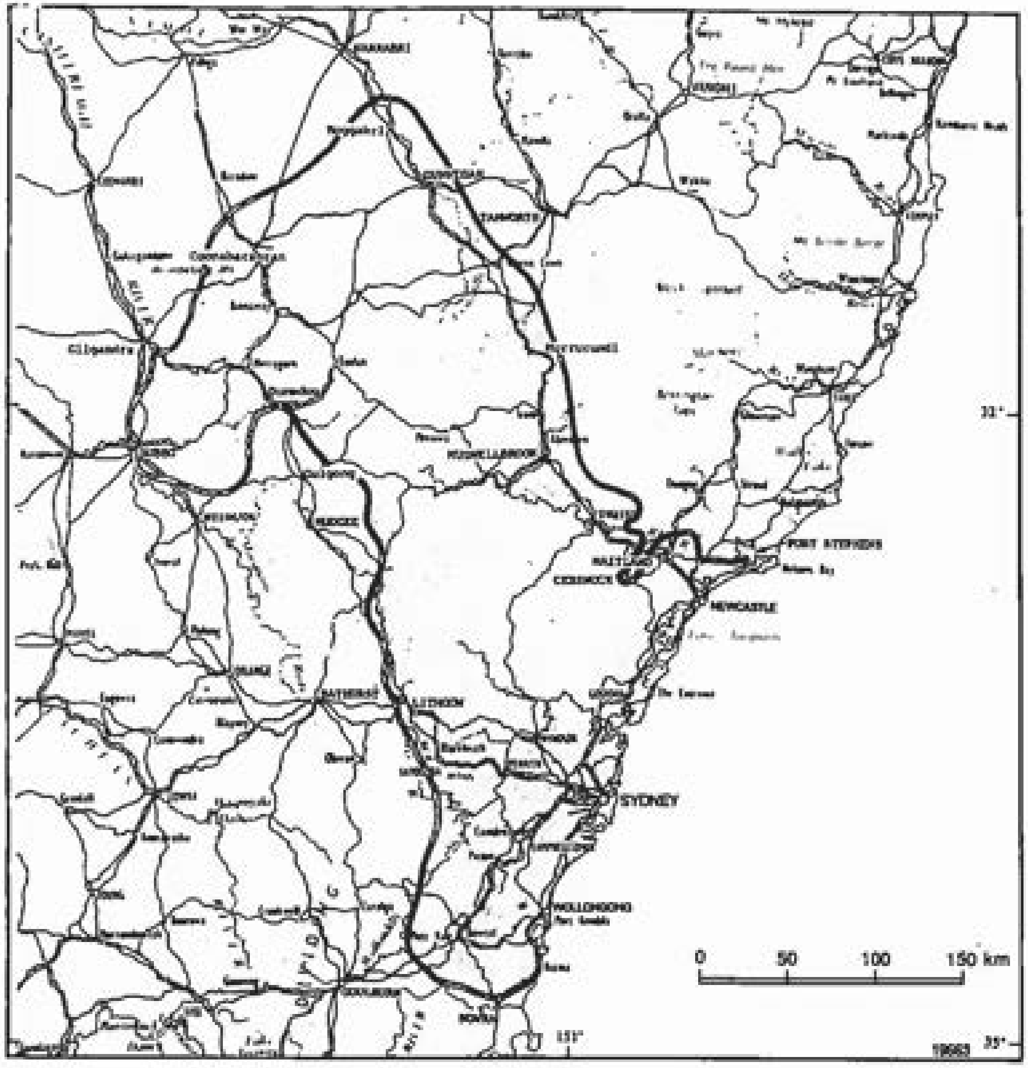


Figure 1. The "Main Coal Basin" of NSW. NSW Geological Survey 1925 map.

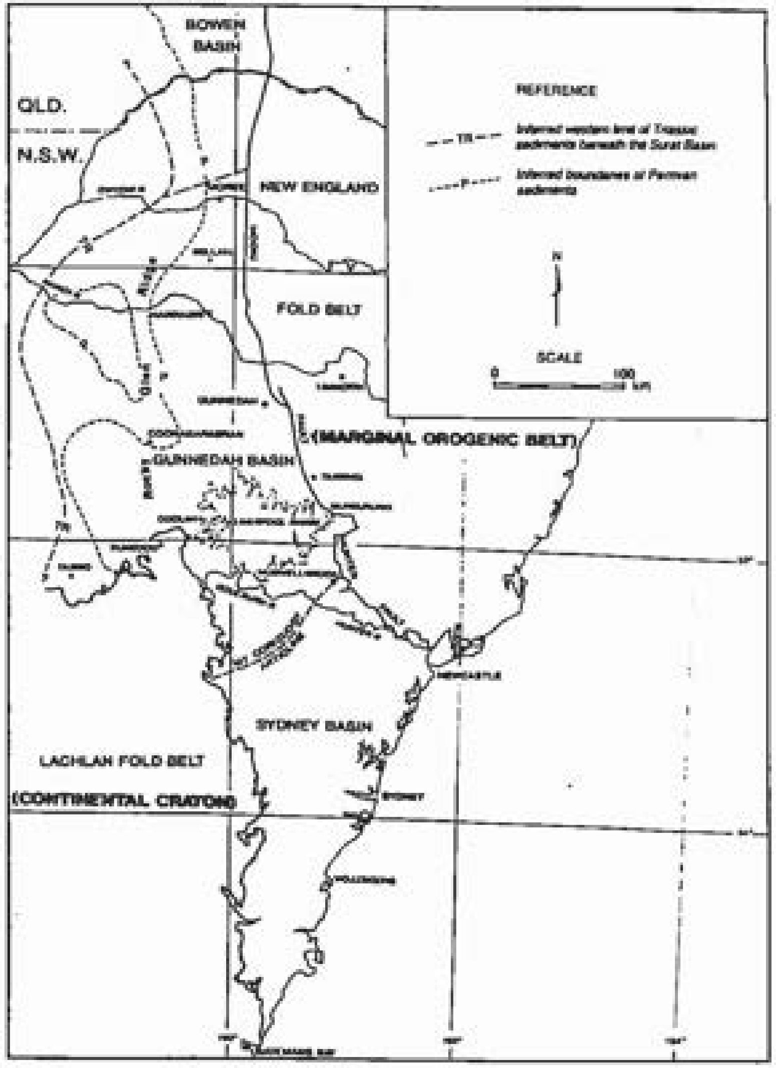


Figure 2. The Sydney–Gunnedah–Bowen Basins in NSW and the tectonic setting.

THE GUNNEDAH BASIN - MEMOIR OF A LAST FRONTIER

During those 10 years, the Department drilled 154 cored boreholes totalling over 55,000 m in 10 programmes (figure 3)

The first half of that period was devoted to scout drilling, 27 boreholes were drilled in six programs, totalling 8,200 m.

1. Four cored boreholes drilled in the *Narrabri - Weetaliba Drilling Programme* along the western area of the basin.
2. Eight cored boreholes drilled in the *Boggabri - Maules Creek Drilling Programme*. This programme revealed the enormous potential of the region.
3. Five cored boreholes located along a line from Boggabri to Caroona in the *Gunnedah Drilling Programme*.
4. Three scout boreholes drilled along the western area of the Gunnedah Basin as part of the *Great Australian Basin Drilling Programme*.
5. Three cored boreholes drilled in *Breeza Drilling Programme* covering the Breeza - Caroona area.
6. Four cored boreholes located west of Boggabri drilled in the *West Boggabri Drilling Programme* to assist in town planning.

The scout drilling phase was followed by a regional exploration phase between 1981 and 1985. This period saw the most intensive drilling ever undertaken by the Department. Over 47,000 m were drilled in 127 cored holes, some up to 1000 m in depth. 35000 m of this drilling was completed in one year in 1981/1982.

1. Nine cored boreholes drilled in the *Goulburn River - Binnaway Drilling Programme* in the south-western corner of the Gunnedah Basin and the contiguous north-western corner of the Sydney Basin.
2. The largest coal drilling programme ever undertaken by the Department, the *Gunnedah Basin Regional Drilling Programme*; was carried out during 1981-82 and involved approximately 31 000 m of drilling in 62 fully cored boreholes, some up to 1000 m deep. The holes were sited on a grid pattern with 12 km spacing along east - west lines approximately 24 km apart.
3. A follow-up programme also during 1982 focussed on the *Breeza - Caroona* area and consisted of some 4000 m of drilling in 15 fully cored boreholes. The holes were generally spaced at 4 km centres and targeted the Black Jack Group.
4. A second follow-up programme, *the Narrabri Drilling Programme*, was carried out during 1984-85 as a joint venture between the Department and the Electricity Commission (now Pacific Power) and involved 8600 m of cored drilling in 41 boreholes spaced at 4 km centres.

The boreholes together with coal company and petroleum exploration drilling provided an excellent regional coverage of the basin north of the Liverpool Range and an extensive database for geological investigations by the Department and university research groups.

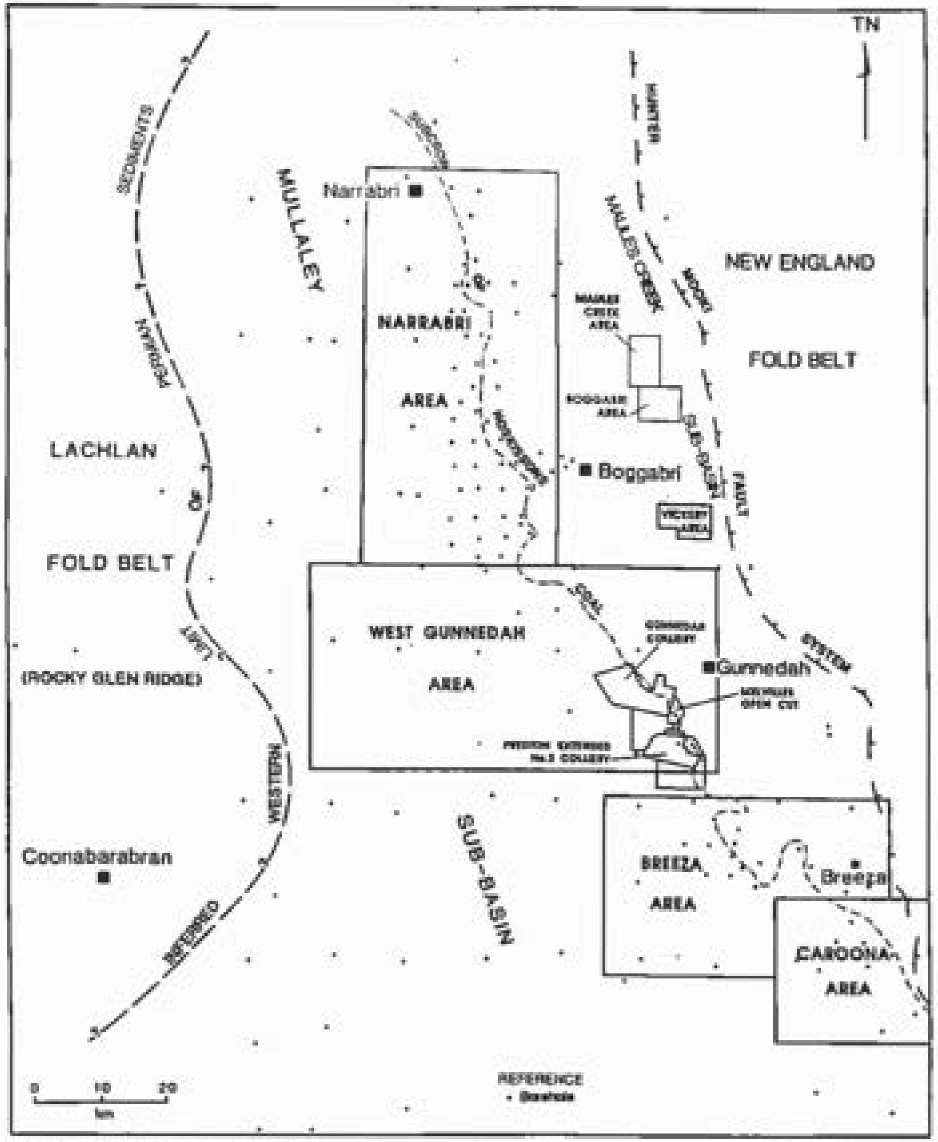


Figure 3. Borehole locations and coal resource areas in the Gunnedah Basin.

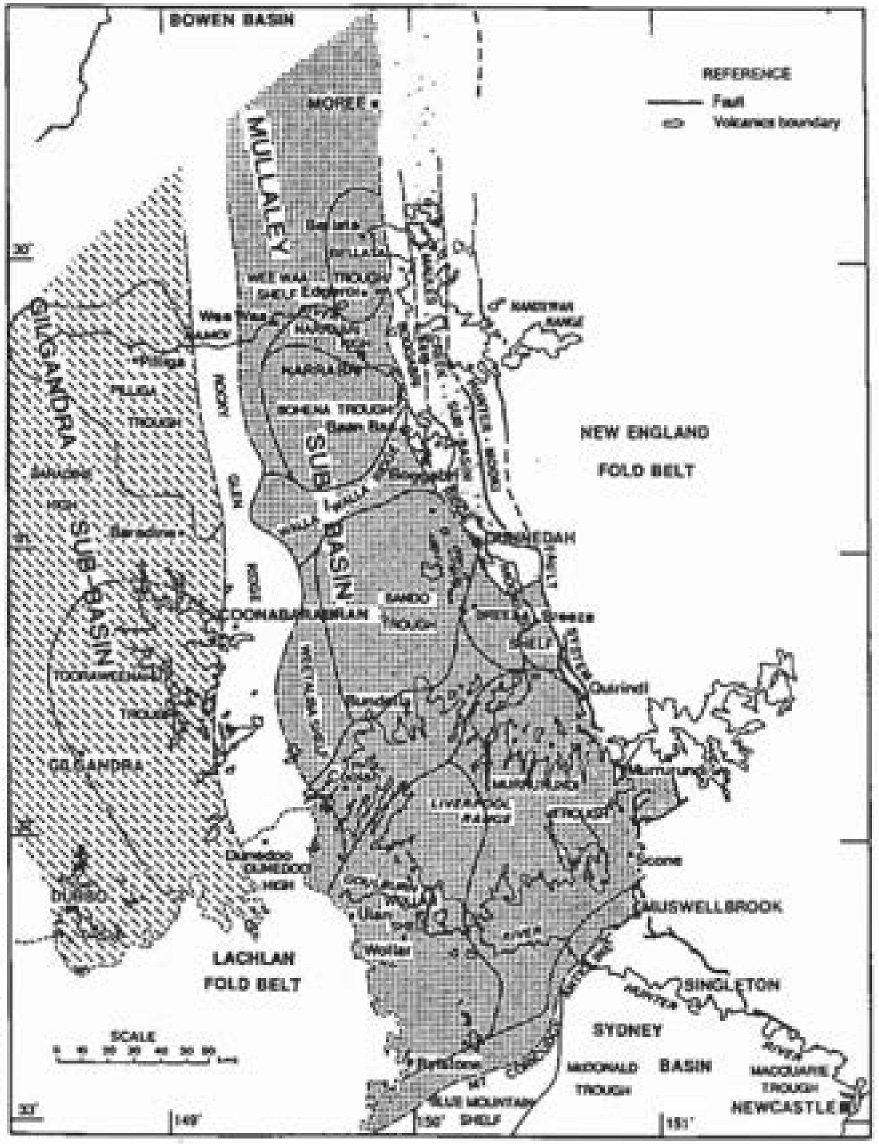


Figure 4. Structural subdivision of the Gunnedah Basin (Tadros 1993)

THE GUNNEDAH BASIN - MEMOIR OF A LAST FRONTIER

RESEARCH PROGRAMME

Although a routine study of drilling results was probably adequate to provide a basic understanding of the stratigraphy and a broad knowledge of the basin's resources, it was decided that a comprehensive research programme was required in order to provide a thorough understanding of the geology of the basin, its tectonic history and structure, and the different processes which controlled and influenced deposition in order to improve reliability of assessment of its fossil fuel resources. The research programme was carried out mainly in the period between 1987 and 1990 and involved processing and synthesising available information and applying modern basin analysis techniques to improve geological interpretations and increase reliability of a comprehensive assessment of the coal resources of the basin.

THE RESULTS

These studies have dramatically changed our perception and knowledge of the various aspects of the geology of the Gunnedah Basin and its resources; some are presented below.

Tectonics and Structure:

Our ideas on the basin structure have improved significantly. Prior to 1981 for example, we had a very sketchy idea about the structural configuration of the basin, its origin and tectonic history. The Gunnedah Basin was considered a structural trough in a foreland setting, bounded by a regional unconformity surface over the Lachlan Fold Belt to the west and by the New England Fold Belt to the east along the Hunter - Mooki Fault System, and is probably continuous with the Bowen Basin to the north.

Basin-wide analysis of the data which became available after 1981 (including drill core, geophysical borehole logs, seismic surveys, regional aeromagnetic and gravity surveys and Landsat and ERTS satellite imagery) has indicated that the basin has complex structural and morphotectonic features and their recognition has given an insight into the manner in which the basin developed. In its early history, the basin was controlled by extensional tectonics which affected the eastern margin of Australia from the Late Carboniferous to the Early Permian (Scheibner 1974, 1976). The present foreland basin configuration only began to form after the mid-Permian period of deformation (diastrophism of Leitch 1974) in the New England Fold Belt (Herbert 1980) when the Hunter-Mooki Fault System developed.

The structural and morphotectonic elements associated with the early history of the basin, strongly influenced basin development and sedimentation in the Permian and Triassic and provided the basis for a useful structural subdivision of the basin (Tadros 1988, 1993) (figure 4). It is now recognised that the basin consists of three north-north-westerly sub-basins lying between meridional basement ridges. The largest, the Mullaley Sub-basin is in turn subdivided by transverse basement highs and ridges into a series of linearly arranged troughs. These structural elements and the early tectonic history of the Gunnedah Basin have left an exceptionally strong imprint on almost every sedimentary unit preserved in the basin.

The studies also resolved problems related to the nature of the Permo-Triassic boundary (figure 5). Compressive deformation which initiated the foreland basin setting intensified towards the end of the Permian and caused major uplift, basin tilting and erosion particularly in the north and north-east (Tadros 1986). As a result,

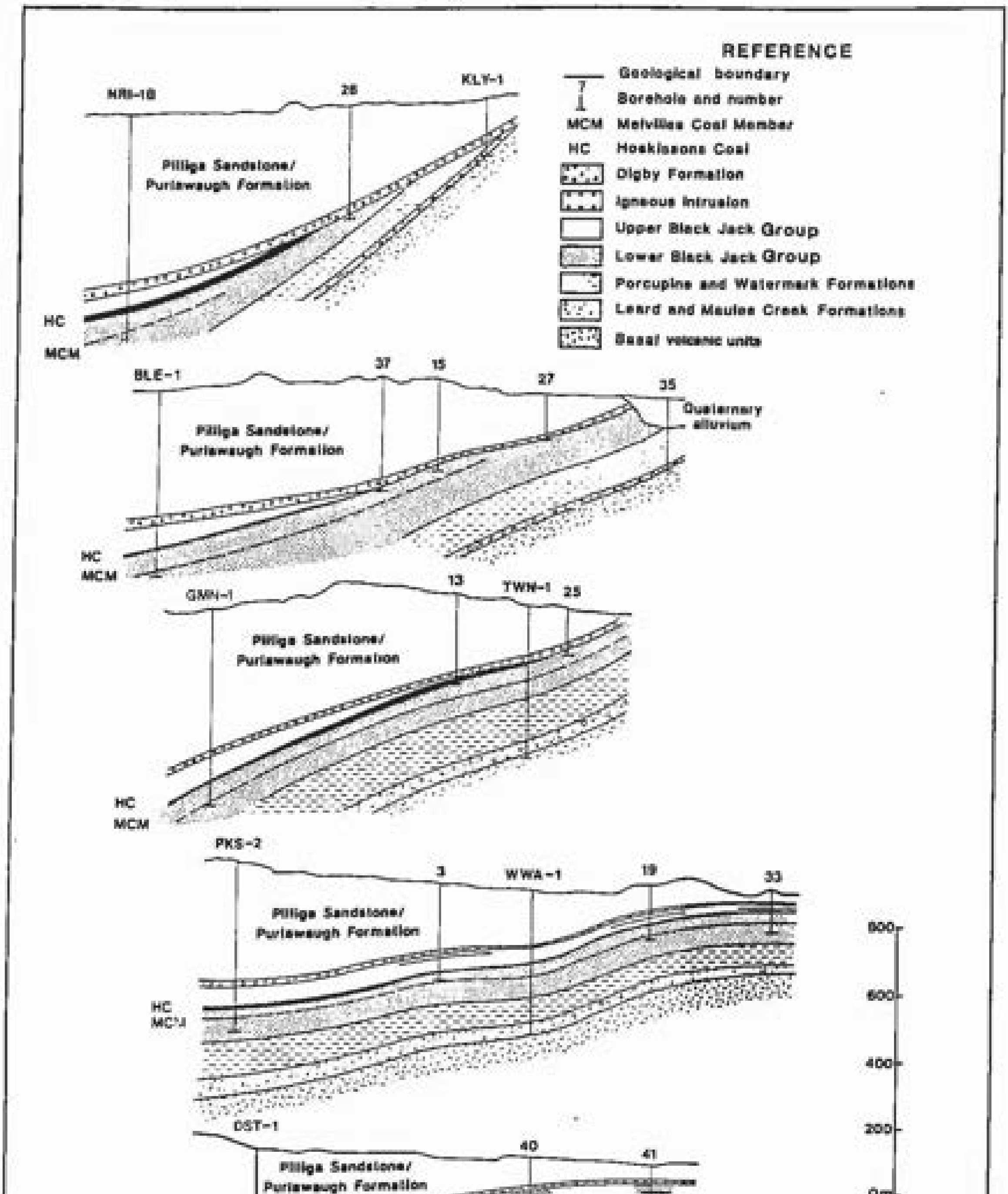


Figure 5. Structural relationship between the Permian and Triassic rocks in the northern Gunnedah Basin (Tadros 1993).

the Triassic sediments directly overlie a Permian sediment wedge with an angular unconformity.

Sedimentology and basin analysis

In absence of extensive exposures, drill core (and geophysical borehole logs) provided an excellent opportunity for the geologists to apply modern basin analysis techniques and develop predictive sedimentary models to solve problems in resource exploration. The work resulted in a great improvement in the reliability of coal seam correlations due to increased understanding of the factors controlling seam continuity, splitting, quality and thickness trends, which are important in coal resource assessment.

Distinct changes in the character of the sedimentary sequence and coal quality across the south-westerly trending transverse structural features have been recognised and in turn contributed to the development of the tectonic and structural models for the whole basin as mentioned earlier.

Stratigraphy

Results of the depositional analysis combined with sedimentology, petrology, palynology, structural and tectonic analyses have greatly assisted in the establishment of a genetically-based, meaningful and usable stratigraphic framework for the Gunnedah Basin sequence (figure 6). The genetic approach to stratigraphic analysis provided the basis for subdivision of the basin fill into widely correlatable and mappable sedimentary units, many of which have significance in resource exploration.

Resources:

Coal

The exploration has also confirmed that the Gunnedah Basin contains coal resources of considerable economic potential, with the Mullaley and Maules Creek Sub-basins containing some 29 billion tonnes of potentially usable in situ coal or 38% of the total in situ coal resources of New South Wales.

Mullalley Sub-basin

Exploration in the Mullaley Sub-basin has indicated that the bulk of the coal resources of the Gunnedah Basin is contained in the Late Permian coal measures, particularly in the Hoskissons seam. Seven other seams have also been identified, successfully correlated and estimated to contain some 10 billion tonnes of in situ coal.

Four areas have been delineated and studied in detail, all containing thermal quality coal suitable for the export and local markets.

Maules Creek Sub-basin

Results from the Department's early drilling in the Boggabri-Maules Creek area attracted great attention and the area soon became the target of intensive drilling by coal exploration companies and the Maules Creek Sub-basin is now the subject of three important mining projects in the Vickery, Boggabri and Maules Creek areas

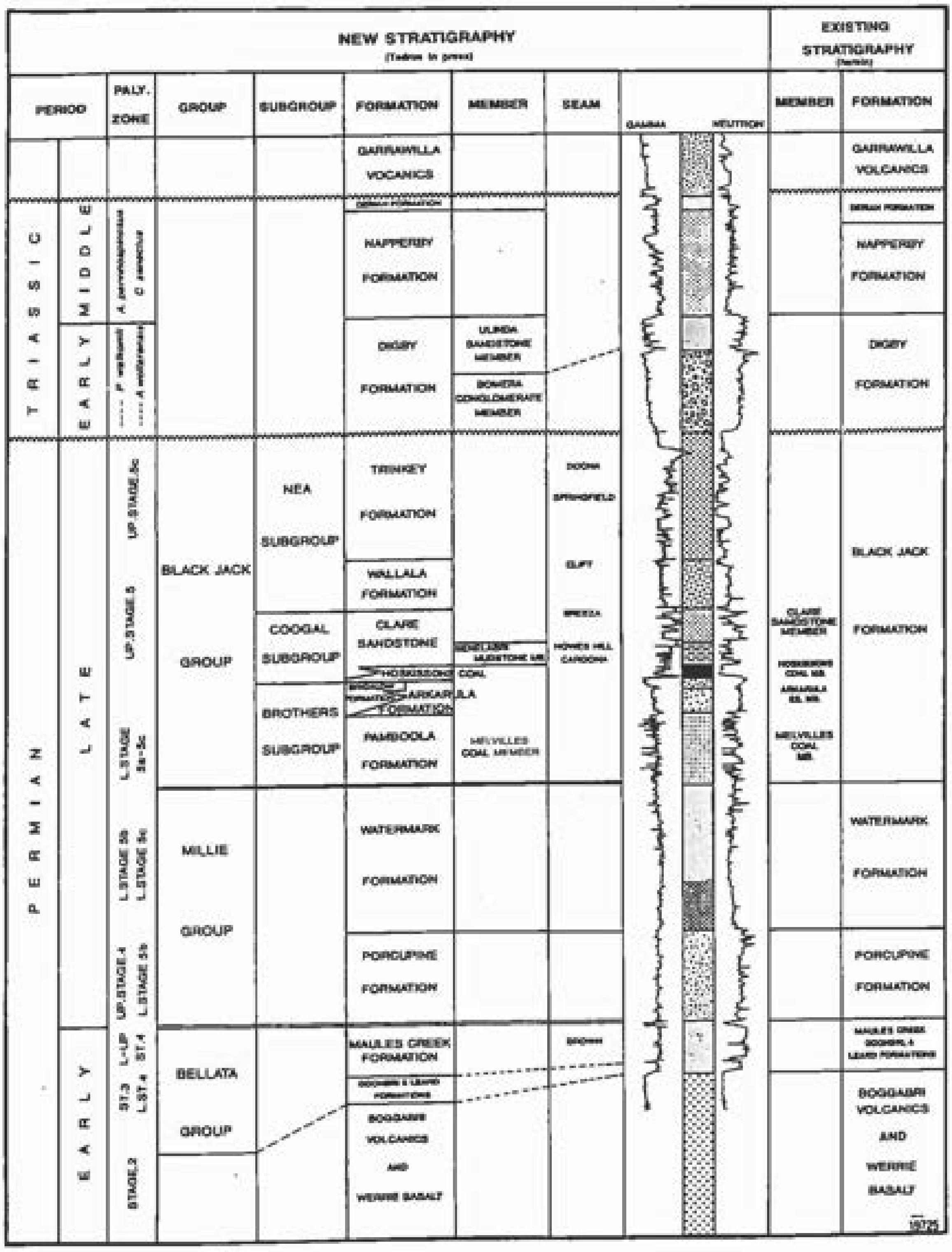


Figure 6. New stratigraphy for the Gunnedah Basin (Tadros 1993).

aimed at producing up to 20 mt per annum. The sub-basin is estimated to contain 2.3 billion tonnes.

Petroleum and Gas

The Gunnedah Basin received little attention from petroleum explorers in the past. Only 15 petroleum wells were drilled in the basin in the period from 1963 to 1967, but with lack of success, and none until 1985.

The Department's exploration drilling has indicated good petroleum source rocks at several stratigraphic horizons. Sandstones with good to excellent reservoir potential also occur at several stratigraphic levels and many are sealed by regionally extensive clayey units or intraformational claystone sequences. The "Western fluvial sandstones" within the Brigalow Formation and Clare Sandstone, is only one example of a rock unit with an excellent reservoir potential both for methane from coal seams and from other hydrocarbon sources. This information together with reporting of several minor gas shows from many locations has revived interest in petroleum exploration in the basin. This was further augmented by the discovery in 1985 of natural gas in Wilga Park No. 1, south-west of Narrabri. Interest in the basin is continuing with recent exploration being targeted at petroleum and coal seam methane.

Documentation

Prior to 1981, geological reporting on Gunnedah Basin generally involved local areas or selected parts of the stratigraphic sequence and much of the earlier work was based on the study of poor outcrop and sparse subsurface information. Only a few published reports are available for that period and basin-wide reporting was almost non-existent except for an unpublished report completed in 1981 by Russell who reviewed earlier work and summarised the stratigraphic nomenclature for the Gunnedah Basin north of the Liverpool Range.

Since 1981, when the drilling activity intensified and abundant core became available for study, many internal reports, research theses and publications were produced. There are now over 35 national and international publications directly based on the Department's core drilling in the Gunnedah Basin with the Memoir representing the culmination in basin-wide reporting.

The Gunnedah Basin Memoir (Tadros 1993)

The idea of publishing a Memoir on the Gunnedah Basin was conceived early in the 1980's during the initial interpretations and the preliminary assessment of the results from the Regional Drilling programme of 1981/1982. However, comprehensive basin-wide interpretation and assessment necessary for the Memoir had to wait until the last drilling programme was completed in 1986. An overview project was commenced in July 1987 to assess and document the massive amount of data and geological information obtained from Departmental drilling programs between 1975 and 1986 and completed in July 1989. The overview provided a usable database for the Memoir. The first draft of the Memoir was compiled in June 1990 and subsequent revisions, improvements and minor updates were completed in March 1993.

The period of 10 years from inception to publication of the Memoir is not unreasonably long considering the area of the basin (some 50,000 km^2), the time spent on the drilling and then compiling and synthesizing the data, dealing with complex correlations of stratigraphic units and coal seams where data points are generally spaced some 4 to 8 kms apart. Many supplementary tools had to be used and new methods and techniques applied in order to improve understanding of the basin geology and increase reliability of correlations. University research groups extended this analysis to the non-coal-bearing sections of the sequence, completing the coverage of the basin rocks and allowing a comprehensive understanding of the sedimentology of the basin.

Quarterly Notes of the Geological Survey of New South Wales and other forms of publications were used as a forum for discussion and feed-back which helped to fine-tune ideas prior to final publication in the Memoir. Much of the work was also reviewed locally and internationally.

The Gunnedah Basin Memoir is a comprehensive reference of the current knowledge of the basin. It contains a wealth of information and brings together, not only the vast amount of raw data on the basin, but also the synthesised information, interpretation and modelling, and application of modern basin analysis techniques to the assessment of the basin's fossil fuel resources.

The memoir is divided into six parts.

Part 1 introduces the subject, sets the scene for detailed discussions in the main text, and provides information on the geography of the region, the present infrastructure and the history of exploration and mining. Also included is an overview of previous geological work on the basin. Part 2 discusses the tectonics and structure of the basin.

Parts 3 and 4 provide extensive treatment of the stratigraphy and sedimentology of the Permian and Triassic rocks in the Gunnedah Basin. Details of lithostratigraphy are given in Part 3, along with discussions on palynostratigraphy and genetic stratigraphy. Detailed sedimentology is covered in Part 4, using the concepts of depositional episodes and the depositional systems.

Specialised topics are grouped in Part 5, including a geophysical study, a detailed analysis of the rocks forming the floor of the Gunnedah Basin, a study of igneous intrusions and their influence on the coal, an analysis of the petroleum potential of the basin, a study on the influence of depositional setting on Permian coals and a petrographic study of the coal.

The coal resources of the basin have been given ample space in the Memoir in Part 6. Topics cover the procedures and criteria used in resource assessment, a detailed analysis of the main coal seams, their distribution and coal characteristics. This is in addition to detailed studies of seven coal resource areas in the Maules Creek and Mullaley Sub-basins.

The Memoir should form a valuable source of information for research workers as well as geologists in the exploration and mining industries.

MAGNETOSTRATIGRAPHY OF THE LATE PERMIAN COAL MEASURES, SYDNEY & GUNNEDAH BASINS : A REGIONAL & GLOBAL CORRELATION TOOL

H. THEVENIAUT, C. KLOOTWIJK, C. FOSTER &
J. GIDDINGS*

* In cooperation with : J. Beckett (NSWDM), A. Brakel (AGSO), P. Carr (Wollongong), J. Claoué-Long (AGSO), C. Diessel (Newcastle), R. Glen (NSWGS), A. Hutton (Wollongong), B. Jones (Wollongong), P. Jones (AGSO), K. Moelle (Newcastle), J. Roberts (UNSW), P. Schmidt (CSIRO), J. Shergold (AGSO)

SUMMARY

Litho- and biostratigraphic correlation of drillcores from the Late Permian coal measures of the Sydney, Gunnedah and Bowen Basins suffers from the uncertainties commonly experienced in correlation of continental sequences. AGSO, in collaboration with others, has started a study on the potential use of magnetostratigraphy as an additional correlation tool. Initial results show that the coal measures postdate the Permo-Carboniferous Reverse Superchron ("Kiaman") and that reversal sequences in the upper coal measures may be correlatable between the Sydney and Gunnedah Basins. The demonstrated presence of reversal sequences in the lower coal measures, of Kazanian-Djulfian and probably Ufimian age, highlights the need for re-evalution of the Early to Late Tatarian age commonly concluded for the top of the "Kiaman" from Late Permian stratotypes in Russia and Tatarstan.

INTRODUCTION

The late Palaeozoic is characterized by a long interval of reverse polarity of the Earth's magnetic field ("Kiaman"), from about the Middle Carboniferous to the Late Permian, followed by a period of polarity changes with average reversal frequencies of up to about two per million years in the latest Permian and in the Early Triassic (Gallet et al., 1992; Steiner and Opdyke, 1993). Such reversal rates offer prospects for magnetostratigraphic correlation and dating in the Late Permian coal measures of eastern Australia where biostratigraphic dating potential is limited. To use magnetostratigraphy as a correlation and dating tool, however, we need to define the extent of the "Kiaman" in eastern Australia, and the magnetostratigraphy of the Late Permian.

The late Palaeozoic interval of reverse polarity was first defined by Irving and Parry (1963) from eastern Australian sections and was termed the "Kiaman Magnetic Interval". Nowadays it is known as the Permo-Carboniferous Reverse Superchron (PCRS) (Anonymous, 1979). On the basis of palaeomagnetic results from Carboniferous sections in the Hunter Valley, Irving (1966) defined the older boundary of the "Kiaman" as the "Paterson Reversal". This marks the change from normal polarity in the Paterson Volcanics (Paterson Toscanite) to

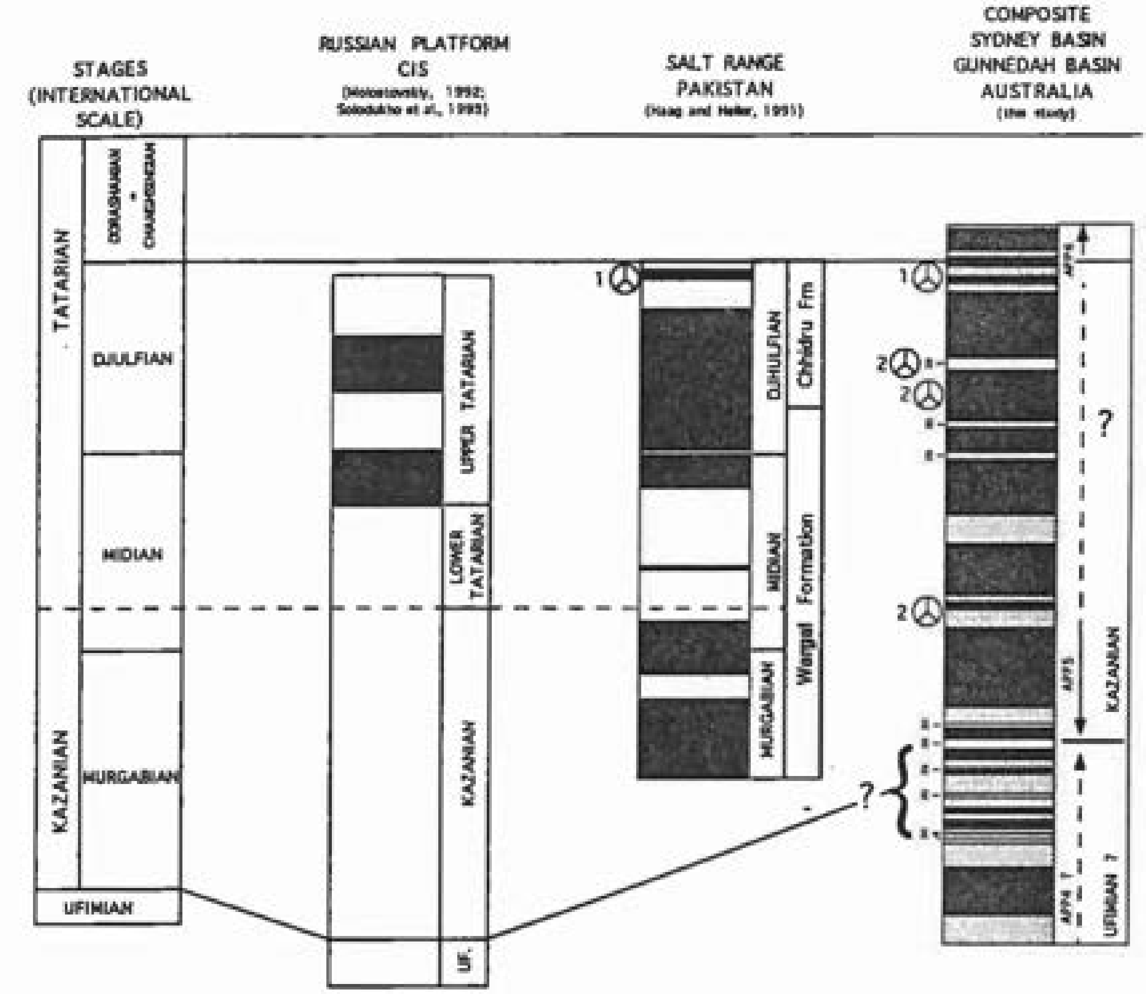


Fig.1 Tentative global correlation of Late Permian magnetostratigraphic profiles. 1= Protohaploxypinus microcorpus Zone, 2= Dulhuntyispora parvithola Zone (= AAP5). Reference timescale after Archbold & Dickins (1991), Kapoor (1992) and Kozur (1992). Salt Range timescale adapted after Pakistani-Japanese Research Group (1985).

reverse polarity in the overlying Seaham Formation (upper kuttung glacial sediments). The younger boundary was defined as the "Illawarra Reversal", then no better defined than post-Gerringong Volcanics (upper marine latites) and pre-Narrabeen Group (Irving, 1963) (Narrabeen chocolate shales). This left the younger boundary of the "Kiaman" undefined within the latest Permian coal measures of the Sydney Basin, compromising the use of magnetostratigraphy as a regional correlation and dating tool.

Recently, progress has been made overseas in defining the base and top of the PCRS. High quality magnetostratigraphic profiles with good biostratigraphic control for the mid-Carboniferous of North America and detailed magnetostratigraphic profiles for the Late Permian of Russia and Tatarstan are now available, although none of those profiles locates the boundaries of the PCRS at zone level. In the eastern Australian original type-region, however, little progress has been made since the pioneering studies of Irving and Parry (1963) to define more closely the boundaries of the "Kiaman", other than studies limited to reconnaissance magnetostratigraphy of drillcores from the Illawarra Coal Measures (Facer, 1981) and a more detailed magnetostratigraphy of the Narrabeen Group (Embleton and McDonnell, 1980).

The Australian Geological Survey Organisation, in cooperation with research groups at the Universities of Newcastle, New South Wales and Wollongong, as well as CSIRO, the New South Wales Geological Survey and the Coal Geology and Petroleum Branch of the New South Wales Department of Mineral Resources, has now started a program to define more closely the boundaries of the "Kiaman" and the magnetostratigraphy near the onset and after the end of the PCRS in the original "Kiaman" type region. Here, we present results from a pilot study to locate the younger boundary of the PCRS, with particular emphasis on the potential of magnetostratigraphy for regional and global correlation and dating of the Late Permian coal measures in the Sydney and Gunnedah Basins.

LATE PERMIAN POST-PCRS MAGNETOSTRATIGRAPHIC CONSTRAINTS

The younger boundary of the PCRS is conventionally taken as the boundary between the Early and Late Tatarian in the Permian stratotypes of Russia and Tatarstan (Fig. 1). The boundary is based on a considerable body of magnetostratigraphic results which reveal a consistent pattern of reversals across the various Tatarian stratotypes and lithologies studied (e.g. Khramov and Rodionov, 1981; Khramov, 1987; Molostovskiy, 1992; Solodukho et al., 1993). Unfortunately, the results are not always readily accessible, and, while the studied stratotypes no doubt have great potential for development of a magnetostratigraphic timescale, the value of existing results needs to be re-examined.

Recent magnetostratigraphic studies of marine, Permo-Triassic boundary sections do not support the magnetostratigraphic interpretation of the mainly continental stratotypes in Russia and Tatarstan. A detailed study of the uppermost Permian Chhidru and Wargal Formations of the Nammal Gorge in the Salt Range of Pakistan (Haag and Heller, 1991) concluded that the mixed polarity region of the Illawarra Superchron, which succeeds the PCRS, had already been established in the Murgabian of the south central Tethys (Fig. 1). The latter may be equated with the Guadalupian of North America and the Kazanian of the International Time Scale. The younger boundary of the PCRS would thus predate the Tatarian. An older age for the start of the Illawarra Superchron than the Early to Late Tatarian boundary concluded in Russian studies on the Late Permian stratotypes, was reached earlier from less robust magnetostratigraphic studies on Permo-Triassic boundary sections in the Sichuan province of southcentral China and a compilation of earlier data (Heller et al., 1988; Steiner et al., 1989). Considerable magnetostratigraphic work carried out on mainly continental Permo-Triassic boundary successions within the Germanic facies realm of northwestern Europe (e.g. Menning, 1986; Menning et al., 1988), suffers from the absence of detailed biostratigraphic control, and relies on global correlation for locating the PCRS-Illawarra Superchron boundary. It does not therefore constitute an independent constraint on its location.

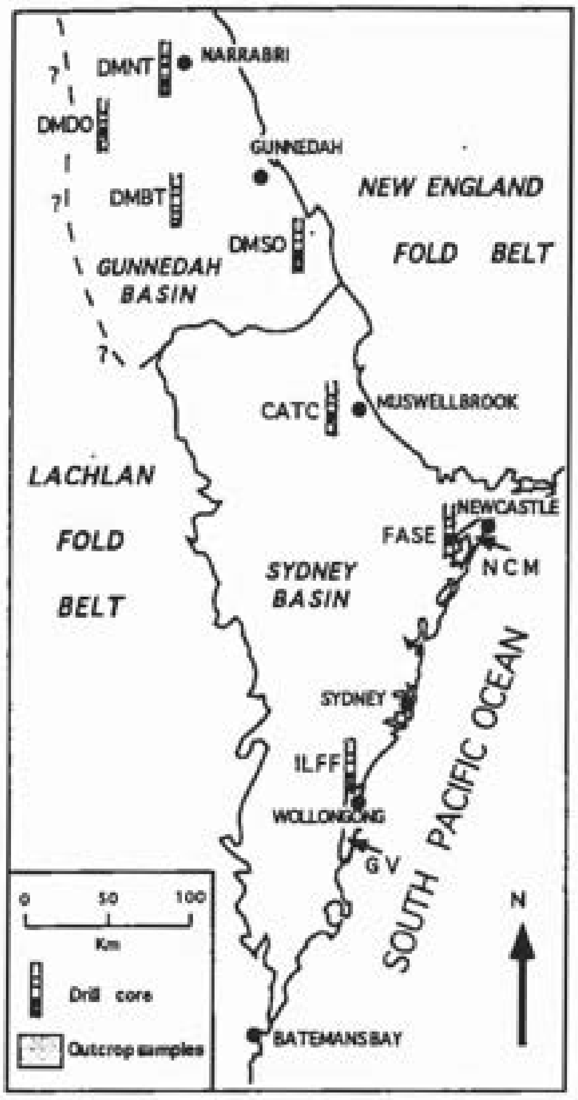


Fig.2 Overview of drillcore and outcrop sites in the Sydney and Gunnedah Basins.

The Late Permian coal measures of the Sydney, Gunnedah and Bowen Basins provide a unique opportunity to evaluate the findings from the mainly continental Permian stratotypes in Russia and Tatarstan. The sequences span the time-interval under dispute, show a high sedimentation rate that offers considerable resolution in time, and have been drilled extensively. The sequences have some palynological control, with one of us (CF) having first-hand knowledge of the spore-pollen and faunal associations of both the eastern Australian sections and the Permian stratotypes in Russia and Tatarstan. A particularly significant circumstance is the widespread occurrence of tuffaceous horizons throughout the sequences that may be suitable for U-Pb (SHRIMP) dating. This offers the first prospect of accurate chronostratigraphic constraints on the PCRS-Illawarra Superchron boundary and the reversal sequence of the coal measures. Lastly, magnetostratigraphic analysis of drillcores from the coal measures may result in more reliable and more detailed regional correlation and dating of prospective coal seams than can be obtained from lithostratigraphic and biostratigraphic studies alone, enabling its potential as a fast and effective exploration tool to be evaluated.

SAMPLING

In the southern Sydney Basin between Wollongong and Gerringong, oriented cores were drilled from the Late Permian Gerringong Volcanic Facies (Fig. 2) of the Broughton Formation and overlying Pheasants Nest Formation (Carr, 1983; Bull and Cas, 1989). We sampled five of the nine volcanic units (Blow Hole, Bumbo, Dapto, Cambewarra and Berkeley Latites: 18 sites, 180 samples) and the three intercalated, fine-grained, reddish and green-greyish volcaniclastic sedimentary units (Westley Park, Kiama and Jamberoo sandstone members: 9 sites, 94 samples).

MAGNETOSTRATIGRAPHY OF LATE PERMIAN COAL MEASURES

For the coal measures both surface outcrop and drillcore material was sampled. Oriented cores were drilled from tuff horizons in the Newcastle Coal Measures in coastal outcrops south of Newcastle and in an open-cut coalmine near Teralba (Nobbys Tuff: 2 sites; Reids Mistake Formation: 2 sites; Awaba Tuff: 3 sites; 70 samples in total). Unoriented cores were drilled along the axes of 7 commercial drillcores spread over the Sydney and Gunnedah Basins (Fig. 2, Table 1). Samples were taken at an average interval of 1 to 2 metres in tuff horizons (preferred if present), fine-grained sandstones, siltstones and mudstones. Detailed directional control on the complex magnetization pattern characteristic of rocks along the Tasman seaboard was established using the oriented samples to provide a key to the interpretation of data from the unoriented cores. The unoriented cores were taken specifically to establish polarity patterns with good stratigraphic control.

TABLE 1: DRILLCORE SAMPLE DATA

Core	Proprietor	Id	Interval (m)	Length (m)	#Samp	Spacing (m, aver)
ILUKA55	Kembla Coal & Coke	ILFF	381.8-557.4	175.6	153	1.15
FAI DDHN 1968	FAI Mining Group	FASE	11.5-144.2	132.7	69	1.92
DDH 2000-C000	Coal & Allied	CATC	20.1-345.7	325.6	123	2.65
Springfield DDH1	NSWDM, Coal Branch	DMSO	311.6-648.8	337.2	130	2.59
Dampler DDH1	NSWDM, Coal Branch	DMDO	595.6-694.9	99.3	46	2.16
Brigalow DDH2	NSWDM, Coal Branch	DMBT	448.7-546.3	97.6	46	2.12
Narrabri DDH2	NSWDM, Coal Branch	DMNT	497.8-593.5	95.7	45	2.13

Samples of the ILUKA55 drillcore at Coal Cliff in the southern Sydney Basin cover the basal part of the Narrabeen Group and the Illawarra Coal Measures, from the Wombara Shale down to below the Tongara seam. The samples from core FAI DDHN 1968 of Teralba in the northwestern Sydney Basin cover the Newcastle Coal Measures from the Hartley Hill seam to the Borehole seam. Samples from the DDH 2000-C000 drillcore of Muswellbrook in the northeastern Sydney Basin cover the Wittingham Coal Measures from the Bowfield seam to the Edinglassie seam. Samples from three (Springfield #1, Dampier #1, Brigalow #2) of the four drillcores of the Gunnedah Basin cover the Digby, Black Jack and Watermark Formations with sampling of the Narrabri #2 drillcore extended down to the Porcupine Formation.

TREATMENT AND RESULTS

All measurements of remanence have been made using either a 2G-Enterprises or a ScT cryogenic magnetometer. About a quarter of the samples have been studied so far in detail (pilot specimens) using alternating field (AF) and thermal demagnetization techniques and principal component analysis. Generally, several pilots have been selected per outcrop site (1 to 5 for the Gerringong Volcanic Facies sites, 3 to 4 for the coal measures sites) and one pilot per 2 to 3 drillcore samples.

Gerringong Volcanic Facies

We can make some general observations based on the 58 pilots studied so far. For the latites, the remanence clearly comprises two main components of magnetization: a softer north-northwesterly- to east-northeasterly-directed, upward-pointing magnetization of moderate to steep inclination, and a harder, southerly-directed, downward-pointing magnetization with steep inclinations. For the sedimentary units, this latter, reverse magnetization is rarely observed: when present it forms the last few percent of the magnetization and is ill-defined in direction. Generally, only the upward-pointing magnetization is present. We interpret the upward-pointing or normal polarity component of magnetization found *throughout* the Gerringong Volcanic Facies as an overprint magnetization of Late Cretaceous age related, like other similar overprints found throughout the Sydney Basin, to elevated temperatures and fluid flow stemming from rifting along the Tasman seaboard. The reverse magnetization is interpreted as the primary magnetization, confirming Irving and Parry's (1963) original interpretation. The Gerringong Volcanic Facies thus represents the youngest unit of the PCRS presently known in Australia.

Coal Measures

Pilot demagnetization studies have been carried out so far on less than half (drillcores 235; outcrop 30) of the samples. Routine thermal or AF demagnetization produced interpretable results for no more than a quarter of the samples so analyzed (Fig. 3a,b). The unaltered tuffs were generally well-behaved during either of the demagnetization methods. This is less so for the sandstones, siltstones, mudstones and kaolinized tuffs, because the presence of sulphides in these lithologies is probably the source of magnetic phase changes and viscous magnetization behaviour observed after thermal treatment above 350^{0}C. AF treatment at the peak-field limit (100 mT) is insufficient for complete demagnetization of the sulphides. In contrast, application of combined AF and thermal demagnetization produced interpretable results for about 70% of the specimens (Fig. 3c-f). This procedure consists of partial AF demagnetization up to 15 mT for removal of a drilling-induced overprint, if any, followed by partial thermal demagnetization up to 330^0-350^{0}C, and subsequent AF demagnetization from 17 mT up to 100 mT.

The intensity of natural remanent magnetization (NRM) varied little across the various lithologies and was around 1 - 2 mA/m for both drillcore and outcrop samples. In the oriented samples from the tuff horizons in the Newcastle Coal Measures, three components could be identified: a magnetically soft component of normal polarity close to the local Earth's field direction and obviously of recent origin; an intermediate component of normal polarity that is in good agreement with other determinations along the Tasman seaboard of an overprint of Late Cretaceous age; and a hard component of both normal and reverse polarity. The hard component is east-west directed and inclined at about 80^0. A fold test is indicative of a primary origin. The unoriented samples from the drillcores show a similar magnetization pattern (Fig. 3). We have yet to

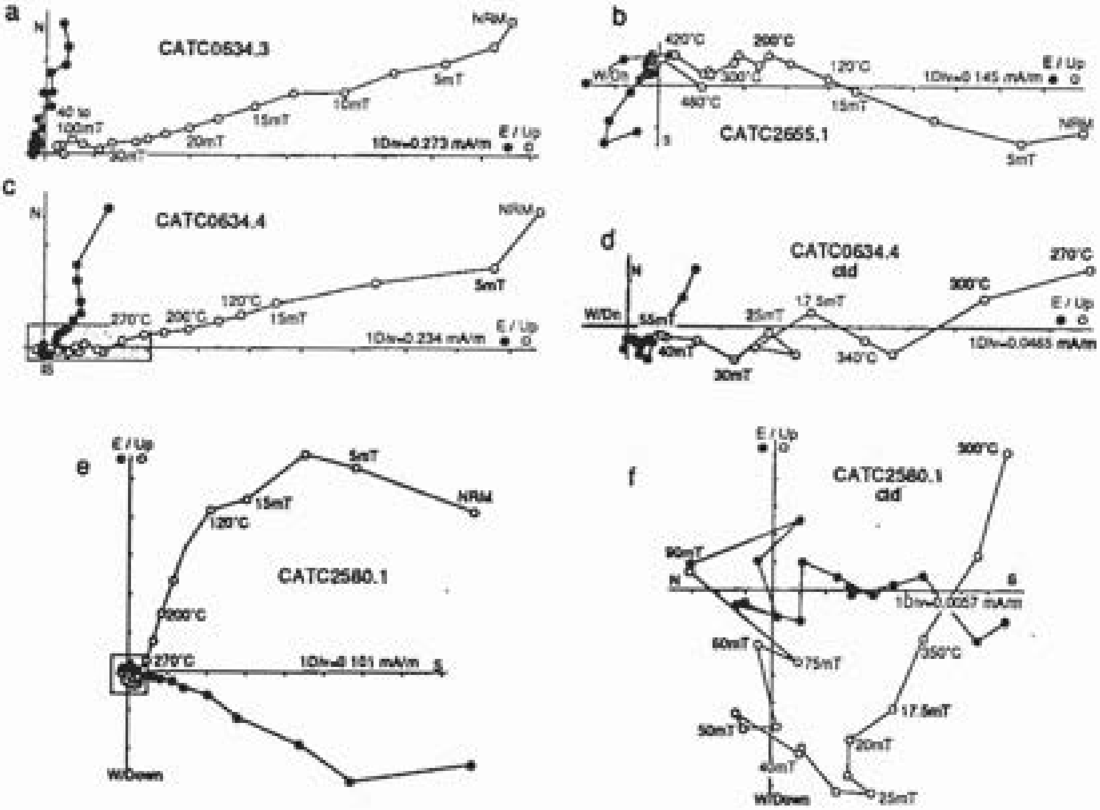


Fig.3 Zijderveld plots of representative specimens during alternating field (d) or combined alternating field and thermal (a,b,c,e,f) demagnetization. The samples are from unoriented drillcores. The orthogonal projection on the vertical plane is therefore shown in geographic (field) coordinates, but the horizontal projection is shown with arbitrary North. Numbers denote successive peak field values in mT or ^{0}C; ctd indicates partial enlargment as indicated by shaded box.

analyze their results systematically in terms of soft recent and drilling-induced overprints. An intermediate component of normal polarity (mean inclination: $I_m = -68^0 \pm 4.8^0$), removed below 350^{0}C, may represent a Late Cretaceous and/or recent overprint. A harder component, identified upon subsequent AF-demagnetization and displaying both normal and reverse polarities and higher inclination ($I_m = -82.6^0 \pm 6.3^0$), is interpreted as the primary magnetization. This interpretation may be tested through the application of a foldtest in later studies, after we have determined constraints on the fiducial orientation of the samples and regional bedding attitudes. A positive baked contact test around a basaltic intrusion within the Piercefield seam of the Wittingham Formation (Fig. 4, CATC drillcore) supports a primary origin for this hard component.

IMPLICATIONS FOR CORRELATION AND DATING

A compilation of the results obtained thus far shows potential for the magnetostratigraphic correlation of drillcores from the coal measures across the Sydney and Gunnedah Basins, and possibly the Bowen Basin. The Trinkey Formation of the upper Black Jack Group stands out as an interval of successive normal and reverse polarities in the three Gunnedah Basin drillcores that

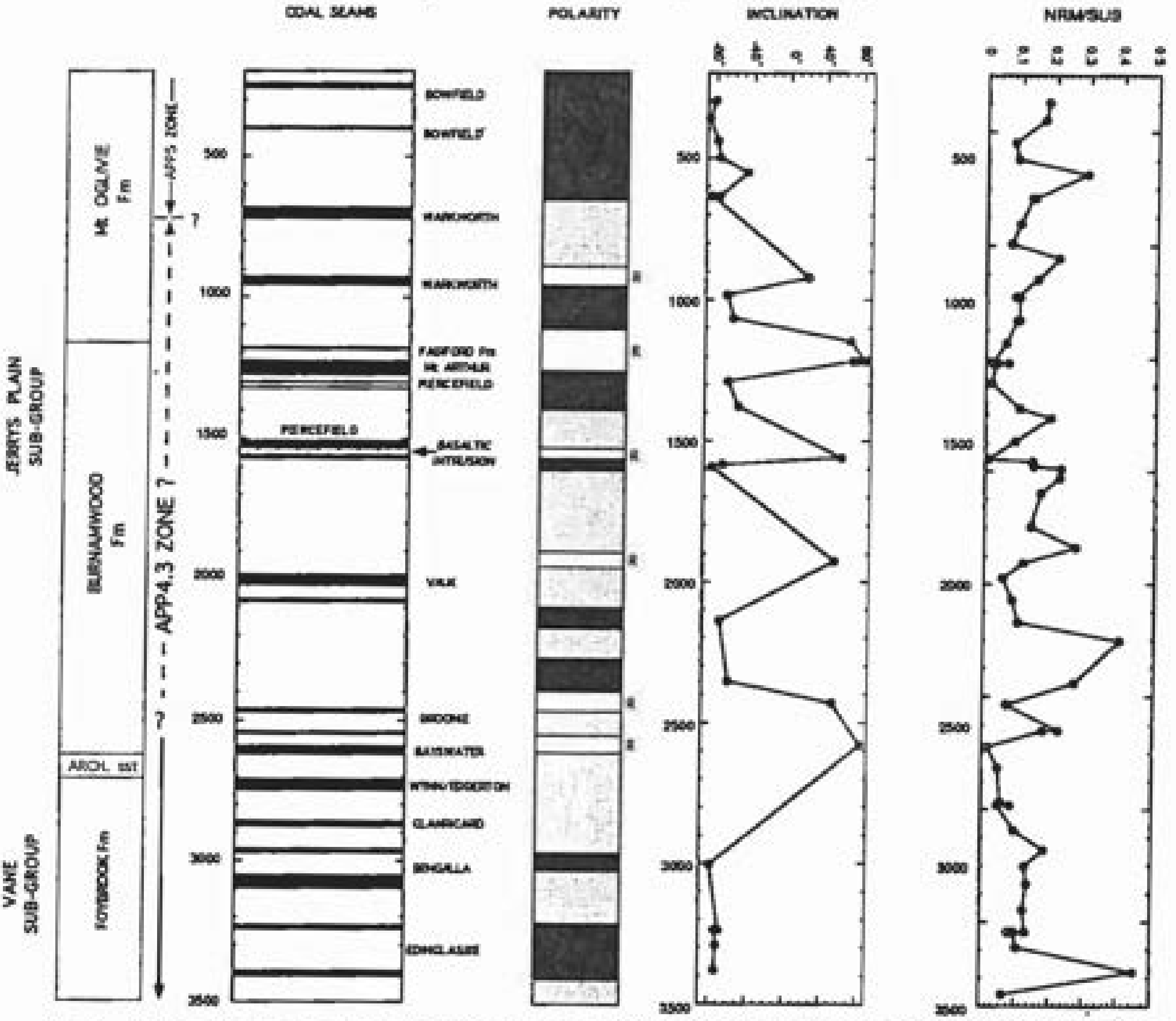
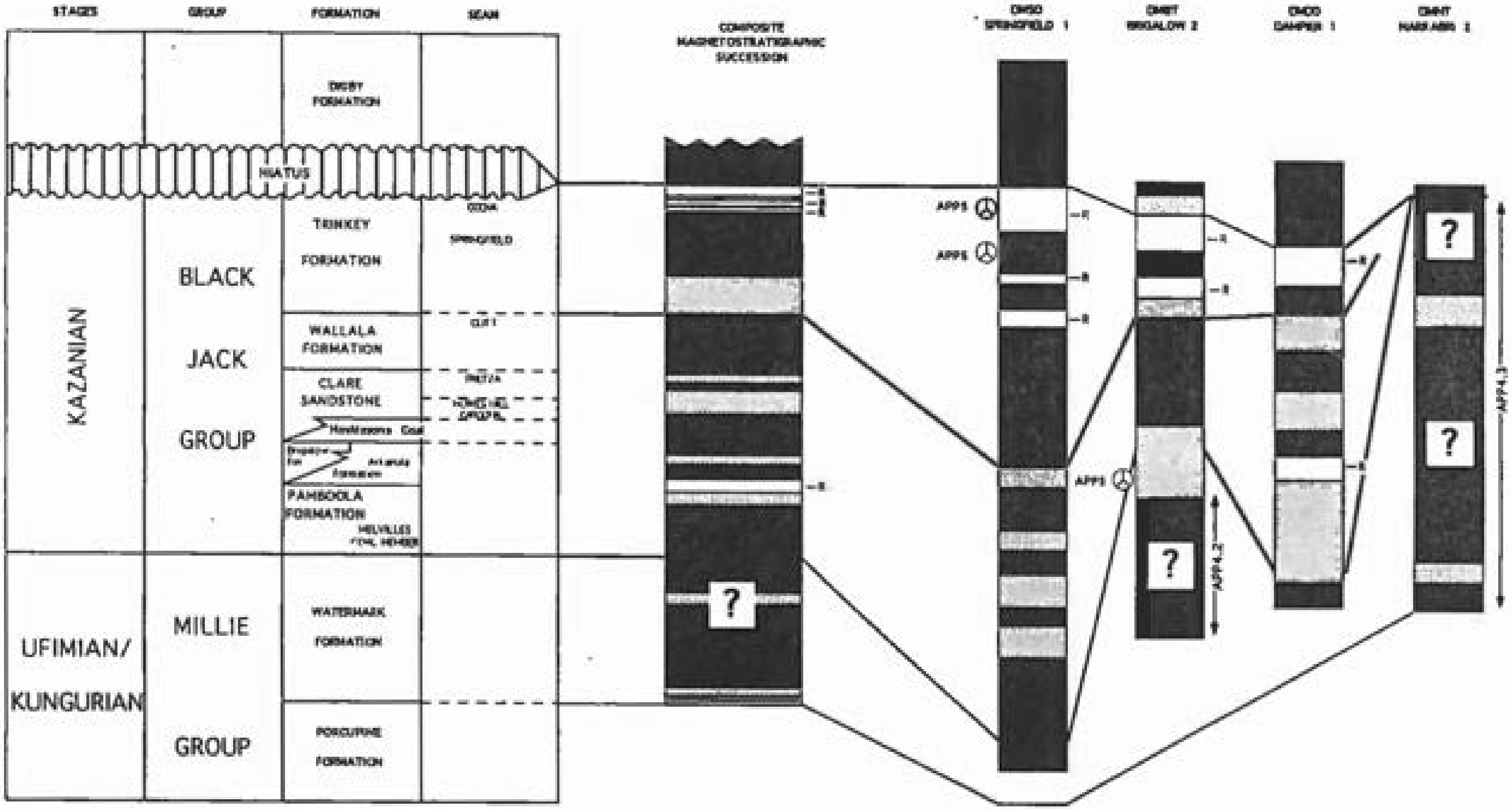


Fig.4 Preliminary magnetostratigraphy for core CATC (Mount Pleasant DDH2000-C000) of the Wittingham Coal Measures at Muswellbrook. Palynological correlation from McMinn (1987).

contain a record of this formation (Fig. 5). The remainder of the studied successions is characterized by normal polarity, apart from a single reverse polarity observation in the lower part of the Black Jack Group of the Dampier #1 drillcore. At the present cursory level of sampling and analysis and on the basis of the available palaeontological control for the Dampier #1 drillcore, it appears equally plausible that this reverse polarity interval from the Gunnedah Basin postdates or correlates with the well-determined reverse polarity intervals from the Wittingham Coal Measures (Figs 4,5,6; CATC drillcore) of the northwestern Sydney Basin. The reverse intervals of the latter (Fig. 4) are tentatively assigned to palynozones APP4.3 and APP5 of Price (*in* Draper et al., 1990), from re-evaluating correlations shown by McMinn (1987), whereas the reverse polarity interval of the former is tentatively assigned to palynozone APP5 (Fig. 5). In the Newcastle Coal Measures of the northeastern Sydney Basin a reverse polarity interval in the Nobbys Tuff was observed both in the drillcore from Teralba (FASE) and in the outcrop at Newcastle harbour (Fig. 6). Coastal outcrops south of Newcastle show another reverse polarity interval in the younger Awaba Tuff (Fig. 6). A tentative correlation of these reverse polarity intervals in the Newcastle Coal Measures with some observations of reverse polarities in the lower part of the ILUKA55 drillcore (ILFF) from the Illawarra Coal Measures is indicated in Figure 6. Possible correlation of the distinct pattern of three successive reverse polarity intervals in the Newcastle Coal Measures and Illawarra Coal Measures with a comparable pattern in the Upper Black Jack Formation of the Gunnedah Basin (Fig. 6) (upper Black Jack Group, Fig. 5) will be examined further.

The present results have important implications for the biostratigraphic location of the younger boundary of the PCRS. The normal polarity observations at the base of the studied cores indicate that the top of the PCRS has apparently not yet been reached in any of the cores. This locates the top of the PCRS somewhere between the top of the Gerringong Volcanic Facies and the studied part of the Wittingham Formation (CATC core) from the northwestern Sydney Basin (Fig. 6). Palynological control on the Gunnedah Basin cores (Foster unpublished; McMinn, 1993) and the Sydney Basin cores (McMinn, 1987) and correlation between fauna-bearing sequences in Queensland and Russia (Foster, Palmieri & Bondereva, in prep.) indicates a Kazanian age for at least part of palynozone APP5. Palynofloral correlations between Australia and fauna-bearing sequences in Austria and the Salt Range of Pakistan provide a Djulfian age for the succeeding APP6 palynozone. Consequently the succession of normal and reverse polarities observed in the studied upper part of the Wittingham Coal Measures of the northwestern Sydney Basin and in the Lower Black Jack Formation of the Gunnedah Basin belong to the interval Kazanian-Djulfian. We assume a probable Ufimian age for the studied lower part of the Wittingham Coal Measures of mixed polarity and for the tentatively normal polarity succession observed in the Watermark Formation of the Gunnedah Basin (Figs 1,5,6). If sustained by further work, such observations date the end of the PCRS as no younger than Ufimian. Such an early end of the PCRS appears to be supported by the well-established normal polarity observations of Murgabian age in the basal part of the Nammal Gorge magnetostratigraphic profile (Fig. 1; Haag and Heller, 1991). Interpretations of magnetostratigraphic profiles from Sichuan (Heller et al., 1988; Steiner et al., 1989) have also suggested a younger end for the PCRS, but these studies are less robust in their magnetostratigraphic and biostratigraphic control than the Nammal Gorge study and the reliability of these interpretations needs further demonstration.

The results presented highlight an emerging contradiction concerning the age of the younger end of the PCRS. On the one hand, we have evidence for an Ufimian or older age from the sections of the continental eastern Australian coal measures and a Murgabian or older age for the marine Nammal Gorge section of the Salt Range. On the other hand, a younger Early to Late Tatarian age is concluded from the Late Permian stratotypes in Tatarstan and Russia (Fig. 1). Palaeontological control on the base of the Tatarian is reasonably well established, and a correlation with Australia through the marine Permian of Greenland, Austria and the Salt Range of Pakistan has been made (Fig. 1). This correlation is not likely to be a source of discrepancy in the ages for the younger boundary of the PCRS. We cannot exclude with confidence that the



Stratigraphy after Tedros (1993)

Fig.5 Tentative magnetostratigraphic correlation of four selected cores spread over the length of the Gunnedah Basin, see Figure 2. Full lines indicate tentative correlation of formation boundaries.

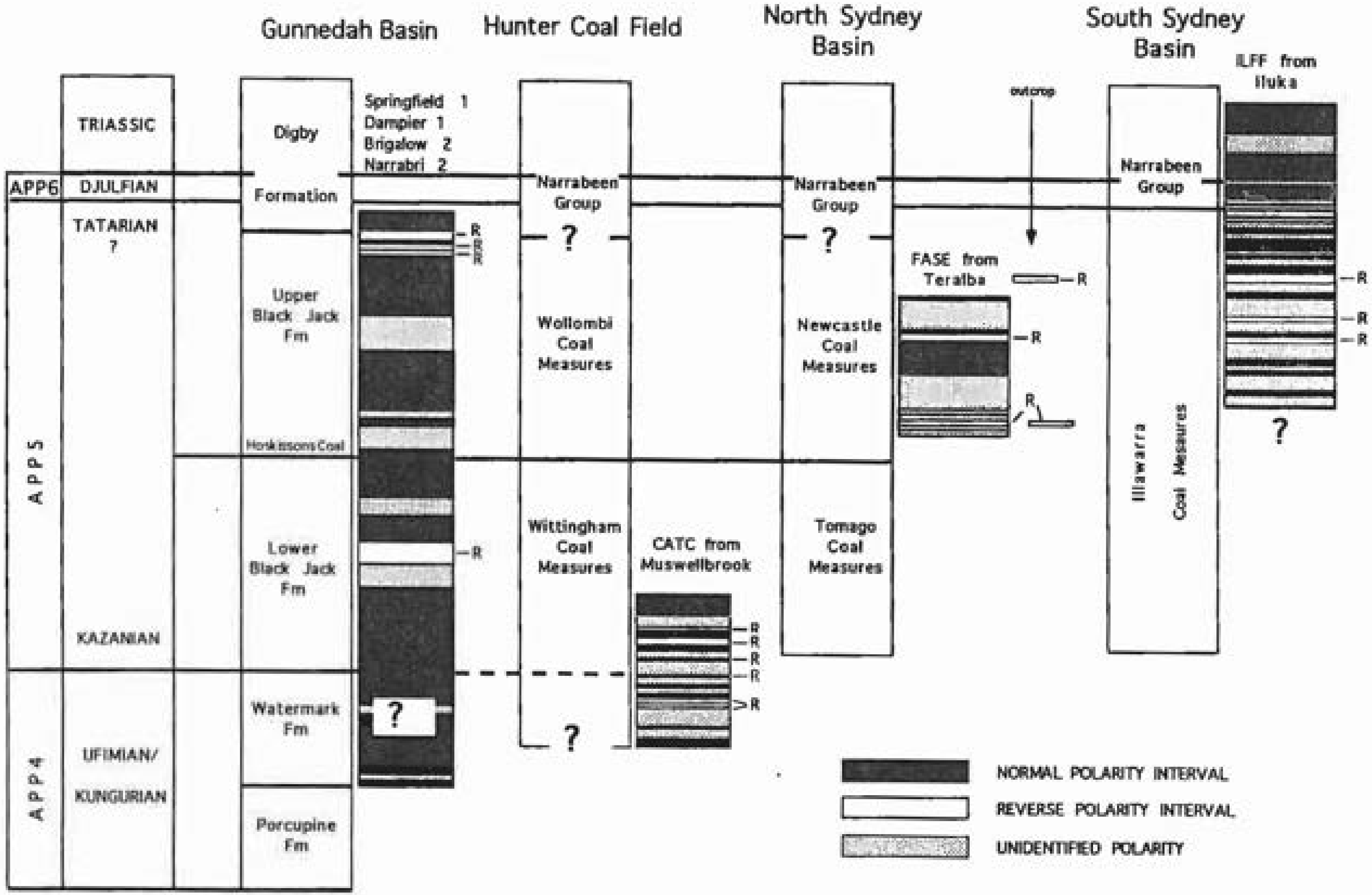


Fig.6 Tentative magnetostratigraphic correlation of drillcores from the Gunnedah and Sydney Basins and outcrop samples from the Newcastle Coal Measures.

conflict may arise from unrecognized normal polarity overprints of Late Cretaceous age in the Australian data, whose effect would be to make an otherwise reverse polarity interval appear mixed. Such overprints are of prevalent and pervasive occurrence in rocks along the Tasman seaboard, but their effect is less severe inland. The mutually supportive interpretations for an older age from both continental sections (Sydney and Gunnedah Basins) and a marine section (Nammal Gorge, Salt Range) make it more likely that the cause of the discrepancy may have to be sought in the interpretation of palaeomagnetic results from the Late Permian stratotypes of Tatarstan and Russia.

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PERMIAN SHRIMP AGES & CORRELATIONS WITHIN EASTERN AUSTRALIA

J. ROBERTS[1], D. BRIGGS[1], J. CLAOUE-LONG[2], C. FOSTER[2]
& D. MAIDMENT[2]
[1] Department of Applied Geology, UNSW
[2] Australian Geological Survey Organisation

Suggestions that sediments in the Sydney-Bowen Basin, traditionally referred to as Permian in age, were younger than 275 Ma, and that the duration of Permian deposition within those basins was limited to some 25 Ma were made at the 25th Newcastle Symposium (Roberts et al. 1991). However, SHRIMP dating and stratigraphic studies since 1991 now provide firm evidence that the Carboniferous-Permian boundary within Australia is located between 300 Ma (the age of the Stephanian C in Europe; Hess & Lippolt 1986) and 295 Ma (from early Permian rocks in southern Queensland).

Our former ideas, based on SHRIMP ages from rhyolites in the Booral Formation, McInnes Formation and Koolanock Sandstone in the Myall Region of the Southern New England Orogen, were incompatible with the age of the top of the Carboniferous in Europe, and suggested that the important cold climate *Levipustula levis* Zone and *Nothorhacopteris* Flora both had extraordinarily long ranges. To further test the first hypothesis, which was based on samples taken above the last occurrence of *L. levis*, an additional date was made from rhyolite beneath the *L. levis* Zone within the Booral Formation. This sample proved younger than any of the previously dated samples (from the Booral Formation, McInnes Formation and Koolanock Sandstone) and was virtually identical with that from the Lakes Road Rhyolite Member of the Alum Mountain Volcanics (Fig. 1). Field examination of one of the few well exposed rhyolites (in the Booral Formation) revealed that, despite an appearance of conformity, internal flow banding, and sharp basal contact with sediments, the upper part of the unit was intrusive. Rhyolite veins penetrate the overlying dark siltstone, stoping off small blocks, and the flow banding bends upwards into spaces within the overlying siltstone. Given this evidence, together with the presence of possible felsic sills elsewhere within the region (Campbell & McKelvey 1972), and the lack of lateral continuity along strike, we now interpret the rhyolites as sills intruded during an igneous event corresponding with that responsible for extrusion of the Lakes Road Rhyolite Member of the Alum Mountain Volcanics (Roberts et al. 1993; Roberts et al. in press). Two further SHRIMP dates of Early Namurian age from crystal tuffs within the Johnsons Creek Conglomerate, the uppermost Carboniferous unit within the Myall region of NSW, indicated that: 1) the underlying McInnes (= Koolanock Sandstone) and Booral Formations were far older than the Permian age initially reported; 2) the *L. levis* Zone in the Hunter-Myall region is confined to the Namurian; and 3) the *Nothorhacopteris* Flora is Carboniferous in age, ranging from the late Visean to Westphalian.

PERMIAN OF EASTERN AUSTRALIA

A correlation chart for Permian rocks from the New England Orogen and Sydney-Bowen Basins, based on eastern Australian biozones (partly after Draper et al.

1990; Briggs 1993) and SHRIMP and conventional zircon ages, is given in Fig. 1. The chart incorporates the suggestion of Foster (1979, 1982) that the lower parts of the Rewan and Narrabeen Groups are uppermost Permian, with the Permian-Triassic boundary coinciding with the appearance of members of the genus *Aratrisporites* at the base of the *Protohaploxypinus samoilovichii* Zone of Helby (1973). Briggs disagrees with this interpretation, and prefers the placement of the boundary within the older *P. microcorpus* Zone (see Fig. 1 and Briggs 1993). Correlatives of at least part of the Tatarian within Australia can be recognised by the *P. microcorpus* Zone (=APP6 of Price, in Draper et al. 1990), used in the sense of Helby et al. (1987) to include the *Playfordia crenulata* Zone of Foster (1982), which appears at the close of coal measure deposition. The *P. microcorpus* Zone is linked with the Tatarian of Russia by way of its occurrence at the top of the Dzhulfian to Dorashamian Chhidru Formation of the Salt Range of Pakistan, and lower *Bellerophon* Formation in the Bletterbach-Butterlock section of the Austrian Alps where Pittau (in Massari et al. 1988) reported correlative palynofloras of the *P. microcorpus* and *P. crenulata Zones* of Foster (1982); as noted above, Helby et al. (1987) included both of these zones within their *P. microcorpus* Zone, and that usage is followed in Fig. 1. The Austrian palynofloras contain a key link with Tatarian floras of Russia and with an assemblage in the *Martinia* Limestone of Greenland which has a minimum age of early Dzhulfian based on conodonts, ammonoids and palynofloras (see Balme 1979). A tie with the Kazanian of Arctic Russia is provided by foraminifera of the *P. minuta* Zone in the Ingelara Formation (Palmieri, Foster & Bondareva, in prep.) and provides firm evidence for the earlier suggested correlation of Briggs (1993). The co-occurring palynoflora from immediately above and below the lower sample dated at 263 Ma in GSQ Springsure 18 belongs to Upper Stage 5 (APP5).

In the lower part of the Permian succession of eastern Australia, two samples from the Alum Rock Conglomerate in southern Queensland from above the *Trigonotreta* n. sp. Zone and beneath the *Strophalosia subcircularis* Zone (Briggs 1993) provide an age constraint for the lower part of the system. These samples have ages of 292 and 294 Ma and, with Hess & Lippolt's (1986) date of 300 Ma for the Stephanian C in Europe, suggest that the Permian-Carboniferous boundary is at around 298 Ma. With palaeontological evidence, they also indicate that deposition within the Sydney Basin commenced at around 295 Ma and was followed shortly afterwards by bimodal volcanism. Conclusions concerning the Sydney Basin are based on Stage 2 (at the base) and Stage 3a palynofloras and the *Trigonotreta* n. sp. Zone within the Lochinvar Formation, and Stage 3a palynofloras at the base of the Alum Mountain Volcanics.

In the Myall Syncline, palynofloras of Stage 3a and 3b age within the Alum Mountain Volcanics appear to restrict the stratigraphic position of the mainly basaltic lower part of the formation and suggest a possible hiatus between the Burdekins Gap Basalt Member and the Lakes Road Rhyolite dated at 274.1±3.4 Ma (Roberts et al. in press). A bleached upper surface on the top of the basalt at Burdekins Gap supports this hypothesis. The Lakes Road Rhyolite is within error of the ages of three rhyolite sills referred to above.

Within the Bowen Basin, lack of fossil control on the Camboon Andesite, from low in the sequence, led to concentration of the dating program on upper parts of the succession. Samples from bentonitic clays within the Ingelara Formation in GSQ Springsure 18 give potentially conflicting results, that from 435.4-435.6 m having an age of about 250 Ma, and that from between 498.5-498.7 m an age of around 263 Ma. However, ages of around 250 Ma for the Black Alley Shale, and 256 Ma for the Condamine beds in southeast Queensland relative to the biostratigraphic positions of these two units (see below; Fig. 1), and the presence of Kazanian foraminifera adjacent to the lowermost sample, suggest that the uppermost Ingelara date is too young. The Black Alley Shale date of 250 Ma is essentially the same as the age taken by Claoue-Long et al. (1991) for the Permian-Triassic boundary. However, the sample dated by Claoue-Long et al. (1991) has subsequently been identified (from conodonts) as Permian in age (Lin 1993), meaning that the Black Alley Shale and overlying Bandanna Formation are still interpreted as Permian. The Black Alley Shale immediately overlies the *E. ovalis* Zone within the 'Mantuan *Productus* bed' of the uppermost Peawaddy Formation (Briggs in prep.).

In southeastern Queensland, a volcanic from the upper Rhyolite Range beds, from approximately 20 m above the *Echinalosia discinia* Zone, is dated at around 257 Ma. The stratigraphic position of the *Echinalosia discinia* Zone versus the age of the volcanic suggests either a disconformity within the upper volcanic part of the Rhyolite Range beds, or that the age is too young. An ignimbrite bracketed by sediments containing the *E. ovalis* and *E.* n.sp. G Zones of Briggs (1993) within the Condamine beds is dated at around 256 Ma, an age compatible with those of the Black Alley Shale and lower Ingelara samples.

Two conventional zircon dates have been made from the upper part of the Permian succession of the Sydney Basin (Gulson et al. 1990). The Awaba Tuff from 50 m below the top of the Newcastle Coal Measures has an age of 254±4 Ma, close to that of the Condamine and upper Rhyolite Range beds. McMinn (1985 fig. 3) reported *Triplexisporites playfordi* at the top of the Newcastle Coal Measures and their equivalents, marking the base (or the *P. crenulata* part) of the *P. microcorpus* Zone (=Tr1a of Helby 1973), although in the Newcastle Coalfield the latter zone apparently does not appear until the base of the Narrabeen Group (Grebe 1970). Taking into account these biostratigraphic data and SHRIMP dates from Queensland, the age of the Awaba Tuff appears to be too old. The Thornton Claystone from near the base of the Four Mile Creek Subgroup of the Tomago Coal Measures is dated at 266±0.4 Ma. The claystone lies above the Kulnura Marine Tongue (upper Wallis Creek Subgroup) containing the *Pseudostrophalosia* n. sp. Zone of Briggs (1993). Both the latter species and the morphologically close but older *P. ingelarensis* have been identified within the Ingelara Formation in the Bowen Basin (Briggs in prep.), though neither species has been identified from the vicinity of the dated sample of Ingelara Formation in GSQ Springsure 18. Provided the Ingelara Formation is correctly identified in the latter well, the Thornton Claystone date of 266±0.4 Ma, from above the *Pseudostrophalosia* n. sp. Zone, lies beyond the error bar for the Ingelara sample and is also too old. The Thornton Claystone lies in the lower part of the broad palynological interval zone APP5 (='upper Stage 5'), which extends from within the Wallis Creek Subgroup to near the top of the Newcastle Coal Measures (McMinn 1985). The age of the Thornton Claystone is further constrained by its position above the incoming of the spore *Microreticulatisporites bitriangularis* Balme & Hennelly 1956, which, despite some uncertainty regarding its biostratigraphic significance, has been used to subdivide APP5 by McMinn (1985) and Price et al. (1985; in Draper et al. 1990). The lowest recorded occurrence of *M. bitriangularis* in the Tomago Coal Measures is apparently that at 403.2 m in DM Stockton DDH3 (McMinn 1985, microfiche) in the upper Wallis Creek Subgroup some 60 m below the Thornton Claystone. In the Bowen Basin *M. bitriangularis* first appears in the upper Ingelara Formation (McLouglin 1988), further suggesting that the zircon date on the Thornton Claystone is too old.

INTERPRETATION OF ZIRCON AGES

A number of the seven zircon ages from the upper part of the Permian pose difficulties with correlations. Given the biostratigraphic succession provided by Briggs (1993), it appears that the older Ingelara (263 Ma), Condamine and Black Alley ages may be correct, whereas the younger Ingelara sample (249 Ma) appears to be too young and the Awaba Tuff and Thornton Claystone ages too old. The age of

252.2±3.6 Ma for the boundary clayrock at the top of the Changxing Formation, taken by Claoue-Long et al. (1991) as indicating the Permian-Triassic boundary but now reported as Permian (Yin 1993), is incompatible with the age of the Black Alley Shale and position of the top of the Tatarian (Fig. 1). Clearly, further analyses within both the Sydney-Bowen Basin and potential boundary stratotype section at Meishan, China, are required to resolve these problems. However, despite these conflicts a number of advances have been to our understanding of the history of the Sydney Basin; these are indicated below.

DATABLE EVENTS IN THE SYDNEY BASIN

1. Deposition commenced at around 295 Ma following a long hiatus from the ?late Westphalian. This latter interval coincides with the deformation, uplift and intrusion of the Central Complex of the SNEO, and uplift and erosion of the Tamworth Belt (Dirks et al. 1993).

2. Bimodal volcanism within the Sydney Basin took place initially between 293 and 283 Ma, being reflected in the Alum Mountain Volcanics, basalts within the Lochinvar and Allandale Formations, and the Gyaran Volcanics. A later igneous event at around 275 Ma produced further rhyolitic volcanism in the Myall Syncline and the intrusion of acid sills in the northern Stroud-Gloucester Syncline. Could these later events be connected with the intrusion of the Barrington Tops Granodiorite (269 Ma from K-Ar) and be synchronous with the uplift that give rise to the Greta Coal Measures?

3. Younger ('Gerringong') basic volcanism in the southern Sydney Basin was dated by K-Ar methods at around 253 Ma (Facer & Carr 1979). Although zircons cannot be recovered from these rocks, zircon dates from Queensland and the Newcastle Coal Measures and correlation by brachiopod zones with Queensland suggest that the 'Gerringong' volcanism is older than 253 Ma.

4. On the basis of correlation (*Pseudostrophalosia* n.sp. Zone) between the Ingelara Formation and the Kulnura Marine Tongue, and zircon ages in Queensland, the Thornton Claystone is likely to have an age of around 260 Ma rather than 266±0.4 Ma.

5. The Awaba Tuff from near the top of the Newcastle Coal Measures (256± 4) is dated as older than the Black Alley Shale in the Bowen Basin (250 Ma) but appears from palynofloral evidence given by McMinn (1985) to be close to the *P. microcorpus* Zone.

6. Permian deposition within the Sydney Basin appears to extend through an interval of about 53 Ma, not the ~25 Ma originally proposed by Roberts et al. (1991).

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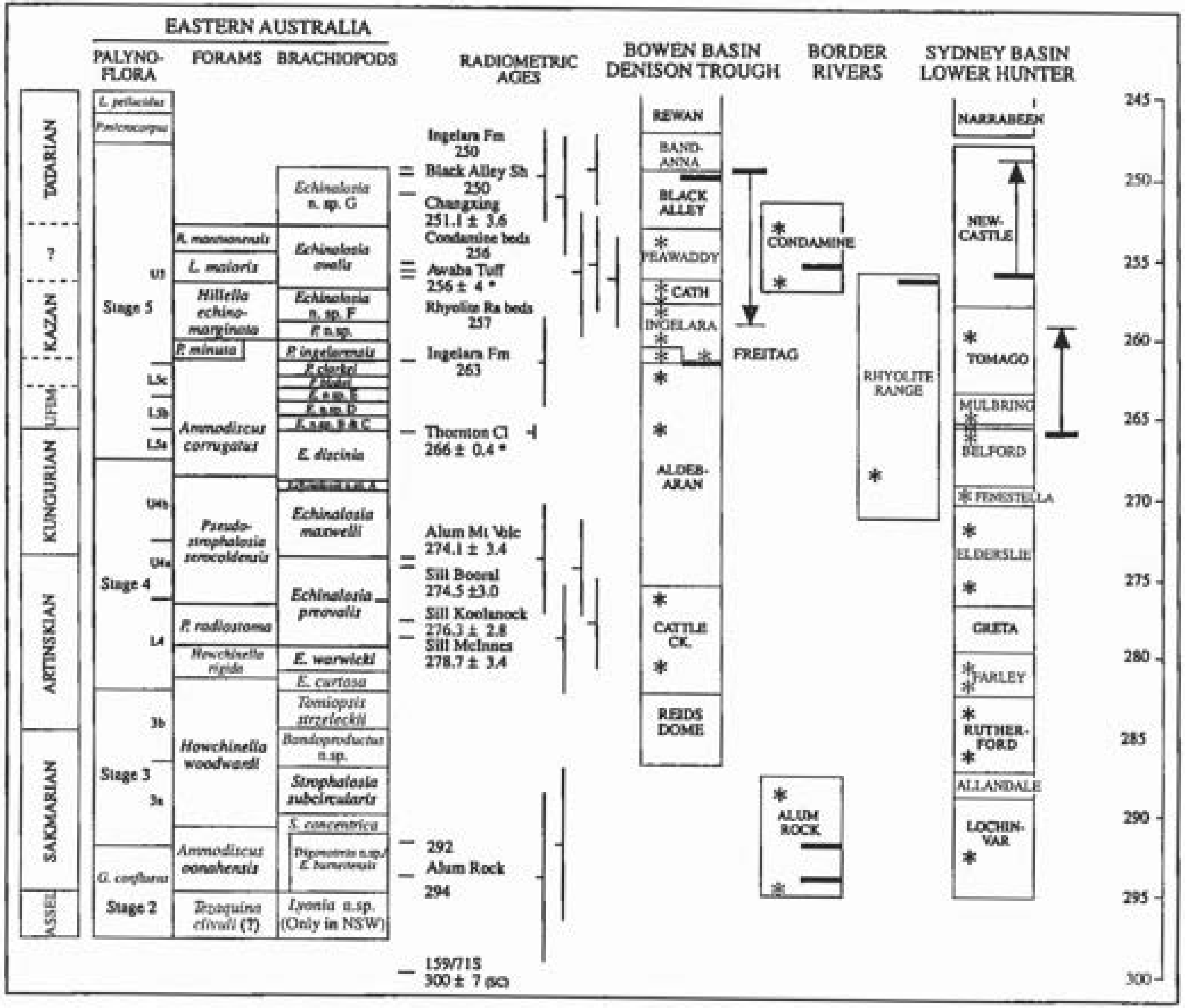
Fig. 1. Correlation chart for the Permian of the Sydney and Bowen Basins and Border Rivers area of southeastern Queensland indicating the stratigraphic positions of SHRIMP and other zircon dates. Asterisks indicate the location of brachiopods referable to the zonal scheme of Briggs (1993). Foraminiferal zones are from Palmieri (in Draper et al. 1990).


EASTERN AUSTRALIA
PALYNO-FLORA
FORAMS
BRACHIOPODS
RADIOMETRIC AGES
BOWEN BASIN DENISON TROUGH
BORDER RIVERS
SYDNEY BASIN LOWER HUNTER
TATARIAN
?
KAZAN
UFIM
KUNGURIAN
ARTINSKIAN
SAKMARIAN
ASSEL
L. pellucidus
P. microcorpus
Stage 5
U5
L5c
L5b
L5a
U4b
U4a
Stage 4
L4
3b
Stage 3
3a
G. confluens
Stage 2
R. mannanensis
L. maioris
Hillella echino-marginata
P. minuta
Ammodiscus corrugatus
Pseudo-strophalosia seracoldensis
P. radiostoma
Howchinella rigida
Howchinella woodwardi
Ammodiscus oonahensis
Trinquina clivuli (?)
Echinalosia n. sp. G
Echinalosia ovalis
Echinalosia n. sp. F
P. n.sp.
P. ingelarensis
P. clarkei
E. n.sp. E
E. n.sp. D
E. n.sp. B & C
E. discinia
Echinalosia maxwelli
Echinalosia preovalis
E. warwicki
E. curtosa
Tomiopsis strzeleckii
Bandoproductus n.sp.
Strophalosia subcircularis
S. concentrica
Trigonotreta n.sp./ E. burnettensis
Lyonia n.sp. (Only in NSW)
Ingelara Fm 250
Black Alley Sh 250
Changxing 251.1 ± 3.6
Condamine beds 256
Awaba Tuff 256 ± 4 *
Rhyolite Ra beds 257
Ingelara Fm 263
Thornton Cl 266 ± 0.4 *
Alum Mt Vole 274.1 ± 3.4
Sill Booral 274.5 ±3.0
Sill Koolanock 276.3 ± 2.8
Sill McInnes 278.7 ± 3.4
292
Alum Rock
294
159/71S 300 ± 7 (SC)
REWAN
BAND-ANNA
BLACK ALLEY
PEAWADDY
CATH
INGELARA
ALDEB-ARAN
CATTLE CK.
REIDS DOME
FREITAG
CONDAMINE
RHYOLITE RANGE
ALUM ROCK
NARRABEEN
NEW-CASTLE
TOMAGO
MULBRING
BELFORD
FENESTELLA
ELDERSLIE
GRETA
FARLEY
RUTHER-FORD
ALLANDALE
LOCHIN-VAR
245
250
255
260
265
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COALBED METHANE EXPLORATION BY PACIFIC POWER IN NSW – THE FIRST FIVE YEARS

C. WEBER
Pacific Power

ABSTRACT

Since 1988 Pacific Power has vigorously pursued the investigation of coal bed methane in New South Wales. Coal basins currently considered to be prospective include the Permian Sydney, Gunnedah and Gloucester Basins and the Triassic - Jurassic Clarence Basin. In these basins factors such as coal thickness, depth and rank are favourable for in-seam methane development. Coal seam permeability may be a little low overall.

INTRODUCTION

Pacific Power is responsible for the generation and bulk transmission of electricity in New South Wales. It is State owned and headed by a Board whose Chairman reports to the Minister for Energy in the New South Wales Parliament. Assets exceed $10 billion and turnover is $3 billion per annum. In 1992/93 Pacific Power paid a total of $700 million to the State Government in company tax equivalent and dividends. It employs some 6,000 people.

Powercoal Pty Ltd, a wholly owned subsidiary company, operates eight underground coalmines which supply some 10 million tonnes per annum under contract for use in Pacific Power's seven coal-fired power stations. (A further 10 mtpa is purchased from private suppliers under contract.) None of the coalmines currently requires the installation of special methane drainage facilities.

Currently, some 94% of the electricity produced by Pacific Power is generated in conventional pulverised fuel (coal-fired) plant. The remaining 6% is hydro-electricity. Options for future generation capacity include gas-fired plant, in particular for peaking duty.

Since 1988 Pacific Power has vigorously pursued the investigation of coal bed methane in New South Wales. It currently holds three Petroleum Exploration Licences in the Sydney Basin, covering a total of 7000 km^2 (Figure 1). In addition, it holds title to an area in the Permo-Triassic Gloucester Basin and is a partner in joint ventures in the Gunnedah and Clarence-Moreton Basins.

This pursuit of coal bed methane has been motivated by a number of factors:

CARL WEBER

This pursuit of coal bed methane has been motivated by a number of factors:

. A strategic need to diversify from coal into gas.

. The fact that coal bed methane resources are located close to power stations and the market place.

. Coal bed methane is an environmentally friendly fuel.

. The sheer size of the methane resource base.

. The potential for production costs to be competitive.

. Uncertainties concerning interstate gas supplies.

. Opportunities related to specific gas plays.

ENVIRONMENTAL CONSIDERATIONS

The use of coal bed methane would have positive impacts on the environment:

* The combustion of methane results in substantially less atmospheric pollution than the combustion of coal.

* Methane which might otherwise leak into the atmosphere (thus contributing to the Greenhouse Effect) is harnessed for use.

* There is minimal disturbance of the land surface.

* It permits access to primary energy resources in areas uneconomic for conventional mining or constrained due to existing surface land use.

Set out below are some comparisons in relation to atmospheric carbon dioxide emissions from power stations:

Victoria - brown coal:	1180 t/Gwh
NSW - black coal power stations:	925 t/Gwh
Methane in open cycle gas turbines:	600 t/Gwh

Coal bed methane is free of sulphur.

COAL BED METHANE AND PACIFIC POWER

The major by-product of coal bed methane is groundwater, which is pumped from coal seams in order to liberate the methane. In some cases, this water may have to be purified prior to release, or re-injected into the ground.

GAS RESOURCES

Drilling is currently too sparse to determine the Sydney Basin in situ gas resources, but the 30 or so deep gas investigation wells indicate that in excess of 200,000 PJ of coal seam gas (methane and carbon dioxide) may be present in the Illawarra Coal Measures and their lateral equivalents. This compares favourably with the 70,000 PJ natural gas reserves in the North West Shelf.

The composition of this coal seam gas is commonly almost pure methane. However, carbon dioxide appears to be particularly abundant in the southern end of the basin and is dominant at scattered locations throughout the basin. The reason for the presence of carbon dioxide distribution is unclear. Igneous activity is believed to responsible in some areas. To the north, in the Hunter Coalfield, however, both intruded and unintruded seams may contain pure methane, whilst nearby holes exhibiting a minimum of igneous activity may contain a high proportion of carbon dioxide. Some gas analyses have also recorded significant (5% to 20%) nitrogen.

EXPLORATION STRATEGY

The exploration strategy involves:

- An initial programme of cored investigation boreholes at selected sites.
- The development of a trial production field at one, possibly two, sites.
- The evaluation of existing technology, as currently applied in the US.
- The development of modified and new technology for coal bed methane extraction in NSW.
- Participation with private enterprise, collaboration with research organisations, and co-operation with Government.

A number of factors need to be considered. These include:

- Gas Content and Composition
- Coal Quanity and Quality
- Depth to Coal
- Coal Rank
- Gas Desorbability

- Coal Composition
- In Situ Stress/Propensity to Fracture
- Permeability
- Hydrogeology
- Markets
- Distribution Networks
- Land Use

Much of the above information is obtained from the cored investigation well programme, where coal cores are subject to gas desorption, gas analysis, lost and residual gas determination and chemical analysis. Rank and maceral composition is determined using coal petrography. Representative core is selected for sorption isotherm and laboratory permeability studies.

Well testing (for permeability) is carried out on the principal seams, using straddle packer isolation. In addition, in situ stress determinations are made above and below target seams.

To date, a total of nine deep cored investigation boreholes has been drilled in the Sydney, Gunnedah and Gloucester Basins. Two boreholes have been drilled as part of technology trials.

RANK

In general, the desorbable gas content of a coal increases with rank. Sydney Basin coals are sub-bituminous and coal rank, as measured by bitrinite reflectance (R max), ranges from 0.7% in shallow coals in the north, to 2.0% in deep coals in the more central parts of the basin (Middleton, 1988).

The rank variations are believed to be due to depth of burial, rather than to increases in heat flow arising from tectonism. Local increases in rank are commonly due to the effects of igneous intrusions, which took place in the Jurassic (alkaline intermediate plugs and sills) and, more commonly, in Tertiary times (dolerite).

In any one region, there is generally a modest increase in rank with depth. For example, in the north, rank increases from 0.7% to 0.9% within a 600 m interval. Lateral variation is substantial: the rank of the time interval at the top of the Permian increases from 0.7% in the north to almost 1.5% in the centre of the basin (Figure 6).

COAL BED METHANE AND PACIFIC POWER

RESULTS TO DATE

Investigations undertaken by Pacific Power to date can be divided into two strands:

- gas resource evaluation, and
- production technology evaluation.

Resource Evaluation

Coal Development

Since the methane is present only within coal seams, the estimation of quantities of gas in place is fundamentally dependent on the estimation of coal quantities. Very few of the areas currently under investigation have been drilled on the 1 km to 4 km centres recommended by coal reserves codes. Indeed, our current estimate of gas quantities in the Sydney Basin is based on coal thicknesses and gas quantities in some 13 boreholes spread across the basin. The estimate is not as speculative as one might initially believe, for two reasons:

- Overall regional coal development in the Late Permian coal measures of the Sydney Basin varies gradually and consistently across the basin.
- Coal seams have thus far been found to be gas-bearing throughout the basin, except in specific places where the gas has been removed as a result of water table changes or faulting.

Gas Content

In situ gas content in coal varies across the basin. In the central and southern parts of the basin, where cover is typically 450 to 900 m, the coal has a rank >1% (R max) and gas contents range from 10 to 18 m^3/t. In the north west and north east, where the coal rank is generally lower and cover varies from 0 to 900 m, the gas content varies from 0 to 12 m^3/t. It has been found that boreholes drilled on the western side of the basin an yield zero gas contents to depths of 500 m.

Gas content does not uniformly increase with depth. A complex pattern of gas distribution is emerging and parameters relevant to gas extraction are being studied in detail (see Odins and Bocking, this symposium). Collaborative RD is being undertaken with the CSIRO on a number of topics.

Gas content has been found to be influenced by the height above the lowermost prehistoric level of the regional water table. In Sydney Basin Permian strata, the coal seams are aquifers. Coal seams can be completely depleted of gas to depths in excess of 500 m where such seams lie above the height of existing or ancient stream levels.

Permeability

Permeability in the Sydney Basin has been found to vary from 5 microdarcies to 50 millidarcies. In general, the permeability has to date been found to be lower than in the commercial fields of the U.S. However, it is not as yet possible to make direct comparisons, because of different methodologies.

In the one hole drilled to date the Gloucester Basin, permeability varies from less than 1 mD in deeper seams to well in excess of 100 mD in shallow seams.

The Sydney Basin coals are quite strong (10-20 MPa UCS) and cleat development is proportional to the vitrinite content, which is often low. As a result natural cleat development provides only low permeability, typically 0.1 - 0.3 millidarcies. However the dull coals are prone to fracturing and consistently give higher permeabilities, typically 1-10 millidarcies.

The presence of authigenic minerals such as calcite has been found to reduce the permeability of seams. The origin and distribution of such minerals is under investigation.

Straddle packer well testing is routinely carried out to ascertain in situ permeability (Koenig et al, 1992). By combining the results of this testing with coal properties determined from drill core, it can be concluded that:

- Permeability increases with increased fracture development.
- Fracture density is inversely proportional to the amount of bright coal.
- Permeability is inversely proportional to the degree of mineral impregnation.

Sorptive Capacity

The sorptive capacity of Sydney Basin coals has been observed to vary for differing coal maceral compositions as well as rank. Vitrinite rich coals have been found to have a sorptive capacity up to 20 per cent greater than inertinite rich coals of the same rank from the same location. This is particularly important in the Sydney Basin where seams can contain up to 90% inertinite.

COAL BED METHANE AND PACIFIC POWER

Gas Desorbability

There is considerable variation in the rates at which methane desorbs from the coal. Some high-ash coals take in excess of 20 days to release 60% of their gas; some friable coals take less than two hours to do the same. Samples with very high gas contents (17-23 m^3/t daf) generally took around 10-12 days to release 60% of their gas.

Investigation of the relationship between desorbability and other parameters, such as permeability, depth, coal rank and ash content is in progress.

Technology Evaluation

By far the most commonly used methane recovery technology involves surface wells and a process known as hydraulic fracture stimulation. The process involves several steps:

- Hydraulic pressure is applied downhole to the coal seam in order to develop a vertical fracture in the coal up to 80 m in length.
- Whilst under pressure, the open fracture is propped with sand, in order to prevent its closure upon release of the pressure.
- Water is pumped to the surface from the seam until the hole is dry. This can take some three years.
- As water is removed, methane (up to 100% pure) is released and collected at the surface. The gas pressures involved are very low and it can take years for a well to build up to maximum flow.

The ability to develop a suitable fracture is dependent upon the (in situ) stress regime. The Sydney Basin is reputed to have high horizontal stresses and/or balanced stress fields, neither of which are particularly conducive to fracture development. Measurement of insitu stress is thus an important part of the exploration programme.

Results have varied. Horizontal stresses are high in general and commonly are higher than vertical stress. Both balanced and directionally unbalanced fields have been found to be present.

CARL WEBER

In 1992 Pacific Power and CSIRO Division of Petroleum Resources commenced a joint programme to investigate the potential for fracture development in the Sydney Basin. The program involved the drilling of holes from the surface ahead of coal mining followed by a hydraulic fracture treatment down-hole in the coal seam. The fractures in the seam were initially inspected at the borehole using a down-hole camera and then examined in detail some months later, when the borehole and fracture were exposed during mining.

In late 1992, fracture stimulations were performed by CSIRO in two surface boreholes intersecting the Great Northern seam at Munmorah Colliery, using unique, slimhole fracture technology developed by CSIRO in Melbourne. The boreholes were mined-through some months later during routine underground development at the colliery.

In each case a near-vertical sand-propped fracture was produced parallel to the face cleat in the coal. One fracture was in excess of 50 m long and up to 8 mm wide. The other, which has only been exposed in mine workings on one side of the borehole, has a minimum proven length of over 20 m and a maximum propped thickness of 10 mm. Both fractures extended from the seam roof to the floor.

The depths at which they were performed (230 m) are not normally regarded as being conducive to the development of vertical fractures. Neither the equipment used nor the borehole diameter are at a commercial scale.

The fractures did not grow into the roof or floor rock and had no impact on mining operations. These early results hold out promise that hydraulic fracture stimulation may prove to be viable in the Sydney Basin.

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SOME VARIATIONS IN METHANE SATURATION WITHIN THE PERMIAN COALS OF NEW SOUTH WALES

P.A. ODINS & M.A. BOCKING
Pacific Power, Sydney

INTRODUCTION

Exploration for Coal Bed Methane (CBM) in Australia was first undertaken in the early 1980's by AGL. Detailed investigation studies commenced in 1991 when Pacific Power, then the Electricity Commission of New South Wales, commenced drilling in the Hunter Valley. Pacific Power has since been one of the major explorers in NSW having completed nine wells expressly for CBM, including one in a joint venture agreement with Australian Coal Bed Methane Pty Ltd.

Early resource estimates often assumed that all the unintruded coal of suitable depth within New South Wales contained methane with the major impediment to its successful extraction being a lack of permeability within the coal.

Results obtained through exploration and subsequent analysis of coal core recovered have shown that although variation in permeability is of significant concern, a fundamental consideration is the methane saturation of the coal seam. The degree of methane saturation is observed to vary both within and between boreholes.

An attempt to explain every variation that occurs in methane saturation levels within Pacific Power's boreholes would be beyond the scope of this paper, however recent studies have revealed a number of interesting trends and relationships.

PACIFIC POWER'S CBM EXPLORATION PROGRAM

Pacific Power is the largest power utility in Australia with a current generating capacity of approximately 12 GW, the vast majority of which is supplied by conventional pulverised coal fired plant. Coal consumption is in the order of 20 Mt per year.

Investigations into the viability of utilising CBM as a fuel for future power generation have been undertaken by Pacific Power in NSW since 1988, in January 1991 the first borehole drilled expressly for CBM evaluation was commenced. To date a total of nine wells have been completed in Petroleum Exploration Licences held by Pacific Power in the Hunter, Newcastle, Western and Southern Coalfields of the Sydney Basin, the Gloucester Basin, and through joint venture involvement with Australian Coalbed Methane, the Gunnedah Basin of NSW (figure 1). Coal samples from each borehole were subjected to a thorough testing program, enabling the acquisition of gas desorbtion, sorptive capacity, permeability and coal quality data.

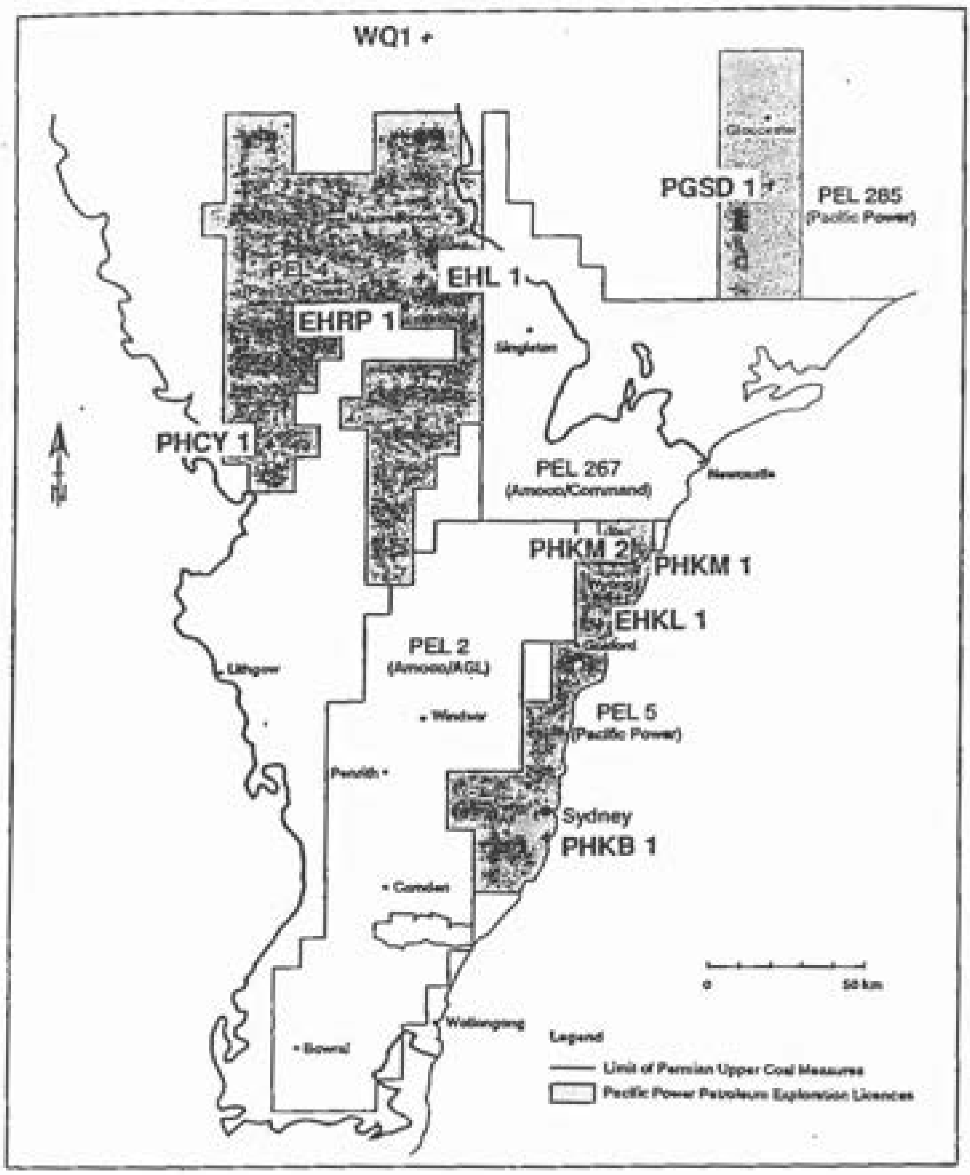


Figure 1. Location of Pacific Power's CBM Exploration Boreholes

METHODOLOGY

Summary

All coal seams with a nominal thickness greater than 0.3 m encountered within the wells were subjected to full gas desorption testing and all gas tested coal was subjected to chemical analysis allowing the gas content of the samples to be corrected for ash. Selected intervals within coal seams were also subsequently subjected to sorption isotherm testing, although the expense of such testing has resulted in a limited number of such analyses. In situ borehole testing was also performed where possible to enable measurement of downhole stress and permeability. This has enabled the determination of sorptive capacity at reservior pressure. Where possible, results from the testing program have been incorporated into this report, for wells where testing is currently incomplete the available information has been used.

Total gas content data was collected for representative coal samples from the boreholes covered in this study (Bocking *et al.*, 1992, Rehfisch *et al.*, 1992, Smith *et al.*, 1992, Odins *et al.*, 1993). High ash samples (>65%) were not included as the results were not directly comparable to those obtained from sorption isotherm testing, which was run on relatively low ash coal in an atmosphere of pure methane. It should be noted that the samples tested for sorption isotherms were sub samples of the intervals tested for gas desorption.

Gas Desorption

Methane contents have been determined by the "Direct Method", in which the amount of desorbable gas within a coal seam (Q2) is determined by desorbing HQ coal core obtained from drilling within a sealed canister and collecting the gas generated from the coal in an inverted cylinder containing acidified brine. Measurements of gas volume versus time are taken. Gas lost during the core encapsulation procedure (Q1) is estimated by plotting gas volume desorbed against the square root of time, the resulting curve is then regressed and extrapolated back to time zero (defined as half the time between the core being pulled off bottom and reaching the surface). In addition gas 'locked' into the coal structure (residual gas, Q3) is released via grinding in a sealed mill and the gas collected is calculated against the weight of the sample. All results are corrected to standard temperature and pressure conditions. The total amount of gas contained in the sample (Q_t) is the sum of these three amounts and is expressed in cubic metres of gas per tonne of coal (m^3/t).

The desorbed gas is sampled and analysed to ascertain the composition of the gas within the sample. Subsequent proximate analysis of the tested coal intervals allows results to be corrected on a dry ash free (daf) and cumulative floats at a density of 1.90 (cf1.90 basis), allowing an accurate estimate of the gas desorbed from the coal alone by excluding the stone bands within a sampled interval.

Sorption Isotherms

To determine the sorptive capacity of each coal sample for a range of pressures a sorption isotherm is determined experimentally. A crushed and ground coal sample is placed in a high pressure test cell maintained at a constant temperature in an air bath, as sorptive capacity is temperature dependant. For this report all samples were kept at 30° celsius. The cell is then pressurised with methane to the desired test pressure and allowed to reach equilibrium. The system pressure is then reduced by removing a small volume of gas from the cell and the system is again allowed to reach equilibrium. The volume of gas removed and the resulting equilibrium system pressures are measured and a curve is created from the resulting points. The values obtained can then be related to in situ pressure and temperature conditions and compared to the desorbed gas contents for the seam allowing the calculation of methane saturation values (Pinczewsky & Stevenson., 1992).

Methane Saturation

Expressed as a percentage, the methane saturation for a sample is the total desorbable gas content (Q_t) divided by the sorptive capacity of the sample at reservior conditions of temperature and pressure.

Methane saturation values were calculated for samples with both desorption and sorptive capacity data. In this way, methane saturation values were obtained from four Pacific Power boreholes. The values were plotted against depth for all data to obtain general saturation trends and on a well by well basis to gain an understanding of the saturation conditions in individual wells.

These saturation values were also plotted against methane content, vitrinite content, ash content, rank and permeability in order to ascertain which parameters were influencing or influenced by saturation. Due to the limited number of data points (12) an empirical rather than statistical approach was used to evaluate possible relationships. From this work, three relationships were selected for detailed evaluation.

Gas content curves were created for individual boreholes and all data was graphed against depth and the resulting gas content variations were used to infer major methane saturation variations in boreholes with sorption isotherm values.

Methane saturation values for recently completed boreholes with no isotherm results were estimated from other parameters and were also used to illustrate significant variations.

RESULTS

Methane saturation trends - all data

All coal seams examined in this study were undersaturated, with saturation levels varying between 2 - 90%, although the majority of values lie above 35 % saturation. There is a weak tendency for saturation to increase with depth (figure 2). Three parameters were discovered to be accountable for the majority of variations in methane saturation encountered within the boreholes. Two of these parameters, ash and vitrinite content are directly related to coal quality and composition and appear to account for local variations in methane saturation only.

Significant variations in the degree of methane saturation occurring both within and between boreholes and possibly coalfields are thought to be strongly related to coal seam permeability. Detailed results for all these relationships are discussed below and listed in Table 1.

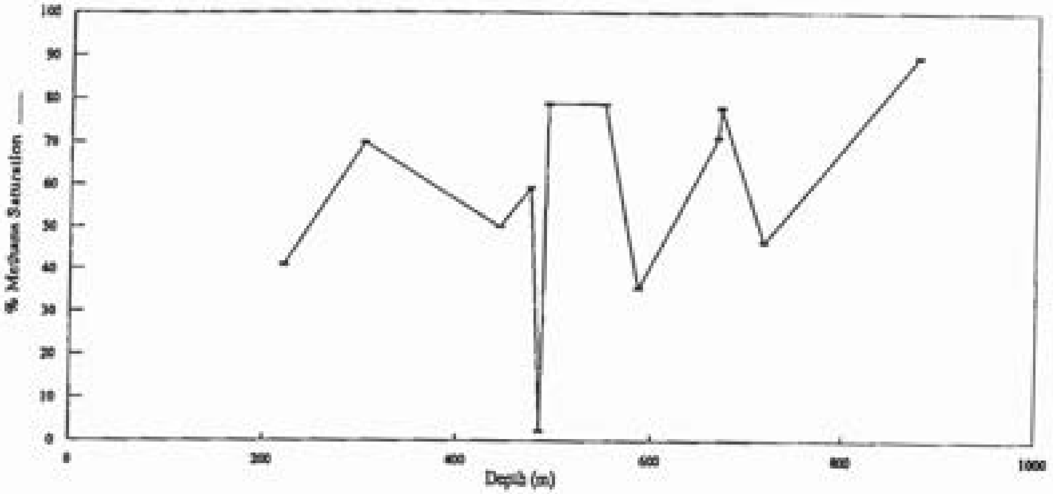


Figure 2. % Methane Saturation vs Depth (m)

BOREHOLE	SEAM	DEPTH m	HYDRO. HEAD m	VIT. CONT	ISOTHERM SAMP		SORP. CAP.		TOTAL GAS CONTENT Q1+Q2+Q3 m3/t		PERM. md	SATURATION % Cont/Cap RAWdaf/SCdaf
					ASH	MOIST.	adb	daf	RAW adb	RAW daf		
EHRP 1	Arrowfield	220.065	185	69.8	7.2	2.9	6.2	7.0	2.5	3.3	0.740	47
	Warkworth	302.595	367	81.8	6.8	2.3	10.2	11.5	7.1	7.6	0.064	66
	Bayswater	443.237	416	38.4	14.7	1.8	9.8	11.8	4.9	6.5	0.520	55
	Clanricard	491.345	490	66.5	7.0	1.8	14.0	15.3	11.0	13.2		86
	Ramrod Ck	548.885	518	72.3	16.6	1.5	11.7	14.4	9.2	12.4	0.340	86
EHL 1	Piercefield	474.020	430	63.3	17.8	1.6	7.5	9.2	4.4	5.6	0.200	60
	Bayswater	586.715	525	46.5	13.5	1.3	10.3	12.0	3.7	4.5	0.004	38
	Ramrod Ck	716.095	695	81.4	11.9	1.3	10.8	12.5	5.0	7.9	0.096	63
EHKL 1	Wallarah	666.330	634	35.2	13.2	1.2	14.6	17.3	10.8	12.5	0.042	72
	Great Nth	669.145	637	67.7	13.0	1.0	15.0	17.6	12.1	14.3	0.042	81
	Vic Tunnel	876.460	810	81.2	37.5	1.8	13.5	22.3	12.1	19.1	0.004	86
PHCY 1	Katoomba	485.880	303	40.5	16.8	2.7	8.2	10.5	0.2	0.3	1.630	2

Table 1. Sorptive capacity and gas saturation for Sydney Basin coals

methane saturation and ash content

Figure 3 illustrates the relationship between raw ash content and saturation versus depth, please note the inverted scale on the ash. These two parameters exhibit a weak affinity indicating that methane saturation decreases with increasing ash. Inherent ash and stone bands within desorption samples are not considered to be methane sources, as such high ash coal contains less methane than low ash coal due to its inferior quality offering less coal per unit weight.

A possible reason for the tendency for high ash desorption samples to have a low degree of methane saturation is the fact that samples taken for sorption isotherm analysis are generally good quality coal whereas the corresponding sample selected for gas desorption testing in the field may be of inferior quality resulting in the desorbed gas content being anomalously low and adversely affecting the methane saturation level. The opposite of this effect is illustrated at 876 m depth where the sample taken for sorptive capacity measurement was higher in ash than the corresponding desorption sample, resulting in a unrealistically high degree of methane saturation for such a high ash sample.

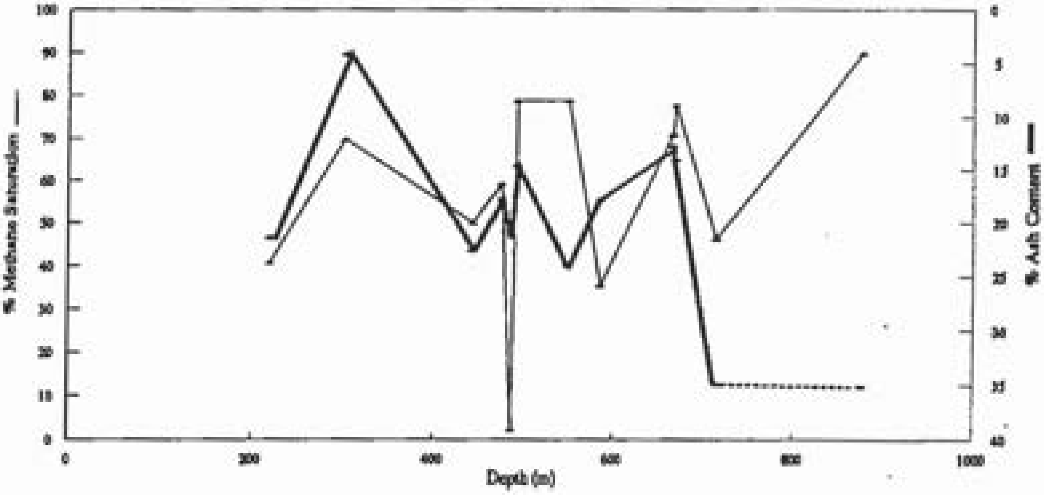


Figure 3. % Methane Saturation and Ash (adb raw) vs Depth (m)

methane saturation and vitrinite content

Figure 4 compares the percentage of vitrinite, the degree of methane saturation and depth, these parameters exhibit a good correlation, with the degree of saturation increasing with the vitrinite percentage or relative brightness of the coal.

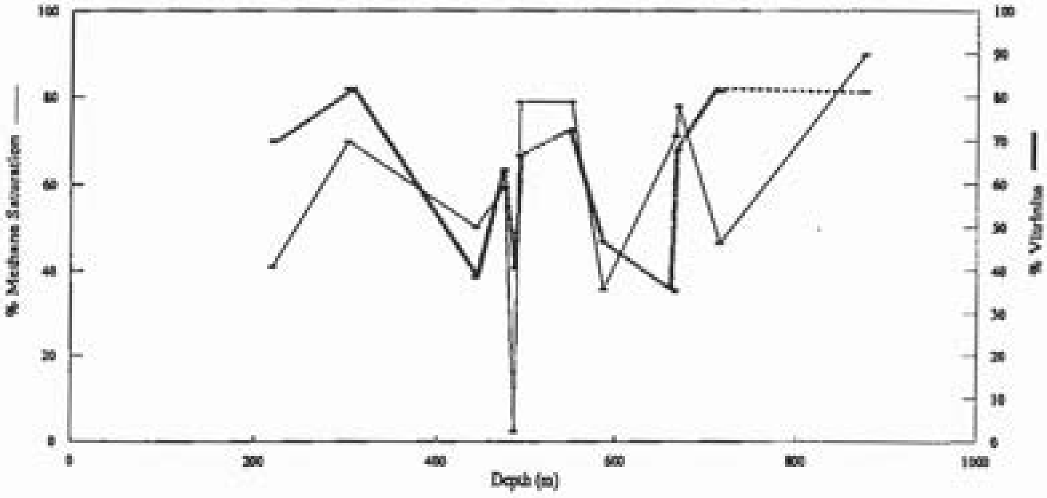


Figure 4. % Methane Saturation and % Vitrinite A vs Depth (m)

Ash content appears to be partially responsible for local variations in methane saturation, with high ash, bright coal samples high in vitrinite exhibiting relatively low degrees of saturation. However, the dominant factor responsible for the relationship is thought to be the link between permeability values and vitrinite content, with brighter coals tending to be less permeable than dull coals (Koenig *et al.*, 1992) resulting in a greater degree of saturation. This effect will be explained in further detail below.

methane saturation and permeability

Figure 5 illustrates all available production permeability data plotted against depth, production permeability values were chosen for this study because of a more complete data set, with values obtained for injection testing generally mirroring those used. From the data set it can be seen that permeability generally decreases with increasing depth with the aforementioned variations due to vitrinite content responsible for minor fluctuations in the curve. On an individual borehole basis most wells illustrate this trend, although three of the wells studied illustrate a reversal of this effect with results that will be discussed further.

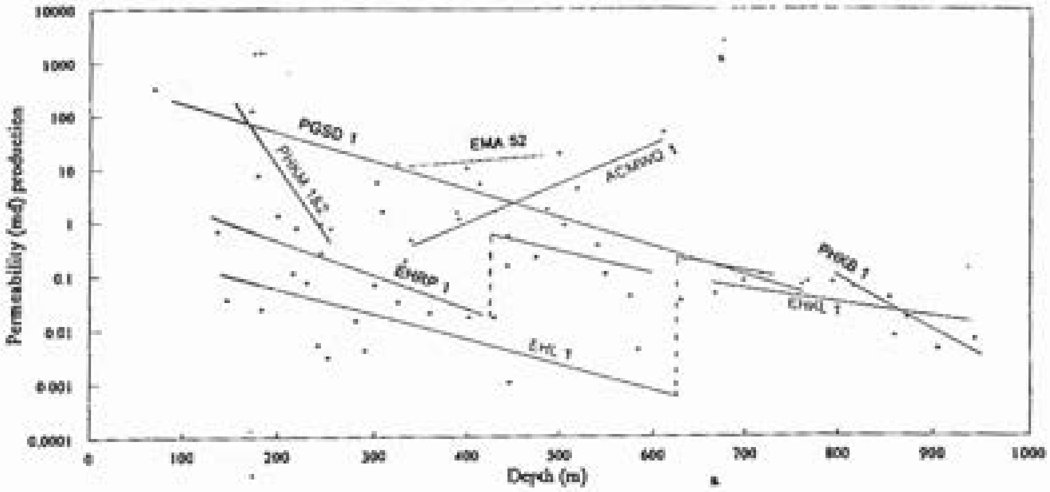


Figure 5. Production Permeability (md) vs Depth (m) - Illustrating permeability trends for Individual boreholes

Comparing the degree of methane saturation with permeability, for all available data results in a strong correlation, (figure 6). The degree of saturation increases with decreasing permeability. An exception is the Bayswater seam in EHL 1 at a depth of 586 m which has a very low permeability for a seam poor in vitrinite (46.5 %). The permeability of the seam at this particular location has been dramatically reduced by an influx of secondary carbonate which occurred after the generation of methane within the seam, resulting in relative methane undersaturation with respect to permeability.

High permeability has resulted in a lower degree of saturation for the majority of samples, implying that in cases where the permeability has been high a greater proportion of the methane generated within the seam has been able to escape either to the atmosphere or to another part of the coal seam through migration resulting in low methane saturation levels. Conversely, in seams with a lower permeability the methane generated within the seam has been trapped, resulting in a greater proportion of methane remaining in the sample and correspondingly higher saturation levels.

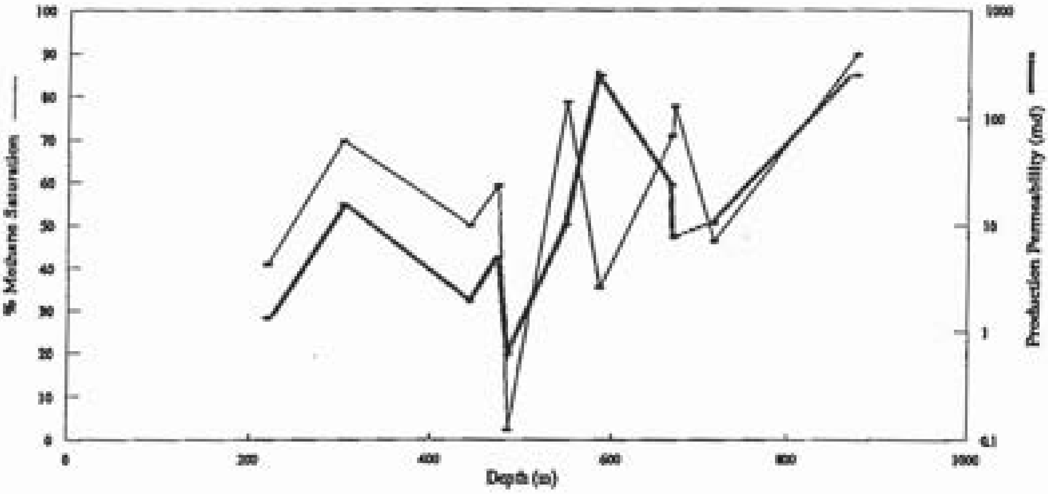
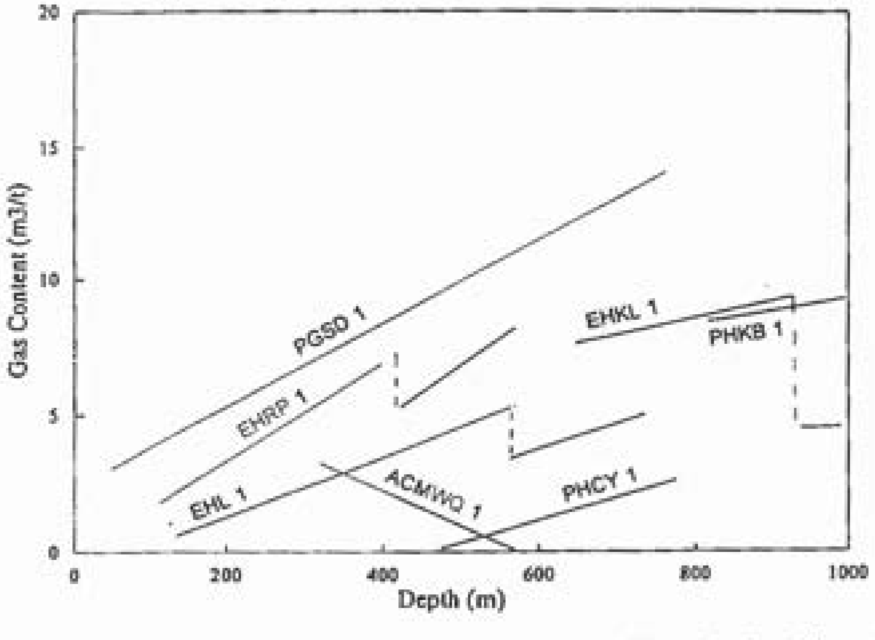


Figure 6. % Methane Saturation and Production Permeability (md) vs Depth (m)

Field results - case studies

The number of sample data points for methane saturation is limited whereas the number of gas content samples is large, ideally to obtain maximum information on saturation variations the use of gas content data where possible is recommended, even if the results obtained are of an empirical nature only (figure 7). In the case of boreholes with no sorption isotherm samples to date, an estimated range of sorptive capacity has been used to calculate approximate saturation levels.



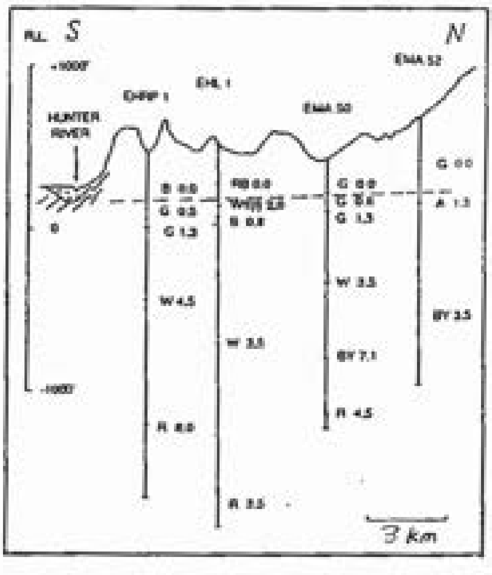


Figure 7. Gas Content Trends - All Boreholes. Figure 8. Gas Content (In situ) vs Watertable, Mt Arthur, PEL 4 (Bocking & Weber, 1993)

highly undersaturated coals

Highly undersaturated coals are those in which the desorbable gas content is close to zero, this category includes coal seams in which the methane has been lost presumably to the atmosphere due to a combination of high permeability, relatively low watertable, either currently or in the past, and in the majority of cases, shallow depth. In the Sydney Basin Permian strata, coal seams are the aquifers.

Commonly exhibiting a high degree of undersaturation are the shallow seams in the Hunter Valley lying above the piezometric level of the nearby Hunter River (figure 8) (Bocking & Weber, 1993) and more significantly the coals of the Western Coalfield which contained no desorbable methane and therefore zero saturation to a depth of 412 m in the Lithgow Newnes area and 560 m in the Coricudgy area (Bocking & Weber., 1991). In both cases highly permeable coals are located on plateaux several hundred metres above the adjacent drainage systems. Loss of methane to the atmosphere due to lateral migration through the coal is thought to be the major mechanism responsible.

Assuming sorptive capacity to be comparable to other coals at similar depths a somewhat more enigmatic case of undersaturation exists in a recently completed well in the Gunnedah Basin in which permeability increases with depth and methane saturation decreases with depth to be virtually zero at a depth of > 500 m (figure 9). In this instance the mechanism responsible for the loss of methane is not yet fully understood but is thought to be associated with the high permeability of the seams relative to their depth and the possibility of methane being stripped from the seam by groundwater movement. Further work including sorptive capacity measurement is planned to further the understanding of the results obtained to date.

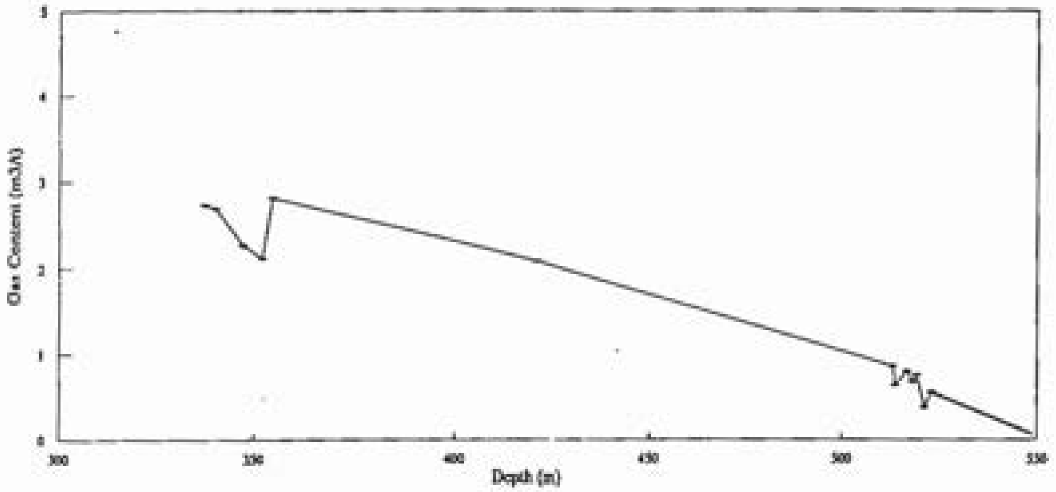


Figure 9. Gas Content (m^3/t) vs Depth (m) - ACM West Quirindi DDH 1

highly saturated coals

The recently completed borehole in the Gloucester Basin is thought to exhibit a relatively high degree of methane saturation within the coal, with gas contents of 3 m^3/t occurring at a depth of 70 metres and increasing with depth (figure 10). The coal seams in this well are highly permeable, generally low in ash and contain very little carbonate, in addition the seams dip at approximately 20°. This combination of factors should result in highly undersaturated coal.

The reason for the apparent anomaly in the degree of saturation is thought to be related to the existence of a localised, thick, impermeable clay layer unconformably overlying the coal measures. It is believed that this strata is associated with the current drainage system and of relatively recent origin. This layer has prevented the escape of methane to the atmosphere. Although the methane generated in situ may have previously been lost, the high permeability of the coal coupled with the dip allows the possibility of constant methane "recharge" from the seam at depth.

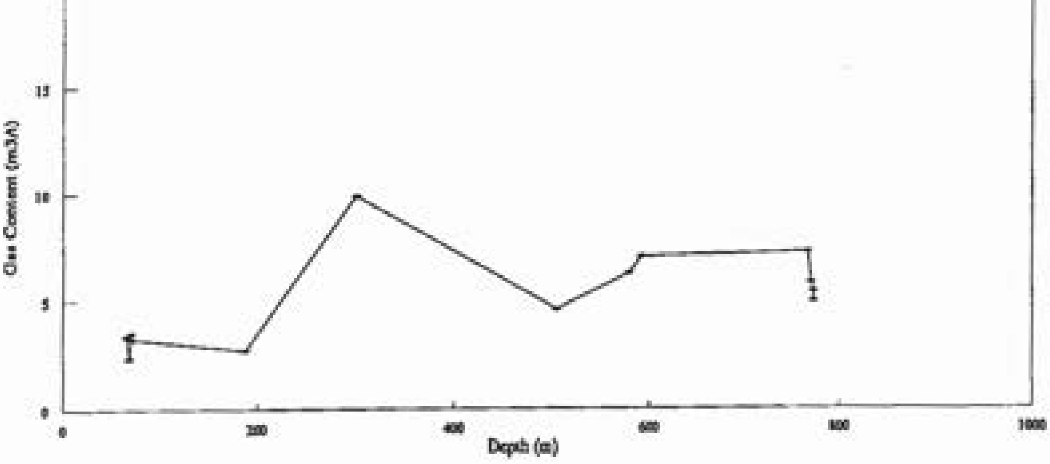


Figure 10. Gas Content (m^3/t) vs Depth (m) - Pacific Power Gloucester Stratford DDH 1

Work on this borehole, including sorption isotherm analysis, is still to be completed, it is hoped that this anomaly can be further investigated in the future.

Conclusions

Preliminary studies based on limited data have shown that the degree of methane saturation in a coal seam is closely associated with its permeability, with vitrinite and ash content having a lesser influence.

It has been shown that relatively impermeable seams have a higher degree of methane saturation than permeable coals.

Current exploration strategies tend to target high permeability seams in order to maximise the area of coal methane can be sourced from during production, case studies have shown that care should be taken to examine the possibility of gas depletion due to the relative position of ancient or existing watertables and that the existence of structural or lithological 'gas traps' may be of greater importance to the viability of a site than was previously thought.

Conversely, areas of relatively low permeability may become areas favourable for methane production if effective permeability stimulation can be achieved, due to their relatively high degree of methane saturation.

ACKNOWLEDGMENTS

The Authors wish to acknowledge the permission of Pacific Power and Australian Coalbed Methane to include data from current exploration programs in the presentation of this paper.

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A COMPARATIVE STUDY BETWEEN COALBED METHANE BASINS, WITH A FOCUS ON PEL 2, SYDNEY BASIN, AUSTRALIA

S. WALLER
Amoco Australia Petroleum Co.

This study focuses on the background and the initial activity associated with Amoco Australia Petroleum Company's coalbed methane (CBM) exploration in PEL 2 in the Sydney Basin, New South Wales, Australia. It also contrasts CBM exploration with conventional gas exploration, and contrasts the Sydney Basin with some other international CBM basins.

Amoco Australia Petroleum Company's (AAPC) parent, Amoco Production Company, has been exploring for coalbed methane since 1975. Amoco consistently vies for the top position in worldwide coalbed methane production, and leads the world in coalbed methane research and technology. Since 1976, Amoco has spent approximately A$857 million (US$600 million) on exploration, research, and development of coalbed methane projects. Amoco now operates over 900 wells, which produce over 12.7 million cubic metres of gas per day (450 million cubic feet) from operations in the states of New Mexico, Colorado, and Alabama, USA. This represents approximately 11% of Amoco's natural gas production worldwide (data as of 12/93).

Unfortunately, relatively few coal-bearing basins are commercially productive. Reasons for non-commerciality of CBM resources include lack of reservoir permeability, diagenesis, undersaturation, thermal immaturity, wellbore and operating costs, distance to pipeline, and unfavorable business conditions.

COMPARISON OF CBM WITH CONVENTIONAL GAS PROJECTS

Coalbed methane exploration and production (E & P) technology has become a subset of the technology dealing with exploration and production of conventional gas (or oil) resources. The upstream side of CBM provides a unique combination of risks and rewards. Some risks are a factor of CBM being a relatively immature technology - other risks are endemic to CBM.

Coalbed Methane

The key difference in the E & P end is that the level of geotechnical risk is considered to be lower relatively early in CBM projects, and may be higher at the onset of development. Some unique advantages of CBM are: (1)A coalbed forms its own reservoir, source rock and seal, (2) CBM does not require structural closure or trap timing (or even stratigraphic closure) to trap it in the classical manner, (3) Coal can store an enormous amount of methane in its microporous matrix (unlike conventional reservoirs, where the effective storage is in the intergranular porosity macropores). This typically results in a long well life.

Some threshold reservoir qualities may be assessed with relatively few coreholes tied to surface geology. If threshold reservoir qualities are met, then the basin may be explored in increasingly expensive stages to quantify the production potential (see Table 3).

Geotechnical risk is still present even after the potential development areas are established. Prediction of fractured reservoir quantity and quality laterally away from control points may be difficult. Seismic methods are being researched to help in this, but most CBM fields have been developed primarily by the cumulative knowledge of respective coalfields and extrapolation from well data. The latter may be sufficient to proceed with development if reservoir parameters are favourable, and do not vary significantly between wells.

Conventional

In contrast, most conventional plays run a higher geotechnical risk of the seal, reservoir, and source rock not being congruent to form a trap. Trap timing is usually a crucial factor in conventional plays; it is usually not in CBM. Trap preservation, however, is very important to both. A pressure leak through a fault or an unconformity can cause a CBM or conventional reservoir to become undersaturated or devoid of hydrocarbons.

Usually a conventional play is delineated by seismic identification of structural and stratigraphic traps. However, the interplay of trap timing and components are such that a dry hole on one structure does not necessarily condemn another. A good example of this is the Llanos Basin in Colombia. The first wildcat was drilled in 1945, but it took 29 years and 22 wildcat wells before the first discovery was made in 1974. It took 40 more wildcats and 9 more years before the giant oilfield of Cano Limon (1.15 billion BOE) was discovered (Petroconsultants, 1993, L. Park, pers. comm.).

However, once a conventional gas structure is identified as productive, and the size of the structure is confirmed by detailed seismic and well testing, the development risk is considerably lessened. Lateral variations in reservoirs certainly exist, but they may or may not be condemnatory on a field-wide scale.

SYDNEY BASIN METHANE COMPARISON

Geotechnical Parameters		
E & P Parameter	**Conventional**	**Coalbed Methane**
Trap Timing	Very important Many different factors have to come together for trap to work.	Less important Hydrostatic pressure and coal forms its own trap
Seal and source rock	Very important Many structures are barren because of leakage, or no migration took place.	Less important Coal tends to form its own source and seal, given thermal maturity
Porosity	Very important Major determinant of production	Less important Porosity rarely cause of uneconomic CBM play
Permeability	Important but usually not primary cause of failure	Very important Primary cause of failure of most CBM plays.
Saturation	Less important Most reservoirs have a g/w or o/w contact, but completion strategies can avoid problem	Important
Strategic Activities		
Activity	**Conventional**	**Coalbed Methane**
Stratigraphic Coreholes	Less important Establish some reservoir parameters, but may not evaluate trap per se	Important Economical method to evaluate much about the trap and quantify resource base
Regional seismic	Very important Establish location of traps	May be important But difficult to use to locate traps per se
Test wells	Very important Primary way to evaluate production potential of the trap	Very important Primary way to evaluate permeability and help evaluate prod potential
Long term pilots	Not important Production potential is known relatively shortly after completion	Important Production potential must be modeled, especially in water wet reservoir

Table 1: Comparison of geotechnical parameters and strategic activities between coalbed methane and conventional gas plays.

STEPHEN WALLER

INTERNATIONAL CBM BASINS COMPARABLE TO SYDNEY

CBM basins are initially evaluated by comparing them to threshold geological criteria (e.g. appropriate thermal maturity, adequate coal thickness). The Sydney and U. Silesian Basins are examples of projects that have passed this stage. The next threshold is whether the basins meet potential production criteria (e.g. gas content, permeability). The final stage is development; the San Juan is an example of this final stage.

The San Juan Basin (USA)

The San Juan Basin is the world's most prolific CBM play. The San Juan has over 2100 CBM wells on production, with an average production of 17,670 cubic metres of gas (624 MCFD) per well. Amoco currently produces approximately 12.0 million cubic metres of gas per day (425 MM SCFGPD) from their San Juan Operations.

Most of the production is from the Cretaceous Fruitland Formation, which is 60 to 90 metres thick overall. The Fruitland typically has 6 to 24 metres of net pay, spread out over 1 to 9 seams. A large "fairway" zone which is overpressured and highly fractured contains the best production.

The San Juan Basin contains an enormous CBM resource: approximately 1.585 Trillion cubic metres of gas (56 TCF) (GRI, 1992?). Its exploitation was aided by, and initially required, significant tax credits and other favourable commercial incentives. There is relatively little competition for surface use for urbanization, but the environment has warranted and received careful attention.

Perhaps the most significant differences between the San Juan and the Sydney Basin are: (1) The San Juan coals are Cretaceous age, and formed in a relatively warm climate. Different macerals, and the structural history, resulted in more highly cleated vitrains and bright clarains; (2) The coals are overpressured in the most productive San Juan fairway. This allows them to hold a higher gas content, and achieve higher flow rates; (3) There is a well-established gas sales and production infrastructure in the San Juan, with a larger and more diverse market. In the San Juan's semi-arid, dominantly rural setting, location, land, road, and operating costs are moderate.

Upper Silesian Basin (Poland)

The Upper Silesian Basin in Poland, like the Sydney Basin, has many shallow coreholes but no CBM completions. While the Upper Silesian Basin is approximately 526,300 hectares (1.3 million acres), the coalbed methane industry's area of concentration/government nomination area has been only 85,000 ha (209,950 ac). Mining areas and cities cover other large prospective areas.

The upper Silesian Basin contains a Carboniferous coal sequence that is up to 2200 metres thick. This lies in fold and fault zones defined by the Variscan and Alpine Orogenic cycles. The faulting is widespread, and some throws are more than 300 metres.

	SAN JUAN BASIN[1]	**SYDNEY BASIN**	**UPPER SILESIAN BASIN**
Formation	Fruitland Coal	Illawarra Coal Measures	Laziska Bds, Mudstone, Sandstone, and Paralic Series
Geologic Age	Cretaceous	Upper Permian	Carboniferous
Avg. Coal Rank	High vol. A Bituminous	High vol. B Bituminous	High vol B Bituminous
Vitrinite Reflectance	0.5 to 1.7% Ro	0.6 to 1.7% Ro	0.8 to 1.6% Ro
Average Depth	915 m	850 m	1000 m
Net Coal Thickness	6 to 24 m	10 to 25+ m	60 to 80 m
Individual Seam Thickness	<1 to 5 m	0.2 to 5 m	ave 0.7 to 1.5 m, up to 13.5 m
Avg. Fraction of Pure Coal	78% (22% ash)	~ 88% (12% ash)	~ 83% (ave 15 -19% ash)
Gas Content	18.2 cub. m/tonne	10+ cub. m./tonne	5 to 14 cub m/tonne
Range of Permeability	0.1 md to 2 darcies	not well defined	unknown
Well Spacing	1.3 sq km (320 acres)	unspaced	unspaced
Reservoir Pressure	1700 to 12400 kPa (250 to 1800 psi)	not well defined, probably 7000 to 11750 kPa	not well defined
Pressure Gradient	6.79 to 15.83 kPa/m (0.3 to 0.7 psi/ft)	9.793 kPa/m (0.433 psi/ft)[2]	not well defined
Average Reservoir Temp	43 deg C (110 deg F)	46 deg C (114 deg F)	normal temperature gradient
Carbon Dioxide Content	0 to 14%	0.5 to 15%	1 to 5%
Number of Productive CBM Wells	2108	0	0
Key Commercial Challenges	Gas price competition, Tax Issues	Competing surface usage, Fiscal terms, Legal/regulatory framework	Tax and Currency Issues

Table 2: Comparison of the Sydney, San Juan, and Upper Silesian Basin Coalbed Methane Plays

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[1] *Most data on SJB courtesy of Jack McAnear, March 1992*

[2] *Assumes 6.8947 kPa per foot, 3.281 ft/m*

There are many favourable CBM characteristics of the Upper Silesian Basin from a technical standpoint. The net coal thickness is excellent: it tends to be 60 to 80 metres. The coals are predominantly vitrinite, which tends to cleat more intensively. The cleat permeability has been further enhanced by tectonic fractures.

The coals tend to be in an optimum thermal maturity range (0.9 to 1.1% Ro), and gas content appears to be acceptable.

Some major technical concerns exist. The largest may involve how significantly the fracture permeability diminishes with depth. The coals are spread out vertically, and could not all be completed with a single well. For example, a wellbore in the middle of the basin hit the top of the coals at 670 metres and TD'd at 1896 m MD -- and this well did not fully penetrate the coal sequence. There tends to be 60 to 80 seams in a well, averaging 0.7 to 1.5 metres per seam. Many thin seams over a broad interval make completions much more difficult and expensive. (Above data from public documents purchased from Polish Institute of Geology, and Larry Knox, pers. comm.).

The geological unknowns are the absolute permeability of the coals, their relative permeability, the diffusivity, gas saturation, and perhaps even pay thickness (as opposed to gross coal thickness). Unfavorable results in any one of these, or other, areas could condemn the play. As in most CBM plays, the nongeological risks could eliminate commercial development, even if the geological factors are favourable. In order for a project to succeed, investors must have some assurance regarding legal, tax, ownership, and financial foundations.

SYDNEY BASIN

Amoco Australia Petroleum Company (AAPC) was attracted to explore in the Sydney Basin because of the critical need to find new natural gas reserves for eastern New South Wales, because of the perceived stability of the political and industrial climate in Australia, and because the Sydney Basin possibly has favourable geological attributes for coalbed methane. AAPC entered the play by farming into PEL's 260 and 255 (now PEL 2), held by Australia Gas Light (AGL) in 1991. AGL's interest is owned by their subsidiary, International Oil Proprietary (IOP). This coincided with a farm-in by AAPC into PEL 267, held by Command Petroleum (via Sydney Oil Company) and the Government Insurance Office (GIO), in May of 1991.

At the outset, the encouraging geological attributes for the basin were:

1. Relatively thick coals on a summed gross seam basis. Coreholes such as the AGL Bootleg #8 and the Moonshine #13 penetrated the entire Illawarra Group, and were very helpful in establishing a stratigraphic framework.

2. Gas shows and mine "gas-outs", especially in the southern coalfield

3. Some indications of commercial gas content and gas compositions

4. Coals within the depth range of potential production, although predominantly deeper than optimal range

5. Some indications of thermal maturity within the gas generation 'window'.

The points of uncertainty were:

1. Reported low permeability in the prospective coal reservoirs; most coal relatively deep. Permeability was reported to be adversely influenced by cleat infilling/diagenesis and high lateral stresses.

2. Relatively gentle structural features that may do little to enhance permeability over a broad area

3. Some areas where coal gas is high in carbon dioxide

4. Unknown variation of net pay thickness in coal

5. No production, or production tests from the coals. There have been some non-completed gas tests in the basin, but these have been from the Triassic sandstones.

6. Over 65% of the PEL's covered by operationally restricted areas such as mines, parks, urban areas, rough terrain, and military bases.

Exploration Activity to Date

AAPC has drilled 7 coreholes, conducted extensive lab analyses, conducted two vertical seismic profile and limited shear seismic programs at corehole sites, conducted weeks of fieldwork, spent months on regional geological studies, and has undertaken select engineering and business studies to date.

The first coreholes were drilled to establish basic reservoir and stratigraphic conditions, and to correlate these with existing coreholes in the basin. Coreholes drilled later by AAPC tested exploration hypothesis. The Duncans Creek #1 highlighted the potential of the Lapstone Monocline Prospect as an area where the regional fractures in the coal were enhanced by localized fracturing. The Avon River #1 was drilled to test whether the shallower coals in PEL 255 were undersaturated, if they were more permeable because of lower vertical stress, and to establish pay thickness and reservoir parameters for the poorly understood Pheasants Nest coals.

If the reservoir analyses are prospective, then the coreholes will be followed up by test wells to test the permeability. If those are positive, then they may be followed by a pilot project to model production. That could be followed by a development decision.

WELL NAME	REASON FOR DRILLING	TD Date	Total Depth, FM @ TD (m)	Top Depth Coals
Narellan #1	Test basic reservoir properties and correlation to AGL analyses of Illawarra Coals in Bootleg #8	12/91	1250.0 Budgong	747.1
Riverstone #1	Stratigraphic test of Illawarra Gp in deepest area of basin; test reservoir thickness and properties in large area of sparse data.	3/92	1536.1 Budgong	1008
Duncans Creek #1	Test potential for higher permeability in Illawarra Gp along Lapstone Monocline and intersection with Burragorang Fault Zone; Test if high CO2 zone extends east of Lapstone fault.	1/93	1259.5 Budgong	781.1
Avon River #1	Test potential for higher permeability in Illawarra Gp in shallower coals in southern basin; test perm enhancement between two major lineations north of Nepean Monocline. Test if coals are undersaturated.	2/93	656.87 Budgong	422.7
North Castlereagh #1	Test potential for higher permeability in the Illawarra Group along Lapstone Monocline in northern PEL 2. Test if coal thickens to west of Riverstone #1, and if high CO2 zone extends to eastern flank of monocline.	5/93	462.25 Budgong	836.7

TABLE 3: Rationale and summary of coreholes drilled by AAPC to date. All depths and thicknesses in metres.

Reservoir Parameters

The Sydney Basin CBM target sequence is the Upper Permian Illawarra Coal Measures, and their lateral equivalents. The Bulli, Balgownie, and the Wongawilli Seams, are the most important. The American Creek Seams, the Tongarra, and the Woonona are also objectives. The Figtree and Unanderra Members at the base of the Illawarra may be too deep and argillaceous to be economical.

Some reservoir parameters of the Illawarra Group coals may be acceptable for an economic play. Net coal depth and thickness is adequate and ranges from less than 12 metres (40 feet) to 23 metres (75.5 feet) of in AAPC's prospect areas in PEL 2. Early indications are that many coals have a reasonable gas content and gas composition.

Durains and dull clarains, which tend to possess a lower fracture density, predominate in the basin. The Sydney Basin durains are dull simply because of a different maceral composition, and not because of ash dilution. Therefore, they have gross gas contents similar to brighter lithologies.

Coal fracture permeability is the greatest concern. Accurate measurements of permeability are very difficult in slim coreholes, because the drillstem test equipment and test periods are restricted. Permeability in fractured core is also difficult to measure, because the core separates along the fracture planes, and measurements are suspect. Therefore, accurate permeability measurements may not be available until individual test wells have been drilled, tested, and analyzed. Permeability may be low because of high lateral stresses and a predominance of sparsely cleated lithologies in the Illawarra Group.

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THE INGLESIDE CUTTING – A FAULT ZONE & SOME 'MISPLACED' DYKES

D.F. BRANAGAN
Dept. of Geology & Geophysics, The University of Sydney

INTRODUCTION

In previous papers (Branagan, 1991, Mills & Branagan, 1990, Branagan et al., 1988, Norman & Branagan, 1984) complex fault zones at Pyrmont, Cammeray and elsewhere in the Sydney area were described. Thrusting, strike slip and normal faulting were present, and at Pyrmont there was a thin weathered dyke which cut across the fault zone.

A road cutting on the Mona Vale Road near Laurel Drive [unsealed and undeveloped] (Mona Vale 1:25 000 map MV 40307263) [Fig. 1] is described in this paper. This cutting, some 80m in length with a maximum depth of 5m, displays both faulting and intrusion on a similar scale to that at Pyrmont and elsewhere in the Sydney region (Branagan, op. cit., Mills & Branagan, op. cit., Branagan et al., op. cit., Norman & Branagan, op. cit.), but there are some significant differences, and in particular the deformation seems to have been less intense. Branagan & Packham, (1970, 34) mention this cutting in passing, but refer only to "sedimentary structures" not features of tectonic origin.

Both sides of the cutting contain interesting structural features, and some correlations can be made across, but there are also discrepancies.

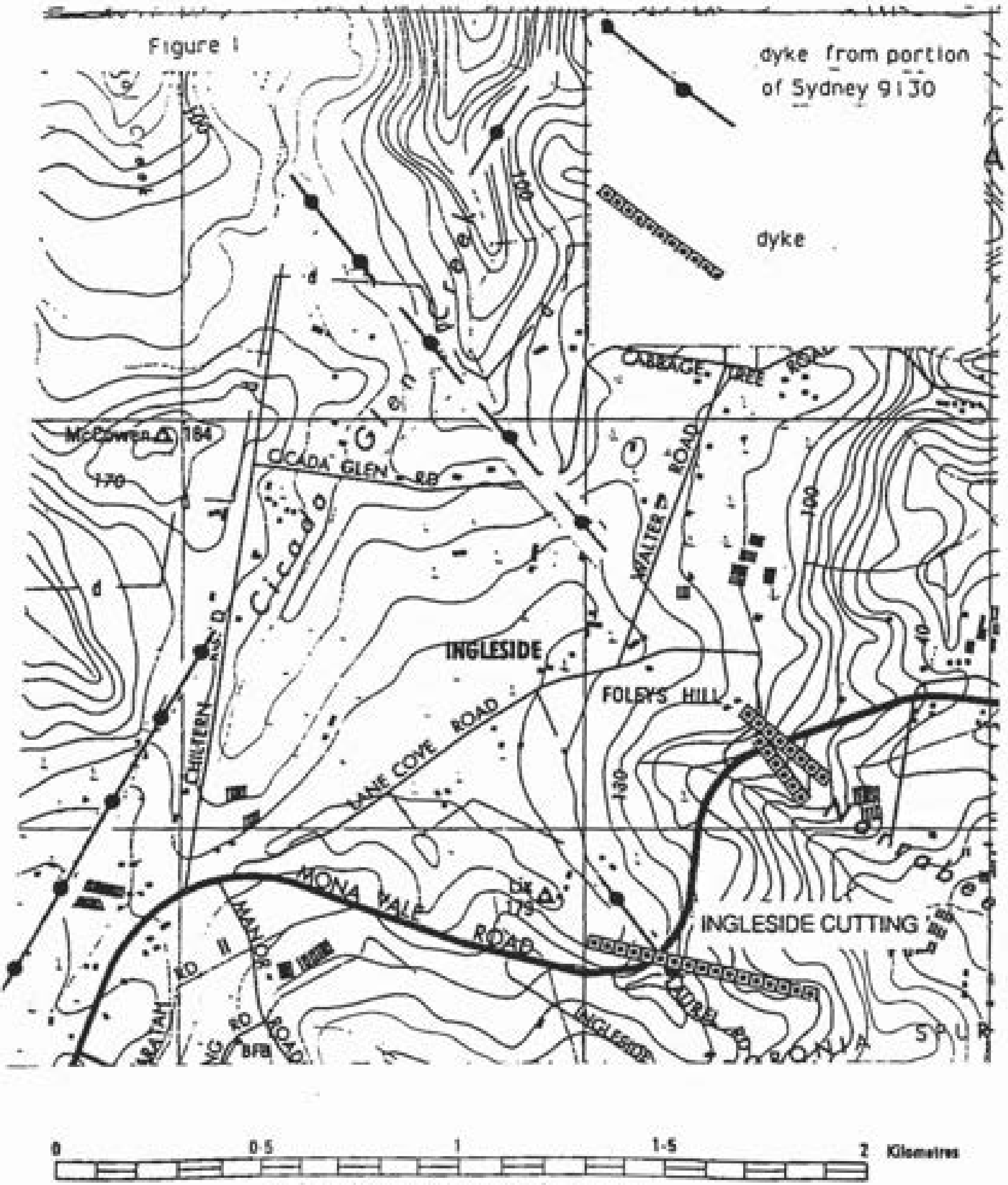
The general features of the site are shown in Figs. 1, 2 & 3, plan and two sections.

The rocks belong to the Hawkesbury Sandstone, and consist of massive and cross-bedded sandstone, including a pebbly layer, with several interbedded siltstone and shale lenticular layers. On both sides of the cutting, what were presumably shaly layers have been covered by concrete blocks and cemented-in-place sandstone blocks.

In general the cutting might be said to expose a very gentle asymmetrical anticline, which is probably the result of the tectonism, although some "built-in" irregularity caused by the sedimentary history (particularly the lenticular nature of some units) has probably also played a part.

Norman (1986) recorded structural data from this cutting, (Fig. 4), and this paper expands his material, and clarifies the position of dykes in the area.

INGLESIDE CUTTING



FAULTS

The most obvious example of faulting can be seen on the eastern side of the Ingleside cutting, where the bedded grey sandstone beds to the north abut against massive yellow sandstone which is cut by irregular iron bands (Fig. 2). The curved "pattern" of bedding at the base of the yellow block suggests that this south side has been dragged down. No direct correlation can be made across the nearly vertical boundary between the two sandstone types in the lower part of the cutting. Norman (op. cit.) refers to it as a vertical breccia/fault zone, striking 154^{0}, but it does not have the characteristics of other breccia zones described in earlier papers (Branagan, 1985).

At the top of the cutting the thin sandstone bed there appears to be merely draped over the fault zone below, and the bed is not faulted, but is intersected by a slightly radiating fracture system.

A zone of weak rock several metres immediately south of the fault has been covered by protective material, but adjacent (on the south side) is a narrow zone of fractured whitish sandstone.

North of the fault are some vertical fractures, spaced about 1.5m apart, filled with ironstone. These are wider at the base and die out before the top of the cutting. There is no evidence of any strike slip on these features, and they appear to be merely tension gashes.

Correlation across the cutting can be made between the exposures of the pebbly sandstone. This sandstone is displaced in a small V-shaped zone on the western side between two fractures trending about 140^{0} (Fig. 3).

The "normal" fault, south side down is not easily recognised on the higher (west side) of the cutting. On this side there are several normal faults exposed at the top of the cutting, but each of these blocks shows displacement of less than one metre, north side down, i.e., in the opposite sense to the normal faulting on the east side of the cutting. This suggests we are seeing a scissor hinge type fault.

To the north along the cutting, within the relatively undisturbed sandstone, there are fractures spaced about 2m apart, trending 140^{0}, some impregnated with iron. These continue through the rocks exposed the full height of the cutting, unlike those on the eastern side.

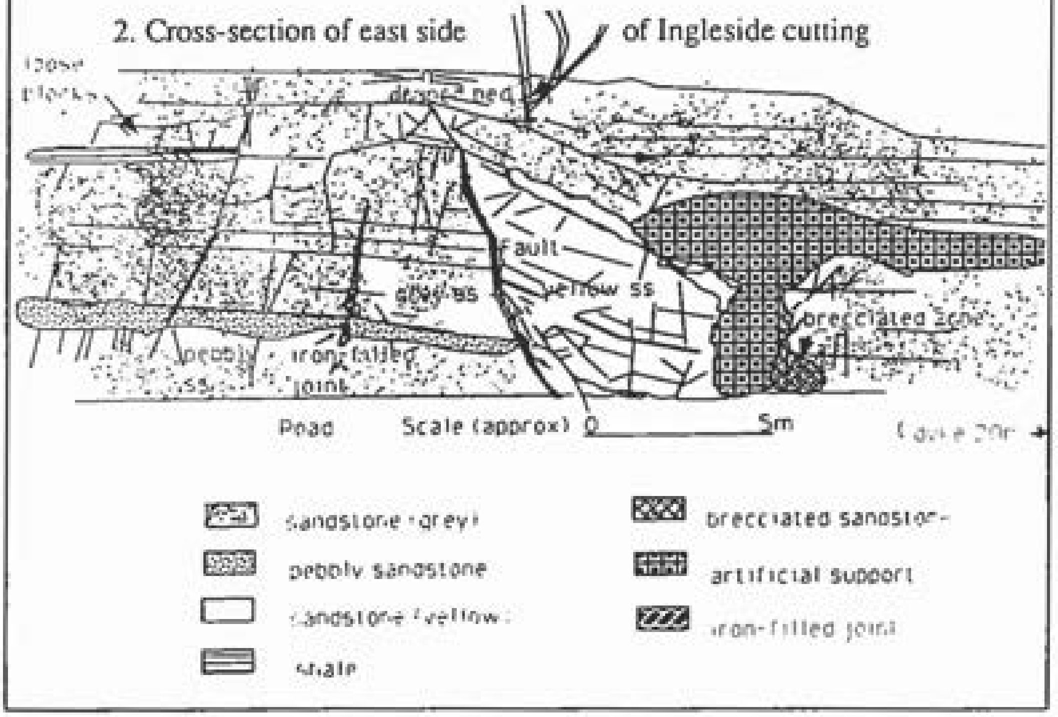
Comment

How does this site fit into the general pattern seen so far on the Hornsby Plateau? There are some major differences. No evidence of thrusting has been seen at this locality, and zones of sandstone shatter, re-cemented breccia are poorly developed, although Norman (op. cit.) indicates otherwise. Strike slip has possibly occurred, but no direct evidence can be adduced. In general the locality seems to have been essentially affected by tension, rather than by shear or compression.

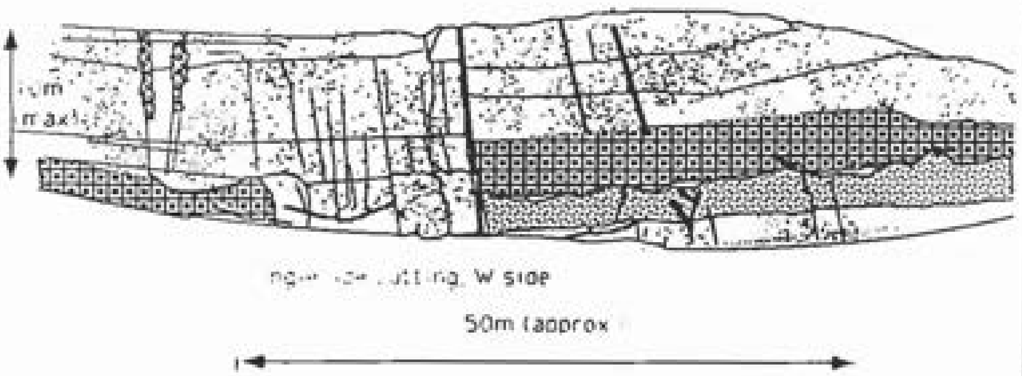
The dying out of the fault at the top of the east side of the cutting, might, at first glance, suggest faulting contemporaneous with sedimentation, but the splayed fractures in the top-most bed exposed in the cutting clearly indicate a post-depositional time of faulting. The small amount of "normal' displacement, both southerly and northerly indicates that only a small volume of rock has been involved in the deformation.

INGLESIDE CUTTING

2. Cross-section of east side of Ingleside cutting



3. Cross-section of west side of Ingleside cutting



DYKES

The Sydney 1:100 000 map (NSW Dept of Mineral Resources, 1983) correctly places a dyke in the Ingleside cutting, which is surprising, considering its poor outcrop. The outcrop is not clear if one is passing in a vehicle, and the heavy traffic in both directions through a cutting lacking paths makes inspection on foot relatively hazardous! On the map it is shown with a strike of 138°. Rickwood (1985; 285) queries this occurrence regarding it as being "in an improbable topographic position". The dyke occurrence here is noted in Branagan & Packham, (1970, 34), but no strike is stated.

A weathered dyke certainly occurs here, less than 1m wide (Norman states 30cm) on the eastern side of the cutting, trending 117°. It is split into several dykes on the western side. Bushfires in January, 1994 have exposed some of the area immediately adjacent to the cutting, but unfortunately outcrops are poor, and only a probable hardened contact zone consisting of ironstone adjacent to the dyke is traceable for some 400m. There is little sign of the split dyke beyond the western side of the cutting, and although outcrop is poor it seems to have only limited extent.

Nearby, (about 400m north-easterly, and down hill) two dykes, 2m apart, are well-exposed in a cutting on Mona Vale Road (Fig. 1), trending 148° (2.5m wide) and 136° (15cm wide), These dykes are recorded by Branagan & Packham (op. cit.), Norman (op. cit.) and Rickwood (op. cit., his Foley's Hill dykes), and Norman also records structural data (Fig.5), but the dykes are not shown on the Sydney map. However a south-east trending dyke (136°) occurring a little to the northeast (Fig.1), would, if extended, cut Mona Vale Road at the correct location. The strike of 136° suggests that Rickwood's comment about the Ingleside cutting (quoted above) may be correct, and that the dyke mapped as occurring in the Ingleside cutting has been observed in the lower cutting to the northeast, recorded there by Herbert, but incorrectly plotted. Some distance to the south-west (west of the Bahai Temple), a .6m wide dyke, trending about 026°, crops out (Fig. 1). This is the named Bahai Temple dyke of Rickwood, identified in Branagan & Packham (1967) and shown on the Sydney 1:100 000 geology map.

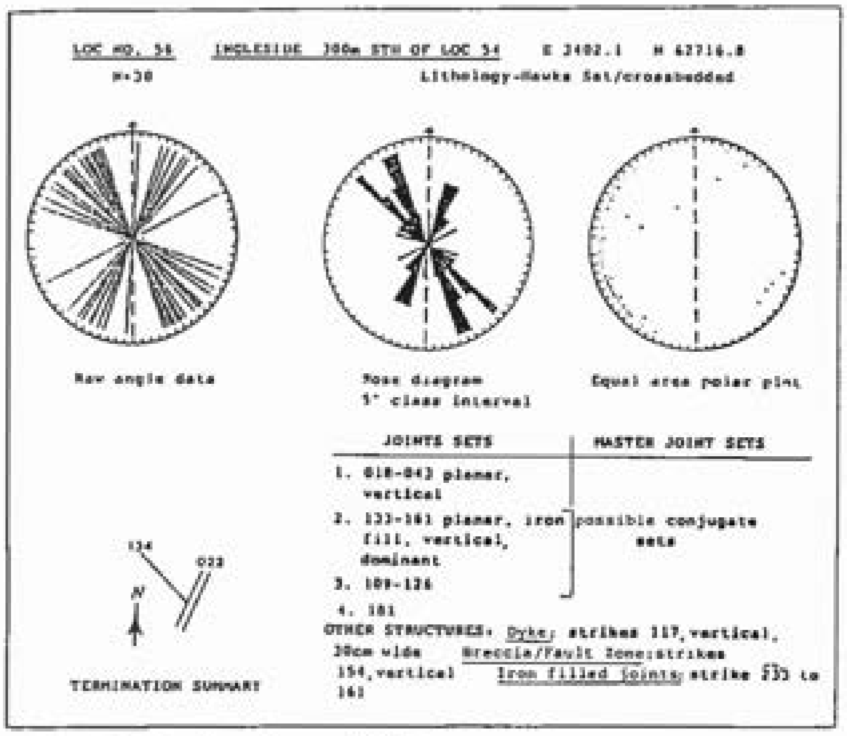
The 138° trend incorrectly shown on the Sydney Geological Map for the Ingleside dyke makes it appear as part of a pair of extensive intrusions mapped north of Coal and Candle Creek, continuing northwest almost to Cowan Creek, and possibly including also the Long Reef dyke to the southeast.

The true strike of 117° of the Ingleside dyke closely relates to the strike of two dykes on the Warringah Parkway, near Oxford Falls (Sydney Map, op. cit.). If the Ingleside dyke trend of 117° is projected to the east, this would bring it to the coast on the south side of Turrimetta Head. However no dyke is to be found in this cliff section.

It is to be hoped that the excellent work carried out by Rickwood will be followed up by publication of more detailed maps, and recording of other dyke occurrences, such as the two exposed during construction of the Warringah Freeway through Artarmon.

There appears little doubt now that there are more dykes present in the coastal zone than inland. Although Rickwood suggests this may be an accident of lack of outcrop, there have been sufficient large-scale engineering works, more cuttings and

INGLESIDE CUTTING



LOC NO. 56 INGLESIDE 300m STH OF LOC 54 E 3402.1 N 62716.8

N=30 Lithology-Hawks Sst/crossbedded

Raw angle data

Rose diagram
5° class interval

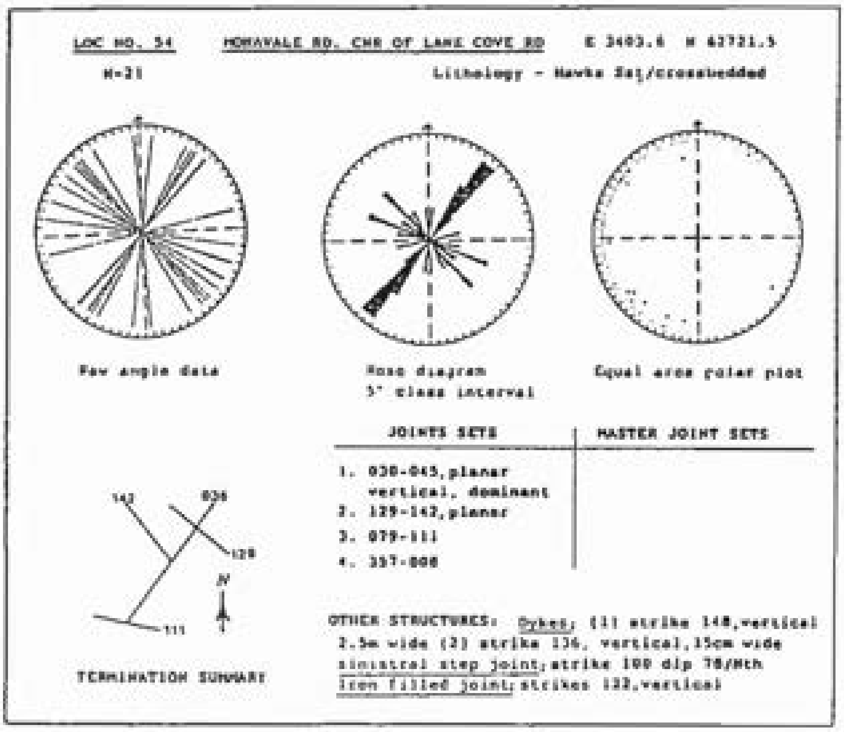
Equal area polar plot

JOINTS SETS	MASTER JOINT SETS
1. 018-043 planar, vertical	
2. 133-161 planar, iron fill, vertical, dominant	possible conjugate sets
3. 109-126	
4. 181	

OTHER STRUCTURES: Dyke; strikes 117, vertical, 20cm wide Breccia/Fault Zone; strikes 154, vertical Iron filled joints; strike 133 to 161

TERMINATION SUMMARY

4. Ingleside data from Norman (1986)



LOC NO. 54 MONAVALE RD. CNR OF LANE COVE RD E 3403.6 N 62721.5

N=21 Lithology - Hawks Sst/crossbedded

Raw angle data

Rose diagram
5° class interval

Equal area polar plot

JOINTS SETS	MASTER JOINT SETS
1. 030-045, planar vertical, dominant	
2. 129-142, planar	
3. 079-111	
4. 357-008	

OTHER STRUCTURES: Dykes; (1) strike 148, vertical 2.5m wide (2) strike 136, vertical, 15cm wide sinistral step joint; strike 100 dip 78/Nth Iron filled joint; strikes 132, vertical

TERMINATION SUMMARY

5. Mona Vale Rd data from Norman (1986)

excavations become available for examination in the western part of the Hornsby Plateau and the Cumberland Plain to indicate that there is a real difference.

CONCLUSIONS

This short paper is designed to set out the geology of a single outcrop, but in doing so also corrects some previously published information. It suggests that there is still plenty of local detailed geology in need of description, before general statements can be made with confidence about regional structure and the tectonic history that caused it.

A co-ordinated attack by interested members of the geological community is warranted, to build up a central bank of the basic information on both fault zones and dykes. This would be of great practical value to engineers and developers, and of theoretical value to those concerned with the geological history of the region.

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UPLIFT OF THE SYDNEY-BOWEN BASIN, EASTERN AUSTRALIA : COMPARISON WITH THE TECTONICS OF THE COLORADO PLATEAU, SOUTHWESTERN USA

C.L. FERGUSSON
Department of Geology, University of Wollongong

INTRODUCTION

The uplift histories of eastern Australia and the Colorado Plateau are considered herein in the hope that they provide constraints on the uplift of the eastern Australian highlands. Timing of uplift in relation to major tectonic events has been a point of contention for both regions. In Australia, the eastern highlands formed from either passive erosion of highlands uplifted during the Palaeozoic and early Mesozoic (Lambeck & Stephenson 1986) or during initiation of the eastern Australian passive margin in the late Mesozoic (Lister & Etheridge 1989). Uplift of the Colorado Plateau has been attributed to either the Late Cretaceous-Early Tertiary Laramide Orogeny (Coney 1987a) or the mid Tertiary Basin and Range extensional tectonic event (e.g. Hintze 1988). The Laramide Orogeny has some similarities with the Late Permian-Early Triassic Hunter-Bowen Orogeny, that deformed and uplifted the New England Fold Belt and the Sydney-Bowen Basin. Development of the Tasman and Coral Seas may therefore be the Australian equivalent of the major extensional Basin and Range event in the USA.

LARAMIDE OROGENY AND HUNTER-BOWEN OROGENY

The most impressive product of the Late Cretaceous-Early Tertiary Laramide Orogeny of the western USA is the major uplifts that form the Rocky Mountains. In addition, deformation was widespread throughout the western United States and Mexico with thrusting and accompanying magmatic activity. The orogeny is related to west-dipping subduction of the Pacific Ocean floor under a high-stress regime imparted by high convergence rates that developed in the Late Mesozoic and Early Tertiary (Coney 1978). In the Colorado Plateau the Laramide Orogeny formed spectacular monoclines that affect pre-Eocene strata (Davis 1984). Classic Laramide uplifts (Rocky Mountains), east of the Colorado Plateau, have been related to an Andean-style active margin with a gently dipping subducting slab (Jordan *et al.* 1983).

Timing of uplift of the Colorado Plateau is disputed. One view is that the plateau was uplifted, along with the Rocky Mountains, during the Laramide Orogeny (e.g. Coney 1987a). This seems logical as the monoclines formed in the

Colorado Plateau would have developed at the same time as the uplift. The monoclines form much of the existing topographic surfaces in the Colorado Plateau with flat upper limbs raised up to 1000 m above the flat lower limbs. These structures are truncated by an Eocene unconformity, that is overlain by thick Early Tertiary lacustrine deposits (Hintze 1988). Middle and Late Tertiary volcanics, including cauldrons, ignimbrite sheets, basaltic volcanics and laccoliths, are widespread across the Colorado Plateau and many volcanic successions also rest on the Eocene unconformity surface.

The Late Permian-Early Triassic Hunter-Bowen Orogeny affected the New England Fold Belt and adjoining Sydney-Bowen Basin. Major deformation and regional metamorphism occurred in the Devonian-Carboniferous subduction complexes and Early Permian rift basins in the eastern part of the New England Fold Belt (Harrington & Korsch 1985; Fergusson & Leitch 1993). Deformation migrated westwards into zones of thin-skinned tectonics in both the Tamworth-Yarrol belt and the adjoining foreland basin (Glen & Beckett 1989; Fergusson 1991; Liang 1991). A major Andean-style magmatic chain developed along the former subduction complexes and forearc basins, and is related to a west-dipping subduction zone located to the east (Harrington & Korsch 1985; Fergusson & Leitch 1993). The Hunter-Bowen magmatic chain and foreland fold-thrust belts have a similar tectonic setting to the Laramide magmatic chain and thrust belt.

The Blue Mountains uplift occurs in a similar tectonic setting to the Colorado Plateau; i.e. both occur on the cratonic side of their respective orogenic belts. Uplift of the Blue Mountains appears to have occurred at the same time as formation of the Lapstone Monocline and related structures. The Lapstone Monocline is morphologically similar to the monoclines of the Colorado Plateau; they have the same relatively simple geometry with flat upper and lower limbs separated by a gentle to locally steep middle limb (see Branagan & Pedham 1990; Davis 1984). They were formed from horizontally directed crustal shortening and geometrically they appear to have been generated as fault-propagation folds developed ahead of an advancing thrust at deeper levels in the underlying basement and strata (see Suppe 1985). The Lapstone Monocline formed after deposition of Triassic marine strata and prior to formation of the Early Jurassic Nortons Basin diatreme (Pickett & Bishop 1992). If the monocline is pre-Jurassic then it well may be related to the Hunter-Bowen Orogeny (see also Herbert 1989).

Other structures were formed in other areas of eastern Australia by the Hunter-Bowen Orogeny. In Queensland, west of the thin-skinned thrust belt of the Folded Zone and Gogango Overfolded Zone (Fergusson 1991), occur some broad gentle folds and the basement uplift of the Anakie Inlier. The Anakie Inlier appears to form a Carboniferous antiformal uplift, that was reactivated in the Hunter-Bowen Orogeny (Johnson and Henderson 1992). None of these structures are as nearly impressive, in terms of present-day morphology, as the Lapstone Monocline.

EXTENSIONAL TECTONICS IN THE SOUTHWESTERN USA AND EASTERN AUSTRALIA

In the southwestern USA two major episodes of extension occurred. The first formed in a period of lower rates of convergence from gravitational collapse of thickened crust that had developed during the Laramide Orogeny (Coney 1987b). The second episode of extension occurred later in the Oligocene-Miocene in response to development of the San Andreas transform system and release of the southwestern USA from convergent margin activity (Coney 1987a, b). The first episode formed the metamorphic core complexes whereas the second episode developed the Basin and Range topographic province with abundant high-angle normal faults accompanying horst and graben formation. Many geologists have attributed uplift of the Colorado Plateau to the second phase of Basin and Range extension (e.g. Hintze 1988). This is in spite of the fact that the monoclines, which appear related to uplift, are of Laramide age as is shown by their truncation at the Eocene unconformity surface. Widespread magmatism accompanied Basin and Range structural development and a popular concept is that uplift of the Colorado Plateau was caused by igneous underplating accompanying these events.

In eastern Australia a major extensional event occurred in the Late Cretaceous and Early Tertiary and formed the Tasman and Coral Seas in addition to rifting in Bass Strait, the Gippsland and Otway Basins, Lake George, central Queensland and throughout the Queensland Plateau (Veevers 1984). In central Queensland, development of half grabens, now filled with oil shale deposits, was relatively widespread and is considered to have formed a topographically subdued "basin and range" province in the Early Tertiary. Other half grabens, such as Lake George, although locally impressive, are relatively minor features upon a much larger landscape devoid of any evidence for extensional tectonics. Uplift of the eastern Australian highlands has been related to a phase preceding the main oceanic rifting event. Lister and Etheridge (1989) infer that uplift was caused by igneous underplating at an upper plate passive margin in southeastern Australia and somehow related to a lower plate passive margin in Queensland.

It has been argued that fission track data indicate that uplift was associated with continental rifting in southeastern Australia (Dumitru *et al.* 1991). In particular, Dumitru *et al.* have shown that late Cretaceous uplift appears to have affected a coastal stretch and gradually dies out up to about 100 km inland. Features, such as the Woronora and Hawkesbury Plateaux in the Sydney region may therefore be related to a Late Cretaceous phase of uplift in contrast to the older Hunter-Bowen age inferred for the Blue Mountains uplift (see above).

CONCLUDING REMARKS

The model of Lambeck and Stephenson (1986), that the highlands are relics of older orogenic belts, appears to have some validity when it is considered that regions, with considerable topographic relief, are relics of older mountain belts in intracratonic settings. For example, the mountains of central Australia are presumably relics of the Alice Springs Orogeny. Other regions, such as the Appalachian mountain chain of eastern North America, also have remanent relief and may be relics of Late Palaeozoic closure of the Iapetus Ocean. However, as the Appalachians occur adjacent to a passive margin their uplift history is bound to be considered problematic by some.

The uplift of the Blue Mountains is broadly similar in style to uplift of the Colorado Plateau, which is considered by some as a relic of the Laramide Orogeny. This seems logical as the Rocky Mountains uplifts, widespread throughout the western USA, are also relics of this orogeny. The same may well be true for eastern Australia. Attempts to relate uplift to passive margin processes have as an essential component that massive igneous underplating was responsible for the long term preservation of the uplifted region. It is very difficult to assess the validity of largescale deep crustal processes, such as underplating, as they can only be examined by indirect methods.

The hypothesis that the eastern highlands are a relic of the past orogenic history (Lambeck & Stephenson 1986), with modifications in regions, such as central Queensland by subsequent extensional events, remains the best explanation for the formation of much of the eastern highlands.

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ESCAPE TECTONICS & THE REDISTRIBUTION OF PERMIAN BASINS IN THE SOUTHERN NEW ENGLAND FOLD BELT

W.J. COLLINS
Dept. of Geology, The University of Newcastle

Introduction

It has long been recognised that the Late Permian synorogenic detritus of the Sydney Basin was derived from the "rising" southern New England Fold Belt (NEFB) during the Hunter-Bowen Orogeny (HBO). The associated deformation in the basin was west-directed thrusting (e.g., Glen and Beckett, 1989), but it is evident in all the Early Permian rift-basins of the southern NEFB: For example, major NW-SE strike-slip faulting in the Manning Basin, and complex south-directed thrusting and cleavage-forming deformation in the Nambucca Basin. These structures, with contrasting styles of fabric development and seemingly incompatible horizontal compressive stress orientations, compared with those of the HBO in the Sydney Basin, have not been generally considered as part of a single tectonic event.

Until recently, little work has been carried out on the effects of the HBO in the accretionary prism of the southern NEFB. They are evident largely as major dip-slip and strike-slip faults (e.g., Landenberger et al., 1994). Reconciliation of fault kinematics in the southern NEFB and of fold geometry in the Early Permian basins suggests that deformation was part of a single, complex event associated with Late Permian collision, producing a typical fold-thrust belt that was modified by oroclinal bending during "escape" of crustal fragments into continental recesses along an irregular plate margin.

Pre-Late Permian tectonic setting of eastern Australia

The NEFB developed as a convergent continental margin against the stabilised Lachlan Fold Belt in the Devonian and Carboniferous. From west to east, it consists of a calcalkaline arc (Connors-Auburn belt), forearc (Tamworth-Yarrol belt) and an outboard subduction/accretion complex (Wandilla-Gwydir belt), the latter separated by a major dislocation zone containing abundant ultramafic slices of ophiolite affinity, the Peel-Yarrol Fault System.

A series of extensional basins associated with extrusion of mafic volcanic rocks developed in the Early Permian (e.g., Leitch, 1988). In the southern part of the NEFB, they include the Sydney-Bowen, Stroud-Gloucester, Werrie and Myall basins, all of which developed as a major overlap sequence on the Tamworth Belt. Another basin, the Manning Basin, is characterised by distinctive debris flows and possibly developed as a pull-apart during transtension on the ancestral Peel Fault in the southern NEFB (e.g., Cawood, 1982). The Nambucca Basin, located entirely within the southern NEFB, also contains abundant mass flow deposits, mainly turbidites and diamictites, but includes large lenses of pillowed and massive basalt, which suggest that the basin was a deep oceanic trough (Leitch, 1988). Southward, the deep water sediments pass into shallow-water shelf facies on the northern margin of the Carboniferous Hastings Block, an allochthonous tectonic fragment similar to the fore-arc region of the Tamworth belt (Lennox and Roberts, 1988).

Age of Hunter-Bowen Orogeny in the Sydney Basin

Collins (1991) discussed the isotopic constraints on the timing of deformation in the Sydney Basin. Deposition of the 266 ± 1 Ma Thornton Claystone (Gulson et al., 1990) predated deformation and onset of the major uplift event in the southern NEFB, the latter recorded as high-energy fluvial and alluvial fan deposits in the upper Tomago and Newcastle coal measures. Uplift and shedding of detritus continued during eruption of the 256 ± 4 Ma Awaba Tuff (Gulson et al., 1990), stratigraphically located near the top of the Newcastle Coal Measures. Accordingly, the age of uplift associated with the HBO occurred in the 250-265 Ma period, which is Late Permian.

MAJOR LATE PERMIAN TECTONISM IN THE SOUTHERN NEFB

"Permian Dispersal"

A major feature of the NEFB that must be explained by any tectonic model is the double-width of its southern part, compared with the north, which increases from ~200 km to ~400 km. After resolving the original tectonostratigraphic configuration of the subduction/accretion complex by unwinding folds and translating major bounding faults, Cawood and Leitch (1985) described this doubling as the "Permian dispersal" event, which they surmised was an Early Permian event. However, as shown below, the "dispersal" is a Late Permian feature.

Late Permian age of Nambucca Basin deformation

One of the most enigmatic features of the southern is the *east-west trending* slaty cleavage in the deep-water facies of the Permian Nambucca Block; it is the only area in the NEFB with regional-scale, latitudinal structural trends. Cleavage dips moderately north, and the tectonic vergence is southward (Offler, unpubl.), toward the shelf-like deposits of the Hastings Block. The Hastings Block also underwent latitudinal shortening, but cleavage was poorly developed and open, km-folds were formed (Lennox and Roberts, 1988).

Orogenesis obviously post-dated the deformed Lower Permian sediments and was synchronous with the growth of greenschist facies metamorphic mineral assemblages, which define the well-developed slaty cleavage. Fifteen slaty and phyllitic rocks yielded ages of 270-250 Ma using the K-Ar technique, with two others yielding ages of ~280 Ma (Leitch and McDougall, 1979; Fig. 2). Therefore, the enigmatic E-W structural trends are a Late Permian feature!

Late Permian age of major "dispersal" faults

The bounding "dispersal" faults that separate the major tectonic blocks in the southern NEFB include the Yarras suture, the Nowendoc, Kilburnie-Dingo, Wongwibinda-Yarrowitch faults, and the Peel-Manning Fault System.

The east-west Permian foliations of the Nambucca Block are truncated by the >200 km-long, Wongwibinda-Yarrowitch fault system (WYFS), which must also be Permian in age, or younger. S/C mylonites developed in 300 Ma old granitoids of the Hillgrove Suite

(Collins and Offler, unpubl.) along the WYFS. Where the metamorphic grade was sufficiently high, biotite grew in the C (shear)-plane and yield Rb-Sr ages in the range 255-266 Ma (Landenberger et al., 1994), which indicates a Late Permian for deformation.

Other faults in the region, including the Dingo and Kilburnie, are higher-level structures where deformation was of lower metamorphic grade. The slightly older biotite ages (265-275 Ma) for these faults reflects partial resetting of biotite from the original 300 Ma magmatic age (Landenberger et al., 1994).

Late Permian age of major uplift

The WYFS is the major bounding fault of the Wongwibinda and Tia migmatitic complexes and was largely responsible for exhuming these deeper crustal rocks. Displacement on the ~260 Ma old WYFS, estimated by integration of shear strain across the deformation zone, is of the order of 9 km (Farrell, 1994). 260 Ma ages of blueschist facies rocks from the northern NEFB, obtained from ^{40}Ar/^{39}Ar age spectra of phengites (Little et al., 1993), also indicate major uplift at this stage. It appears that exhumation of all the deeper-level "metamorphic culminations" in the NEFB occurred at ~260 Ma, the Late Permian. This major uplift event in the accretionary prism of the NEFB was largely responsible for shedding detritus into the evolving Sydney-Bowen Basin, rather than uplift on the Hunter Thrust (Collins, 1992).

Late Permian age of Oroclinal Bending

Field mapping as far back as the 1960s suggested the presence of an orocline in the NEFB, (Lucas, 1960), which was substantiated by further mapping (Olgers et al., 1974; Korsch, 1981; Flood & Fergusson, 1982). More recent aeromagnetic surveys have confirmed its existance (Wellman & Korsch, 1988).

Murray et al. (1987) assumed that the age of the orocline was Late Carboniferous, but evidence presented below suggests that it was a Late Permian feature: (1) Early Permian sediments are intensely deformed in the axis of the orocline near Texas (Olgers et al., 1974); (2) cleavage and bedding in the Early Permian Dyamberin beds have been rotated into concordance with the regional oroclinal structure east of the Wongwibinda Complex; (3) the foliation in the Dundurrabin granite, located farther to the east, is also concordant with the orocline and has been dated at 270 Ma using a Rb-Sr analysis of biotite. As recrystallization is minimal in the granite, the age represents a partial reset and must be considered a maximum. Irrespective, it constrains the age of oroclinal bending to <270 Ma and, based on the isotopic data from other Hillgrove Suite granitoids, the age of deformation is ~260 Ma (Landenberger et al., 1994).

None of the major Late Permian (255-265 Ma) "dispersal" faults of the SNEFB cut the orocline, yet the WYFS must have displacement in the order of hundreds of km to explain rotation of the Nambucca-Hastings Block. It implies that oroclinal bending was *after* the "Permian dispersal". Furthermore, the WYFS is one of a series of splay faults off the Peel Manning Fault System (PMFS), which cuts folded and tilted Permian strata of the Stroud-Gloucester Syncline and the Manning Basin. Therefore, Permian dispersal and oroclinal bending may be considered as the terminal deformation phases of the HBO (D_4 of Collins, 1991). These regional-scale field relations indicate that oroclinal bending was a Late Permian feature.

The orocline is cut by voluminous Early Triassic post-tectonic granitoids (245-250 Ma old: Shaw et al., 1991), constraining the age of deformation to Mid- or Late Permian.

Origin of Oroclinal Bending

Oroclinal bending developed in the terminal stages of the HBO in the southern NEFB and was associated with major "out-of-sequence" strike-slip faults such as the Peel Fault. The HBO involved collision of the outboard Gympie Terrane with an irregular Late Permian continental margin. Prior to collision, the margin was probably composed of several Carboniferous arc festoons, which generated an irregular continental margin with localised salients and recesses.

Initial, continent-normal collision formed a typical craton-verging and migrating fold-and-thrust belt in the Sydney Basin, during east-west compression. Following the initial development of meridional folds, ongoing compression caused anticlockwise rotation of the Tamworth Belt, resulting in formation of the arcuate Hunter-Mooki and related thrusts and backthrusts. With continued compression, much of the shortening was accommodated by sinistral strike-slip movement on the Peel-Manning Fault System and associated splay faults in the accretionary prism. As a result of large-scale material transfer by strike-slip faulting, the accretionary prism material from the south "escaped" laterally northward into a Permian continental recess that existed in the present-day New England region, effectively doubling the width of the accretionary prism. In the process, the Hastings-Nambucca block was translated northward and rotated into its present position. Farther northward, the prism was pinned against the adjacent arc, possibly as a result of ongoing west-directed thrusting in the northern NEFB, preventing tectonic escape along the continental margin. Accordingly, the leading edge of the wedge was obliquely thrust onto the arcuate Carboniferous arc, producing the Texas orocline.

Ongoing collision in the northern NEFB, possibly associated with ENE-WSW compression, tightened the structure, particularly in the vicinity of Grafton, producing the present double orocline. Farther north, beneath what is now the Clarence-Moreton Basin, the more northerly Carboniferous arc segment was thrust westward over the orocline, as shown by aeromagnetic data. This suggests that deformation in the Bowen Basin may have developed slightly later than in the Sydney Basin.

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SEQUENCE & SEDIMENTOLOGY OF EARLY PERMIAN SECTIONS ALONG THE PEEL-MANNING FAULT SYSTEM

C.G. SKILBECK, T.R. SHARP, & E.C. LEITCH
Dept. of Applied Geology, University of Technology

INTRODUCTION

This paper presents a progress report of a systematic study of Early Permian strata preserved in the vicinity of the Peel-Manning Fault system of the southern New England Fold Belt. There is little published sedimentological data available for these rocks for which two contrasting basin models have been proposed (Leitch, 1988; Aitchison and Flood, 1992). In an attempt to further constrain tectonic interpretations of these rocks, we have logged sections at a number of locations (Figs 1 and 2).

Preliminary study of relatively common marine invertebrates confirms the Early Permian age of most of these sections and ongoing work by Dr D. Briggs (UNSW) on the fossils recovered should eventually allow detailed correlations amongst them. Biostratigraphic information is not available for the section at Bungendore Spur or that recorded from the Upper Barnard River, and the ages of these rocks is based on lithological correlations. The Tarakan Formation of the Cobbadah district was assigned by Brown (1987) to the Early Permian, however, palaeontological evidence for this age is equivocal. In addition, the rocks differ in their provenance and sedimentological character from Early Permian strata further south, and we suggest it is more likely that they are Late Carboniferous in age (Skilbeck, Leitch and Briggs, *in prep.*).

MEASURED SECTIONS

Data for nine sections measured by tape and compass traverse are presented in Figure 2. These range in thickness from about 65m (Upper Barnard River) to in excess of 1300m at Hanging Rock near Nundle. All sections, except for that at Bungendore Spur for which the evidence is equivocal, young towards the Tamworth Belt (i.e. mostly west). Sections at Ironbark Creek (Price, 1973) and Kensington (Wilson in Brown, 1987) have been formally named, however, we refer to them herein by location. The upper Barnard River Section was first located by Allan (1987) and that at Bungendore Spur by Fuccenecco (1986).

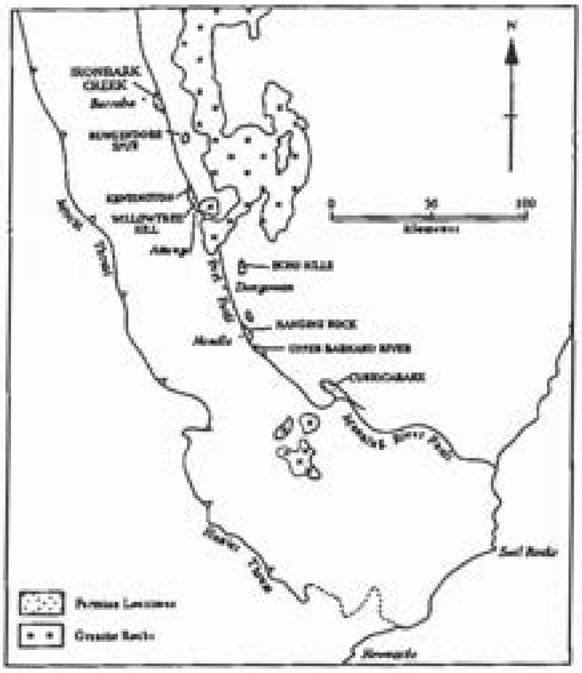

Figure 1: Location of measured sections shown on Figs 2 and 3.

The Echo Hills rocks were described in detail by Blair (1983). The limestone-bearing part of the section at Kensington measured by Wilson (1979; see Brown, 1987) has yielded a Devonian coral (D. Briggs *pers. comm.* 1993) and is here considered to belong to the Tamworth Group which outcrops extensively to the south and east.

RELATIONSHIPS TO ADJACENT ROCKS

The stratigraphic top of most sections is faulted against older rocks. Basal relationships are variable. The Upper Barnard River (Allan and Leitch, 1990) and Curricabark sections rest unconformably on ?middle Palaeozoic accretionary subduction complex rocks, whereas at Ironbark Creek and Willow Tree Hill the oldest rocks are in contact with sheared serpentinite. At the latter location the coherent Permian section is separated from siliceous rocks of the Woolomin Formation by a zone of intercalated serpentinite and Early Permian strata in a zone about 50m wide. At Hanging Rock and at Bungendore Spur cherts apparently underlie the sections, but the contacts are not exposed. Blair (1983) interpreted the basal contact at Echo Hills as a fault and this is consistent with the discordance between the strike of prominent conglomerate beds (010°-015°) and the strike of the base of the sequence (175°). However, there is no evidence of veining, brecciation or enhanced cleavage in rocks within 3m of the contact. In addition, the contact is highly irregular with an apparent relief of up to 10m and the conglomerate beds may prograde along this surface.

FACIES ASSOCIATIONS

Five major facies associations (FAs)have been identified in the measured sections as outlined below.

Facies Association 1: Siltstone/Limestone

This FA is typified by thin dark grey to black micaceous siltstone beds that in places contain concentrations of fenestellid bryozoans and small brachiopods that occur in massive to laminated, fissile beds up to 1m thick. Grey fetid bioclastic limestone occurs in beds from 0.1 to 2m thick interstratified with the siltstone, particularly in the M1 section at Curricabark. Concretions are conspicuously present at the latter locality.

EARLY PERMIAN SEQUENCE, PEEL FAULT

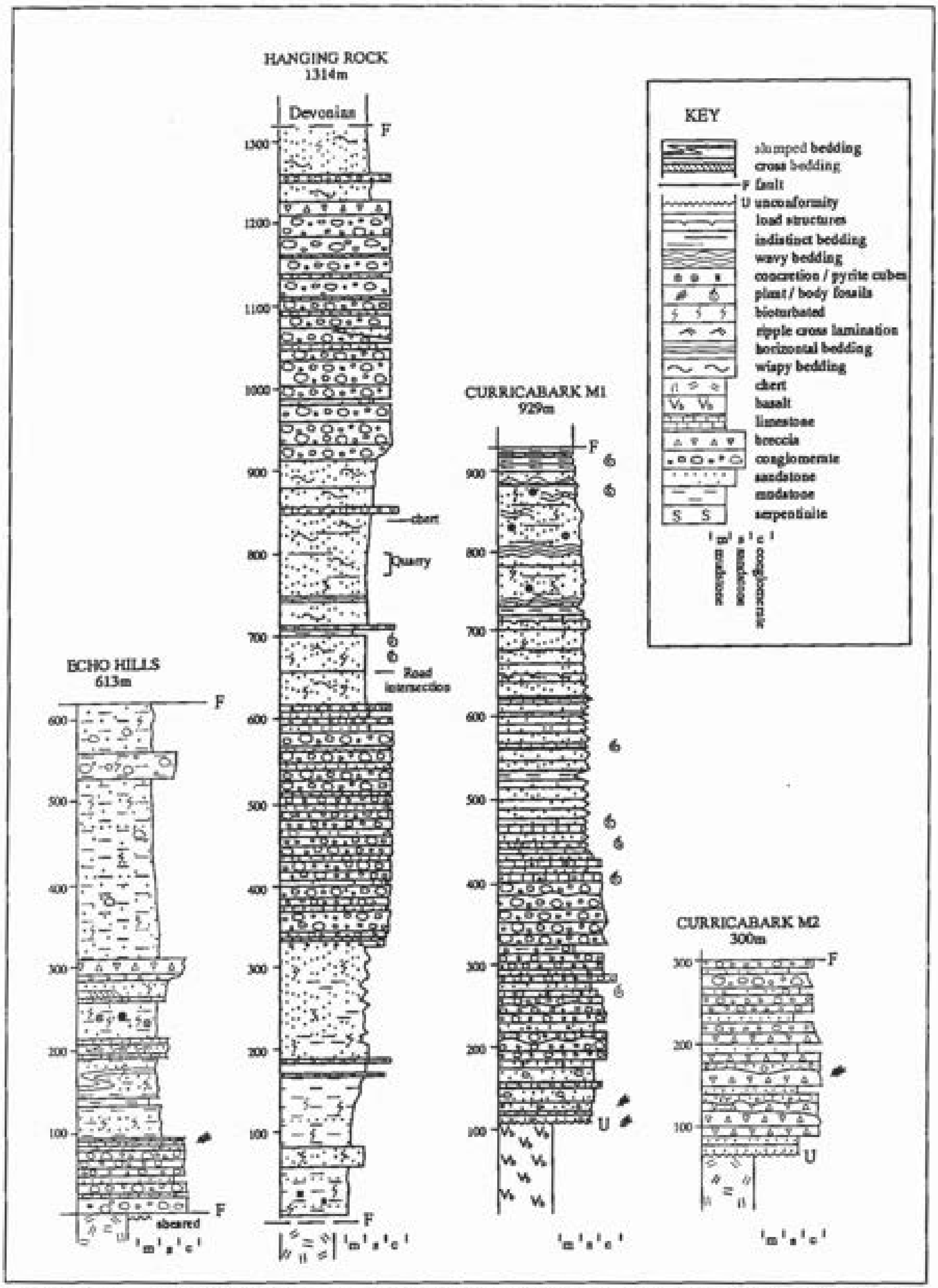

Figure 2: Sections measured at locations shown on Figure 1. Key applies to Figs 2 and 3. Scale is in metres. Note that vertical scales on Figs 2 and 3 are significantly different.

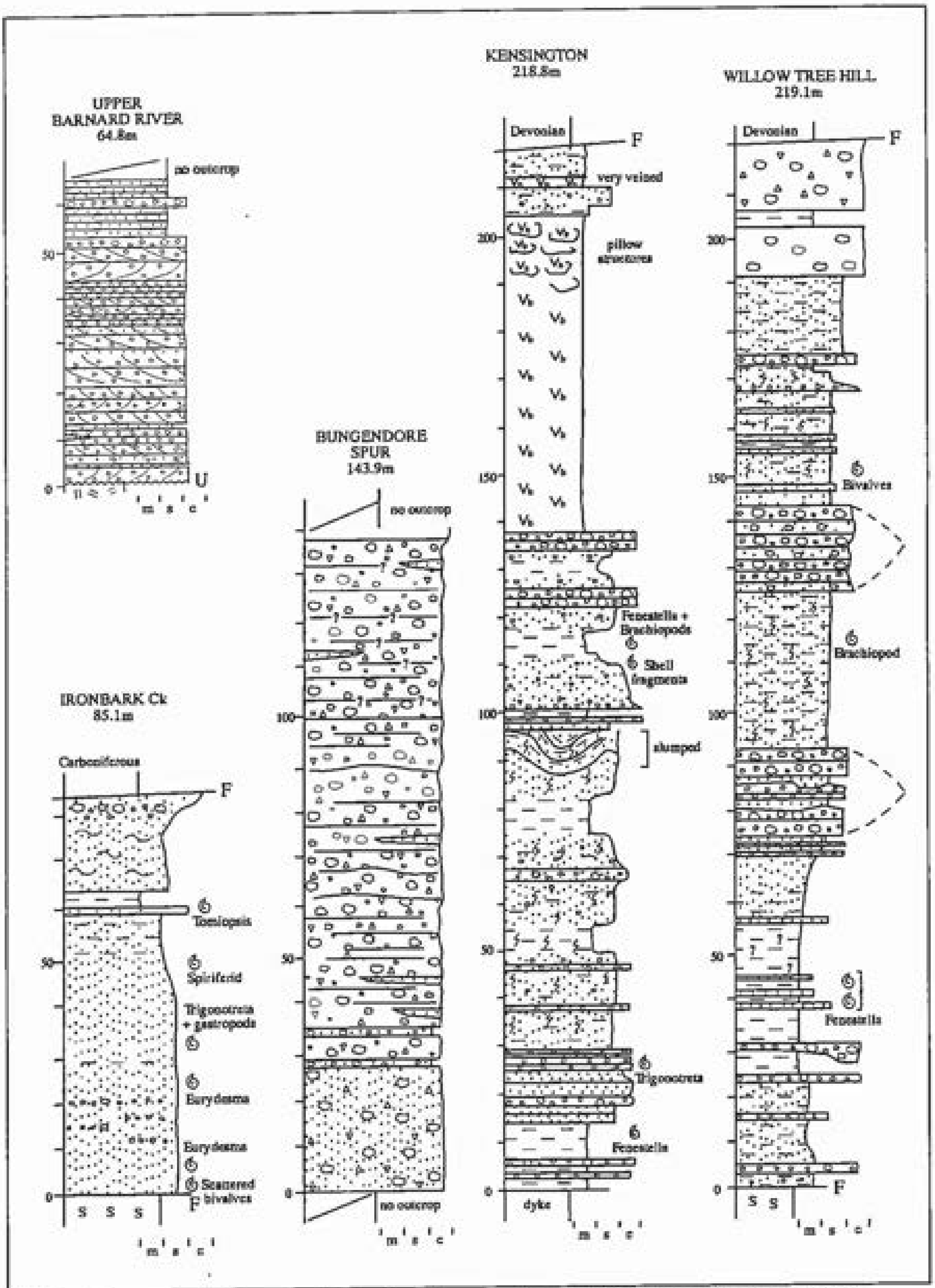

Figure 3: Sections measured at locations shown on Figure 1. For Key see Fig. 2. Scale is in metres. Note that vertical scales on Figs 2 and 3 are significantly different.

EARLY PERMIAN SEQUENCE, PEEL FAULT

Facies Association 2: Sandy siltstone/Paraconglomerate

The typical rock of this FA is an ill-sorted sandy siltstone, commonly containing scattered rounded pebbles and showing widespread evidence of bioturbation. Other rock types present include silty sandstone, pebbly siltstone and paraconglomerate. Internal depositional sedimentary structures are absent apart from uncommon wispy horizontal lamination. Fossils, predominantly robust brachiopods, bivalves and gastropods, occur in a few thin, laterally discontinuous layers. A variant included in this FA is a fine to medium grained, massive to wispy bedded, burrowed sandstone, that is commonly associated with the sandy siltstones.

Facies Association 3: Orthoconglomerate/Sandstone

Interbedded orthoconglomerate and sandstone units form prominent intervals in many sections. These intervals range from a few metres to greater than two hundred metres in thickness, and are characteristically stratified on a metre scale. Some intervals extend laterally for at least several hundred metres (e.g Echo Hills), whereas others are of more restricted lateral extent, lensing out over 100-150m (e.g. Willow Tree Hill). Individual conglomerate beds range from massive to graded, and many have irregular bases. Orthoconglomerate clasts are of granule to cobble grade, range from subangular to subrounded and are equidimensional. Interstratified sandstone, in beds 0.2-0.5m thick, is medium- to very coarse-grained and in places pebbly. Locally there are concentrations of angular siltstone blocks which are of intraformational origin. Sandstone beds commonly pinch out laterally. Internal bedding ranges from massive to indistinct wispy horizontal lamination and very rare cross lamination.

Facies Association 4: Cross-bedded sandstone/Conglomerate.

Cross- and planar-bedded granule to pebble grade conglomerate and medium to coarse sandstone occur interbedded on a metre scale at the base of the Upper Barnard River and Curricabark M2 sections. Tabular planar, curviplanar and trough cross sets are all present, with set thicknesses ranging from 0.2 - 2.0m.

Facies Association 5: Massive-bedded fossiliferous sandstone

Medium to coarse-grained sandstone in which heavy-shelled molluscs and brachiopods are concentrated in bedding parallel layers occur in the lower part of the section at Ironbark Creek. The sandstone is largely structureless, but contains scattered, rounded pebbles.

ENVIRONMENTAL INTERPRETATION

The presence of widespread brachiopods, bryozoans and crinoids indicates that FAs 1 and 2 accumulated in a marine environment. Both show few depositional structures, FA 1 because it accumulated in a quiet environment into which silt was normally the only material transported, and in which limestone formed during periods of negligible terrigenous clastic input. An offshore but relatively quiescent marine environment is indicated. The poorly sorted character of many FA 2 rocks, and the absence of depositional structures is attributed to pervasive biological activity. These rocks were probably initially well-bedded sandstone and siltstone that were deposited in a shelf environment of more proximal character than FA 1, although one that was not subject to strong currents. The origin of the pebbles in many of the rocks is uncertain. Rocks very similar to these occur widely in the Sydney and Gunnedah Basins where this attribute has been explained by mass movement and/or ice-rafting (e.g. McClung, 1980; Skilbeck & McDonald, 1993), and a similar explanation may apply to the rocks of FA 2.

The characteristic sedimentary structure in the conglomerates of FA 3 is horizontal stratification that is not environmentally diagnostic. Wispy structure within some interstratified sandstones is thought to be a product of biological activity on formerly well-bedded units, and the intercalation of rocks of this facies with marine strata of FA 2 supports a marine site of deposition for the conglomerates. We envisage these rocks having been deposited rapidly during periods of increased sediment supply at which time gravel deltas advanced seawards. The relatively poorly rounded character of many clasts suggests short fluvial transport and only limited residence in a shore-zone environment.

Sandstones and conglomerates of FA 4 occur at the base of sections that show unconformable basal contacts. Cross and horizontal stratification in many of the rocks suggests a shallow water environment in which strong currents were active. Scattered marine fossils indicate some of these rocks are marine, but elsewhere (e.g. Upper Barnard River) coarsely cross-bedded sandstone and conglomerate may be of fluvial origin.

FA 5 is thought to have been deposited in a shallow marine environment as evidenced by the association of marine fossils and massive sandstone throughout the sequence. A depositional mechanism for the latter is difficult to determine because of the absence of sedimentary structures.

PROVENANCE

A variety of clast types are present in the conglomerates examined. The most common components are chert and grey-green siliceous argillite which are ubiquitously present and, to a lesser extent, silicic volcanics. Subordinate lithologies include granite, pegmatite, andesite, basalt, sandstone, granule conglomerate (in turn containing quartzite and siliceous volcanic clasts), siltstone intraclasts, limestone and vein quartz.

Where the Permian sections have been interpreted to unconformably overlie basement (Echo Hills, Curricabark M1 and M2 and the upper Barnard River), chert is the dominant clast type, although at Echo Hills quartz-intermediate sandstone, porphyritic siliceous volcanics, and metabasalts are present in minor amounts. The Curricabark M1 section overlies basaltic basement and this lithology is locally predominant in the basal conglomerates. In both Curricabark sections, siliceous volcanics are more common towards the top.

Most chert, siliceous argillite and metabasalt clasts closely resemble the rocks of the Woolomin and Cockburn Formations and their correlatives exposed northeast of the Peel-Manning fault system, and forming the basement to a number of the Early Permian sections. A few siliceous sedimentary rock clasts resemble rocks of Devonian age from the Tamworth Belt, which may also have supplied some metabasalt (cf Allan and Leitch 1990; Vickers and Aitchison 1993). Silicic volcanic clasts have not been studied in detail but many resemble phases of the Early Permian Alum Mountain and Boggabri Volcanics erupted to the south and west (see Leitch and Skilbeck 1991). It is possible that the upsequence increase in silicic volcanic debris in Permian sections marks the onset of this volcanic activity, and these eruptions provide a n obvious source for the tuff beds found scattered through the sections. The source of the granitic boulders in the section at Bungendore Spur is uncertain but might be the nearby Bundarra plutonic suite of Early Permian age.

DISCUSSION

The nature of the basin(s) in which the Early Permian sequences preserved in the southern part of the New England Fold Belt accumulated is debated. Leitch (1988) argued that all of the Early Permian rocks accumulated in a rift basin he termed the Barnard Basin and which, in the Early Permian was possibly contiguous with the Sydney Basin (Leitch and Skilbeck 1990). In contrast Aitchison and Flood (1992) and Vickers and Aitchison (1993), following Korsch (1982), have argued that the rocks accumulated in a series of pull-apart structures that apparently were isolated and approximately coincide with present outcrop areas.

The difficulties experienced in determining the nature of ancient sedimentary basins from the character of deformed and disrupted strata is well established. As noted by Reading (1980) sedimentary facies are not diagnostic. Sedimentary characters shown by the Early Permian rocks are indicative of sedimentation in a region affected by fault-induced source rejuvenation and linear clastic input, but this could have occurred equally in an environment dominated by strike-slip or extensional tectonics. If the ages of coarse clastic wedges within the Early Permian sequences can eventually be closely constrained, then this may help identify basin type, for rejuvenation is more likely to be a relatively local affect in a strike-slip basin and of more regional extent in a rift-related basin.

We consider that the best indication of the character of the Early Permian basin derives from a consideration of the overall tectonic setting of the New England Fold Belt at the start of the Permian. At about this time the following geological phenomena occurred: (i) the opening of the Sydney-Bowen Basin which is clearly of rift character, (ii) rapid eastward shift of convergent plate boundary elements of the east Gondwana margin as a result of roll-back, that would have produced an extensional stress field, (iii) widespread Early Permian magmatism that is of a character consistent with rifting, (iv) emplacement of the elongate high aspect ratio Bundarra batholith, (v) extensional unroofing of metamorphic complexes, (vi) tectonic stripping of Carboniferous and Devonian strata in the east of the Tamworth belt, and (vi) the emplacement of serpentinite masses at high crustal levels. It would be surprising indeed if a major element of extension was not involved in the development of sedimentary basins at this time.

The best evidence for a strike-slip (pull-apart) origin for sedimentary basins comes from syn-depositional source displacement, as demonstrated for the Late Tertiary Ridge Basin (Crowell 1974). Compressional deformation contemporaneous with basin development is anticipated in strike-slip belts, and intra-basinal unconformities, of varying age, are predicted in strike-slip basins whereas volcanism, particularly of calc-alkaline type, is normally absent. Neither syndepositional source displacement nor compressional deformation have been demonstrated for the Early Permian rocks, although rapid sedimentation which characterises strike-slip basins is indicated (Mayer 1972). Abundant magmatic rocks of Early Permian age, including some of calcalkaline affinity (Moody *et al.*, 1983), occur in southern New England.

In conclusion, we would note that the obliquity of opening of sedimentary basins ranges greatly and that strike-slip and extensional faulting occur together in most fault-controlled basinal complexes. Recent discussion with respect to New England early Permian sequences is concerned with their overall tectonic control, the scale of the basins in which the rocks accumulated, and their degree of isolation. Deposition possibly spanned 30 million years during which period major changes in basin architecture and tectonic control could have taken place.

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USING THE FORELAND TO INTERPRET THE OROGEN

L. ELLIOTT
Santos Ltd, Brisbane

INTRODUCTION

The sediment preserved in the Bowen/Sydney and Surat foreland basins (Figure 1) document the post Carboniferous deformational history of eastern Australia. These deformations should be present in the orogen but due to widespread erosion of the cover rocks, a number may not have been identified or have been incorrectly dated.

This paper reviews the timing of the structural events based on the analysis of seismic and well data, updating Elliott (1993). The timing of the deformations is constrained by interpreting the sedimentary record and therefore absolute age is not yet possible . Until the sediments are accurately dated using zircon analysis (Roberts et.al., 1991), there is ample opportunity for miscorrelations with volcanic or intrusive events in the orogen.

The improved understanding of deformation in the foreland allows some constraints to be placed on models which have been proposed for the evolution of the orogen. This paper suggests alternate interpretations for a number of areas and events within eastern Australia.

STRUCTURAL STYLE AND TIMING

Figure 2 shows the timing of the various structural events in the foreland, together with their relative style and intensity.

The area is compressional from Early Permian to mid Cretaceous. The Denison Trough area of the Bowen Basin shows minor extension which is probably unrelated to events in the eastern orogen.

A number of Early Permian compressional events are recognised. These are best developed in the Denison Trough where the earlier half grabens were inverted. The amount of inversion is dependant on the individual half graben.

One of these, the "mid Aldebaran" unconformity can now be identified on seismic data east of the Taroom Trough.

The next structural sequence boundary identified on seismic data is the boundary between the Rewan Formation and Showgrounds/Clematis Sandstone in the Bowen Basin which correlates with the Narrabeen Group and Hawkesbury Sandstone boundary in the Sydney Basin. This event can only be identified in areas of pronounced structural uplift, but can be seen in both well log correlations and seismic data. Contrary to earlier notions, this is the most important Triassic deformation affecting the foreland, with numerous thrusts developed at this time in addition to structural inversion in the Denison Trough. The end Moolayember Formation deformation rejuvenated the earlier structures and resulted in substantial erosion, however no penetrative faulting is seen in the Bowen or Sydney Basins at this time.

Two post Triassic compressional deformations can be identified. The first is a mild deformation which probably formed most of the Jurassic hydrocarbon traps in the area. This event caused a rejuvenation of earlier structures. The major post Triassic deformation is however a Mid Cretaceous event. Structural evidence for this event include small and large scale thrusts which are commonly observed throughout the Surat and Clarence Moreton Basins.

Subsequent to this Mid Cretaceous compression, rifting of the Eastern Australian margin occurred. The Tasman Sea commenced opening from the south in the Cenomanian with the Coral Sea formed in the Eocene (Veevers et al, 1991). This extensional event produced small scale normal faults documented by Lohe and McLennan (1991) and Daneel (1992) in the Sydney and Clarence-Moreton Basins, and half grabens in the Gladstone -Dauringa areas during the Eocene. The mid Miocene compressional event seen along the southern Australian margin does not appear to affect the area under discussion to any significant extent.

TECTONIC DEVELOPMENT

The following discussion attempts to provide alternate explanations of events present in the region based on knowledge of the foreland.

Elliott (1993) divided the post Carboniferous tectonic development of eastern Australia into three periods - Early Permian - Middle Triassic, Late Triassic - Mid Cretaceous and Mid Cretaceous - Present and provides much of the basic data drawn upon here.

Using the Foreland to Interpret the Orogen

Early Permian - Middle Triassic

The Early Permian - Middle Triassic period is characterised by the emergence of the Bowen - Sydney basins as a compressional foreland behind a volcanic arc. Murray (1990) proposed that the Meandarra Gravity Ridge extending from the Sydney Basin into the Bowen Basin developed in response to early Permian extension which created a volcanic filled graben extending approximately 2000km in length. This "graben" has not been imaged on any of the seismic lines in the region and Leaman's (1990) explanation that the gravity anomaly is an expression of interference effects between the orogenic belts on either side is to be preferred. The extension seen in the Denison Trough appears to be limited to that area and is probably related to extension on the west coast of the continent. Other Early Permian "troughs", "rifts" or "grabens" located within the New England Orogenic belt may be remnant thrust basins due to the dominantly compressional nature of the orogen.

The Esk Trough has been proposed as a Middle Triassic pull apart basin formed by wrenching (Korsch et.al., 1989). Seismic evidence is considered to demonstrate that it is a thrust remnant basin, and can be compared structurally with some of the troughs associated with the Adavale Basin (see Evans et.al., 1990) formed in the mid Carboniferous deformation.

Faults such as the Leichhardt-Burunga fault on the eastern side of the Taroom Trough have been proposed as large wrench faults (Korsch et. al., 1990). The consensus from seismic data elsewhere along the faults is more consistent with these faults being thrusts. The fault planes of the Triassic thrusts are not imaged on seismic, unlike the later Cretaceous thrusts. The Permian - Triassic volcanic arc was uplifted by thrusting in the Triassic, allowing the associated granites to be exposed through subsequent erosion. The continuity of the Permian-Triassic arc along strike suggests wrench faulting is subordinate to thrusting as the method of deformation and formation of "terranes".

The Texas - Coffs Harbour "Orocline" is likely to be the result of thrusting and basin scale folding in the Mid Triassic. Plunging folds which are eroded, give the same "S" shape geometry (Korsch et. al., 1990, Fig 5). This model allows the granites to be thrusted into their present position forming a large anticline and removes the need for much of the tectonic gymnastics previously needed to explain the orocline. The intense microfolding within the rocks in the Coffs Harbour area is probably older and may represent either Permian or Early Triassic deformations. The "Orocline" was further folded in the Mid Cretaceous to give the present Clarence-Moreton Basin.

Lindsay Elliott

Late Triassic - Mid Cretaceous

The Late Triassic to Mid Cretaceous history is characterised by the Surat foreland succession. This basin was much more extensive than presently preserved and comprises the present Surat, Clarence-Moreton and Maryborough Basins. The Surat sequence covered most of the Bowen-Sydney Basins, the now exposed Anakie Inlier and most of the previous Permian-Triassic volcanic arc.

A volcanic arc co-existed with the Surat foreland to the east of the present coast line, and parts of the arc are preserved in the Maryborough Basin (Grahams Creek Volcanics) and islands in the Whitsunday Group. Parianos et. al., (1993) confirm the Whitsunday Volcanics as calcalkaline and closely resemble volcanics from modern convergent plate margins. Granites in the northern exposed portion of the Bowen Basin were probably part of this system but are in their present position due to thrusting.

The effects of the Late Jurassic structural event are likely to be overshadowed by the mid Cretaceous deformation, however it is possibly associated with commencement of the Grahams Creek Volcanics in the Maryborough Basin (Figure 2). The mid Cretaceous compressional deformation has been responsible for the uplift and erosion of most of the Bowen/Sydney and Surat foreland together with their volcanic arcs. Basin scale folding occurred at the mid Cretaceous deformation. The Clarence-Moreton Basin is a "syncline", with the granites to the west forming a large "anticline" which is now devoid of Jurassic - Cretaceous sediment due to erosion. The present elevation of the Permo-Triassic granites suggests at least 2000m of uplift occurred at the Mid Cretaceous deformation.

In the northern Bowen Basin, the Folded Zone thrust system was emplaced with corresponding uplift of the northern Bowen Basin and Anakie Inlier. The Early Cretaceous granites within the northern Bowen Basin are sheared (Chris Patterson pers. comm. 1993) suggesting that they have been structurally transported with the thrusting. It is likely however, that the tight folding could be at least partly Early Triassic in age, which has been further deformed by Cretaceous thrusting, based on seismic data from the northern Taroom Trough (Elliott, 1993).

In the Sydney Basin structures such as the Lapstone Monocline are probably dominantly mid Cretaceous in age but are likely to correspond to a zone of early Triassic faulting. Thrusting occurred in the Maryborough and Clarence-Moreton Basins. An orogenic margin similar to those seen on the eastern edges of the Taroom Trough and Sydney Basin can be seen on seismic data on the eastern side of the Maryborough Basin.

Mid Cretaceous - Present

Following the mid Cretaceous deformation the Tasman Sea commenced opening in the Cenomanian (Veevers et. al, 1991). The main effects of this are minor normal faults in the Sydney and Clarence - Moreton Basins and the development of half grabens in central Queensland in the Eocene. The half grabens are restricted to the area of the Folded Zone thrust sheet suggesting extension back along the former mid Cretaceous thrusts.

CONCLUSIONS

A wider perspective for the history of the New England Orogen can be gained from the evaluation of the successive foreland secessions using data from petroleum exploration. However, further zircon dating needs to be undertaken to allow direct correlation of the sedimentary sequences preserved in the foreland with magmatic and metamorphic events in the orogen. Additional apatite fission track studies should confirm the previously greater extent of the Surat foreland basin. The potential limitations are, the lack of sufficient sediment thickness or elevated temperature gradients necessary to reset earlier ages.

Those studying the orogen, need to make greater use of the vast data set available from the foreland and when using seismic data , over reliance should not be placed on single line interpretations. Small areas need to be placed in their regional context.

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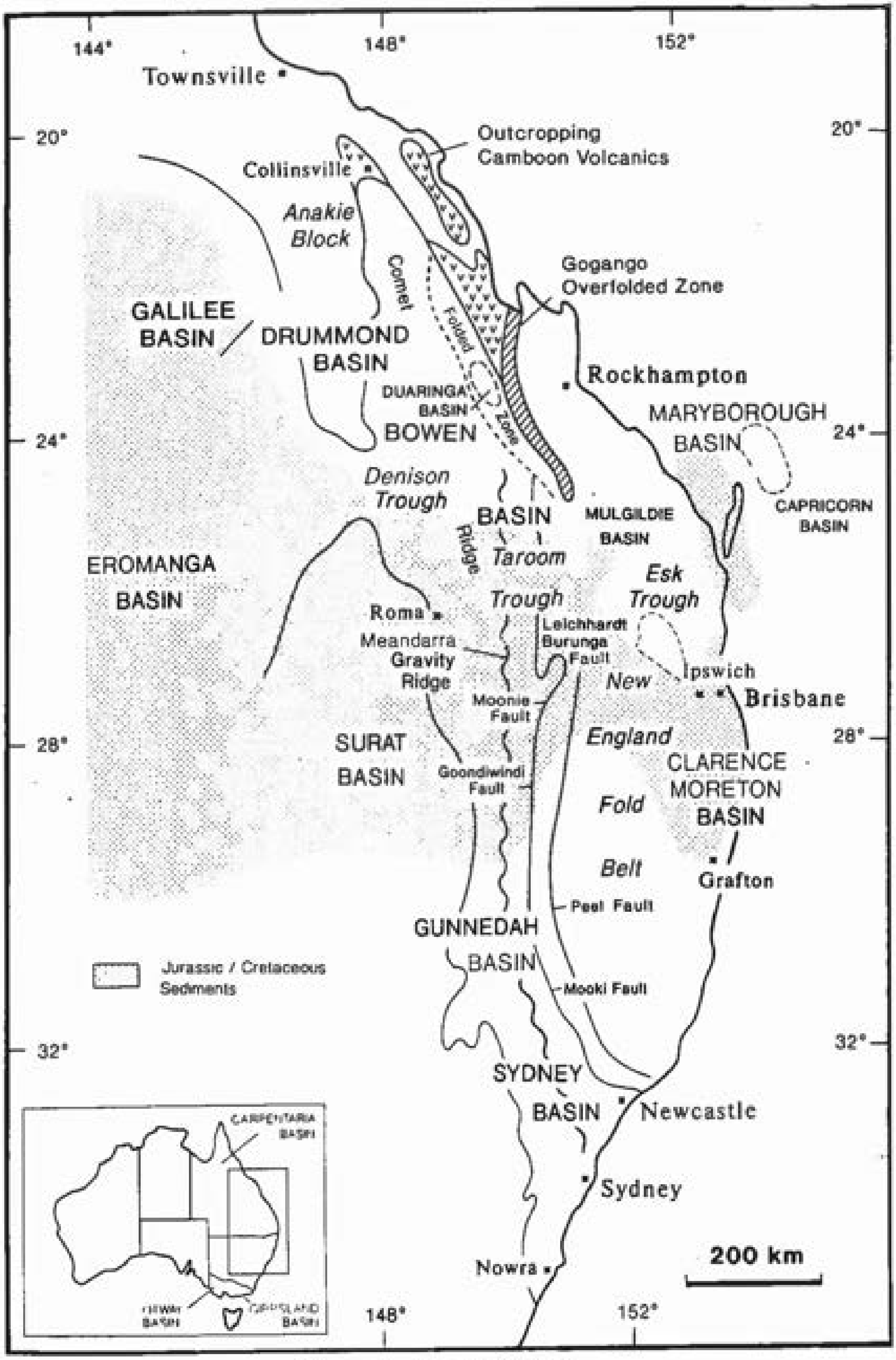

Figure 1 - Location Map

Using the Foreland to Interpret the Orogen

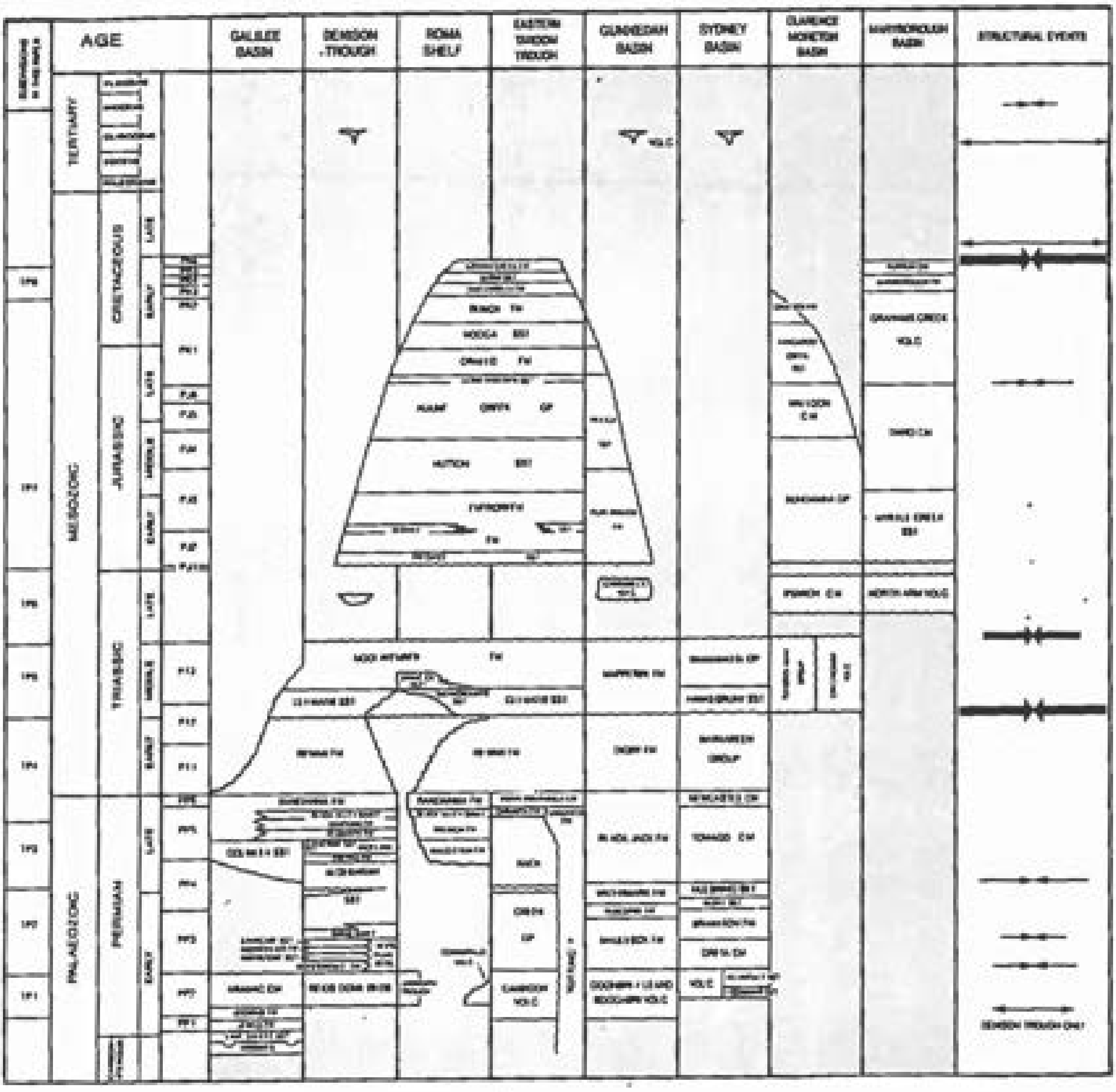

Figure 2 - Stratigraphy

CLEAVAGE CRITERIA FOR DISTINGUISHING BETWEEN DEFORMED STRIKE-SLIP & RIFT BASINS : IMPLICATIONS FOR THE EARLY PERMIAN OF SOUTHERN NEW ENGLAND

M. VICKERS
Department of Geology & Geophysics, University of Sydney

ABSTRACT

Strike-slip basins have penecontemporaneous sedimentation and deformation. Cleavage development is rare, because deformation occurs before diagenetic lithification is mature. This feature allows us to distinguish between ancient rift-controlled extensional basins and strike-slip basins, and is applied to the Early Permian of southern New England.

The Lower Permian Manning Group is intimately related to the regionally important Peel-Manning Fault System, which probably controlled sedimentation and certainly controlled deformation. The rocks occur as narrow, elongate, fault-bounded slivers, with highly asymmetric sedimentary facies. In many places, basin margin sedimentary breccias and conglomerates do not reflect the composition of adjacent basement rocks, indicating that sources and depocenters have been displaced.

Manning Group sediments rarely show cleavage, and at Kangaroo Tops have been demonstrably deformed within a strike-slip regime. This information leads to the conclusion that Lower Permian Manning Group sediments were deposited in strike-slip basins.

The Peel-Manning Fault System acted as a major strike-slip structure in the Early Permian, and the wide Manning Fault Zone probably reflects a restraining bend in the system. Under this regime, the locus of transtension (basin formation) and hence the locus of transpression (basin deformation) frequently jumped from one fault strand to another. This allowed rapidly deposited sediments to accumulate quickly and be deformed without cleavage.

INTRODUCTION

Lower Permian sedimentary rocks occur as generally fault bounded packages, either adjacent to or within the regionally significant Peel Manning Fault System (Fig. 1). The largest exposed area of these rocks (Manning Group [Voisey, 1957; Mayer, 1972]) is at the southern tip of the New England Orogen, in the Manning River area. They have been explained as extensional (rift controlled) sediments (eg. Leitch, 1988), or strike-slip basins (Aitchison and Flood, 1992; Vickers and Aitchison, 1992). It is difficult to distinguish between these two models (eg. Jenkins, 1992), because these basin types have many features in common.

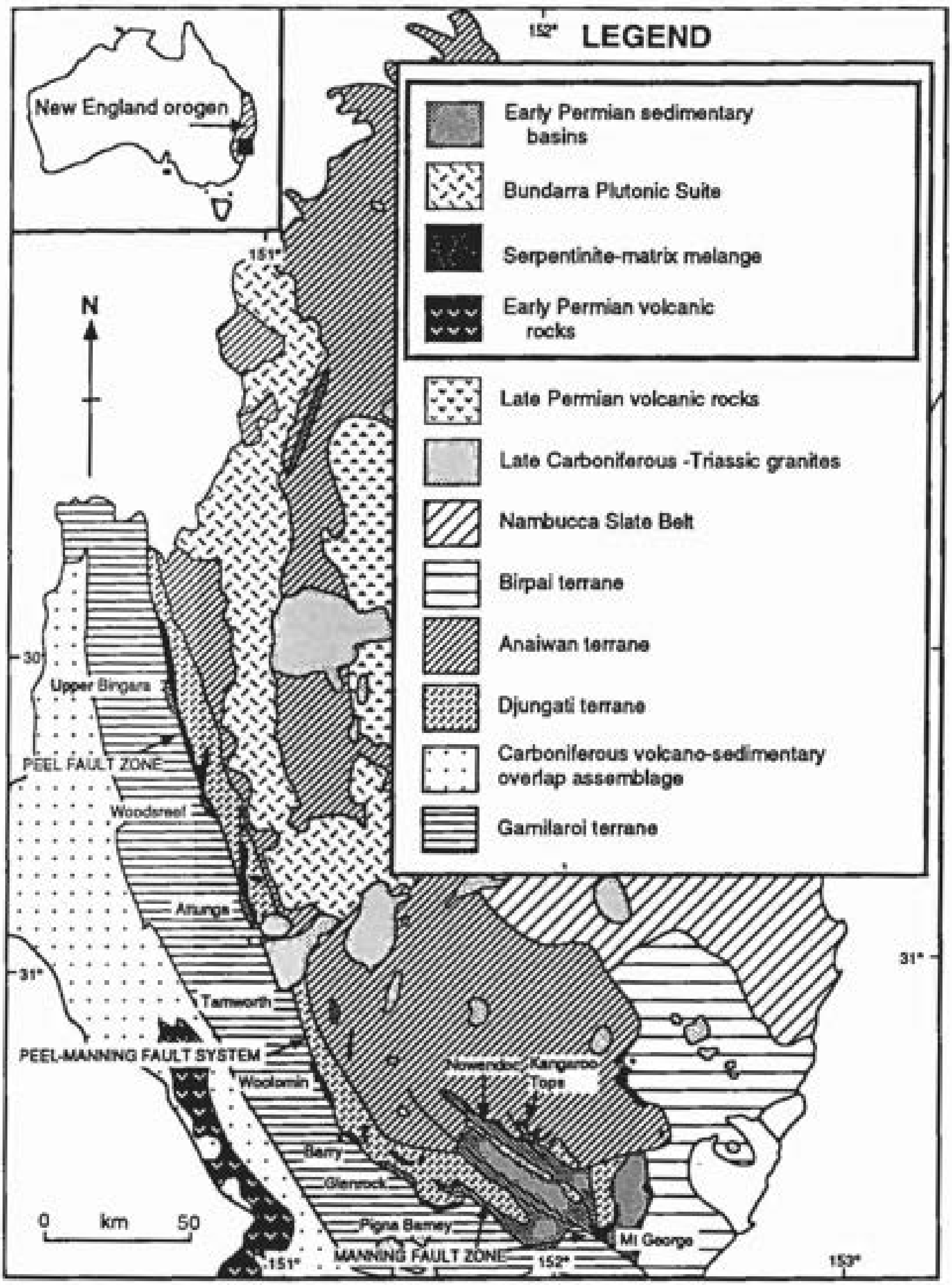

Fig. 1. Terrane map of the southern New England Orogen, showing Lower Permian Manning Group and similar sedimentary rocks. (after Aitchison and Flood, 1992)

CLEAVAGE, STRIKE-SLIP BASINS AND THE MANNING GROUP

In this paper, I discuss cleavage, which rarely develops in strike-slip basins because deformation takes place before diagenetic lithification is mature. This feature allows us to distinguish between ancient rift-controlled extensional basins, and strike-slip basins. This and other evidence is used to argue a strike-slip origin for the Lower Permian sedimentary rocks aligned along the Peel-Manning Fault System.

CLEAVAGE DEVELOPMENT IN DEFORMED BASINS

Rift Basins

Regional extension (= basin formation) and regional compression (= basin deformation) in orthogonal rift-controlled tectonic environments are separated by a large amount of time. This is because significant changes in the regional tectonic environment must occur. As a result, diagenetic lithification of basin sediments is likely to be highly mature. Significant deformation of these rocks will result in cleavage development.

Strike-Slip Basins

Features of Californian and other well-studied modern basins and their controlling faults help us identify ancient examples (Reading, 1980). Strike-slip basins are often narrow and elongate. They are usually fault-bounded and characteristically have huge stratigraphic thicknesses of sediment. Asymmetric development of facies and extreme facies variations are commonplace. Deformation is usually complex and includes strike-slip faulting, en echelon fold development and thrusting of basin sediments over adjacent basement. Narrow zones of basin-margin shearing often occur. (Table 1)

Many small Californian basins have developed in response to strike-slip deformation along the San Andreas Fault Zone. The San Andreas Fault Zone is a complex of anastomosing strands, responding to a restraining bend within the strike-slip fault system. Regionally, the locus of deformation (transtension = basin formation; transpression = basin deformation) frequently jumps from one fault strand to another. The time between these events is usually less than 5 Ma (Crowell, 1984).

This short time frame requires that sedimentation in Californian strike-slip basins is penecontemporaneous with deformation. Because the sediments have had insufficient time to undergo diagenesis, they are not fully lithified; their diagenesis is highly immature. Hence, during deformation, these poorly consolidated sediments respond as plastic materials, and cleavage does not develop. On a fine scale, much deformation within these basins is concentrated on bedding-failure planes, often less than 5 mm thick. Even so, plastic response to deformation is usual, and cleavage development is rare.

This important feature (lack of cleavage in deformed, narrow, asymmetric basins), allows us to distinguish between ancient strike-slip basins and orthogonal rift-controlled extensional basins. It can be used to test basin formation models for the Manning Group, which in turn has important implications for the Early Permian development of New England.

FEATURE	**BASIN**		**TYPE**	
	Strike Slip	**Rift (R) / Half Graben (HG)**	**Foreland**	**Manning**
Elongate	yes	yes	yes	yes
Narrow	yes	often	rarely	yes
Overall dimensions	very small	small to large	large	very small
Fault bounded	one or both sides	R - both sides HG - one side	one side	both sides
Boundary faults	S/S, thrust, reverse, normal	normal	thrust	generally steeply dipping. Displacement and dip uncertain
Marginal unconformities - preservation	rare	R -rare HG - one side	one side	Rare
Facies architecture	highly asymmetric	R - symmetric HG - asymmetric	slightly asymmetric	highly asymmetric
Facies: lateral and vertical	highly varied	Extensive	very extensive	varied
Sediment provenance	often mis-matched with basin margin	adjacent to basin margins	adjacent to basin margin	often mismatched with basin margin
Sediment deposition	very rapid	rapid to gradual	rapid to gradual	very rapid
Sediment thickness	very thick	thin to thick	thin to thick	very thick - up to 9 km (Mayer, 1972)
Basin life	very short (<5 Ma)	medium to long (>5 ma)	Long (>20 Ma)	very short (probably <5 Ma)
Deformation style	strike-slip faults, en echelon folds, basin over basement thrusting	elongate, margin-parallel folds, monoclines	folds and thrusts. deformation increases towards one margin	strike-slip faults, en echelon folds, basin over basement thrusting
Cleavage in deformed basin	rare	likely	common	rare

Table 1. Features of Strike-Slip, Rift, Half Graben, and Foreland basins as well as Lower Permian Manning Group-type sediments.

DISCUSSION: APPLICATION TO EARLY PERMIAN NEW ENGLAND

Lower Permian Sedimentary Rocks

Lower Permian Manning Group sediments in southern New England fulfil many recognition criteria used for strike-slip basins (summarised in Table 1). These and other similar Lower Permian sediments (Voisey, 1938, 1939, 1957; Mayer, 1972) are generally faulted against basement, although two examples of unconformities have been documented (Allen and Leitch 1990). The usual facies arrangement consists of basal sub-angular conglomerates, overlain by sub-rounded conglomerates and then by a thick succession of diamictites and turbidite sandstones. Angularity of clasts in basal conglomerates indicates a very short transport history, but clast provenance is often mismatched to local basement (Vickers and Aitchison, 1992). The Manning Group is interpreted as having been deposited on a marine slope-apron by high density mass- and debris-flows (Vickers and Aitchison, 1992, 1993; Jenkins, 1992). Facies development is asymmetric (Mayer, 1972; Vickers and Aitchison, 1992). Huge stratigraphic thicknesses have been documented (up to 9 km: Mayer, 1972) which accumulated in a short time, possibly much less than 5 Ma (Vickers and Aitchison, 1992).

In general, Manning Group rocks dip moderately to steeply south-west. Near strike-parallel faulting is common and NNW trending en echelon folds have been mapped at Cooplacurripa. Cleavage is rarely observed, even where the rocks are significantly deformed (eg. near major faults or on metre-scale wavelength folds).

Peel-Manning Fault System

The 375 km strike length Peel-Manning Fault System (Fig. 1) separates distinctly different element of the New England Orogen. To its west and south, moderately deformed Devonian island arc rocks (Gamilaroi terrane; Flood and Aitchison, 1988, 1992) and Carboniferous continental-margin overlap rocks occur. To its east and north, highly deformed Devonian ocean-floor chert (Djungati terrane; Flood and Aitchison, 1988) and the greywacke - chert dominated Anaiwan terrane (Flood and Aitchison, 1988) occurs (Fig 1). In many places, the fault system is delineated by serpentinite-matrix mélange.

The Peel-Manning Fault System disappears northward under Mesozoic cover near Warialda, and reaches the coast near Black Head, south of Taree. It comprises 2 major têt-à-têt fault zones. The 275 km long Peel Fault Zone is NNW trending, up to 5 km wide and occurs from Warialda (north) to Pigna Barney (south). At Pigna Barney, the character of the system changes and the NW trending, up to 35 km wide Manning Fault Zone continues SE for 100 km to Black Head.

The Warialda-Tamworth (northern) segment of the Peel Fault consists of a multi-stranded fault zone up to 2 km wide, usually containing faulted slivers of Early Cambrian (Aitchison et al., 1992) dismembered and highly sheared Weraerai terrane (Aitchison and Flood 1988) ophiolitic rocks. At least three separate areas of Early Permian sedimentary rocks outcrop within this fault segment. The Tamworth-Pigna Barney (southern) segment of the Peel Fault, consists of anastomosing fault strands containing slivers of Gamilaroi terrane, Djungati terrane, Weraerai terrane and Early Permian sedimentary rocks in a zone up to 5 km wide. The overall width of the fault zone increases southwards to Pigna Barney. Outcrops of Early Permian sedimentary rocks also occur within this fault segment.

East of Pigna Barney, the trend and width of the fault system increases, along with an increased abundance of Permian sedimentary rocks. The NW trending Manning Fault Zone is up to 35 km wide. Early Permian Manning Group rocks occur as elongate NW trending fault slivers, possibly up to 8 km wide and 65 km long, juxtaposed against either narrow basement blocks or other Manning Group blocks. Some faults terminate in "hook-structures", truncated by adjacent NW trending faults (eg. at Pigna Barney, Kangaroo Tops, Mount George). By analogy with deformation observed at Kangaroo Tops, I proposed (Vickers, 1993) that these structures may indicate sinistral strike-slip deformation.

Lithologies cannot be offset-matched across the Peel-Manning Fault System, so its sense and magnitude of movement is not well constrained. However sinistral strike-slip motion along it has been proposed by several workers (Corbett, 1976; Cawood, 1982; Cawood and Leitch, 1984; Leitch, 1988; Leitch and Skillbeck, 1991; Collins, 1992; Vickers, 1993), based mainly on sinistral microstructures within the Weraerai terrane (Corbett, 1976; Offler and Williams, 1985, 1987; Offler et al., 1989) or regional lithological groupings (Cawood, 1982; Leitch, 1988; Leitch and Skillbeck, 1991). Sinistral deformation of 10 km on one fault system strand can be demonstrated at Kangaroo Tops (Vickers, 1993).

Early Permian New England Tectonics: strike-slip dominated.

It is often difficult to distinguish between strike-slip and rift basins. Together, the Manning Fault Zone and Manning Group sediments display many features common to both strike-slip and rift basins (eg. narrow, elongate, faulted boundaries, lack of marginal unconformity preservation).

However, several aspects of both sedimentation and deformation of Lower Permian sedimentary rocks associated with the whole Peel-Manning Fault System can only be explained by a regional strike-slip tectonic regime. In particular, the Lower Permian rocks show asymmetric, varied facies development, the proximally derived sediments are often mismatched to local basement, and very thick sediment piles accumulated in small, short lived basins. Deformation styles include strike-slip faults, en echelon folds, and lack of cleavage in the sedimentary rocks, despite considerable deformation.

CONCLUSIONS

- The Peel-Manning Fault System is an extensive strike-slip structure, active in the Early Permian. It exerted a major influence on regional tectonics and sedimentation.
- Extension was not the dominant regional tectonic regime in the Early Permian; localised contemporaneous transtension and transpression were controlled by strike-slip motion on the Peel-Manning Fault System.
- Sediment supply, its rapid accumulation in small basins adjacent to the fault system and basin deformation were all controlled by localised transpression and transtension in a regional strike-slip setting.
- Strike-slip basins rarely develop cleavage, so on this basis they can be distinguished from ancient, deformed rift basins. Sedimentation in strike-slip basins is penecontemporaneous with deformation. Diagenetic lithification is immature. The sediment responds to deformation as a plastic, so cleavage rarely develops.

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CARBON ISOTOPES & SEQUENCE STRATIGRAPHY ABOUT THE PERMIAN-TRIASSIC BOUNDARY IN THE SYDNEY BASIN

R. MORANTE & C. HERBERT
School of Earth Sciences, Macquarie University

INTRODUCTION

The largest extinction event of the Phanerozoic occurred at the end of the Permian when it is estimated that over 90% of marine species and about 70% of land vertebrates became extinct (Erwin 1994). This was accompanied by a postulated sea-level fall of the order of 300 m (Holser and Magaritz 1987). During this event there must have been marked changes in carbon flux between the oxidised and reduced global reservoirs of carbon. This is reflected at the Permian/Triassic (P/Tr) boundary in marine sediments in Eurasia by a dramatic reduction in the ratio of $^{13}C/^{12}C$ in carbonate sediments (Holser and Magaritz 1987). The oxidation of vast amounts of stored ^{12}C-enriched reduced carbon led to the alteration of the ratio of $^{13}C/^{12}C$ in living organisms and precipitated carbonate rocks, which is shown by $^{13}C/^{12}C$ profiles of the Chinese stratotype section, where a $\delta^{13}C$-excursion to more negative values occurs across the palaeontologically determined P/Tr boundary (Baud et al. 1989, Chen et al. 1991, Dao-Yi & Zheng 1993). The negative $\delta^{13}C$-excursion, generally reported in *marine* intervals for inorganic carbon (C_{carb}), has also been found in organic carbon (C_{org}) in Austria (Magaritz et al. 1992). Our investigations into C-isotope stratigraphy in the Sydney Basin reveal similar $\delta^{13}C$-excursions in *non-marine* organic carbon. This suggests that the negative excursion of the C-isotope record at the P/Tr boundary may provide a globally correlatable time horizon independent of traditional biostratigraphical correlation in carbonate and organic-rich siliciclastic facies in both marine and non-marine environments.

Traditionally the P/Tr boundary in the Sydney Basin was placed at the contact of the "Permian" coal measures and overlying "Triassic" Narrabeen Group (David 1950). Subsequently, on the basis of palynomorph correlation between Australia and Pakistan, the boundary was placed at the *top* of the *P. microcorpus* zone (Balme 1970, Helby et al. 1987) well above the base of the Narrabeen Group in the transition from the Dooralong Shale to the Munmorah Conglomerate in the north, and in the lower part of the Scarborough Sandstone in the south. The position of the P/Tr boundary in Australia, as indicated by the carbon-isotope excursion correlated with the Chinese stratotype (Chen et al. 1991), lies close to or at the base of the *P. microcorpus* zone and is closely linked with the disappearance of the *Glossopteris* flora at the top of Stage 5.

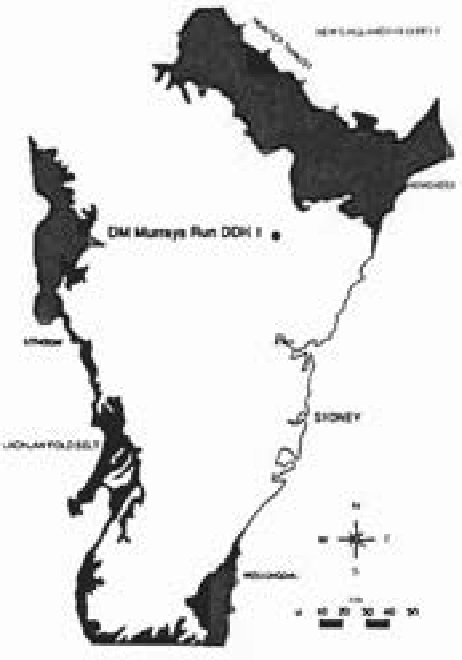

Figure 1. Location of DM Murrays Run DDH 1 in the Sydney Basin.

METHODS

Samples of organic carbon were obtained from shales in the fully-cored borehole DM Murrays Run DDH 1 (Fig. 1). Borehole sampling avoids surface weathering effects and enables accurate stratigraphic positioning of samples. DM Murrays Run DDH 1 was chosen for detailed study because it penetrates the earliest Triassic section identified in the Sydney Basin to date. Biostratigraphy was based on existing palynology supplemented with new determinations by R. J. Helby.

Preparation of the organic carbon for analysis largely followed the methods of Magaritz et al. (1992). Crushed cleaned shale samples of 1-2 grams were treated with heated hydrochloric acid at 80° C for 3 hours to react carbonate. The acid-treated samples and cupric oxide were placed in 6 mm quartz tubes, that were evacuated and sealed before furnace combustion at 800°C for 5 hours. The measured ratio of $^{13}C/^{12}C$ in the CO_2 produced by combustion of the organic carbon was determined on a Finnigan MAT 252 mass spectrometer. The measured ratios of $^{13}C/^{12}C$ were reported in the standard format of $\delta^{13}C$ relative to a standard carbonate (PDB) expressed in parts permil ($^{o}/_{oo}$). The standard deviation of the $\delta^{13}C$ determinations on 45 repeat analyses of an anthracite laboratory standard was 0.13 $^{o}/_{oo}$. The combustion yield of CO_2 enabled the total organic carbon (TOC%) to be determined.

ISOTOPE RESULTS

In DM Murrays Run DDH 1 the profile of $\delta^{13}C$ against depth shows a negative excursion in $\delta^{13}C$ values from about -24 $^o/_{oo}$ at depths greater than 780 m to values predominantly less than -26 $^o/_{oo}$ and as low as -29.6 $^o/_{oo}$ at depths less than 742.7 m (Fig. 2). This $\delta^{13}C$-excursion is in the same sense as $\delta^{13}C$ profiles determined on C_{org} in a marine section in Austria straddling the P/Tr boundary (Magaritz et al. 1992). The magnitude of the $\delta^{13}C$-excursion (as much as -5 $^o/_{oo}$) in DM Murrays Run DDH 1 is comparable to excursions detected elsewhere in Australia (Morante et al. 1994). A -5 $^o/_{oo}$ $\delta^{13}C$-excursion implies a transfer of carbon, from the reduced to the oxidised state, equivalent to 4 times the global biomass of carbon today (Spitzy and Degens 1985).

STRATIGRAPHY

Herbert (1993) showed that a significant hiatus separated the Late Permian coal measures from the overlying coal-barren Narrabeen Group. The hiatus is represented by a disconformity over most of the basin, and by an angular unconformity over locally active structures such as the Lochinvar Anticline (note that the stratigraphic position of the unconformity in DM Murrays Run DDH 1 is revised here). In many places, a palaeosol overlies the coal measures, either directly on the top coal or, as in DM Murrays Run DDH 1, on the topmost carbonaceous siliciclastic sediments (Fig. 3).

The Late Permian coal measures were deposited during a large-scale regression as relative sea-level fell from a mid-Permian highstand (Herbert 1980, 1994a in prep). In the Newcastle Coal Measures this is reflected by the up-sequence dominance of thick fluvial conglomerates deposited in the Lake Macquarie Syncline to the east of the Lochinvar Anticline (Herbert 1994b in prep). In contrast, immediately to the west of the anticline, the coal measures in DM Murrays Run DDH 1 are dominated by finer-grained siliciclastic sediments, coal and oil shale.

The negative $\delta^{13}C$-excursion commences about 50 m below the coal measures/Narrabeen Group boundary (Fig. 2), but accelerates in the last 6 m within thinly interbedded/laminated dark grey siltstone/claystone which can be considered as part of a high-frequency depositional sequence deposited during a single cycle of base-level change (Fig. 3). The interval commences above an erosional surface (sb at 758 m, Fig. 2) indicating a base-level fall. During the following base-level rise, about 14 m of upward-fining fluvial sandstone (lowstand systems tract) was deposited above the sequence boundary. This sandstone was overlain by interbedded fine-grained sandstone and shale above a transgressive surface (ts, Fig. 3), indicating a deepening lacustrine/estuarine margin featuring shrinkage cracks, the sphenopterid fern *Neomariopteris*, and reed-like *Phyllotheca* (transgressive systems tract, Fig. 3). Maximum transgression, when the rate of base-level rise was fastest, is represented by the more shaley dark grey part of the section (mfs, Fig. 3). Above this surface, and as the rate of base-level rise slowed to a highstand and began to fall, the shale coarsens and becomes more silty (highstand systems tract) with shrinkage cracks and plant remains (*Glossopteris* leaf), indicating shallowing conditions. A 30-cm-thick palaeosol cap indicates subaerial exposure with base-level fall to complete the cycle. This last Permian base-level fall recorded in the basin probably coincides with the major 2nd-order, end-Permian sea-level fall (SB at P/Tr, fig. 2, 3).

In DM Murrays Run DDH 1, the Narrabeen Group rests with a sharp, erosional, disconformity on the palaeosol capping the coal measures. The basal Dooralong Shale grades up to the Munmorah Conglomerate in three coarsening-up parasequence sets (M1-3, Fig. 2). These are interpreted as having been deposited in estuarine coastal plain to alluvial plain environments in the highstand systems tract of a 3rd-order depositional sequence as the rate of rising relative sea-level slowed to a highstand and began to fall.

DISCUSSION

The most rapid part of the negative δ^{13}C-excursion takes place in the top part of a 21-m-thick sedimentary cycle at the top of the coal measures in the 3rd-order Belmont Sequence (sb to SB, Fig. 3). This cycle is considered comparable in magnitude to, at least, a high-frequency, 5th-order sequence with a duration of the order of tens of thousands of years. A *Glossopteris* leaf identified by G. J. Retallack (pers comm. 1993) occurs in the upper part of the δ^{13}C-excursion, less than 1.5 m below the coal measures/Narrabeen Group sequence boundary, indicating that end-Permian *Glossopteris* extinction was either gradual or not completed until well into the δ^{13}C-excursion. The steepest slope of the negative δ^{13}C-excursion commences at a maximum flooding surface and is erosively truncated at the lowest value of -29 $^{0}/_{00}$ at the coal measures/Narrabeen Group sequence boundary (mfs to SB, fig. 3). As the interval from the maximum flooding surface (mfs) to the sequence boundary (SB) in figure 3 is equivalent to about half the high-frequency sequence the duration of the steep part of the excursion could be equivalent to half the sequence duration (i.e.,

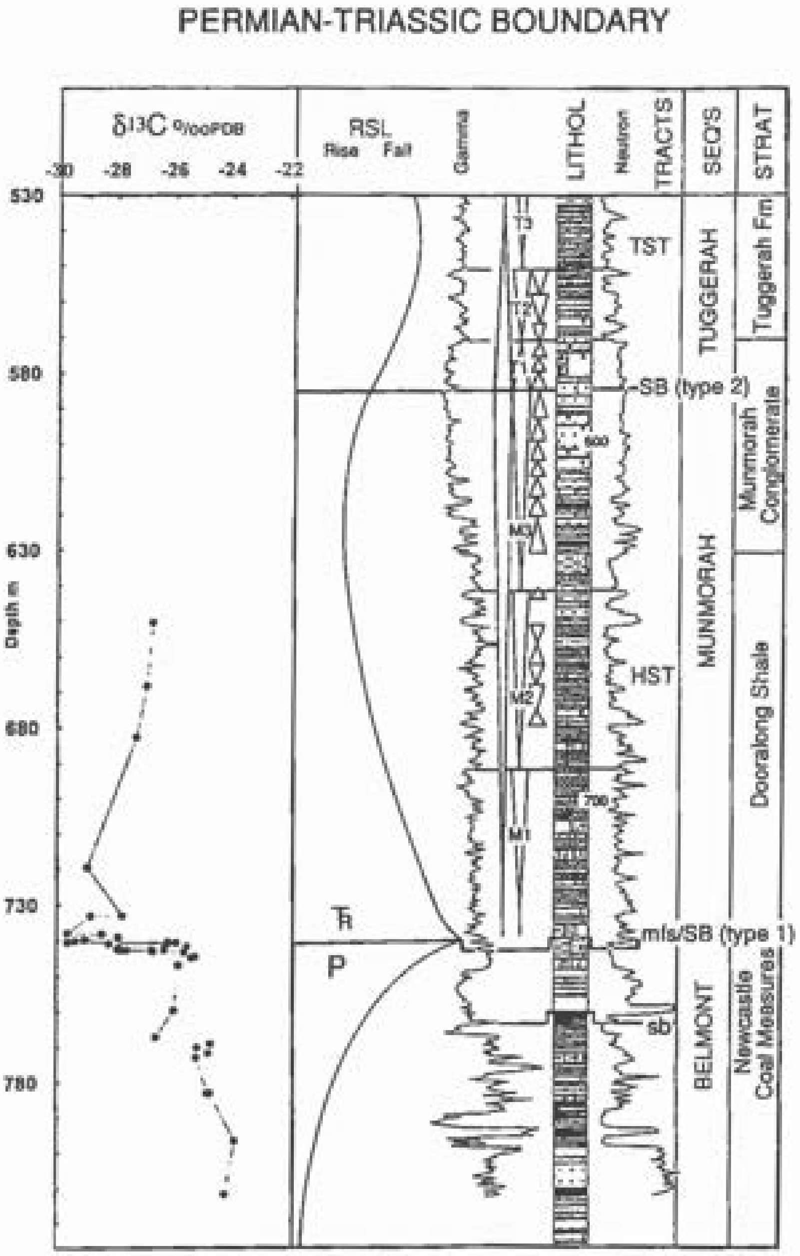

Figure 2. Carbon-isotope data compared with a sequence stratigraphic analysis of 3rd-order sequences in the Late Permian Newcastle Coal Measures and the Early Triassic lower Narrabeen Group (Dooralong Shale to Tuggerah Formation) in DM Murrays Run DDH 1. A number of more positive C-isotope values were obtained from Triassic shales identified as palaeosols by G. J. Retallack. Because the carbon may have been partially degraded these results are not shown. The lower part of the Belmont Sequence (Herbert 1994a in prep.) is not defined here. Bends in P/Tr boundary allow for cable stretch, causing the gamma and neutron logs to be almost 4 m deeper than the graphic log. RSL=relative sea-level, SB= 3rd-order sequence boundary, mfs=maximum flooding surface, LST=lowstand systems tract, TST=transgressive systems tract, HST=highstand systems tract, sb=high frequency sequence boundary. Triangles at right indicate upward-coarsening parasequences and upward-fining fluvial/estuarine sandstones; triangles in middle indicate progradational and retrogradational trends for parasequence sets (M1-3, T1-3); triangles at left indicate trends for systems tracts.

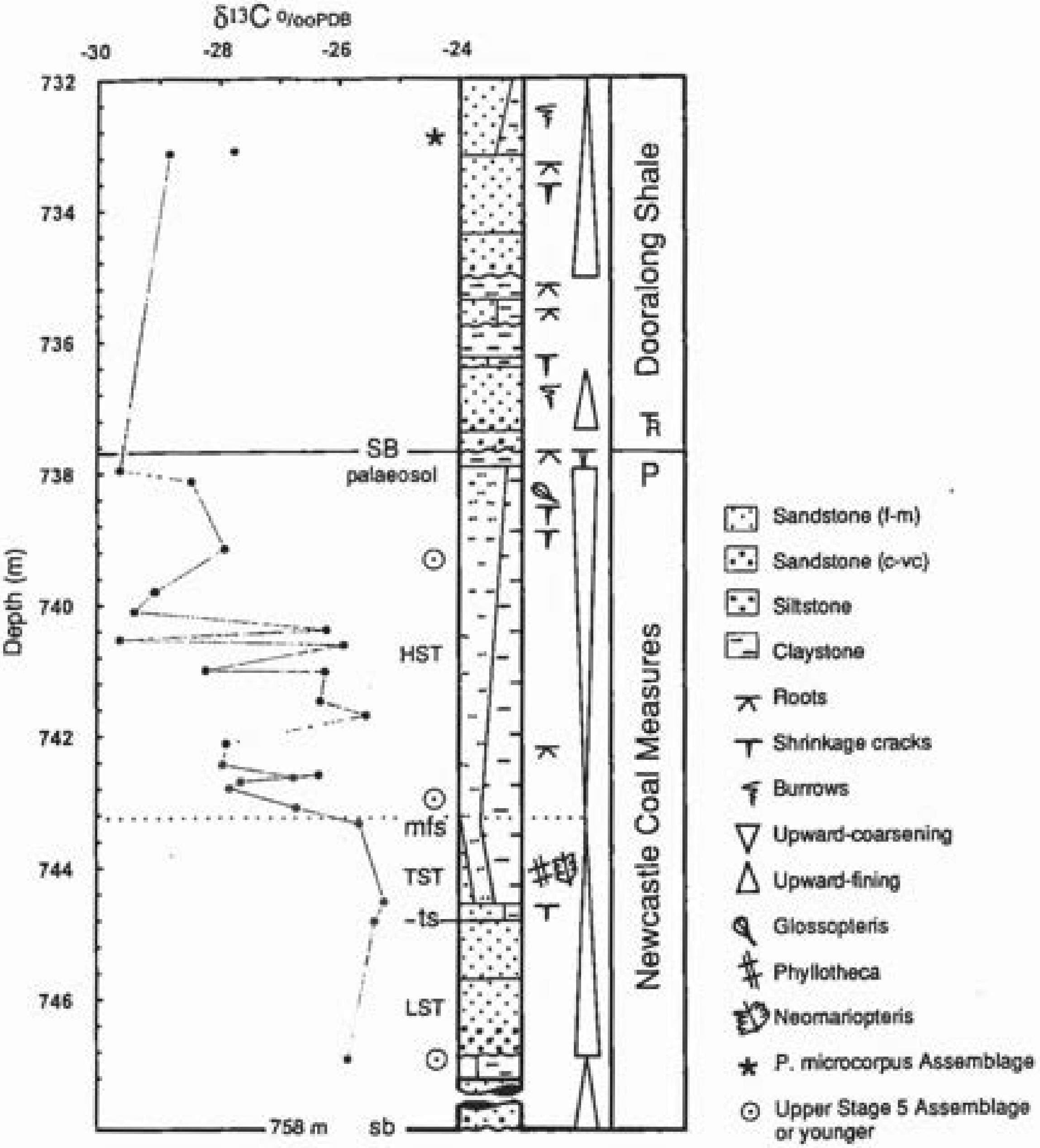

Figure 3. Detailed plot of the upper, steepest part of the negative $\delta^{13}C$-excursion with a high-frequency (5th-order?) sequence at the top part of the 3rd-order Belmont Sequence, Newcastle Coal Measures. sb= high frequency sequence boundary at 758 m (below base of diagram-see Fig. 1), ts=transgressive surface. Other abbreviations as for Fig. 2.

many thousands to tens of thousands of years). This implies that the $\delta^{13}C$-excursion was not geologically instantaneous. In our opinion, this is also an incomplete swing as Morante et al. (1994) obtained values as low as -34 $^{o}/_{oo}$ in Western Australian marine intervals before they returned to slightly more positive values around -28 $^{o}/_{oo}$. Thus the $\delta^{13}C$-excursion may not be fully represented in Sydney Basin sediments, but may have been completed within the overlying P/Tr hiatus.

Because the lowstand and transgressive systems tracts of the Munmorah Sequence are missing and presumably not deposited within the present confines of the basin, it is evident that sea-level did not re-establish itself in the Sydney Basin until it had risen considerably from the previous end-Permian sea-level fall. Only at that time, did rising relative sea-level create accommodation space for Triassic estuarine and alluvial aggradation in the highstand systems tract. Therefore, the hiatus containing the Permo-Triassic boundary lasted from near the falling inflection point (SB) of the last Permian sea-level fall to near the rising inflection point (mfs) in the Munmorah Sequence when highstand systems tract sedimentation commenced (represented as mfs/SB, Fig. 2). This is equivalent in time to about half a 3rd-order sequence, perhaps in the order of from half a million to one million years.

CONCLUSIONS

The $\delta^{13}C$-excursion provides a global datum in the sedimentary record about the P/Tr boundary. Its location between the uppermost Newcastle Coal Measures and the overlying Narrabeen Group confirms the traditional placement of the boundary in the Sydney Basin (David 1950). The unconformity at the coal measures/Narrabeen Group boundary represents a hiatus equivalent to about half a 3rd-order sequence, or about half to one million years.

The negative $\delta^{13}C$-excursion detected in *marine* P/Tr sediments in Australia and elsewhere is also found in *non-marine* sediments of the Sydney Basin. The excursion culminates at an unconformity (sequence boundary) 1.5 m above the topmost sample identified as Upper Stage 5 or younger, and 5 m below the lowest sample containing palynomorphs from the *P. microcorpus* zone. This indicates that the P/Tr boundary is associated with major changes in both lithology and flora detected in eastern Australian sedimentary basins. The last *Glossopteris* specimen found in DM Murrays Run DDH 1 occurs less than 1.5 m below the coal measures/Narrabeen

Group unconformity suggesting the *Glossopteris* flora survived until the latest Permian in the Sydney Basin.

The negative $\delta^{13}C$-excursion began gradually over a 50 m interval representing many tens to several hundreds of thousands of years, and accelerated in the uppermost 6 m of the Late Permian coal measures representing a period of tens of thousands of years.

ACKNOWLEDGEMENTS

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SOME ASPECTS OF COALBED METHANE IN THE NEWCASTLE COALFIELD

M. CREECH
Oceanic Coal

ABSTRACT

Recent research results into the distribution of methane in the Newcastle Coalfield shows that this distribution is a relict feature of coalification, with only minimal gas movement evident since the emplacement of the numerous dykes in the region.

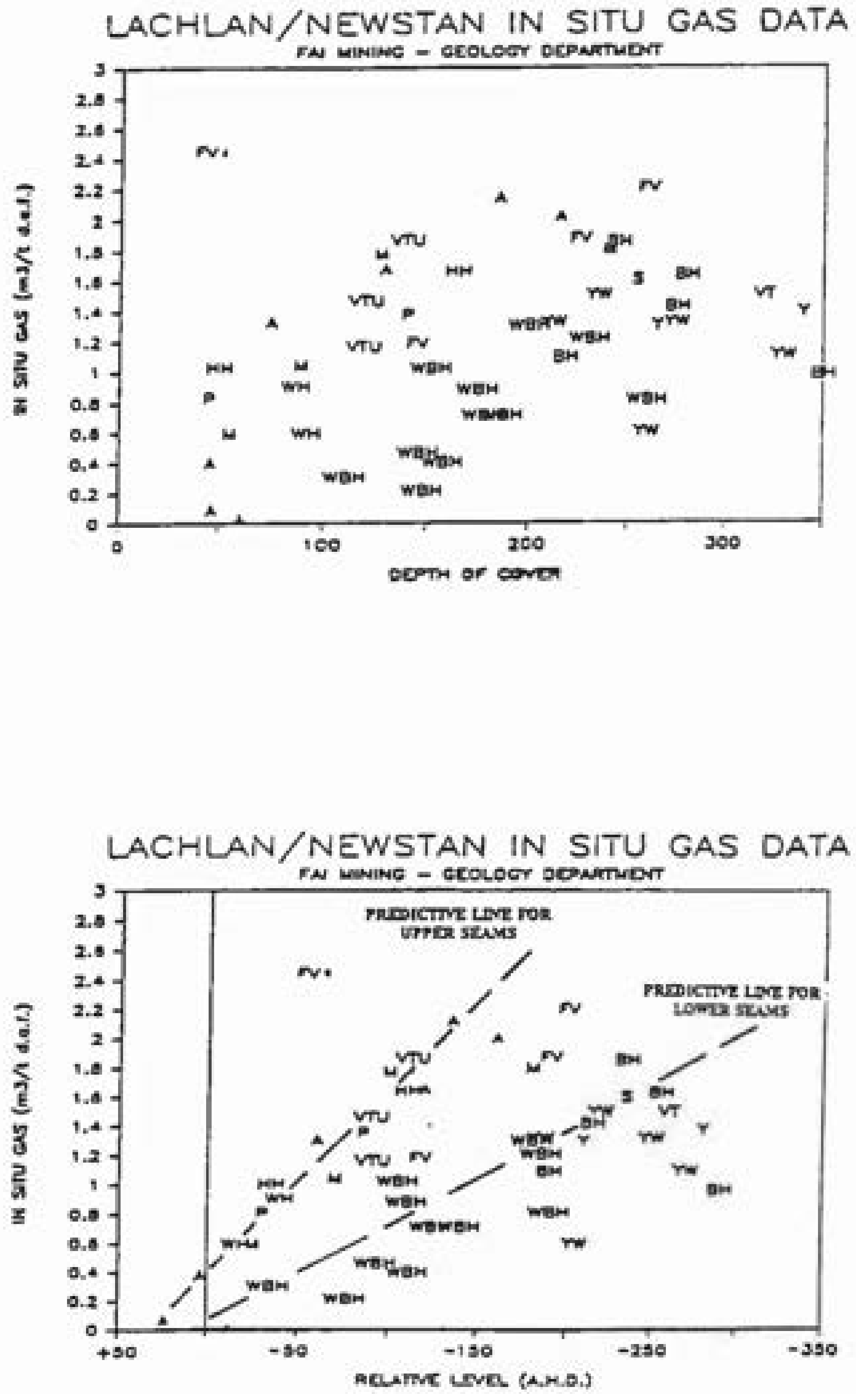
Relative level has been shown to be a more appropriate factor than depth of cover to relate to gas content, and a good relationship between rank and gas content is evident. Evidence that during coalification the axis of the Macquarie Syncline may have been further to the east is presented. Aspects of vertical gas distribution trends, the effect of macerals and the incorporation of ash in gas analysis are also discussed.

The notion that gas distribution may be a relict feature has been proposed by Creedy (1988) for the coalfields of the United Kingdom. Cleat mineralisation (evident throughout the Newcastle Coal Measures) and stress fields which close up cleat networks, are two mechanisms which can restrict gas migration, producing relict distributions. Evidence supporting this possibility for the Newcastle Coalfield comes from three main supportive lines:

1. Relative Level

Graphing gas content against relative level, rather than depth of cover has proven more appropriate (see Fig. 1) and has been

FIGURE 1



LACHLAN/NEWSTAN IN SITU GAS DATA

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clearly demonstrated to predict gas contents more reliably in areas of high topography (Table 1). This supports the notion of a relict gas distribution because relative level is a far more permanent feature than the present topography.

TABLE 1

GAS CONTENT PREDICTIONS
MT. SUGARLOAF DRILLING

	Prediction Using Depth of Cover	**Prediction Using Relative Level**	**Actual**
N1929 Pilot	(115m) 1.4	(+65m) 0	0
N1929 Australasian	(135m) 1.6	(+55m) 0	0.2
N1929 West Borehole	(186m) 1.6	(-6m) 0.4	0.2
N1941 Hartley Hill	(98m) 1.2	(+12m) 0.2	0.17
N1941 Fern Valley	(145m) 1.6	(-20m) 0.4	0.2

* Refer Fig. 1 for Predictions

2. Faults, Dykes and Washouts

A major fault and dyke zone was recently penetrated at Teralba Colliery and the gas content of the worked seam had fallen significantly on the southeast side of this zone. While an additional heading was driven through this zone a series of gas samples was taken (Figure 2a), their distribution indicating that the full seam fault in this zone was the only controlling feature, not the numerous dykes and other smaller faults. It is probable these NW trending faults existed during coalification, the dykes being a later event (Hamilton, 1981) and therefore not influencing the gas distribution.

Dykes have been found however to affect the gas retention of coal by increasing rank and porosity. Samples taken near the 20cm thick dyke in Figure 2a either uncharacteristically rapidly desorb gas or contain negligible desorbable gas, indicating significant in-situ gas loss.

Washouts have been found to effect gas distributions, in that gas contents increase at the down-dip side of the washout (Fig. 2b) indicating that they represent a barrier to upward migration of gas in-seam. An increase of up to 1.5 to 2.0 m^3/tonne within 2-300m of a structure is in agreement with the range across the full seam fault in Figure 2a.

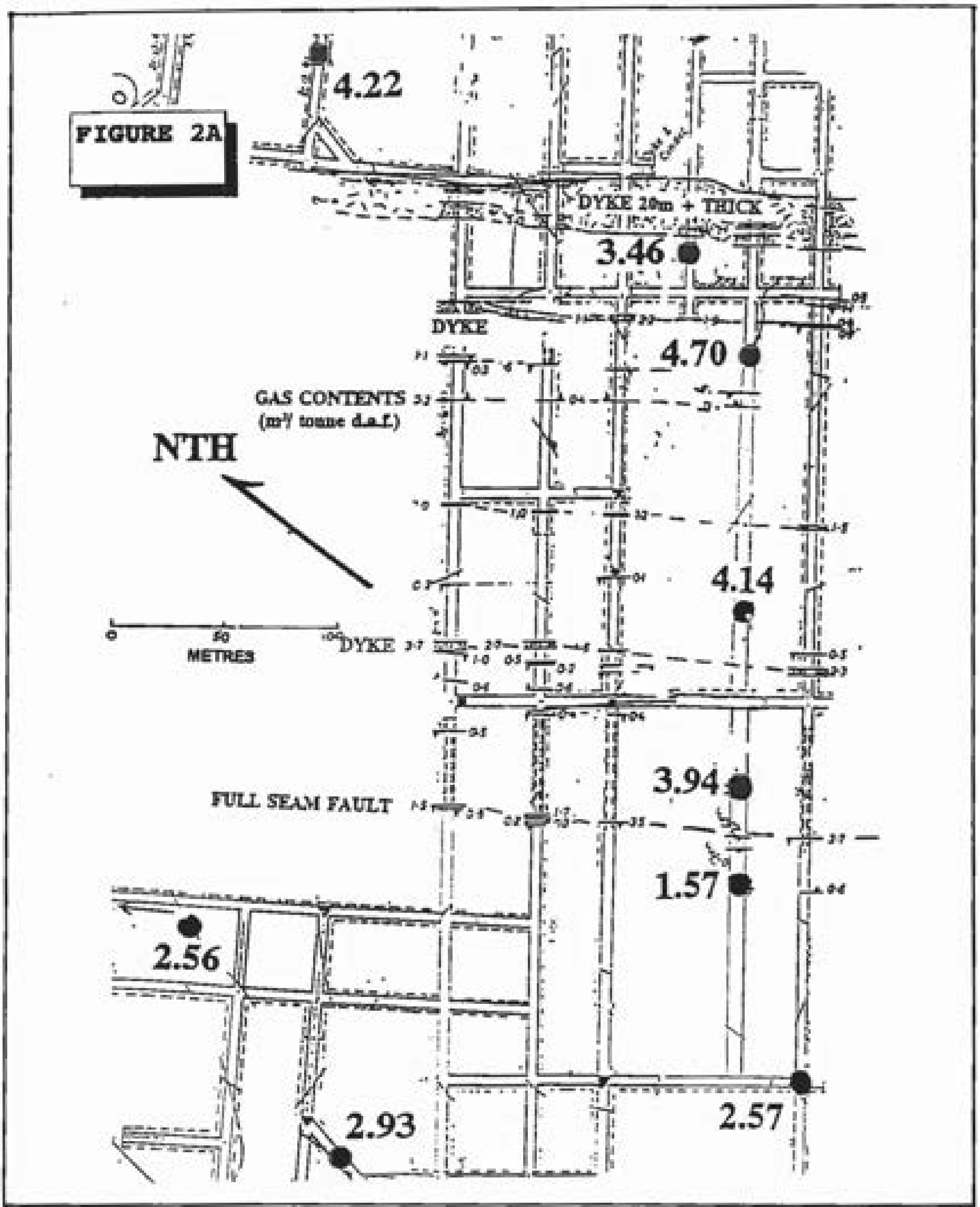
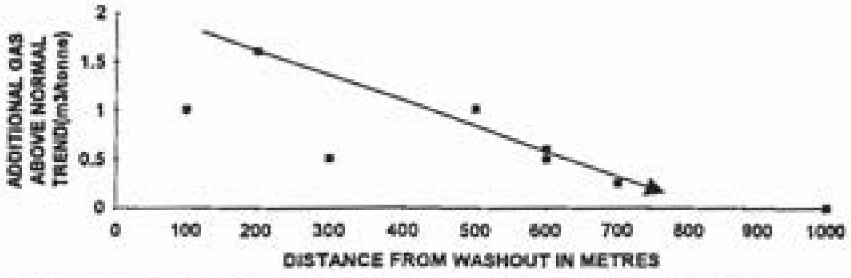


FIGURE 2A

FIGURE 2B INCREASE IN GAS CONTENT APPROACHING A WASHOUT



3. Regional Gas Distribution

The regional gas distribution in conjunction with rank broadly corresponds with relative levels and the dominant structural feature, the Macquarie Syncline (Fig. 3 & 4). However gas contents near the axis of the Macquarie Syncline appear to remain steady or increase to the east, even though both cover and relative levels are becoming shallow. This may be supportive evidence for a pre-existing axis located approximately 5km to the east of the present day axis, a possibility first raised by Blayden (1971).

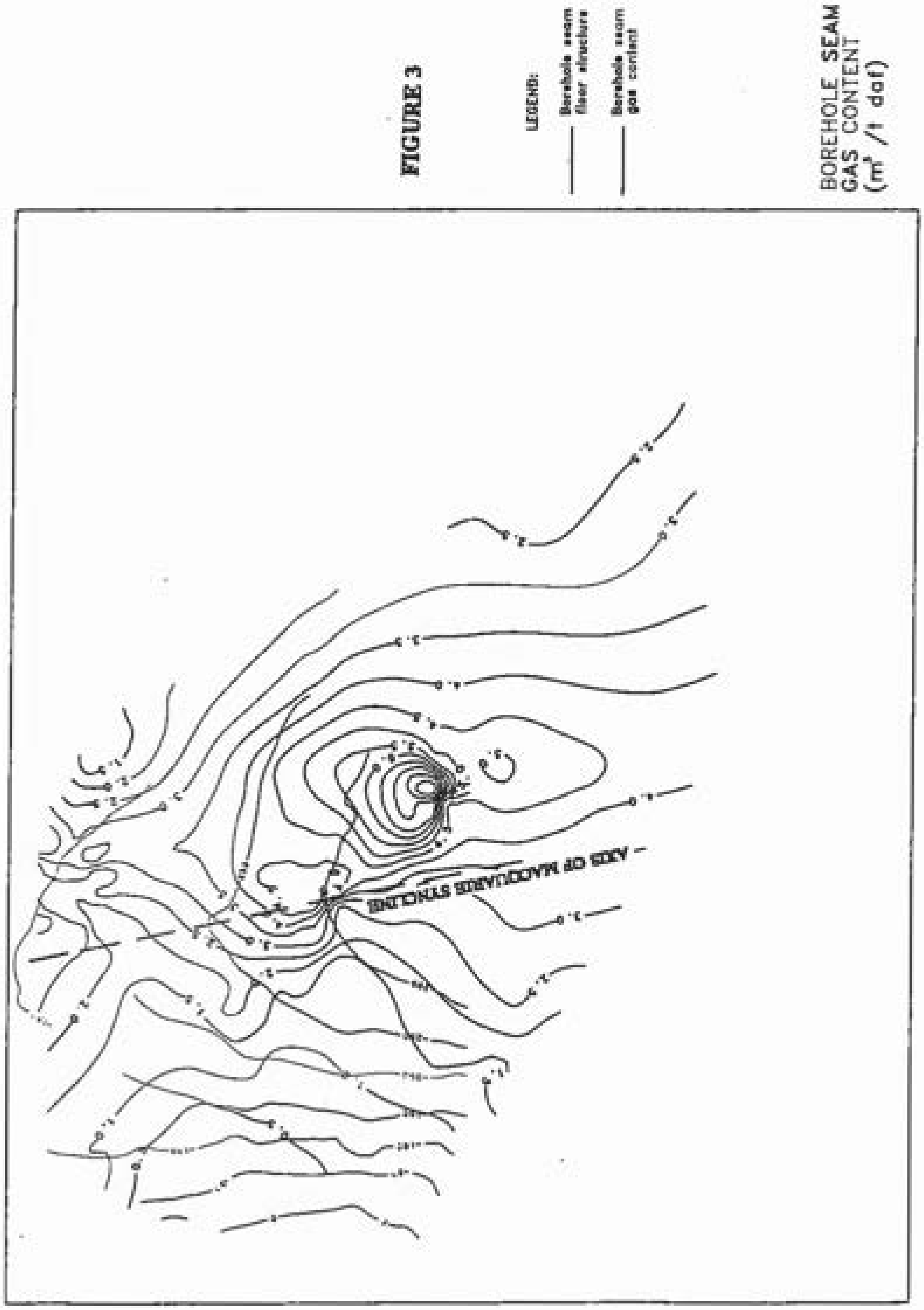
Such a proposition is also supported by the geometry of the structural controls mentioned previously. Structure contours run perpendicular to the faults and dykes in this region, so these structures should not be restricting gas migration. However if the axis was to the east these contours would run north-south (the area in Fig. 2 is located on the Macquarie Synclinal axis) and consequently these structures would then impede the upward migration of gas in-seam.

The anticipated trend of increasing gas with depth also does not hold in this area. Gas contents generally increase to some point below the Australasian seam, then decrease or remain steady. This may reflect the greater lateral continuity of these lower seams (which include the economic seams), the more numerous pyroclastic bands within the upper seams or some aspect of coal permeabilities. Maceral variations are currently being researched, however initial work on washed coal (f1.4) data has identified an interesting trend (Table 2). The effects on gas distribution of the numerous clastic wedges (early differential compaction for instance) in the upper seams of the Newcastle Coal Measures requires further research, as does the possible effects of the silling of the Tomago Coal Measures noted in deep holes in the region.

TABLE 2

MACERAL ANALYSIS (F1.4) (Sample Population - 170)			
	Vitrinite	**Exinite**	**Inertinite**
Aust to Mont/Wave Hill	88-90	3 - 3.4	7 - 9
Victoria Tunnel	83	3.5	13
Young Wallsend to Borehole	74.5-78.5	4.5 - 5.5	17 - 21

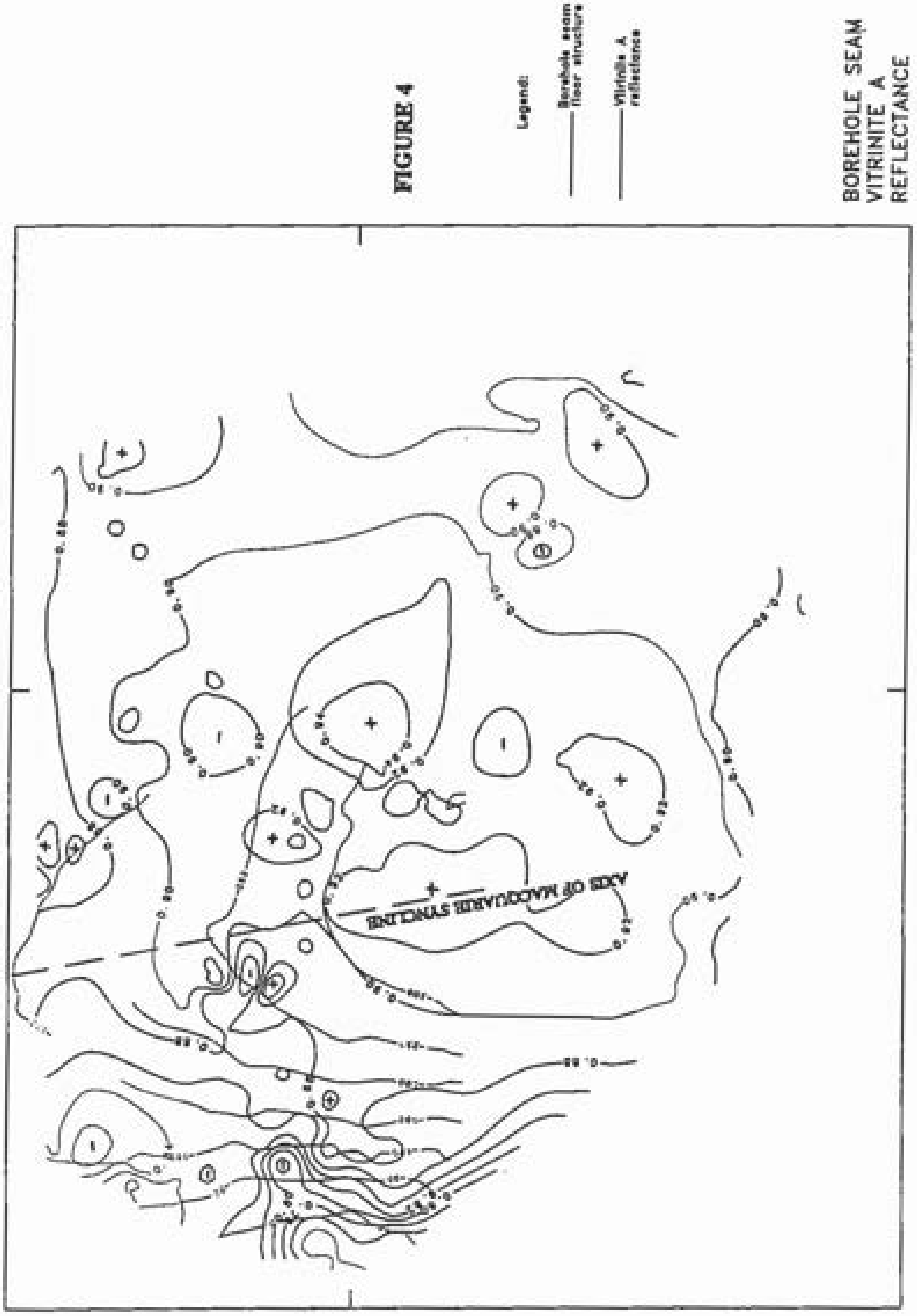
FIGURE 3



LEGEND:
Borehole seam floor structure
Borehole seam gas content
BOREHOLE SEAM GAS CONTENT (m^3 /t daf)
AXES OF MACQUARIES SYNCLINE

FIGURE 4

BOREHOLE SEAM VITRINITE A REFLECTANCE



MICHAEL CREECH

The practice of reporting gas contents on a dry ash free basis (d.a.f.) was recently tested for its applicability with the testing of a series of coal bearing rocktypes of various ash contents from two drillholes in the Newcastle Coal Measures. This has been done in conjunction with M. Mahoney of C.R.L. (Newcastle) and will be the subject of a soon to be published paper. However the results can be illustrated (Fig. 5) by plotting ash and moisture against 'as analysed' gas content, expressed as a proportion of the d.a.f. value. The data plots close to the theoretical line joining the '0% ash - 100% d.a.f.' point and the '100% ash - 0% gas' point. Therefore the reporting of gas on a d.a.f. basis enables correct comparisons of gas contents to be made for various rock types containing different amounts of carbonaceous material.

More research work is being undertaken as a PhD research project by the author. This work includes maceral analyses, studies of regional trends in rank, structural controls, washouts and possible relationships with interseam strata.

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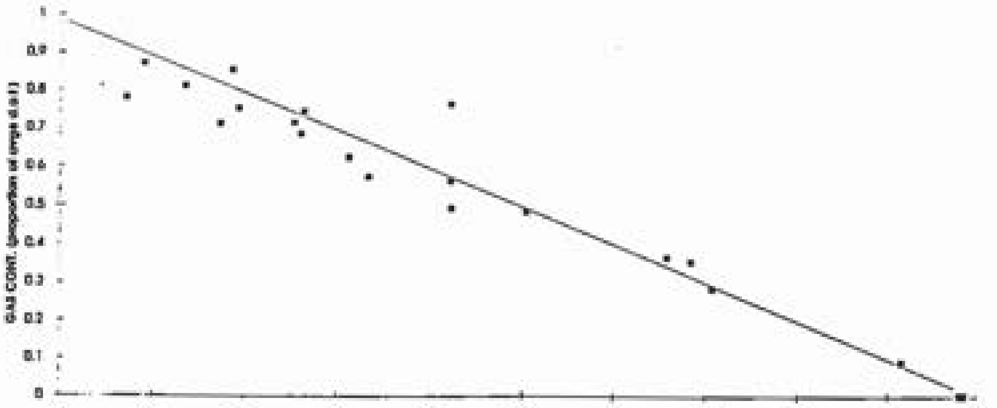
FIGURE 5 AS ANALYSED GAS CONTENTS



METHANE SORPTION STUDIES AT SOUTH BULLI (NSW) & CENTRAL (QLD) COLLIERIES USING A HIGH PRESSURE MICROBALANCE

P.J. CROSDALE[1] & B.B. BEAMISH[2]

[1] Dept. of Geology, James Cook University

[2] Dept. of Geology, University of Auckland

ABSTRACT

Bright and dull coal lithotypes from medium volatile bituminous coals of South Bulli and Central (German Creek) Collieries have been characterised for methane sorption properties. In dry, isorank samples, bright (vitrinite-rich) coal has greater sorption capacity but lower sorption rate than dull (inertinite-rich) coal. In equilibrium moist samples, differences in gas properties are less apparent but initial desorption rates of bright coals remain lower than dull coals.

INTRODUCTION

Results of gas sorption studies are presented from two pairs of bright and dull coals from South Bulli ($\overline{R}_{omax}$ 1.27%) and Central (German Creek) Collieries ($\overline{R}_{omax}$ 1.45%). They are representative of a larger suite of results examining gas sorption characteristics in these two collieries in relation to coal type.

A variety of opinions exist as to the importance of coal type on sorption properties. Fusinite has been found to sorb more methane than vitrinite (Ettinger et al., 1966) while the opposite has also been observed (Beamish et al., 1993; Lamberson and Bustin, 1994). Maceral composition has also been found to have little effect (Faiz et al., 1992).

METHODOLOGY

Samples

Samples of dull and bright coal were hand picked from in seam drill cuttings and from underground mine workings following lithotype logging. Particle size greatly influences gas sorption rates and a uniform particle size is required for direct comparison of results. The size selected for analysis was dictated by the drill cuttings. Samples were sieved at -5.60+2.00mm prior to picking, with approximately 1g used. Analyses were performed at both equilibrium moist and dry conditions. Equilibrium moist conditions are thought to simulate the in ground state but analysis is difficult. Dry coal testing is less complicated and ensures comparability of results. Methane adsorption isotherms were determined on finely crushed (-0.212mm) coal.

Gas Sorption Testing

Gas sorption testing used a microgravimetric technique (Beamish and O'Donnell, 1992; Beamish and Gamson, 1993; Levine et al., 1993). Prior to testing, moist samples were evacuated at -95kPa for one minute, the pressure simulating equilibrium moist conditions and a short time to minimise moisture loss. Oven dried samples were evacuated at greater vacuum and for one hour. Following evacuation, methane was introduced at 5MPa and the -5.60+2.00mm size sample left to resorb gas until the weight change did not exceed 0.01 mg/hr. Pressure was then reduced to the estimated *in situ* gas pressure (3MPa for South Bulli; 2MPa for Central) and the sample left until the weight change did not exceed 0.01mg/hr. Samples were then allowed to degas at atmospheric pressure. Adsorption isotherms were performed on crushed coal (-0.212mm) up to maximum gas pressures of 7 to 10 MPa using 1 MPa steps.

Testing of moist samples was problematic. High relative humidity, necessary to prevent moisture loss during analysis, can be maintained in the sample environment by the use of a K_2SO_4 solution. However, buoyancy correction factors are difficult to calculate with certainty owing to variable and different gas densities in the sample and counterweight chambers of the balance. High humidity environments may also damage the balance.

Moist samples were tested in a dry gas environment. Moisture loss during the course of testing results in the final sample weight being significantly less than its initial weight. A correction factor was applied which assumed a constant rate of moisture loss for the duration of the test. The final weight change for moist samples is therefore zero.

Gas Content Calculation

Weight recorded by the microbalance must be corrected for buoyancy effects. A buoyant force applied to all balance components, including the sample, equals the weight of gas displaced. The weight of displaced gas is estimated from the volume of the balance, including the sample, and the gas density at each pressure, derived from the real gas equation.

Volume of the microbalance components, including weighing arms, sample pans and counterweights, was experimentally evaluated. Initial sample volume was calculated from its helium density as determined in the microbalance prior to methane adsorption. Knowing the density of sorbed methane on coal (= 618.9g/l; van der Sommen et al., 1955), the weight of sorbed methane can be calculated (Crosdale, 1993; Levine et al., 1993) :

$$W_s = (W_{mb} - \rho_g(V_{mb} - V_c))/(1 - \rho_g/\rho_s)$$

where :

W_s = weight of sorbed methane V_c = volume of coal ρ_s = sorbate density

W_{mb} = microbalance output weight V_{mb} = microbalance volume ρ_g = gas density

RESULTS AND DISCUSSION

Adsorption Isotherm

Adsorption isotherms indicate the coal's sorption capacity at different pressures and have been used to estimate the degree of gas saturation (Table 1). The Langmuir Volume (V_L) of the adsorption isotherm represents the maximum gas holding capacity of the coal. Langmuir Pressure (P_L) is the pressure at half the Langmuir Volume.

Results for Central Colliery (Table 1; Fig 1) indicate dry coal holds more gas than moist coal. Coal type influences are shown with dry bright coal having greatest sorption capacity. However, no significant difference in Langmuir volume is observed between bright and dull coals in equilibrium moist samples. Further analyses are required to confirm these trends.

Sorption Rate Behaviour

Gas saturation calculations are derived from the adsorption isotherm and the gas content of the coarse sample. Gas saturations of $>80\%$ are generally achieved (Table 2) prior to desorption to atmosphere. Comparison with known seam gas contents (Tables 2 and 3) indicate the coal in ground is undersaturated with respect to methane except at South Bulli site 1.

Comparison of desorption rates from the *in situ* pressure to atmosphere is made using an estimation of the effective diffusivity (D_e). Calculation is based on the desorption rate during the first ten minutes and assumes a unipore spherical model with uniform pore distribution. As neither assumption is usually true (Smith and Williams, 1984), the calculated diffusivities do not describe the whole desorption curve and separate evaluation of macropore and micropore diffusivities is required (Smith and Williams, 1984; Beamish and Gamson, 1993).

Effective diffusivities for all samples are generally of the same order of magnitude (10^{-4} s^{-1}). Moist samples appear to have greater diffusivities than dry but this result may be influenced by assumptions used for calculating gas contents of moist samples. Bright coals generally have lower diffusivities than their dull coal equivalent in both moist and dry states and release gas more slowly.

Analysis of moist coal desorption is complicated by lack of knowledge of the true moisture state of the sample. Significant moisture loss occurs as sample weight at the end of desorption is less than its initial weight. Calculations have assumed a constant rate of moisture loss for the whole experiment as this gives the most reasonable overall isotherm shape. This assumption requires the final gas content of the moist coal to be zero, which is unlikely as dry coals show a significant residual gas content.

Moist coal desorption may be similar for both bright and dull coal (Figs 2 and 4) or bright coal may desorb more slowly (Fig 3). In the dry state, dull coal always shows an initial period of more rapid desorption than the bright coal, followed by a period in which the dull desorption rate is slower (Figs 2 to 5).

CONCLUSIONS

Methane sorption rate and capacity vary according to coal type and rank. The higher rank Central Colliery coal has a greater sorption capacity than the South Bulli coal but is more undersaturated. Moisture state is important in determining gas contents and desorption rates. In comparable moisture states, dull coal always desorbs more quickly than its equivalent bright coal. Bright coals have a greater gas storage capacity than dull coals when dry but the difference is less marked in moist coal.

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- Central Colliery
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Table 1 Adsorption Isotherm, Central Colliery, Site 1

	Bright Coal		Dull Coal	
Sample Weight (equilibrium moist) (g)		0.44227		0.37833
Sample Weight (dry) (g)		0.43499		0.36688
Equilibrium Moisture (%)		1.43		3.03
Particle Size (mm)		-0.212		-0.212
Temperature (°C)		23.5		23.5
Helium Density (dry) (g/cc)		1.34		1.45
Langmuir Coefficients	moist	dry	moist	dry
Langmuir Pressure (P_L) (MPa)	2.40	1.17	2.08	1.32
Langmuir Volume (V_L) (scc/g)	21.5	28.3	21.1	26.3

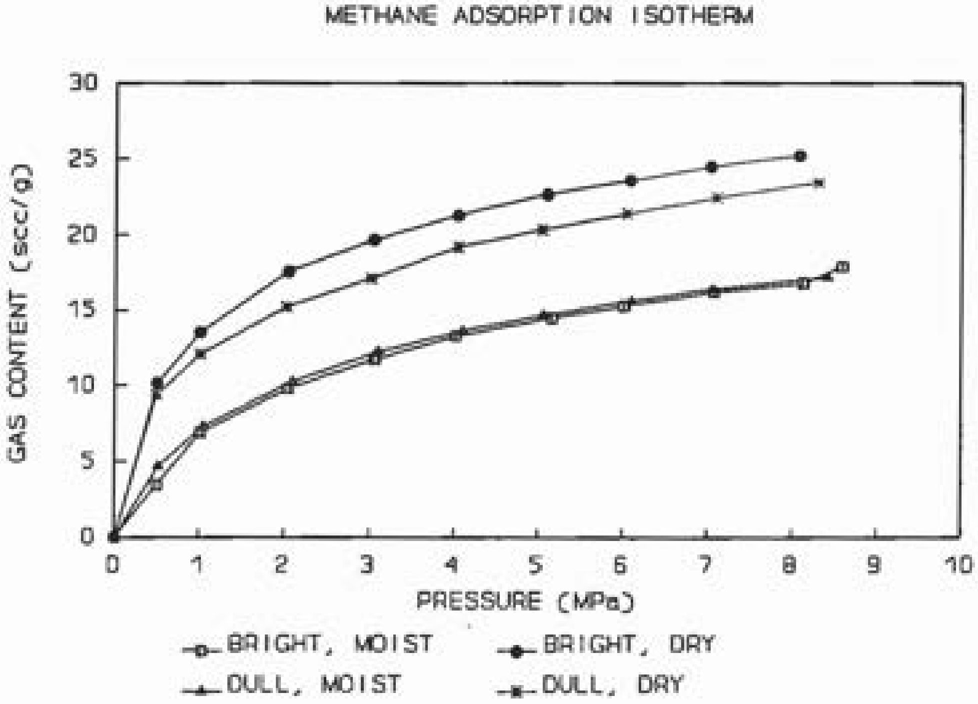

Figure 1 Methane Adsorption Isotherm, Central Colliery, Site 1

METHANE SORPTION AT SOUTH BULLI AND CENTRAL COLLIERIES

Table 2 Central Colliery - coal and gas properties

	SITE 1				SITE 2			
	Bright Moist	Bright Dry	Dull Moist	Dull Dry	Bright Moist	Bright Dry	Dull Moist	Dull Dry
weight (moist) (g)	1.00660		1.00910		1.01404		1.01076	
weight (dry) (g)	0.99170	1.00243	0.99190	0.99190	0.99654	0.99654	0.99219	0.99219
moisture (%)	1.48	0.00	1.70	0.00	1.73	0.00	1.84	0.00
particle size (mm)	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00
temp. (°C)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
He density (g/cc)		1.34		1.45		1.33		1.39
gas cont. at 5MPa (scc/g)	15.6	22.4	12.3	18.4	18.4	22.7	17.1	18.4
% gas saturation at 5MPa	95	98	82	89				
gas cont. at 2MPa (scc/g)	11.6	17.7	8.6	13.7	15.2	18.3	12.9	15.1
% gas saturation at 2MPa	99	98	81	85				
est. final gas cont. (scc/g)	0.0	5.5	0.4	5.9	0.0	6.3	0.0	5.3
effect. diffusivity(D_e)(s^{-1})	3.6E-6	1.5E-6	6.9E-6	5.5E-6	8.9E-7	1.8E-6	2.7E-6	4.0E-6
seam gas content (m^3/t)	5.5				6.0			

Table 3 South Bulli Colliery - coal and gas properties

	Site 1				Site 2			
	Bright Moist	Bright Dry	Dull Moist	Dull Dry	Bright Moist	Bright Dry	Dull Moist	Dull Dry
weight (moist) (g)	1.00372		1.00085		0.90242		0.92664	
weight (dry) (g)	0.98733	0.98733	0.98276	0.98276	0.88908	0.88908	0.91112	0.91112
moisture (%)	1.63	0.00	1.81	0.00	1.48	0.00	1.67	0.00
particle size (mm)	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00	-5.60 +2.00
temp. (°C)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
He density (g/cc)		1.29		1.44	1.39	1.28	1.29	1.40
gas cont. at 5MPa (scc/g)	5.7	15.7	8.3	14.5	8.6	14.6	15.6	17.5
% gas saturation at 5MPa								
gas cont. at 3MPa (scc/g)	6.0	14.9	7.8	13.4	8.2	14.1	12.9	15.7
% gas saturation at 3MPa								
est. final gas cont. (scc/g)	0.5	5.6	0.4	4.9	0.1	6.7	0.5	4.9
effect. diffusivity(D_e)(s^{-1})	2.7E-6	8.6E-7	2.3E-6	1.6E-6	1.3E-6	1.1E-6	2.2E-6	2.8E-6
seam gas content (m^3/t)	8.0				5.0			

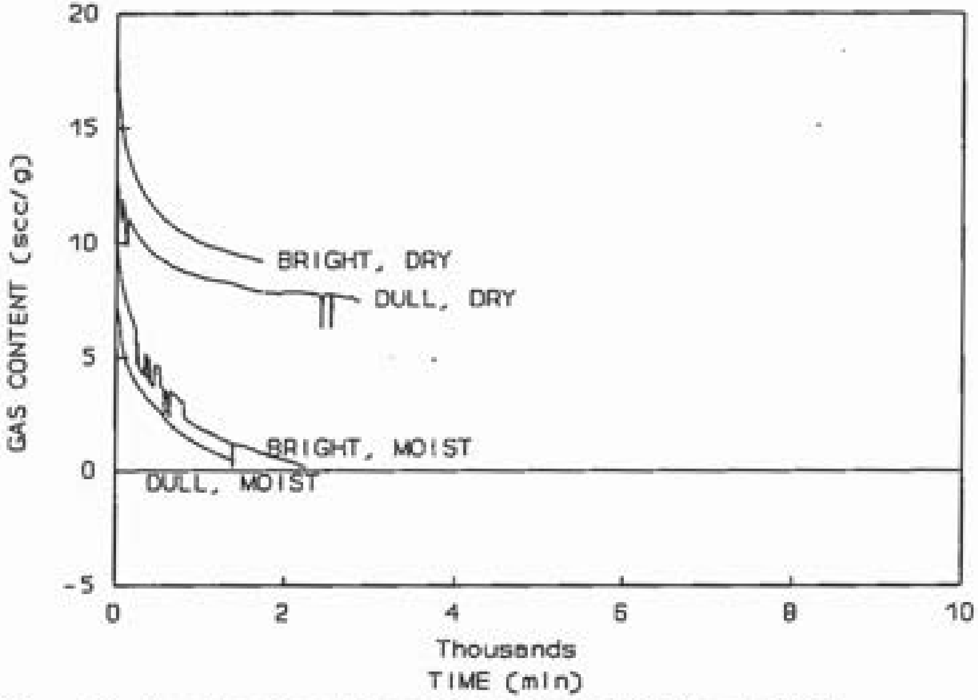

Figure 2 Desorption to atmosphere from 2MPa, Central Colliery, Site 1

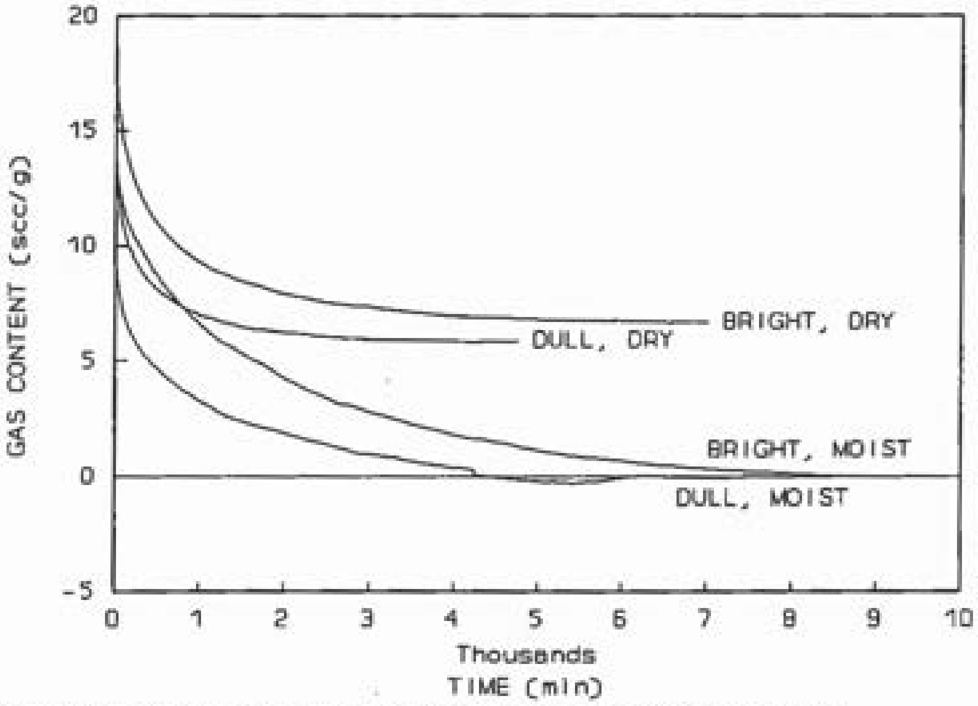

Figure 3 Desorption to atmosphere from 2MPa, Central Colliery, Site 2

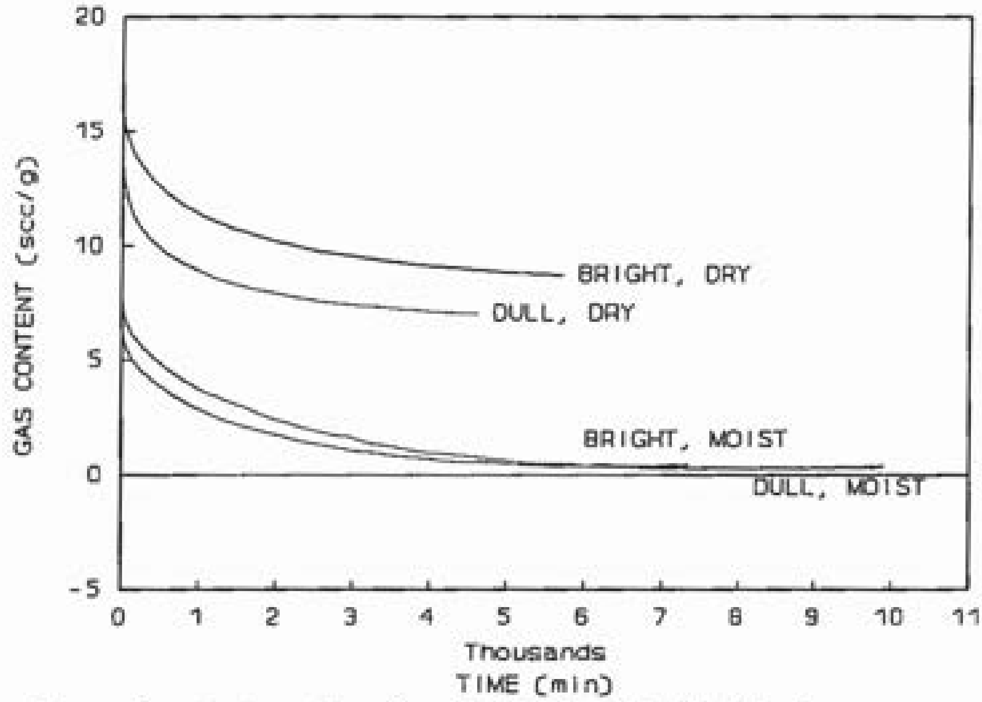

Figure 4 Desorption to atmosphere from 3MPa, South Bulli, Site 1

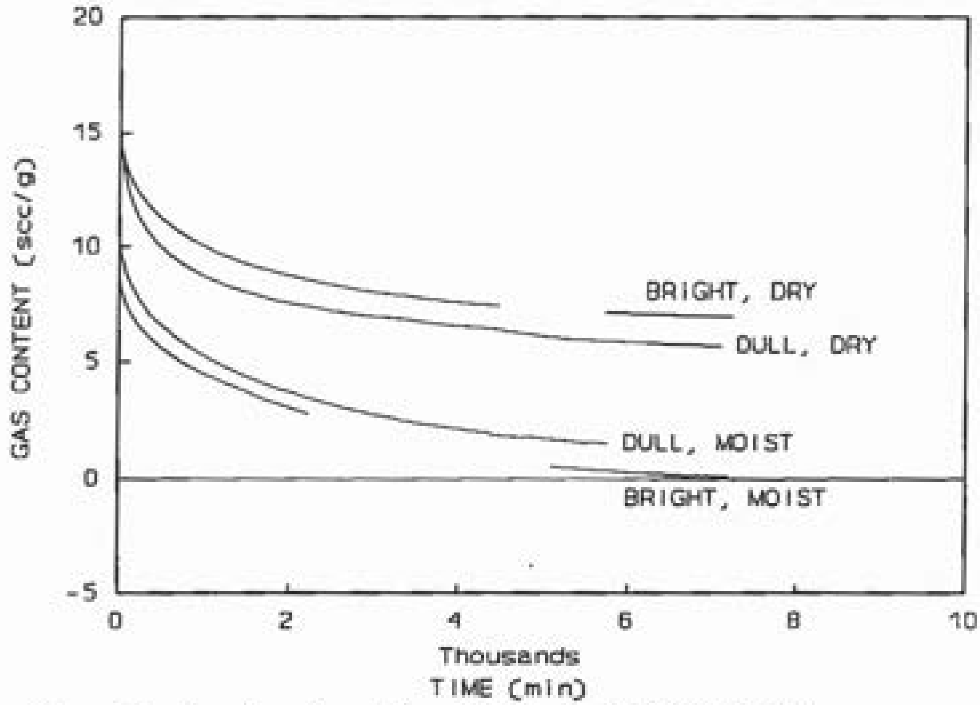

Figure 5 Desorption to atmosphere from 3MPa, South Bulli, Site 2

GEOLOGICAL SURVEY OF CANADA COALBED METHANE RESEARCH – CBM POTENTIAL OF COALS FROM THE WESTERN CANADA SEDIMENTARY BASIN

W.D. KALKREUTH, M. DAWSON & J.D. HUGHES
Institute of Sedimentary & Petroleum Geology,
Geological Survey of Canada

INTRODUCTION

The Geological Survey of Canada is currently carrying out coalbed methane assessments in a number of coal-bearing basins in Canada (Fig. 1). Main focus of these studies has been the Western Canada Sedimentary Basin (WCSB). Major coal deposits within the WCSB occur in the Canadian Rocky Mountain Front Ranges, Foothills and adjacent Interior Plains and account for approx. 90% of Canada's measured coal resources, estimated to be in the order of 20 000 megatonnes (Smith, 1989). Coal rank

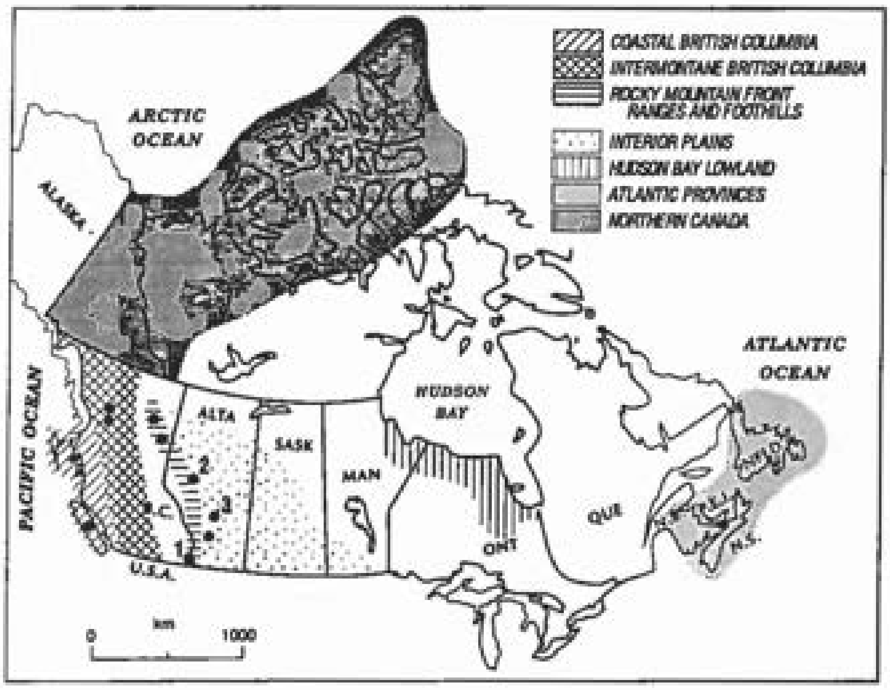

Fig. 1: Distribution of coal-bearing basins in Canada (Smith, 1989) and areas (o) currently being evaluated for coalbed methane potential. Locations discussed in this paper: 1 = Front Ranges, British Columbia; 2 = Foothills and Plains, west-central Alberta; 3 = Plains, Alberta.

at and near surface ranges from lignite in the Interior Plains to low volatile bituminous coals in the Foothills and Front Ranges. Estimates of coalbed methane volumes in the WCSB are as high as 85 x 10^{12} cm^3 for the Alberta part of the basin (Nicols and Rottenfusser, 1991) and would as such exceed the known conventional gas resources by a factor of 14.

The Geological Survey of Canada's coalbed methane assessment studies involve the petrographic and chemical characterization of coal seams as they relate to measured gas desorption volumes of core samples, regional studies on coal distribution, coal rank and reservoir depth including computer modelling and the determination of methane adsorption isotherms of economically important coal seams or coal-zones.

In the current paper preliminary results are presented, a) from the Fernie Basin (Location 1, Fig. 1), in which coal seams of the Kootenay Gp. (Fig. 2) were tested for their coalbed methane potential; b) from the Foothills and adjacent foreland (Location 2, Fig. 1), in which coalbed methane volumes were estimated on a regional scale for coals of the Gates Formation (Fig. 2); and c) from the Interior Plains (Location 3, Fig. 1), where on a regional scale coalbed methane potential has been estimated for selected Mannville Group (equivalent to Luscar Gp., Fig. 2) coals using a computer modelling system developed for Canada's National Coal Inventory. Three dimensional models of coal beds and adjacent rock units developed by this system are utilized to evaluate reservoir characteristics and locate optimal drilling targets; d) from calculated Langmuir methane adsorption volumes for selected coals from the study areas.

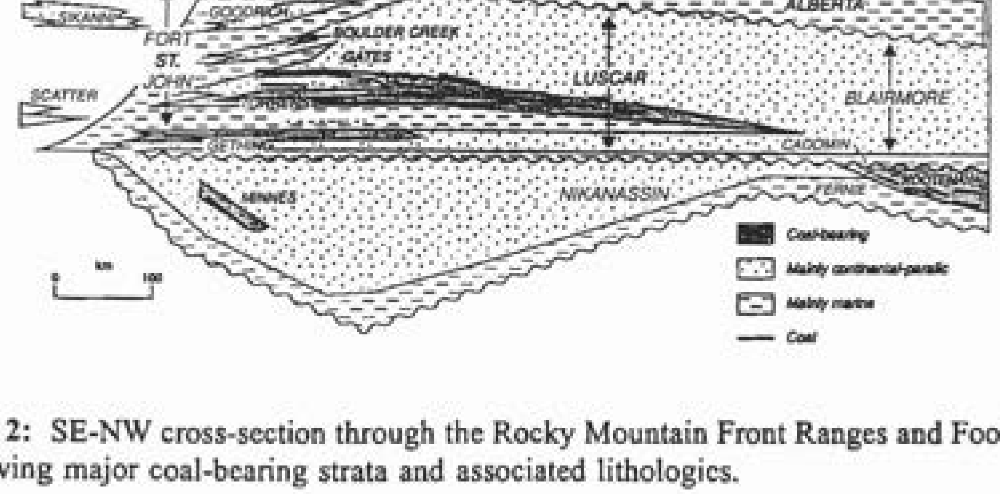

Fig. 2: SE-NW cross-section through the Rocky Mountain Front Ranges and Foothills, showing major coal-bearing strata and associated lithologies.

COALBED METHANE POTENTIAL WESTERN CANADA

RESULTS AND DISCUSSION

Rocky Mountain Front Ranges

The coal seams tested for CBM potential form part of the Jurassic-Cretaceous Kootenay Group of the Fernie Basin, B.C. (Figs. 1 and 2). The lower part of the Kootenay Gp. contains up to 14 minable seams. Measured and indicated resources are in the order of 1000 megatonnes (Smith, 1989) and as such comprise a high coalbed methane reservoir.

A total of four CBM test boreholes were drilled in 1990, and gas desorption values were recorded for most of the seams intersected. The seams were subsequently analyzed petrographically and chemically to determine coal rank and composition. The example shown here comes from Borehole KPP 90-1 (Fig. 3), which intersected a total of 16 coal seams with a cumulative coal thickness of 39.89 m. Vitrinite reflectances range from 1.42-1.83 % Rmax corresponding to medium volatile bituminous coals (MVB) at the top of the section (Fig. 3) and low volatile bituminous coals (LVB) at the bottom. Comparison of gas desorption volumes (Fig. 3) with petrographic characteristics indicate that gas desorption volumes reflect primarily the amount of mineral matter contained in the seams. The type of organic matter and the mineralogy of the coals show subtle and in part contradictory trends relative to gas desorption,probably reflecting the role of other processes, including water flushing. The gas desorption volumes recorded here (maximum of 15.54 cm^3/g (m.m.f) and gas adsorption capacity values from methane adsorption isotherms (>20 cm^3/g, m.m.f) at pressures between 4000 and 8000 kPa indicate a relatively high CBM potential for the Kootenay coals from the Fernie Basin.

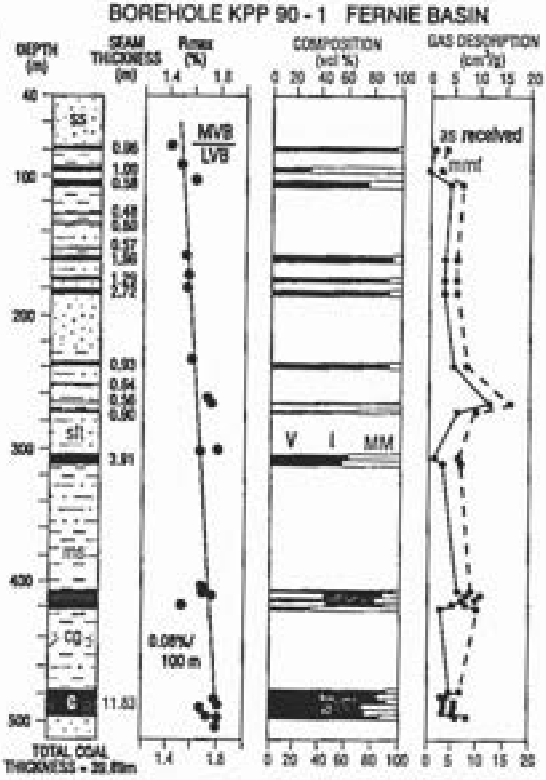

Fig. 3: Lithological profile of the Kootenay Gp. in borehole KPP 90-1 showing petrographic characteristics of the coal seams and associated methane desorption volumes (V=vitrinite, I=inertinite, MM=mineral matter), from Kalkreuth et al. (in press)

Foothills and adjacent Foreland

Economically important coal seams occur in the Rocky Mountain Foothills and adjacent foreland in the Grande Cache and Hinton areas of west-central Alberta (Location 2, Fig. 1). The coals are Lower Cretaceous (Luscar Gp.) and Upper Cretaceous/Tertiary (Saunders Gp.) in age and are currently being mined at Smoky River, Obed Marsh, Cadomin-Luscar and Coal Valley (Fig. 4). Cumulative coal thicknesses for Lower Cretaceous strata reach 17 m in the Smoky River area (Fig. 4), whereas the Upper Cretaceous/Tertiary coal-bearing strata contain up to 47 m of coal in the Coal Valley area. The reflectance data indicate subbituminous/high volatile B bituminous coals for the Upper Cretaceous/Tertiary coals in the Outer Foothills and Alberta Plain, whereas the Lower Cretaceous coals have a reflectance range from 0.85-1.74% Rmax (high volatile A to low volatile bituminous). Reflectance data obtained from petroleum exploration wells to the east (Fig. 4), where Luscar Gp. coal seams occur at greater depth in the Alberta Syncline indicate a coalification maximum in the Hinton area (2.48% Rmax, semi-anthracite).

In the paper presented here a coalbed methane iso-capacity (cm^3/g) map is shown for the basal part of the coal-bearing Gates Formation of the Luscar Gp. (Fig. 5). The coalbed methane estimates are based on coal rank variations (vitrinite reflectances and coalification gradients), reservoir depth, geothermal gradients, averaged surface temperature and an assumed average ash content of 10 wt.% for the coal zone. The regional coalbed methane estimates were calculated using a computer program published by Ryan (1992) and have been restricted to the area east of the deformed belt. The coal-bearing strata in the Foothills are intensively folded and faulted and the relationships between coalbed methane adsorption capacities of seams and the degree of structural deformation are as yet poorly understood.

The iso-capacity map indicates high coalbed methane capacities for the Gates coals in the Alberta Syncline with a maximum potential in the Hinton area (>21 cm^3/g, Fig. 5) and east of Grande Cache. Cumulative coal thicknesses for the coal-zones are in places >10 m (Fig. 5) and would as such make the basal Gates Formation an ideal target for CBM exploration. The seams occur however at a depth level (Fig. 5) currently not considered within the range of an economic production of the gas.

The Upper Cretaceous/Tertiary coals of the Saunders Gp. (Fig. 4) occur at more favourable depth levels in the Alberta Syncline (<1100 m) but have only a marginal coalbed methane potential due to their relatively low rank levels (Dawson and Kalkreuth, in press).

It should be noted that the coalbed methane capacity map illustrates what the adsorption capacity of the coals may be. Actual in-situ gas contents will vary dependent on local geological and hydrological conditions.

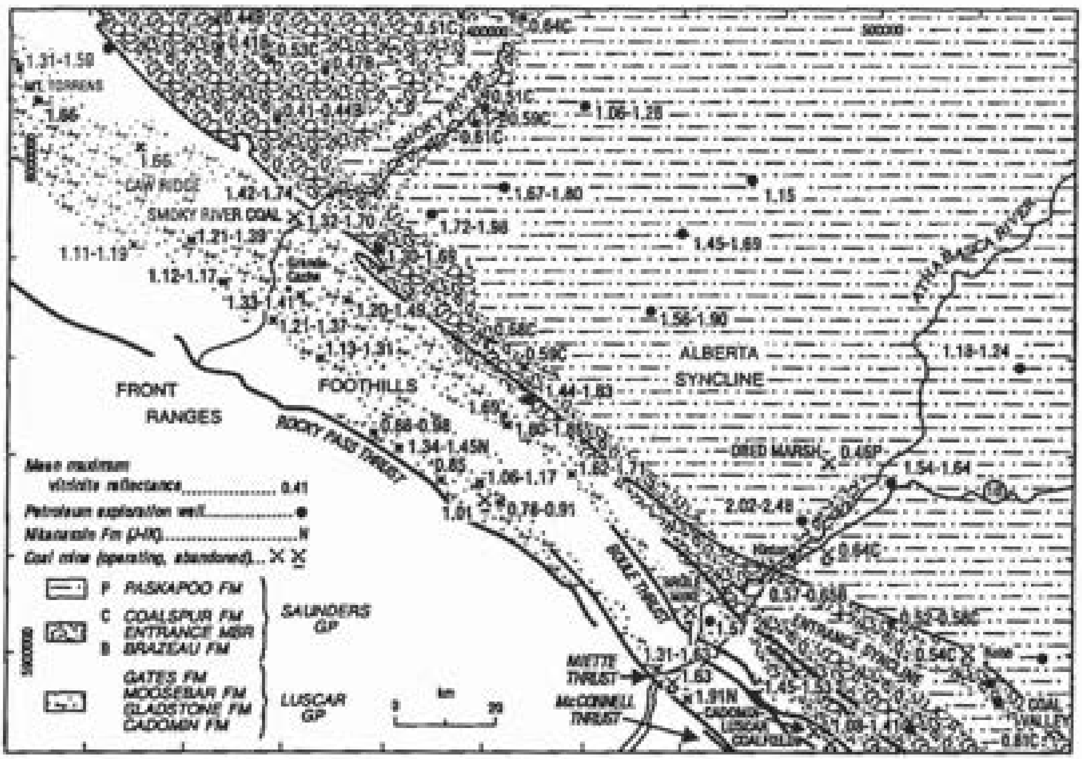

Fig. 4: Distribution of coal-bearing strata in the study area and vitrinite reflectance variations for outcrop and subsurface samples (Dawson and Kalkreuth, in press).

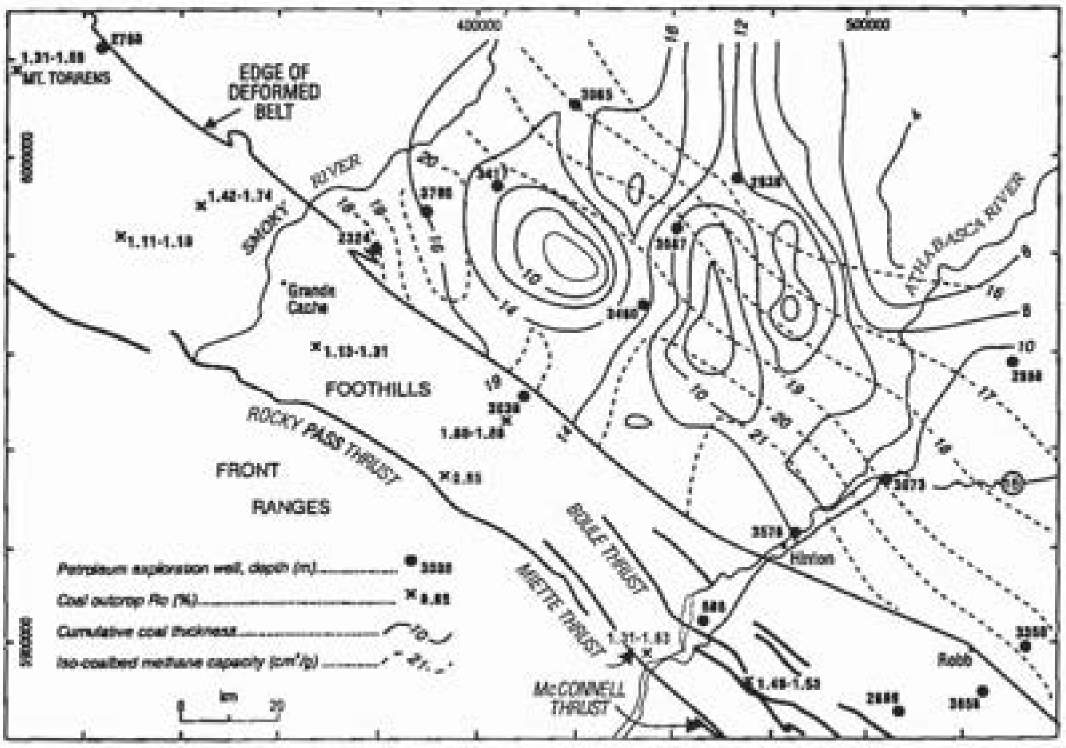

Fig. 5: Cumulative coal seam thickness for the basal coal-zone of the Gates Formation and estimated coalbed methane capacities (Dawson and Kalkreuth, in press).

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Alberta Plains - Computer-based Reservoir Assessment

The mid-Cretaceous Mannville Group (Luscar Gp. equivalent, Fig. 2), which underlies much of the Alberta Plains, comprises the most prospective coalbed methane reservoir in this region due to its elevated rank compared to younger coal-bearing units. Drilling for conventional hydrocarbons has provided a database of more than 55,000 wells penetrating Mannville Group strata at depths suitable for coalbed methane production. In order to select optimal targets for industry coalbed methane testing, digital log data captured from 500 wells penetrating thick Mannville Group coals in a 45 by 50 km area of central Alberta (Fig. 1, Location 3), were utilized to develop a three-dimensional computer model of coal seams and adjacent strata between the pre-Cretaceous unconformity and the uppermost coal beds, a stratigraphic interval of approximately 175 m. Wells were selected according to age and available log suites, and were filtered to a minimum spacing of 500 m. LOGANAL, a multiple-well analysis system developed by the Geological Survey of Canada (GSC), was utilized to normalize the log data and to develop statistical relationships which were used to classify these data into lithological units. Classified lithological data were uploaded to the GEOMODEL multi-layer geological modelling system, also developed by GSC, where the computer model was created. Layers mapped in this model include the basal unconformity, two conventional hydrocarbon reservoirs between the unconformity and the lowest coal, and 25 coal beds within the Medicine River and overlying coal seams. The completed computer model was imported into a Geographic Information System (GIS) and integrated with maturity data (vitrinite reflectance) determined from cuttings, and pressure and water chemistry data from other electronic databases. The GIS provided the ability to combine spatial datasets to produce maps of optimal drilling targets, as well as, extensive additional visualization and analysis capabilities.

Coal seam development and the location of oil and gas reservoirs in the target area are strongly controlled by the geometry of the underlying unconformity surface in this area (Fig. 6). Relatively high water tables preceding and contemporaneous with coal development have resulted in the thickest coals forming over unconformity highs. Unconformity lows are characterized by thinner coal seams separated by numerous rock partings, and are the location of fluvial systems containing conventional oil and gas reservoirs. Aggregate seam thickness over the area ranges from 0.6 to 22.57 m, with a mean thickness of 9.58 m. This translates into coal resource densities from 0.78 to 29.35 Megatonnes/km^2, or a total in situ resource of 28 Gigatonnes. Theoretical in situ gas estimates obtained from depth and maturity data range from 8.0 to 11 cm^3/g, which indicates a potential in situ methane resource in the order of 240 billion m^3 or 8.5 Tcf.

Optimal drilling targets within this area were selected according to aggregate coal thickness, theoretical gas content, and the degree of flexure of the generally homoclinal beds (which determines the presence of cleat controlling permeability). Flexure was measured utilizing maps of dip angle and aspect generated from selected coal beds in the model. These maps were combined using a weighted index overlay to produce a map showing optimal drilling locations.

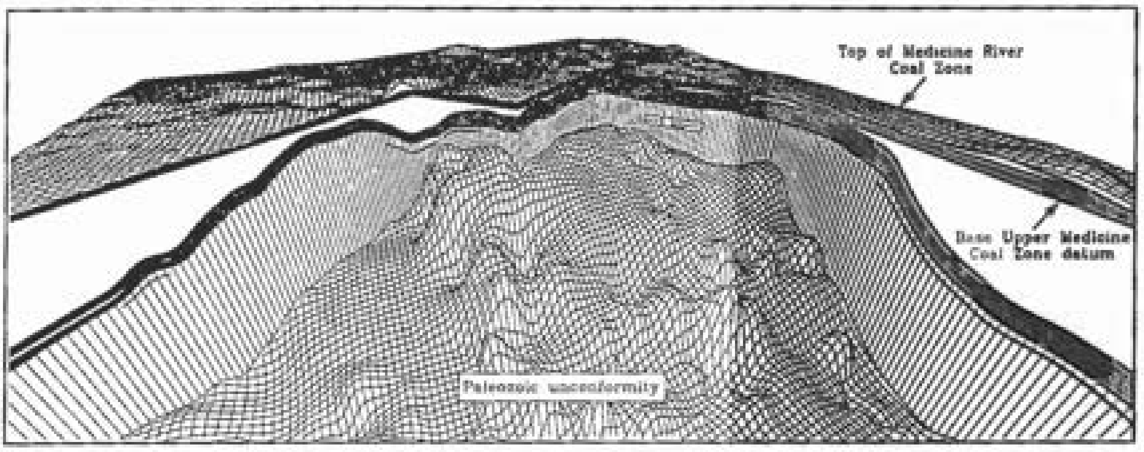

Fig. 6: Three dimensional view of a coalbed methane drilling target located over a high on the underlying Paleozoic unconformity surface derived from a computer model based on 500 boreholes. The Medicine River Coal Zone in this part of central Alberta locally reaches 14 m in thickness. The 45 by 50 km area studied may contain in situ methane resources of up to 9 Tcf.

Coalbed Methane Adsorption Isotherms

Adsorption isotherms have been produced for coals with varying ranks (0.60-2.50% Rmax) from different coal deposits in Western Canada (Fig. 1) and form the basis for a database upon which resource estimates of individual coal basin can be made. The results presented here come from Mist Mountain Formation (Kootenay Gp.) and Gates Formation (Luscar Gp.) coals of the Rocky Mountain Front Ranges and Foothills (Fig. 2). Figure 7 illustrates the relationships between calculated Langmuir methane volumes (dry ash free basis) and total inertinite and dry ash contents. Coals are of similar rank and equilibrium moisture, but with varying inertinite and dry ash content. It can be seen that for coals with similar inertinite content, the Gates Formation coals appear to have higher Langmuir methane volumes than those of the Mist Mountain Formation (Fig. 7). Although the total inertinite content of the Gates coals is generally lower than that of the Mist Mountain coals, the difference between the two cannot be explained by petrographic composition alone and may be related to other factors such as the elemental composition hydrogen and oxygen ratios within the coals.

A similar relationship can be seen between the two sample sets of coal when comparing ash contents (Fig. 7). Although the Langmuir volumes are corrected to a dry ash free basis, there appears to be a distinct difference between the adsorbed volumes of coalbed gas for the Gates and Mist Mountain formation coals. The Gates coals tend to have very high Langmuir volumes for low ash samples (Fig. 7), whereas, the adsorptive capacities of the Mist Mountain coals appear to be suppressed.

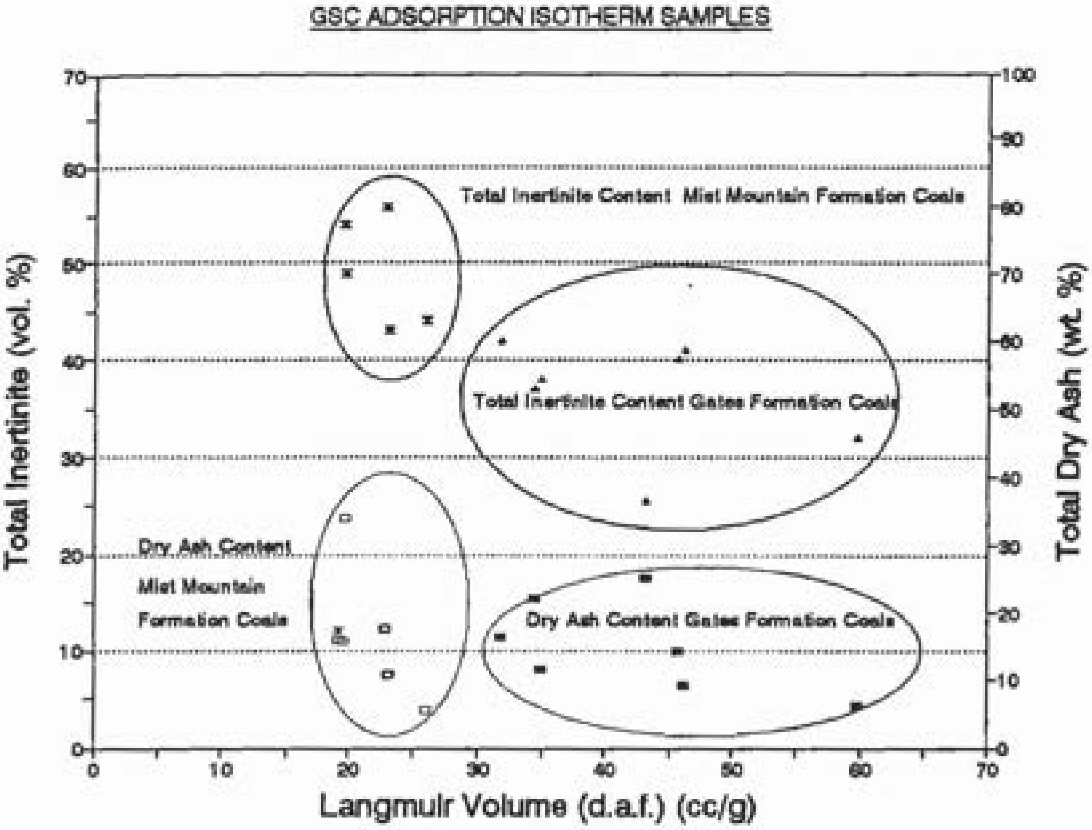

Fig. 7: Langmuir methane volumes versus inertinite and ash contents for selected coals from the Rocky Mountain Front Ranges and Foothills.

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CYCLICAL SEDIMENTATION IN THE LOWER NEWCASTLE COAL MEASURES

C. HERBERT
School of Earth Sciences, Macquarie University

INTRODUCTION

The 400-m-thick Late Permian Newcastle Coal Measures (NCM) and the underlying 40-m-thick Dempsey Formation form a southwest-thinning siliciclastic wedge of marine, deltaic and alluvial sediments that prograded across the subsidence axis of the foredeep or retroarc Sydney Basin (Herbert 1980). Environmental interpretations have assumed continuous deposition without explaining the juxtaposition, with sharp contacts, of fluvial gravel, finer-grained deltaic sediments, and peat mires. I attempt to resolve this difficulty by referring the contrasting depositional environment to different stages of relative sea-level (RSL).

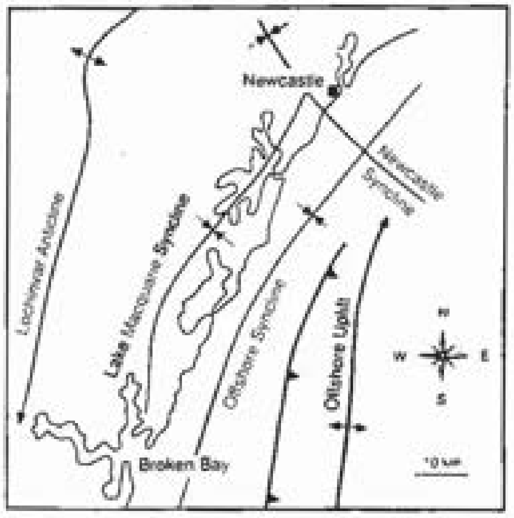

Fig. 1 The Newcastle Coal Measures were deposited in the Lake Macquarie and Offshore Synclines in a north-south oriented half-graben between the Lochinvar Anticline and the Offshore Uplift.

REGIONAL PALAEOGEOGRAPHY

The NCM was deposited in a north-south half-graben, about 50 km wide, situated between the syn-sedimentary flexural Lochinvar Anticline (Herbert 1993) and the upthrusted Offshore Uplift (Bradley 1993a & b) (Fig. 1). The coal measures thicken eastwards in the faster subsiding Offshore Syncline and thin westwards onto the slowly subsiding flank of the Lochinvar Anticline (Fig. 2b). The NCM also thin to the south in the direction of marine shoreline progradation and decreasing subsidence (Fig. 2a).

The Dempsey Formation and the Waratah Sandstone comprise stacked, marine shale/sandstone, shoreface intervals that downlap to the southwest onto marine maximum-flooding-surfaces (Herbert 1994a submitted). Landwards, to the northeast, the marine intervals pass into paralic upward-coarsening deltaic intervals, coal, and fluvial conglomerate. Thus, the base of the NCM become younger to the southwest as it passes laterally into the marine Dempsey Formation (Fig. 2a). Cycles of conglomerate to coal to paralic delta are interpreted as high-frequency 4th-order sequences controlled by changes in RSL (Herbert 1994b submitted).

PALAEOENVIRONMENTAL INTERPRETATION

Deposition in the coal measures took place in a complex of paralic coastal plain environments landward of a marine barrier (Figs 2, 3). Upward-coarsening shale/sandstone intervals, conglomerates, and coals deposited in these environments are discussed below.

Upward-coarsening shale/sandstone intervals

Two types of repeated upward-coarsening shale/sandstone intervals are interpreted to have been deposited in marine and paralic environments. Stacked marine intervals in the Dempsey Formation/Waratah Sandstone are interpreted as offshore silt/prograding beach ridges bounded by marine flooding surfaces (marine shoreface parasequences, Fig. 2a). Upward-coarsening shale/sandstone intervals in the lower NCM are interpreted as crevasse splays, crevasse subdeltas, and small deltas which prograded into shallow, brackish lagoons and interdistributary bays landward of the Waratah Sandstone barrier islands (paralic delta parasequences, Figs 2, 3). Brackish and marine conditions are indicated by burrows in sandstones and the occurrence of acritarchs in all but the uppermost NCM (McMinn 1982, 1984). Deltaic intervals are sheet-like with gently-inclined heterolithic strata downlapping onto flooding surfaces on top of coals.

Conglomerates

Fluvial conglomerates, up to 60 m thick, are characterised by inclined bedding planes, with dips up to 45°, which impart a sigmoidal shape to each conglomerate body. Diessel (1992, fig. 6.50) inferred that the principal surfaces of deposition were originally deposited as more gently inclined fluvial lateral accretion beds, and agreed with Britten et al. (1975) that compaction of the underlying peat during deposition steepened bedding into forms that mimic

CYCLICAL SEDIMENTATION

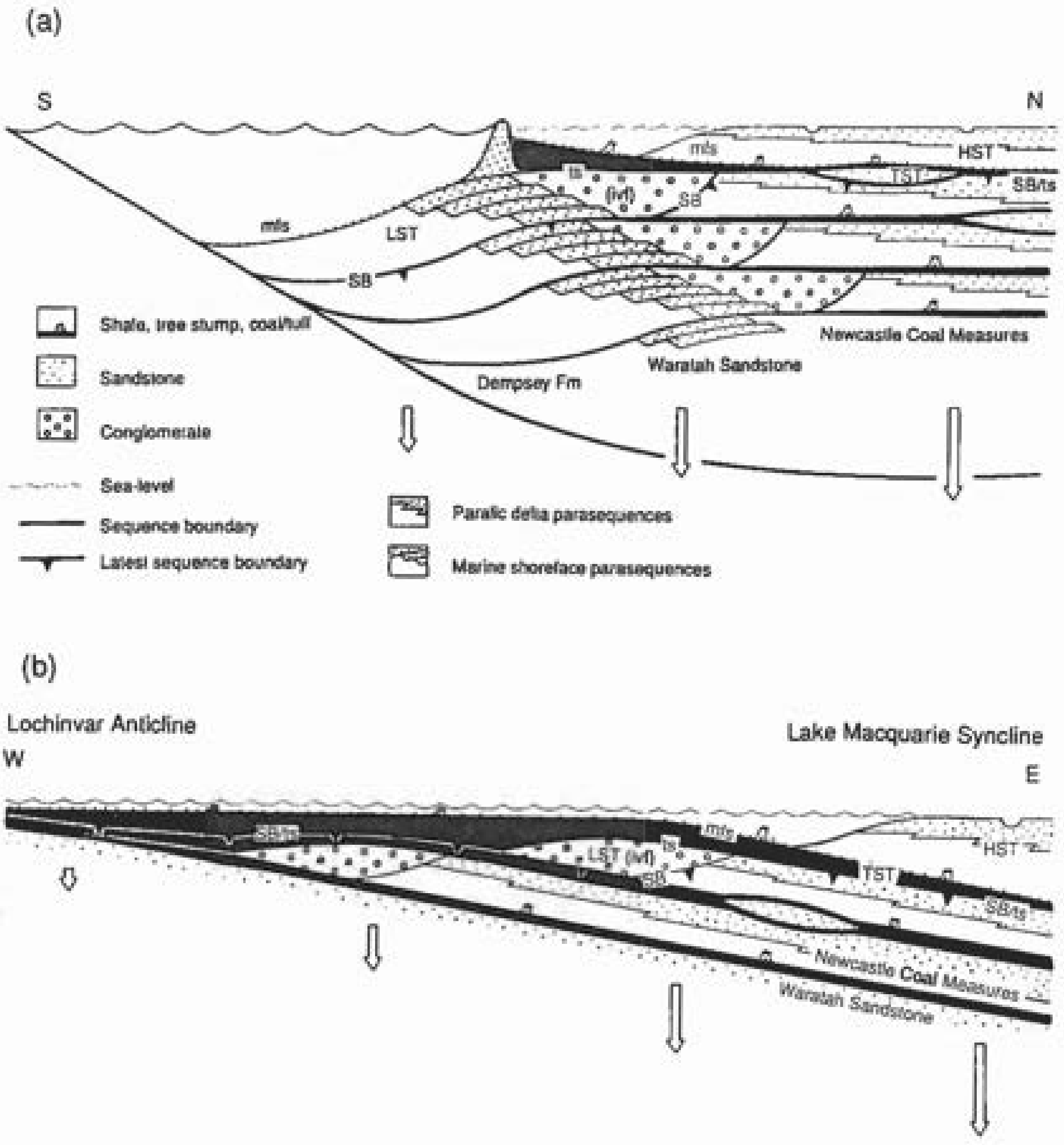

Fig. 2 Depositional geometry of cycles (high-frequency 4th-order sequences) in the Newcastle Coal Measures. Youngest cycle is depicted during HST deposition showing uncompacted and compacting peat. For clarity, sequence-stratigraphic boundaries are shown only for the youngest sequence. LST=lowstand systems tract, TST=transgressive systems tract, HST=highstand systems tract, SB= 4th-order sequence boundary, ivf=incised-valley-fill, ts=transgressive surface, mfs=maximum flooding surface. **(a)** Regressive part of lower NCM oriented N-S, approximately in the direction of LST marine shoreface progradation and decreasing subsidence (arrows), and perpendicular to HST progradation. The transgressive barrier shoreface has low preservational potential and is prone to modification during subsequent RSL fall. **(b)** Lower transgressive part of the NCM oriented E-W, approximately in the direction of HST paralic delta progradation, coal seam coalescence, and decreasing subsidence (arrows), and perpendicular to LST progradation.

giant crossbeds. Basal erosional surfaces commonly cut through the deltaic intervals down to the underlying coal, suggesting that the entire delta front was subaerially exposed to stream incision by a fall in RSL. The fluvial channels were directed into compaction moats formed at the toe of the abandoned delta-fronts.

Coal

Stratigraphic relationships indicate that the major coals formed from peat mires which blanketed *abandoned* sedimentary surfaces, and were not coeval with substantial siliciclastic deposition. Peat mires were probably woody, in rain-fed (ombotrophic) bogs at a 70° S palaeolatitude similar to those forming today in the boreal wetland regions of Canada (Martini and Glooschenko 1985). A 10:1 compaction ratio for peat to coal (Ryer and Langer 1980) implies decompacted 20- to 50-m-thick peats, which probably built up the highest surfaces on the coastal plain and tended to reduce or exclude associated siliciclastic sedimention. Seam convergence lines define the westward extent of deltaic progradation and outline the lobate shape of successive delta fronts (Fig. 3c). Repeated delta progradation and subsequent draping by peat mires led to the successive convergence of the Borehole, Yard, Dudley, and Nobbys Coals to form the West Borehole Coal in the western more slowly subsiding part of the Newcastle Coalfield (Fig. 2b).

RELATIVE SEA-LEVEL CHANGE

Deposition during one of the 4th-order RSL cycles within the lower NCM is discussed below (Figs 2, 3).

Relative sea-level fall

A fall in RSL terminated the progradation of previous highstand paralic deltas and exposed the coastal plain. Lower base-level rejuvenated streams draining the New England Orogen where a repository of gravelly alluvium had accumulated during the highstand. Hinterland tributaries incised the alluvium and flanking piedmont fans to provide immediately available detritus for transport to the basin. Tributaries merged into a single trunk stream before they entered the Newcastle half-graben from the northeast (Fig. 3a). Finding the lowest topography, the trunk stream was deflected around the abandoned delta-front in a moat created by compaction of the underlying peat. Fluvial sediments crossed the coastal plain in confined channels that fed directly to the marine shoreline. The abundant sediment supply to the shoreline initiated seaward progradation of the upward-coarsening shoreface parasequences of the Dempsey Formation/Waratah Sandstone.

Rising relative sea-level

Rising RSL caused gravel to aggrade in the channel incised during the previous fall (sometimes as much as 60 m). As the rise accelerated, alluvial deposition migrated upstream, north of the basin to be confined to hinterland valleys in the New England Orogen and fringing piedmont fans. Correspondingly, sediment supply to the marine shoreline declined and the Waratah Sandstone beach ridges were transformed into transgressive barrier islands above a transgressive surface. The surface landward of the sandy barriers (Fig. 3b) was covered by forested, rain-fed (ombotrophic) peat mires whose growth was stimulated by the rising water-table.

Maximum rate of rising relative sea-level

The vertical accumulation of peat kept pace with the earlier rates of rising RSL and inhibited shoreline transgression. However, during the maximum rate of rise, peat growth was insufficient to prevent inundation by expanding lagoons and restricted marine bays landward of the barrier complex. The paralic flooding surface which spread across the top of the peat mire is marked by an abrupt transition from coal to prodelta siltstone. Trees on the surface of the peat mire were drowned and preserved in growth position or as fallen logs. At this time, or during the next phase, the marine shoreline barriers may have been submerged as shoals, but still protected the paralic environment from open marine processes.

Relative sea-level highstand

During RSL highstand, lagoons and restricted bays landward of the marine barrier shoreline, or shoals, provided sufficient accommodation space for small paralic deltas to prograde westwards from the Offshore Uplift (Fig. 3c). Explosive volcanoes from this area not only showered the coal measures with air-fall and base-surge pyroclastics but also provided volcano-lithic detritus by the erosion of its associated ignimbrite sheets (Jones et al. 1987). High RSL caused the impounding of coarse alluvium in hinterland valleys of the New England Orogen while finer-grained sediment was deposited and trapped in the paralic environment, starving the marine shoreface and shelf (Waratah Sandstone and Dempsey Formation respectively).

CYCLICAL SEDIMENTATION

Relative sea-level fall

Falling RSL at the start of another cycle terminated the deposition of paralic deltas and the entire back-barrier was exposed to fluvial incision (Fig. 3a) initiating another high-frequency sequence of conglomerate-coal-paralic delta.

SUMMARY

(i) Most models of coal-measure deposition regard alluvial, peat mire, deltaic, and shoreline environments as *coeval*, lateral facies. However, in the Newcastle Coal Measures, high-frequency, RSL changes activated these environments at *different* times.

(ii) The depositional cycles are equivalent to 4th-order depositional sequences, which commenced with subaerial erosion surfaces (sequence boundaries) overlain by channelised fluvial conglomerate in incised-valleys in lowstand systems tracts. Following lowstand fluvial deposition, raised peat mires extended over the entire non-marine area of the coalfield in transgressive systems tracts. Paralic maximum flooding surfaces developed by submergence of peat mires followed by the progradation of crevasse splays, crevasse subdeltas, and small deltas into lagoons and restricted marine bays in highstand systems tracts. Marine shoreface parasequences were deposited during RSL lowstands, out of phase with paralic delta parasequences deposited during RSL highstands.

(iii) Two source areas supplied sediment into the Newcastle half-graben. An easterly source on the Offshore Uplift shed volcanic detritus into the Newcastle Coalfield via paralic deltas, and the New England Orogen shed volcano-lithic detritus in braided streams. The supply from the New England Orogen was switched on, or increased, by a fall in RSL while supply from the Offshore Uplift was switched off, reduced, or overwhelmed; and *vice-versa* during a rise in RSL.

(iv) The NCM was deposited on the tectonically active side of a foreland basin where increasing subsidence created greater amounts of subaerial accommodation landward of the marine shoreline leading to the deposition of a thick non-marine/paralic section and a thin coeval marine section.

ACKNOWLEDGEMENTS

This study was supported by an Australian Research Council Special Investigator Award to J. J. Veevers.

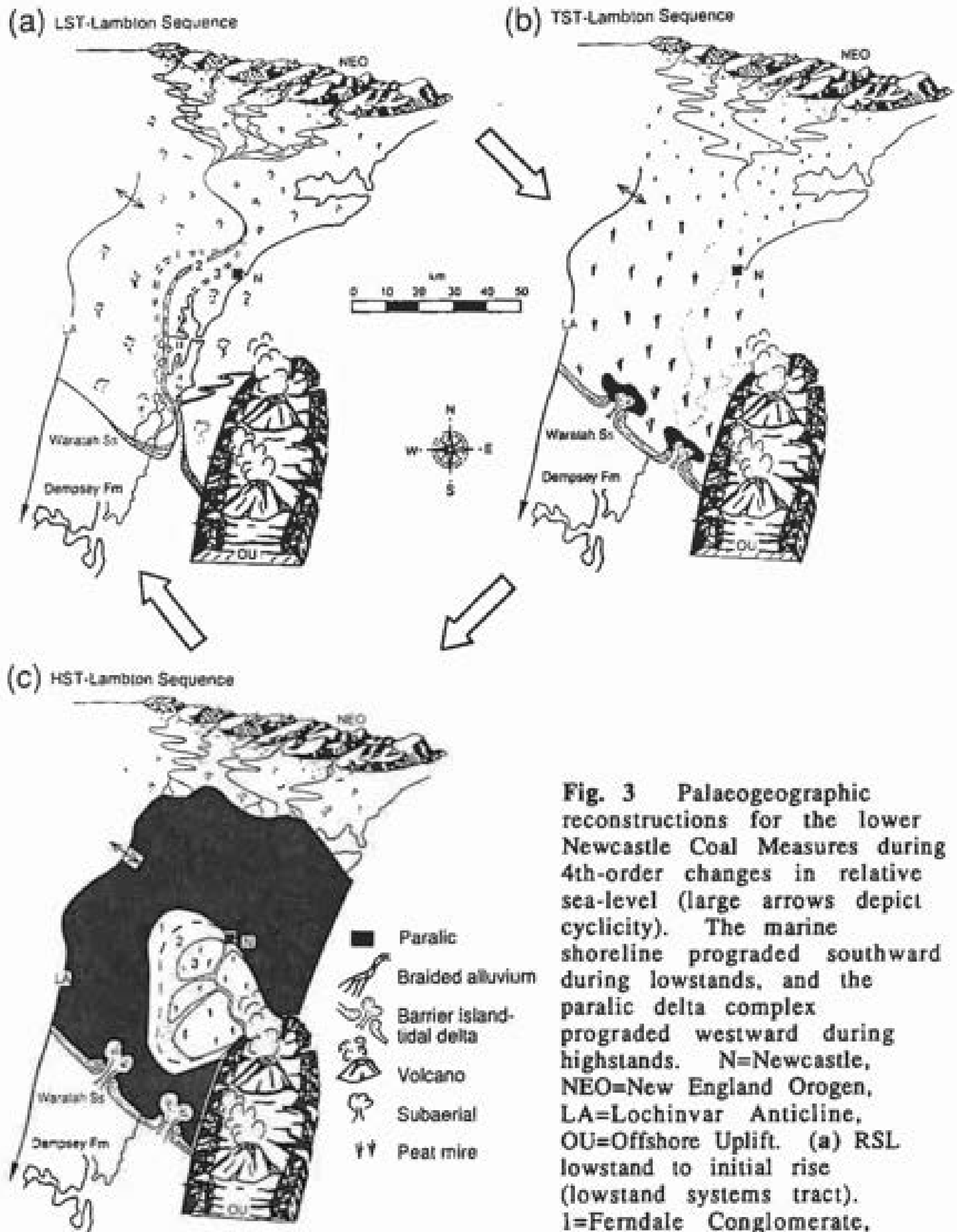

Fig. 3 Palaeogeographic reconstructions for the lower Newcastle Coal Measures during 4th-order changes in relative sea-level (large arrows depict cyclicity). The marine shoreline prograded southward during lowstands, and the paralic delta complex prograded westward during highstands. N=Newcastle, NEO=New England Orogen, LA=Lochinvar Anticline, OU=Offshore Uplift. (a) RSL lowstand to initial rise (lowstand systems tract). 1=Ferndale Conglomerate, 2=Cockle Creek Conglomerate, 3=Signal Hill Conglomerate. (b) Early RSL rise to maximum rate of rise (transgressive systems tract). (c) Slowing rates of RSL rise to early fall (highstand systems tract). Location of backstepping delta fronts based on seam convergence lines from Branagan and Johnson (1970), Warbrooke (1981), Bowman and Whitehouse (1984). 1=Borehole/Yard Coals, 2=Yard/Dudley Coals, 3=Dudley/Nobbys coals.

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TRACING THE BULLI & BALGOWNIE SEAMS ACROSS THE SYDNEY BASIN

M.B.L. HILL, M. ARMSTRONG, S. COZENS & J. BYRNES
New South Wales Department of Mineral Resources

ABSTRACT

The Department of Mineral Resources commenced an audit of the State's coal, coal seam methane and petroleum resources in 1992. One of the first areas examined was the central part of the Basin lying between the Southern, Western, Hunter and Newcastle Coalfields. Little has been published about the geology of this area and before attempting a resource assessment, it was necessary to produce a working model of the stratigraphy and sedimentology. This paper presents the preliminary results of that study. The geology of the upper part of the sequence is examined using east-west and north-south cross sections. A new model is presented dividing the upper coal measures into an alluvial plain facies and a deltaic facies. It is suggested that fluvial systems covered the Basin from Cape Horn seam time onwards but with several long hiatuses during which blanket coals developed. The Bulli, Balgownie and Cape Horn seams can be correlated with certainty across most of the Basin. These correlations are discussed and a stratigraphy for the Central Basin area is proposed.

In July 1992, the Coal and Petroleum Geology Branch of the New South Wales Department of Mineral Resources commenced an audit of the State's coal, coal seam methane and petroleum resources. This action was in response to a directive from the Premier that an audit of the State's natural resources be completed over a five year period so that balanced decisions could be made about land use and conservation.

One of the first areas to be examined was the Central Sydney Basin lying between the Southern, Western, Hunter and Newcastle Coalfields. The area includes the old Central Coalfield and the Wattagan Coal District. This area was selected for the following reasons:-

- The Central Basin area has been neglected in the past because the seams lie predominantly at depths below 600 metres - too deep to be mined economically by the then available technology.
- The area is now believed to contain important coal resources at depths between 600 and 750 metres, which are likely to be mined in the future. It also has the potential to contain significant quantities of coal seam methane which could supply the State's natural gas needs for many years.
- There are many land use issues emerging which could lead to the sterilization of resources but there is insufficient knowledge available to permit informed planning decisions.

Initial research showed that there was little published material on this part of the Basin, no established stratigraphy and no definitive seam correlations. Seam by seam correlation was undertaken as a precursor to resource assessment.

The coal measure sequence does not crop out in the Central Basin area and less than 30% of the boreholes drilled in the area have been geophysically logged. It was therefore necessary to depend on lithological and depositional environment logs. All available cores were examined, relogged and photographed. Marker horizons were delineated and cross sections prepared. Figure 1 shows the locations of cross sections used in this paper.

Borehole density is irregular and in some places sparse. Spacings of over 30 kilometres are not uncommon particularly in the north and northwest of the area (in the region covered by the Wollomi, Yengo and Dharug National Parks). It is possible, however, to recognize consistent patterns within the upper part of the coal measure sequence and to correlate the units with some certainty.

Correlation was commenced in the northern part of the Southern Coalfield and was extended step by step to the north, northwest and west. The major units above the middle of the Eckersley Formation were found to extend across the Central Basin Area and to correlate with named units in the Western and Newcastle Coalfields. Southern Coalfield stratigraphic nomenclature (Standing Committee, 1992) has been used as a basis for a Central Basin stratigraphy but has been modified where necessary. Table 1 shows the stratigraphy of the upper part of the coal measure sequence in the Southern Coalfield. Table 2 is a comparison chart showing the stratigraphy of the surrounding coalfields and, where possible, the equivalent units. Table 3 shows the proposed stratigraphy of the Central Basin area.

The upper part of the coal measure sequence, from middle Eckersley Formation time, consists of a fluvial sand facies containing discrete and laterally extensive coals. One thick tuffaceous unit forms an excellent marker horizon. The facies thickens from the south to the north towards the Hunter Valley and to the northeast towards Gosford, but thins to the west and northwest. The sands in general coarsen to the north and northeast.

The basal unit of the facies is a lithic sandstone which is directly overlain by the Cape Horn Coal Member but which is restricted to the north and northeast of the area. The sandstone has a maximum known thickness of 15 metres and is here named the St Albans Sandstone Member.

The Cape Horn Coal Member extends across the area to Mt Tomah in the west, Howes Valley in the north (40 km southwest of Singleton) and Gosford in the northeast where it is known as the Fassifern Seam.

The Burragorang Claystone overlies the Cape Horn Coal member in the Southern Coalfield.

The unit can be correlated across the Basin as far as Mt Tomah, Howes Valley and Gosford where it is known as the Awaba Tuff. In the Southern Coalfield and to the north as far as Penrith and Cape Banks the unit normally consists of approximately 1 metre of white claystone. Further to the north it thickens to an average of over 5 metres, has a characteristic yellow and buff colour and is indistinguishable in appearance from the Awaba Tuff as intersected to the north of

Gosford. The name Awaba Tuff is preferred for this unit in the proposed stratigraphy for the Central Basin area.

The Lawrence Sandstone Member overlies the Awaba Tuff. This unit comprises lithic sandstone with minor siltstones and claystones. It can be traced to the north as far as Howes Valley but does not occur in the far west or the north east. In the Sydney-Dural area the unit is replaced by siltstones, claystones laminites and minor sandstones.

The Balgownie Coal overlays the Lawrence Sandstone Member. This seam can be traced across the basin to the west as far as Lithgow and Mt Tomah, where it is known as the Woodford seam, to the north as far as Howes Valley, and to the northeast as far as Gosford where it is known as the Wallarah-Great Northern seam.

The Loddon Formation overlays the Balgownie Coal. The unit can be correlated directly across the Basin to Mt Tomah in the west, Howes Valley in the north and Gosford in the northeast. It can be subdivided into 3 members throughout most of the Central Basin area (but not in the northeast from Spencer and Glenorie towards Gosford). The upper member, here named Dural Sandstone Member, consists of lithic sandstone with minor siltstones and claystones.

The middle member is here named the Balmain Coal Member. This seam is not a split of either the Bulli or Balgownie seams and its most southerly appearance is in the Holsworthy-Campbelltown area of the Southern Coalfield.

The lower member is here named the Penrith Sandstone Member. This unit consists of lithic sandstone with minor siltstone and claystone in the west, north and northeast of the area. In the east and southeast including Dural, Liverpool and Cape Banks, it comprises claystones, siltstones, laminites and minor sandstones.

The Bulli Coal overlays the Loddon Formation. This unit can be traced continuously to the north as far as Howes Valley, to the west as far as Lithgow and Mt Tomah where it is known as the Katoomba Coal Member and to the north-east as far as Gosford where it is known as the Vales Point Coal Member.

TRACING SEAMS ACROSS THE SYDNEY BASIN

Coal seams occur above the Bulli Coal in two areas, between Colo and Upper Colo and near Glenorie. It is suggested that these seams and the associated sandstones should be considered as part of the Illawarra Coal Measures and not of the Narrabeen Group. This sequence is here named the Comleroy Formation.

In the proposed stratigraphy for the Central Basin area the Eckersley Formation has been subdivided into two formations. The lower pelitic (deltaic) section retains the name Eckersley Formation, while the upper arenitic (fluvial) section is named the Nepean Formation.

The authors' original intention was to correlate the Central Basin sequence with the Wollombi Coal Measures of the Hunter Valley. A thirty kilometre gap separates Howes Valley from a line of boreholes trending northwest - southeast along the southern rim of the valley (Department of Mineral Resources Doyles Creek and Whybrow boreholes). Correlation was not possible because none of the major units could be recognised with certainty in any of these boreholes.

The coal measure sequence from the top of the marine Darkes Forest Sandstone - Watts Sandstone up to the Narrabeen Group thickens to the north from the southern coalfield to Howes Valley but then thins further to the north (68m in DM Picton DDH2 to 321m in DM Howes Valley DDH1 and to 248m in DM Doyles Creek DDH11). The thickness of this sequence varies dramatically in the boreholes running northwest - southeast along the southern edge of the Hunter Valley (230m in DM Doyles Creek DDH10, 200m in DM Doyles Creek DDH2, over 300m in Doyles Creek DDH3, and 248m in DM Doyles Creek DDH11). It is suggested that the Wollombi Coal Measures may not contain the full sequence as originally deposited and that it is possible the upper part has been eroded by the Narrabeen Group.

It is suggested that the sands and conglomerates of the alluvial sand facies were derived from the north of the present basin boundary and were eroded during periods of uplift of the New England Block. Fluvial systems deposited the sands across the basin to the south, southeast and west. Uplift occurred irregularly and blanket coals including the Cape Horn, Balgownie, Balmain and Bulli Seams were deposited during the hiatuses.

Acknowledgement

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TRACING SEAMS ACROSS THE SYDNEY BASIN

Plan 1. The Sydney Basin – The location of transverse, longitudinal cross sections & the Central Sydney Basin Area.

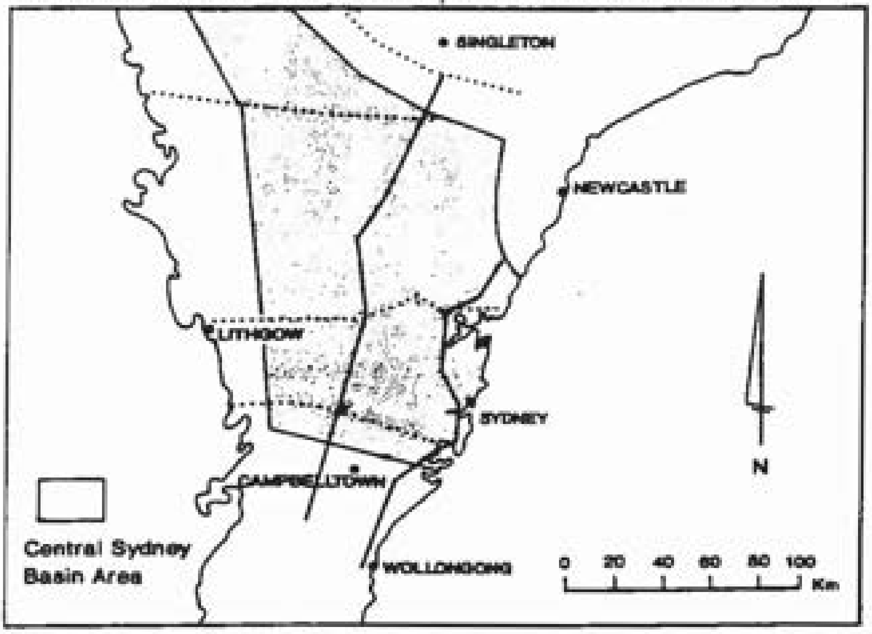

TABLE 1. Stratigraphy of the upper part of the Sydney Subgroup – Southern Coalfield

<table>
<tr><th colspan="3">SOUTHERN COALFIELD</th></tr>
<tr><td colspan="3">NARRABEEN GROUP</td></tr>
<tr><td rowspan="5">SYDNEY SUBGROUP</td><td colspan="2">BULLI COAL</td></tr>
<tr><td colspan="2">Loddon Formation</td></tr>
<tr><td colspan="2">Balgownie Formation</td></tr>
<tr><td>ECKERSLEY FORMATION</td><td>Lawrence Coal Member
Burragorang Claystone
Cape Horn Coal Member</td></tr>
<tr><td colspan="2">WONGAWILLI COAL</td></tr>
</table>

TABLE 2. Comparsion of the stratigraphy of the Southern, Western Newcastle and Hunter Coalfields showing equivalent units.

<table>
<tr><th colspan="2">SOUTHERN COALFIELD</th><th colspan="2">WESTERN COALFIELD</th><th colspan="2">NEWCASTLE COALFIELD</th><th colspan="2">HUNTER COALFIELD</th></tr>
<tr><td colspan="8">NARRABEEN GROUP</td></tr>
<tr><td colspan="2">Bulli Coal</td><td rowspan="8">FARMERS CREEK FM</td><td>Katoomba Coal Mb</td><td rowspan="4">MOON ISLAND BEACH FM</td><td>Vales Point Coal Mb</td><td rowspan="8">WOLLOMBI COAL MEASURES (UPPER PART)</td><td rowspan="7"></td></tr>
<tr><td colspan="2">Loddon SS Mb</td><td></td><td></td></tr>
<tr><td colspan="2">Balgownie Coal Mb</td><td>Woodford Coal Mb</td><td>Wallarah - Great Northern Coal Member</td></tr>
<tr><td rowspan="4">ECKERSLEY FM</td><td>Lawrence SS Mb</td><td rowspan="4"></td><td></td></tr>
<tr><td>Burragorang CS Mb</td><td colspan="2">Awaba Tuff</td></tr>
<tr><td>Cape Horn Coal Mb</td><td rowspan="3">BOOLAROO FM</td><td>Fassifern Coal Mb</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">WONGAWILLI COAL</td><td>MIDDLE RIVER COAL Mb</td><td>UPPER - LOWER PILOT COAL MEMBER</td><td></td></tr>
</table>

TRACING SEAMS ACROSS THE SYDNEY BASIN

TABLE 3: The proposed stratigraphy for the uppermost part of the coal measures - Central Sydney Basin area.

<table>
<tr><td rowspan="7">ILLAWARRA COAL MEASURES</td><td colspan="2">NARRABEEN GROUP</td></tr>
<tr><td>Comleroy Fm (New)</td><td>Unnamed Seam</td></tr>
<tr><td>Bulli Coal</td><td></td></tr>
<tr><td>Loddon Fm</td><td>Dural SS Mb (New)
Balmain Coal Mb (New)
Penrith SS Mb (New)</td></tr>
<tr><td>Balgownie Coal</td><td></td></tr>
<tr><td>Nepean Fm (New)</td><td>Lawrence SS Mb
Awaba Tuff
Cape Horn Coal Mb
St Albans SS Mb (New)</td></tr>
<tr><td>Eckersley Fm</td><td></td></tr>
</table>

FRACTURE PATTERN OF THE ILLAWARRA COAL MEASURES, SOUTHEASTERN SYDNEY BASIN

H. MEMARIAN & C.L. FERGUSSON
Department of Geology, The University of Wollongong

INTRODUCTION

The fracture pattern of the Sydney Basin is remarkably complex for relatively flat-lying sedimentary rocks and a better understanding of this pattern is of importance, to coal mining and civil engineering works (Shepherd & Huntington 1981).

The surface study of joints and other fractures in the southeastern part of the Sydney Basin has been mostly based on Landsat imaginary and air-photo interpretation (Bowman 1974; Mauger et al. 1984). Results of these studies usually reflect fracturing of the Hawkesbury Sandstone, which covers most of the Southern Coalfield. Similar studies in underground coal mines are limited to working coal seams and their adjacent roof and floor strata.

This paper reports the findings of extensive fracture mapping of the Illawarra Coal Measures exposed along the coastal platforms and adjacent cliffs, between Coalcliff and Wollongong. Fracture mapping has enabled identification of four phases of deformation active from the time of Late Permian deposition until the present. Syn-depositional mild warping and normal faulting has been recognised for the southeastern Sydney Basin (Wilson *et al.* 1958; Bunny 1972, Jakeman, 1980) and has been confirmed by the present study. Regional joint systems formed after deposition and developed in three major directions. All fracture sets were reactivated with common strike-slip movements.

JOINTS

Different characters of fractures were measured in the field, among them are orientation, spacing, persistence, planarity, termination, surfacial features, opening, infilling, lateral movement and interactions with other fractures. Displacements along joints as little as 0.5 mm were recorded. More than 10,000 fractures were surveyed during the course of this study. Methods used for gathering field data include mapping of entire outcrops, scanline surveys and random sampling.

Joints were categorised as either regional or local. A regional set is defined as those that are well developed over the study area and can be traced beyond it, both horizontally and vertically. A local set have a limited distribution and are normally related to a particular structure, such as a dyke. Regional and local joints are often parallel or subparallel to each other, even in a single outcrop. Regional joint sets never interfere with each other. In localities where fracture patterns consist of two or more regionally distributed sets, joints cut through each other with no sign of interaction. An example is shown in Fig. 1, where the regional joint sets strike 040° (NE) and 125° (SE). The members of the first set are long and open, while the joints of the later set are fine and mostly closed.

A well develop systematic joint is normally rectangular in shape, with its upper and lower terminations bounded by upper and lower limits of a single mechanical layer. The length of an original joint is generally a few times its height. Joints are principally vertical and have developed in many geographic directions. Subhedral crystals of calcite cover some fracture walls and indicate that the fracture was open at depth (Lorenz & Finley 1991). The infilling also demonstrates that joints were filled with fluids at the time of fracturing.

Joints cut pebbles within conglomerate and show no significant shear offset in the plane of the joint. Frequent plumose structures and lack of original shearing demonstrate that almost all of the joints originally developed as extension fractures (mode I). Conjugate joint sets are a consequence of two separate fracturing events of different orientation (see Engelder 1982). Signs of shearing that are widespread along the joints are the products of subsequent reworking of refractured joints.

The orientation of joints is strongly depend on rock type, pre-existing sedimentary structures, joints, faults and dykes. Joints are very well developed in sandstone, siltstone and laminite, while relatively little data was obtained from claystone or coal. The orientation of a set of joints changes as much as 15°, even in a single outcrop, mostly due to differences in rock type. None of the joint sets are developed in all of the studied outcrops. Most joints fall into three major orientations, namely N-NNE, NE-ENE, and SE.

Both regional and local joint sets developed in the N-NNE direction. Cross cutting relations show a wide range of ages for these joints. NE-ENE striking joints have a mean orientation of 045° in the Coalcliff area, while south of Coledale they strike between 050-075°. SE joints have a pronounced regional distribution and formed early in the history of joint formation. In addition to the above mentioned directions still other joint orientations occur, namely E and SSE. An example is given in Fig. 1 where, in addition to regional NE and SE joints, some relatively short and fine 010°, 030° and 095° fractures, are developed. These occur adjacent to or in between 040° joints (insets a,c,d). 095° fractures also occur at the end of some 125° joints. The last group of fractures are non-systematic and occur normal to the 040° joints (insets b,e).

FAULTS AND DYKES

Faults of the study area are normal and strike E-SE and N-NNE. The E-SE group are either major and consist of a single break or are minor and zonal. They strike 90-145° and dip 50° to more than 70°. Their throw decreases rapidly both horizontally and vertically. The downthrown block is either to NE or SW. Faults have decreasing dip with increasing depth as is characteristics of listric faults. Another notable characteristic of these faults, consistent with a listric geometry, is the dip of strata, which is towards the fault plane, on the downthrown side.

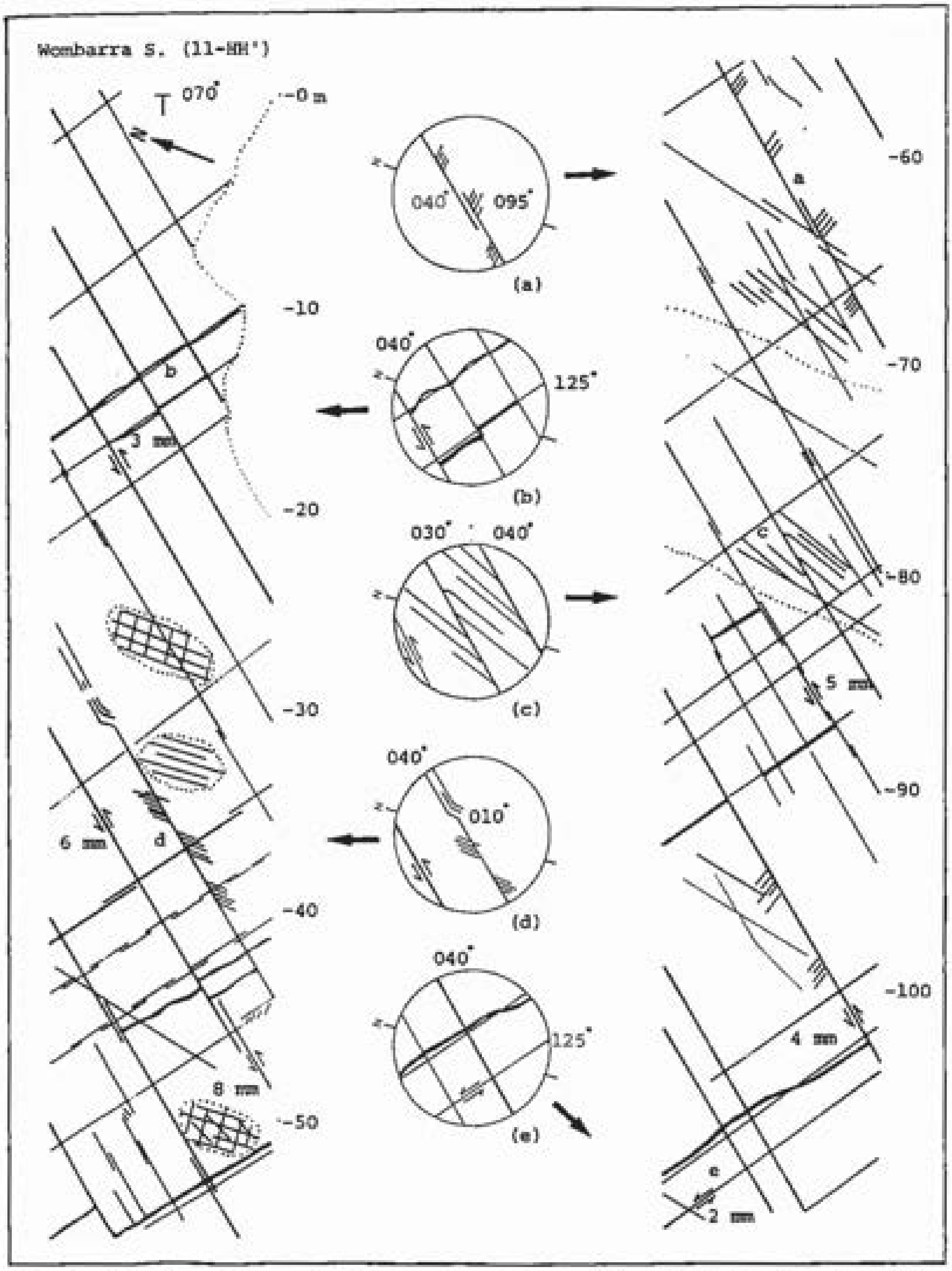

Fig. 1 The first 110 m of a 280 m long, 10 m wide and 070° oriented scanline at Wombarra, NSW. This outcrop is made of horizontal layers of laminites of the Late Permian Wilton Formation. The 040° and 125° joints are regional and belong to the first phase of joint formation, while the relatively short 010°,030° and 95° joints are members of the third phase of joint formation. Sketches in the central column are at the same scale as the scanline and show simplified joint relationships referred to in the text.

Reports on the syndepositional faulting in the southern Sydney Basin (Hanlon 1956; Wilson *et al.* 1958; Wilson 1975) were not considered adequately documented by Hutton *et al.* (1990) and Lohe *et al.* (1992), but have been confirmed by the present study. Several small normal faults with displacements up to 5 cm occur in the Coalcliff Sandstone adjacent to the Clifton Fault. They have an identical orientation to the Clifton Fault. Microscopic study of these fault surfaces shows no brittle deformation of sand grains and indicates that the faults affected unlithified strata. This is confirmed by the presence of growth fault controlled deposition with thicker strata preserved in the downthrown blocks. This evidence indicates that the Clifton Fault was active at the time of deposition of the Late Permian Coal Cliff Sandstone.

The N-NNE faults occur mainly in the northern and central parts of the study area. Their characteristics include: a strike of 000-025°, a dip between 70-90°, downthrow either to the east or west, occurrence in groups of subparallel fractures, small normal components and an associated parallel set of joints. In more brittle rocks, like sandstones, these faults are subvertical faulted joints while in more ductile rocks fault dip is less.

Although lateral movements are frequent, no strike-slip faults developed initially in the study area. All strike-slip movements took place along pre-existing fractures, which were one of joints, normal faults and dykes. Lateral movements along these faults are horizontal, with no oblique component. These movements are accommodated by incremental slip, sometimes less than 1 mm, along the members of a recracked joint set. In Fig. 1 subsequent sinistral movements has occurred along NE and SE joints.

In the northern part of the study area, the most widespread and persistent lateral slips are dextral and sinistral movements along NNE and NE striking fractures, respectively. Elsewhere in the study area, both sinistral and dextral movements were recorded for N, NNE, NE and SE fracture sets. One compressional stress field cannot be responsible for all of these movements.

Dykes were mostly injected through fractures which were propagated by magma pressure. Tension responsible for dyke formation, usually propagates a joint zone with one of its central members intruded by magma. The frequency of these joints rapidly decreases away from the dyke. In the Southern Coalfield most of the dykes strike ESE (100-120°) with another regional set with a NE strike. Numerous relatively small NNE dykes are concentrated in the northeastern part of the coalfield.

RELATIVE AGES OF STRUCTURES

The fracture pattern of the Illawarra Coal Measures formed cumulatively from the Late Permian to the Present. Although it is possible to assign a relative age for each joint set at a particular location (Memarian 1993), it is difficult, and probably unwise, to generalise it regionally. Most of the joints have lost their morphological features due to subsequent deformation, which usually has enlarged them dramatically, both horizontally and vertically. Subsequent deformation has also destroyed cross cutting relations that presumably existed between neighbouring fractures. Preserved cross cutting relationships, presently observed between fracture sets, mostly developed in the succeeding deformations.

All of the fractures developed in one direction are not the result of a single deformational event. For example most NNE striking joints were initiated in a relatively early deformational event, while others developed as tension joints in association with younger dykes. A third group of NNE joints that postdate the dykes are the products of the much more recent compressional event (see below). In general, three phases of joint formation are recognised in this part of the basin. The joints of each phase comprise a few different sets, which might have local or regional distribution. As no shear joints formed originally in this area, each set indicates the direction of prevailing σ_1 at the time of joint propagation.

The time gap between sedimentation and jointing can be relatively short (Hancock 1985). Cook & Johnson (1970) reported early syndepositional joints in ironstone interclasts embedded in the Coal Cliff Sandstone in the Scarborough area. Joints interclasts and neighbouring sandstone layers were thought to have differed only in orientation and Cook & Johnson (1970) concluded that the joints in interclasts formed soon after they were deposited as thin ironstone layers. These layers were eroded in a high energy fluvial environment and the resultant interclasts were embedded in newly deposited sandstone layers. Sandstone layers were in turn jointed due to the contemporaneous stress field.

The most dominant joint sets in the Coalcliff-Scarborough area strike NNE and NE. The orientation of these joints in more than 100 subrounded ironstone interclasts of 1-40 cm in diameter, as well as numerous 2-10 cm thick ironstone bands and thick sandstone layers are identical and ranges between 005-020° for the NNE and 040-050° for the NE joints. The variation in strikes for each set is mostly due to changes in rock type. The similarity between joints in ironstone interclasts, ironstone bands and thick sandstone layers indicates that joints formed regionally after deposition of the Coal Cliff sandstone.

Jointing was initiated in the succession after lithification enabled brittle deformation as is shown by the widespread occurrence of plum structures and the consistent regional orientation of joints throughout the succession. The only fractures which formed during deposition were normal faults and mud cracks, both with local distribution.

Slumping and faulting of soft sediments in the vicinity of the Clifton Fault, supports the idea that some of the E-SE faults where active during deposition of the Illawarra Coal Measures. E-SE normal faults have increased, both in size and number, during the later extensional episodes, which were active up to the Early Tertiary.

The age of N-NNE faults in relation to ESE-SE faults, is reported to be uncertain (Shepherd 1990). Lohe and McLennan (1991) suggested that the movement on N-NNE faults of the Southern Coalfield predate the ESE-SE faults. The present study shows that while some of the E-SE faults were active during deposition of the Illawarra Coal Measures, all of the N-NNE faults are post depositional and postdate formation of similarly oriented sets of N-NNE joints.

Cross cutting relationships indicate that all dykes are post depositional and developed after the formation of regional joint sets and most of the normal faults of the study area. No dyke formed after the commencement of the compression in the Tertiary (see below). A tension acting from the NNE-NE was responsible for the formation of most of the dykes of this part of the basin.

LATE COMPRESSIONAL EVENTS

Recracking and lateral movements along the strike of pre-existing joints are the last deformational events found in rocks of the study area. Recracking normally took place along the previous infilled and closed joints, but when a propagating front reaches the end of an existing joint, it continued and fractured intact rock. These movements have produced systems of conjugate pairs of faulted joints (Memarian, 1993, Fig. 1). Displacements also occurred along pre-existing normal faults and dykes. Recracking of rock also formed a new set of short secondary joints which are developed either at the tip or at the sides of pre-existing fractures. These fractures are straight to curved and relatively short (1-200 cm). These small fractures develop parallel to contemporary maximum compression and thus they are extension fractures (see Segall and Pollard, 1983). Three sets of secondary fractures have been mapped in the study area, namely NNE, E and SSE.

In the scanline presented in Fig. 1, except for the 040° and 125° joints, the rest of the fractures are mostly the products of the more recent compressional episodes. A horizontal compression acting from NNE was responsible for the formation of the secondary 010-030° striking joints, as well as the sinistral movements of 040° joints (insets b, c & d Fig. 1). The 095° secondary joints are the results of an E-W compression (inset a Fig. 1). The same compression sinistrally displaced some members of 125° joints (inset e Fig. 1).

All of the recorded lateral displacements over the study area are readily interpreted as related to 3 compressional stress fields namely: (1) NNE-SSW, (2) E-W and (3) SSE-NNW. The NNE-SSW directed compression is best developed in the northern and central parts of the study area, while the E-W compression is best preserved in the central and southern parts. The relative age of these compressional events are not established yet, although at a few locations, such as in Fig. 1, cross cutting relationships suggest an older age for NNE-SSW compression relative to the E-W one. The SSE compression has been less dominant and traces of this compression are only recorded locally.

Recracking and strike-slip movements of pre-existing fractures and the introduction of secondary joints formed from compressions which are the last significant deformations in this part of the basin. Cross cutting relations between fracture sets indicate that these compressional events post date formation of dykes. In the Southern Coalfield igneous activity was active from the Late Mesosoic to Early Tertiary, and may have been in part related to formation of the Tasman Sea and the rifting between Australia and New Zealand (Carr & Facer 1980; Embleton *et al.* 1986). Rifting responsible for the formation of the Tasman Sea was active between 95 and 55 Ma ago (Veevers *et al.* 1991). Compression would not be anticipated during this interval and hence, the late compressional episodes are probably post Tasman Sea formation or post-earliest Tertiary.

Veevers and Powell (1986) have related post Tasman Sea deformation in eastern Australia to the collision between the Indo-Australian and Pacific Plates. They suggested that this deformation started no earlier than 30 Ma ago. The origin of E-W *echelon* folds in Neogene sediments of the Gippsland Basin is consistent with dextral or anticlockwise motion of Australia relative to the rest of the enclosing plate (Veevers and Powell 1984). In the Illawarra region the dextral motion generated a NNE compression direction which is consistent with the stress field associated with the most pronounced recracking event (see above).

FRACTURE PATTERN OF THE ILLAWARRA COAL MEASURES

DEFORMATION HISTORY

The following scenario is established for the sequence of formation of the major structural features of this part of the basin.

1. Initiation of E-SE normal faults and similarly oriented minor folds during the deposition of the Illawarra Coal Measures and the Narrabeen Group (Late Permian-Early Triassic).

2. Formation of the first phase of joints, namely regional and systematic N, NNE, NE and SE trending joints. These fractures are classified as burial-syntectonic joints (Memarian 1993).

3. Formation of NNE normal faults, more E-SE normal faults and dykes. Formation of the second phase of joints, which mostly have local distributions. This episode was possibly terminated at the end of the extension related to the opening of the Tasman Sea.

4. Recracking of previous fractures and lateral slippage along them. Formation of the third phase of joints, which are basically short and strike NNE, E and SSE. Joints of the NNE and E directions have a regional distribution. Possible reactivation of minor SE trending folds. These compressional episodes are post earliest Tertiary in age.

5. Formation of non-systematic cross joints and widening of the open fractures due to unloading, weathering and surficial movements.

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AN UPDATE ON IN-SEAM DRILLING RESEARCH IN THE COAL INDUSTRY

J. HANES
Consultant Geologist, Figtree

ABSTRACT

The Australian Coal Association Research Program (ACARP) is taking an active role in promoting research in coal mining exploration. This paper summarises the main problems faced by in-seam drilling operators and the research supported by ACARP, AMIRA and CMTE to address the problems. It also provides some explanation of the problems in drilling.

INTRODUCTION

The ACA Workshop "Underground Coal Mining Exploration Techniques" held in Brisbane, November, 1991 determined that in-seam drilling was ACARP's top priority for underground coal exploration research. The preferred approach for research was to develop a comprehensive scope for an integrated research initiative, driven by industry needs and priorities. A scoping study was funded and conducted in 1993 with input from recognised industry experts and operators. The outcome of the scoping study was used to define short and longer term research needs and to select the research projects to be funded by ACARP in 1994.

In-seam drilling operators/supervisors defined the areas of their main problems and helped define the research required (Hanes, 1993a). Providers of research services were invited to make submissions to the 1993 ACARP round conforming with the findings of the scoping study. The Exploration Task Force (of ACARP, Underground Subcommittee) then designed a collaborative research program which included several complimentary and concurrent research initiatives (Hanes, 1993b). The program will be conducted over a three year period from January, 1994. Total funds of $1,500,000 to $2,000,000 are envisaged during the period. Other research agencies such as the Cooperative Research Centre for Mining Technology and Equipment (CMTE) and ACIRL are collaborating in the overall program. The author is being funded by ACARP in 1994 to coordinate the various research projects.

JOHN HANES

DRILL OPERATOR/SUPERVISOR SURVEY

The Survey

Queensland and NSW operators and/or supervisors were surveyed regarding their in-seam drilling problems and the research they believed necessary.

The general fields of drilling covered by the survey were:

a) Long Hole Exploration
b) Across-panel Drainage
c) Face Probe / Drainage

The operators and supervisors assigned the highest priority need to economically and efficiently locating the drill bit with respect to roof and floor and in the XY plane. The other problems were assigned lower priorities.

Drill Bit Location in XY Plane (plus inclination)

Two general systems are currently available or are imminent in Australia to locate the bit in the XY plane and to provide bit inclination. These are the single shot survey camera and the measure-while-drilling (MWD) survey tool.

The single shot tool is a pump-down unit which exposes a photographic disk with information on the quadrant bearing, dip and tool face (attitude of the drill string at the point of the camera). The process of pumping the camera down the hole and then retrieving it is time consuming. The tool is in use in longer down-hole motor exploration holes and some across-panel rotary production work. Its cost is relatively low.

The only operating "MWD" tool approved for use in Australian coal mines is the Dupont tool and its derivatives by AMT (Advanced Mining Technologies). This tool provides azimuth, dip and tool face with the signal sent to the collar by means of a sonic binary pulse when drilling stops at rod changes. The unit is located close behind the bit, between the down-hole motor and drilling rods. The tool appears at this stage to be limited to about 700m depth (although modifications are being designed to improve this).

The Drill Scout MWD tool, supplied by Surtron Technologies (WA) is currently undergoing testing for approval for use in coal mines. This device is an electronic MWD tool who's signal is transmitted to the collar by a continuous cable in a cassette which resides in the drill string.

For long exploration holes and gas drainage holes drilled parallel to proposed development panels, there is a need for a reliable real time, behind-the-bit monitor which can provide survey data at least at each rod change and which can transmit data from the planned depth of hole. Such a tool would obviate the current delays required to pump survey tools into the hole and to retrieve them. To achieve target depths in very long holes, the problem of in-hole friction must be overcome. The more a hole bends the greater the friction. Better survey control through more frequent surveys will help achieve this goal. The current AMT tool partly meets this need. The Drill Scout and the newer AMT tool promise to meet the need when approved and tested and therefore, no allowance was made for research for long hole survey tools in the 1994 ACARP round.

Gas drainage holes are seldom surveyed and their trajectories are estimated based on experience. This practice can fail to danger. The short (50m to 200m) face structure holes are generally drilled with small drill rigs such as the Proram. These drills with their current down-hole configuration are notorious for producing curved holes, some of which have been reportedly shown to turn through 90° within 100m. This can produce useless and dangerous information, especially when used for locating outburst structures.

There is a need for surveying of rotary-drilled across-panel gas drainage holes. Available MWD tools are not suitable for this purpose. The main and minimum need is to know where the holes end.

With the routinely used AW rods for small diameter face holes, it is not possible to use available survey tools during drilling due to the restricted internal diameter especially through rod connectors. Two pump-in tools are available for oil or mineral drilling which can be used on the rods for multishot surveying after drilling is completed. Eastman produce a multishot photographic survey tool and Surtron Technologies distribute the CHAMP electronic multishot (magnetic) system. Neither of these tools is currently fully approved for use in coal mines.

The minimum need is to know the location of the ends of holes. A means of accurately locating the bit at least at completion of drilling is required. ACARP is funding a trial of in-seam seismic technology for bit location in 1994 (Table 1). A demonstration program to trial various survey tools for improvement of hole straightness is being proposed under syndicated research by AMIRA for 1994.

Proximity of bit to roof and floor

Currently, long exploration holes intentionally intersect roof and/or floor at set intervals (often 50m) to ascertain spot levels. This requires a pullback of rods for 6m to 12m after intersecting stone, branching and continuation of drillling. The procedure is time-consuming.

A real-time stone proximity sensor is required at the bit to allow the operator knowledge of where in the seam the bit is located. With this knowledge, he can maintain a straighter hole in the vertical plane (thus reducing bends and friction), maintain the hole in the desired drilling horizon and obtain vital level data without time-consuming deviations.

Natural gamma sensors have been used in Britain (Singleton, 1991) for sensing proximity to roof and/or floor with mixed success. The sensitivity of the natural gamma crystal limits the usefulness of the tool if it is beyond about 0.2m from the stone (Hatherley, P. pers. comm.). AMT is currently developing a roof/floor profiler based on multi-frequency sonic pulsing. The CMTE is considering the use of radar to track the bit relative to roof and floor and microdensity for tracking coal seam ash or roof profile relative to the bit.

Drilling Through Unstable Ground

Long holes drilled for exploration and drainage often encounter unstable zones which are typically associated with geological structures. These zones tend to erode or swell into the hole. Some are accompanied by high gas flows which exacerbate the instability of the hole. Depending on the type of drilling and the size etc of the equipment, the drill can either bog and fail to penetrate the zone or it can pass through the zone which continues to erode behind the bit. Drilling beyond a zone of instability places the expensive downhole motor and survey tool at great risk and the representivity of any cuttings returned is negated. When a hole with an unstable zone is completed, the zone can cave and prevent drainage beyond the zone.

One ACARP project being supervised by Dr Ripu Lama of KCC, "Assessment of Techniques for Maintaining Integrity of Drill Holes For Gas Drainage" will provide an update of suitable methods for achieving this goal (Table 1). A second ACARP project planned to commence in March 1994 is the development of a system for pressurising holes during drilling to maintain hole stability and to provide a suitable environment for use of in-hole logging during drilling.

Recirculation of Drilling Fluids

High capacity downhole motors can use in excess of 300 to 400 litres per minute of water. There is an increasing need to use muds to maintain stability when drilling structurally disturbed ground and to reduce friction in long holes. The use of drilling mud as a drilling medium will necessitate the recirculation of the fluid. The major problem facing recirculation is adequate removal of drill cuttings (fines) from the fluid. The inclusion of fine coal and stone particles in drilling fluid soon destroys downhole motors and clogs drill bits. Research into and development of recirculation technology is an integral part of the longer term development of technology for very long hole drilling.

Detection of Structures

Short holes and many rotary gas drainage holes usually detect structural disturbances by bogging of the bit and failure to penetrate. Smaller structures are sometimes detected by changes in drilling conditions. The introduction of high torque down hole motors has improved penetration of smaller structures and obliterated signs of the structures. Detection of structures currently relies on the diligence and attentive observation of the drill operator.

A system of detection of structures in drill holes is required. The seam roof/floor proximity measuring devices which will be researched shortly will assist to detect small faults of less than a seam thickness displacement, but even smaller structures such as shear zones, which can serve as loci for outbursts, require a more sensitive detector.

The caliper tool being developed by ACIRL, and supported by ACARP, (Table 1) offers promise of a short term solution. It is designed to be run in a hole on the end of drill rods after completion of drilling and withdrawn while recording the diameter of the hole. It has the drawback of adding another run of the rods into the hole after drilling. It should be possible to develop this type of tool so it can be incorporated into the drill stem and activated during the routine withdrawal of the rods.

The geophysical logging sonde (sonic) developed by Queensland University can be inserted into a hole on the rods after drilling to record the sonic (strength) properties of the surrounding coal during withdrawal of the rods. The prototype tool is large, cumbersome and expensive and has yet to be proven, however the turbine power supply and data communication system form a solid platform for further development by the CMTE who are considering applications of radar, seismic or radiometric methods.

A device which monitors changes in drilling parameters associated with structural changes in the seam and relays the significance of the changes to the driller and automatically records these changes for geological interpretation is required. There is uncertainty as to whether recording of parameters at the drill rig will be sufficient or whether monitoring of parameters at the drill bit will be required. Trials of BHP's automatically monitored Proram drill to record basic drilling data followed by refinement of the monitor and interpretation of its data are being funded by ACARP in 1994.

Development of sensors for bit torque, load and RPM as part of longer term research into monitoring behind the bit or motor is being funded by ACARP in 1994 (Table 1). It is expected that sensing these parameters close to the bit will enable better recognition of structures during drilling.

To compliment in-hole detection of structures, especially outburst-prone structures, a research project to define/develop equipment and technology to log return drill fluid for its contained gases is being funded by ACARP in 1994 (Table 1).

Drilling Longer Holes

In 1993, ACARP funded a one year project titled "Optimisation of Long Hole Drilling Equipment" conducted by Dr Ian Gray of SIMTARS. The aim of this project was to identify the technology necessary to enable an increase in the range of long hole in-seam drilling from the present 600 to 1000m, up to 2000m. It involved an examination and analysis of existing in-seam drilling records to determine the current physical limitations on drilling. Sensitivity studies to changes in drilling practice and equipment were undertaken. Having identified the limitations on drilling, the project sought to locate suitable equipment to overcome these or specify research needs. The work is due for completion by March 1994.

Current Research

Table 1 lists research approved in the 1993 and 1994 ACARP funding rounds as well as research and development and trials covered by other funding or proposed for co-operative research. The listed projects represent the start of an integrated research program to commence to address the problems of the industry. The program will be modified to adopt new findings as it progresses.

Drilling Technology Transfer

Drill operators are forced by production constraints to optimise the equipment and techniques they are familiar with and find it difficult to include experimentation in production drilling. There is an agreed need for testing new drill bits, downhole motors, drilling methods, etc, as well as trials of various techniques for overcoming general drilling problems and communication of results and recommendations to the industry as a whole. There is also some need for replacement of current folklaw in drilling with manuals and response curves etc to standardise methods

IN-SEAM DRILLING RESEARCH

TABLE 1
CURRENT RESEARCH PROJECTS

TITLE	PERIOD	ORGANISATION
ACARP 1993		
.1 Maintaining Integrity of Gas Drainage Drill Holes	12 mths	KCC/BHP
.2 Optimisation of Long Hole Drilling Equipment	12 mths	SIMTARS
ACARP 1994		
.1 In-seam drill monitoring and bit location (Stage 1)	12 mths	BHP Research
.2 Equipment and technology research for an underground drilling fluid logging system	6 mths	Lunagas
.3 Caliper probe for in-seam boreholes	12 mths	ACIRL
.4 Borehole pressurisation system	14 mths	AGA
.5 Bit torque, load and RPM sensors	9 mths	AGA
.7 Co-ordination of in-seam drilling research	24 mths	J. Hanes
.8 Supplimentary: Specification preparation for common electrical and mechanical elements for implementation of in-hole data acquisition equipment	3 mths	AGA
OTHER		
.1 Drill Position Sensing	3 yrs	CMTE
.2 Water Jet Drilling	3 yrs	CMTE
.3 Survey Techniues Trials	12 mths	AMIRA

and to improve training response. AMIRA cooperative research programs to support trials of drilling techniques for improvement of drill trajectory are proposed.

The author has instigated regular workshops to bring together the drill supervisors/operators, researchers and suppliers to the industry to further improve technology transfer.

CONCLUSIONS

The Coal Industry currently has need of research to help solve shorter term and longer term problems of in-seam drilling.

The shorter term needs are for:

a) Inexpensive and reliable survey data with minimal delays for data aquisition,
b) A roof/floor proximity sensor
c) Accurate recognition of geological hazards preferably while drilling, or secondly by reliable hole logging after drilling,
d) Methods for maintaining holes in unstable ground
e) Drilling fluid recycling

Longer term needs are for:

a) Improved methods for reducing friction in bores to increase length to 2000m,

b) Behind the bit monitoring of drilling parameters,
c) Automated control and monitoring of drilling to enhance data collection and reduce danger to personnel and equipment, and
d) Intelligent real time computer interpretation and reaction to data from the hole.

To address these needs, the projects listed in Table 1 are current or planned through integrated research, practical testing and demonstrations funded and/or supported by ACARP, other research agencies, operators and some suppliers.

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THE CENOZOIC EVOLUTION OF THE CENTRAL NSW CONTINENTAL MARGIN

G.F. BIRCH
Dept. of Geology & Geophysics, The University of Sydney

High resolution (~8 m), moderate penetration (150 m maximum) airgun (110 cubic inch) seismics obtained on the R/V Rig Seismic Cruise 112 provide a record of the mainly Tertiary section in the detail not previously observed (Fig. 1). Resolution is sufficient to differentiate discrete sedimentary packages, and the penetration allows a complete Tertiary section to be seen. Variable, but typically minor penetration of the underlying Sydney Basin strata was achieved. In isolated regions of the inner shelf the sediment was sufficiently thick (>15 m) to allow resolution of the Quaternary sedimentary sequence. While low seismic coverage provides limited opportunity for detailed interpretation and mapping, the high quality of these data allows general interpretations that will provide the foundation for planning future seismic surveys.

Basement (Permo-Triassic) structure, coincident with the S_2 reflector of Davies (1975, 1979), is well depicted on all transects. Mapping of this surface has been supplemented by high density commercial data. The horizon dips gently seawards on the inner part of the shelf in most areas, but on the mid and outer shelf it is highly irregular due to large rotated fault blocks dissecting this surface. On the inner shelf internal strata dip irregularly landward coincident with the known onland structure of the Sydney Basin. In the northern part of the survey area the central shelf section is acoustically transparent. This transparent zone may be related to intrusives postulated from onland and offshore magnetic data for this area (BMR aeromagnetic data). No age has been established for the S_1 reflector, but it is assumed to represent the onset of the rift/drift tectonic phase on the east coast, i.e. approximately 83 Ma.

A second, prominent reflector, coincident with the S_1 reflector of Davies (1975, 1979) is also evident. This horizon truncates numerous underlying reflectors, and overlying strata very commonly downlap on to it. The position of the shelf break on the S_1 horizon varies from landward to seaward of the present shelf break. This lateral variation indicates a variable supply of sediment along the margin with time. In all transects the surface is smooth and dips gently and uniformly seaward. The age of this reflector has been tentatively correlated with the early to middle Pliocene of the Gippsland Basin by Davies (1979), but it may be older and may relate to the late Miocene/early Pliocene unconformity of the Gippsland Basin (Rahmanian et al., In press).

A third prominent reflector is observed on all lines in the inner shelf area above the moderately dipping Tertiary strata. Indentifying this reflector is sometimes difficult, due to it being lost in the bubble pulse.

The basement-S_2 sedimentary package comprises at least four sequences. The early units exhibit shallow-dipping conformable strata, whereas the middle and late units show either contorted reflectors, or markedly more steeply dipping strata. The thickness of the total package varies markedly due to the irregular basement and the very steep palaeoshelf break.

The S_1-Quaternary sedimentary package exhibits marked variability in internal stratal geometry and comprises two or more sequences whereas in other areas sequences are difficult to separate and a discrete uniformly prograding package is evident. The thickness and lateral extent of this interval also varies geographically with maximum sediment volume occurring adjacent to the Hunter River mouth.

A thin veneer of ?Quaternary sediment is evident on the mid and outer shelf on some transects. Where this presumably ?Pleistocene unit is thick enough to be observable, it is seen to be strongly progradational, especially toward the outer shelf. Complex stratal patterns are evident on the shelf break, indicating that the package probably comprises several discrete units. A nearshore ?Holocene sediment wedge is evident on the majority of transects. This unit exhibits either strongly positive bathymetry with sharp, steep seaward profiles characteristic of shelf sand bodies (Field and Roy, 1984; Roy, 1984; Ferland, 1990), or form a concave inner shelf wedge.

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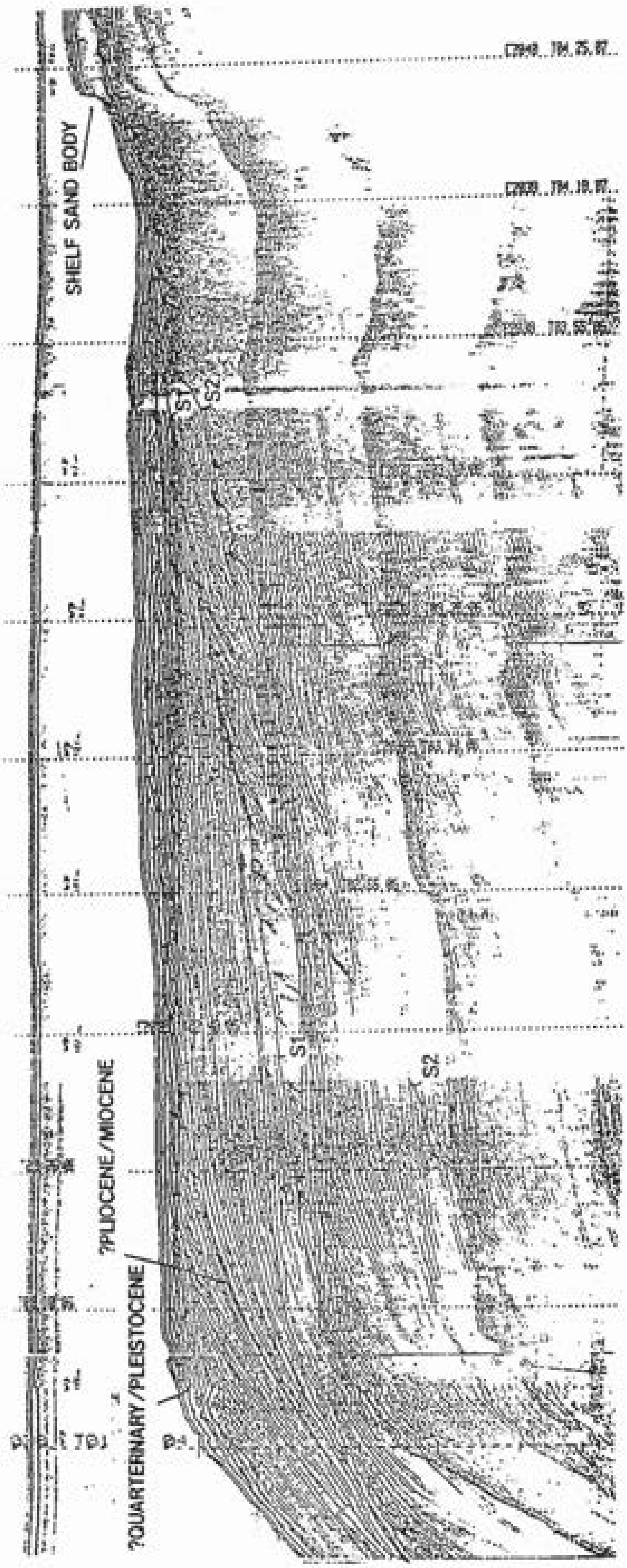

Fig. 1 Record of air gun line showing the Tertiary sediment wedge.

QUATERNARY GEOLOGY OF THE LOWER HUNTER VALLEY

P. ROY[1] & R.L. BOYD[2]
[1] **Geological Survey of NSW, Dept of Mineral Resources**
[2] **Dept. of Geology, The University of Newcastle**

INTRODUCTION

The current interest in the field of estuarine and coastal sediment research stems from the finding that many petroleum reservoirs, previously thought to be fluvial or marine in nature are actually estuarine and located in incised valleys. A second source of interest derives from the location of many major population centres on estuaries world-wide (e.g., London, New York, Bangkok, Shanghai, Newcastle) and the resulting urban development, pollution and siltation problems. Sedimentation models derived from modern examples of Quaternary age such as the Hunter will thus enable us to accurately predict the distribution of reservoir rocks in ancient petroleum plays and also the geotechnical soil properties of various coastal, estuarine and deltaic environments needed for planning engineering and development works. In addition, studies of the lower Hunter Valley sediments will provide a valuable geological framework for addressing local environmental and resource problems. For example, flood mitigation strategies are presently being reviewed in the area below Maitland. Here the nature of the flood plain has been strongly influenced by the evolution of the proto-Hunter estuary in the last 10,000 years and many of the flooding, bridge building and agricultural problems in the area have specific geological causes. In this paper we provide a synthesis of previous drilling in the lower Hunter valley, and the results of recent air photo interpretations and six new cored drill holes acquired in 1993.

METHODS

This investigation is based on air photo interpretations, previous work and drilling conducted in this study. Figure 1 is a map showing the location of the lower Hunter valley and of drilling sites and stratigraphic cross sections mentioned in the text. Detailed maps of the deltaic - floodplain and the bedrock contact with the alluvial fill have been compiled from 1955 floods and 1971 flood mitigation air photographs at a scale of 1:25,000 (Fig. 2).

Deep drilling data are very detailed in some areas, especially at bridge sites and in Newcastle Harbour, but they are sparse or non-existent elsewhere and their relationship to the axis of the paleo-valley is generally unknown. Shallow drilling, mainly water bores, are more widespread but even with these, extrapolation between drilling sites is uncertain. In 1993, a program of shallow drilling and vibrocoring was carried out in the banks and channel of the Hunter, Williams and Paterson Rivers as part of a levee bank restoration project (Public Works, 1993). Detailed analyses by the PWD Geotechnical Engineering Group of the subsurface sediments (together with data from Roy, 1980) provides specific lithological information on recent estuarine and flood plain deposits in the delta region.

Published sources of information include early reports on the geology of the lower Hunter by David and Etheridge (1890) and David and Guthrie (1904). The area near the present coast is described by Thom et al. (1992), and Roy (1980). An unpublished 1972 report by the Public Works Dept. titled "Hunter Valley Flood Mitigation, Hexham Swamp Environmental Impact Report" contains data on the areas' geomorphology, soils, climate, flooding regime and development.

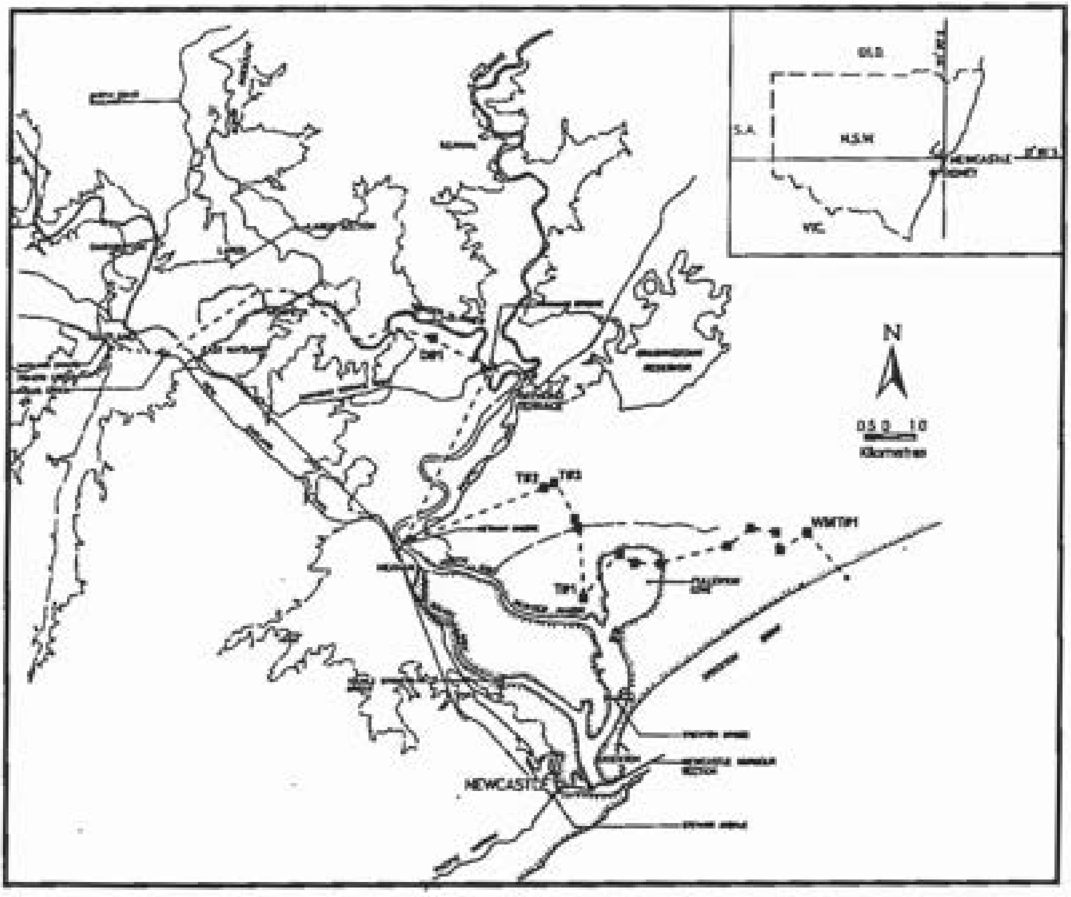

Figure 1. Location of the Lower Hunter Valley and the cross section of Figure 3. Cross section constructed from data in Roy 1980, bridge borings courtesy of the RTA (Maitland, Fishery Creek, Wallis Creek, Irrawang, Hexham) and 1991-3 drilling data (D#1, T#1-3, WMT#1).

QUATERNARY GEOLOGY OF THE LOWER HUNTER VALLEY

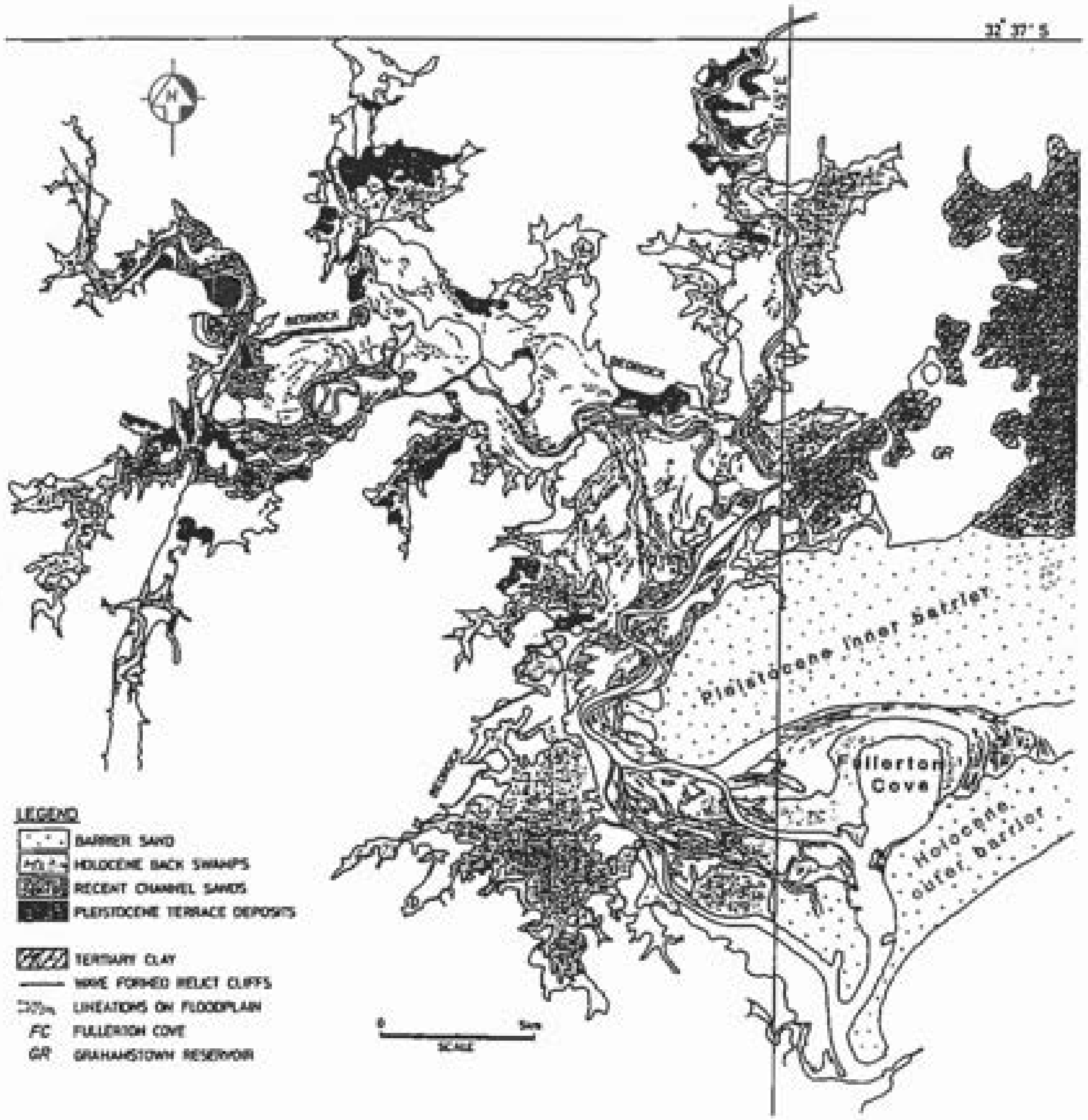

Figure 2. Quaternary depositional environments of the lower Hunter Valley including floodplains, backswamps, coastal barriers and various high level terrace deposits. Contacts between bedrock and the various sediment units, and the lineations shown on the floodplain are based on interpretation of 1:25000 scale air photography flown in 1972.

RECENT DRILLING RESULTS

During 1991-3, drilling in a joint project between the University of Newcastle and the Geological Survey of NSW completed 5 boreholes in the Williamtown, Fullerton Cove, Tomago and Duckenfield areas (Fig. 1). Data from these boreholes represent the first opportunity to document the Quaternary lithofacies of the lower Hunter valley by continuous coring to bedrock. Results from the five boreholes can be summarised as follows:

1) Williamtown DMR-WMT DH#1 encountered 87 m of Quaternary sediments consisting of 10 m of Holocene Outer Barrier sand overlying 18 m of Pleistocene Inner Barrier sand and in turn overlying 39 m of alternating Pleistocene estuarine clays and fluvial sands/gravels.
2) Tomago NU/DMR DH#1 found 38.7 m of Quaternary sediments including 11.5 m of Holocene estuarine mud, 10m of Pleistocene Inner Barrier sand, 10 m of Pleistocene estuarine mud, and 7.2 m of Pleistocene fluvial sand and gravel above Tomago Coal Measures bedrock.
3) Tomago NU/DMR DH#2 consisted entirely of 21m of Pleistocene Inner Barrier sand.
4) Tomago NU/DMR DH#3 nearby also consisted of 20 m of Pleistocene Inner Barrier sand followed by 11.5 m of Pleistocene estuarine clay above Permian bedrock.
5) Duckenfield NU/DMR#4 encountered 7 m of Holocene fluvial sand and mud overlying 23 m of Holocene estuarine mud, and 18 m of Holocene or Pleistocene sand above Permian sandstone.

SEDIMENTATION IN THE LOWER HUNTER VALLEY

Results from the 1993 drilling program together with a synthesis of previous drilling results can be summarised in a generalised cross section of lithofacies distribution down the axis of the valley (Figure 3). Although there is considerable doubt about the geometry of the bedrock valley, this cross section suggests that the Holocene deposits make up less than half of the valley fill. The older sediments are assumed to be of Pleistocene age but they may include some late Tertiary material in the deeper parts of the bedrock valley. Holocene sediment units near the coast are mainly marine dominated sands; those further inland are fluvio-estuarine in origin. The oldest lithofacies are fluvial sands and gravels deposited in the axis of the paleo-channel that formed when sea levels were lower than today. The upper part of the basal fluvial sand unit contains estuarine shell fragments; it is transgressive in nature and was deposited in back-stepping deltas as the valley was being drowned between 12 ka and 10 ka ago.

Marine sands that were accumulating in the valley mouth during the postglacial marine transgression (PMT) include transgressive barrier sands and tidal inlet/flood-tide delta deposits. The latter prograded into the estuary mouth under the influence of strong tidal currents at the end of the PMT and immediately afterwards. They onlap estuarine muds which were laid down somewhat earlier but continued to

QUATERNARY GEOLOGY OF THE LOWER HUNTER VALLEY

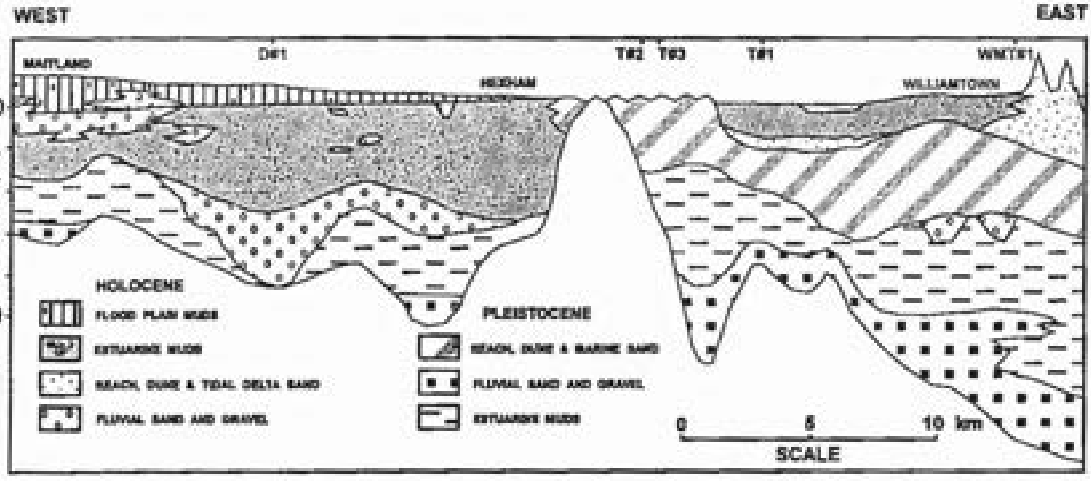

Figure 3. Stratigraphic cross section down the axis of the Hunter Valley showing Quaternary valley fill from Maitland to Williamtown.

accumulate upstream of the tidal delta throughout the stillstand. The muds contain abundant estuarine shell species in the lower delta but are less shelly and more organic rich in its upper part. This reflects the salinity gradient that must have existed in an estuary with large fresh water inflows. The muds are typically soft and only partly compacted; in the lower estuary they reach thicknesses of 30 m but thin to less than 20 m near Maitland. During the early part of the stillstand, deposition of river sands was confined to the headwaters of the estuary up-stream of Maitland in the Hunter and at comparable positions in the Paterson and Williams Rivers. As the estuary filled in with mud and its bed shallowed, the sandy deltas prograded downstream as jetted levees with marginal swamps and overbank (floodplain) deposits. In the present deltaic floodplain, coarse sands and gravels mark the courses of prograded channels but elsewhere fine grained overbank deposits lie directly on estuarine muds with the contact at about mean sea level (Fig. 3).

With increasing maturity the deltaic-floodplain deposits progressively filled in the estuary and its surface slowly elevated above tide level. At present the delta front is mid-way down Kooragang Island; Fullerton Cove represents the last remnant of the former Hunter Estuary - a 95% reduction in its size in 6000 years. Fullerton Cove (and Tilligerry Creek) occupy an interbarrier depression between the inner and outer barriers. Under natural conditions the delta surface is subject to flooding and to slow upwards accretion with flood-borne detritus. The levees and adjacent floodplains have built-up most rapidly with sandy silt and mud; the back swamps accumulated mainly organic detritus and thus accreted more slowly. However, vertical accretion to the delta surface has been retarded by the tendency for the underlying mud basin deposits to compact and dewater. This effect presumably exacerbates flooding in the area down-stream of Maitland where the muds are thickest (Fig. 3).

The subtle lineations mapped from the air photos and shown in Figure 2 appear to show past channel positions as the floodplain evolved. Recent channel variability (based on Nittim 1966) indicates that, since 1870, the river between Maitland and Hexham has experienced a reduction in channel length of 44% (from 16.7 to 9.4 km) and a reduction in sinuosity from P=3.84 to P=1.38.

CONCLUSIONS

Existing drilling data in the lower Hunter Valley indicate multiple phases of valley infilling: deposition during sea level highstands and erosion at times of lower sea level. Holocene and Last Interglacial aged sediments have been radiometrically dated but the ages of the underlying deposits are not known. Clay and sand layers that occur below 59 m in the cored drill hole near Williamtown are an unusual greenish colour and may be of Tertiary age. According to Ringis (1972) the thalweg of the proto Hunter valley, extrapolated seawards to the outer continental shelf, lies at 164-169 m below present sea level. This approximately coincides with the inner edge of the S 1 seismic reflector (Davies 1979) which, according to Roy and Thom (1991), represents a regional erosional event in the late Tertiary.

The pattern of valley sedimentation associated with glacial/interglacial changes in sea level comprises two main phases: (1) A phase of erosion and subaerial weathering while sea level is falling. (2) A phase of deposition associated with rising sea level and interglacial highstands of the sea. The initial deposits are landward transgressing barriers and tidal delta washover complexes composed of marine sand in the mouth of the drowned valley and back stepping bay head deltas composed of fluvial sand. Sea level stillstands are characterised by barrier progradation and mud basin sedimentation in the drowned valleys. Eventually however, estuarine environments of deposition are superceded by flood plain alluvium at which time fluvial channel sands may be delivered directly to the coast thus augmenting barrier progradation. The estuary mouth sands - potential petroleum reservoirs - constitute around 10% of the valley fill and are often contiguous with large prograding barrier complexes. How many times in the past this cycle of deposition and erosion has been repeated remains to be determined by further detailed studies of cored drill hole samples.

Geotechnical investigations in the lower Hunter sediments show that their wide range of structural properties are broadly tied to lithofacies types and thus reflect the distribution of Holocene environments of deposition. Over large areas, the present day flood plain is underlain by soft estuarine muds that are probably continuing to slowly compact. In contrast, the sandy channel deposits that intersect the former estuary represent more stable areas for development. The severity of flooding in the lower Hunter valley can also be largely attributed to the geological development of the delta area. The region between Maitland and Newcastle coincides with a former estuary that existed for a substantial part of the last 9 ka or so. The extremely low gradient of the area between Maitland and Hexham arose through the infilling of the estuary with fine estuarine muds which ultimately produced a horizontal surface. The gradient on the present floodplain reflects varying thickness of flood plain deposits on top of the estuarine muds - thicker at Maitland than at

Hexham. An additional factor in causing low gradients in this area is the continuing compaction of the thick estuarine mud sequence in the subsurface. This causes slow subsidence which undoubtedly exacerbates flooding. The nature of the valley fill is determined by relative rates of sea level change and sedimentation. Where sea level changes exceed sedimentation, estuarine valley fills predominate. Where the reverse is true, deltaic and/or fluvial valley fills occur.

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A REVIEW OF THE TITANIUM & ZIRCONIUM DEPOSITS & THEIR GEOMORPHOLOGY IN THE HUNTER REGION

STANLER WOLLEN
RZM Pty Ltd, Tomago

ABSTRACT NOT RECEIVED AT THE TIME OF PRINTING

PRELIMINARY INVESTIGATION OF THE QUATERNARY SEISMIC STRATIGRAPHY, HUNTER VALLEY CONTINENTAL SHELF

R.L. BOYD
Dept. of Geology, The University of Newcastle

The Hunter Valley continental shelf is part of the Mesozoic-Cainozoic rifted central NSW continental margin and lies offshore from Newcastle. The pre-rift basement consists of Permian-Carboniferous rocks overlain by a Cretaceous to Recent post-rift wedge. The Hunter Valley lies along a major structural boundary between the New England fold belt and the Sydney Basin. The Hunter River has followed this structural trend and incised a deep valley which continues seaward across the shelf in the subsurface. Tertiary and Quaternary changes in relative sea level have translated the sediment depocentre from Maitland seaward almost 100 km to the shelf break and back.

In August 1993 800 km of reflection seismic data were collected off Newcastle from the trawler "Feamot" using an EG&G marine sparker system, a multitip spark array and a single channel, nine element streamer. Data quality was high, regularly penetrating through the upper Permian bedrock on the inner shelf. The objectives of this cruise were to locate the incised Hunter River valley offshore, establish a Tertiary-Quaternary seismic stratigraphy for the region and to correlate the offshore seismic data with the onshore borehole data set from the lower Hunter region.

Seismic results indicate that the incised valley of the Hunter River continues seaward to the mid shelf region but not across the outer shelf. The valley continues along the trend of the Permian-Carboniferous boundary which occurs approximately half way along Stockton Bight. Permian bedrock outcrops on the shelf seaward of Newcastle to the mid shelf and Carboniferous bedrock outcrops seaward of Port Stephens. The post rift sediment wedge consists primarily of several large prograding ?Tertiary delta systems (Fig. 1) which continue almost to the current shelf break. The carbonate-covered surficial units of the outer shelf are largely aggradational and occasionally occur as mounded seismic facies. Few channels cross the outer shelf indicating that recent sea level lowstands may not have reached the shelf break. Slope canyons begin around the 200 m isobath and the shelf break is commonly in water depths below 150 m. In the valley the inner shelf exhibits a Quaternary wedge out to a water depth of around 100 m. Within the wedge is a complex succession consisting of barrier sediments, chaotic seismic facies interpreted as lowstand braided stream deposits and more massive facies interpreted as highstand estuarine muds.

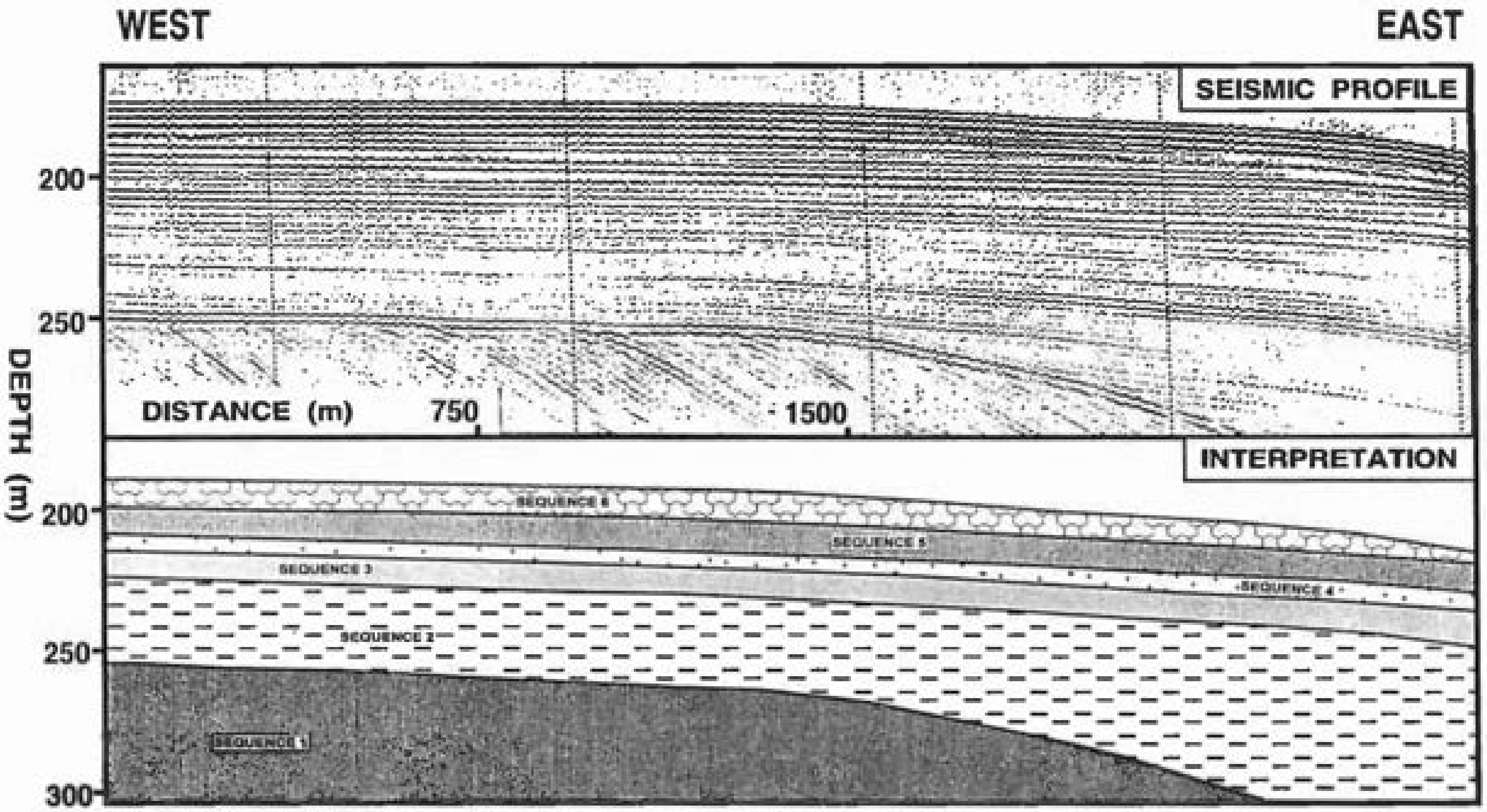

Figure 1. Sparker seismic section on the outer continental shelf seaward of Newcastle Sequence 1 is interpreted as a prograding Tertiary shelf delta to shelf margin delta Sequence 6 is interpreted as aggradational Quaternary carbonates Sequences 2-5 are interpreted as a succession of offlapping and onlapping outer shelf marine units of Tertiary to Quaternary age recording a history of fluctuating Cainozoic sea levels across the outer shelf

LOWSTAND SEDIMENTATION ON THE CENTRAL NSW OUTER SHELF : DESCRIPTION & IMPLICATIONS

M.A. FERLAND[1] & P.S. ROY[2]
[1] **Dept. of Geography, The University of Sydney**
[2] **NSW Dept. of Mineral Resources**

ABSTRACT

Vibrocores collected in 1992 from the mid and outer continental shelf of central NSW contain the first subsurface sediments from this region and record sedimentation during several previous glacial lowstands. The outer shelf sedimentary sequence is dominated by skeletal carbonate sand and cool-water bivalves; the minor terrigenous clastic component (< 20%) is fine-grained, except for occasional well-rounded and heavily iron-stained, coarse to granule-sized quartz grains. The age and composition of the sediment has important implications for the Tertiary outer shelf sedimentary wedge and the relative contribution of sediment from the Sydney Basin.

INTRODUCTION

Our knowledge of Quaternary sedimentation on the outer continental shelf of central New South Wales (NSW) has been constrained by a lack of subsurface data. Early surface sampling surveys of the shelf (e.g., Shirley 1964; Davies 1979) provided evidence of three shore parallel zones divided approximately by depth, each with different sedimentary characteristics: (1) the inner shelf (< 60 m) is comprised primarily of quartzose sand, (2) the mid-shelf (60-120 m) is generally mixed quartz-carbonate muddy, fine sand, and (3) the outer shelf (120-150 m) is dominated by calcareous sediment, much of which appears to be relict. Implications of this tripartite division are discussed by the aforementioned workers, as well as Roy and Thom (1981, 1991), Ferland and Roy (1993), Roy and Keene (1993) and Bickford *et al.* (1993).

Seismic data show that the mid to outer shelf is comprised of a seaward-thickening sediment wedge. It has only been intersected in one drill hole which encountered 420 m of mixed quartz and carbonate shelf sand of Neogene age (see Roy & Thom 1991). Seismic resolution is poor for the upper 10-20 m, which probably represents the Quaternary section and, as a result, little was known about sedimentation during periods of lower sea level.

In 1992, the Australian Geological Survey Organisation (AGSO) conducted a marine survey on the continental margin adjacent to the Sydney Basin. A major objective of Cruise 112 (*RV Rig Seismic*) was to collect vibrocores on the mid to outer shelf between Seal Rocks and Shoalhaven Bight (32.5 to 34.8°S). Previous vibrocoring had been confined primarily to the inner shelf adjacent to Sydney and Newcastle Bight. The extremely successful cruise produced fifty-eight vibrocores, collected in water depths of 30 to 167 m along 9 shelf-normal transects (Fig. 1). Approximately half of the cores were collected from the outer shelf, and they are the focus of this paper. Our aims are to describe the sedimentary sequence, especially that of the outer shelf, and to interpret the depositional environments that have been

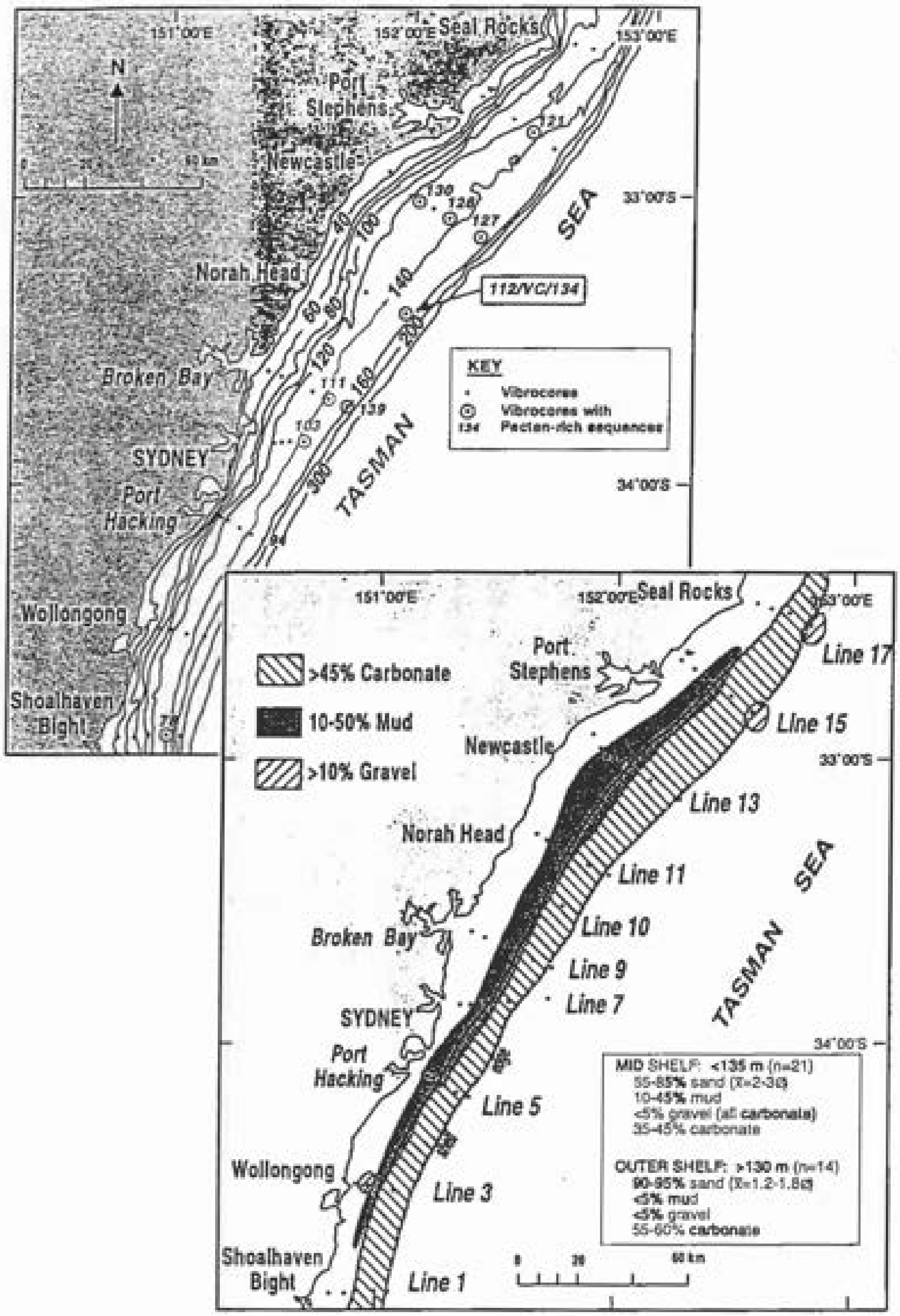

Figure 1. Map of the study area showing (a) shelf bathymetry and vibrocore sites (see text for discussion of Pecten-rich sequences), and (b) the distribution of surface sediment types on the mid and outer shelf.

preserved. These include both highstand and lowstand deposits. We will then discuss these data in terms of their implications for Quaternary sediment budgets and long-term contributions of sediment from the eastern Australian continent, and specifically from the Sydney Basin.

METHODS

Sampling sites were selected prior to the cruise, and then refined as results from previous sites were interpreted. A grab sampler was deployed at each site to determine whether the seabed was suitable for coring; the vibrocorer was deployed at 43 of the 57 sample sites. Six metre long vibrocores were collected in aluminium barrels with an electric vibrocorer, suspended from an A-frame. The ship's dynamic positioning capability permitted coring even during adverse weather conditions. The 75 mm diameter core barrels were fitted with core catchers which greatly reduced the loss of sediment from the barrel. Once retrieved, the cores were immediately examined to determine the depth to which they had penetrated into the seabed. This was later compared with the length of recovered core. A number of the outer shelf cores were slightly compacted by the coring process (c. 15-25% of total length of the core); a major reason for the compaction was the poor sorting and the unconsolidated nature of the sediment. Examination of the core bits, for evidence of abrasion or 'hammering', provided information about why penetration may have ceased. In some cases, gravel or cemented clasts (up to 7 cm diameter) were caught in the core-catcher.

All cores were split, opened and logged on the ship and then refridgerated; one half of each core has been archived with AGSO. Preliminary results are reported in Bickford *et al.* (1993) and Ferland and Roy (1993). Detailed analysis of the vibrocores is in progress and includes photography, logging, resin-peeling and sampling for grain size analysis (at intervals of 30-40 cm) and macrofaunal analysis. Samples have also been collected for dating (conventional radiocarbon, accelerator mass spectrometry, amino acid racemisation). Preliminary results using two of these dating techniques are presented in Murray-Wallace *et al.* (1994) in this volume.

RESULTS

Generalisations about the textural and compositional characteristics of the various shelf sedimentary facies described below result from the preliminary descriptions of all 58 cores, and more detailed logs of eleven vibrocores mainly from the outer shelf, which have been analysed subsequently.

The three shore-parallel sedimentary zones originally identified on the basis of surficial sampling by previous workers, were also identified using grab samples collected during this study. Figure 2a shows the proportion of carbonate in the grab samples, as determined by acid digestion, plotted against water depth. There is a trend of increasing carbonate with increasing water depth. More significantly, this relationship between water depth and the proportion of carbonate was apparent in the vibrocores (Fig. 2b), which record sedimentation down to a depth of 3-5 m below the seabed. Although there is some variability, inner shelf cores generally contain <20 % carbonate, while outer shelf cores contain >50 % on average. Cores collected on the inner shelf prior to this study (Kudrass 1982; Roy 1984) show a similar tendency toward low proportions of carbonate. While relatively few mid-shelf cores from this study have been analysed in detail, there appears to be a wider range of carbonate values depending on the number and type of paleoenvironments encountered in the cores. The trend of increasing carbonate with increasing water depth would be even stronger for the outer shelf, except that some of the calcareous foraminifera tests have been replaced by iron (glauconite?), and hence are retained as acid-insolubles.

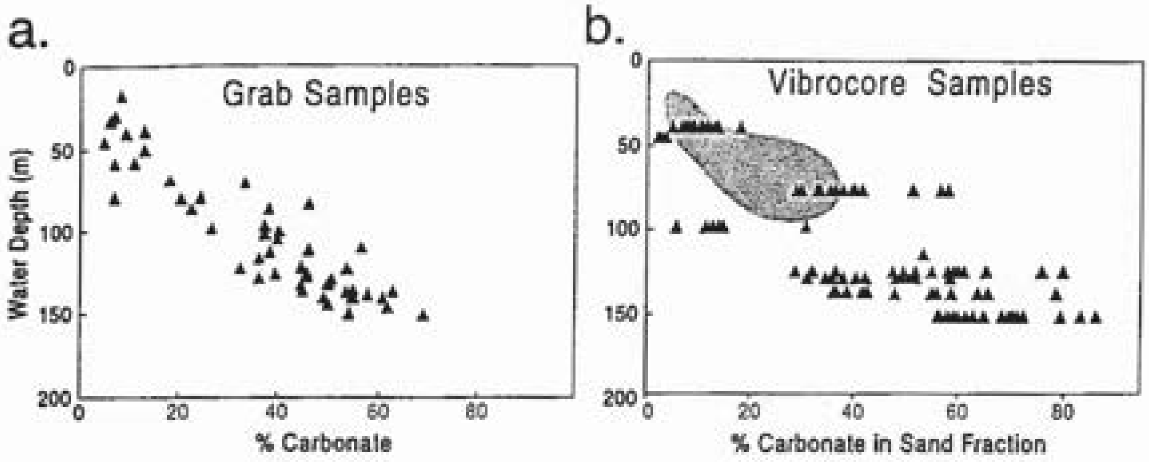

Figure 2. Plot of % carbonate *vs.* water depth for (a) grab samples and (b) for samples from 11 vibrocores, all of which were collected during Cruise 112B. Approximately 15 subsamples from each vibrocore are included in (b); where two cores were collected at the same depth, there is a wider range of carbonate values, depending on the lithofacies encountered. Data (> 100 cores) from Kudrass (1982) and Roy (1984) are included within the shaded polygon. (Note: The amount of carbonate in the vibrocores is under-represented in (b) because the large amount of shell gravel and unbroken valves contained in the cores is not included in the sand fraction.)

Inner Shelf

The inner shelf sedimentary sequence is highly variable in thickness, texture and inferred depositional environment, however it is always dominated by quartzose sand. A comparison of radiocarbon dates from previous studies (Kudrass 1982; Roy 1984) and the stratigraphy sampled in Cruise 112 cores indicates that transgressive and stillstand marine deposits (<12,000 yBP) are usually less than 2 m thick, except where shelf sand bodies occur (locally up to 30 m thick; Roy 1984). Transgressive (?) estuarine deposits were encountered beneath marine sand off Wollongong (site 3A) and Broken Bay (site 9A) within 2 m of the seafloor.

Mid Shelf

Cores collected on the mid-shelf contained very muddy, fine to very fine-grained sand, similar to the surficial sediment identified in those depths on the central NSW shelf (Fig. 1b) (Davies 1979; Roy & Thom 1981). This mixed terrigenous-carbonate sediment is at least 3-4 m thick in places and represents late transgressive to stillstand sedimentation in generally deep water, where energy levels are low enough to permit mud to accumulate. The mid-shelf muddy sand typically contains molluscan fauna such as *Mesopeplum caroli*, *Gazemeda gunii*, *Nemocardium thetidus*, and *Dentalium erectum* which are characteristic of these environmental conditions. Accumulation rates, based on radiocarbon dating here and elsewhere in NSW, are $\leq$ 25-40 cm/1000 years. Some cores from 60-75 m w.d. were characterised by less mud and higher proportions of quartzose sand, whereas other cores contained a fining upward sequence of shallower marine sediments grading into only 1-2 m of Holocene mid-shelf mud. Similarly, the thickness of mid-shelf muddy sediment in vibrocores from the boundary region between the mid and outer shelf (c. 115-125 m w.d.) decreases in a seaward direction; these cores are discussed in more detail below.

Outer Shelf

Some of the longest and least disturbed cores were obtained from the outer shelf sedimentary sequence in c. 120-150 m w.d., and provide high quality stratigraphic data. The surficial shelf sediment is characterized by skeletal carbonate sand and shell gravel (Fig. 1b), which is apparently relict, given the shallow water faunal assemblage and degree of encrustation on the surfaces of shells (Smith & Iredale 1924; Marshall & Davies 1978; this study). If the surficial sediment is relict, then much of the sediment preserved in cores from the present outer shelf was deposited during, or prior to, the last glacial sea-level lowstand, which was approximately 100-120 m below present sea level at about 20 Ka (Chappell & Shackelton 1986; Fairbanks 1989).

All of the cores from the outer shelf were characterised by predominantly calcareous sand with little mud and varying amounts and species of bivalves and gastropods. Ten cores (Fig. 1a) contained alternating sequences of two distinctly different lithologic units which occur in similar proportions through the core: (1) fine-grained skeletal carbonate sand and (2) a coarser unit comprising densely-packed bivalves in a carbonate sand matrix. The molluscan fauna indicates that the two units were deposited under different environmental conditions. The fine-grained skeletal sand is slightly muddy, moderately to poorly sorted and generally deficient in whole shells, although it does contain some bivalves, such as *Mesopeplum caroli* and *Nemocardium thetidus* that are sometimes articulated, thus indicating little or no transport after deposition. These bivalves typically live on the mid shelf today, however their enclosing sediment in outer shelf cores is more calcareous and less muddy than the modern mid-shelf muddy sediment. The coarser unit is characterised by mainly shallow water, robust bivalves including *Pecten fumatus* (dominant), *Tawera gallinula* and *Bassina jacksoni*, in a matrix of skeletal carbonate sand. These latter species typically occur today in the cooler waters of Tasmania, South Australia and Victoria and mainly in water depths of 20-50 m (based on examination of the Australian Museum collection). It is worth noting that most of the valves in both units are extremely well-preserved, unabraded and often retain their original color. This is despite their age, which we know to be at least 18,000 and in some cases > 200,000 yBP, based on radiocarbon and amino acid racemisation analyses of multiple bivalves in core 112/VC/134 (see Fig. 1, and Murray-Wallace *et al.* 1994, this volume).

The outer shelf sedimentary sequence is deficient in terrigenous clastic sediment. The residue after carbonate digestion is generally < 20% and always 0.25 *phi* finer than the total sand sample. It consists of very fine to fine-grained sand and occasional coarser quartz grains. The latter are usually heavily iron-stained, well-rounded and sometimes as large as 5 mm in diameter, although 1-3 mm is more common. Many of the skeletal carbonate fragments are also heavily iron-stained, probably as a result of multiple cycles of reworking. Marshall and Davies (1978) found that much of the carbonate on the NSW outer shelf was similarly iron-stained. While iron-stained sediment is prevalent in the cores in water depths of 130-150 m, we do not see any physical evidence for post-depositional subaerial exposure. These depths are presumably below the predicted sea levels for glacial lowstands (Chappell & Shackelton, 1986).

The rate of sediment accumulation on the outer shelf during highstands appears to be very slow, given that most cores collected there contain only c. 45-60 cm of fine-grained sand overlying the coarser sand unit dominanted by *P. fumatus* valves.

These bivalves, where dated, are of last glacial age, which indicates that there has been <1 m of post-glacial sedimentation (and much of this may be interstadial rather than highstand deposition). Winnowing by currents and/or erosion during subsequent lowstands probably contributes to the extremely slow accumulation rates. In contrast, during lowstands, the present outer shelf becomes a shallow water environment (c. 25-50 m w.d.) where thicker sedimentary sequences are more likely to be deposited, though local variations may occur. The preservation potential of lowstand deposits is directly related to storm-wave reworking and erosion during subsequent lowstands. Murray-Wallace *et al.* (1994) report a case where all evidence of the fine sediment unit deposited during an earlier highstand was apparently removed during the latest lowstand.

As indicated above (and in Fig. 2), subsurface sediment on the mid shelf is of mixed clastic and carbonate composition whereas the outer shelf is overwhelmingly dominated by carbonate. Cores from water depths of c. 115-130 m, at or just seaward of the boundary between these two regions, typically contained a thin deposit of mid-shelf mud over marine sediment with shallow marine bivalves such as *Pecten fumatus*. While the latter were not present in the same abundance as in cores from the outer shelf, their occurrence apparently indicates passage of the post-glacial marine transgression through those locations. (We await the results of radiocarbon dating of these deposits to confirm this interpretation.) In several cores from this intermediate depth zone, the Pecten valves were immediately overlying basal deposits of cemented calcareous iron-stained sand and shell gravel (calcarenite), which occurred as large (c. 7-8 cm diameter) clasts. A core east of Norah Head in 126 m w.d. (Line 11, Fig. 1) contained 35 cm of basal limestone which was grey, chalky, well-cemented and comprised of >90% carbonate. Whilst the material has not been analysed in detail, preliminary examination of the foraminifera suggests that it may be Pliocene to mid-Miocene (Patrick Quilty, pers. comm. 1993). The existence of basal units of calcarenite and old limestone provides evidence of erosional conditions in water depths of 120-130 m that may have approximated the last glacial lowstand shoreline. This is contrasted with the thicker sedimentary sequences (4-6 m) from the outer shelf in 135-150 m w.d., which contain no indication of subaerial exposure and were apparently always below sea level.

DISCUSSION AND CONCLUSIONS

Analysis of the central NSW shelf vibrocores to date provides information which contributes substantially to our understanding of late Quaternary shelf sedimentation, especially that of the mid and outer shelf. Some of the results were expected, while others were more surprising. On many shelves, the proportion of mud in sediment increases with increasing water depth due to the decreased effectiveness of waves and currents. This is not the case in NSW, where outer shelf sediment contains less than 5% mud compared with 40-50% on the mid shelf. This is due in part to the influence of the East Australian Current, which produces relatively high energy conditions on the outer shelf and thus prevents the accumulation of mud. However, the lack of mud in the lowstand pecten-rich sequences in the outer shelf cores is a direct result of their deposition in high energy, shallow shelf conditions during sea level lowstands (within wave base). We are investigating the extent to which these deposits may be comparable with the carbonate shelf sediments described by Bone and James (*e.g.*, 1993) for the southern Australian margin.

A surprising result relates to the three shelf sediment zones previously identified through surficial sampling which have been extended into the subsurface to a depth of 6 m, and back in time to span glacial as well as interstadial conditions. As a consequence, we now know that these sedimentary environments do not simply shift seaward as sea level falls - this is the assumption upon which many basin fill models are based. While there is evidence that the inner shelf quartzose sediment province does migrate some distance seaward during regressions, it does not reach the present outer shelf which is dominated by carbonate depositions during sea level lowstands (Fig. 2b). The fine grained skeletal sand identified in outer shelf cores is the interstadial equivalent of the highstand mid-shelf mud, however it contains much less terrigenous material and less mud. Probably even during interstadial (and certainly during glacial lowstands) what is today the outer shelf was characterised by moderately high-energy conditions which prevented mud deposition. It is also possible that increased aridity during glacials resulted in less terrigenous mud being supplied to the continental shelf.

There is now sedimentologic data for the outer shelf to show that both interstadials and lowstands are characterised by carbonate sedimentation, while highstands are probably essentially non-depositional. The combined evidence provided by the relict surficial carbonate deposits, the mid-late Pleistocene cyclic Pecten sequences in outer shelf cores, and older (Tertiary ?) limestone at depth on the outermost part of the mid shelf suggests that the upper portion of the thick, outer shelf sediment wedge (Davies 1979; Roy & Thom 1991) may be composed predominantly of carbonate. Similarly, the upper slope is characterised by calcareous Neogene silts and muds with little or no terrigenous material (Bickford *et al.* 1993). It would seem, therefore, that terrigenous sediment has not been supplied to the continental shelf through that period. The explanation involves both fluvial and marine processes. At low sea levels, shelf morphology is such that the largest decrease in bed gradient, for rivers that drained the Sydney Basin, occurred on the present inner shelf, which resulted in sand deposition landward of the lowstand coast. The rivers, then devoid of significant bedload, would have flowed through a low-gradient coastal plain to the sea with little terrigenous sand reaching the coast or the continental shelf. As well, the action of high-energy incident waves (predominantly from the south) on a low-gradient, linear coastal-plain coast is to generate a strong northward littoral transport regime (Roy & Thom 1981, 1991). Core data from Cruise 112 support this hypothesis of long-term partitioning of sediment, with quartzose clastic sediment confined primarily to the inner and mid-shelves, while the outer shelf was dominated by carbonate deposition. Roy and Keene (1993) argue that coastal processes of the type described here have influenced the dispersal of sediment from the east Australian continent to the Tasman Sea basin over geological time spans.

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AMINOSTRATIGRAPHY OF QUATERNARY OUTER SHELF SEDIMENTS, NEW SOUTH WALES, AUSTRALIA

C.V. MURRAY-WALLACE[1], M. FERLAND[2] & P. ROY[3]

[1] **Dept. of Geology, The University of Wollongong**
[2] **Dept. of Geography, The University of Sydney**
[3] **NSW Dept. of Mineral Resources**

INTRODUCTION

In 1992, 58 vibrocores were collected across the continental shelf of central NSW along several coastal-perpendicular transects (Fig. 1). The cores were collected with a view to unravelling the depositional history of the shelf, especially during periods of lower sea level. This work summarizes the results of measurements for the extent of amino acid racemisation in molluscs from core (112/VC/134) from the outer continental shelf. In particular, we relate the aminostratigraphy of the outershelf sediments to Quaternary sea level fluctuations, and conclude that much of the deposition occurred during intervals of substantially lower sea level.

Collected in a present day water depth of 150 m close to the shelf-break, core 112/VC/134 is one of nine cores collected on the outer shelf (Fig. 1). All nine cores contain sediments of similar lithological character (Fig. 1), and are considered to be representative of lowstand shelf sedimentation (Bickford *et al.* 1993; Ferland & Roy, 1993). The core consists predominantly of bioclastic carbonate (c. 80-85%), either as fine-grained sand or as disarticulated, unbroken valves and shell fragments in a fine carbonate sand matrix. Shell species indicate deposition in water depths substantially shallower than that which occurs at the site today. Previous studies involving surficial sediment sampling on the central NSW outer shelf had identified shallow water fauna (Smith & Iredale, 1924) and the carbonate-rich nature of the shelf sediments (e.g. Shirley 1964; Marshall & Davies 1978; Davies 1979). The cores on which the present investigation is based, however, represents the first attempt at subsurface analysis and dating. The results presented here represent work in progress, as additional samples are currently being dated using amino acid racemisation and AMS-radiocarbon methods.

METHODS

Vibrocores were collected during Cruise 112 of the vessel *RV Rig Seismic* in October, 1992 on the continental shelf between Seal Rocks and Shoalhaven Bight (Fig. 1). All cores were opened on board the ship, briefly described and then stored at 4°C. Subsequent core processing included photographing, detailed logging, resin peeling, and sampling. Eighteen sediment samples were selected from core

112/VC/134 for analysis (i.e. grain size and texture, carbonate and faunal composition). Specimens of the scallop *Pecten fumatus* (syn. *P. meridionalis*) were selected from twelve intervals for amino acid racemisation dating. Two of these samples were also analysed by conventional radiocarbon methods to calibrate the amino acid data. The extent of amino acid racemisation in these two samples (UWGA-31 and UWGA-32) was determined from the HCl residue from the CO_2 evolution procedure of radiocarbon dating, and followed the methods of Murray-Wallace and Bourman (1990). Amino acid racemisation analyses on the total acid hydrolysate follow the methods outlined by Murray-Wallace (1993). In general, 0.5 to 2 g of shell carbonate was digested for each analysis. Here we report results for the amino acids alanine (ALA), aspartic acid (ASP), glutamic acid (GLU) and valine (VAL).

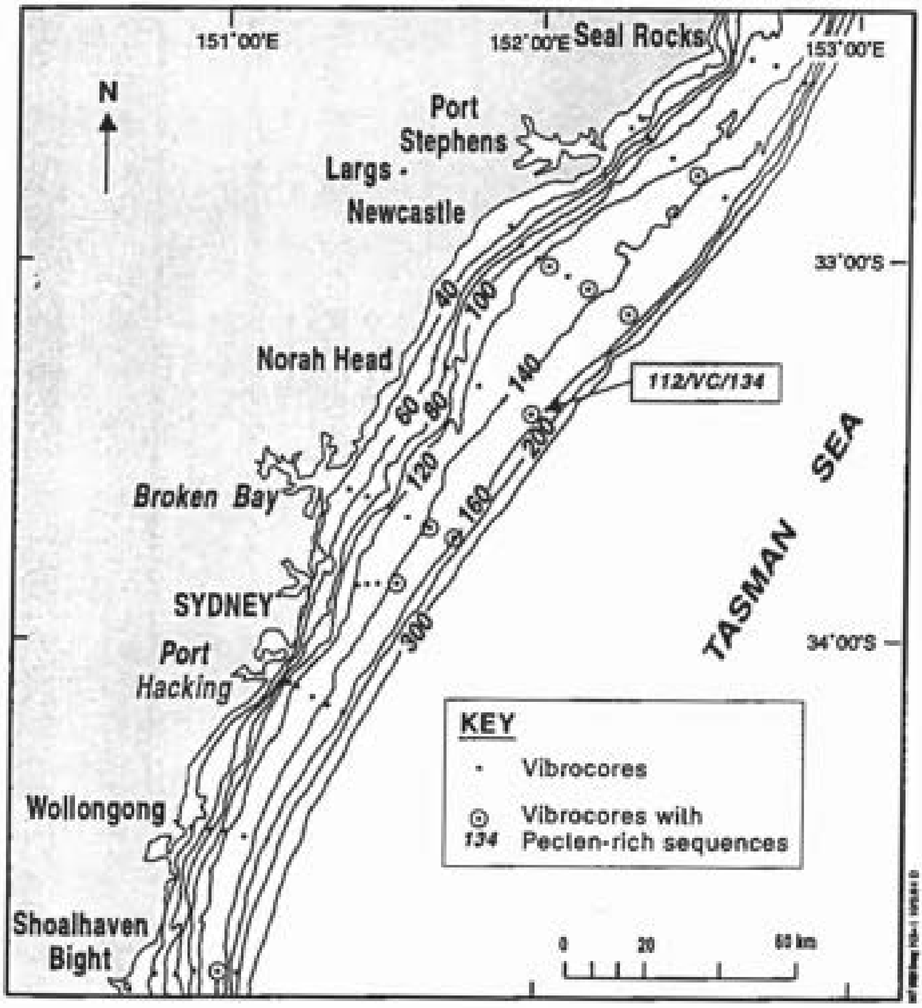

Figure 1. Map showing the regional continental shelf bathymetry, location of Core 112/VC/134, and other vibrocores from the outer shelf that contain similar sedimentary sequences.

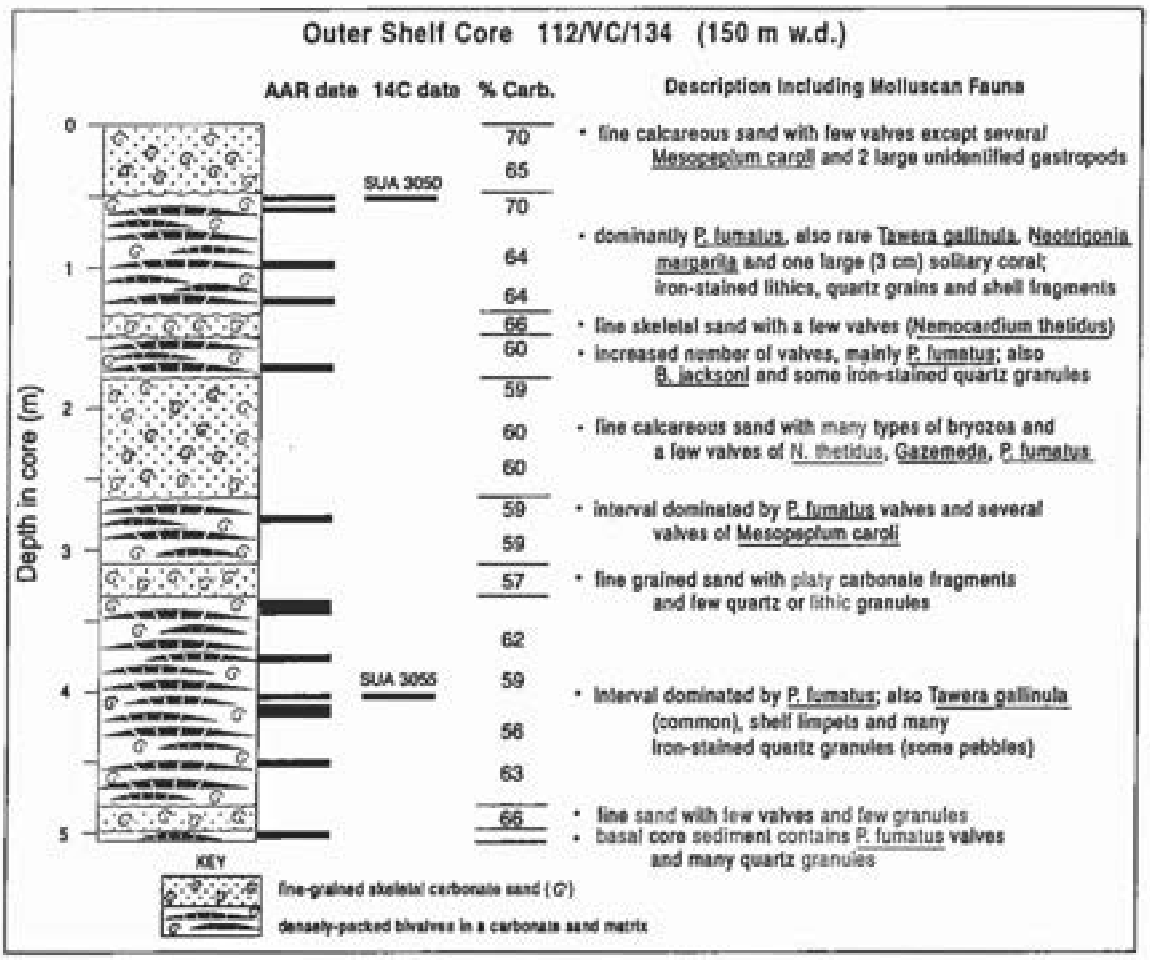

Figure 2. Generalized descriptive log of Core 112/VC/134, including the location of amino acid racemisation and radiocarbon samples within the core, as well as comments on sediment texture, composition and the dominant mollusc species. % Carbonate refers to that of the sand fraction.

RESULTS AND DISCUSSION

Core 112/VC/134 contains an alternating sequence (5.06 m) of (1) fine-grained skeletal carbonate sands and (2) densely-packed bivalves in a carbonate sand matrix (Fig. 2). The identification of these two lithologically-distinct units, based on variations in the number of large bivalves, is further enhanced by the distinctive molluscan species which occur in each unit. The fine-grained skeletal carbonate sands are largely deficient in unbroken valves, but do contain a small number of mid-shelf species including *Mesopeplum caroli* and *Nemocardium thetidus*, as well as several unidentified thin-walled species. In contrast, the bivalve-rich units are dominated by the more robust, shallow water species such as *Pecten fumatus*, with *Tawera gallinla* and *Bassina jacksoni* occurring less commonly.

Grain size analysis (by settling tube) of the total sand fraction showed that the skeletal carbonate sand units are generally fine-grained and moderately to poorly sorted. In contrast, the matrix of bivalve-rich units is medium-grained, moderately to moderately-well sorted sand. Carbonate analyses on the sand fraction of individual samples yielded values of 56 to 70% carbonate by weight (Fig. 3), however, the large number of shell fragments increases the total carbonate to c. 80-85%. It is also noted that sediment colour variations do not appear to correlate systematically with grainsize, carbonate content or the extent of amino acid racemisation in molluscs down-core.

DATING

The relative extent of racemisation for the different amino acids in each mollusc specimen is consistent with previously reported results (Lajoie *et al.* 1980). The extent of racemisation for all four amino acids increases down core consistent with increasing age. Three distinct groupings are apparent and in increasing age are represented by aminogroup 1 (UWGA-31), aminogroup 2 (UWGA-19, 20, 21) and aminogroup 3 (UWGA-22 to 27, 29 & 32) (Table 1). Aminogroups 1 and 2 are from the uppermost bivalve-rich unit while aminogroup 3 samples encompass the four underlying bivalve-rich units (Fig. 3). Aminogroup 1 is of last glacial age as indicated by radiocarbon dating the same interval (17,770 ± 220 yr BP; SUA-3050). Results of recent studies (Bard *et al.* 1990; Barbetti 1991) would imply that this radiocarbon age is approximately 2000 years too young in terms of sidereal years. Aminogroups 2 and 3 are both significantly older than aminogroup 1, and are beyond the range of radiocarbon dating, as no measureable ^{14}C was detected (SUA-3055) (Fig. 3). Aminogroups 2 and 3 are most likely to be of late Middle Pleistocene age (oxygen isotope stages 6 and 8 respectively), by analogy with amino acid data from other sites in southern Australia (Table 2). Within-group variation in enantiomeric ratios is attributed to differences between shells and not a reflection of significant age differences (see also Murray-Wallace & Kimber 1987).

Using a parabolic racemisation kinetic model (Murray-Wallace & Kimber 1993) and the Late Pleistocene radiocarbon date (SUA-3050) and Holocene radiocarbon dated molluscs (Table 2) as a basis for calibration, *minimum* ages of 94,000 and 212,000 yr BP were derived for aminogroups 2 and 3 respectively. A comparison of these results with a more comprehensive empirical data set from southern Australia, in which the extent of amino acid racemisation is plotted against current mean annual temperature (latitude) (Murray-Wallace *et al.* 1991, 1993), supports the notion that these ages significantly underestimate the *true* age of the marine sediments. As the last glacial calibration sample has experienced significantly warmer temperatures (i.e. since ~15 ka) for much of its diagenetic history, ages calculated on the basis of this calibration will always be systematically too young. Despite this, the results attest to the considerable antiquity of these sediments. We also acknowledge as a further uncertainty in estimating diagenetic temperature, the influence of the East Australian Current on bottom water temperatures during successive glacial maxima, interstadials and interglacials. Furthermore, if the *Pecten* samples from the outer shelf have experienced significantly lower diagenetic temperatures than the interglacial material listed in Table 2, their racemisation rates would have been retarded, thus making their true ages older than indicated.

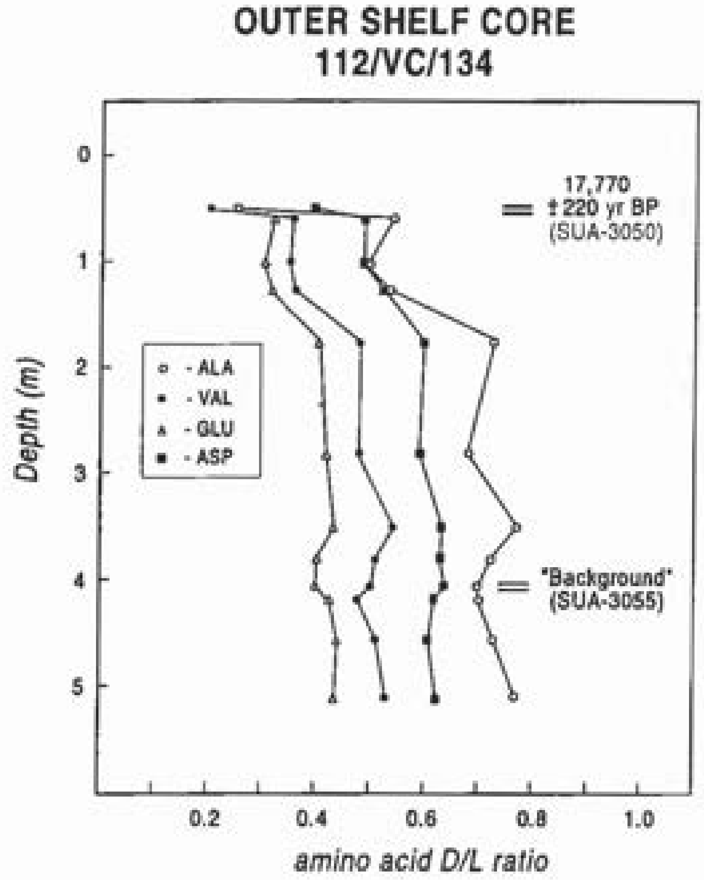

Figure 3. Extent of amino acid racemisation (total acid hydrolysate) in molluscs from Core 112/VC/134, expressed as enantiomeric D/L ratios, plotted against down-core depth. Conventional radiocarbon dates on *Pecten fumatus* from two intervals are also indicated.

As the *Pecten*-rich units are dominated by shallow water mollusc species, that presently occur in water depths of c. 30-50 m on the inner shelves of southern Australia and Tasmania, we favour the view that deposition occurred on the outer shelf, predominantly during intervals of glacio-eustatic sea level lowstands (i.e. glacial maxima). Similarly, the fauna and texture of the finer skeletal sand units indicate deposition in deeper water during interstadials. Despite uncertainties in the level of the sea surface during the last glacial maximum some 20 ka BP (Chappell 1987), we consider it unlikely that the sediments in core 112/VC/134 have ever been subaerially exposed, in view of the absence of calcareous hard grounds, weathering features or pedogenic modification. Morely and Hays (1981) assigned ages of 244 ka and 128 ka respectively to the upper boundaries of the pre-penultimate (stage 8) and penultimate (stage 6) glacials. Thus, we emphasize caution in our preliminary correlation of each of the aminogroups with the timing of each glacial maximum. Further work is in progress in an attempt to refine these correlations.

Table 1 Extent of amino acid racemisation (total acid hydrolysate) in *Pecten fumatus* from core 112/VC/134, outer shelf, New South Wales

Depth (m)	Laboratory Code	AMINO ACID D/L RATIO			
		ALA	VAL	GLU	ASP
0.55 - 0.60	UWGA-31	0.25 ±0.002	0.20 ±0.02	-	0.39 ±0.001
0.60 - 0.65	UWGA-19	0.54 ±0.002	0.35 ±0.001	0.32 ±006	0.49 ±0.001
1.02	UWGA-20	0.48 ±0.001	0.35 ±0.02	0.30 ±0.002	0.51 ±0.001
1.26	UWGA-21	0.54 ±0.004	0.36 ±0	0.32 ±0.004	0.53 ±0.001
1.75	UWGA-22	0.73 ±0.001	0.48 ±0.03	0.40 ±0.07	0.60 ±0.001
2.80	UWGA-23	0.68 ±0.002	0.48 ±0.01	0.41 ±0.004	0.59 ±0.001
3.40 - 3.50	UWGA-24	0.77 ±0.001	0.54 ±0.02	0.43 ±0.001	0.63 ±0.002
3.77	UWGA-25	0.72 ±0.002	0.51 ±0.004	0.41 ±0.01	0.63 ±0.001
4.00 - 4.05	UWGA-32	0.70 ±0.01	0.50 ±0.003	0.39 ±0.001	0.62 ±0.001
4.10 - 4.20	UWGA-26	0.70 ±0.001	0.47 ±0.001	0.42 ±0.04	0.61 ±0.001
4.50 - 4.55	UWGA-27	0.73 ±0.004	0.51 ±0.01	0.43 ±0.07	0.61 ±0.001
4.98 - 5.02	UWGA-29	0.76 ±0.01	0.53 ±0.01	0.43 ±0.001	0.62 ±0.001

Table 2 Extent of amino acid racemisation (total acid hydrolysate) in representative examples of Quaternary molluscs from southern Australia

Locality/ species	Depth of burial (m)	C.M.A.T. (°C)	Age	Amino Acid D/L ratio		
				VAL	GLU	ASP
Robe, SA; *Katelysia* spp.	surface; exhumed midden	14.7	7910±140 (SUA-2613)	0.05 ±0.01	0.11 ±0.01	0.28 ±0.01
Woakwine Range, SA; *Katelysia scalarina*	>1	14.7	125 ka	0.20 ±0.02	0.31 ±0.03	0.54 ±0.06
Largs, NSW; *Anadara trapezia*	1	17.9	125 ka	0.30 ±0.01	0.43 ±0.07	0.58 ±0.04
Redcliff, SA; *Anadara trapezia*	0.90-1.35	19.0	220 ka	0.48 ±0.03	0.62 ±0.02	0.76 ±0.02
Mary Ann Bay, TAS; *Pecten meridionalis*	2	12.5	125 ka	0.24 ±0.01	-	0.44 ±0.004

CONCLUSIONS

1. The extent of racemisation for the amino acids alanine, aspartic acid, glutamic acid and valine, in conjunction with conventional radiocarbon dating indicate that much of vibrocore 112/VC/134 consists of sediments of pre-last glacial age, and are most likely late Middle Pleistocene. Although preliminary, we assign aminogroup 1 to the last glacial, aminogroup 2 to the penultimate glacial and aminogroup 3 to the pre-penultimate glacial.

2. The molluscan fauna indicate several fluctuations in sea level, as the species change from predominantly deep water fauna (>50 m) in the fine sand units to shallow water fauna (<50 m) in the *Pecten*-rich units.

3. The occurrence of aminogroups 1 and 2 in the same *Pecten*-rich unit indicates that deposition during the last glacial was superimposed on a pre-existing deposit formed during the previous glacial lowstand. Presumably the intervening fine grained (interstadial) unit was eroded, however, there is no physical evidence of an erosional discontinuity in the core.

4. In contrast to (3) above, the lower 3.5 m of the core apparently represents deposition during the same glacial phase which, according to the oxygen isotope record (Morley & Hays 1981) may have lasted for 35 ka.

5. The results documented here highlight the extreme difficulty of making seismic- or lithostratigraphic interpretations without direct geochronological control.

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PORT STEPHENS – EVOLUTION OF A QUATERNARY ESTUARY

L. PARSONS
Dept. of Geology, The University of Newcastle

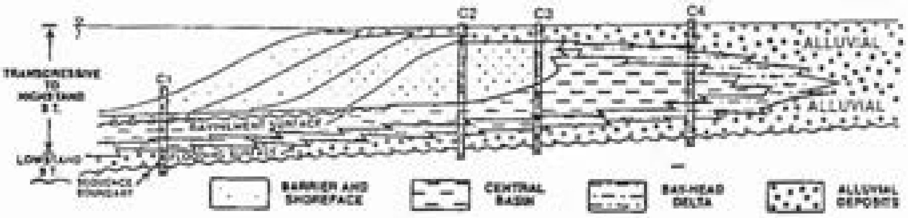
INTRODUCTION

Study of lithified estuarine facies has been sparse due either to an inherently poor potential for preservation or to their complex signature resulting in incorrect classification. If the latter is true then there is a need for an accurate model to predict estuarine lithologies and facies geometry in lithified sediments. A particular application for such a model lies in hydrocarbon exploration and the prediction of potential reservoir sand bodies.

A model developed by Dalrymple et al.(1992) places estuaries into a chronological framework relative to changes in base level. Coastal valleys incised during sea level fall form estuaries during sea level rise and become filled when sea level is stable or rises slower than the rate of sediment input. The model predicts a tripartite zonation based on energy levels and sources. In a wave dominated estuary (e.g., Port Stephens) this includes a sandy fluvial bayhead delta, a central, muddy basin and a sandy marine tidal delta.

The organisation of these facies may be predicted by sequence stratigraphy (see figure 1). Lowstand fluvial material on the lower sequence boundary is overlain by a flooding surface produced by sea level rise. Above this should occur fluvial delta sediments overlain by central basin muds. The muds may interdigitate with overlying prograding marine delta sands or the two may be separated by a ravinement surface in the case of continued sea level rise. Fluvial sediments will then overlie the marine unit. This model was tested by comparison with the sediments of Port Stephens using sequence stratigraphy.

Figure 1. Stratigraphy of a wave dominated estuary based on model by Dalrymple et al. (source: Dalrymple et al. 1992).



LOCATION AND GEOMORPHOLOGY

Port Stephens is located approximately 50km north of Newcastle, NSW and has a length of 21km and a width of 5-8km narrowing to 400m at Soldier's Point, (see figure 2). It is open to the ocean at the east and is fed by the Karuah River to the west. Other tributaries entering the estuary act as tidal conduits but contribute no significant sediments.

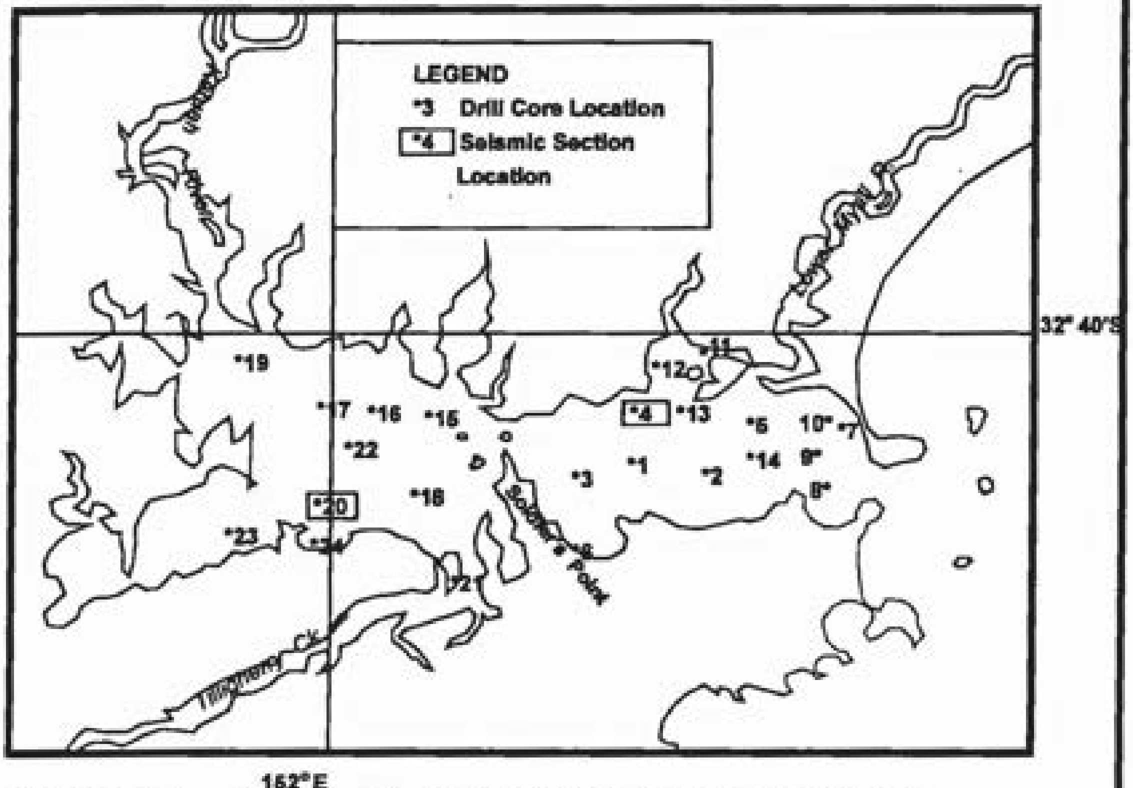


Figure 2. Map of Port Stephens showing locations of drill cores and seismic sections.

Geologically, Port Stephens lies at the boundary between the northern Sydney Basin and the southern New England Fold Belt. The protrusion of resistant Carboniferous volcanic peaks in this region has provided an anchor for the entrapment of marine sediments moving north by littoral drift. This condition accounts for the progradation of Newcastle barriers over the past 120K years (Thom et al.1992), preserving barrier sands from the last

PORT STEPHENS: EVOLUTION OF A QUATERNARY ESTUARY

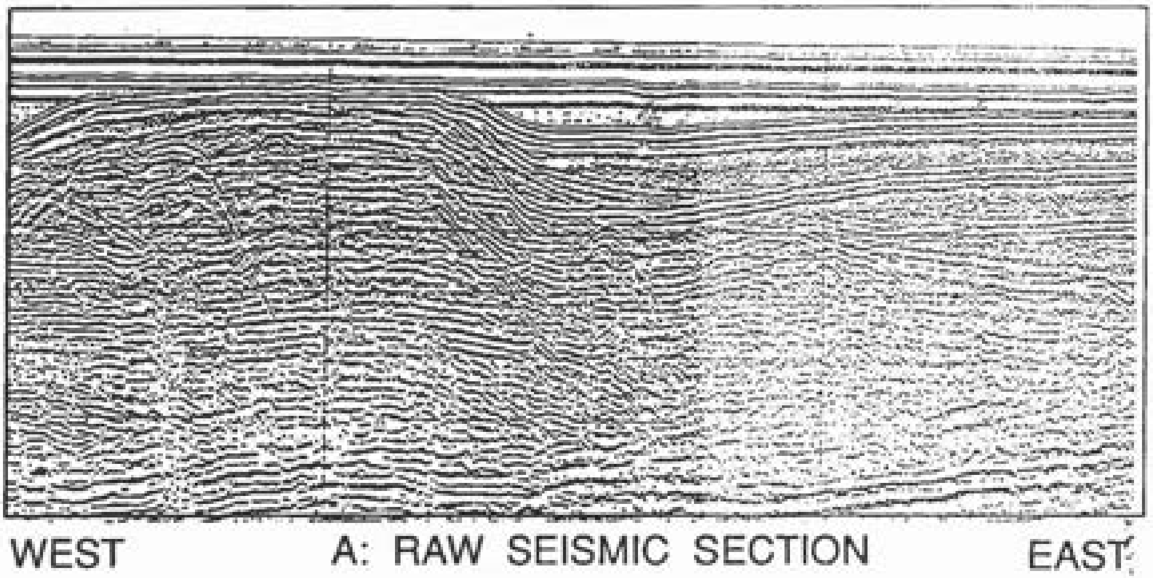
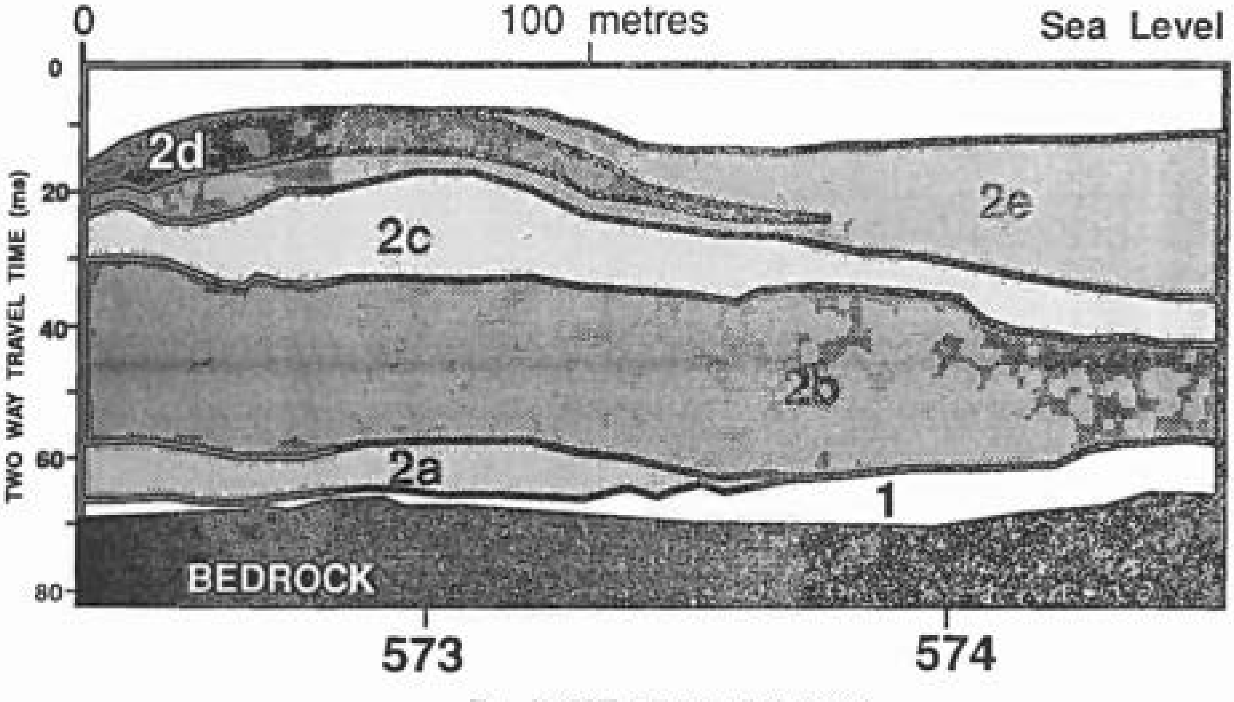
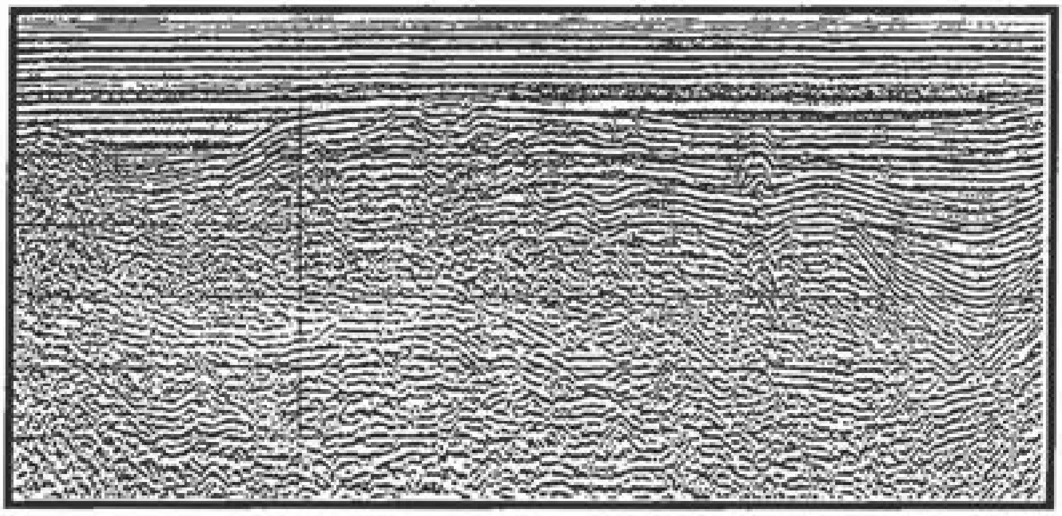


Figure 3. Seismic section from eastern Port Stephens at site of drill core #4.

Interpretation :

1 Last interglacial estuarine sands.
2a Fluvial Sands.
2b Transgressive estuarine sands and clays.
2c Estuarine clays.
2d Holocene estuarine muds.
2e Holocene tidal delta sands.



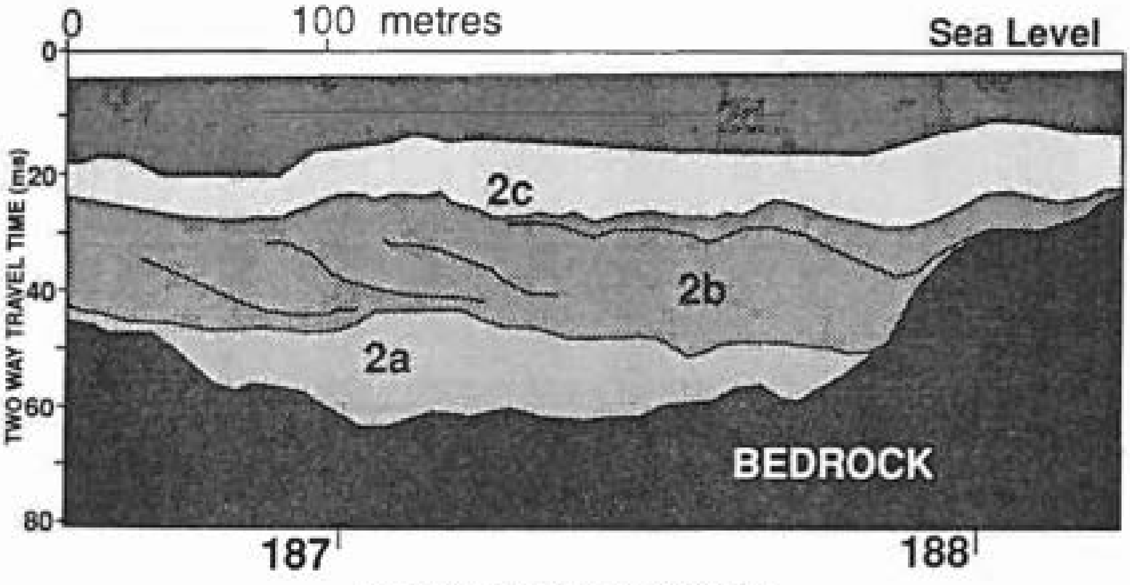


EAST A: RAW SEISMIC SECTION WEST

Figure 4. Seismic section from western Port Stephens at site of drill core #20.

Interpretation:

2a Fluvial Sands
2b Transgressive Estuarine sands and clays
2c Estuarine Clays
2d Estuarine Muds



B: INTERPRETATION

interglacial period.

METHOD

Seismic surveying was carried out between 1969 and 1971 by the NSW Department of Mines resulting in 40 tracklines totalling some 120km linear distance. Sound source was an EG & G boomer providing 150-200j power through a multi-electrode sparker array. The data were filtered in the range of 200-2000Hz and amplified by variable gain compression according to volume of signal recieved.

Seismic data are supplemented by 24 drill core logs obtained by NSW Geological Survey (Roy, 1972) documenting grainsize and sorting, mineralogical composition and microfossil content. These cores are located along the seismic tracklines and provide a lithological reference for the seismic interpretation.

SEISMIC STRATIGRAPHIC APPROACH

Sequence stratigraphy groups seismic reflections between unconformities (reflections against which others terminate) to become sequences with chronological significance. Seismic sequences are divided into seismic facies (Mitchum et al.1977) based on contrasting seismic characteristics such as continuity, frequency and amplitude of reflections.

Seismic interpretations are checked by correlation across crossing tracklines and with drill core logs to ensure continuity. These checks also serve to correct for navigational error which is up to a few hundred metres in some areas of the Port Stephens data set.

RESULTS

Accoustic basement beneath Port Stephens is commonly bedrock and consists of two lithologies. One is accoustically impenetrable, producing diffractions from its high relief surface and is interpreted as the Carboniferous Nerong Volcanics (Sussmilch and Clark, 1928). The other exhibits internal structure including a general dip of up to 20 degrees to the south west. Its surface is horizontal or gently inclined but largely smooth (see figure 3). This rock type is interpreted as the Permian coal measures of the northern Sydney Basin.

The sediments of Port Stephens are categorised into six seismic facies as shown in figures 3 and 4, which may be placed into two broader sequences.

SEQUENCE 1.

This unit is characterised by continuous, low frequency reflections. The material appears largely homogeneous, with limited internal channelling. The upper surface is truncated and dips away to the east, this surface representing a major sequence boundary. No drill cores penetrate this unit but it is interpreted as sands of last interglacial age. The dipping surface may be presumed to be the ravinement of the retreating "inner barrier".

SEQUENCE 2.

The upper sequence is divided into four separate seismic facies which were deposited during the latest sea level cycle, from last glacial age (Wisconsin) to present.

2a. The lowest facies in the upper sequence is characterised by low frequency reflections of varying amplitude, suggesting variable grainsize or mineralogy. The unit possesses little continuity and is chaotic in nature containing a high degree of internal channelling. Both upper and lower surfaces are erosional. This unit is described in drill cores as fluvial sands and gravels or fluvial sands and clays and is interpreted as the lowstand systems tract fluvial deposits.

2b. This facies comprises continuous low frequency, low amplitude reflections dipping in a complex sigmoid-oblique configuration. The unit is extensively channelled in places and containing hummocky clinoform structures. The lower boundary is marked by downlapping terminations while the upper surface exhibits some toplap as well as erosional truncation. Coring in this unit found estuarine clays and fluvial sands and the basic interpretation is of transgressive estuarine material. This unit comprises the transgressive systems tract and represents the post-glacial marine transgression.

2c. Continuous, parallel, low frequency reflections characterise this unit. Shallow channels are contained within the unit but are widely spaced with gradual slopes, indicating low energy conditions. The lower surface is bounded by onlapping terminations often infilling lower channel incisions. The upper surface is truncated in places and often contains acoustically impenetrable mounds of shell bioherms. Drilling indicates early Holocene black muds and estuarine clays for this unit which is interpreted as the present estuary central basin.

2d. Continuous, parallel, horizontal reflections of low frequency characterise this unit. The sediments are homogeneous, containing no internal structure or channelling. Reflections onlap the lower boundary, while the upper boundary remains horizontal. Drilling indicates Holocene black muds as per seismic facies 2d. The unit is interpreted as late Holocene central basin muds.

2e. The latest unit interdigitates with unit 2d although it progressively progrades over it due probably to a higher relative sediment supply. It is characterised by high frequency, high amplitude reflections of varying continuity. Sigmoid reflection patterns and basal downlapping are evidence of stillstand progradation. Many small channels add to the complexity of the unit. Drilling indicates marine sand, in agreement with an interpretation of Holocene marine delta sands.

DISCUSSION

The upper sequence of sediments in Port Stephens consist of lowstand fluvial sands and gravels (2a) overlain by transgressive estuarine clays and sands (2b). Above these lie modern estuarine muds (2c, 2d) and prograding marine deltaic sands (2e). This sequence closely resembles that predicted by the model of Dalrymple et al. (1992) for a wave dominated estuary.

Since this model has been constructed based primarily on observation of modern estuaries, it follows that the modern sedimentary history of Port Stephens should fit the model. It does not follow however that Pre-Holocene estuaries would also fit the model.

Present day estuaries may be seen as a sedimentary response to recent sea level history. The post-glacial marine transgression has caused flooding of incised valleys. All estuaries which existed prior to the Holocene have experienced a fall in sea level. Since estuaries are known to be sensitive to sea level fluctuations, the effect of sea level fall must be taken into account in the study of lithified estuarine sediments.

The sediments of the lower sequence in Port Stephens provide a better indication of what is expected to be preserved as lithified estuarine sediments. This sequence contains gravels, clays and marine sands in a similar pattern to the upper sequence but with an erosional upper boundary. Port Stephens may therefore be described as containing "stacked" or "multiple" estuarine fills produced over several sea level cycles.

The landward progradation of Holocene marine sands into the estuary appears greater than predicted by the model. This may be explained by the relative abundance of marine sediment input and comparative paucity of fluvial sediment input.

It is this abundance of marine sediment which may be responsible for the progradation of Port Stephens estuary over several sea level cycles. A greater amount of marine sediment accumulates at Port Stephens during sea level highstands than can be removed by erosion during the following marine regression.

CONCLUSIONS

Preservation of multiple cycles of estuarine fill within Port Stephens is due to its high marine sediment input. In a broader context, estuarine sediments are preserved when net highstand deposition exceeds subsequent net lowstand erosion. This condition may be attained in regions of high sediment input such as Port Stephens, or in areas where local tectonic subsidence increases accommodation space for estuarine sediments.

Stacked estuarine sequences in the rock record may be expected to follow a pattern of fluvial sands and gravels overlain by estuarine clays and marine sands, followed by a hiatus and repetition of the above sequence. In cases where marine sediment input is less significant than fluvial sediment, the marine sand unit would be truncated and overlain or replaced by fluvial deltaic sands.

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CONGLOMERATE COMPOSITION & PALAEOCURRENT DIRECTIONS IN THE NEWCASTLE COAL MEASURES : IMPLICATIONS FOR NON-MARINE SEQUENCE STRATIGRAPHY

M. LITTLE
Dept. of Geology, The University of Newcastle

INTRODUCTION

The concept of sequence stratigraphy and its predecessor, seismic stratigraphy, have been developed in marine and nearshore environments. Sequence/seismic stratigraphic methods have been generally accepted and many workers have tested their viability in marine/nearshore settings (Posamentier & Weimer, 1993). Initially some doubt was held about the applicability of sequence stratigraphy in purely non-marine environments (Walker, 1990), but a recent investigation (Shanley & McCabe, 1991) has demonstrated the application of this method in non-marine settings. Interest in non-marine sequence stratigraphic studies is increasing as research into non-marine environments is still in its early stages.

Shanley and McCabe (1991) have used changes in depositional architecture, sandstone-connectedness, sandstone/shale ratios and coal-bed geometry to determine systems tracts in a sequence stratigraphic framework. Utilisation of methods such as architectural changes requires exposure at a scale that permits larger architectural elements (e.g., major channels) to be displayed. Architectural element analysis and stacking patterns are of little use to sequence stratigraphers where outcrop is limited. This paper investigates the potential of using conglomerate clast composition to determine systems tracts in a sequence stratigraphic framework. This method has the potential to enable subsurface workers, who have no available outcrop, to apply sequence stratigraphic concepts. Conglomerates from the non-marine Newcastle Coal Measures (see figure 1), located in the northeastern corner of the Sydney Basin, provide an example where conglomerates display significant differences in clast compositions.

PALAEOCURRENT DIRECTIONS AND PROVENANCE OF CONGLOMERATES IN THE NEWCASTLE COAL MEASURES

A review of palaeocurrent measurements, from the Newcastle Coal Measures, in published (e.g., Diessel, 1980) and unpublished literature (e.g., Holmes 1978; Warbrooke 1981) reveals a general flow direction from the north and northeast. A less common flow direction indicates that sediments were being derived from an easterly area. Examination of unpublished theses on the Newcastle Coal Measures reveals that the conglomerates generally consist of cherts, jasper, sandstones, acid volcanics, metagreywacke, granule conglomerate, quartzite and siltstone (eg. Ziolkowski, 1978). Conglomerates that are derived from the east do not contain different lithologies to conglomerates derived from the north and northeast. Rock types found in clasts can also be located in the New England Fold Belt (NEFB) which is presently located to the north of the Sydney Basin. The general palaeocurrent directions flowing from the north and northeast and the presence of NEFB type lithologies contained in the conglomerate clasts of the northern Sydney Basin, indicate the NEFB to be the source area for Newcastle Coal Measure sediments. As previously discussed by Jones et al. (1984), palaeocurrent directions flowing from the northeast and east measured on coastal outcrops located to the south of Newcastle, indicate an extension of the NEFB may have existed to the east of the present day coastline in the Newcastle area.

The NEFB can be broadly divided into two tectonic systems (see figure 1), the Tablelands Complex, a subduction\accretion system, and the Tamworth Belt, an arc and fore-arc basin (Korsch, 1977). The Tamworth Belt and Tablelands Complex are separated by the Peel-Manning Fault System. The Hunter-Mooki Thrust separates the Sydney Basin from the NEFB. The Tamworth Belt mainly consists of volcanics and sediments including sandstone, conglomerate and mudstone (Roberts and Engel, 1987). The Tablelands Complex is composed of volcanics, granite plutons (remnants of a magmatic arc) cherts, schist and meta-sandstones (Korsch, 1977).

SYSTEMS TRACT IDENTIFICATION USING CONGLOMERATE CLAST COMPOSITION

Mechanisms that are likely to cause changes in base level in non-marine foreland basins include tectonic and glacially-driven eustatic changes. Glacially controlled sea-level fluctuations in conjunction with tectonics are likely to control the deposition of higher frequency sequences.

The following scenario provides an example of how glacially controlled eustatic fluctuations may produce conglomerates that contain different proportions of clast lithologies. In this example glaciation occurs in the adjacent thrust belt while it is being continually uplifted. As glaciation in the thrust belt approaches its maximum, the position of relative sea level (RSL) will drop. When rate of eustatic fall exceeds rate of basin subsidence a sequence boundary will begin to form. The period of maximum glaciation will come to an end with significant melting and retreat of glaciers. As glacial retreat begins the position of RSL will slowly begin to rise. During the first stages of glacial melting rivers draining from the glaciers will experience an increase in flow velocity resulting from the increased quantity of water being supplied by the melting glaciers. The elevated rate of discharge during this time will also enable the drainage system to transport pebbles of a larger size. The increased rate of discharge and sediment load that is initiated in the thrust belt may result in an increase in the abundance of lithologies that occur in the more distal parts of the thrust belt and will ultimately be reflected in the conglomerate that results from glacial melting. Increased discharge and flow velocity during this stage may result in trunk drainage developing in a foreland basin. Sediment that is deposited during this time can be considered to be part of a lowstand systems tract (LST). Therefore in this model LST conglomerates will contain a greater proportion of clast types derived from more distal parts of the adjacent fold belt. LST conglomerates are also likely to display larger sized clasts.

Glacially driven eustatic rise, resulting from significant glacial retreat, in conjunction with tectonic subsidence will result in a rise in the position of RSL. This stage of deposition represents the time when a TST will form. Deposition during TST may be represented by coal seams that have transgressive signatures and/or deposition of lacustrine sediments that reflect a rise in the groundwater table. Towards the end of the TST discharge provided by glacial retreat will be nearly exhausted as only a minor part of the glaciers will be left. The trunk drainage system that was initiated by the previous LST may now cease to exist.

A highstand systems tract (HST) will form when the rate of sea-level rise is at a minimum. At this stage the additional discharge and flow velocity previously provided by the melting glaciers is no longer available. The drop in rate of discharge will result in the cessation of trunk drainage will now be replaced by a system that will derive more sediment from a more proximal section of the thrust belt. Conglomerates formed during HST will contain a higher proportion of clast lithologies derived from proximal and less from distal sections of the thrust belt. Because a trunk drainage system will no longer operate, palaeocurrent flow directions will not suggest a flow direction parallel to the basin axis. The dominant trend of flow will be from the adjacent foreland, that is normal to the basin axis.

AN EXAMPLE USING CONGLOMERATE COMPOSITIONS FOR SYSTEMS TRACT INTERPRETATIONS IN THE NEWCASTLE COAL MEASURES

The Newcastle Coal Measures contains numerous conglomerate bodies and provides an area for research of non-marine conglomerates in a foreland basin. The Bolton Point and Teralba Conglomerates (Moon Island Beach Subgroup) have been chosen for investigation as these two conglomerates are separated by the Great Northern Seam, tuffs and scattered lacustrine sediments. Recent investigation of the compositions of the Teralba and Bolton Point Conglomerates in the Catherine Hill Bay area reveal that there is a significant difference in the relative proportions of chert and sandstone. Figure two illustrates the composition of these conglomerates. In this example which deals with only a relatively thin section of strata consisting of two conglomerates separated by a coal seam, tectonic controls on the two conglomerates cannot account for their differences in composition. The previously discussed glacially driven model provides a better explanation for changes in conglomerate composition. Although no dropstones have been found in the Newcastle Coal Measures, examples of these features that indicate active glaciation have been found in the Tomago Coal Measures (Herbert, 1980). Since the Tomago Coal Measures stratigraphically lie beneath the Newcastle Coal Measures, it is likely that glaciation still occurred in the topographically higher NEFB during the deposition of the

Newcastle Coal Measures. Differences in average maximum clast size, based on measurement of the ten largest clasts, occur between the two conglomerates. The Bolton Point Conglomerate has an average maximum clast size of 18cm while the Teralba Conglomerate has an average maximum clast size of 14.5cm. Palaeocurrent measurements taken by the author indicate that both of these conglomerates display a flow direction towards the west of southwest. The Bolton Point Conglomerate and Teralba Conglomerates have flow directions towards 250° and 248° respectively. These palaeocurrent measurements were taken from cross-bedding, clast imbrication, clast long axes and plant orientations.

The sandstone component also contains a small proportion of granule conglomerate (<3%), which has similar colour and coherence as the sandstones. For brevity the following references to sandstones will also refer to the small component of conglomerate. The Bolton Point Conglomerate contains 27% sandstone and 62% chert (normalising these figures gives 30% sandstone and 70% chert). The Teralba Conglomerate is found to contain 40% sandstone and 35% chert (normalising the sandstone and chert figures gives 53% sandstone and 47% chert). Ziolkowski (1978) conducted clast analysis on the Bolton Point and Teralba Conglomerates and found that the Bolton Point Conglomerate contains 16% sandstone and 34% chert, and the Teralba Conglomerate contains 27% sandstone and 11% chert. These percentages are different to the authors findings but when the data is normalised the difference in proportions can be recognised. Ziolkowski's (1978) normalised data gives Bolton Point Conglomerate a composition of 32% sandstone and 68% chert and the Teralba Conglomerate a composition of 70% sandstone and 29% chert.

The grey to green sandstones do not visibly display any effects of metamorphism, but microscopically they display minerals associated with low grade metamorphism. Wilcock (1979) noted the presence of prehnite in some sandstone clasts of the Teralba Conglomerate. The sandstones are likely to be derived from the more proximal Tamworth Belt which has undergone a lower grade of metamorphism than the Tablelands Complex. Offler and Hand (1988) suggest that the Tamworth Belt accommodates metamorphic rocks of subgreenschist facies and the Tablelands Complex contains metamorphic rocks of greenschist facies. The cherts are likely to be derived from the more distal Tablelands Complex as Roberts and Engel (1987) indicate that they only rarely occur in the Tamworth Belt.

The Bolton Point Conglomerate contains a significant proportion of cherts indicating that this conglomerate derived a considerable proportion of its clasts from the Tablelands Complex. Referring to the previous discussion about LST formation, the high percentage of chert and the larger maximum clast size indicates that the Bolton Point Conglomerate can be interpreted as being part of a LST.

The Awaba Tuff, Great Northern Seam, Booragul Tuff and in places lacustrine sediments separate the two conglomerates. Diessel (1992) suggests that the Great Northern Seam may be distally transgressive due to an upward increase in vitrinite fluorescence and the fact that thin lacustrine sediments overlie the seam in places, which suggests a rising groundwater table has drowned the seam. Warbrooke (1981) noted an upward increase in the sulphur content in the Great Northern Seam, which also suggests the seam was formed under a transgressive regime. This evidence may suggest that the Great Northern Seam and overlying lacustrine sediments form a transgressive systems tract (TST). The stratigraphic order of the lower Bolton Point Conglomerate (upper part of a LST), Great Northern Seam and lacustrine sediments (TST) and the overlying Teralba Conglomerate (HST) fit into the sequence stratigraphic order of a LST followed by a TST and finally a HST.

The Teralba Conglomerate contains almost half as much chert as the Bolton Point Conglomerate and significantly more sandstone. The lower proportion of chert and higher proportion of sandstone composition indicates a larger proportion of sediments being supplied from the more proximal Tamworth Belt. Based on the significant contribution of clasts from the more proximal Tamworth Belt and the smaller average maximum clast size, it is possible that the Teralba Conglomerate is part of a HST. The identical palaeocurrent trends suggest that switching of drainage from trunk to local style drainage did not affect palaeocurrents in this part of the Newcastle Coal Measures.

CONCLUSIONS

Significant differences in proportions of sandstone and chert clasts occur in the conglomerates of the Newcastle Coal Measures. The significant variation in conglomerate clast composition of the Newcastle Coal Measures illustrates a potential method of identifying systems tracts in non-marine foreland basins. The concept of using conglomerate clast composition to make systems tract interpretations highlights the need for further investigation of this method, as the above systems tract interpretations need to be correlated with sequence stratigraphic surfaces of a regional nature. The significance of this method is that it could provide subsurface workers, who may lack adequate outcrop and drill core exposure, with a means of placing non-marine sediments in a sequence stratigraphic framework.

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CONGLOMERATE COMPOSITION AND SEQUENCE STRATIGRAPHY

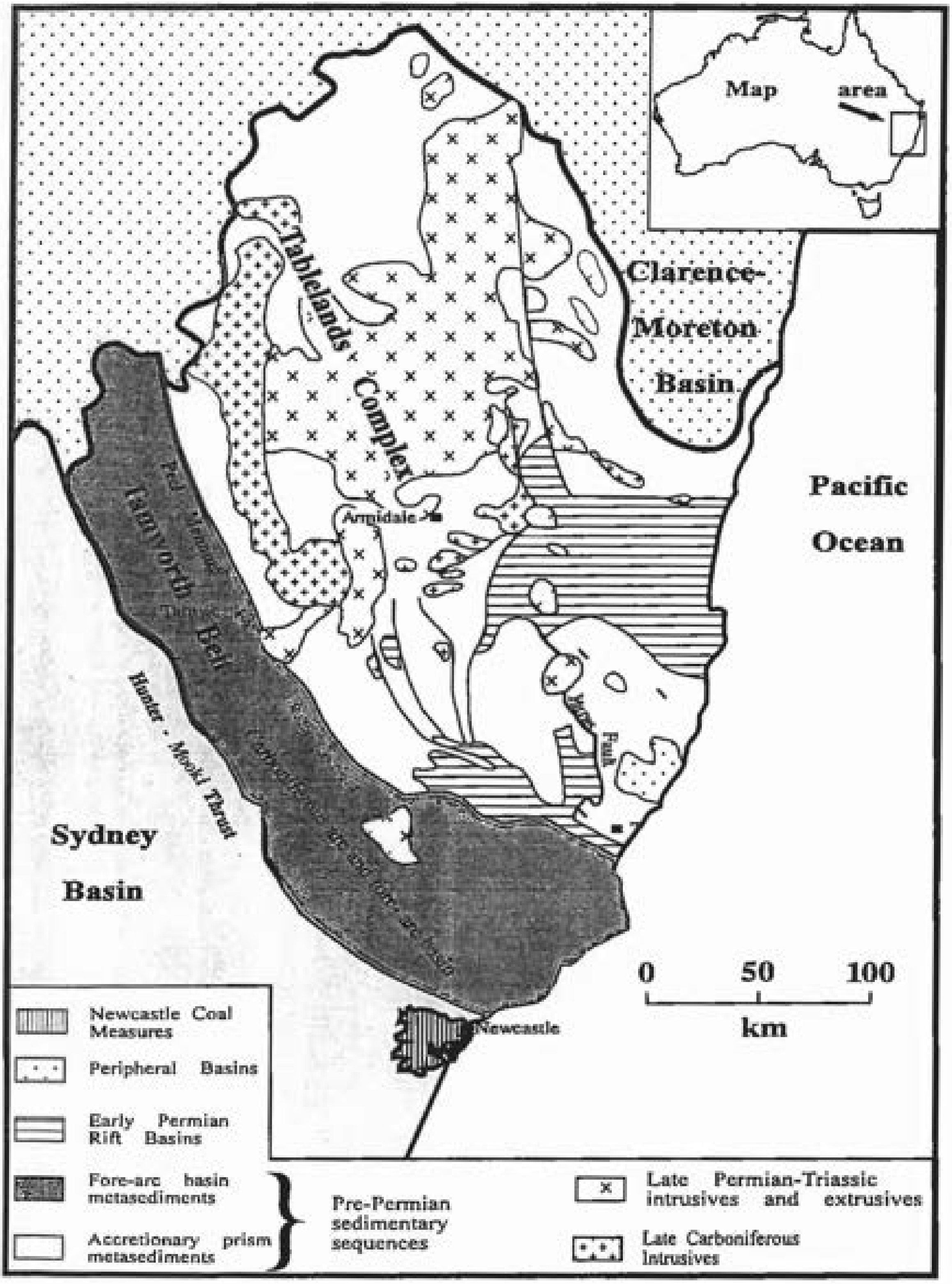

Figure 1. Map of New England Fold Belt and Sydney Basin
(after Collins, 1993, unpublished data)

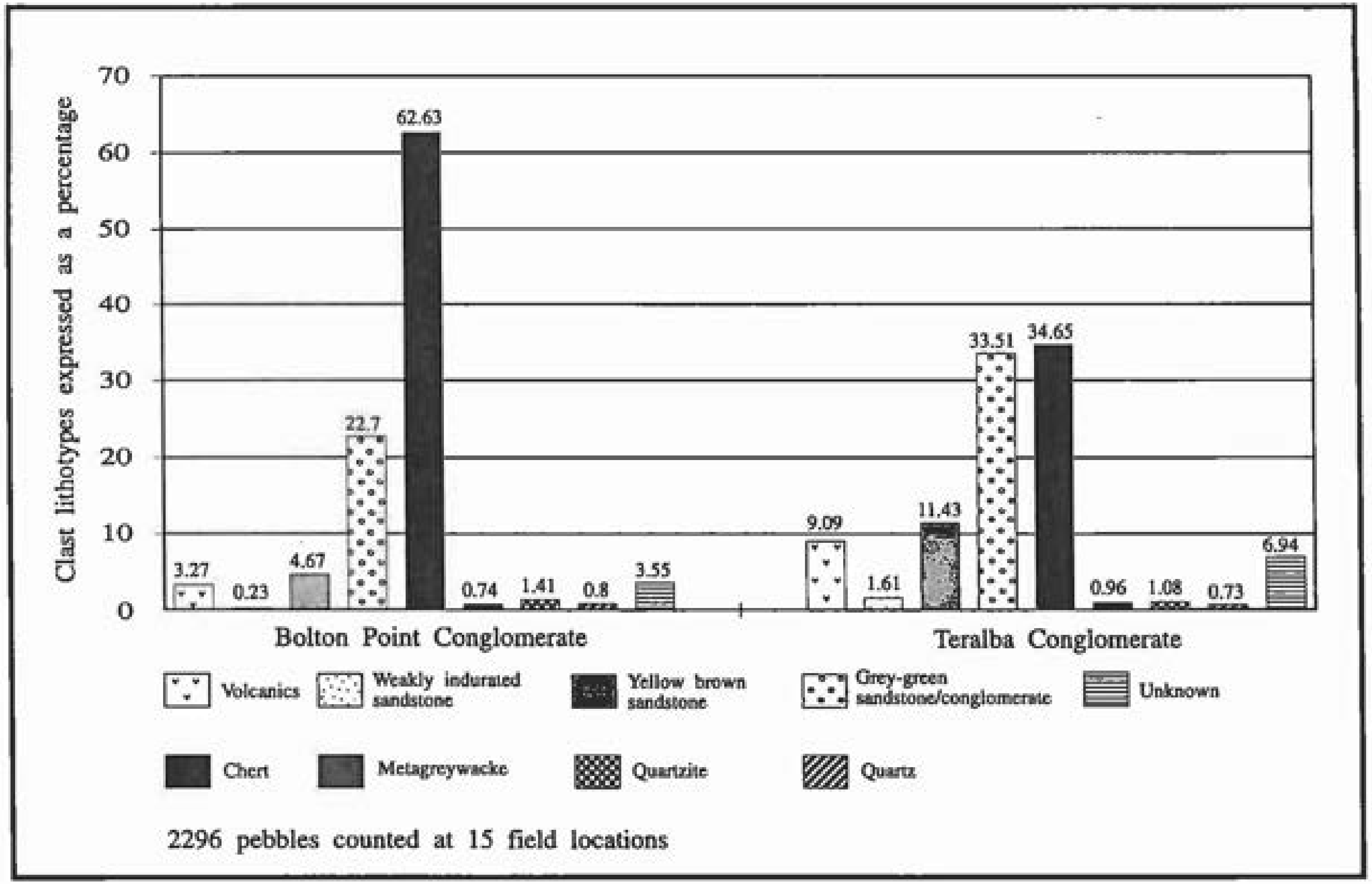

Figure 2. Mean conglomerate clast composition for the Bolton Point and Teralba Conglomerates

STRATIGRAPHY OF THE TALATERANG & SHOALHAVEN GROUPS IN THE SOUTHERNMOST SYDNEY BASIN

C.R. FIELDING[1] & S.C. TYE[2]

[1] **Dept. of Earth Sciences, University of Queensland**

[2] **Dept. of Geology, The University of Wollongong**

The Permian stratigraphy of the southernmost Sydney Basin, between Bateman's Bay in the south and Marulan–Wollongong in the north, is poorly understood. This is in part due to the isolated nature of the region, and the consequent difficulty in accessing key exposures. Since the pioneering mapping effort of McElroy & Rose (1962), several conflicting versions of the Permian stratigraphy have been published (eg. Herbert, 1980; Evans et al., 1983; Evans, 1991). In this paper, we clarify the Permian stratigraphic succession in the Shoalhaven region, and make interpretations as to lateral stratigraphic equivalence of the various units. A companion paper (Tye & Fielding, 1994) addresses the sedimentology of these formations. Our analysis is based on thorough field investigations and drillcore examination undertaken during the second half of 1993.

STRATIGRAPHIC SUCCESSION

The Lower and middle Permian stratigraphic succession in the southernmost Sydney Basin was subdivided into the Talaterang and overlying Shoalhaven Groups by Gostin & Herbert, 1973. While we agree that this fundamental division is appropriate, we find the arrangement of formations within the two Groups (Herbert, 1980) thoroughly confused. In this paper, therefore, we propose a revision of the stratigraphic constitution of the two Groups, and of correlations between their component formations (Fig. 1). The basis for these revisions is detailed below.

1. Talaterang Group

Numerous isolated occurrences of Lower Permian rocks occur within the Shoalhaven district. These rocks invariably overlie older Palaeozoic basement, are laterally impersistent, and yet collectively cover a large part of the southernmost Sydney Basin. The Clyde Coal Measures, Pigeon House Creek Siltstone, Wasp Head Formation and certain unnamed coarse clastic sequences are here considered to be stratigraphic equivalents, and are collectively referred to the Talaterang Group (Fig. 1). Thickness of these units in all instances totals 100m or less, although it is possible that thicker intervals are preserved in the subsurface. In many areas, the overlying

Shoalhaven Group lies directly on older Palaeozoic basement. The base of the Shoalhaven Group is considered to be disconformable on the Talaterang Group (Fig. 1).

Units originally referred to the Talaterang Group by Gostin & Herbert (1973) but here considered part of the overlying Shoalhaven Group include the Yadboro and Tallong Conglomerates, and their equivalents. Furthermore, contrary to the position taken by Herbert (1980), we here demonstrate that the Clyde Coal Measures and Yarrunga Coal Measures are **not** stratigraphic equivalents, the latter forming part of the Shoalhaven Group. We do, however, include the Wasp Head Formation in the Talaterang Group, on the basis of similarity in its structural and stratigraphic position to the Clyde Coal Measures and Pigeon House Creek Siltstone.

The Clyde Coal Measures comprise an association of clastic sedimentary rocks with interbedded coal seams up to 2m in thickness (McElroy & Rose, 1962; Fig. 2). The unit is here interpreted as arising from mainly alluvial plain environments of deposition, with some coastal influences evident towards the top in the type section. In all cases, the Coal Measures unconformably overlie Ordovician to Devonian metasedimentary basement. The assertion by Herbert (1980, p.88) that the unit overlies the Yadboro Conglomerate is incorrect. Rather, the Clyde Coal Measures are overlain disconformably by the Yadboro Conglomerate (eg. on Longfella Ridge; 8927–493844) or disconformably by the Pebbly Beach Formation/Snapper Point Formation where the Yadboro Conglomerate is absent (eg. Clyde River Gorge; 8927–509027, Budawang Creek; 8927–462992). The angular unconformity noted at the "top" of the Clyde Coal Measures by McElroy & Rose (1962; their Sections F and I) is here reinterpreted, from field observations, as arising from preservation of lateral accretion surfaces within small channel sandstone bodies. The type section of the unit may therefore be extended up to the top of an overlying, waterfall–forming sandstone body (Fig. 2). Following this revision, no evidence of coaly material is contained in units immediately above the Coal Measures, as was stated by McElroy & Rose (1962, p.16).

The Pigeon House Creek Siltstone comprises interbedded siltstones and sandstones of interpreted alluvial origin (Fig. 2). In the type section, on the lower slopes of Cambage Head (8927–501887), the base of the unit is unexposed although Ordovician basement occurs a short distance below. The Siltstone is disconformably overlain by the Yadboro Conglomerate (Fig. 2). Elsewhere, the unit is seen to lie unconformably on older Palaeozoic basement, and in places to be directly overlain by the Snapper Point Formation in the absence of Yadboro Conglomerate. The Pigeon House Creek Siltstone is lithologically similar in almost all respects to the Clyde Coal Measures, the only major difference being a lack of coal in the former. The facies assemblage (apart from coal) is identical, as is sandstone composition and palaeocurrent directions (northward in both cases). The two units are therefore here reinterpreted as facies equivalents.

The Wasp Head Formation is recognised formally only in coastal outcrops north of Bateman's Bay (Gostin, 1968). In the type section, the unit comprises c.100m of mainly marine shelf sandstones, with interbedded sedimentary megabreccias near the base here interpreted as debris flow deposits. The unit unconformably overlies Ordovician metasedimentary rocks and is (apparently conformably) overlain by the marine Pebbley Beach Formation (Fig. 2). Imbrication directions within the breccias, and cross-bedding from interbedded sandstones indicate sediment supply from the east and west; this and the texturally very immature nature of the breccias together suggest local sediment derivation from north-trending tectonically active slopes.

Similar, texturally immature coarse clastic facies have been noted in some boreholes, such as Elcom Clyde River 12 (59.82-62.41m) and DM Callala 1 (533.6-570.0m). These rocks comprise matrix-rich, silt-matrix conglomerates and breccias, coarse clasts being composed dominantly of phyllite and quartzite derived from the basement that they invariably overlie. Such deposits are here also correlated with the Talaterang Group.

The various units display similarity in their structural and stratigraphic positions, and are furthermore **mutually exclusive** from each other in their distribution. Each unit directly overlies basement, and is in turn overlain by either the Yadboro Conglomerate or in its absence by the Pebbley Beach/Snapper Point Formation. Interpreted depositional environments vary from alluvial through coastal plain to marine, recording the strongly diachronous invasion of the early Sydney Basin by the sea. Given the lithological similarity and interpreted equivalence of the Clyde Coal Measures and Pigeon House Creek Siltstone, we here propose that the term Pigeon House Creek Siltstone be abandoned, and the definition of the Clyde Coal Measures be extended to include non-coal-bearing fluvial strata. The term Wasp Head Formation may then be used for marine facies occurring at the same stratigraphic level.

2. Shoalhaven Group

Disconformably or ?conformably overlying the Talaterang Group as redefined here are a series of stratigraphic units of interpreted coastal plain to marine shelf origin (Fig. 1) and a coarse clastic unit of interpreted high energy fluvial/coastal plain origin (the Yadboro Conglomerate). The latter, which correlates northward with the Tallong and Megalong Conglomerates, was previously assigned by Gostin & Herbert (1973) to the Talaterang Group. We here argue, however, that the setting of the Conglomerates is such that they must be regarded as part of the overlying Shoalhaven Group.

The Yadboro Conglomerate comprises up to 180m of mainly pebble to cobble conglomerate, of interpreted high energy alluvial and coastal plain origin. The unit disconformably overlies the Talaterang Group (as above) or in its absence directly overlies basement with angular unconformity. Considerable erosion is evident at the base of this unit; underlying units have been removed entirely in some areas and the Conglomerates appear to occupy a series of incised palaeolows. There is, however, no evidence that these "palaeovalleys" were glacially scoured or that they form part of a "Late Carboniferous fluvioglacial drainage pattern" as claimed by Herbert (1972). Indeed, the Conglomerates demonstrably overlie rocks of indisputable Permian age (Fig. 1). Furthermore, the unit and its lateral equivalents are considerably more extensive in a north–south direction than is acknowledged in Herbert's Figure 5.2 (Tye & Fielding, 1994).

The Yadboro Conglomerate forms an east–facing lobe on isopach maps (Tye & Fielding, 1994). Clasts are composed almost exclusively of lithologies from the underlying basement, and range from poorly sorted and angular at the base to moderately/well–sorted and well rounded upward. The fabric is almost invariably clast–supported, and the matrix is coarse sand to fine gravel. Imbrication of coarse clasts in the Yadboro and Tallong Conglomerates indicates that they were deposited in all cases by unidirectional currents flowing eastward. The "Badgery's Breccia" of Herbert (1980) is simply a basal facies of the Tallong Conglomerate and was similarly deposited from eastward–flowing streams. Where the Yadboro Conglomerate is best–developed (in the area around The Castle and Byangee Walls), five distinct depositional cycles, bounded by short siltstone intervals, can be recognised.

The Tallong Conglomerate forms a more east–west–elongate lobe, some distance north of the Yadboro Conglomerate (Tye & Fielding, 1994), although its northern margin cannot be accurately defined. Herbert's (1980) interpretation of the Tallong as an east–directed, incised glaciofluvial system relies heavily on his recognition of thick "diamictites" with "abundant striated pebbles" within DM Callala 1 as representing that unit. A thick interval of silt matrix–supported conglomerates (quite atypical of the Tallong Conglomerate elsewhere) does indeed occur above basement in DM Callala 1, but is abruptly overlain by sand matrix, clast–supported conglomerates characteristic of the Tallong Conglomerate. A clay–rich zone at the top of the lower unit is here interpreted as a palaeo–weathering surface. We believe that the lower, silt–matrix conglomerate unit (which in reality contains very few striated pebbles) may correlate with the Clyde Coal Measures/Wasp Head Formation phase, while only the upper sandy conglomerates (13m thick) correspond to the Tallong Conglomerate (Fig. 3).

Between the two Conglomerate lobes, in the Clyde River Gorge (Fig. 2), a condensed interval of shoreface sandstones and thin conglomerates (referable to the Snapper Point Formation) occurs in the equivalent stratigraphic position. In places, the Conglomerates are capped by a thin coal measure sequence (the Yarrunga Coal Measures, which have been incorrectly correlated with the Clyde Coal Measures). This younger coal measure sequence, encountered for example in DM Callala 1 (520.5–483.4m), comprises interbedded sandstones, siltstones, claystones and coals of interpreted coastal plain origin (Fig. 2). Downdip to the east, and overlying the Yarrunga Coal Measures in places, is the correlative, coastal to shallow marine Pebbley Beach Formation (Fig. 1).

Accordingly, we here reinterpret the Yadboro and Tallong Conglomerates as representing a coarse alluvial apron formed along the western margin of the southern Sydney Basin which acted as a sediment source for the marine Pebbley Beach Formation further east. During the initial stages of marine transgression following accumulation of the Conglomerates, coastal plain coal measure facies formed (Yarrunga Coal Measures), and were ultimately drowned by the sea to be overlain by the Pebbley Beach Formation. We propose that the term "Jindelara Fluvial Facies" (Evans et al., 1983) be abandoned, and that all coal measure sequences at this stratigraphic level be referred to the Yarrunga Coal Measures. **This unit is quite distinct from the older Clyde Coal Measures both in its stratigraphic relationships and in its facies assemblage (Fig. 2).**

The Snapper Point Formation, comprising mainly shoreface sandstones, overlies the Yadboro/Tallong Conglomerates and Pebbley Beach Formation, and in places oversteps these units westward to directly overlie basement. In the west, the Conjola Formation of McElroy & Rose (1962) is evidently equivalent to the Snapper Point Formation, but is of partly fluvial origin. Palaeocurrent data suggest derivation of the unit from the west. We suggest that use of the term "Conjola Formation" be discontinued.

The upper part of the Shoalhaven Group, from the Snapper Point Formation upward, displays a sheet-like architecture, with fine-grained units deposited following marine transgressions (Wandrawandian and Berry Siltstones) separated by regressive, coarser-grained units (Snapper Point Formation, Nowra Sandstone). The Nowra Sandstone also is elongate along the western margin of the basin, and evidently formed by sediment supply from the craton, dispersed by a northward ?tidal current system (Le Roux & Jones, 1994). The overlying Broughton Formation, the uppermost unit of the Shoalhaven Group, represents a complete reorganisation of sediment provenance and dispersal in the basin, with the onset of a major phase of shoshonitic volcanism (Carr, 1982; Bull & Cas, 1989). Sediment dispersal in the lower Broughton Formation was also northward via tidal currents according to Bull & Cas (1989).

CONCLUSIONS

Our field and core investigations have neccessitated a considerable revision of the currently accepted Early Permian stratigraphy in the southern Sydney Basin (Fig. 3). In Tye & Fielding (1994) we present revised palaeogeographic maps for the southern Sydney Basin which accommodate these revisions. Our stratigraphy is consistent with mapped and observed field relationships, and with subsurface drillcore intersections of Lower Permian units. The interpreted distribution and evolution of depositional systems shows similarity to that established in the coeval succession of the Bowen Basin, Queensland (Fielding et al., 1990; Baker et al., 1993).

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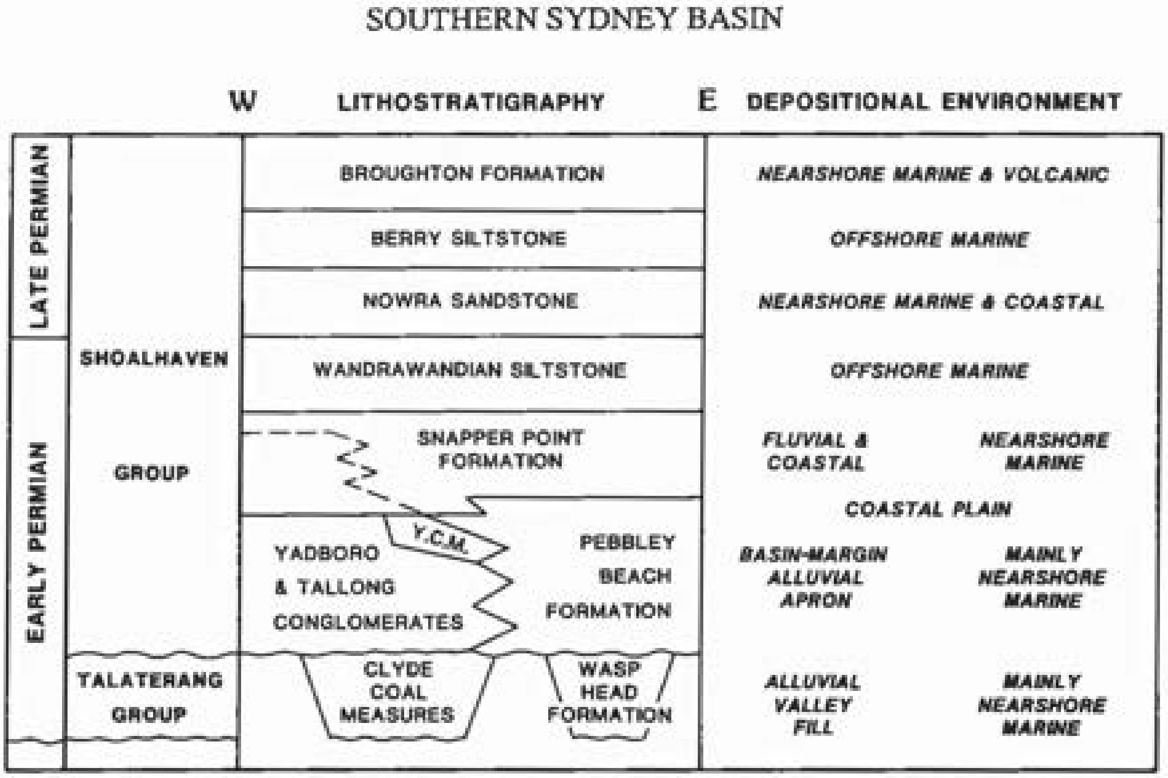

Figure 1. Revised stratigraphy for the Talaterang and Shoalhaven Groups in the southernmost Sydney Basin. See text for details of revisions.

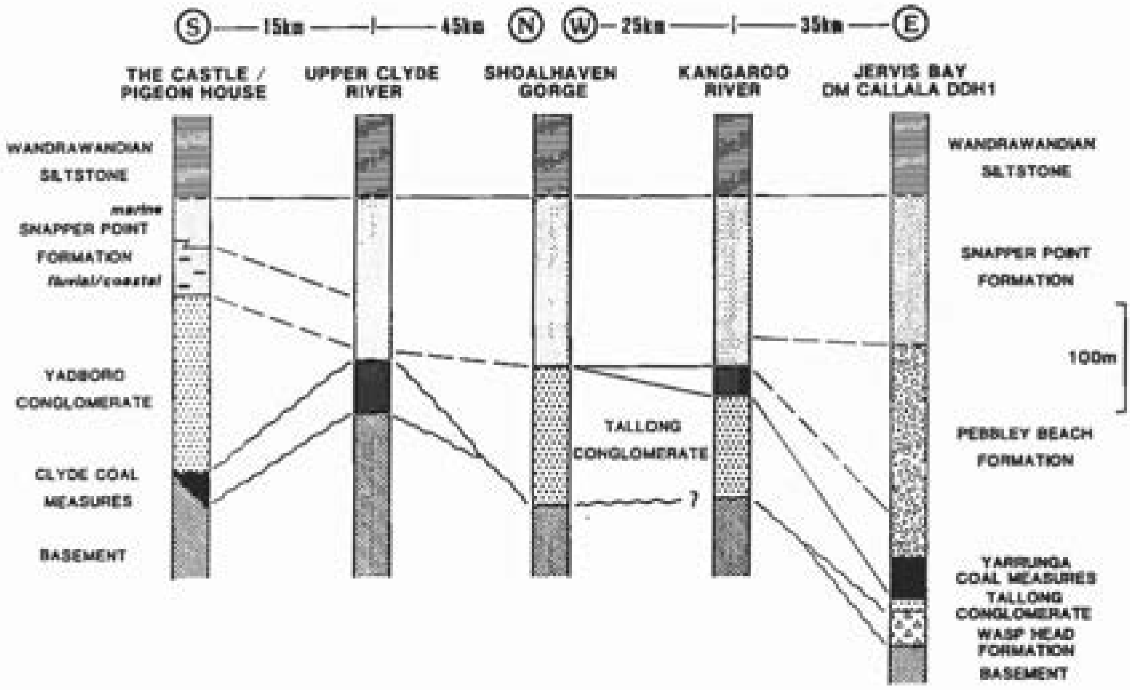

Figure 3. Revised stratigraphic correlations between key outcrop areas in the southernmost Sydney Basin (cf. Herbert, 1980). Note the strongly disconformable base of the Yadboro/Tallong Conglomerates and equivalents.

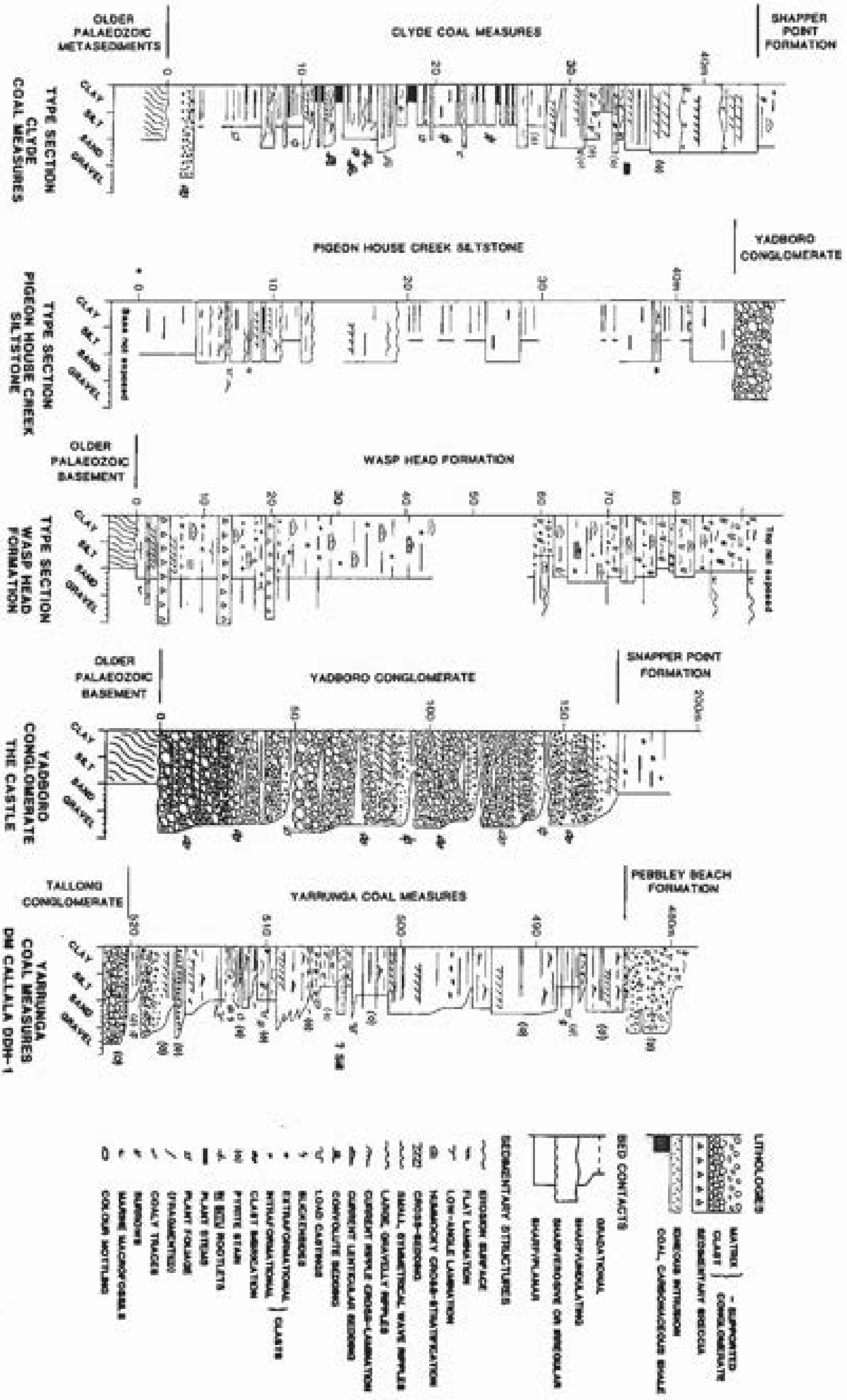

Figure 2. Graphic logs of key sections through the Clyde Coal Measures, Pigeon House Creek Siltstone, Wasp Head Formation, Yadboro Conglomerate and Yarrunga Coal Measures.

SEDIMENTOLOGY OF THE TALATERANG & SHOALHAVEN GROUPS IN THE SOUTHERNMOST SYDNEY BASIN

S.C. TYE[1] & C.R. FIELDING[2]
[1] Dept. of Geology, The University of Wollongong
[2] Dept. of Earth Sciences, University of Queensland

This paper forms a companion to Fielding and Tye (1994) which reinterprets the lower to middle Permian stratigraphy of the southernmost Sydney Basin. In that paper the two group names have been retained (i.e. the Shoalhaven and Talaterang Groups) but considerable rearrangement of formations is proposed. Much of the confused stratigraphic interpretations of the past have resulted from incorrect or vague descriptions of the sedimentology of the various units (e.g. Herbert, 1980; Evans et al., 1983; Evans, 1991). This paper will address the sedimentology of early to middle Permian formations within the southernmost part of the basin in an attempt to clarify both the stratigraphy and palaeogeography.

SEDIMENTOLOGY

Detailed sedimentary sections were measured through all of the units discussed below. Sections appear as Figure 2 in Fielding and Tye (1994).

1. Talaterang Group

a) Clyde Coal Measures: The known outcrops of the Clyde Coal Measures were visited, Bunnair Creek, Budawang Creek and the type section of McElroy and Rose (1962) in the upper Clyde Valley. The lower part of the type section consists of pebble conglomerate at the base, overlain by interbedded fine- and medium-grained sandstones, siltstones and coal. Sandstone is ripple laminated and trough cross-bedded. Siltstone is carbonaceous with abundant plant debris. Coal seams are found in intimate association with carbonaceous siltstone. Coal is typically bright and thin banded. A maximum coal seam thickness of 96cm was observed in the upper Clyde River at site of a 20m long adit.

Towards the top of the upper Clyde River section lateral accretion surfaces are preserved within a 1.5m thick unit of sandstone. McElroy and Rose (1962) incorrectly interpreted the contact between this unit and the overlying unit as an angular unconformity. This unit is overlain by a succession of carbonaceous siltstone beds which are pyrite stained and strongly bioturbated. The top of the formation is marked by a thick succession of medium-grained sandstone beds with trough cross-bedding and ripple cross-lamination. Some of these sandstone units are erosionally based, cutting down into underlying units. Palaeocurrent data from this sequence show a bimodal distribution.

The Clyde Coal Measures are interpreted as alluvial deposits. Palaeocurrent data suggest sediment dispersal was towards the **north** (Fig. 1). The absence of thick channel bodies within the sequence suggests a low energy mud-rich system. Some coarse sediment was transported in small, probably sinuous channels. Towards the top of the succession bimodal palaeocurrent distribution and pyrite staining suggest a tidal influenced coastal environment with the thick cross-bedded sandstones representing probable estuarine channel systems. The Clyde Coal Measures are directly overlain by inner marine shelf deposits of the Snapper Point Formation.

b)Pigeon House Creek Siltstone: The Pigeon House Creek Siltstone crops out below the Yadboro Conglomerate in the vicinity of Pigeon House Creek. A section was measured (Fig. 2; Fielding and Tye, 1994) at Cambage Head near the junction of the Clyde River and Pigeon House Creek and is the type section for the formation as described by McElroy and Rose (1962). The succession consists of ripple cross-laminated and trough cross-bedded fine-grained sandstones and thin bedded carbonaceous grey fine sandstone to siltstone. Palaeocurrent data suggest unequivocally that sediment dispersal was towards the **north** (Fig. 1).

The sequence is interpreted as an alluvial deposit. The facies assemblage is very similar to that described above for the Clyde Coal Measures except that coal is absent. The similarity of the facies and the direction of sediment dispersal suggest that the Clyde Coal Measures and the Pigeon House Creek Siltstone are **facies equivalents**.

c)Wasp Head Formation: The Wasp Head Formation is currently known only from a small stretch of coastline south of South Durras, near Batemans Bay. The basal part of the Wasp Head Formation consists of four lenticular sedimentary breccia units up to approximately 3m thick interbedded with lithic pebbly sandstone. The breccia beds are composed of highly angular clasts up to several metres in diameter. They are poorly sorted and internally chaotic with a silt-rich matrix. Clast petrology is dominated by the lithologies from the underlying Ordovician Wagonga Beds, i.e. phyllite and minor black chert. Many of the large clasts within the breccias show imbrication suggesting palaeoflow towards the **east-southeast**. The four breccias thin towards the east with the uppermost unit developing a sandstone parting also towards the east. The sandstones in this part of the sequence are flat and low angle laminated, ripple cross-laminated, trough cross-bedded and hummocky cross-stratified. Rare bioturbation and molluscs are present. Palaeocurrent data from the cross-bedded sandstone suggest deposition from **northwestward**-flowing currents.

The formation consists of two fining upward sequences. The basal succession (described above) is succeeded in the middle part of the sequence by massive and amalgamated hummocky cross-stratified (HCS) sandstone which, in turn, is overlain by interbedded abundantly bioturbated siltstone, HCS sandstone and thin large scale symmetrical wave rippled conglomerate beds. The base of the second sequence abruptly overlies the interbedded siltstone and sandstone assemblage at the top of the first succession. It consists of a 6m interval of medium-grained swaley cross-stratified sandstone (SCS) which fines upwards into thick bedded abundantly bioturbated siltstone with thin interbeds of flat laminated and HCS sandstone. Dropstones and coalified log impressions are common throughout the upper part of the formation.

The Wasp Head Formation is interpreted as a shallow marine succession containing two deepening-upward sequences. The lower part of the unit probably represents foreshore to inner shoreface environments with active longshore currents. Massive sandstone, amalgamated HCS and SCS represent deposition on the upper shoreface. The interbedded bioturbated siltstone and HCS sandstone are lower shoreface/transition offshore deposits. The interpretation of the sedimentary breccia units within the Wasp Head Formation is critical for both palaeogeographic and stratigraphic interpretations. The breccias are interpreted as debris flows derived from the west. We have found no evidence that they are glacial related debris flows as proposed by Gostin (1968). The grade, texture and fabric of the breccias suggest local derivation from a steep, tectonically active slope. Eastward palaeoflow suggests derivation from a north-trending structure, possibly the western margin of a graben or half graben related to an early phase of extension (cf. Fielding et al., 1990).

d) Related units: Several units have been encountered at the stratigraphic level of the Talaterang Group which cannot be classified as either the Clyde Coal Measures or the Wasp Head Formation. A silty matrix supported conglomerate occurs at the base of Callala 1 and has been previously identified as Tallong Conglomerate by Herbert (1980). This unit, however, definitely underlies the Tallong Conglomerate which is clast supported with a sandy matrix. The contact between the two units is sharp and the top of the matrix supported unit shows a clear weathering profile. The basal 2m of Elecom Clyde River 12 (62.4-59.8m) also consists of a silty matrix supported breccia. The clasts are angular and elongate, and composed almost entirely of basement phyllite.

It is here suggested that these basal units are equivalent to the strata described above. Alternatively, they may represent an earlier depositional episode, perhaps of Carboniferous age.

It is suggested that the term Clyde Coal Measures should be used for all non-marine strata at this stratigraphic level in the southern Sydney Basin (Fielding and Tye, 1994).

2. Shoalhaven Group

a) Yadboro and Tallong Conglomerates: The Yadboro Conglomerate crops out in the vicinity of Yadboro within the Budawang Range, at the southern extremity of the Morton National Park. In this area the Yadboro Conglomerate is composed of five distinct depositional cycles delineated clearly by vegetated benches along cliff lines at Byangee Walls and The Castle. Each depositional cycle is a crude fining-upwards sequence, approximately 25-50m thick. The base of each cycle consists of poorly sorted, clast-supported, cobble to boulder conglomerate with a maximum clast size in the range 20-40cm. Clasts are typically subrounded to well rounded and are dominated by basement quartzite, quartz and phyllite. The matrix is poorly sorted but is dominated by sand-sized sediment. Individual beds are difficult to discern within stacked conglomerate sequences but they seem to be dominated by planar cross-bedded units and flat stratification. Sandy facies become more prevalent upwards within each cycle. Sandstone is medium- to coarse-grained and dominated by flat lamination and trough cross-bedding. Sandstone beds may be laterally persistent, lenticular bodies or small (approximately 2-3m wide and 25cm deep) scour fills. Clast size within conglomerate units also decreases upwards within each cycle. The top of each cycle is marked by a thin bed of light grey siltstone up to 40cm thick.

The Yadboro Conglomerate reaches a maximum thickness of approximately 180m in the vicinity of Pigeon House Creek and the western end of Byangee Walls, and forms an east facing lobe (Fig. 2) which extends approximately 25km north-south and 20km east-west. Palaeocurrent measurements taken from imbricated clasts and cross-beds indicate east to southeast palaeoflow (Fig.1).

Outcrops of the stratigraphically equivalent Tallong Conglomerate are to be found in the vicinity of Tallong, Marulan and within the Shoalhaven Gorge downstream of Tallowa Dam. The formation consists of identical facies to the Yadboro Conglomerate and has a maximum thickness of 214.3m (Long Swamp DDH, 1889). Palaeoflow was towards the east (Fig.1).

The Badgery's Breccia crops out beneath Badgery's Lookout on the edge of the Shoalhaven Gorge where it unconformably overlies older Palaeozoic basement. At the base it consists of angular to sub-rounded cobble to boulder sized clasts of basement lithologies within a medium to very coarse sand matrix. It is poorly sorted and mainly clast supported. Imbrication data collected from large clasts within this unit suggest palaeoflow towards the east. The unit passes upwards into stratified facies with more rounded clasts, which in turn are overlain by shallow marine facies of the Snapper Point Formation. The facies within the Badgery's Breccia are typical of the Tallong and Yadboro Conglomerates.

An outcrop of conglomerate, identical to both the Tallong and Yadboro Conglomerates, was also encountered at Touga Creek (GR 8928-365251) in an area between the two lobes of the Yadboro and Tallong Conglomerates.

The Yadboro and Tallong Conglomerates are interpreted as high energy alluvial braidplain deposits. Conglomerate facies represent bar or sheet deposits. Sand facies are interpreted as minor channel and slack water deposits. The Badgery's Breccia is also a stream flow deposit and simply represents the basal facies of the Tallong Conglomerate. The Tallong and Yadboro Conglomerates are interpreted as a semi-continuous alluvial sheet that was initiated during a passive phase of thermal subsidence across the whole basin. There is no evidence that the Tallong and Yadboro Conglomerates represent sediment infills of glacial incised valleys as proposed by Herbert (1972).

b) Yarrunga Coal Measures: Coal measures have been reported stratigraphically above the Tallong Conglomerate in Kangaroo River (Herbert, 1980), DM Callala DDH 1, Genoa Oil Coonemia 1, Bellambi Shoalhaven DDH1 and most of the Yarrunga Creek bores.

In DM Callala DDH 1 (520.5-483.4m) the coal measures consist of interbedded siltstones and fine- to medium-grained sandstones. Sandstones are flat laminated, ripple cross-laminated and cross-bedded with many beds fining upwards to siltstone. Siltstones are carbonaceous with abundant plant debris, flat laminated in part and are typically pyrite-stained. Both sandstones and siltstones are sparsely bioturbated.

The Yarrunga Coal Measures are interpreted as being deposited in a coastal plain environment and consist of distinctly different facies to the Clyde Coal Measures. The Yarrunga Coal Measures are a part of a sandy fluvial succession that lies above the Tallong and Yadboro Conglomerates and are represented in the Yadboro area by the uppermost bench on the lower cliffline of The Castle and Byangee Walls. This fluvial sequence is equivalent stratigraphically and supplied sediment to the marine Snapper Point Formation to the east (Fielding and Tye, 1994).

c) Pebbley Beach Formation: The Pebbley Beach Formation is the basal marine facies representing the initial stage of a major marine phase over much of the southern Sydney Basin, which ended with the deposition of the Wandrawandian Siltstone. In inland areas the formation is poorly exposed but consists of hummocky cross-stratified, fine, bioturbated sandstone with minor pebbly lag conglomerate. At coastal exposures (Point Upright) the formation is considerably finer-grained.

The Pebbley Beach Formation is a shallow marine deposit probably laid down on the upper shoreface and foreshore. It represents the initial drowning by the sea and hence overlies fluvial and coastal plain facies (Yarrunga Coal Measures). It also overlies Clyde Coal Measures or basement where the fluvial facies were absent or thin enough to be eroded by the transgression.

d) Snapper Point Formation: The Snapper Point Formation is dominated by shallow marine facies. Fluvial and shallow marine facies are interbedded in the western part of the area, within the vicinity of the Yadboro Conglomerate. These represent the Jindelara fluvial facies of Evans et al.,(1983). Fluvial facies consist of coarse pebbly sandstones with abundant trough and planar cross-bedding. Marine facies are dominated by HCS and bioturbated siltstones. The contact with the underlying Pebbley Beach Formation is sharp to gradational.

e) Overlying formations: The Wandrawandian Siltstone represents the maximum flooding of the southern Sydney Basin during the Permian. A subsequent regression led to the deposition of the Nowra Sandstone represented by the uppermost cliffline at The Castle. The Berry Siltstone and Broughton Formations represent a final transgression and regression within the Shoalhaven Group.

PALAEOGEOGRAPHY

The interpreted depositional development of the sequence is illustrated in four stages (Fig. 3).

1) Deposition began with the Clyde Coal Measures (alluvial) and Wasp Head Formation (marine) within grabens or half grabens possibly related to extension comparable to the Reids Dome Beds in the Bowen Basin (Fielding et al., 1990). Palaeoflow within the Clyde Coal Measures was to the north, representing axial drainage, parallel to graben margins (Fig. 3A). Some transverse sediment supply is indicated by, for example, the Wasp Head Formation breccias.

2) Passive thermal subsidence ensued, resulting in a major marine transgression across the entire basin. High energy braidplain fluvial systems deposited coarse sedimentary sheets from the west. Palaeo-valleys filled by the Tallong and Yadboro Conglomerates, acted as depocentres within major transverse fluvial depositional systems. The eastern and central parts of the area were drowned by the initial marine transgression (Pebbley Beach and Snapper Point Formations, Fig. 3B).

3) A decrease in energy within the fluvial system due to a rise in relative sea-level and erosion of the source area led to a more quiescent environment. Finer grained, sandy facies characterised these fluvial deposits. The Yarrunga Coal Measures accumulated on coastal plains during this phase on elevated platforms created by the pre-existing alluvial system. The fluvial system continued to feed sediment to the marine Pebbley Beach and Snapper Point Formations in eastern and central areas. As the marine conditions continued, the fluvial system was gradually drowned and shallow marine sedimentation (Pebbley Beach and Snapper Point Formations) spread over the entire area (Fig. 3C).

4) A major transgression occurred and offshore, marine sediments accumulated over much of the area to form the Wandrawandian Siltstone (Fig. 3D).

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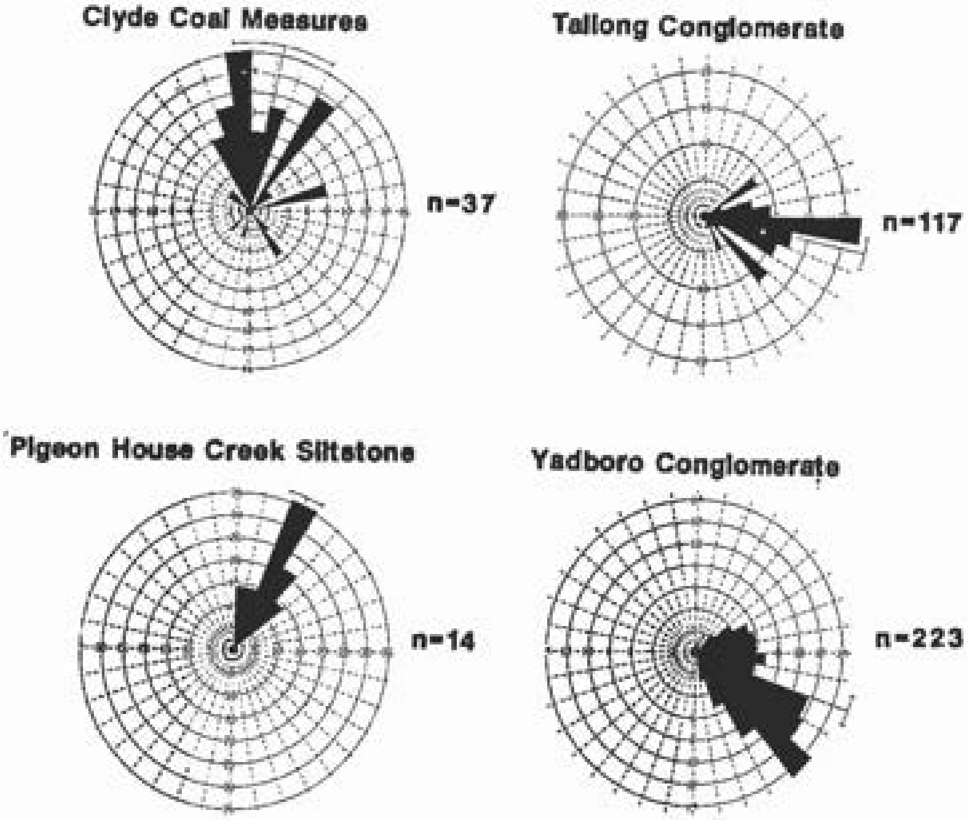


Figure 1. Summary of Palaeocurrent data for Clyde Coal Measures, Pigeon House Creek Siltstone, Yadboro Conglomerate and Tallong Conglomerate.

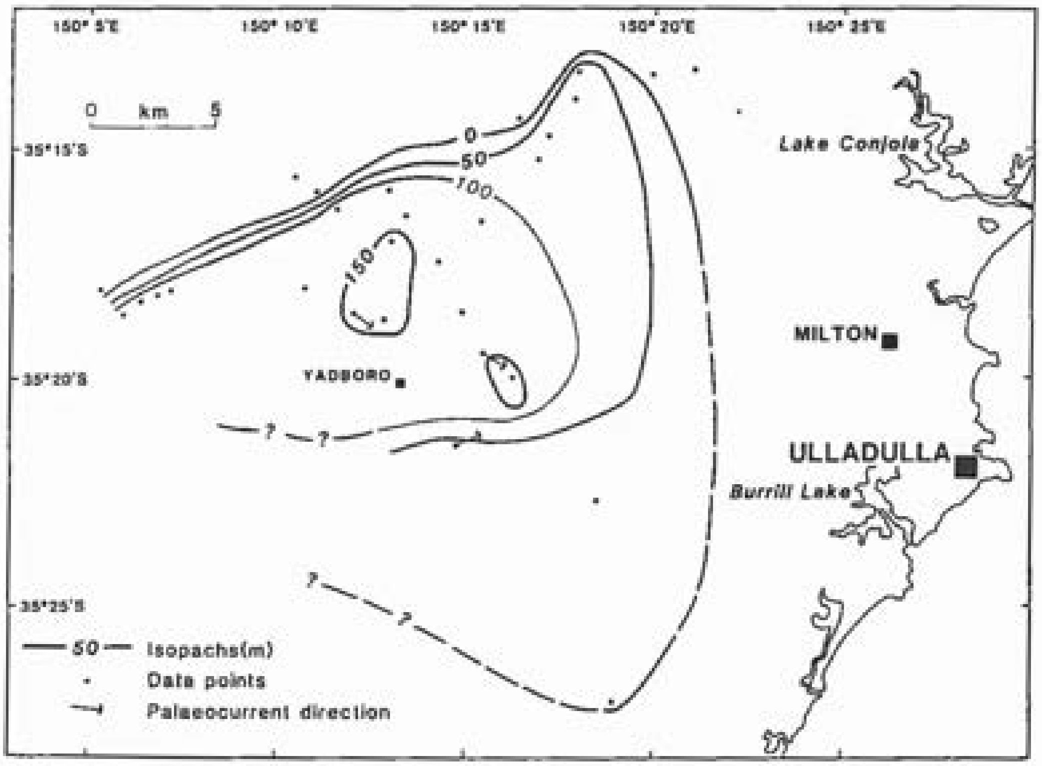


Figure 2: Isopach Map for Yadboro Conglomerate.

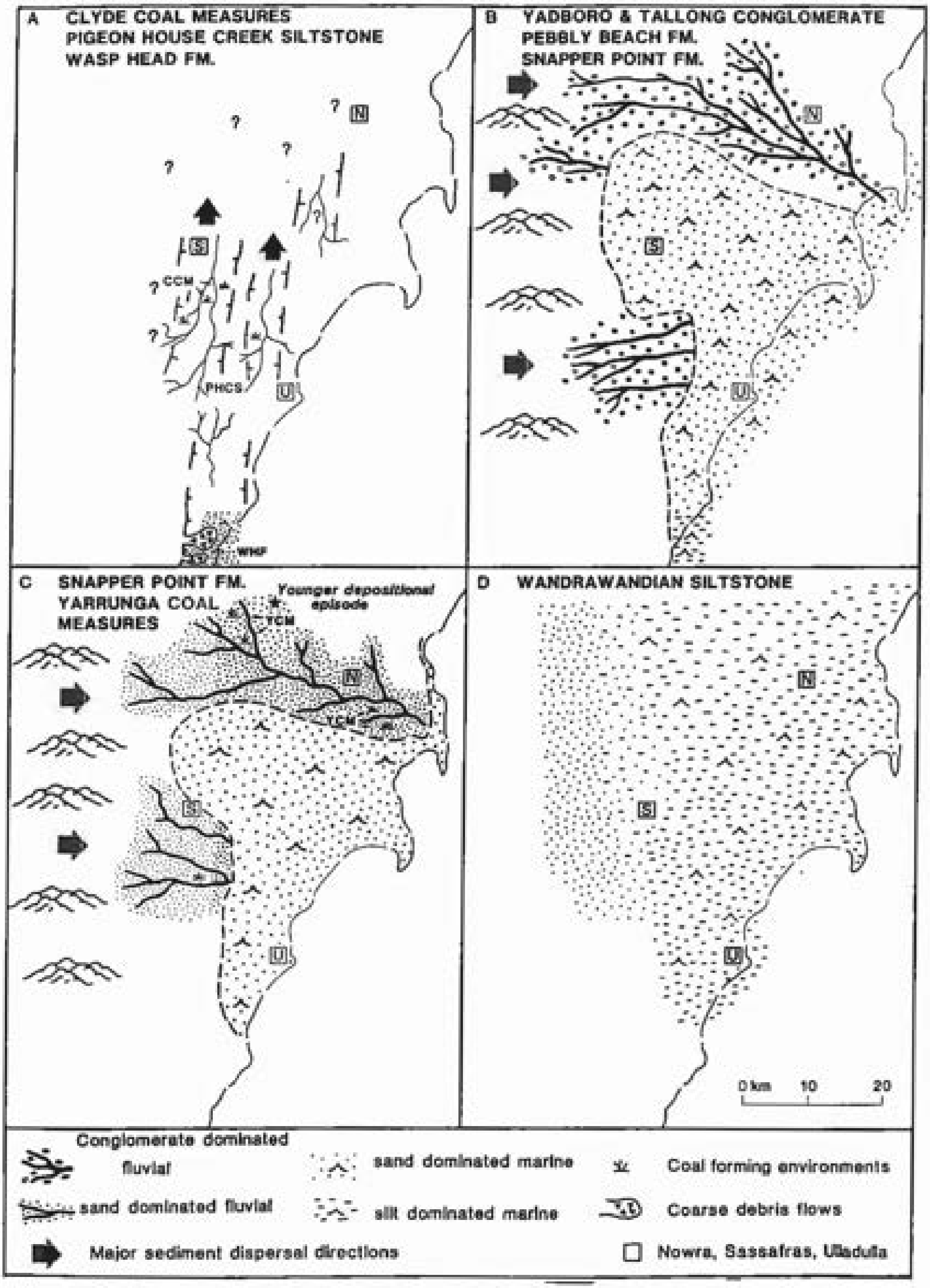


Figure 3: Schematic representation of palaeogeographic development for the southern Sydney Basin during the Early to Middle Permian. CCM: Clyde Coal Measures, PHCS: Pigeon House Creek Siltstone, WHF: Wasp Head Formation, YCM: Yarrunga Coal Measures. Refer to text for detailed discussion.

APPLICATION OF FACIES & ARCHITECTURAL ANALYSIS TO OPENCUT COAL MINING : THE LATE TRIASSIC CALLIDE COAL MEASURES, EAST-CENTRAL QUEENSLAND

P.J. JORGENSEN & C.R. FIELDING
Dept. of Earth Sciences, University of Queensland

INTRODUCTION

The Late Triassic (Carnian - Rhaetian) Callide Coal Measures are preserved in a partly fault-bounded basin remnant near Biloela in east-central Queensland. The basin is thought to have formed as a late orogenic, intermontane trough during the latter stages of the Hunter-Bowen Orogeny. The preserved sequence comprises up to 150m of clastic sedimentary rocks interbedded with coals which include one of the thickest black coal seams in Australia (the Callide Coal Seam, up to 23m thick). Coal is mined by opencut methods in several discrete areas within the preserved Callide Basin.

The succession grossly fines upward, comprising a lower, conglomerate-dominated association which contains virtually no coal, and an upper finer-grained association containing all significant coal seams. The contact between the two associations is an abrupt gradation in most areas. The upper association is dominated by sandstone, heterolithic sandstone/siltstone and siltstone. Coals are typically high in ash, interbedded with clastic strata and strongly compositionally banded. The thickest seam in the sequence has conventionally been referred to as the Callide Seam. Rather than being a single, extensive coal body, however, this seam is now known to be a mosaic of component seams which overlap each other in a complex fashion. The internal geometry of the Callide seam in the southernmost part of the preserved basin is illustrated in Figure 1. Component seams are separated by clastic partings which vary locally in thickness up to several metres; these range in grain-size from claystone to coarse sandstone.

The Callide Coal Measures have been interpreted as an alluvial plain assemblage by previous workers. These studies have established a high-energy, high gradient alluvial origin for the lower, conglomeratic association, and a low gradient, lower energy alluvial plain environment for the coal-bearing association. The present study builds on the results of previous work, and in particular examines the three-dimensional geometry and architecture of clastic and organic facies, and their mode of formation. The study is relevant to mining of the Callide seams, for a variety of reasons; 1. gross distribution of lithologies affects pit design (particularly given the pronounced present-day topography across the mine area), and choice of drill pattern and explosive charge for overburden blasting, 2. distribution and grade of clastic inter- and overburden in places shows a relationship with coal quality, and 3. an understanding of facies geometry (particularly that of seam partings) in three dimensions is critical to effective mining in a situation where coal is extracted by mechanical excavator and despatched to customers without any washing or other treatment.

FACIES ANALYSIS

A suite of nine lithofacies are recognised within the Callide Coal Measures (Table 1), representing a modification of previous schemes. The lower association is dominated by Facies A and B (high-energy, coarse-grained alluvial channel deposits and associated lower energy deposits). These facies are largely restricted to the lower association, occurring only rarely within the coal measures proper. The other seven facies (C–I) characterise the upper coal-bearing association, and are interpreted as deposits of major alluvial channels, crevasse splay and other floodplain entities, and peat-forming wetlands (Table 1). The facies assemblage is typical of alluvial coal measures, in containing a limited variety of floodbasinal (non-channel) facies, no minor mouth bar deposits such as are typical of delta plain assemblages, and no evidence of marine influence on sediment deposition. The complex internal geometry of coal bodies and interbedding with clastic partings is also considered characteristic of alluvial coal measure sequences.

Throughout the preserved basin, palaeocurrent data from major channel deposits (Facies C) indicate southward alluvial drainage and sediment dispersal (Fig. 2). Within the mine section in the southern (Dunn Creek) area, a series of maps have been compiled to show the three-dimensional geometry and architecture of facies (Fig. 3). These maps, based on successive splits within the Callide Seam (Fig.1), show a number of important relationships which allow the origin of the various facies to be constrained (Table 1). The maps illustrate the point that clastic sedimentation occurred contemporaneous with accumulation of the Callide Seam. Coarse clastic sediment deposition was consistently limited to the western and eastern fringes of the present mine area, leaving a "core" of essentially continuous, thick coal (up to 23m) in the central area. Maps are based on data from a dense network of boreholes (illustrated in Fig. 3), and highwall exposures.

FACIES MAPS

The lowest split mapped (**C62/C7**) shows the edge of a major channel belt on the western edge of the mine area, and an elongate splay lobe projecting eastward across the central area. A further such lobe occurs in the east, possibly derived from the northeast. The two lobes coalesce in the centre of the map, flanked by an elongate but laterally extensive area of floodbasin mudrocks. Continuous coal occurs in areas distant from these clastic systems.

The overlying **C61/C62** split shows a continuation of the same alluvial channel belt as in the previous map, in the extreme west. An elongate, thread-like play runs eastward from the edge of the major channel body into the central area and is flanked by a broader area of floodbasinal mudrock. Peat accumulation continued unabated in the east.

The C5/C6 split map shows once again evidence of major channel activity in the extreme west and a splay/floodbasin mudrock unit projecting eastward across the western half of the mine. This may be a continuation of the system mentioned above, suggesting positional stability of the western channel belt over a considerable period of time. The extreme edge of a further clastic sediment belt is recorded in the east, composed mainly of floodbasinal mudrocks. Peat accumulated in the central area, continuous with the underlying seams.

In the C4/C5 split map, a major, north–south elongate, channel sandstone body is preserved in the eastern half of the mine, marking a distinct lateral shift in channel belt location. Palaeocurrent data from outcrop indicate southward sediment dispersal. The channel belt is flanked on both sides by areas of floodbasin mudrock. Peat accumulated continuously in the central area, and a lobe of mudrock is preserved in the far northwest.

The C3/C4 map shows re–establishment of the eastern channel system and flanking overbank deposits after a period of peat accumulation (Fig. 1). Peat accumulation continued without a break in the central area, but the edge of a further channel belt is recorded in the far southwest. A possible splay body is preserved in the northwest.

Similar patterns are recorded in the overlying C22/C3 split, with pronounced expansion of clastic systems westward and eastward into the mine area. The eastern channel belt was re–established following a period of peat accumulation, and lobate to elongate splay bodies are associated with its western margin. A further major, elongate splay body tapers southward across the central area, while at least two splay bodies and their parent channel body are preserved in the west. Palaeocurrent data from one of these splays demonstrates its derivation from the west. Figure 4 presents a more detailed version of this map, in order to show facies geometries more clearly.

SYNTHESIS

The facies maps presented illustrate both the external geometry of the different facies and their arrangement in three–dimensional space. Channel belts are mainly north–south elongate (consistent with palaeocurrent data), and up to 2200m wide. The limited spread of palaeocurrent directions, and the sheet–like internal geometry of Facies C, suggest deposition in rivers of low sinuosity. This is further supported by the presence of "islands" of fine–grained sediments within channel belts at the C4/C5 and C3/C4 levels, interpreted as channel braids. Some channel belts were positionally stable over long periods, while others were temporarily abandoned and later re–established in the same position.

Channel belts are flanked by relatively narrow belts of overbank deposits: clearly, sediments were confined to channels except in major floods, perhaps as a result of compactional loading of the channel belts into underlying peat. At times, however, coarse sediment was introduced into peat mires via splays, probably caused by breaching of channel banks during floods. Such splays led to the deposition of mostly elongate (rather than lobate) bodies of sand, again flanked by areas of mud deposition. Some of these bodies range up to 2500m in length and 1000m in width. Some channel belt margins show multiple splay bodies along their mapped length.

While clastic sediments were being deposited in parts of the studied area, peat accumulation continued uninterrupted in other parts leading to the complex seam geometry described. The preservation of relatively low-ash coal (c. 20%) adjacent to sites of active clastic sedimentation requires explanation: the combined effect of incision of coarse clastic bodies and compactional loading into peat may have been to lower the topographic elevation of clastic systems, thereby restricting overbank sedimentation.

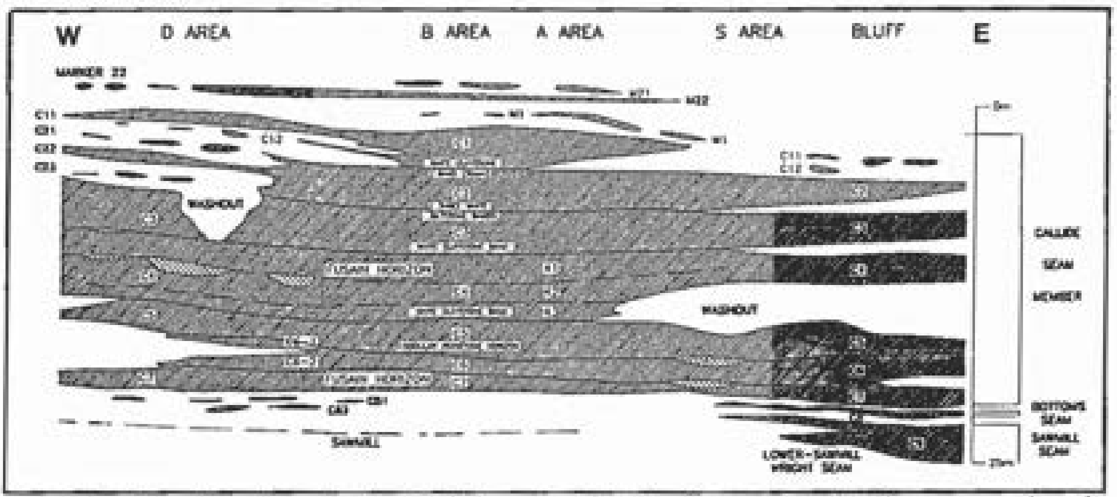


Figure 1 – Stratigraphy of the Callide seam in the Dunn Creek mine area, showing complex arrangement of component coal plies.

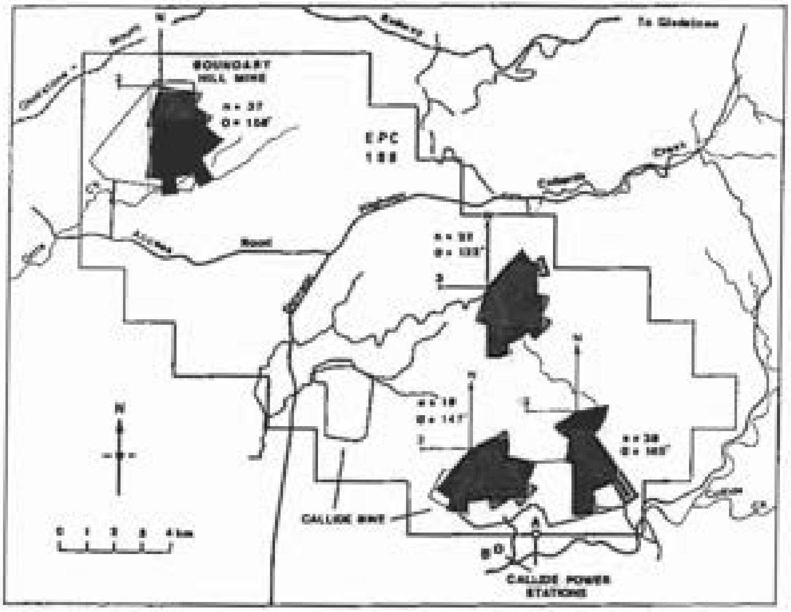


Figure 2 – Map showing palaeocurrent data gathered from channel sandstones (Facies C). Southward sediment dispersal is indicated consistently across the basin.

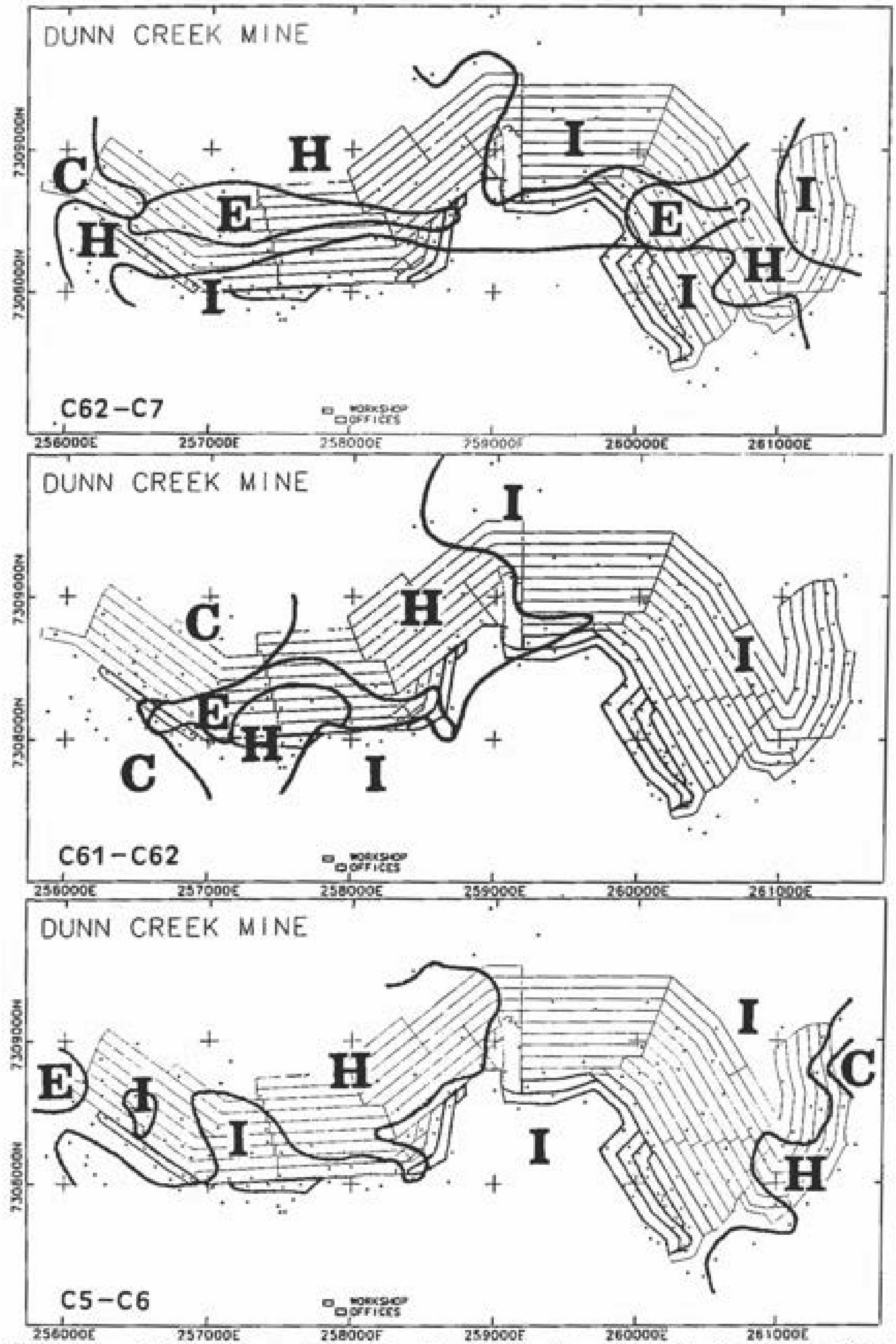
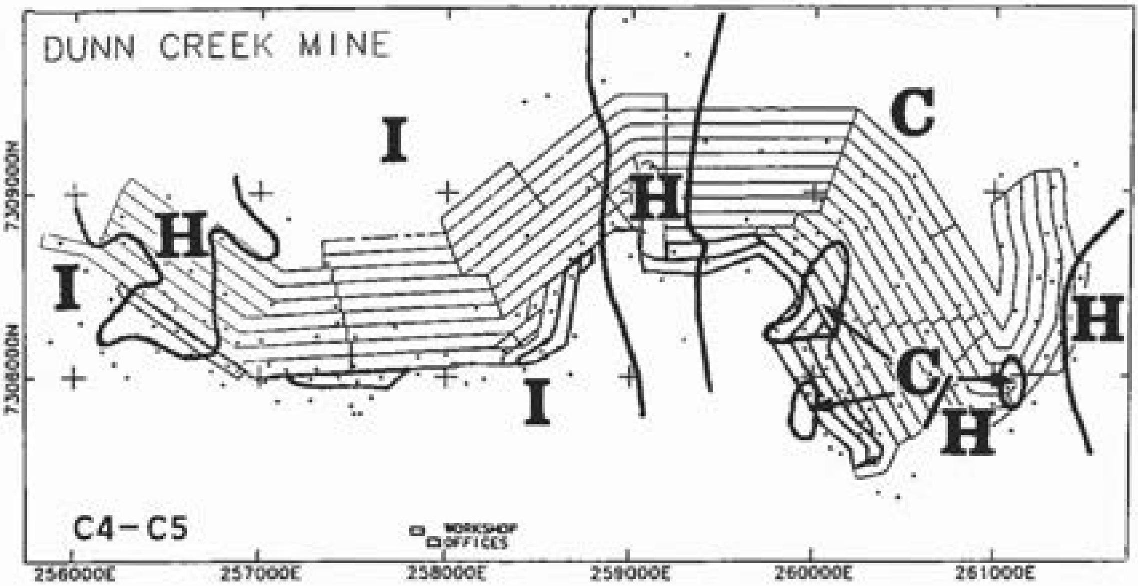
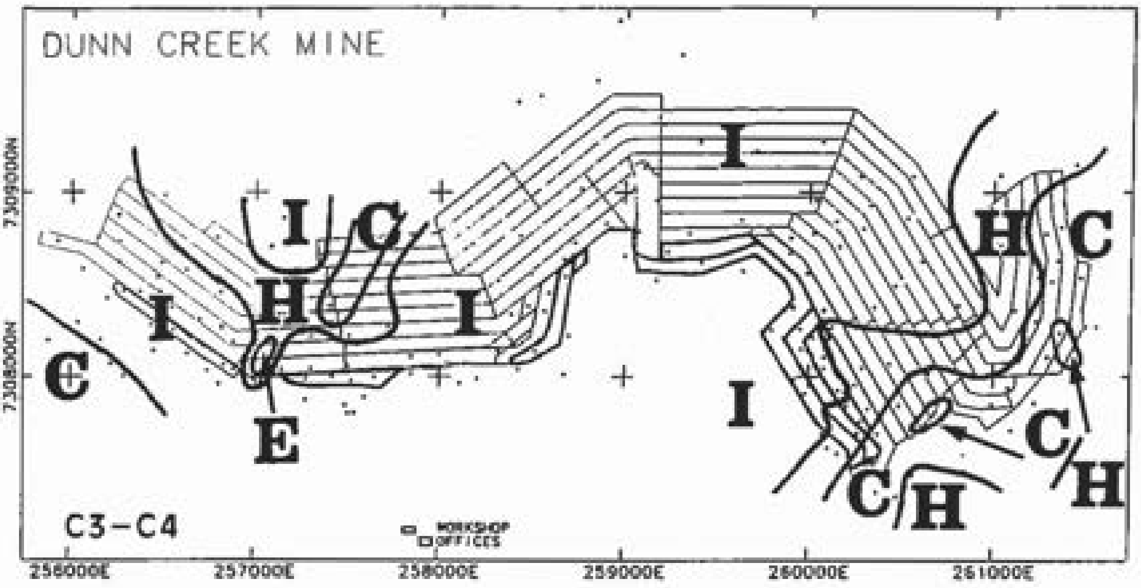
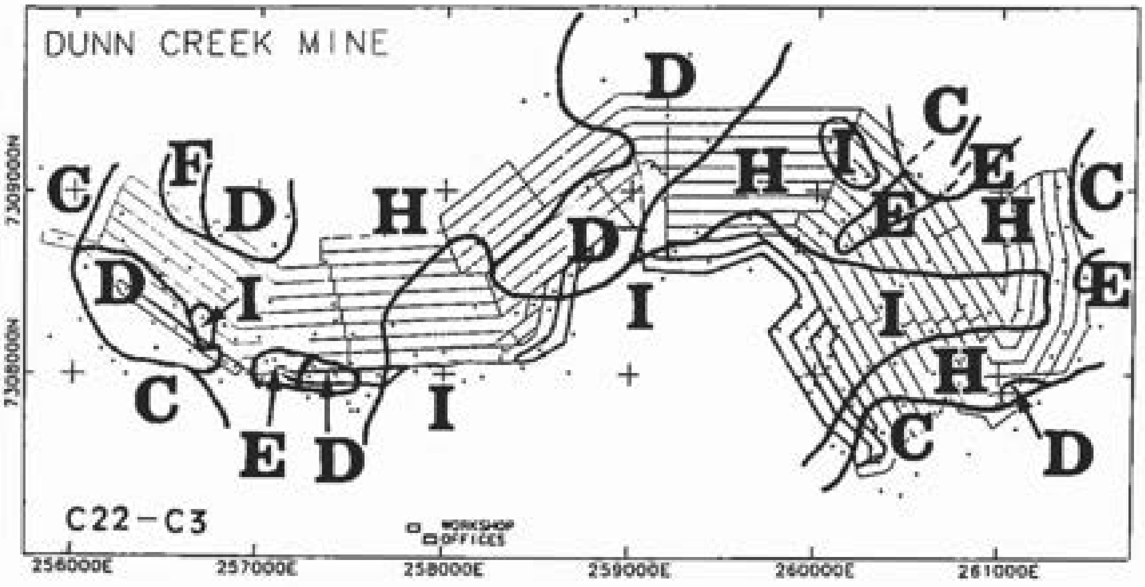


Figure 3 – Series of maps showing the distribution of lithofacies (Table 1) in successive splits of the Callide Seam in the Dunn Creek area (Fig. 1). See text for details.

FACIES ANALYSIS, CALLIDE BASIN







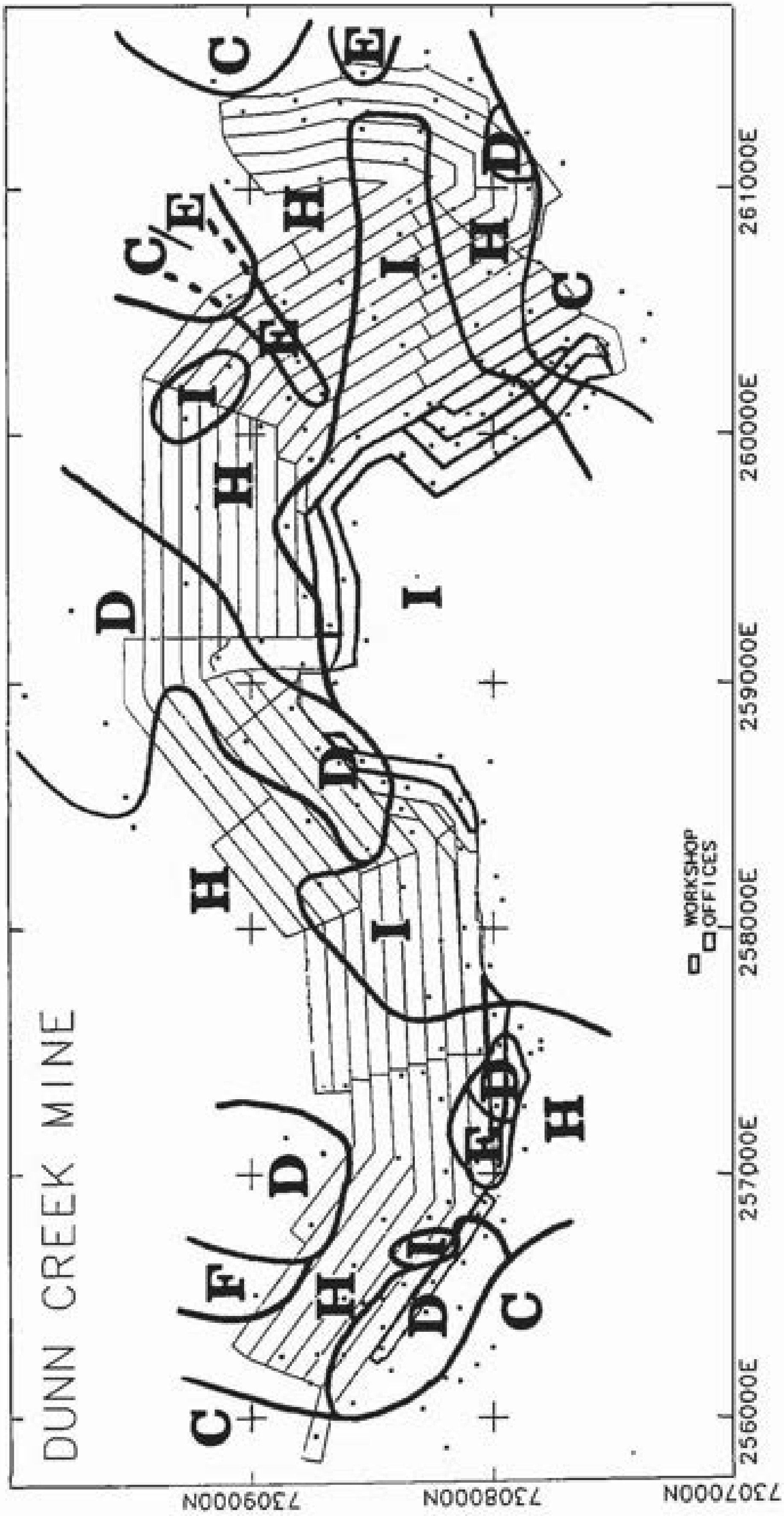


Figure 4 – Larger-scale facies map of the C22/C3 split, showing lithofacies.

Table 1 – Characteristics of Callide Coal Measures lithofacies.

Facies	Interpretation	Lithology	Sedimentary structures	Geometry
A	Hyperconcentrated flood flow in high-gradient alluvial channels.	Pebble to cobble conglomerate, clast and matrix supported, sandy matrix, sharply based units <20m thick, some with fining-upward trend.	Crude flat bedding, scoured bases to some beds, rare trough cross-bedding.	Laterally extensive.
B	Waning-flow deposits associated with Facies A.	Mostly coarse grained sandstone, some interbedded fine sandstone, siltstone and pebbly layers, sharply or gradationally based units <1.5m thick.	Flat lamination, ripple cross-lamination, some trough cross-bedding.	Laterally extensive.
C	Active fills of shallow, low sinuosity alluvial channels.	Fine to very coarse grained sandstone and minor granule to pebble conglomerate, sharply (planar or erosively) based fining up units <10m thick.	Small scale channel fills, small to large scale trough cross-bedding, minor ripple cross-lamination and flat lamination, load casts, shale clasts.	Elongate belts up to at least 2.2km wide.
D	Proximal, plant debris rich crevasse splays.	Fine to very coarse grained sandstone with abundant thin coaly traces, sharply (planar or erosively) based units <1.5m thick.	Trough cross-bedding, ripple cross-lamination, abundant coaly traces, siderite nodules associated with coaly material.	Elongate to lobate, up to at least 2km long and 1km wide.
E	Proximal crevasse splays.	Fine to coarse grained sandstone, minor siltstone partings, sharply based units <2m thick.	Flat lamination and ripple cross-lamination, rare trough cross-bedding.	Elongate to lobate, up to 2.5km long and 500m wide.
F	Distal crevasse splays.	Fine to coarse grained sandstone, coarsening upward from siltstone at base, units <4m thick.	Planar and trough cross-bedding, ripple cross-lamination, flat lamination (grain size banding).	Lobate.
G	Overbank (levee) deposits.	Thinly interbedded sandstone (fine to medium grained) and siltstone, units <4m thick.	Horizontal lamination, ripple cross-lamination, water escape structures, sandy streak.	Elongate belts parallel to channel deposits.
H	Suspension fallout in quiet-water, floodbasin environments.	Siltstone, massive to thinly bedded, units <7m thick, with tuffaceous claystone-siltstone beds (<1.1m).	Ripple cross-lamination, flat lamination, water escape structures, abundant plant rootlets.	Laterally extensive.
I	Peat mire.	Coal, carbonaceous siltstone with thin clastic partings and tuffaceous claystone/siltstone beds, units <23m thick.	Massive, banded and thinly laminated coal.	Laterally extensive; minor lens-shaped pods.

SEDIMENTOLOGY OF COALCLIFF SANDSTONE, SOUTHEASTERN SYDNEY BASIN : FLUVIAL INTERPRETATION BASED ON BOUNDING SURFACES & ARCHITECTURAL ELEMENTS

M.H. DEHGHANI & B.G. JONES
Dept. of Geology, University of Wollongong

SUMMARY

The Coalcliff Sandstone is the lowermost formation in the Late Permian to Middle Triassic Narrabeen Group. It excellently exposed along the coastal cliffs and shore platforms between Scarborough and Coal Cliff. Lateral profiles and architectural elements have been used to delineate up to five multistorey channel sand bodies, discriminated by hierarchical bounding surfaces, in the Coalcliff Sandstone. The internal architecture of the sandstone consists of a sixfold hierarchy of bounding surfaces.

The primary depositional elements within the channel sandstone are downstream accretion elements (DA) which can be seen as mesoforms and partly or totally preserved macroforms. Dominant lithofacies in these elements are St and Sp indicating deposition of 3-D sinuous crested dunes and 2-D straight crested dunes (using Ashley's, 1990 terminology) respectively. Other preserved elements are: overbank fines (OF); sandy bedforms (SB); gravel bars (GB); and lateral accretion (LA) deposits.

The Coalcliff Sandstone shows an overall fining upward sequence which was deposited in a low to intermediate sinuosity, mixed load fluvial channels. In the Coal Cliff area, it has an erosional contact with the underlying Illawarra Coal Measures and gradational lateral and vertical contacts with the Wombarra Shale.

INTRODUCTION

The Coalcliff Sandstone was first named by Hanlon *et al.* (1953) who measured its type section between Coal Cliff and Scarborough (Fig. 1a). Harper (1915) first recognised fluvial channels at the top of the Bulli Seam. Diessel *et al.* (1967) recognised three groups of strata above the Bulli Seam and considered a fluvial origin for the sandstone and conglomerate groups. A fluvial origin also was proposed for the Coalcliff Sandstone by Ward (1972), Jones (1986), Hamilton *et al.* (1987) and Reynolds (1988).

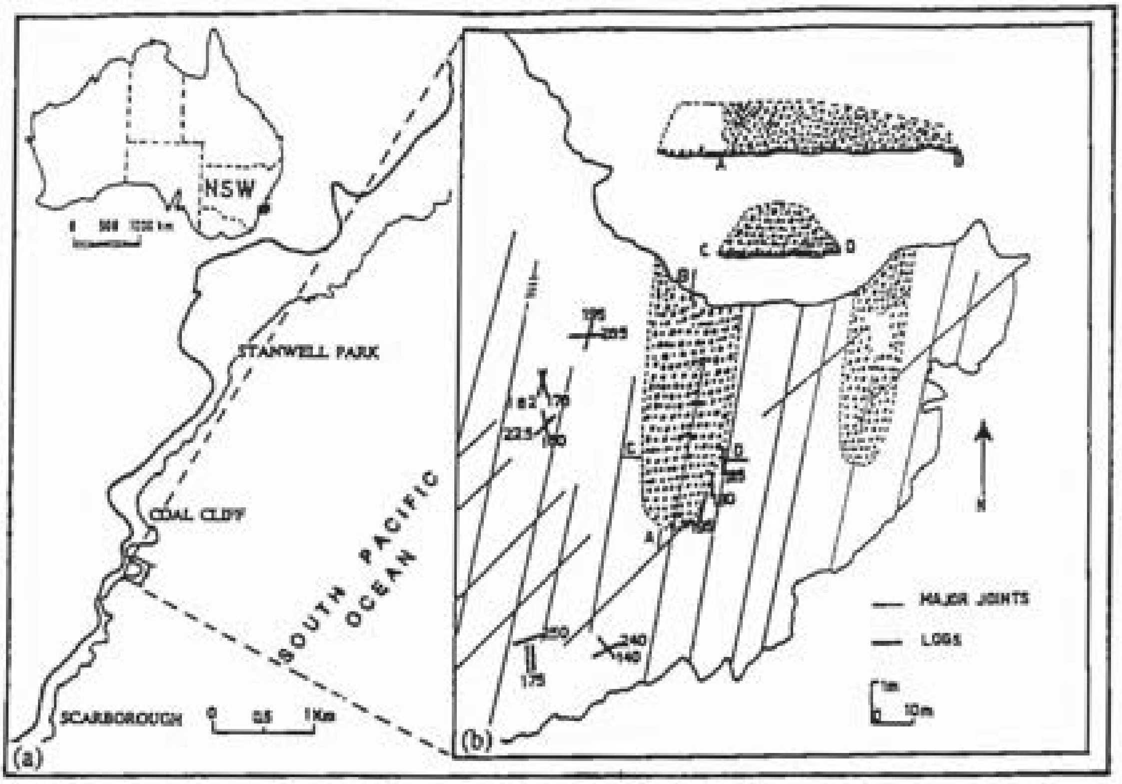


Fig. 1. (a) Locality map. (b) Detailed map of shore platform south of Coal Cliff, showing conglomeratic mesoform. This mesoform is interpreted as a longitudinal bar deposit, and its elongation is almost parallel to the palaeocurrent.

LOWER BOUNDARY

The Coalcliff Sandstone has an erosional contact with the underlying Illawarra Coal Measures. It has partly or totally eroded the clastic strata at the top of Bulli Seam, which is the most economically exploited coal seam in this area. In some localities (Fig. 2a, d), the erosional surface cut down to the Bulli Coal and eroded a small portion of the Bulli Seam. Major erosional surfaces can be produced by tectonic uplift and by eustatic sea level falls (Shanmugam, 1988), but usually these two factors act together and it is not easy to differentiate them.

The Coalcliff Sandstone is underlain by four different types of deposit. Three of these (the Bulli Coal; highly carbonaceous dark gray mudstone; and laminated shale and fine-grained sandstone; Fig. 2c) either belong to or have close affinity with the underlying Illawarra Coal Measures (Diessel *et al.*, 1967; Clark, 1992). The fourth lithology is a well laminated shale and fine-grained sandstone with ironstone bands which represents outwash or overbank sediments of the Coalcliff river (Dehghani & Jones, 1993).

BOUNDING SURFACES AND ARCHITECTURAL ELEMENTS

Laterally extensive exposures of the Coalcliff Sandstone along the coastal cliffs and shore platforms between Scarborough and Coal Cliff (Fig. 1a) were selected for this study. Both lateral and vertical facies changes were examined using architectural elements and bounding surface analysis as developed by Miall (1985, 1988a, b), following earlier work by Brookfield (1977, 1979) and Allen (1983).

HIERARCHY OF BOUNDING SURFACES

Six orders of bounding surfaces are recognised within the Coalcliff Sandstone (Fig. 2a). Their description and interpretation will be given below.

First and Second-order Surfaces: these surfaces record boundaries of cross-bed sets and cosets, respectively. Little or no internal erosion can be seen on these boundaries and they can be traced laterally for up to a few tens of meters. Second order bounding surfaces indicate a change in flow direction or conditions.

Third-order Surfaces: these surfaces bound the top of mesoforms (e.g. 2-D or 3-D dunes) or separate them within the macroforms (e.g. bank-attached or compound bars). These mesoforms show reactivation surfaces and dip in the general palaeocurrent direction, indicating down-stream accretion. Third-order surfaces extended tens of meters and are sometimes capped by fine-grained bar-top sediments. They indicate changes in bedform orientation or stage within the macroforms.

Fourth-order Surfaces: tops of macroforms are bounded by these surfaces. In the Coal Cliff area, the uppermost channel sandbody represents a preserved macroform which extended laterally for several hundreds of meters. This macroform starts with in-channel deposits at the bottom, and shows fine-grained ripple cross-laminated sandstone of levee or bar-top origin at the top. Immediately north of the Clifton Fault, the thickest (6.6 m) preserved macroform in the Coalcliff Sandstone can be seen. This macroform exhibits superimposed bedforms composed of: channel floor lag deposits; cosets of trough cross-bedded sandstone; cross-laminated sandstone; and vertically accreted overbank deposits at the top. Fourth-order surfaces bound the tops of these macroforms whereas third-order surfaces separate bar-top and in-channel deposits (Fig. 2a).

Fifth-order Surfaces: bound the lower parts of subordinate channels (Fig. 2a). The Coalcliff Sandstone in this area comprises up to five multistorey subordinate channel sandstone bodies. These show fining upward sequences (Fig. 2b) and the upper parts of earlier channel deposits were eroded by the succeeding channels. They are up to several hundreds of meters in lateral extent. The basal surface (fifth-order) is often covered by a single layer of intraformational ironstone bearing gravel (Fig. 2a) which represents channel floor lag deposits. These fifth-order surfaces are interpreted to be erosional surfaces produced by migrating macroforms.

Sixth-order Surface: represents the basal boundary of the Coalcliff Sandstone (Fig. 2a) which is a major erosional surface. This surface extends laterally for several kilometres and is commonly paved with channel floor lag deposits. It can be considered as a double rank surface, because on the one hand, it bounds the lower surface of the Coalcliff Sandstone and on the other hand, it represent the lower boundary of the Narrabeen Group in this area as well.

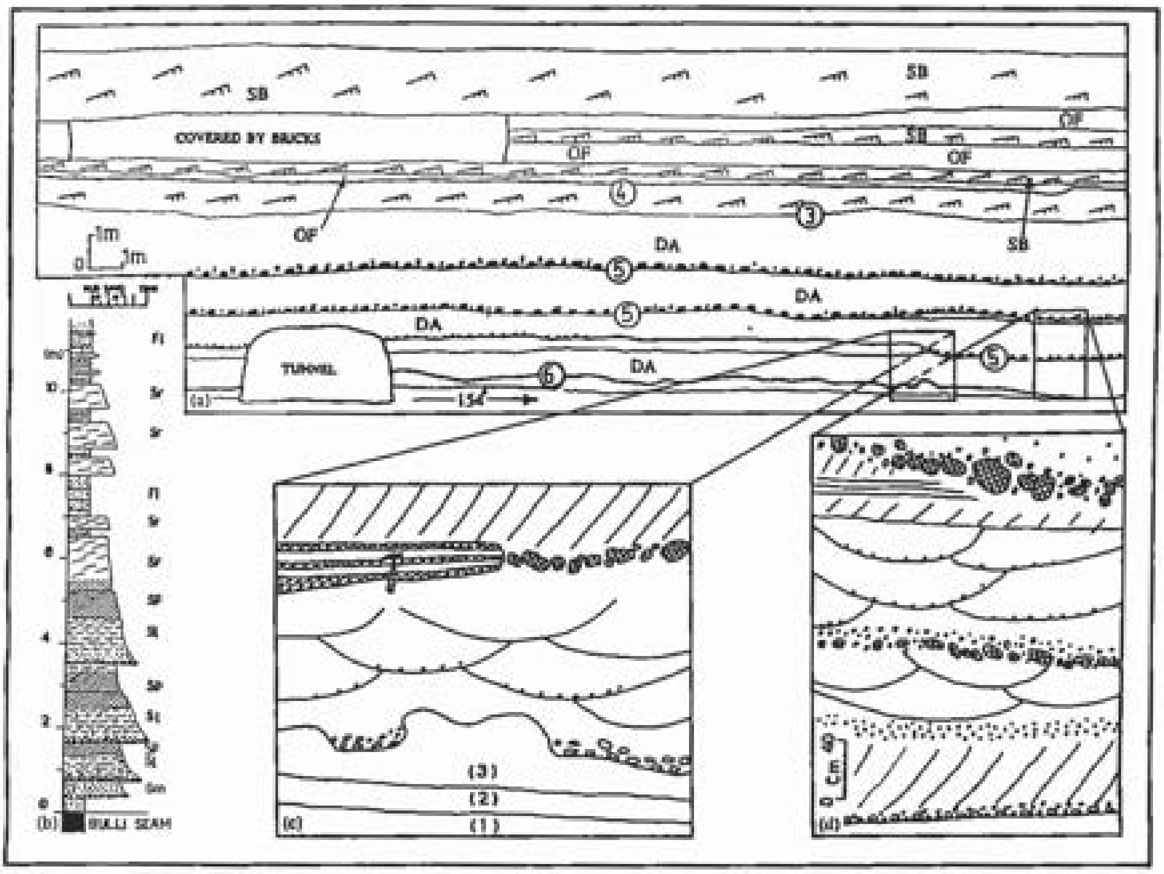


Fig. 2. (a) Lateral profile, showing hierarchy of bounding surfaces (numbers) and architectural elements (capital leters), see text for explanation. (b) Vertical profile of Coalcliff Sandstone, exhibiting multistorey fining upward sandbodies with corresponding lithofacies (about 150 m south of Coal Cliff adit). (c) Close-up of a reworked fine-grained unit and resultant ironstone nodule stringer (note to the erosional contact), preserved deposits under the sandbody are: (1) Bulli Seam; (2) highly carbonaceous dark grey mudstone; (3) laminated shale and fine-grained sandstone. (d) Close-up of the lower part of the Coalcliff Sandstone, showing ironstone stringer (real size), in the lower part all the strata at the top of Bulli Seam is eroded by the Coalcliff river.

ARCHITECTURAL ELEMENTS

The following architectural elements are recognised in the Coalcliff Sandstone (using Miall's, 1985, 1988a code): downstream accretion (DA); overbank fines (OF); sandy bedforms (SB); gravel bedforms and bars (GB); and lateral-accretion bedforms (LA). Concave-up channel element (CH) cannot be seen in this area probably due to the high angle of the outcrops relative to the palaeocurrent direction.

Downstream Accretion Element (DA): The dominant architectural element in the Coalcliff Sandstone is the downstream accretion element (DA). It forms macroforms and mesoforms which were deposited in the major channels. They are bounded by fifth and fourth-order surfaces (except lowermost sandbody which is bounded by a sixth-order surface at the base). This element shows an upward decrease in set thickness and grain size. Recognition of macroforms is based on evidence of long term lateral, oblique or downstream accretion of smaller bedforms (mesoforms) on inclined bedding surfaces (Miall, 1988b). In the Coalcliff Sandstone in-channel bedforms, produced mostly by downstream accretion, are represented by deposits of the 3-D dunes (sinuous crested) and 2-D dunes (straight crested) that migrated along the channel floor or at the top of host bedforms. In the direction of flow, DA elements can be traced for at least tens of meters. In an across-flow direction, the extent of DA elements is unknown, but they are probably similar in scale to the encompassing major channels.

Gravelly Bedform Element (GB): on the shore platform south of Coal Cliff (Fig. 1b) a conglomeratic mesoform, which is almost parallel to the palaeocurrent trend direction is preserved. It is massive to crudely stratified with Gm lithofacies. The lower part is bounded by a fifth-order surface and is paved with ironstone lag gravels and coalified and petrified logs. This conglomeratic mesoform is interpreted as a longitudinal bar deposit in the channel. In some places ironstone lag deposits accumulated and formed conglomeratic beds with Gm lithofacies (similar to the G2 facies of Allen, 1983). Generally, the GB element is not common in the Coalcliff Sandstone.

Sandy Bedform Element (SB): In the upper part of the Coalcliff Sandstone, mudstone is interbedded with fine-grained sandstone. The sandstone shows ripple cross-lamination (Sr) and isolated small planar-tabular cross-bedding (Sp). Sandbodies with a lenticular geometry are interpreted as crevasse splay deposits whereas those that are laterally uniform and extensive are interpreted as sheet-flood deposits.

Lateral Accretion Element (LA): Lateral accretion is recognised by low-angle bedding surfaces that dip oblique or orthogonal to the flow (transport) direction. In places, where bedforms can be seen in 3-D, bedforms with foresets oblique to the palaeocurrent are interpreted as LA elements (probably deposits of bank-attached bars). Overall, this element is rare in the Coalcliff Sandstone. Lateral accretion with epsilon cross-bedding (Allen, 1963), which normally represents point bar deposits, was not found in this area. Several authors have argued about epsilon cross-bedding and its role for deducing the type of the channel. Collinson (1978) noted that absence of epsilon cross-bedding does not prove that point bars were not involved. On the other hand, Jackson (1978) argued that epsilon cross-bedding is not only present in point bar deposits of meandering river systems but it can occur in any river showing surfaces of lateral accretion.

Concave-up channel elements (CH) are not present, probably due to the high angle cliffs with respect to the palaeocurrent direction, but indirect criteria, such as erosional surfaces and scouring with channel-floor lag deposits, are conspicuous in the study area.

Overbank Fines Element (OF): The Coalcliff Sandstone shows an overall fining upward sequence with fine-grained overbank deposits at the top. This fine-grained deposit is interpreted as an OF element which is interbedded with SB elements (Fig. 2a). On the platform immediately south of Coal Cliff, wave generated symmetrical ripple marks and trace fossils (probably *Planolites*) were recognised in an OF element. These features, plus the lack of desiccation cracks in OF elements indicate a wet flood plain area (pond-like) with a stagnant body of water in some places. OF elements, also can be seen within the Coalcliff Sandstone, but often this element is partly or totally eroded prior to the deposition of the succeeding sand body (Fig. 2c). At the top of the uppermost macroform (Fig. 2a) a laterally extensive fine-grained sandstone shows a conspicuous cross-laminated lithofacies. This sandstone is interpreted as a bar-top or possibly part of a levee deposit. The presence of stacked units with non-erosive bases implies that the levee deposits are probably aggradational. The OF element in the Coalcliff Sandstone forms from about 10% to more than 30% of the sequence by volume.

LITHOFACIES

In this study the lithofacies code of Miall (1978) was used. Dominant lithofacies in the Coalcliff Sandstone are planar cross-stratified (Sp) and trough cross-stratified sandy facies (St) which are related to deposition of 2-D dunes (straight crested) and 3-D dunes (sinuous crested) respectively. Cross-laminated sandy facies (Sr; Fig. 2b) that indicate deposits of bar-top and crevasse splays are abundant. Other recorded lithofacies are: massive and crudely bedded gravel (Gm); parallel laminated siltstone and fine sandstone (Fl); and erosional scours with intraclasts (Se).

FLUVIAL INTERPRETATION

Field evidence from mesoforms, macroforms and the relationships between them indicate a fluvial environment of deposition for the Coalcliff Sandstone. These criteria include: (1) fining-upward channel-fill deposits; (2) closely spaced erosional surfaces in multistoried sandbodies; (3) channel-floor scouring and associated lag deposits that demarcate channel bases; (4) palaeocurrent data indicate a unidirectional palaeocurrent for individual mesoforms and macroforms; (5) presence of overbank deposits with crevasse splays; (6) lack of body fossils and paucity of trace fossils; (7) abundant coalified and petrified logs and plant fragments. A fluvial interpretation is also supported by the lack of sedimentary structures indicative of shallow marine and estuarine environments such as: herringbone cross-bedding; flaser and lenticular bedding; mud drapes foresets; and abundant reactivation surfaces. Trace fossils are very rare.

Internal architecture of the Coalcliff Sandstone supports a fluvial origin as well. The dominant element is downstream accreted mesoforms and macroforms that indicate continuous sedimentation. In channel deposits comprise St facies, indicating deposits of 3-D, sinuous crested dunes in the deeper part of the channel, and Sp facies indicating deposition of 2-D straight crested dunes (transverse bars). Fining upward sequences show sedimentation during high to waning flow stages. High percentages of fine-grained sediments (from less than 10% to about 30%) indicate a mixed load-dominated system. Well developed fining-upward and high percentages of fine-grained deposits favoured a high sinuosity system (Walker & Cant, 1984), but paucity of laterally accreted bedforms, closely spaced erosional surfaces in multistoried sandbodies indicating high rates of lateral migration (highly erodable bank), abundant downstream accreted elements, lack of clay plugs, and relatively uniform palaeocurrent trend does not support a meandering system for the lower part of the Coalcliff Sandstone. Overall, evidence points to a low to moderate sinuosity, mixed-load fluvial system for deposition of the Coalcliff Sandstone.

In sequence stratigraphy terminology the sixth order bounding surface of the base of the Coalcliff Sandstone could represent a tectonically influenced (allocyclic) boundary or a more localised erosion surface possibly influenced by small eustatically influenced sea level changes. In the past this surface has been interpreted as a widely developed erosion surface across the Sydney Basin (Herbert, 1980, 1993). In this context it represents a type 1 unconformity which bounds base of the Narrabeen Group Sequence. However, in the Coal Cliff area this boundary is now recognised as a localised feature (Clarke, 1992) with the Coalcliff Sandstone and equivalent coarse-grained units occurring as lenses within the Wombarra Shale. Since the Coalcliff Sandstone is not a laterally continuous blanket deposit, the erosion surface at the base of the unit should be classed as a type 2 unconformity rather than a major sequence boundary. This conforms with the interpretation presented by Arditto (1991) who placed the base of the next sequence boundary at the contact between the Wombarra Shale and Scarborough Sandstone.

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SCARBOROUGH SANDSTONE IN THE SOUTHEASTERN SYDNEY BASIN : AN EARLY TRIASSIC SANDY TO GRAVELLY BED-LOAD FLUVIAL DEPOSIT

M.H. DEHGHANI & B.G. JONES
Dept. of Geology, University of Wollongong

INTRODUCTION

The Scarborough Sandstone is the coarsest grained unit in the Late Permian to Middle Triassic Narrabeen Group. It was named by Hanlon *et al.* (1953) who measured its type section in the Clifton area.

The Scarborough Sandstone has an erosional contact with underlying Wombarra Shale which is laterally extensive on a basin-wide scale. This contact represents a type 1 unconformity and an important sequence stratigraphic boundary (Arditto, 1991), which essentially coincides with the Permian-Triassic boundary. This unit has a gradational contact with Stanwell Park Claystone and together they represent a depositional system in this area.

Ward (1972), Bunny (1972), Bowman (1974) and Hamilton *et al.* (1987) postulated a fluvial depositional environment for the Scarborough Sandstone. Excellent exposures of this formation between Clifton and Bulgo have been examined for detailed sedimentological work to assess the form and style of the palaeoriver(s).

LITHOFACIES

Lithofacies nomenclature in this study follows the system proposed by Miall (1978), who defined lithofacies based on grain sizes and sedimentary structures. The Scarborough Sandstone is divided into ten main lithofacies, which are grouped in three facies assemblages: conglomerate; sandstone; and fine-grained deposits. Description and interpretation of each facies utilising mostly two and limited three dimensional outcrops is given below.

CONGLOMERATE FACIES ASSEMBLAGE

Conglomerate comprises between less than 15% to more that 25% of the unit. A persistent polymictic conglomeratic unit with thickness of about 2 m occurs in upper part of the unit and is locally interbedded with sandstone. The best exposure for studying this conglomerate is south of Bulgo. Conglomerate occurs in four facies: massive to crudely bedded (Gm); planar cross-bedded (Gp); trough cross-bedded (Gt); and scours fills (Ge).

Massive to Crudely-bedded Conglomerate (Gm)

One of the most common conglomerate facies in the Scarborough Sandstone is massive to crudely bedded polymictic pebble-size conglomerate which is locally interbedded with sandstone lenses. Sheets and lenses of conglomerate, ranging in thickness between less than 0.5 m to more than 2 m are present. In places horizontal stratification is visible due to vertical changes in grain size, clast sorting and amount of matrix. The average grain size is about 1 to 2 cm, but some clasts are up to 8 cm. Gravels are well rounded and much of the conglomerate is clast supported which usually prevents imbrication developing; nevertheless imbricated gravels are present and show locally consistent current orientation, with the *b*-axis dipping upcurrent. The lower part of the conglomeratic units often show clast supported conglomerate with abundant ripped-up mudstone clasts, whereas in some places the amount of matrix increases upwards and matrix supported conglomerate occurs at the top of these units. South of Bulgo, the conglomeratic unit contains abundant coalified and petrified fossil trunks. The average length of trunks is about 3 m, but trunks up to about 10 m in length were also recorded. This facies also occurs as thinner lag deposits and scour fills (Ge).

Interpretation: these conglomeratic units represent accumulation of gravel size sediments when the river had its highest competency. Presence of large fossil trunks within these units and clast imbrication, support a high energy system. Imbricated clasts and lack of planar cross-bedding, indicate the progradation of thin sandy-gravel sheets across the channel floor and bar surface rather than avalanching on the lee sides or lateral flanks of bars. During episodes of high water and sediment discharge these sheet grow upward and downstream by accretion of diffuse gravel sheets. The clast supported nature of the lower part may indicate that during flood stage only gravel-sized grains moved as bed-load or alternatively sand-sized grains were winnowed from the gravels, whereas increasing amounts of sand toward the top of the bar indicate a decrease in the competency of the river. As Rust (1972) discussed these gravelly bars only formed and moved downstream during flood and bankfull discharge. These clasts were deposited when the flow reduced and the larger deposited clasts acted as traps (obstacles) for other clasts; as a result, a bar developed with horizontal bedding and imbricated clasts. Imbrication develops when all the clasts are in the motion at high flow stage (Rust, 1984). Presence of ripped-up mudstone clasts especially in the lower parts of the conglomeratic units, indicate recycling of overbank deposits by lateral migration of the channel. Overall, the criteria indicate longitudinal bar deposits in the channel. Multiple scoured surfaces and sandstone lenses within these units prove that the sheet conglomerate was not deposited in a single depositional event.

Planar Cross-bedded Conglomerate (Gp)

This facies is common in the Scarborough Sandstone. The thickness of the planar cross-bedded conglomerate units normally ranges between 0.5 m to 1.2 m and the sets are up to tens of meters in length. The Gp facies is noticeably finer than facies Gm, and a similar relationship was reported by Steel and Thompson (1983) and Rust (1984). Foresets are planar and rarely tangential with the angle of foresets ranging between 10° to 30°. They often show a heterolithic lithology compose of gravel and pebbly sandstone. The *ab* plane of the clasts on the foresets often fails to show any preferential orientation.

Interpretation: during the waning flow stage or in areas were flow expands, lee-side separation eddies may develop behind bars (Miall, 1985). This is accompanied by a tendency towards foreset growth and development of transverse bars with Gp lithofacies. Planar cross-bedded conglomerate indicates deposition on avalanche foresets resulting from the migration of transverse gravel bars (Luttrell, 1993). Similar bars have been described in modern braided river systems (Rust, 1972). Well defined foresets in these bars, reflect a lower water and sediment discharge than longitudinal bars. A similar facies was described by Forbes (1983) as "diagonal bar deposits" in a modern sinuous gravel-bed channel system. As Rust (1984) discussed, Gp facies may also be attributed to falling flow stage and are produced when longitudinal bars emerge and flow diverges from the bar axes into adjacent channels.

Trough Cross-bedded Conglomerate (Gt)

Trough cross-bedded conglomerate lenses are less common in the Scarborough Sandstone. Imbrication is not developed in them and they are mostly associated with Gm and Gp lithofacies.

Interpretation: This facies exhibits a scour fill morphology and was probably deposited in the deeper parts of the river. Its association with Gm and Gp lithofacies may indicate that during flood these facies were formed in topographically low areas in the channel floor or in places where river had been confined. When the flow depth started to fall, Gm and Gp lithofacies were deposited above the Gt lithofacies.

SANDSTONE FACIES ASSEMBLAGE

Sandstone is the most abundant facies assemblage in the Scarborough Sandstone and constitutes between about 60% to 70% of the unit. The dominant grain size is medium-to very coarse-grained and pebbly sandstone, recorded facies are: planar cross-bedded sandstone (Sp); trough cross-bedded sandstone (St); ripple cross-laminated sandstone (Sr); and plane bedded sandstone (Sh).

Planar Cross-bedded Sandstone (Sp)

Planar cross-bedded sandstone occurs in various scales, ranging from less than 10 cm up to 1.3 m in thickness and tens of meters in length. The sets may be separated from each other by a thin (a few clasts thick) gravelly layer. Superimposed planar cross-bedded sandstone sets are abundant in some places (e.g. south of Stanwell Park beach). This facies is associated with St, Gm and Gt lithofacies.

Interpretation: this lithofacies represents deposits of 2-D (Ashley, 1990) straight crested dunes (transverse bar of Smith, 1970; Miall, 1985). As Walker & Cant (1984) described, planar cross-bedding is widespread in braided river deposits. The lithofacies was produced by migration of straight crested sand sheets. Sand supplied by the river slipped down the avalanche face of the bar and was deposited as planar cross-beds. These bars generally form in shallower water than trough cross-bedded sandstone (Miall, 1985), probably in area where flow expanded over a large compound bar. As Cadle & Cairncross (1993) documented, part of the Sp facies could be related to slip face migration of braid bars in the river. The thin gravelly layers that separate Sp facies from each other are interpreted as "armour surfaces" (Forbes, 1983). Reactivation surfaces in the Sp facies suggest fluctuations, in river discharge.

Trough Cross-bedded Sandstone (St)

Cosets of trough cross-bedded sandstone are less common in the Scarborough Sandstone. In vertical sections, which are subparallel to the palaeocurrent direction, troughs are well defined by scours and range in thickness between 10 cm and 50 cm. Foresets are tangential to the underlying erosional surface and the base of the trough is often covered by gravel. Similar fluvial facies are widely known (e.g. Rust, 1978; Allen, 1983; Kumar, 1993).

Interpretation: trough cross-bedded sandstone is the deposit of 3-D (using Ashley's, 1990, terminology) sinuous crested subaqueous dunes. The sets formed by infilling of trough-like scours as flow power decreased. Laboratory studies have shown that 3-D dunes were shaped by less vigorous currents than 2-D dunes (Allen, 1968). These dunes form in deeper water than 2-D dunes (Miall, 1985). They are usually associated with Gm, Gp and Sp lithofacies and are likely to be formed at the time of bankfull discharge of the river.

Plane Bedded Sandstone (Sh)

Plane bedded sandstone comprises thin (normally less than 20 cm, but up to 50 cm thick) sandstone layers with nearly horizontal lower boundaries. Internal horizontal stratification is visible due to differences in grain sizes. The facies occurs at the top of Sp and St lithofacies and rarely as individual layers up to 1.1 m thick. Smith (1970) recorded this facies in the tops of transverse or longitudinal bars.

Interpretation: plane beds at the top of the tabular cross-stratified sets can be due to deposits of upper flow regime in shallow water (Cadle & Cairncross, 1993). Similar facies were recorded by Smith (1970) and Allen (1983). Allen (1983) mentioned that "plane-bedded simple bars" were produced by flows at least as severe as those producing cross-bedded bars; he explained the difference in shape and internal geometry as a function of the grades of debris made available. Thick horizontally bedded sandstone units can be related to longitudinal sandy gravels (Smith, 1970), possibly indicating transportation of the sand sheets under high energy conditions (Rust, 1972; Desloges & Church, 1987).

Ripple Cross-laminated Sandstone (Sr)

This facies occurs as bar-top deposits and also as fine-grained sandstone lenses in the overbank area. It consists mostly of non-climbing ripple types but includes trough-shaped current ripples with asymmetric foresets. Overall, this facies is uncommon in the Scarborough Sandstone.

Interpretation: ripple cross-laminated sandstone was deposited during waning flood stage at the top of bars or in the floodplain area. They are deposits of asymmetric current ripples. Lack of climbing ripples in this lithofacies indicates a deficiency of fine-grained sands in suspension during the time of deposition.

FINE GRAINED FACIES ASSEMBLAGE

Fine-grained deposits are the least abundant facies assemblage in the Scarborough Sandstone and comprise between 0% to 10% of the formation. They are well developed in the lower middle part of the formation and can be differentiated into two lithofacies: (1) parallel laminated mudstone and fine-grained sandstone (Fl); and (2) massive mudstone (Fm).

Parallel Laminated Mudstone and Fine Sandstone (Fl) and Massive Mudstone (Fm)

The lamination present in this sediment is due to variation in colour, texture and grain size. The thickness of laminae range between 1 mm to 2 cm. Preserved Fl lithofacies is rare, but where present it is well developed. For example, a Fl lithofacies north of Coal Cliff beach is 2.3 m thick and contains two crevasse splay deposits within it; another unit at the north end of Stanwell Park beach is up to 2.1 m thick. Truncation of the upper boundary by the succeeding sandbody is common. These deposits were developed in the overbank area and are associated with ripple cross-lamination.

Interpretation: Fl lithofacies was developed by deposition from suspension in floodplain areas. These deposits, also contain abundant mica, supporting deposition from suspension. However, fine-grained sandstone and siltstone with ripple cross-lamination in beds up to 30 cm thick occur in the floodplain area. Such units occasionally show erosive bases and upward fining. As mentioned by Bridge (1984), they are probably deposits of discrete overbank flooding events. In a fluvial system where coarse-grained deposits are dominant, deposition of fine-grained material can only occur in sheltered floodplain areas. However, abundant ripped-up mudstone clasts in the conglomeratic units of the Scarborough Sandstone implies erosion and recycling of otherwise unpreserved fine-grained deposits. The only preserved crevasse splay deposits recognised in the Scarborough Sandstone are about 200 m north of Coal Cliff beach.

Massive mudstone (Fm) is less common; it represent vertically accreted deposits in the floodplain area. This lithofacies represent the distal floodplain or floodplain lakes, where only the finer grained sediments could reach.

PALAEOCHANNEL DEPTH AND WIDTH

Primary sedimentary structures were formed at the time of deposition and can be used for deducing channel parameters such as depth and width. The more reliable and direct method for measuring bankfull channel depth is using thickness of preserved macroforms in the fluvial deposits. Cutbank height and scour depth, also can give direct evidence of channel depth.

Indirect methods using empirical equations were developed for modern and ancient rivers by numerous authors. For example, the ratio of dune high to flow depth can be used for estimating channel depth. However, these equations have certain limitations that were discussed by Ethridge & Schumm (1978).

Channel Depth

Allen (1970), based on experimental and field measurements, formulated a relationship between dune size and flow depth. The derived equation was $H= 0.086\ D^{1.19}$, where H is the dune amplitude and D is the flow depth. The computed channel depth for the Scarborough Sandstone is between 1.5 to 4.7 m. As commonly the upper part of the preserved dune is eroded by succeeding bedforms, the calculated depth would thus be a minimum depth.

The calculated depth is smaller than Evans's (1990) assumed ratio of 1:5 for dune height to bankfull channel depth which give maximum depth of 6.5 m for the Scarborough Sandstone. The calculated depth, also coincides with preserved cutbank height (2.9 m north of Stanwell Park beach).

Channel Width

The bankfull channel width has been estimated using the empirical equation of Leopold & Maddock (1953), recommended by Allen (1968), as follows: $W= 42\ D^{1.11}$, where D is the channel depth and W is the width of the corresponding river. The calculated width using this formula is between 95 m to 298 m for the Scarborough river. Evans (1990) concluded that the bankfull width to depth ratio in gravel and sand bed-load streams is 20:1 which is close to calculated width. Field evidence from the transverse gravel bars south of Bulgo indicate that the gravelly bed-load part of river must have had a width of a few hundred metres. In this locality gravelly bars more than 65 m wide are recorded.

DISCUSSION

Vertical profile measurements through the Scarborough Sandstone included detailed lithofacies analysis using two dimensional data from photomosaics of outcrops plus three dimensional exposures of this sandstone south of Bulgo. These outcrops have been examined to delineate the detailed sedimentology and fluvial style of this channel sandstone.

The conglomerate facies assemblage includes Gm, Gp and Gt lithofacies. Gm represents deposits of longitudinal bars in the channel during high discharge. It also appears as scour fills (Ge) and as lag deposits separating bedforms and paving the base of them (surface armouring). Gp and Gt are related to deposits of transverse gravel bars and 3-D sinuous crested dunes respectively. Gp represents lower water and sediment discharge rates than the Gt lithofacies. A persistent conglomeratic unit appears in the upper part of the formation; it indicates a higher energy system which was probably related to renewed tectonic activity in the hinterland area.

The sandstone facies assemblage is well developed as individual units or between conglomeratic units. It is composed of Sp, St, Sr and Sh facies. Sp represent deposits of 2-D straight crested dunes while St shows deposits of 3-D sinuous crested dunes in the deeper parts of the river. Sr is related to deposits of linguoid current ripples at the top of bars during waning stage or in the overbank area. Sh is present at the top of bedforms or as individual layers, and it shows upper flow regime plane bed characteristics indicating very shallow flows.

The fine-grained facies assemblage is the least abundant in the Scarborough Sandstone. The overbank deposits include two lithofacies: parallel laminated mudstone and fine sandstone (Fl); and massive mudstone (Fm).

Overall, the Scarborough Sandstone exhibits the characteristic deposits of a sandy to gravelly bed-load river in a high energy system. This is supported by well rounded gravels; high coarse- to fine-grained ratio; dominance of framework gravels as opposed to gravels produced as lag deposits (Rust, 1978); and an abundance of longitudinal bars in the channel deposits. However, during evolution of this unit, noticeable suspension-load is also recognised in some stages. Calculated depth for the Scarborough river is 3 m to 5 m and width of about 100 m to 300 m.

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DEPOSITIONAL STYLES OF CHANNEL & OVERBANK DEPOSITS IN THE MIDDLE JURASSIC WALLOON COAL MEASURES, CLARENCE-MORETON BASIN, NSW.

J.V.R. YAGO, C.R. FIELDING & J. KASSAN
Dept. of Earth Sciences, The University of Queensland

INTRODUCTION

Being a mineable source of steaming coal, bentonite and a potential source of oil and gas in the sub-surface (Fielding 1993), the deposits of the Middle Jurassic Walloon Coal Measures have proven to be an economically significant stratigraphic interval within the Clarence-Moreton Basin. The unit was named after its type locality in the township of Walloon located approximately 40 kms. west-southwest of Brisbane (Figure 1). The erosionally truncated sequence comprises 600m of interbedded volcanic lithic sandstone and siltstone, claystone (occasionally carbonaceous), and coals that outcrop at the margins of the 16000 sq. kms. Clarence-Moreton Basin, NSW.

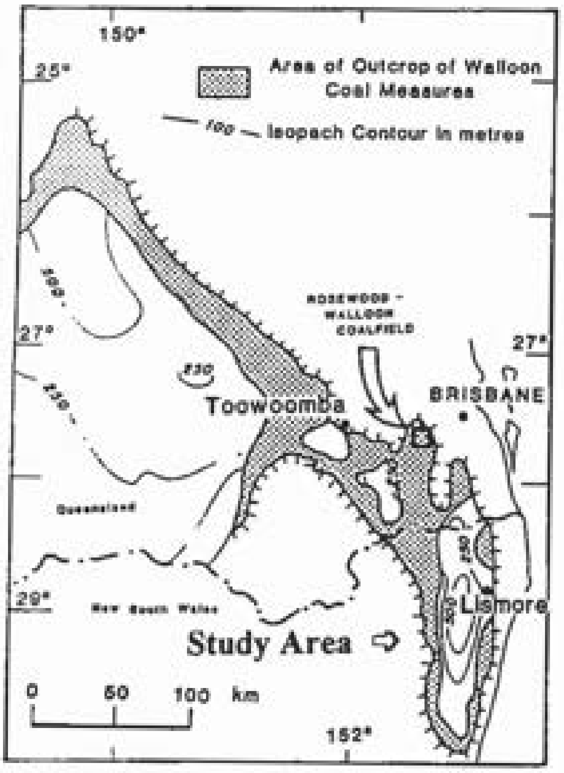

Figure 1. Isopach map of the WCM. Note the location of the study area (modified from Fielding, 1993).

In this paper, we present a preliminary report on a field study which concentrated on the particularly good exposures of the Walloon Coal Measures of the Clarence-Moreton Basin in NSW (Figure 2). It aims to provide a facies analysis that includes an analysis of external and internal geometry of sediment bodies in the Coal Measures. Previous work has relied mainly on vertical profile examination for facies interpretation. The main aim of this paper is to provide an architectural analysis based on lateral profile studies, to allow a better understanding and interpretation of the depositional environment of the sequence.

AREA OF STUDY AND METHODOLOGY

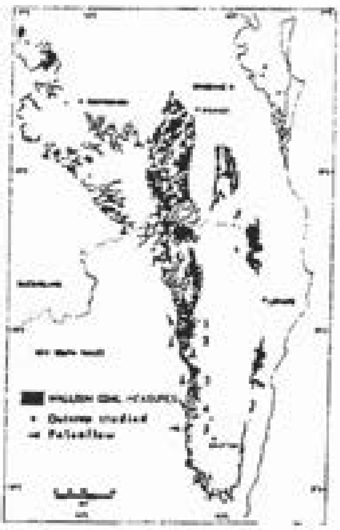

Figure 2. Distibution of the WCM. Note the location of the outcrops and paleoflow directions (modified from Gould, 1968).

Well exposed natural outcrops of the Walloon Coal Measures were studied along the western margin of the Clarence-Moreton Basin between the township of Mallanganee and west of Grafton where the sequence is exposed in a road cut in the Gwydir Highway, (Figure 2). Two- and three-dimensional outcrops were examined using colour photographic mosaics. This included the tracing and delineation of external and internal (where possible) geometries of different sediment bodies. Sedimentological logging of vertical sections was conducted at accessible parts of the outcrops to give a continuous record of lithology and to aid in the architectural analysis. Paleocurrent directions, bounding surfaces plus other pertinent structures were measured and delineated, and recorded directly on the photographic mosaic while in the field. Paleocurrent readings were dip corrected to allow easier visualization and interpretation of the traced profile. A sample of five of the profiles examined are described and interpreted here, namely:

1. J 0015-- (9440-3-S Mallanganee 693964)
2. J 0023-- (9439-4-N Yates Flat 696815)
3. J 0024-- (9439-2-S Coaldale 766495)
4. J 0029-- (9438-1-N Copmanhurst 812347)
5. J 0030-- (9438-4-S Gundahl 718217)

[Note: *Outcrop #-- (Sheet #; Map Name, Grid Reference)*]

STRATIGRAPHY

The Walloon Coal Measures overlie the Marburg Subgroup. The exact nature of the contact between the two units cannot be determined in the study area. Previous work regarding the basal contact of the Walloon Coal Measures has identified a problem of definition because of its conformable and gradational nature. Fielding (1993) identified in the type section that a fundamental compositional change occurs across the boundary from quartzofeldspathic (Marburg Subgroup) to volcanic lithic composition (Walloon Coal Measures). The only rigorous definition of the Walloon/Marburg boundary appears to be petrographic (Fielding 1993). Disconformably overlying the Walloon Coal Measures in the study area is the Middle to Late Jurassic Kangaroo Creek Sandstone (Table 1).

Interpretation

Geometrical relationships, and the systematic paleocurrent measurements taken on the different sandstone units, indicate that these sandbodies were laterally accreted. The lateral accretion planes show a migration of the point bar from southwest to west with a stream flowing from the southeast to the northwest. Figure 3 shows a schematic plan view of how the ancient stream was flowing in relation to the current exposure. With gently dipping accretionary planes, a high width/depth ratio can be predicted. In this area, the channel width was relatively narrow and probably did not exceed 50m., with a depth of not more than 5m. This also suggests a small radius of meander curvature.

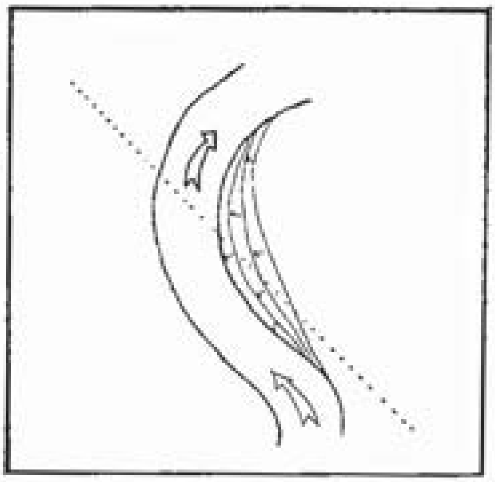

Figure 3. Schematic plan view of outcrop. Dotted line shows possible present stream profile.

The flat-bedded sandstone unit could have been part of the upper portions of the point bar (*cf.* Willis, 1989 and 1993). Preservation of this relatively fine-grained unit indicates that migration only by expansion occurred during the final stages of bar migration. However, outcrop conditions were not conducive to preservation of current lineation or large scale convex-up bedding surfaces, so the interpretation of the flat bedded unit (storey II) as a waning flow, upper flow regime deposit, is tentative at this stage

PROFILE 2: J 0023 - YATES FLAT & PROFILE 3: J 0024 - COALDALE

Description

Profile 2 is located along Gerard's Creek south of Mount Pickapene Forest Reserve. Exposures of the Walloon Coal Measure are very much limited to deeply incised portions of creeks. A series of small road cuts were also studied along Coaldale Road (Profile 3). Remnants of the WCM in both areas are highly weathered and friable. Here, the lithology is dominated by grey to brown sandstone. The presence of ironstone bands gives rusty brown coloration to some parts of the outcrop. The outcrops in this area are generally fine- to medium-grained sandstone with distinct pebbly conglomerate containing clasts of felsic volcanic rocks, chert, quartz, intraformational mudrocks, and pieces of coalified woody debris. Also present are occasional light grey layers of siltstone not exceeding 0.10m (mostly <0.05m) in thickness. A relative increase in the amount of quartz in some portions of nearby outcrops was observed. Sedimentary structures in Profiles 2 and 3 are ripple cross lamination and cross bedding . The sandbodies are sheets continuous over the length of the exposure and tens of centimeters in thickness. In places these are interrupted by small channelized sandstone bodies. These cross-stratified channelized

	Stratigraphic Unit	Subdivision	Lithology	Petrography
M.-L. Jurassic	Kangaroo Creek Sandstone		sandstone, minor mudrock and conglomerate	quartzose
M Jurassic	Maclean Sandstone Member		sandstone	feldspathic
	Walloon Coal Measures	-upper (minor coal) -middle (coal) -basal (no coal)	coal, claystones, mudrocks, sandstones	volcanic lithic
E. Jurassic	Marburg Subgroup		sandstone, mudrocks, minor conglomerates	quartz-lithic

Table 1. General stratigraphy of the Clarence-Moreton Basin

The basal and upper contact of the Walloon Coal Measures will always be a mapping problem because of their poor exposure. The presence of the Maclean Sandstone Member reported to be overlying the Walloon Coal Measures in the eastern margin of the basin was not observed in the study area. Lastly, the relationship of the Maclean Sandstone Member and the overlying Kangaroo Creek Sandstone is likewise unclear in the area. Flint et. al. (1975, 1976) have shown a partly unconformable contact between the two units while recent work of Shaw and Geary (1983) place a major unconformity between the two units.

PROFILE 1: J 0015 - MALLANGANEE

Description

Forming part of the basal subdivision of the WCM (without coal seams), this exposure consists of generally light grey, lithic sandstone. Some parts of the outcrop show brownish to rusty coloration due to oxidation of rare ironstone bands. The sandstone is volcanic lithic in composition ranging from very fine to medium-grained. The accumulated thickness of the outcrop is ca. 7m. At least four major storeys within a multi-storey sandbody were recognized with sharp and sometimes erosive bases separating each unit

Storeys are numbered in ascending stratigraphic order I to IV. Storeys I, III and IV are dominated by medium scale trough cross-bedded sandstones (preserved set thicknesses 0.3-1.5 m), whereas storey II comprises predominantly horizontally laminated fine to very fine-grained sandstones, with abundant plant debris. Foresets in cross-bedded sandstones show dips of 17-20° and commonly exhibit basal lags of intraformational, grey mudclasts

The overall paleocurrent direction measured is towards the west. But these readings show at least 3 directional changes from base to top of section starting from the southwest and shifting progressively to the westnorthwest.

sandstone units have a trough-shaped lower bounding surface, and are less than 5m in cross-sectional width. Ripple marks are very well exposed as top surface form sets in some portions of fine-grained sandstone beds, with current directions to the north. Paleocurrent readings taken in two adjacent Gerard's Creek exposures show a bipolar direction to the northnorthwest and the southsoutheast. Paleoflow of major trough axes measured along Profile 3 indicate northward drainage.

Interpretation

Based on the limited exposures in the area, the WCM is interpreted to have been deposited in low energy fluvial environments regularly affected by high-energy depositional events such as floods. The channel sandstone deposits show an apparent bipolar paleoflow over a series of isolated outcrops. This is interpreted to reflect low stage processes in the sinuous channel. The flat-bedded fine-grained sediments are interpreted to represent proximal floodplain deposits or alternatively reflect gradual channel abandonment and fill. Cross-cutting relationships between channel bodies along Coaldale Road suggest a depositional environment of continually shifting channels with widths not exceeding 40m and depths of a few meters.

PROFILE 4: J0029 - COPMANHURST

Description

Part of the middle subdivision of the Walloon Coal Measures (coal-bearing strata), the sediments in this area form a general fining upward sequence of interbedded very fine-grained sandstone, siltstone, claystone and a thin coal at the top, capped by an erosive-based sandstone unit. The sediments dip 10° to the northeast.

Four sediment bodies were differentiated:

Unit I - a lower fine grained interval of interbedded fine-very fine grained sandstones and siltstones, with a thin (0.20m) coal seam at the top of the preserved interval,
Unit II - a thinly bedded, fine to medium grained sandstone unit, exhibiting pervasive ripple cross-lamination,
Unit III - a fine to medium grained, erosively based sandstone unit, with abundant internal erosion surfaces arising from mutually intersecting trough cross-bedding,
Unit IV - a sharp-based, horizontally laminated and ripple cross-laminated sandstone unit (fine to medium grained).

The volcanic-lithic sandstone in the basal portion of the outcrop (Unit I) is grey in colour, generally horizontally laminated with abundant carbonaceous laminae, and rich in plant fossils. Sandstone occurs as thin interbeds of less than a decimeter in the 2-meter exposed portion of this basal unit.

Unit III erosively truncates the ripple cross-laminated sandstones of Unit II. The internal architecture of Unit III comprises mutually intersecting medium scale trough sets. Erosional scours are common and sometimes lined by coaly debris. Paleocurrent readings in this cross-stratified unit show a paleoflow to the northwest.

The topmost recognisable unit in this outcrop (Unit IV) is a sharply-based, 0.60m thick fine-grained sandstone, mainly horizontally laminated with coaly plant debris. Ripple form sets were observed in some portions with an average wavelength of 0.40m and an amplitude of 0.05m. Internal lamination in these sets is not exposed, but paleocurrents are easterly.

Interpretation

The outcrop in this area is interpreted to be a proximal crevasse splay deposit with preserved crevasse channel fill, and capping flood basinal sediments. This crevasse splay deposit may extend several hundred meters to the northwest (based on a nearby outcrop of poor quality). The crevasse deposit is up to 4m thick. It is a complex, channelized splay with multiple channels of a few meters in width. Due to the continuous cross-cutting relationships of channels it could be inferred that the margin of a major channel belt is nearby. These proximal crevasse channels may have remained open for a considerable time. Transported vegetation was found in the channelized splay deposits

PROFILE 5: J0030 - GWYDIR HIGHWAY

Description

The sediments studied here form part of the upper subdivision of the WCM below the contact with the Kangaroo Creek Sandstone. The outcrop is a series of connected road cuts almost a kilometer long. Three sets of profiles were made running from east to west along the Gwydir Highway. The sediments are of volcanic lithic composition. With at least 30m of cumulative vertical exposure, three gross intervals may be defined in ascending stratigraphic order:

Unit I - At the base of the interval is a poorly exposed 10m section of sandstone,
Unit II - some 7-9m of interbedded fine-grained sandstone, siltstone and coal ,
Unit III - at least 12m of sandstone.

The poorly exposed basal interval comprises mainly fine- to medium-grained sharply based sandstone. Sedimentary structures within this interval include abundant trough-cross bedding with set thickness ranging from 0.15-1.50m. Erosional scours are present and minor ripple cross-lamination and horizontal lamination could be seen. Ironstone formation is widespread in nodule form or as banded layers.

The middle interval is mainly composed (65-70%) of thin-bedded siltstones with coaly laminations. Fine-grained sandstone lenses, ironstone concretions and banded layers occur within these dark grey siltstone beds. The interbedded very fine grained sandstone is mostly horizontally laminated with coaly plant remains. The sandstone interbeds rarely exceed 0.40m in thickness. In places the siltstone coarsens up into fine-grained sandstone. The coal occurs as highly oxidized thin beds of not more than 0.20m thickness with smectite-rich claystone (air fall tuff, mostly unreworked) occurring as very thin bands of less than 0.05m.

Unit III is a mainly light brown, fine- to medium-grained sandstone. Portions of the sandstone show crude fining upward trends. The unit is characterized internal by cross-stratification and flat lamination. The cross-sets generally occur in a cross-cutting arrangement with set thickness ranging from 0.05 to 3.00m. The lower bounding surfaces of the cross-stratified units are mainly erosive and trough shaped.

The circular mean of paleocurrent readings (n=298) taken from the whole profile is towards the west-southwest, with a considerable spread. This represents a palaeoflow towards the present western margin of the basin. A swing in palaeoflow from south-easterly in Unit I to westerly in Unit III can be demonstrated from detailed analysis of paleocurrent data.

Interpretation

Two major styles of sediment bodies are represented in Profile 5: composite multi-storey-multi-lateral channel bodies (Units I and III) and flood basinal deposits (Unit II).

The sandy, major channel deposits (Units I and III) in places show complete component channel cross-sections in outcrop. Channel widths of not more than 60m and depths of ca 6m were measured. Within these major channel deposits are small channel bar form deposits probably formed during low flow stage. The presence of paleosols within channel bodies suggests vegetation growth during periods of minimal flow. Lateral transition from thick main channel sandstone deposits to interbedded channel fill was also observed

The middle interval is interpreted as overbank deposits. They occur as thinly bedded sheets with lateral extent of at least a kilometer. Some of the interbedded sandy materials with coarsening upward characteristics are tentatively interpreted as crevasse splay deposits. Many of these blanket deposits are a few decimeters thick, and in many cases occupy small channel forms.

CONCLUSION

Analysis of paleocurrent data indicates that the Walloon Coal Measures in the study area were formerly continuous into the southeastern Surat Basin to the northwest (Fig. 2). A sediment source to the south and east is indicated. Sediments accumulated on a vast alluvial plain, crossed by mainly small, narrow meandering streams. These rivers were separated by floodbasins and discontinuous swamp environments that were continually affected by overbank sand deposition and reworking by channel migration

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THE MYSTIC ART OF COAL DEPOSIT MODELLING

B. MULLARD
NSW Department of Mineral Resources

INTRODUCTION

The arrival of computers has revolutionised many areas of geology. Computers have become an essential element in analysing the vast amount of data generated by exploration programmes. The high cost involved in drilling and sampling demand that as much information as possible be squeezed from the data.

In coal geology computers have revolutionised the data acquisition and storage phases of exploration and have provided the means to create an interactive model of a coal deposit from which reserves can be delineated, extraction schedules generated and coal quality variations analysed.

But how closely do these models match reality?
What errors are likely to be made?
How much confidence should be placed in the model?
What is the likely accuracy of resource /reserve estimates derived from the model?

The use of computers to construct these models creates the illusion of accuracy and rigour. Computer based techniques offer the geologist a wide range of interpolators such as kriging, trend surface techniques, triangulation and inverse distance weighting. All of these methods allow the geologist to vary model parameters, such as search distance, weighting factors, etc., in a trial and error manner until the geologist feels that the model provides a reasonable approximation to reality. However, this results in most coal deposit modelling being more of a mystic art than a science, dependant on rules of thumb, intuition, and the black box magic of the computer.

This paper examines the nature of coal deposit variability and from the insights gained suggestions are given for quantifying and improving model accuracy.

COAL DEPOSIT MODELS

A model in its most general sense is a representation of reality. A computer based coal deposit model is a symbolic model. It may employ several trend surface equations, grids of interpolated data points or a mathematical technique for interpolating points to represent the coal deposit. Often the model will have been constructed from borehole data.

Consequently the model will be an extrapolation of the properties of millions of tonnes of coal from a total sample weight measured in kilograms.

THE MYSTIC ART OF COAL DEPOSIT MODELLING

A coal deposit model is the result of a mathematical manipulation of the original sample data. Being based on sample data a coal deposit model is statistical in nature. In using the model to infer coal properties one can, at best, only talk in terms of probabilities.

The accuracy of the model is dependent on the underlying variability of the coal deposit, the algorithm used to interpolate between sample points, the sampling pattern and the experience of the geologist constructing the model.

The Nature of Coal Deposit Variability.

Coal deposits show an enormous range of variation, from relatively simple single seam deposits of uniform coal properties through to complex multiple seam environments with seam splitting having large variations in coal properties over short distances.

The variations observed in coal deposits are principally a reflection of the sedimentary environment and the tectonic framework of the basin in which the coal was deposited.

The ability to extrapolate from limited data to produce a model is dependent on two main properties, the covariance structure of the deposit and the trend of the deposit.

Covariance refers to the common observation that the closer two sample points are to each other the more likely they are to have similar values. In statistical terms the variance between two points increases as the distance separating the points increases. This concept is often described as the zone of influence of a data point. Beyond a certain distance, commonly referred to as the range, variance reaches a maximum and the sample points are said to be independent of each other. Most modelling systems make use of this concept by using a search radius to include only those samples within a reasonable distance of a point to be estimated for use in interpolating the unknown point.

Trend, refers to the tendency of coal seams to vary in a regular and predictable way. For example a seam may thicken from 1 to 4 metres from west to east. Where a regular trend is present it can be used to accurately extrapolate coal properties using limited data. Figure 1 illustrates the difference between trend and covariance.

For most coal deposits trend is the dominating feature. The regional nature of the two principal influences, sedimentary environment and tectonic framework, result in coal seams having definite trends that can be used to extrapolate between and beyond data points.

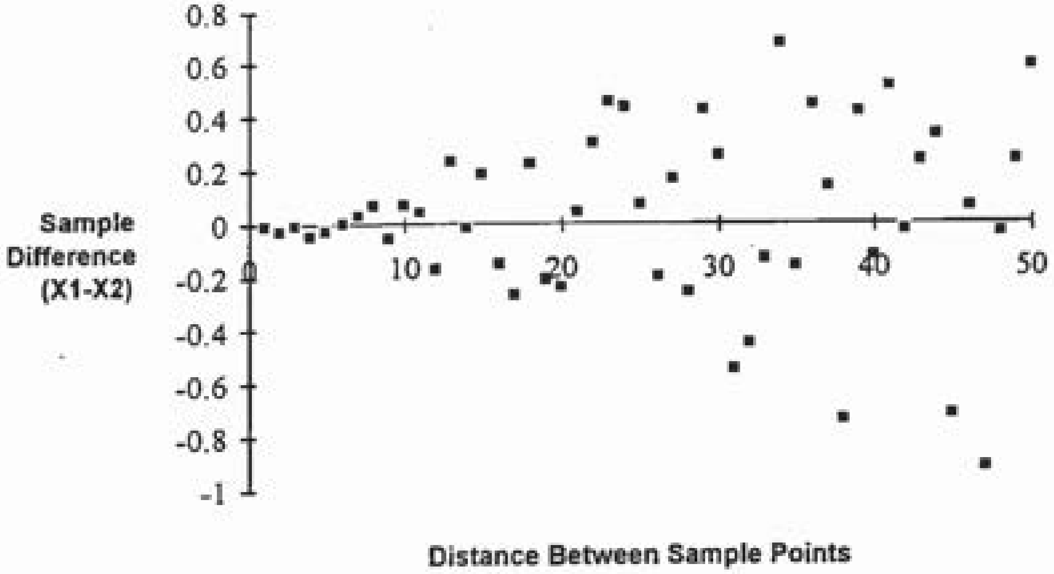
Sampling Patterns

The choice of sampling pattern can significantly affect the accuracy of the final model. In part the choice of sampling pattern is dependent on the nature of the coal deposit. Where a strong trend is suspected the most efficient method of sampling the deposit is by way of a triangular grid (hexagonal lattice). A triangular drilling grid can be up to 30 percent more efficient than a square drilling grid for the same maximum interpolation distance.

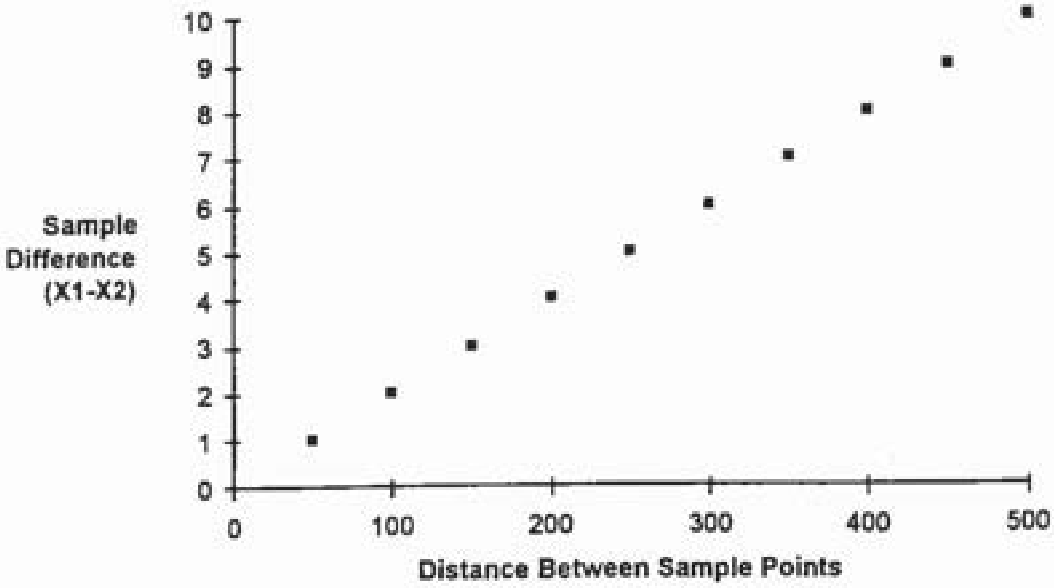
While a triangular grid may be the most efficient method of sampling a deposit where strong trend is expected it may not be appropriate where trends are weak or absence. In these circumstances the more sample points one has the more accurate the resulting estimate is likely to be. In these cases the more traditional square grid may be more appropriate (Rudenno 1983).

Figure 1

a) Each point represents the difference between two values of varying spacing. Increasing distance between points results in increasing variability and hence is less predictable. Note that the data does not display any trend.



b) Once again each point represents the difference between two values. However, with increasing distance a perfect trend is evident. With strong trends prediction over large distances are possible.



Interpolation Algorithm

There are three main types of interpolation methods:

a) Moving average techniques
b) Trend Surface techniques
c) Geometric techniques

Moving average techniques are best suited to deposits that do not display strong trend. These techniques include inverse distance and kriging methods. Moving average techniques commonly use a distance weighted average of surrounding data to estimate an unknown point. Moving average techniques do not normally extrapolate unknown data values outside the range of the sample data.

Trend surface techniques are best suited for deposits known to display strong trend. These techniques may extrapolate data above and below the range of the surrounding data points.

Most geometric techniques were developed before the advent of computers. Because Geometric Methods are extremely easy to implement they have proved to be extremely popular and were among the first methods to be computerised. These techniques include the popular polygonal block method, that when computerised consist of assigning the value of the closest sample point to the point to be estimated. A common problem with geometric methods is that they tend to give undue weight to extreme data points thus biasing the model.

Most modelling systems present a bewildering array of modelling options. These options include a wide range of interpolators, choices concerning search radius, interpolation distances, number of sample points to be included and maximum and minimum data ranges. This is where there is maximum scope for practising the mystic art of coal deposit modelling. A geologist well versed in these skills can increase or decrease reserve estimates at will by careful choice of interpolator or modelling parameter. Figure 2 shows a possible interpolation from 5 points to a central point using inverse distance. Figure 3 shows an alternative interpolation using a trend surface technique. This comparison demonstrates how coal reserves can be increased or decreased depending on the choice of an interpolator. Without further information concerning the nature of the deposit it is impossible to determine which model is correct.

OPTIMISATION PROCEDURES

Is it possible to determine the best modelling technique or choice of modelling parameters for a particular coal deposit?

A possible method would be to:

a) Examine the data and form a hypothesis as to the nature of the underlying geological variability.

b) Having a tentative notion as to what is required, a modelling technique is chosen which best fits the available data and the perceived nature of the geology.

c) Test the model's predicative ability against a fresh sample drawn from the same deposit.

Figure 2

Interpolation to a central point from 5 surrounding sample points using an inverse distance interpolator. Because inverse distance is a moving average technique the central point is lower than the four 2m sample points. (Note the North - south cross-section.)

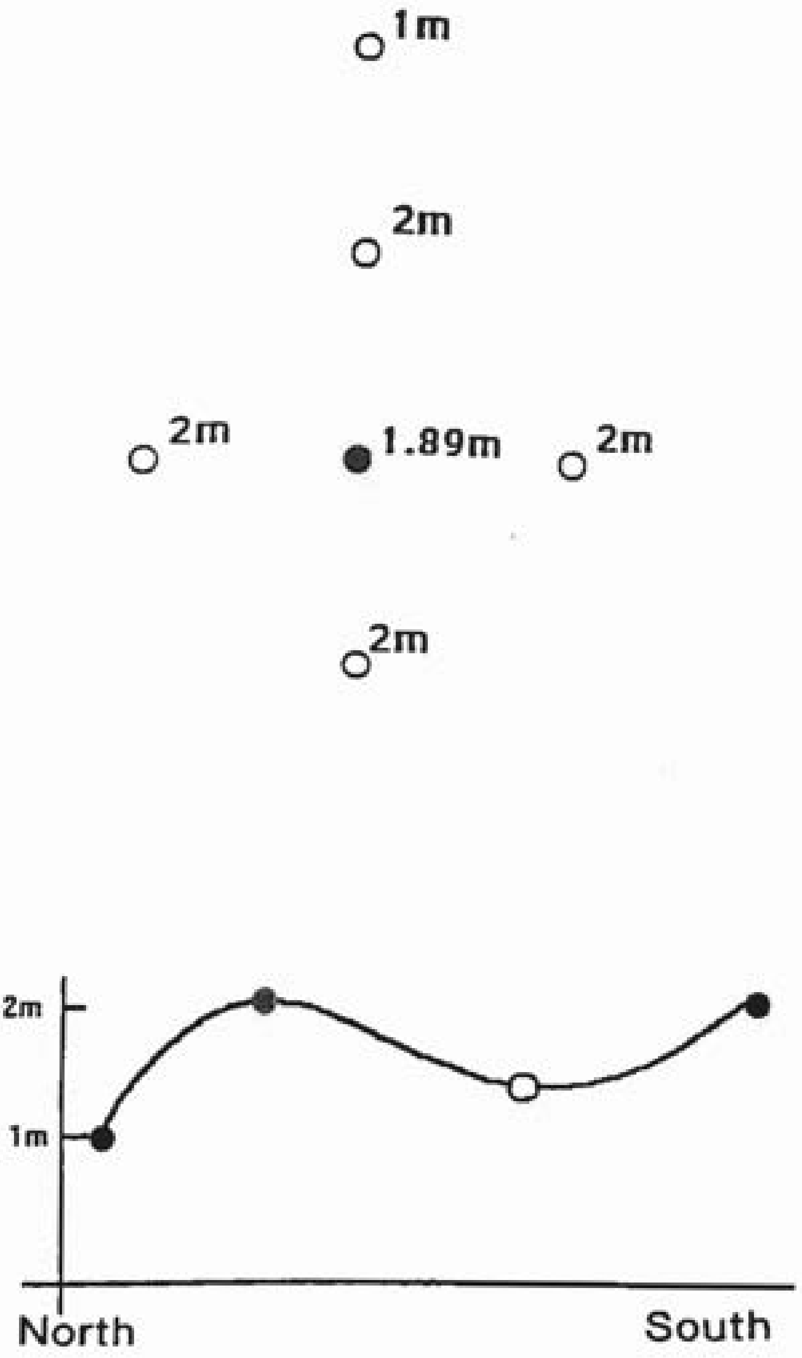


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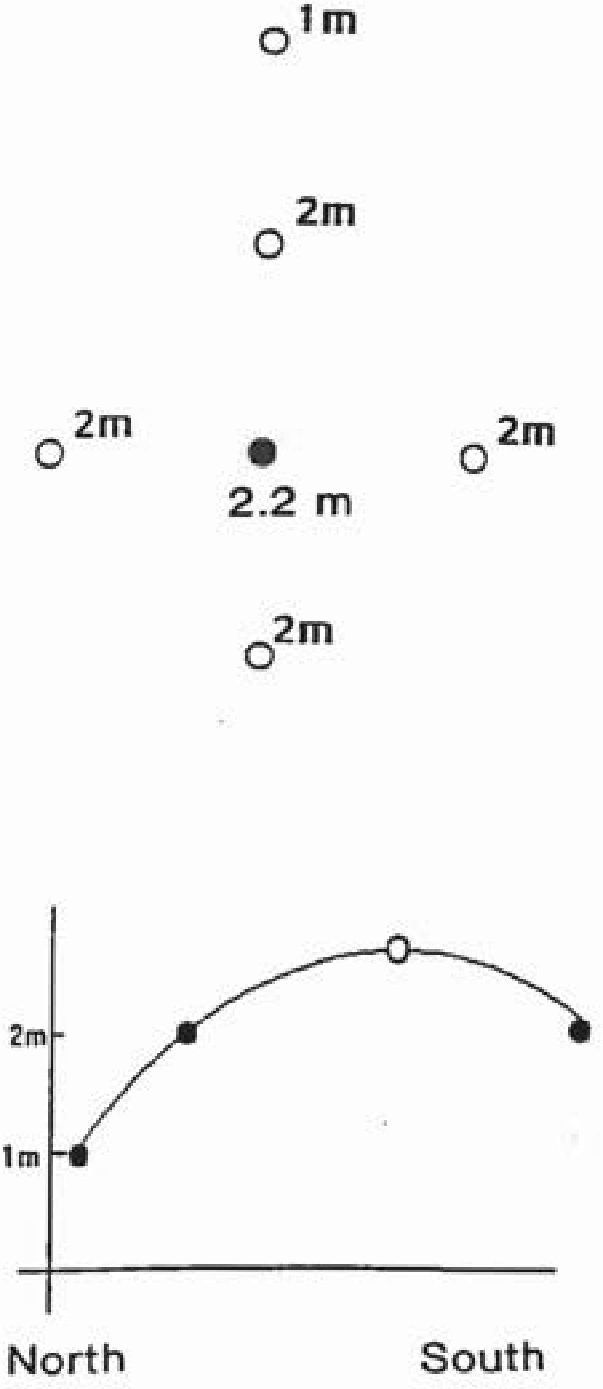
Figure 3

Interpolation to a central point from 5 surrounding sample points using a trend surface interpolator. By following the trend the central point is interpreted to be higher than the four 2m sample points. (Note the North - south cross-section.)



The above procedure works very well where it is possible to go out and obtain a fresh independent sample. However, the high cost of exploration programmes in most cases would prohibit such a verification procedure.

Statistical techniques known as cross-validatory choice and assessment procedures offers an alternative (Stone 1974). The basic concept consists of setting aside part of the data without any examination. The remaining data is then used to develop the model while the set aside data provides an unbiased comment on the efficiency of the modelling technique.

The size of the set aside sample can be as small or large as required. In addition the procedure can be repeated any number of times. In fact an individual sample could be set aside. The geological model could then be optimised for the remaining samples, and then geological model could be tested against the set aside case. This procedure could be repeated for every sample. While computationally difficult the procedure effectively squeezes the data dry.

A similar optimising procedure could be used to design drilling programmes by identifying areas where additional drilling would have the greatest impact in reducing uncertainty. For example if the deletion of one sample point in an area caused significant changes to the model's reserve estimate, then this would indicate that the model is highly dependent on that one sample. This is where the model is most uncertain and where additional drilling could be required to increase the level of support for any interpretation of the geology within the area.

A variation of this procedure known as the Jacknife (Miller 1974) could be used to derive rough confidence limits for coal reserve estimates derived from virtually any model based on boreholes. To obtain confidence limits using the Jacknife procedure reserve estimates are obtained with each borehole deleted in turn. The variation in these values can then be used (not directly) to obtain an estimate of the variability of the deposit and define confidence limits. However, for the model to be valid the boreholes must be independent of each other. That is, the distance separating each borehole must be beyond the range of any co-variability in the data. In addition the interpolation procedure must be capable of extracting any trend in the data. While these conditions may seem restrictive it is the author's opinion that in many cases borehole data after the removal of trend can be treated as independent, particularly in the early stages of a coal exploration programme when drilling is typically widely spaced.

The major advantage of this method is that it is not dependent on the interpolation procedure and therefore can be used to develop rough confidence limits for the numerous interpolation procedures available. This is in contrast to kriging where the estimation of confidence limits is integral to the modelling procedure.

CONCLUSION

The choice of a modelling procedure should only be undertaken after careful consideration of the nature of the deposit to be modelled. The process of obtaining a valid geological model should not be a matter of blind luck. With a knowledge of the nature of the deposit to be modelled, an understanding of the characteristics of the modelling procedure to be used and by the use of statistical procedures to validate the model, coal deposit modelling can move from being a mystic art to a science.

THE MYSTIC ART OF COAL DEPOSIT MODELLING

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WAVELENGTH OPTIMISATION FOR THE MICROFLUORESCENCE INTENSITY MEASUREMENTS OF VITRINITE & INERTINITE

L.C. GAMMIDGE & C.F.K. DIESSEL
Dept. of Geology, The University of Newcastle

An ACARP supported project No.C1622 was carried out to determine the optimum wavelengths for excitation and measurement of vitrinite and inertinite, using commercially available equipment. At present there is no standard procedure for fluorometry of coal macerals and different methods used by laboratories involved in this work produce varying results by virtue of their system of fluorometry.

When coal is irradiated by a beam of light at a specific wavelength or band of wavelengths it may fluoresce. Energy is used by the molecule to promote electrons to unstable higher energy atomic or molecular orbitals. The energy released as the electrons return to their ground state is emitted as fluorescence. Some energy is converted in inter- and intramolecular reactions, so the emitted fluorescence is of lower energy (i.e. it has a longer wavelength, about 150nm to 200nm longer). Vitrinite and inertinite emit maximum fluorescence intensity in the red range of the spectrum, therefore an excitation beam approximately between 430nm and 530nm is desirable (Diessel & Gammidge 1994). Fluorescence is a reflection of the coal's composition, so it is different for individual macerals and also varies with rank.

Microfluorescence of vitrinite is a characteristic which has been linked to the thermoplastic or coking properties of coal (Diessel 1985, 1986, Wolf et al. 1983) as well as for detecting oxidation and weathering of coal (McHugh 1986). There are two phases of vitrinite fluorescence. Figure 1, after Zhiwen et al. (1993), illustrates the change in fluorescence intensity with increased rank. The first fluorescence response is known as primary fluorescence, it gradually decreases to a minimum level at approximately 5.5%Rr (mean random) vitrinite reflectance, the secondary phase of fluorescence reaches a peak between 0.9%Rr (Zhiwen et al.,1993) and 1.30%Rr (Hagemann et al.,1989) depending on the origin of the coal and the measuring wavelength used. It is the secondary fluorescence phase of vitrinite which correlates well with coal thermoplastic properties, such as Gieseler Fluidity.

The results of microfluorescence analysis would be more useful if a standard procedure were adopted. Two microscopes were used for this project, both utilised a high pressure mercury lamp HBO 100/2 and a series of filters placed between the light source and the coal sample to produce the excitation beam.

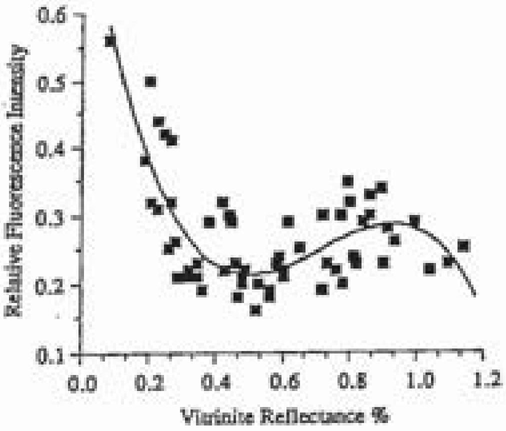

Figure 1. The relationship between huminite/vitrinite fluorescence intensity and rank using blue light excitation (410-490nm) measured at 546nm (After Zhiwen et al 1993).

The following filter sets were tested:

Wavelength	Bandwidth	Dichroic Mirror	Barrier Filter
395-440nm	45nm	FT460nm	LP470nm
436nm	8nm	FT460nm	LP470nm
450-490nm	40nm	FT510nm	LP520nm
485nm	20nm	FT510nm	LP520nm

These filter sets are not a very efficient method of producing the excitation beam because the substantial luminous flux generated by the mercury lamp is largely blocked out by the filters. Figure 2. shows the position of the filters with respect to the spectral emission intensity of the high pressure mercury lamp.

There are two methods of measuring fluorescence, monochromatic fluorometry involves measuring fluorescence intensity at a single band of wavelengths, while spectral fluorometry is the measurement of fluorescence intensity over a range of wavelengths. Both methods of measurement were used. The four excitation filter sets above were used in a Carl Zeiss axioplan microscope which has a grating monochromator between the sample and the photomultiplier. Fluorescence intensity of vitrinite macerals was scanned between 450nm and 750nm. A mean fluorescence spectrum was calculated using 50 individual spectra, for each of the 25 samples. This procedure was carried out for each separate filter set.

The bandwidth and the range of the filters were significant to the fluorescence intensities produced. The highest fluorescence intensities were acquired with the 395-440nm filter, the 45nm bandwidth includes two peaks in the spectrum of the mercury lamp (see Figure 2), the luminous flux passed through the filter is relatively higher than for the other three filters. The intensity of fluorescence using the

450-490nm and 485nm filters was less and a higher gain setting on the instrumentation was needed, so electric noise was amplified. The spectra produced using these filters had a greater variation. The 485nm filter with its comparitively narrow bandwidth of 20nm produced the least intensity, this is attributed mainly to the low emission intensity of the mercury lamp at this wavelength interval. This is unfortunate since the range of this filter is the most desirable within the preferred excitation range for vitrinite and inertinite.

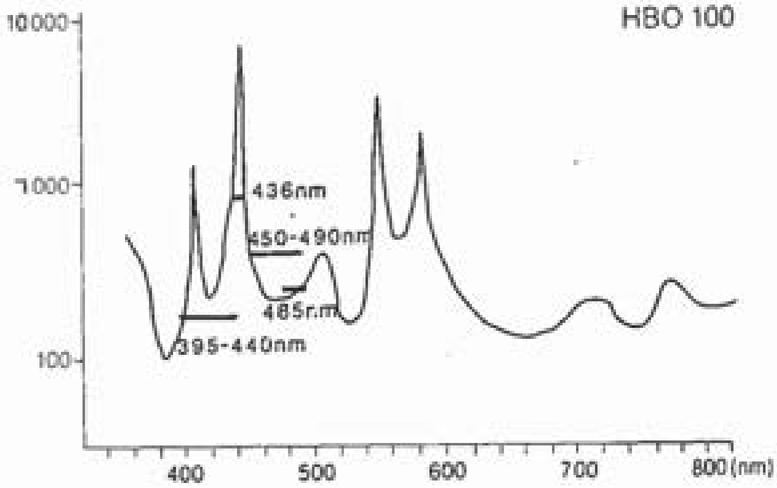

Figure 2. The relative spectral intensity distribution of the HBO100 mercury lamp, with the wavelengths of the filters under test shown. The vertical position of the filters illustrated is arbitrary.

The narrow bandwidth of the 436nm filter resulted in a smaller spread of results compared with the other filters. The spread of results is demonstrated in Figure 3, fluorescence intensities were produced using the 436nm and 450-490nm filter sets. Although the 450-490nm results are higher in intensity the variation is lower using the 436nm filter. Therefore, the 436nm filter is recomended to create the excitation beam for vitrinite and inertinite fluorescence mesurements (Diessel & Gammidge 1994).

The second objective of the project was to experiment with the wavelength of measurement. The distribution of fluorescence intensities graphed against a rank parameter such as vitrinite reflectance, varies depending on the measured wavelength.

A grating monochromator was used to measure the fluorescence spectra between 450nm and 750nm. Figure 4 is an example of three mean spectra at different ranks, using 436nm excitation, the lower ranked samples have maximum fluorescence intensity at lower wavelengths, as rank increases the wavelength of the maximum fluorescence intensity shifts to the red end of the spectrum. The maximum intensity also decreases as rank increases.

The monochromatic fluorescence results demonstrated that the distribution of fluorescence intensity measured at 650nm had an approximate bell shaped curve and has a peak at about 1.1% Rm vitrinite reflectance, this correlates well with the thermoplastic properties of coal. The spectral fluorescence distributions of vitrinite and inertinite indicate that although the wavelength of maximum reflectance varies with rank a strong enough signal is produced by vitrinite and inertinite for measurement.

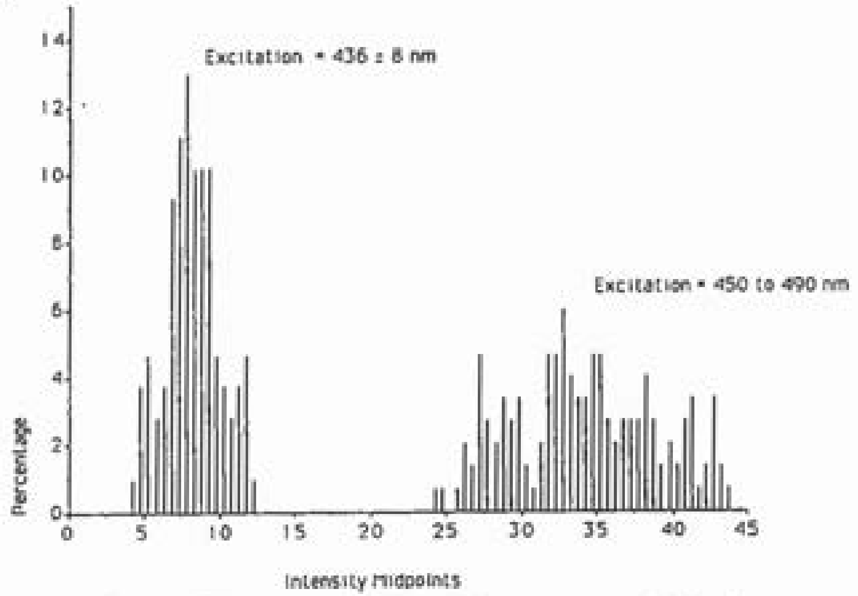

Figure 3. A comparison of fluorescence intensities on telovitrinite in a high volatile bituminous coal, using the 436nm and the 450-490nm excitation filters, measured at 650nm.

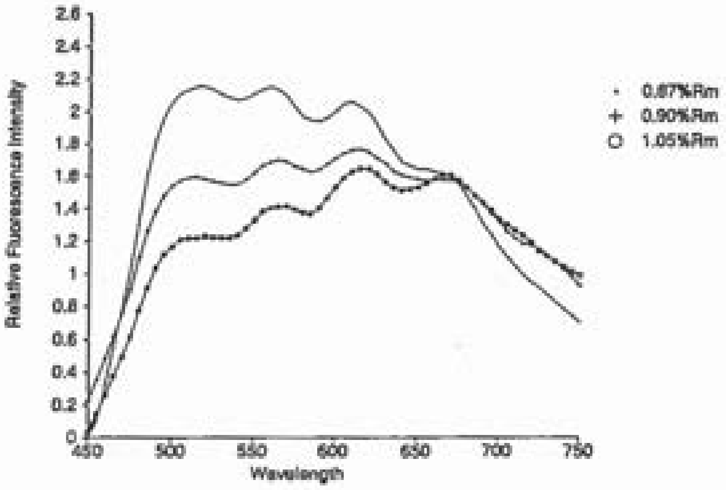

Figure 4. Relative spectral fluorescence intensity of three bituminous coals measured using the grating monochromator.

Therefore microfluorescence measurements on coal, at a rank most suitable for coking (between 0.9 and 1.3%Rm vitrinite reflectance) microfluorescence are optimised by using a narrow band filter centred about 436nm to produce the excitation beam and measuring the fluorescence intensity at 650nm.

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DETERMINATION OF STRESS RELAXATION AXES IN DRILL CORE USING LASER MICROMETRY & PALAEOMAGNETISM

P.W. SCHMIDT & M.A. LACKIE
CSIRO Division of Exploration & Mining, N. Ryde

ABSTRACT

The method of determining stress relaxation axes builds on the experience developed in using palaeomagnetism as an orientation marker throughout the Sydney-Bowen Basins. This has proved extremely reliable and versatile. Preliminary work shows that stress relaxation axes may be delineated using a laser micrometer by detecting variations in drill core diameters as a function of angular rotation. Cross-sectional diameters vary from 30 µm to 150 µm. This paper reports on the monitoring of the stress relaxation of drill core from soon after the drill core was extracted from a drill hole. Data from hole TMC61 at Tahmoor, hole C448 at Ulan and the Department of Mineral Resources hole Varroville 2 are presented.

METHOD

In order to facilitate the measurement of the diameter of drill core, a computer controlled system was constructed which rotated and translated the drill core through the scanning space to automatically measure the diameter every 1.4° (360°/256) of rotation and every 2 cm of translation. Pilot runs established that 256 diameter measurements over one rotation of the core (hereafter called a slice) was adequate to delineate the cross-sectional shape of the drill core. The diameter of each slice is a periodic function of rotation, repeating each 180°. Measurements of each half rotation were therefore averaged. FFT analysis was then performed on the 128 measurements to determine the magnitude and the phase of the "fundamental" and thus identify the stress relaxation axis. The data were treated statistically using the appropriate methods (Fisher & Powell, 1989) to yield mean relaxation axes from all acceptable slices for each sample.

Examples of the results obtained from laser micrometer measurements of drill core ellipticity are shown in Fig. 1. The figure shows the results from two fine-grained sandstones from hole TMC46 at Tahmoor. The samples are approximately 30cm long and span about 1 metre of drill core. The plots show drill core diameters for slices which are separated by 2cm over the length of the core. Observe the excellent consistency in drill core shape of all the slices and the nearly identical results for the stress relaxation axes of the two samples.

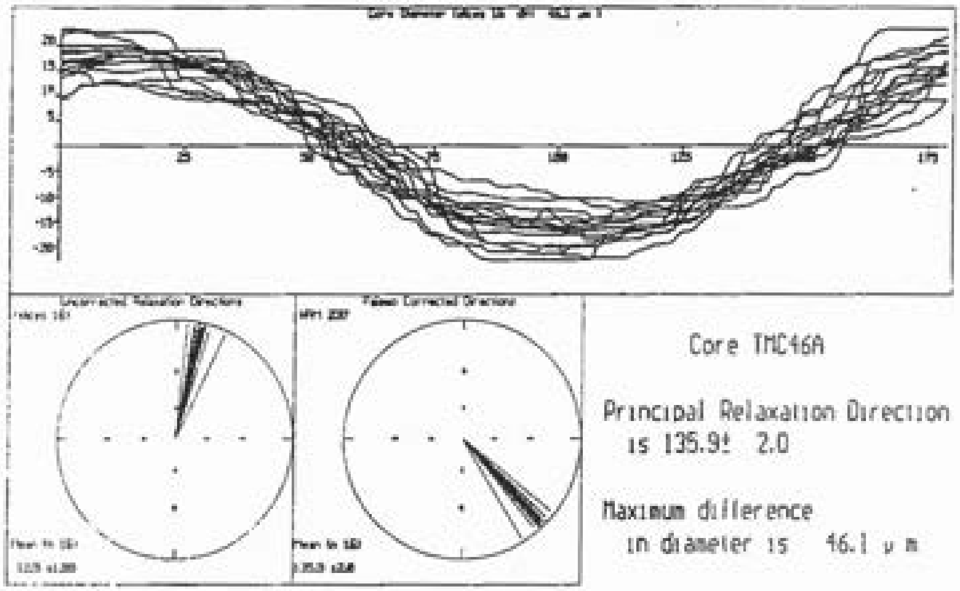
Figure 1. Plots of laser diameter measurements for two drill core samples from drill hole TMC46 from Tahmoor.

The top section of the figure is a plot of the diameter of the core (minus the mean diameter) for each individual slice over 180°. 0° refers to the fiducial line marked on the sample. Ordinate is in µm. All slices are plotted with concordant means. Number of slices plotted and maximum difference in diameter measurements is shown at the top of the plot.
The bottom left hand corner of the figure is a plot of the uncorrected relaxation axes obtained from a FFT of the diameter data for each slice. The top of the stereonet represents the zero of the core diameter plot. The angle at which the line is drawn from 0° represents the relaxation axis (phase of the fundamental harmonic) obtained from the FFT. The length of the line from the centre represents the percentage of the power spectrum that is the fundamental harmonic. 100% would be a line from the centre to the edge of the circle and so on. Slices with low fundamental harmonic contributions to the power spectrum (ie. <50%) or high second harmonics were not included in the calculations of mean relaxation directions for the samples. The mean direction and associated error obtained from all of the viable slices is shown in the bottom left hand corner of the plot. The number of slices used in the calculation is shown above this by "n". The mean is also indicated on the plot by a small arrow on the circumference of the circle.

The bottom centre plot of the figure contains the same information as the plot to its left but the axes have been palaeomagnetically corrected and thus now the top of the circle represents geographic north.

Note: "direction" within the figure refers to one half of the relaxation axis.

STRESS RELAXATION

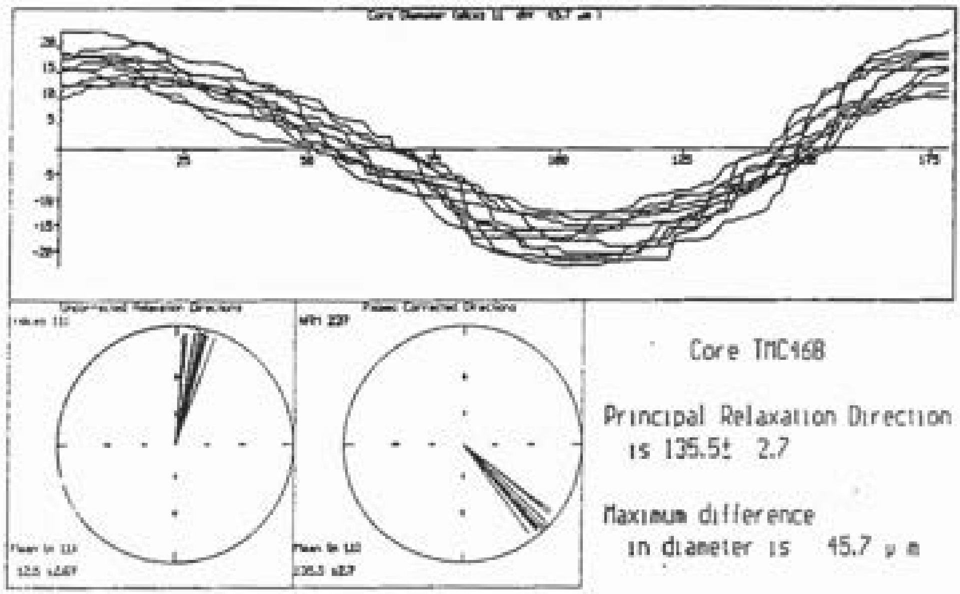


A1

Core TMC46A

Principal Relaxation Direction
is 135.9± 2.0

Maximum difference
in diameter is 46.1 μ m



A2

Core TMC46B

Principal Relaxation Direction
is 135.5± 2.7

Maximum difference
in diameter is 45.7 μ m

The diameter difference which is observed for all slices measured over the two samples is approximately 45 µm.

The remanence of the drill core samples was measured with a longcore magnetometer (Schmidt & Anderson 1991). In some cases, samples or adjacent samples are subsampled and the remanence measured with a more sensitive cryogenic magnetometer to confirm the stability of the remanence. The remanence directions obtained from either the longcore or cryogenic magnetometer are used to palaeomagnetically orientate the stress relaxation axes so that they are presented with respect to geographic north.

RESULTS

Data from hole TMC61 at Tahmoor, hole C448 at Ulan and the Department of Mineral Resources hole Varroville 2 are presented. Drill core samples were obtained just after the core was extracted from the drill hole. Samples were of the order of 30cm long and usually two or three sections were taken. The samples were then transported to the CSIRO Rock Magnetism Laboratory where the ellipticity of the sample was measured with the laser micrometer. The samples from Tahmoor were measured at varying time intervals at the same position. The samples from Ulan and Varroville were measured continuously over about 24 hours along the length of the core. This meant that each "slice" was measured at approximately 5 hour intervals for the Ulan sample and at approximately 3 hour intervals for the Varroville sample. The sample from Varroville broke after 10 hours, ending the experiment.

Figure 2 shows the laser micrometer data for 2 slices from a siltstone drill core sample from a depth of 134m from drill hole C448 at Ulan. The sample has clearly relaxed over the "day" that the measurements were done. At 6 hours after the sample was cored, the sample varied from being circular by about 10 µm, by 26 hours the sample had relaxed about 50 µm. The transition through the day is easily observed. The relaxation direction is delineated at 11 hours and is quite distinct at greater than 16 hours. The direction is the same at all of the later time periods. This sample was remeasured a week later and the stress relaxation direction was the same but the sample had relaxed a further 40 µm to a 90 µm difference.

Figure 3 shows the result from a siltstone sample from a depth of 395m from drill hole TMC61 at Tahmoor. Measurements were made 4 hours after the sample was cored and 7 hours after the sample was cored. The relaxing of the core from the 4 hour to 7 hour result is obvious, with the core relaxing from about 20µm to about 55 µm. The stress relaxation axis is the same for the 2 time periods. The core was measured one week later and had relaxed to about 75 µm with the stress relaxation axes similar to the initial measurements.

STRESS RELAXATION

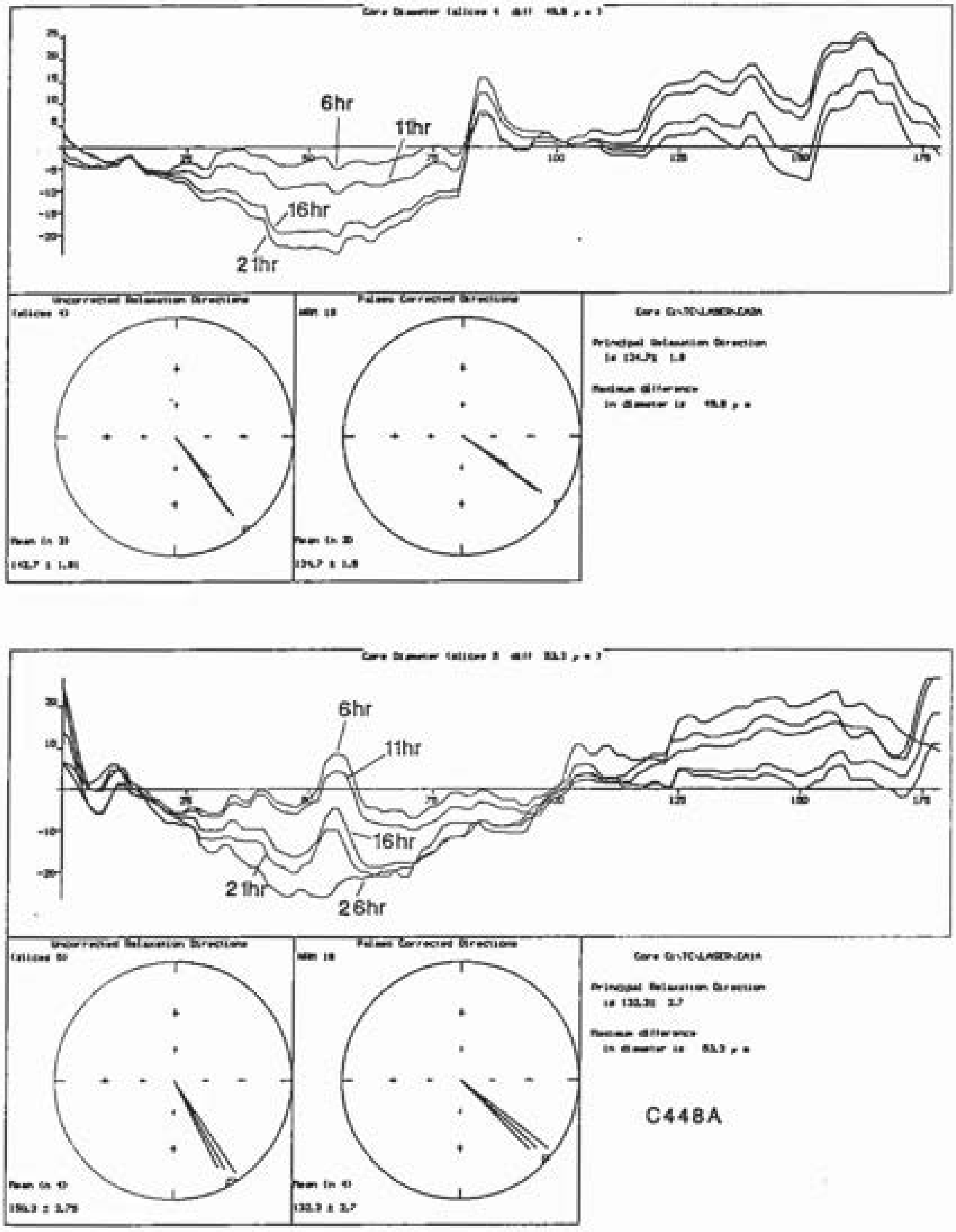


Figure 2. Plots of laser diameter measurements for a drill core sample from drill hole C448 from Ulan. The plots are of two slices separated by 0.5cm. Each plot shows the measurements made at that particular slice at the time after the sample was cored as shown. Observe the relaxation of the core from about 10μm at the 6hr measurement to about 50μm at the 21hr measurement. See Fig. 1 for an explanation of the plots.

Figure 4 shows the result from a fine sandstone sample from a depth of 386m from drill hole TMC61 at Tahmoor. The sample was measured at 5 hours after it was cored and at 24 hours with no coherent direction observed in that time period. The diameter difference observed was about 15 µm. The sample was then measured a week later and a distinct ellipsoid shape was observed with a diameter difference of about 60 µm. Measurements were repeated at 10 days and 41 days with a slight change in the stress relaxation axis. The measurement made on day 41 was over the length of the core (50cm) with the same relaxation axis observed along the length of the core.

Figure 5 shows the result from a siltstone sample from the Wongawilli Seam from a depth of 901m at Varroville. The results shown are for a single slice with measurements made at periods of 3, 6 and 9 hours after the sample was cored. Once again the core can be seen "relaxing" over this time period with it relaxing from about 20 µm at 3 hours too about 70 µm at 9 hours. Only the 9 hour result shows a preferred "fundamental" axis and even that is not clear with it representing only 50% of the FFT power spectrum. This suggests more than one stress direction is operative.

SUMMARY

From the three examples presented it is apparent that drill core relaxes after it has been cored. The drill core relaxes from a circular shape to a slightly elliptical shape. The long axis of the ellipse is thought to be the stress relaxation axis for the sample. The time period that the relaxation occurs over differs for siltstones and sandstones, with the siltstones tending to mostly relax over 24 hours while the sandstones take longer (days) than this. Cross-sectional diameters vary by about 50 to 70 µm, although in some sandstones it is less while in some siltstones the diameters can vary by up to 150 µm.

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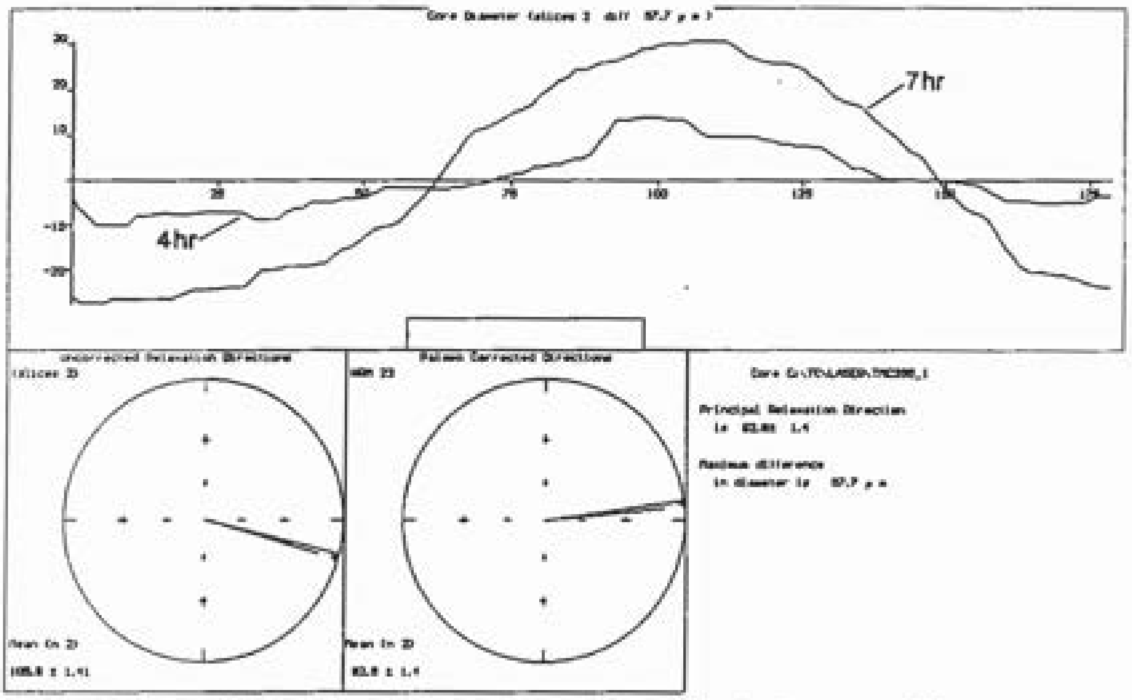

Figure 3. Plots of laser diameter measurements for a single slice at 2 different times, for a siltstone drill core sample from drill hole TMC61 at Tahmoor. Observe the relaxation of the core from 20 µm to 60 µm in 3 hours. See Fig. 1 for an explanation of the plots.

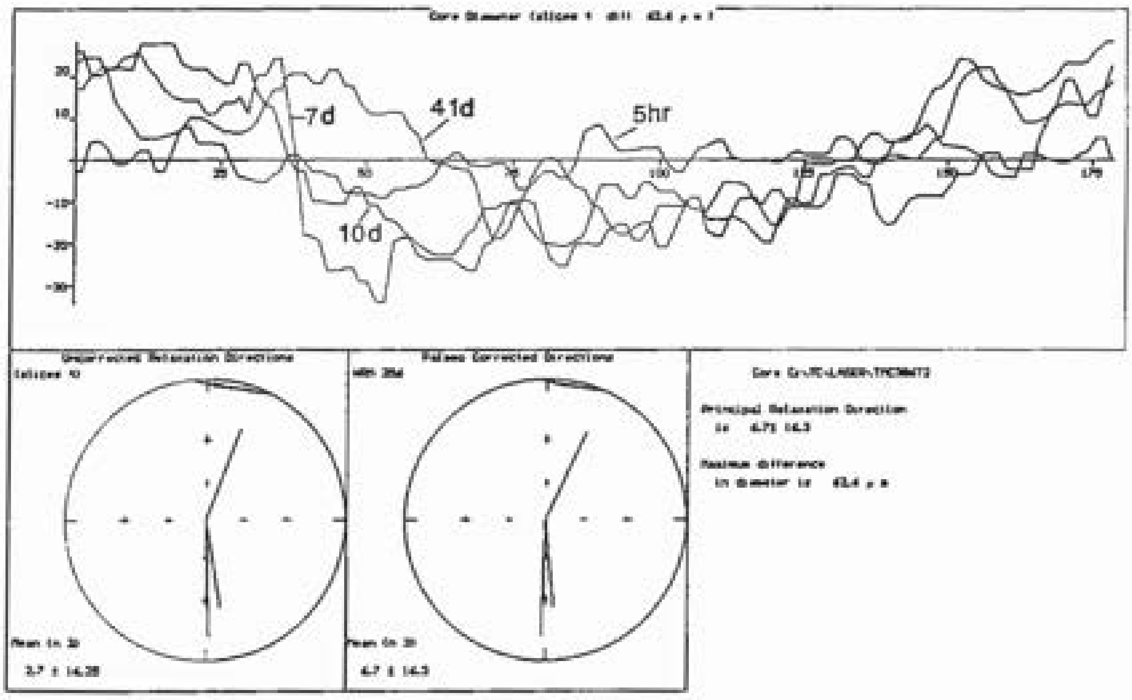

Figure 4. Plots of laser diameter measurements for a single slice at 4 different times, for a sandstone drill core sample from drill hole TMC61 at Tahmoor. Observe the relaxation of the core from 20 µm to 60 µm. This sample is different from the siltstone sample shown in Fig. 3 in that it has relaxed over a longer period of time. See Fig. 1 for an explanation of the plots.

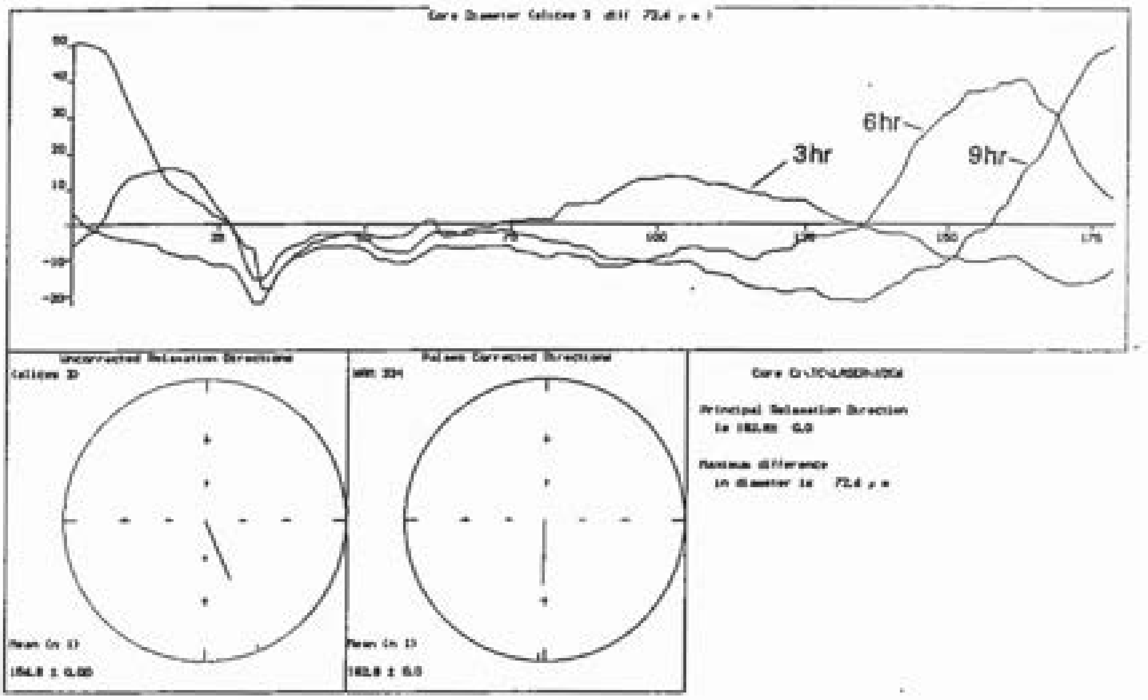

Figure 5. Plots of laser diameter measurements for a single slice at 3 different times, for a siltstone drill core sample from the Department of Mineral Resources drill hole DDH2 at Varroville. Observe the relaxation of the core from 20 µm at the 3 hour measurement to 70 µm at the 9 hour measurement. See Fig. 1 for an explanation of the plots.

AEROMAGNETICS FOR MINE HAZARD DETECTION

W. STASINOWSKY[1] & G.R. POOLE[2]
[1] **Mining Geophysics Pty Ltd, Brisbane**
[2] **BHP Steel, Collieries Division, Wollongong**

Increasing resolution in aeromagnetic surveys has led to their use for helping to detect various mine hazards.

Instrument resolution has been of the order of 0.01 nT (nano-Tesla) for some time, but previous surveys were limited to ± 2 nT because of the effects of the metal aircraft.

Intersection of a sill in an exploration bore prompted reprocessing of the old data. Interpretation was difficult because of 2 nT noise and the presence of a nearby magnetic dyke, but the result was an interpreted limit to the sill. Subsequent drilling proved the interpretation to be correct.

Because of the success of the above, two more aeromagnetic surveys were flown using a helicopter. Good data quality and micro-levelling allowed anomalies of the order of 0.1 nT to be interpreted. Some anomalies proved to be weakly magnetic dykes with susceptibilities below what was traditionally thought to generate detectable anomalies. Other anomalies proved to be caused by either fracture zones or fracture associated fault zones.

The survey was so sensitive that it mapped what was interpreted to be the structural fabric of the area, including the pattern of the larger joints.

Although aeromagnetics could only detect some of the mine hazards facing underground operations, it proved a very cost effective way of adding to the information at the geologist's disposal.

ACKNOWLEDGMENTS

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SEISMIC MONITORING OF LONGWALL EXTRACTION AT TAHMOOR COLLIERY

R.J. DIXON & P. HATHERLY
CSIRO Division of Exploration & Mining, Kenmore

INTRODUCTION

It has long been recognised that continuous seismic monitoring can be used to measure the response of a rock mass to mining. Australian work includes that of McKavanagh and Enever (1980) and Grezel, Leung and Ahmed (1984) where targets have been gas driven outbursts in coal mines, and that of Godson, Bridges and McKavanagh (1980) where there was an attempt to predict rock bursts in the deep mines at Mt Isa.

Seismic monitoring has been extensively used in coal mines in countries such as Poland (Gibowicz, 1984), Germany (Will, 1984), and the United Kingdom (Davies, Styles and Jones, 1987). In metalliferous mining the work in the South African gold mines (Mendecki, 1993) and Canadian nickel mines (Morrison, 1993) has been outstanding. Many of these mines now use seismic monitoring networks on a continuous basis. They provide a means of locating seismic events around deep mine workings. It is also possible to determine factors such as the mode of failure and the energy release, all in real time.

In 1992, the CSIRO Division of Geomechanics hosted a visit by Dr Peter Styles of Liverpool University. His efforts were directed towards establishing a project to investigate the possibility of using seismic monitoring to identify precursors to outbursts during gate road development. His previous work predicting outbursts over a number of years at Cynheidre Colliery (Davies et al, 1987) was particularly successful. However, Cynheidre operated an advance longwall without any predrainage. Thus, although the Australian situation is different, an attempt to repeat the work in Australia was certainly justified.

THE INITIAL MONITORING AT TAHMOOR COLLIERY

Sponsorship for a trial survey was obtained from Kembla Coal and Coke. During 1992, a monitoring station was set up on the ground surface, directly above the soon to be developed longwall panel 11. The station consisted of a three component seismometer situated on a rock ledge in a pit dug approximately 0.5 m into the ground. A heavy duty 12 volt battery in the pit was used to power amplifiers and a radio link which sent continuous readings to a digital tape recorder housed at the mine offices.

Each tape recorded 12 hours of continuous data. The upper frequency was 64 Hz.

Initial recordings were made over a one month period as gate road development progressed for longwall panel 11. The tapes were changed by mine staff and sent to CSIRO and Liverpool University for processing. Tapes were then recorded in a cyclic manner with a rolling week of recording.

Results of that work are described in a report to Kembla Coal and Coke (Styles, 1992). Unfortunately, the results are inconclusive as no outbursts of significance occurred during the monitoring period.

SUBSEQUENT MONITORING

At the completion of the trials, the monitoring equipment was left on site in case of further need. In July 1993, longwall panel 11 was extracted directly beneath the station and CSIRO (now the Division of Exploration and Mining) took the opportunity to monitor the associated seismic activity. Seismic activity was recorded almost continuously from the morning of the 23rd of July 1993, through to 7.00 am on the 30th of July 1993.

METHOD OF ANALYSIS

At CSIRO, the data tapes were replayed through a PC and an automatic event detection algorithm was used to detect the seismic events and to store them in a computer data base. Events from any particular time can be recalled, displayed and plotted. The data base can also be interrogated to allow determination of statistics such as the number of events per unit time and the number of events of a certain amplitude per unit time.

TYPES OF EVENTS

Styles' work in classifying events at Tahmoor was extremely useful. He reported the following types of events:

i.) Low frequency (6 Hz) sinusoidal events with durations of several minutes. These were attributed to the cutting action of continuous miners. We did not observe any of these events in the current data. However, they could well have passed undetected by the event detection algorithm which was directed towards detecting impulsive type events. It is also quite possible, that the cutting noise from a longwall shearer has a different character and reduced intensity when compared to a continuous miner.

ii.) Low frequency (12 Hz) emergent events with durations of several seconds which were attributed to road traffic noise. We are not aware of these in the current data either, but again, the detection algorithm was not tuned to their detection.

iii.) 'Normal' seismic events with dominant frequencies between 5 to 25 Hz, with sources up to 6 km from the recording station. The number of events was usually less than 10 per hour. These were attributed to roof and floor failures. The same types of events are present in the current data.

iv.) High frequency seismic events with dominant frequencies above 25 Hz and with sources less than 1 km from the recording station. These events comprise the majority of longwall extraction data. Figure 1 shows an example.

There is probably no real difference between the 'type iv' and the 'type iii' seismic events. Higher frequencies can be expected with closer sources and smaller magnitudes. Roof and floor failure would again be the driving mechanism.

In addition to these events, our data base contains noise bursts which are due to wind gusts, local noise etc. An example of such an event is shown in Figure 2. Its character is quite different from the above events.

NUMBER OF EVENTS WITH RATE OF ADVANCE

Figure 3 shows a plot of the number of events recorded every hour and the cumulative advance of the longwall. The longwall position is in relative metre units and the monitoring station is located at approximately 25 m. For the 6 shifts between the 24th and the 25th of July, the longwall was directly beneath the station and no coal was cut.

In Figure 3, the initially high number of events is due to surface noise caused by starting the system and conducting noise tests. After this period, approximately 100 events were detected each hour until the wall stopped on the 24th July.

After the wall stopped the number of events dropped to 50 or so per hour. An initial reaction might be that these events represent background noise unrelated to mining. However many of the events from this period are similar to Figure 1. They are true seismic events and on the basis of the interval between the P- and S-wave arrivals, their sources are less than 1 km from the monitoring station - ie within longwall panel 11. Over the period of that day and a half the roof remained active. Note also that the activity decreases to about 30 events per hour late on the 25th of July (the gap in the data earlier that day is due to a cessation in recording).

On the 25th of July cutting started again and the number of events immediately increased. The initial rate of advance was not great and there was another halt in production on the 26th. All of this can be seen in the seismic data.

Continuous production started on the 27th of July and the number of events increased further to 100 events or more per hour. This continued through to the end of the monitoring period.

10.30 AM 28th of JULY

Figure 3 can be analysed from many perspectives. For example, there is a suggestion of a cyclic pattern. Possibly this relates to cyclic loading. However, the events around 10.30 am on the 28th of July deserve special mention.

At this time, the number of events greatly exceeds that observed during any other period. While the events are almost certainly of seismic origin they do not show separate P- and S-wave arrivals and at times are almost continuous. For example, Figures 4 and 5 show three distinct events occurring in less than 3 seconds. The lack of distinct P and S phases suggests that perhaps they originate very close to the monitoring station or that perhaps there is a different source mechanism.

Two similar and closely spaced periods of intense seismic activity were reported by Peter Styles. These occurred during the afternoon of the 24th of April 1992 and there is a circumstantial link with a small outburst in panel 600 which occurred on the same day. More significantly, however, Davies et al (1987) found that such events were the precursors to outbursts at Cynheidre. Styles (1993) further suggests that such 'emergent' events can be generated by rapid phase transitions - ie gas desorbtion.

In the case of the current data, no outbursts were recorded on the 28th of July. However, we have no knowledge of the location of the intense seismic activity. Possibly there was a release of gas elsewhere within the rock volume within the range of the monitoring station.

FURTHER PLANS

The initial results of Peter Styles and these recent results provide us with an excellent starting point for further work. In January 1994, a new project started with the assistance of ACARP, BHP Australia Coal, CSIRO and Gordonstone Coal Management. It involves the use of South African real-time monitoring software and geophone strings grouted along the length of boreholes. The intention is to establish the location and height of the seismic events and to map in space and time, the fracturing process within the roof and floor.

The initial monitoring will be performed at Gordonstone Mine where concern is shared with neighbouring Crinum Mine that aquifers within surface Tertiary basalts might be breached as a result of longwall mining.

SEISMIC MONITORING AT TAHMOOR COLLIERY

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NumbChannels=  3
SampleFreq= 512.03 Hz
NumbSamples=  1024
Vertical Scaling=16.00
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Figure 1. Typical seismic event recorded from within Longwall Panel 11. The initial arrival is the P-wave which is followed some 125 milliseconds later by a S-wave. Top trace is vertical component, next two are horizontal. Dominant frequency is greater than 25 Hz.

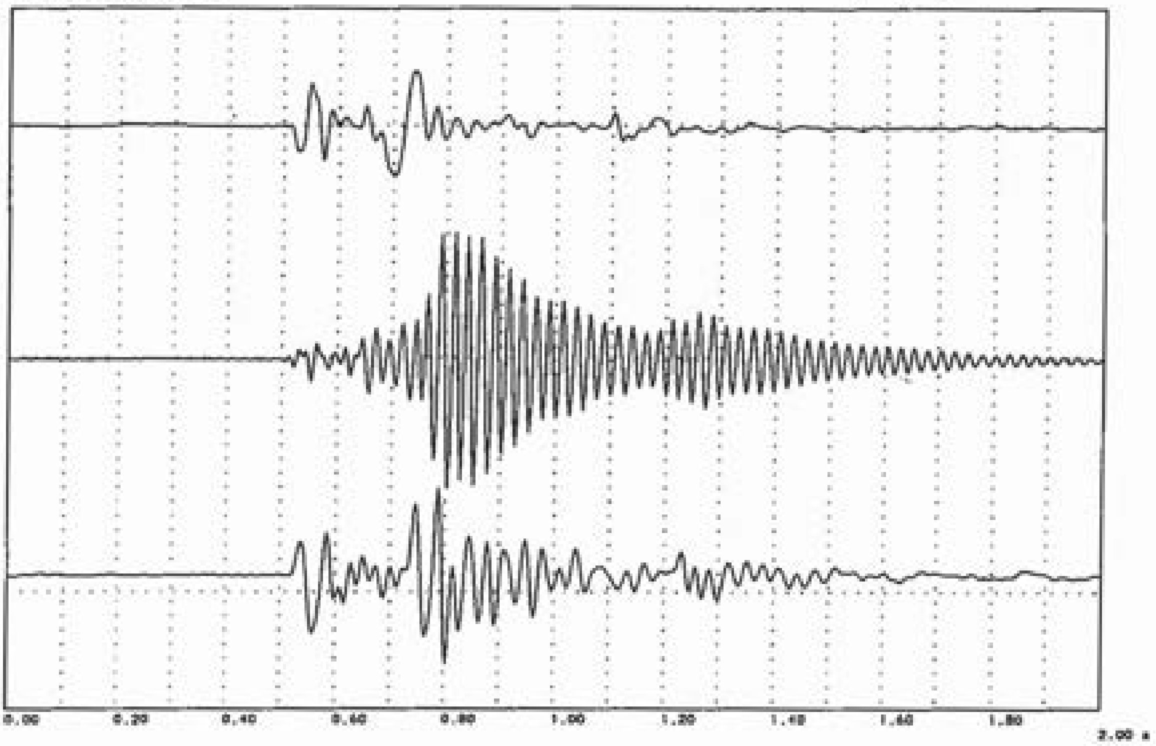

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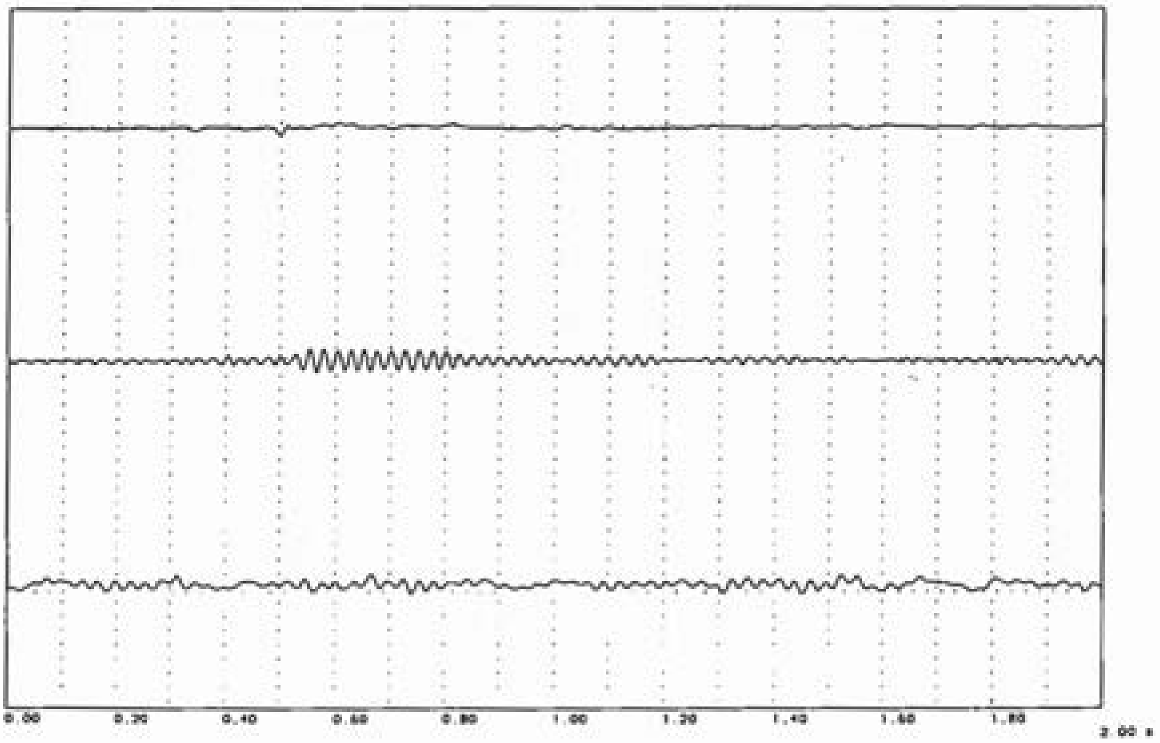
Figure 2. A 'noise' event.



Tahmoor Longwall mining

Events, metres vs time
counts/hour (no averaging)

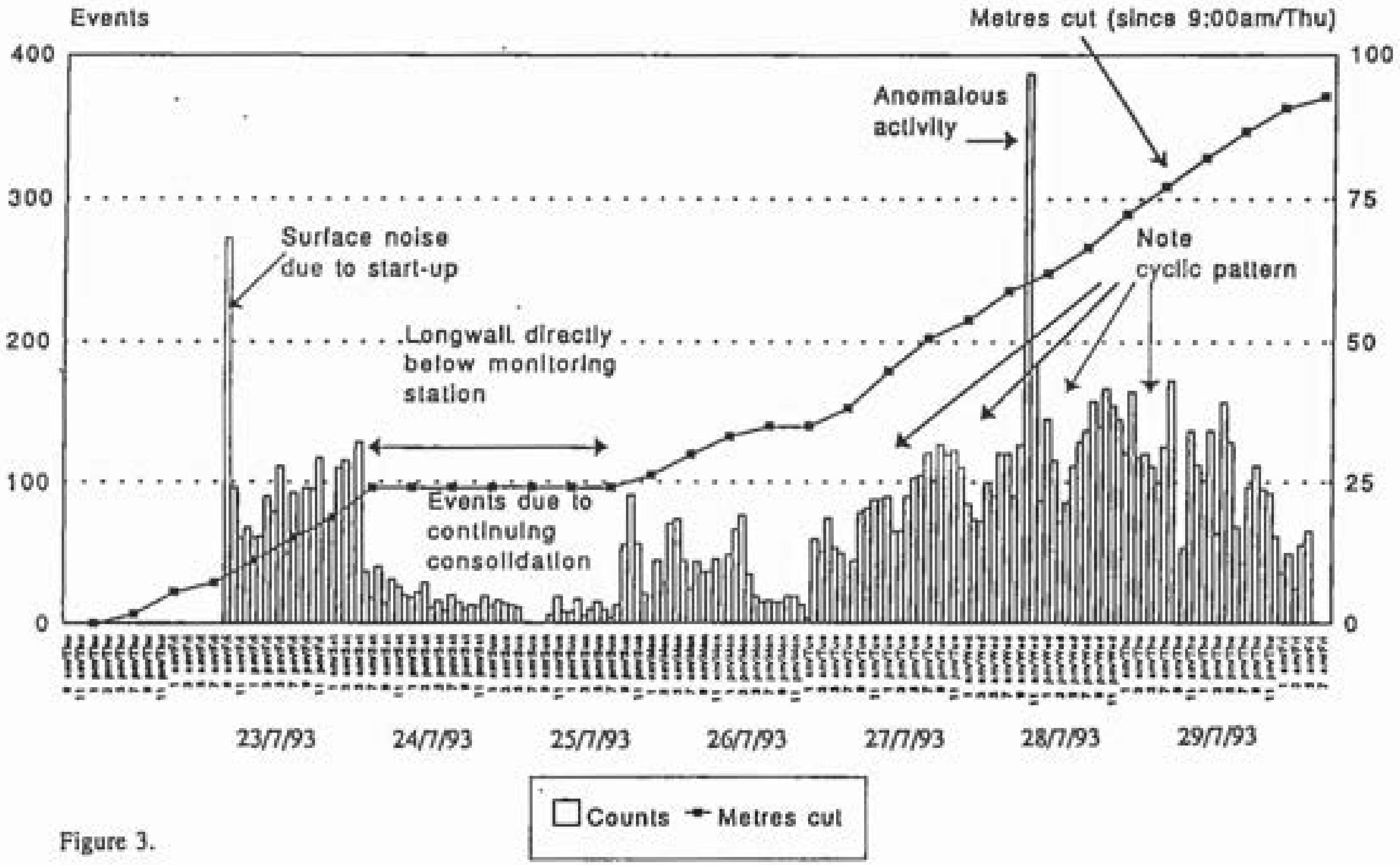


Figure 3.

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Figure 4. A typical event during the period of intense activity on 28/7/93.

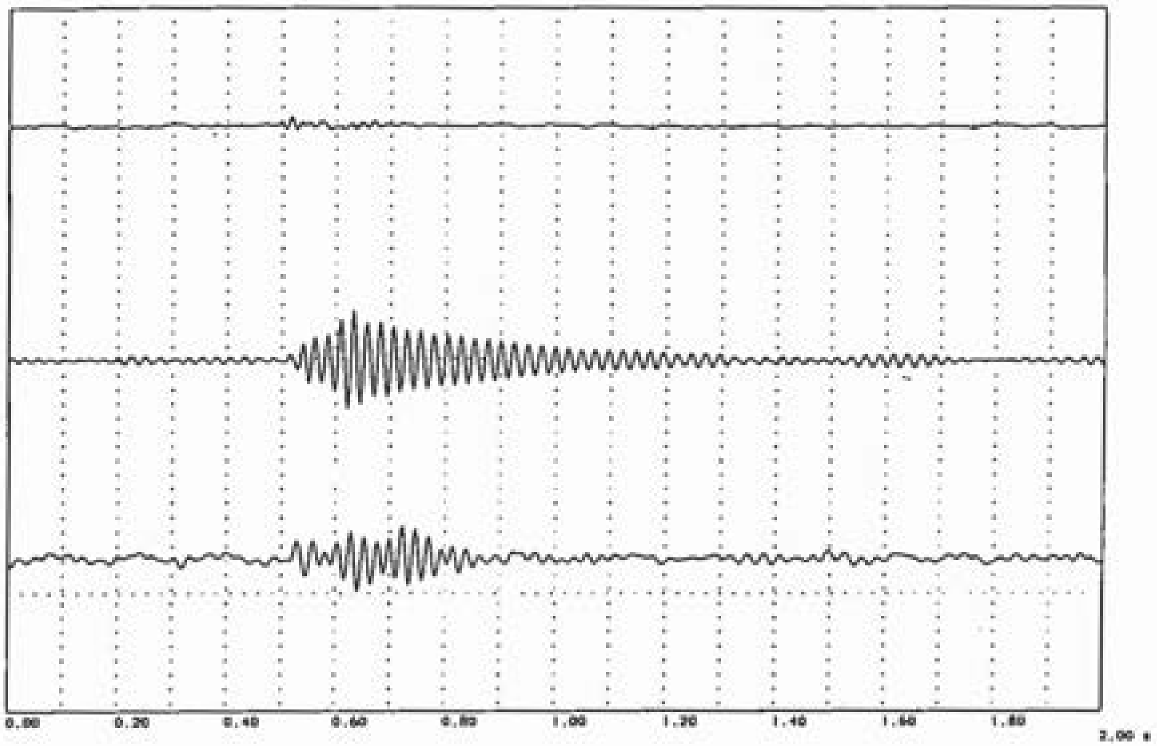

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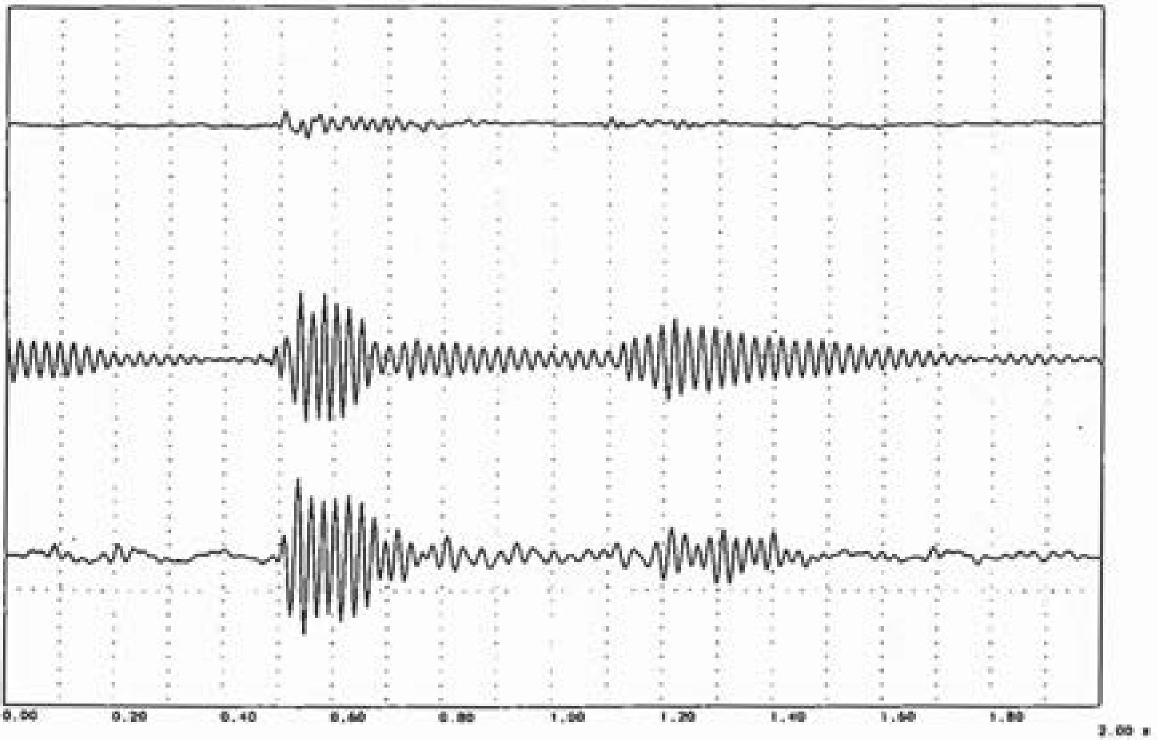
Figure 5. Two more events from 28/7/93 immediately after that of Figure 4.



APPLICATION OF DEPOSITIONAL MODELS TO POTENTIAL UNDERGROUND COAL EXTRACTION AT WARKWORTH MINING, SINGLETON, NSW

B.T. SMITH
Dept. of Applied Geology, University of Technology

INTRODUCTION

Warkworth Coal Mine is located 11km southwest of Singleton in the Upper Hunter Valley of New South Wales. The current operation is open cut, with exploration programmes concerned with both expanding this, and feasibility studies for underground mining.

The depositional geology above two of the underground target seams at Warkworth Mine has been examined. These are two of the six recommended for exploitation by the consultancy firm McElroy Bryan Geological Services Pty Ltd in 1989. They comprise seams 7 and 9/10 (Vaux and Piercefield) in the upper Wittingham Coal Measures within the Jerrys Plains Subgroup of the Singleton Supergroup.

The main objective of this work was to produce palaeogeographic reconstructions of the sediments between and above the Vaux/Piercefield seams in order to determine the possible palaeochannel locations. This has been achieved by using 56 diamond drill core logs and selected core samples. Cross-sections and contoured net lithological thickness maps have been generated, the latter by utilizing the engineering software package TECHBASE. A detailed facies analysis has not been undertaken, rather, a broad appreciation of facies types has been observed. This information has the potential to be applied in roof behaviour predictions for underground mining.

STRATIGRAPHY AND DEPOSITIONAL HISTORY

Beckett and McDonald (1984) studied the depositional geology of the Jerrys Plains Subgroup by analysing diamond drill core from twenty-five holes between Saxonvale and Aberdeen. They concluded from facies characteristics that there were three major depositional phases; a wave-dominated delta plain, a river-dominated delta plain, and tide-dominated delta plain.

According to Beckett's and McDonald's model the Vaux seam is the uppermost unit of the river-dominated lower delta plain. The Piercefield seam is in the lower portion of a river-dominated upper delta plain. The lithologies from such environments would thus be expected to be from meandering river channels with point-bar, levee bank, swamp, crevasse splay, and overbank deposits.

SMITH, B.T.

MINE GEOLOGY

Over forty coal seams have been identified in the Warkworth lease area and have been classified under fifteen coal seam names. To date fifty correlatable plies have been identified, all of which lie in the Jerry Plains Subgroup. For ease of correlation and mining these seams have been numbered from the base upwards. Thus the seams in this study regional known as the Vaux and Piercefield are referred to as seams 7 and 8 to 10 respectively.

The regional dip within the lease area is around 6° to the WSW, but increases sharply to the east where it abuts the Mt. Thorley Monocline.

Drill hole information and exposure by mining has revealed broad open folds over the lease area, but these do not pose any great problem to mining. Minor faulting is fairly common, with displacements generally less than 3m. Several seams in the sequence characteristically split and coalesce.

The lease plan and drill hole locations used in this study are provided in Figure 1.

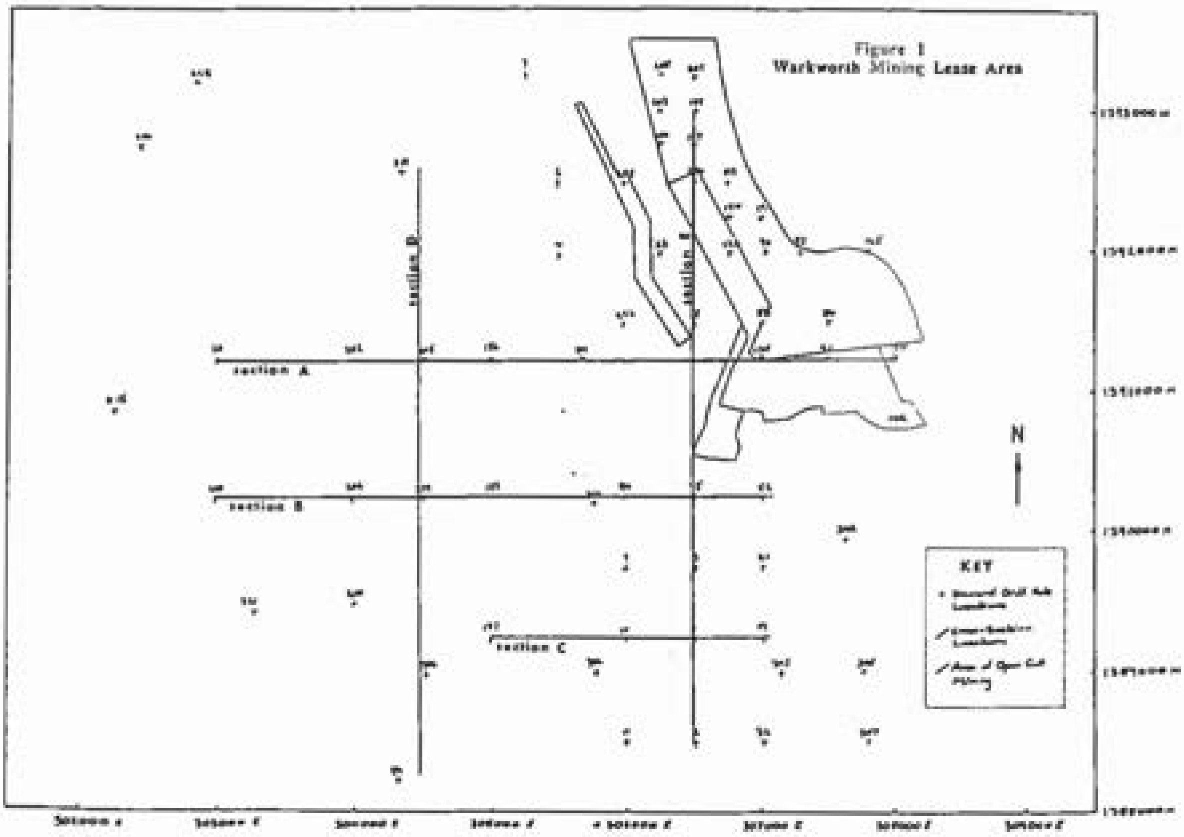


Figure 1
Warkworth Mining Lease Area

DEPOSITIONAL MODELLING APPLIED TO UNDERGROUND MINING

METHOD OF INVESTIGATION

The stratigraphic intervals investigated herein are those above seam 7 and seam 10. These have been subdivided using the continuous coal seams as boundaries, resulting in four separate units:

i) between seams 7 and 8;
ii) between seams 8 and 9;
iii) between seams 9 and 10;
iv) the immediate 30m above seam 10 (this cutoff has been selected on the broad assumption that the amount of goafing is approximately 10 times the seam thickness extracted).

In cross-section construction the interpretation of immediate depositional environments has been simplified by removing the regional dips and using the roofs of seams 7 and 10 as datums.

LITHOLOGICAL ANALYSIS

The rocks within the entire sequence range from fine to coarse grained sediments. The dominant characteristics are summarised in Table 1. This information is based on data from brief descriptive logs produced by Warkworth Mining. Selected samples were analysed for this study, but will not be discussed further here.

Table 1: Dominant Characteristics Within Each Interval

Interval	Thickness (m)	Dominant Lithology	Dominant Structures
7 - 8	0.5 - 5	Sandstone	Fining Upward
8 - 9	2 - 38	Sandstone	Fining Upward
9 - 10	0 - 6	Sandstone/Mudstone	Coarsening Upward
30m Above 10	30	Sandstone	Coarse Lag Deposits

PALAEOGEOGRAPHIC RECONSTRUCTIONS

Palaeoenvironment reconstructions for the intervals studied were developed using descriptive log information from the 56 bore holes selected (Figure 1).

Palaeochannel location was achieved by calculating net sand, net intebedded sandstone/siltstone, and net conglomerate (where present) for each interval. Percentage isopleth maps of this data were then constructed and compared with isopach maps. The most influential comparison is between the contour maps of coarse grained sandstone and conglomerate percentages with interbedded sandstone/siltstone distribution. In theory the thicker areas of coarse grained deposits will define the channel location, or in the case of stacked facies, a zone of channel locations. The interbedded sandstone/siltstone represents overbank deposits such as levee banks, and would therefore be expected to be peripheral to the channels.

Many factors can affect the lithological distribution; for example the compacting of sediments by overlying channels could compress some areas, leaving other similar areas unaffected. Lithological response to compaction is also a function of the ability of grains to pack together thus reducing pore space to a minimum.

Interval 7 - 8

The palaeochannel zone for the interval between seams 7 and 8 appears to involve a sand dominated major meander loop of approximately 1km in width (Figure 2a). This channel may represent either a single deep channel (unlikely), or a meander 'belt' within which the subsidiary channel meanders and/or braids back and forth.

The sands are generally fine to medium grained, with units being less than 1m thick, and intercalated in finer sediments. In the south there are occasional units greater than 1.5m thick which may form structurally stronger roofs.

Interval 8 - 9

Due to the significant thickness of the interval between seams 8 and 9, and the complex stacking of facies, the palaeochannel location more difficult to interpret.

The occurrence of conglomerate to the northeast and its absence in the south provides evidence that current direction was from the north. This corresponds with the provenance being derived from the New England Fold Belt (Herbert, 1980). Analysis of thin-sections from this interval confirm this theory with rock fragments being predominantly devitrified glass of volcaniclastic origin, as well as occasional foliated metamorphic rock fragments.

The average channel width is approximately 600m with little variance. Again this channel is likely to be a confined braided system rather than one large single channel (Figure 2b).

The potential roof behaviour of this interval is not easily predicted without more geotechnical information, but it is considered that due to the amount of finer lithologies and their thicknesses, there will not be any severe problems with collapse.

Interval 9 - 10

This interval is not laterally extensive, and represents a split between seams 9 and 10 (Figure 2c). These seams are usually considered as a single unit in the areas where they coalesce. The shape of the split is irregular, but generally trends north-south through the centre of the lease with an average thickness of 2m, increasing to 6m in the far south. To the east and west it thins, fines and eventually disappears. This deposit is similar in character to the case study of Horne *et al* (1978), who also describe a crevasse splay in a similar setting; a transitional lower delta environment.

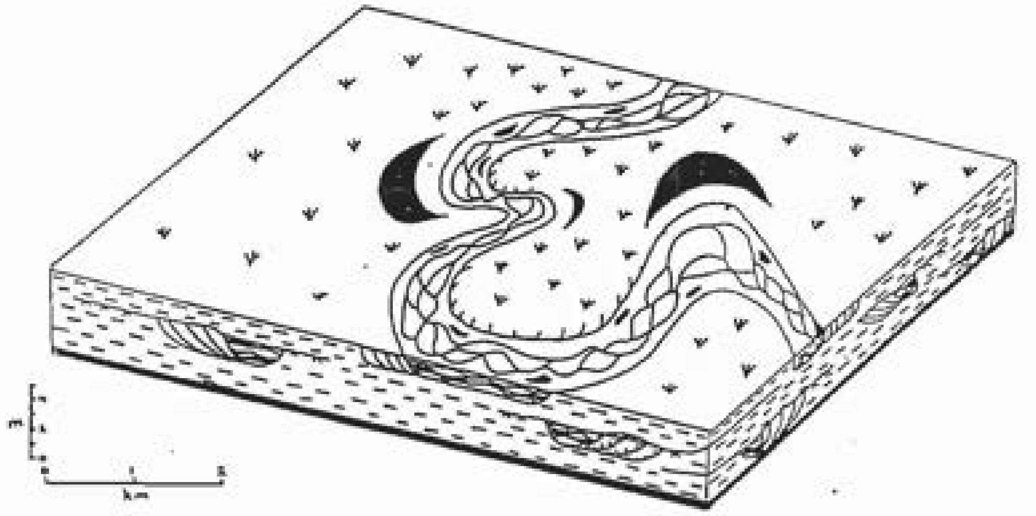


Figure 2a Interval 7 - 8; Braided meandering system

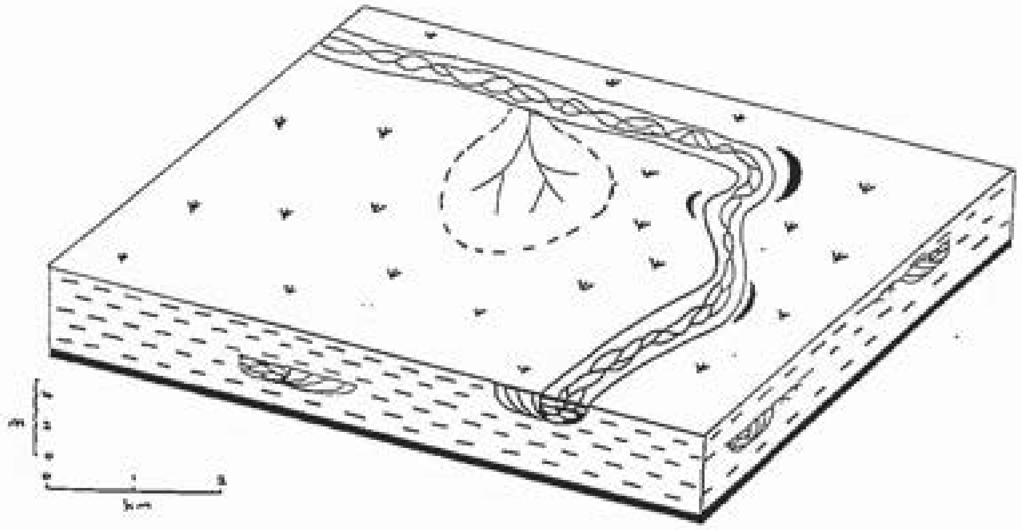


Figure 2b Interval 8 - 9; Braided meandering system with possible crevasse splay deposits

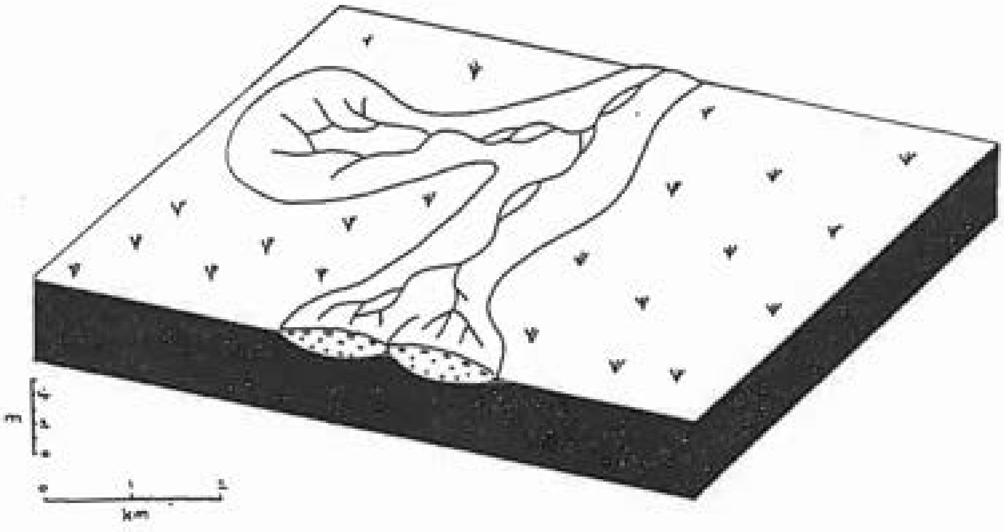


Figure 2c Interval 9 - 10: Crevasse splay deposit

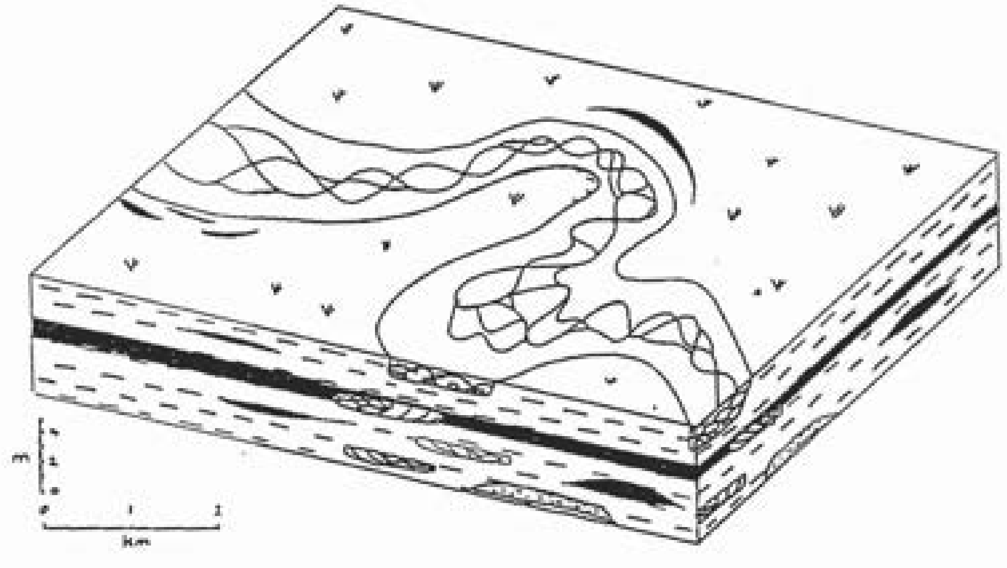


Figure 2d Interval above 10: Coarse grained, relatively confined braided meandering system

The coarsening upward nature of the rocks, and thinning and fining units towards the edges of the deposit support the possibility that this split is a crevasse splay. It appears that this splay is bilobate, and possibly extends further south than the lease boundary. The main distributor channel from which this deposit was fed would have been to the north.

There would be no foreseeable problems in collapse of the immediate roof for this interval, although the area above seam 10 may influence this, based on the amount of goafing which could occur.

Above Seam 10

This interval of 30m displays the most variation in lithology and therefore depositional environment. The contouring exercise and cross-section construction have both suggested a wide meander loop which was well - established towards its centre, and at its edges either gradually gave way to swamps on its floodplains, or in some cases spread over and onto the swamp itself (Figure 2d).

During the main channel's existence the thalweg shifted its position several times within the meander belt. This is shown in section where thick conglomerate deposits alternate with sandstone units.

The shape of the meander loops for this channel are broader at the areas of most curvature than the others previously describedd. This is likely to be the result of the higher energy environment which must have existed in order for the large deposits of conglomerate to have accumulated. Again, it is evident that provenance direction was northwards, based on the thick accumulation towards the north.

It should be stressed that this meander system, as in all of the cases, defines a zone or belt rather than one channel. However, this 30m sequence has more variety in its stacking of facies, and more contrast laterally than observed within all the other intervals.

It is predicted that the well established channel locations of this sequence may cause unsatisfactory roof behaviour. These rocks may be laterally and vertically cohesive which would mean a self-supporting roof. However, the structural aspects of these units is unknown, and only when these have been analysed can a more conclusive model be obtained.

CONCLUSION

Three of the four sedimentary intervals discussed in this study are channel sequences within meandering fluvial systems; the fourth derives from a splay event. The individual intervals have generally fining upward characteristics (except for the splay deposit), but the overall nature of the entire sequence investigated, that is from the roof of seam 7 to 30m above seam 10, is coarsening upward. This suggets that the depositional environment was progressively becoming more regressive, with the coastline having moved further to the south.

Whilst intervals 7/8, 8/9, and above 10 are geometrically channel fill sequences, the interval between seams 9 and 10 contrasts markedly. Its confined lateral extension and lithological type and distribution (dominantly coarsening upward) lead to the conclusion that this deposit originated from a crevasse splay rather than a meandering or braided channel system.

According to the delta model of Horne *et al* (1978) the entire sequence fits into the transitional lower delta to upper delta plain environments. This also complies with the model proposed by Beckett and McDonald (1984), which suggests that the top of the Vaux seam (seam 7) represents the boundary between the lower and upper river-dominated delta plain environments. From the evidence in this report, the previous work is confirmed although on this smaller scale the transition appears to have been more gradual than perhaps originally appreciated. The channel locations proposed are considered to be meandering, wide, heavy bedload channels which contain a braided or meandering system at normal flow stage. The lateral continuity of the coarser lithologies varies through the sequence. In the upper part above seam 10 the channels are well established, suggesting that the river courses were confined to a belt or 'shoestring' by finer material in the abandoned channels and overbank environments, typical of a meadering system (Walker and Cant, 1984). In the lower sequences there does not appear to be such a well-defined lateral confinement and it is concluded that these are more typical of the braided systems expected in the transitional lower delta plain environment.

From the revelations of this study, it appears that roof behaviour above seam 7 will be favourable for the longwall minging technique. The conditions above seam 10 however, hold potential self-supportive strength in restricted areas, and this could lead to unpredictable roof behaviour. It is stressed that further information is required on structural analysis and facies interpretation before more conclusive models can be provided.

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A GEOLOGICAL MODEL FOR THE DISTRIBUTION OF COAL TYPE & QUALITY IN THE KATOOMBA SEAM, ILLAWARRA COAL MEASURES, SYDNEY BASIN

L. WALSH[1] & J. ESTERLE[2]
[1] **Dept. of Geology, QUT**
[2] **CSIRO Division of Exploration & Mining**

INTRODUCTION

With increased demands to produce high quality coal cheaply and effectively, it is imperative that coal mining and processing procedures run at optimal efficiency. Of particular concern is the prediction of changes in coal quality in advance of mining or reporting to the preparation plant. Coal quality is dictated by rank, grade, and type, all of which reflect the depositional and burial history of the coal seam. The distribution of the latter two parameters, grade and type, directly reflect the processes of peat accumulation during the formation of the coal body. These processes of plant growth and decay respond directly to sedimentological changes in flooding regimes that control both the quality and the geometry of the deposit. Therefore, geological models which delineate the shape of the deposit and the distribution of coal grade and type across the deposit can aid in mine planning and quality control. The purpose of this investigation was to construct such a model from existing mine data for the Katoomba Seam, Illawarra Coal Measures, Sydney Basin. This model was then used to interpret a depositional scenario for the accumulation of peat types in the seam.

LOCATION AND GEOLOGICAL SETTING

The study of the Katoomba Seam was undertaken in Clarence and Canyon collieries, which are located on the western edge of the Sydney Basin near Lithgow, New South Wales (fig. 1). The seam in this area is sub-bituminous thermal coal and it varies in thickness from > 4 m to < 1.5 m, and it can be traced further to the east at the town of Katoomba. It has been mapped as the lateral equivalent of the Bulli Seam in the Southern Coalfields (Branagan, 1962). The Katoomba Seam is the uppermost member of the Charbon Sub-Group of the Mid to Late Permian Illawara Coal Measures (Herbert and Helby, 1980). This sub-group contains 3 other seams, the Irondale, Middle River and Lithgow, which are separated by coarse to fine grained clastic sediments with some conglomeratic units (fig. 2). The Katoomba Seam is overlaid by fine to coarse grained clastic sediments organised into a series of small coarsening upward sequences and capped by a thick (~20-30 m) and extensive sandstone unit, the Clwydd Sandstone Member. The depositional environment for the Illawarra Coal Measures in this area has been interpreted to represent fluvial to lower delta plain sedimentation (Bembrick, 1983).

METHODS

Data for seam correlation and delineation of the deposit geometry were compiled from available borehole records and geophysical logs supplied by Clarence and Canyon collieries (Poppitt, unpub. data; Thomas, unpub. data; fig. 1). The interval used in this study was from the base of the Katoomba Seam up to and including the Clwydd Sandstone. The total roof sequence was not present in all records so isopach and lithology maps of roof rock could not be constructed. The borehole data was used to plot and isopach total seam thickness.

The distribution of coal types and grade was determined from available strip samples collected in-mine by staff at both collieries. Strip samples consisted of a coal "brightness" profile (AS 2519) and ash yields for vertical ply samples. A north-south cross section was constructed from these to encapsulate variations in coal type and quality (fig. 1). Claystone bands occurring in the lower portion of the seam were used as marker horizons for the seam datum. Both coal type and ash yield were correlated and contoured across the section. Based on the distribution of seam thickness and brightness profiles, 3 sites were selected for sampling for petrographic analysis: two sites in Clarence mine at 4 m and 2.4 m thickness, and the third in the Canyon mine where the seam was 2 m thick. At each site, the seam was subdivided into distinctive plies and channel samples were collected for petrographic analysis (AS 2519 and 2856).

RESULTS

The Katoomba Seam varies from < 1 to ≥ 4 m in thickness and is overlaid by a non-erosive unit of interbedded sediments leading up to the Clwydd Sandstone. The thickness of this interbedded unit varies from 15 to 50 m and it is organised into a series of thin coarsening upward sequences with numerous lenses of fine grained mudstone. From the available borehole data, this unit increases in thickness to the south and east and becomes more fine grained. The thickness of the overlying Clwydd Sandstone varies from 17 to 25 m in the north but its thinning southern extent is difficult to confidently establish. Its base is undulatory and appears incisive in places.

The general geometry of the Katoomba seam is best illustrated by the isopach map of total seam thickness and cross section in Figures 1 and 2. Coal thickness is greatest (≥4 m) in a narrow northwest trending belt in the northeast of the study area (fig. 1). Seam thickness declines rapidly to the northeast (however, data are sparse), and gradually to the west and south to < 1.5 m. In the south, there is a slight increase in thickness to 2.7 m in a central belt of the Canyon colliery. Except to the northeast, the thickness contours are broadly spaced and exhibit an involuted pattern.

From cross section, the floor of the seam is undulatory to concave, whereas the top of the seam declines in elevation as the seam gradually thins (fig. 3a). The coal types are distributed relative to the deposit geometry. The seam is floored by a dull, high ash coal which varies locally in thickness from 1 to 1.5 m, increasing in the swales of the floor. To the south in Canyon Colliery, this unit thins and often pinches out. The basal dull coal is overlaid by dull coal with minor thin, wispy (< 1 mm) vitrain bands. This unit varies in thickness from 0.8 to > 2 m and it extends across the depoist, becoming the dominant coal type in the thin zone between the collieries. In Clarence mine, the dull with minor bright coal zone contains 2 or more extensive, thin (2-5 mm) tuffaceous claystone partings. Although individual claystone bands are impersistent, the zone in which they occur is maintained across both collieries. In the southern Canyon mine they increase in number and are associated with thin zones of dull banded to interbanded coal. In Clarence mine, the main upper section of the seam consists of a dull banded coal which varies in thickness from <0.7 to > 2 m. The unit is variably capped by either roof rock or a dull coal, often with clay bands. In Canyon Colliery, a sheared zone of bright banded coal occurs in the top of the seam. Contacts between all coal types are gradational and appear undulatory on a regional scale (fig. 3). The distribution of ash yield within the seam is presented in Figure 3. Ash yield is highest in the dull coal at the base of the seam, 20 to > 35%, and decreases up section to < 10 to 15% in the upper main seam. To the south, ash yield increases to 15 to 25% in the main seam. In general, ash content increases as the seam thins, but the patterns in the southern colliery suggest narrow zones of high and lower ash coals.

Although the upper main seam is mapped collectively as a dull banded coal, field observations suggest that it is more appropriately described as an interlayered coal unit containing 7 to 30 cm thick zones of dull coal with minor vitrain bands interspersed with thin (1 to 7 cm) bundles of thinly banded coal. The distribution of these bundles is best displayed in the brightness profiles collected for petrographic analysis (fig. 4).

The results of the petrographic analysis are presented as bar charts adjusted to match ply thickness. Weighted averages for total seam group maceral composition (mmf) at each location were not significantly variable and averaged : Vitrinite 35-40%, Inertinite 56-62%, Liptinite 2-3%. Although there is some slight trend for increasing vitrinite with decreasing thickness and with increasing ash content, the more significant trends were in the vertical variability in maceral composition which followed the distribution of megascopic coal types (fig. 4).

As expected, total vitrinite contents are increased in the ply samples of interbanded to dull banded coal (~30-60%), when compared to the duller coal types (< 30% vitrinite). These latter coal types are dominated by structured semifusinite macerals with minor amounts of inertinite attritus. Total liptinite content is low in all coal types. Among the vitrinite group macerals, the increases are a result of both increased structured telovitrinite (from intact plant remains) and matrix detrovitrinite. In the profiles from the thinner parts of the seam, where sample increments were more closely spaced, the ply immediatley overlying the claystone partings shows increased vitrinite content and mineral matter (fig. 4, location 2).

DISCUSSION AND CONCLUSIONS

The Katoomba seam in the study area forms an elongated body approximately 17 x 8 km which thins by gradual tapering on all but the northeastern side which may have been secondarily eroded. The undulatory base of the deposit and associated thickening of dull high ash coal suggests initial paleotopographic control which was overgrown as the deposit expanded during peat accumulation. Early flooding and volcanic ash falls are suggested by the thin blanket partings but these do not grade laterally into thicker splits. The convexity of the top of the seam and the non-erosional roof contact, coupled with upwardly decreasing ash contents, suggest that the peat developed a domed morphology successively removed from extensive flooding. Involuted patterns observed in the thickness contours may represent internal drainage patterns in the mire similar to those observed in modern domed peat deposits (Staub et al, 1991).

The distribution of coal types relative to ash yield suggests that plant types and decay conditions changed in response to decreased flooding as the deposit developed and changed its external morphology (Cameron et al, 1989). The composition of the basal high ash, semifusinite-rich coal suggests initial accumulation in an oxidising environment which could result from persistent water table fluctuation in topographically low areas (Esterle and Ferm, 1994). Widespread ash falls or clastic-laden flooding events, would serve to cap underlying peat, but also provide increased nutrients and a substrate for increased plant growth. The thin and wispy vitrain bands appear microscopically as small rootlets with suberinised periderm (< 0.5-1mm), dispersed in an oxidised semifusinite-rich matrix. The increase in vitrain rootlets could indicate either slightly better preservation conditions or a shift in plant type. The repeated occurrence of thinly banded coal bundles intercalated with duller coal in the upper main section of lower ash coal suggests that these conditions were fluctuating. In the thinned seam at Canyon, the banded bundles are associated with clastic partings, but this association is not evident in the thicker Clarence area. Flooding may still have instigated the changes but floodwaters did not carry abundant clastics.

A suitable modern analogue for the Katoomba seam development might be one of many cold-temperate domed peat deposits which form in response to high humidity and/or rising water levels (Cameron, et al, 1989; Clymo, 1983). In those that form in originally ponded areas, the succession is from a fine grained decomposed peat to a better preserved root peat formed from reed/sedge communitites. Peat accumulation in this latter community stabalises the bog so that shrubs or small trees, which live outside the mire in drier elevated areas, can encroach across the surface of the mire. However, the acidity and decreased mineral matter in the peat provide poor substrate and this encroachment is short-lived, and replaced again by smaller plants, often mosses. The thin bundles of vitrain-rich interbanded coal in the Katoomba seam may represent repeated attempts of colonisation by a different vegetation to that of the duller coals. Using a standard 10:1 peat:coal compaction ratio and an average 1mm/yr peat accumulation rate, attempts, or cycles occurred on the order of every 7000 to 30,000 years. That the eventual demise and burial of the deposit was brought about by rising water levels is suggested by the gradational roof contact into coarsening-upward sequences of fine grained rocks.

In conclusion, the geometry and distribution of ash yield and coal type in the Katoomba seam suggest similarities to modern domed peat deposits which form in cold to temperate climates, similar to that of the Permian. The regular distribution of grade and type relative to the geometry of the deposit allows mine planning for quality control.

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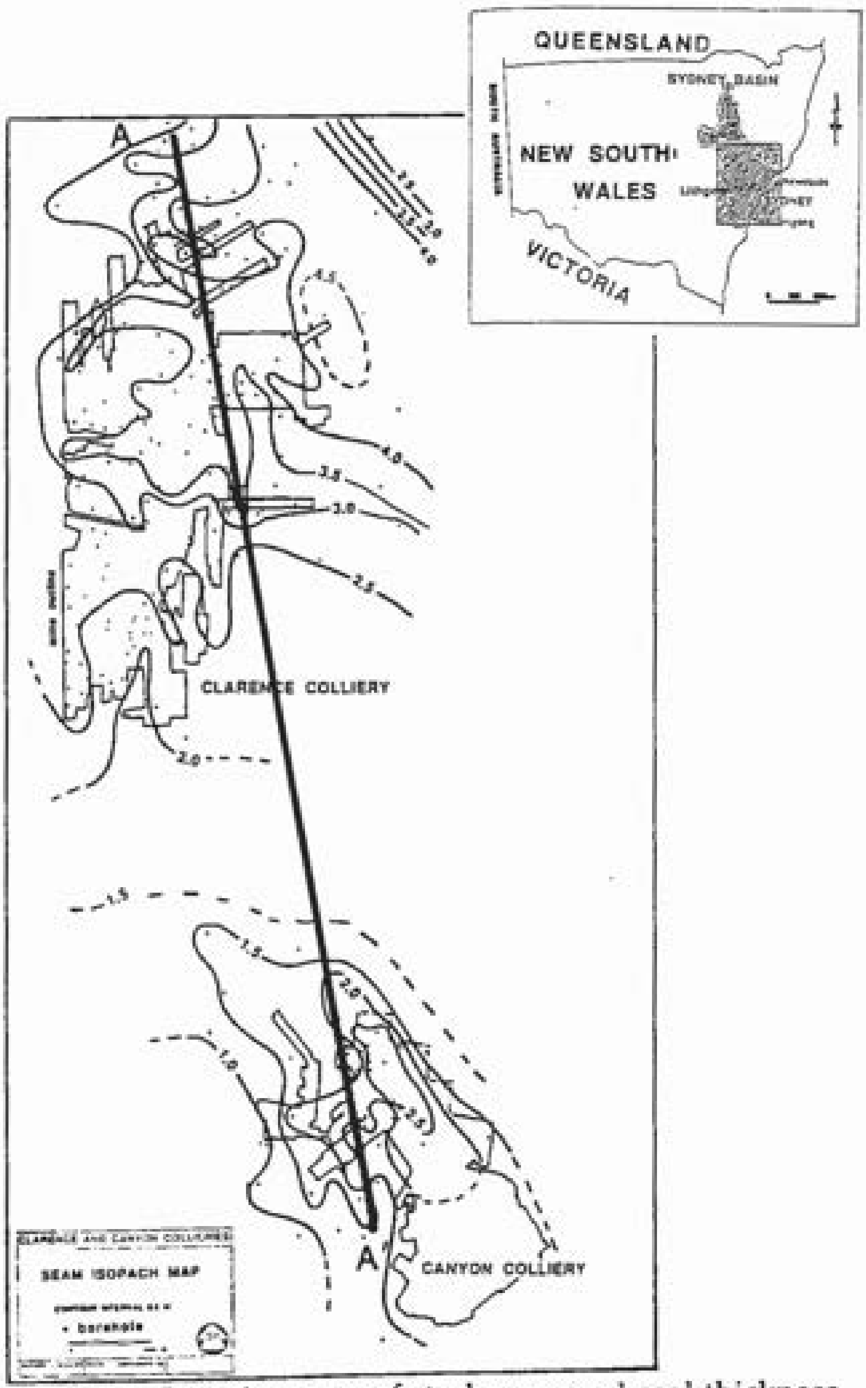

Figure 1. Location map of study area and coal thickness isopach for the Katoomba seam. Section AA' presented in Figure 3. after Walsh (1993).

KATOOMBA SEAM

NARRABEEN GROUP		CALEY FORMATION	Hartley Vale Claystone Member Govetts Leap Sandstone Member Victoria Pass Claystone Member **Clwydd Sandstone Member** Beauchamp Falls Shale Member
ILLAWARRA COAL MEASURES	CHARBON SUBGROUP	not formally named	**Katoomba seam**
		Burragorang Claystone	
		not formally named	Middle River seam Lithgow Seam
		Marrangaroo Conglomerate	

Figure 2. Stratigraphic units in study area (after Herbert, 1980).

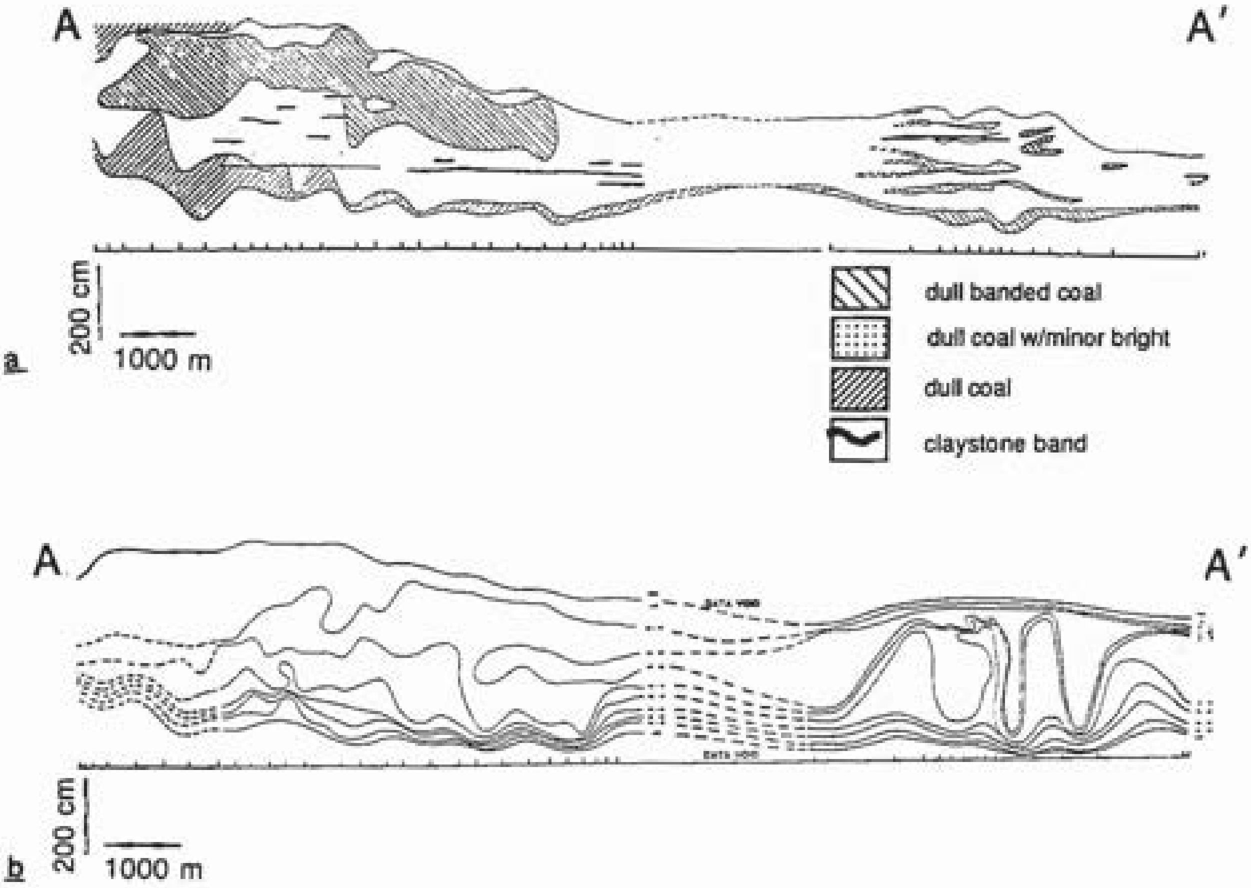

Figure 3. Generalised model for coal type and ash yield distribution in the Katoomba seam. a. coal type and b. ash yield. Ticks indicate strip sample location. Location of section given in Figure 1 (after Walsh, 1993).

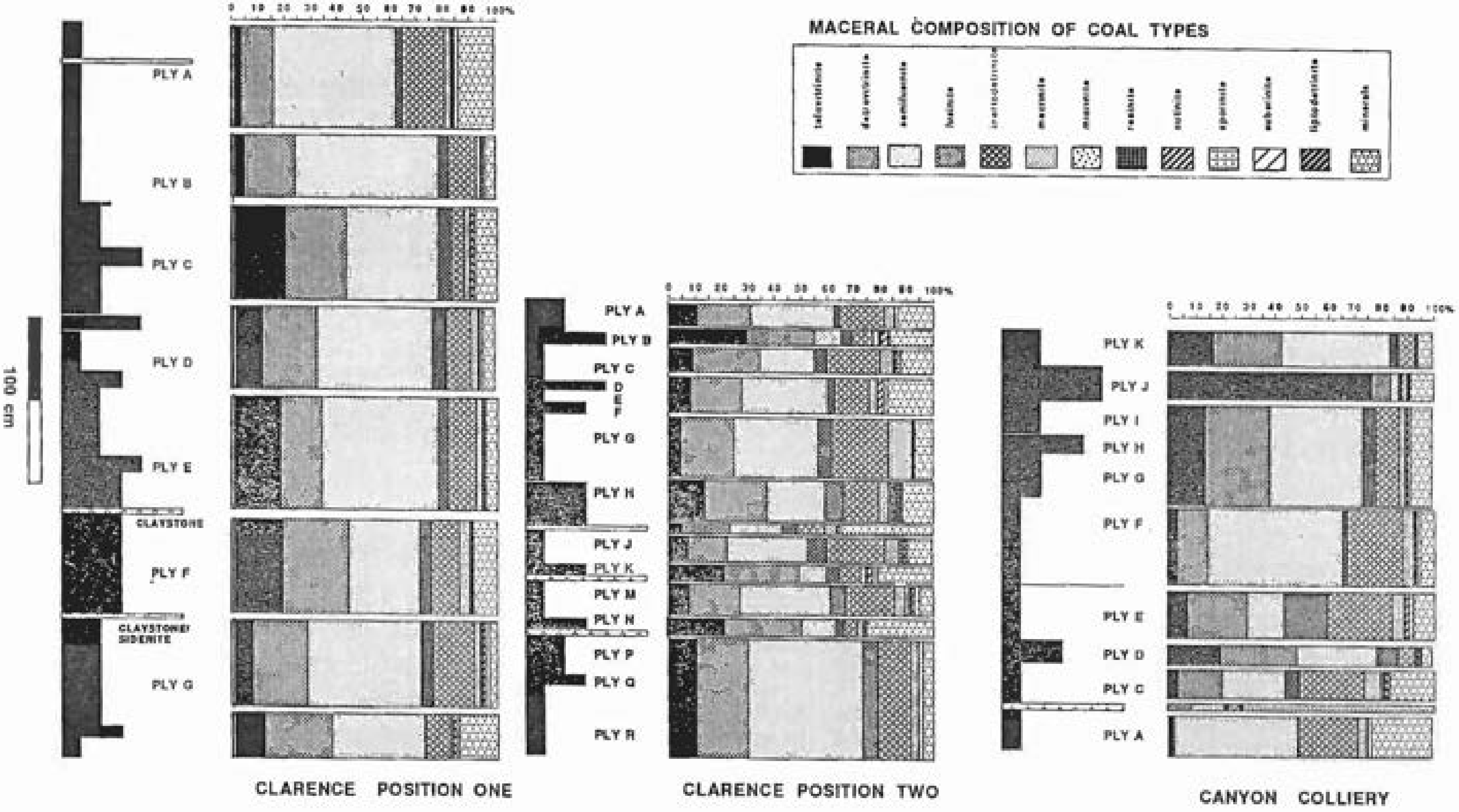

Figure 4. Petrographic composition of coal types occurring in brightness profiles from Clarence and Canyon collieries (after Walsh, 1993).

MOBILITY OF DUMPED HARBOUR DREDGE SPOIL, NEWCASTLE, NSW

E. FRANKEL
Dept. of Applied Geology, University of Technology

INTRODUCTION

The Port of Newcastle is located at the mouth of the Hunter River, approximately 120 km north of Sydney, NSW. The port is controlled by the MSB Hunter Port Authority *(HPA)*, an authority of the Maritime Services Board of NSW *(MSB)*. The port experiences a relatively high siltation rate in its berthing basins and shipping channels from sediment eroded from the catchment and transported down the Hunter River. Dredging in the Hunter River first commenced in 1845 and has been virtually continuous since 1859. This dredging includes capital works to develop new facilities as well as maintenance dredging to remove ongoing siltation.

During 1990, the HPA took possession of a new multi-purpose dredger, the *David Allan*. The split-hopper style vessel has a capacity of 1,000m^3. It is capable of operating as both a trailer suction and grab hopper dredger.

The majority of the material dredged from within the Port of Newcastle has been dumped offshore. Over the years the dump ground area has progressively been relocated further offshore. The dumping site currently in use is located approximately 5.0 km south-east of Nobbys Head.

Australia is a signatory to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, otherwise known as the London Dumping Convention *(LDC)*. Following the ratification of the LDC, the MSB has had to periodically obtain a permit from the Federal Government to dump dredge spoil offshore. As part of the current permit conditions, the MSB is required to study the mobility of dumped spoil both during and after dumping, and to give consideration to the environmental significance of such mobility.

DEVELOPMENT OF SEDIMENT DISPERSAL CONCEPTUAL MODEL

A preliminary study carried out by Patterson Britton and Partners in 1989 showed that:

- material dredged from the Port of Newcastle as part of the maintenance programme comprises mostly silts and clays. Sand sized material is typically less than 30% by weight and often less than 10%;

- although the material dumped offshore comprises mostly silts and clays, it is believed that as much as 95% to 99% of the material which is dumped in any operation falls rapidly to the seabed. The subsequent dispersion of this material is then influenced by the near-bed current field and bed slope. The much smaller proportion of sediment which remains suspended in the water column is advected from the dump ground by the ambient current field;

- the sediment which accumulates in the port and is removed by dredging represents a minor proportion of the total sediment load transported through the port and into the ocean each year by floods. The current annual maintenance dredging volume of approximately 0.5 million barge tons *(300,000 m^3 insitu)* is estimated to be less than 10% of the average annual sediment discharge of the Hunter River. Furthermore, the Hunter River can discharge over 40 times more sediment in a major flood event than that associated with the average annual amount of maintenance dredging;

- based on a knowledge of the offshore sediment distribution, the tendency is for fine sediments, ie. less than sand sized, whether dumped or discharged during floods to be transported offshore into depths greater than 50m with a bias for movement to the south of the river entrance;

- environmentally sensitive areas along the Newcastle coastline which may be potentially affected by the dumping operations comprise reefs and fishing grounds, marine archaeological sites *(ship wrecks)*, and beaches, however the potential impacts of the dumping need to be considered in the context of the relatively high natural sediment supply from the Hunter River;

- the spoil ground itself is highly regarded as an amateur fishing ground.

A conceptual model for the redistribution of the dumped materials established that the movement of these materials offshore from Newcastle may be considered with regard to the dumping operation itself *(bottom dumping from a split hopper barge)*, and with regard to subsequent far-field dispersion.

After release from the hopper, the dredged material descends through the water as a well defined jet. Large volumes of water are entrained in the jet, with a small proportion of the collapses on impact with the bed. Material which is not deposited immediately moves out radially under its own momentum. Dynamic collapse and "settlement" takes place within a radius of about 200m.

MOBILITY OF DREDGE SPOIL

Once the collapsed spoil plume has settled, the bottom material is available for erosion and transportation out of the dump ground under the influence of the bottom current field. The bottom settled component is potentially the more significant with regard to possible environmental impacts compared to the very minor amounts of dredge material remaining in the upper portion of the water column.

VERIFICATION OF THE CONCEPTUAL MODEL

In order to verify the conceptual model it was considered that the approach should concentrate on detailed petrographic sedimentological studies which would provide direct information on the longer term outcome of sediment supply and the natural sorting and transport processes, ie. it would avoid the need to measure currents and predict sediment movement from these current data.

It was important that the sediment sampling exercise be sufficiently widespread so as to extend into areas which were outside the significant dispersion zone of the sediments from the dump ground area. The like confines of this zone were, however, not fully known. It was therefore proposed to approach the seabed mapping in a progressive staged manner in order to both control costs and provide an informed basis for on-going decision making A preliminary examination of the seabed *(using Sidescan sonar and limited sediment sampling)* was undertaken initially to establish broad limits for a subsequent, more detailed sediment sampling exercise.

Limited Sediment Sampling

The limited sediment sampling exercise was aimed at describing the broad extent of dispersed sediments from the dump ground relative to the natural background sedimentary environment. The results were used to pre-plan the subsequent, more detailed sediment sampling program as well as verify aspects of the Sidescan interpretation. Representative sediment samples were also collected from inside the port *(dredged and undredged areas)* as part of the limited sediment sampling exercise.

The exercise showed that the shelf sediments are dominantly sand sized quartzose (*sometimes iron stained)* which fine downslope and grade into muddy carbonate materials at a depth of about 85m.

A strong sedimentological signature with a pronounced lithic character was recognised in the vicinity of the dump ground. Furthermore a significant mud content, consistent with the conventive descent model was evident in these materials.

Detailed Sediment Sampling

Coverage of the detailed sediment sampling exercise was primarily required to capture the main dispersion zone of the sediments from the dump ground area. The limited sediment sampling exercise was assessed to have largely achieved this and what essentially remained was the need to fill in detail.

Compilation of results of all of the sampling indicated a sediment distribution on the shelf with the following characteristics:

Coarse Fraction (Sand and Gravel)

The coarse fraction of the sediments varies considerably depending on location, processes and provenances. The coarser fraction of the sediments is dominated by quartz in the shallower mid-shelf and nearshore regions and by carbonate skeletal debris in the deeper outer shelf. In general, rock fragments (*lithics*) are rare (*<1%*) except in the area of the existing and previous dump grounds where they may constitute up to 30% of the coarse fraction. Here the lithics vary in size (*occasionally up to 50mm in diameter*), but are predominantly in the coarse to medium sand fraction. Few lithics (*up to 30% on occasions*), occur in the coarse fraction of the river mouth sediments.

Gravel is relatively rare in the sediments and is usually composed of shell *(mainly mollusc)*. Occasionally siliciclastics make up the bulk of the gravel, but this is uncommon except in some parts of the dump ground.

The deeper outer shelf sediments are dominated by insitu and pelagic *(mainly foraminiferal)* skeletal debris with rare quartz. These materials are relatively fine with the dominant modes around 0.125mm to 0.088mm. These sediments are largely irrelevant to the inner shelf (*and thus dump ground*) sediment distribution other than to provide a regional context.

The mid-shelf areas *(approximately 50m depth)* are dominated by rounded and reasonably well sorted medium to coarse iron stained quartz sands. These materials are very distinctive and probably represent a relict *(Pleistocene?)* population.

Coarse to medium, sub-angular to rounded clean quartz sands dominate the inner shelf and near-shore. Gravel is generally skeletal debris and occasionally siliciclastic material.

The dump ground sediments form a specifically confined facies on the inner shelf plain. There appears to be very little shore-parallel spread in these sediments. The shore-normal spread is less clear, possibly due to previous dumpings (*inshore)* and also the tendency for the finer fractions to saltate downslope. They are rich in both lithics and quartz. The grain size is mostly in the medium to coarse sand fraction with occasionally gravel (*up to perhaps 10% with grain size to 50mm).*

Mud Fraction

Regionally, the mud content of the sediments was found to increase across the inner shelf from a depth of about 50m where 2% is typically present to the limit of sampling at 100m where approximately 50% mud occurs with the carbonate sands.

There is a localised accumulation of muddy sediments in the existing dump ground and in the vicinity of the mouth of the Hunter River. The elongated morphology of the features and the distribution of the surrounding sediments containing a mud fraction of "Trace-2%", both point to mud transport pathways heading south-east away from the dump ground and the mouth of the Hunter River. Offshore of the 45m bed contour, the dump ground and entrance muds signature is rapidly masked by the naturally dispersed muddy sediments of the outer areas of the inner shelf plain and the inner shelf slope. Beyond about 60m, no effect of the dump ground muds is discernible.

The observed mud pathway appears to be more significantly influenced by downslope dispersal than might otherwise have been postulated on the basis of the preliminary conceptual model alone, ie. a shore-parallel component heading say down the coast was not found. Rather, the muddy provenances graded quite rapidly to background in the shore-parallel direction.

Those muds naturally occurring on the shelf and in the entrance area of the Hunter River were found to be quite different from those in the dump ground, the distinction characterised as follows:

- **"Natural" Muds**
  A brown flocculant mud which settles readily in fresh or slightly brackish water. This behaviour was retained even with considerable amounts of mud in the sample.

- **Dumped Muds**
  Muds found in the dump ground are dark brown or black, they lack an infaunal *(worm)* population and do not flocculate readily in fresh or brack water. At times there is considerable, finely divided organic detritus present.

FACIES PARTITIONING OF THE INNER SHELF

An overview of the full sedimentological and morphological database suggests that the shelf in the Newcastle Region partitions into six different facies which may be defined as follows:

- **Facies 1 - Muddy Carbonate Sands**
  Up to 50% mud with the coarser fraction, which is a relatively fine sand, dominantly skeletal debris (*eg. pelagic foraminifera, sponges, etc)*. There is minor quartz in these sediments which mainly occur toward the base of the inner shelf slope and further offshore.

- **Facies 2 - Transitional Sediments**
  Variable mud content *(approximately 2% to 30%)* increasing with depth with the coarser fraction exhibiting varying proportions of quartz and skeletal debris. In essence, these sediments are a mixture of Facies 1 and 3 (*occasionally 4 as well)*. They occur landward of Facies 1 in a zone of variable width possibly related to bathymetry.

- **Facies 3 - Iron Stained Quartz Sands**
  Occurring near the outer edge of inner shelf plain and tending down the inner shelf slope, these sediments exhibit small amounts of mud (*up to about 2.55)*. There is a broadening in the distribution of this facies *(determined largely on the basis of mud percentage)* inshore towards the dump ground and river entrance zone. The quartz and skeletal components of the coarser fractions are generally fairly well rounded and ubiquitously coated by an iron oxide film. Representative of relict mid-shelf materials commonly found on the NSW coast, ie. inner shelf sands.

- **Facies 4 - Clean Quartz Sands**
  These quartz sands characterise the inner shelf plain. This facies comprises mainly angular to rounded quartz with little or no rock fragments and mud. The quartz is generally clean, occasionally polished, of medium to fine grain size and reasonably well sorted. The Facies 4 sands contain varying amounts of skeletal debris.

- **Facies 5 - Clean Fine Quartz Dominated Muddy Sands and Sands**
  Fine, angular quartz dominated sands with varying amounts of mud (*0% to 30% or more)*. This material appears to have a restricted distribution with fluvial provenance controlling - it does not seem to be reworked or redistributed in any way. Little or no skeletal material and few rock fragments (*up to 3% on rare occasions)*.

- **Facies 6 - Dumped Sediments**

  An artificial facies created by the mixing of dumped material and natural inner shelf sediments, ie. mixed mainly with Facies 4, but some Facies 3 as well. Discernibly different from the other sediment facies due to presence of lithic fragments. Dumped sediments are rock fragments rich *(up to 30%)*, the quartz is clean or stained and the mud content highly variable *(from a trace to 30% or more)*. Some skeletal debris is generally present. The distribution of this facies is confined to the vicinity of the existing and previous dump ground sites.

Although quite separate in nearly all respects, for the purpose of this study it is useful to describe the harbour sediments as a separate facies.

- **Facies 7 - Harbour Sediments**
  Depending on where these sediments occur in the Port of Newcastle, they are either medium to coarse quartz lithic dominated sands or muddy sands on banks and upstream channels or mud dominated materials with varying amounts of very find quartz/lithic sand in dredged areas. Mixing of these materials with F4 and F3 creates F6.

CONCLUSIONS

By use of relatively simple geological principals, the verification of the conceptual model for dispersal of dumped dredge spoil from Newcastle Harbour has been possible (Figure 1).

Assuming a continued maintenance dredging requirement involving the disposal offhsore of similar quantities and types of material to that dumped in the past it would be expected that little information beyond that which has already been established to a high level of confidence in the prototype, would be forthcoming from a modelling study.

Finally, it is worth stating that the features of the verified conceptual model of dredge spoil movement, in particular the fact that practically all the finer muddy fraction of the dumped spoil *(the majority of the material which is dumped)* moves away from the dump ground area in a quite contained dispersion pathway heading offshore, suggests that consideration could be given, if deemed desirable, to an inshore shift of the dump ground from its present position without affecting the final destination or movement processes of the spoil.

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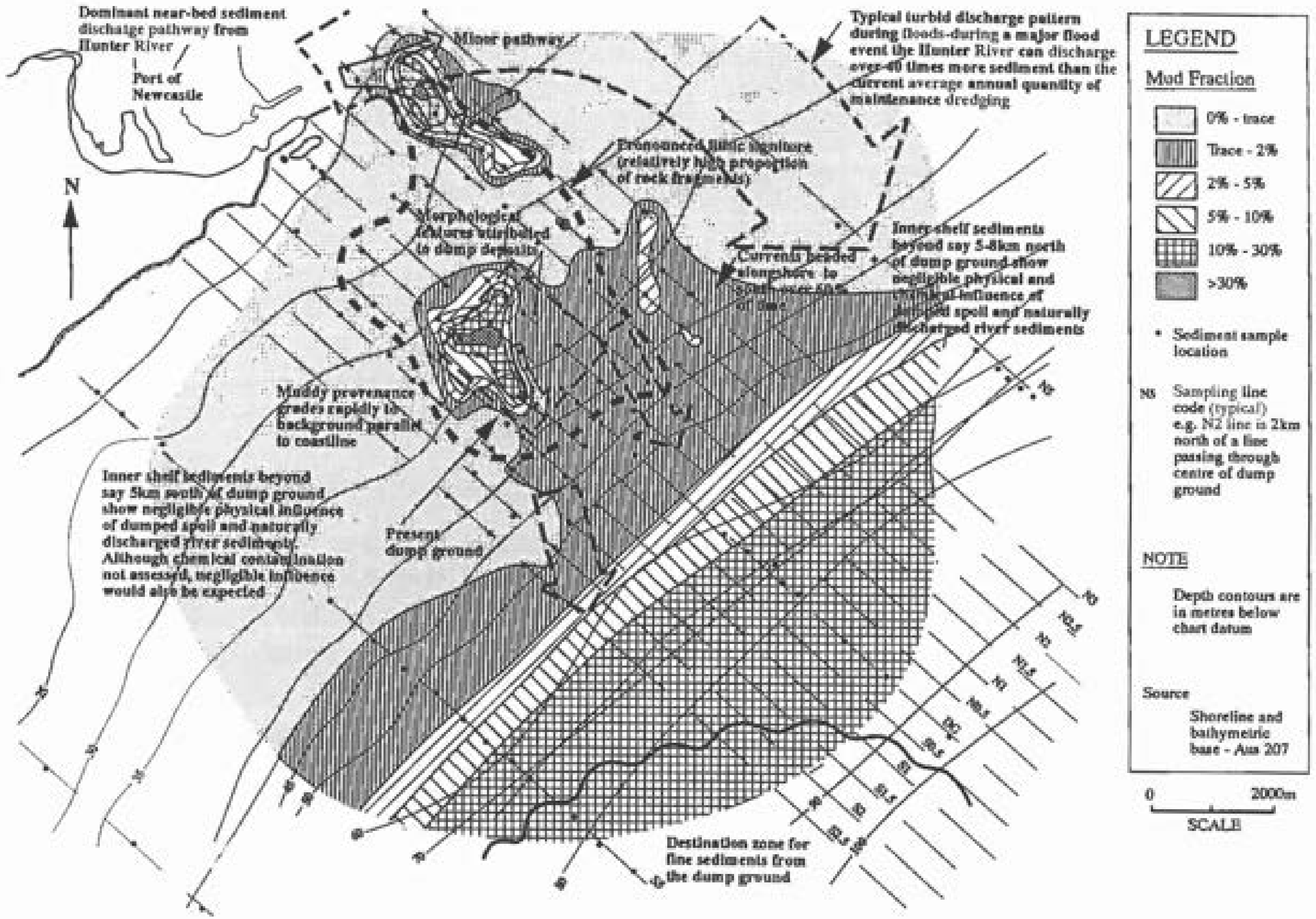

Figure 1. VERIFIED CONCEPTUAL MODEL
FAR FIELD DISPERSION OF DREDGE MATERIAL

TIDAL PALAEOMORPHS IN & AROUND THE SYDNEY BASIN

W.F. GEYL
New Lambton

Abstract

Tidal palaeomorphs (TP) are relict tidal landforms, valleys or prior streams with great meanders, recognised on maps on which morphoetric analysis allows quantitative comparison with tidal 'neomorphs', giving support to visual recognition. They are ubiquitous, world-wide, between sea level and perhaps 900m. Some NSW examples are presented from near the waterparting round the Sydney Basin where 'rejuvenation' has not penetrated: Wingecarribee R. etc, Cudgegong R. etc. Palaeonto/sedimentological evidence should be found where TPs are seen on the maps and will then require a complete rethink of Cainozoic geology-geomorphology. My hypothesis would be favoured by Ch. Lyell, opposed by W.M. Davis.

(For a discussion of the 'hypothesis of tidal palaeomorphs', and of the morphometric graph and visual scheme for comparing them with rivers, and other information, see draft: "Lyell unblemished", or Geyl (1985).)

Introduction

For more than a century the geomorphologists/geologists of the world have been united in barking up the wrong tree. Or should I say, paddling up the wrong creek? They have disregarded Charles Lyell's reservations towards all-out fluvialism, and have instead blindly followed a dead-end creek, turned into a sacred cow by W.M. Davis, to mix metaphors. I am now sure that my 'hypothesis of tidal palaeomorphs' (1968, 1976b, 1985) will show Lyell to have been right in this respect, as in so many others. Many TPs can exist in areas where others have already shown relict coastal features.

Since its inception thirty years ago, the hypothesis of tidal palaeomorphs has evoked practically no response, certainly less than it deserves. As a result, I have not been able to keep working at it all the time; particularly since retiring in 1978 I have only intermittently spent time on it. Last year I was asked to give some talks for the local 'University of the Third Age', and for some reason chose my neglected research. Picking up the thread again, my eyes were opened more fully to the earthscience-shaking significance of my 'hypothesis of tidal palaeomorphs', and I am now more convinced than before that I am onto something worthwhile. An article: 'Lyell unblemished', and another, 'Tidal palaeomorphs and the Times Atlas', have been written in draft form.

I hope I may live to see them published. Another article, on TPs in Australia, is in the offing; it needs reworking, as much of its draft text was used to produce the general text of this paper. Perhaps this late outburst of enthusiasm will put tidal palaeomorphs on the map.

There is plenty of map-material waiting to be used with examples from the USA, from The Netherlands, and from elsewhere. There is an embarrassment of riches. Not only do I find TPs on many maps, but commonly many of them are found on a single sheet! Some areas, of course, are barren. I no longer feel apologetic about having what I always thought was just an outlandish good idea. The feature of tidal palaeomorphs is so ubiquitous, in Australia and the rest of the world, besides being found to over 600m, that the Cainozoic will need to be reassessed with an open mind, which many will find hard to do. I am grateful to the U3A organisers for jogging me into action.

Examples

The first published examples of TPs in Australia were presented in Newcastle (1968) at the 3rd Newcastle Symposium: Swamp Creek near Kurri Kurri, NSW (also appeared in Geyl, 1968, Fig. 7), Windeyers Creek and tributary near Raymond Terrace. (See display and handout). Most of my earlier work was done on 1-inch to 1-mile maps with 50-ft contour interval. On many old maps, my own and departmental, my pencil shadings of 'stepped surfaces' are still to be seen, as well as outlinings of TPs along 'significant contours', or lines simply emphasising the trace of the river following the old course of the TP. But many large palaeomeanders are only visible from the trace of the river, not the contours, particularly on the plains. Langford-Smith has shown 'great meanders', his 'prior streams', to occur there, so they exist not only as valley meanders. It must be realised that it may thus be a matter of chance where the contours are in relation to channels, which may only have been a few tens of feet deep; smaller palaeotidal channels, with depth a mere five-hundredth of the wavelength, may be less deep than the contour interval. For L_w=1000m, $W_{w.lo}$=130m & $D_{w.max}$=2m, $C_w \approx 2km^2$; for 5000, 800, & 9m: $C_w \approx 33km^2$. See Figure 1 for plots of L_v to C_r for TP examples. For Key to symbols used, letter-code, see below Figure 2.

Figure 2 shows great valley meanders on the Robertson plateau, NSW, from the 1" Kiama sheet, reduced to nearly 1:100 000. At the head of the Wingecarribee River, the valley floor has Quaternary alluvium marked on the 4-mile Wollongong geological map, and this extends landward well onto the adjoining Moss Vale 1" sheet, where more large meander-like forms can be seen (not shown here), and up the Medway (!) Rivulet, which also has TPs. Here the 2400ft contour is generalised as the significant contour, but the swampy valley floor lies lower downvalley than expected from data on tidal streams. For the middle of the 3.3km meander, elevation is already less than 2300ft, a depth of say 110ft, 33m, and maximum wadden stream depth for that L_w should be around 7m.

On Figure 1 it can be seen how the Wingecarribee (W) plot for L_v to C_r falls not on the wadden line, but near the higher estuary line: higher perhaps because the Dutch estuaries have a greater tidal range than the wadden? So perhaps the Wingecarribee once had a high tidal range? Otherwise, it must be considered that it has lost some of its once-tidal catchment area as a result of later aggression from the East: not from the S or N, where the headwaters of the creeks have not yet been rejuvenated, though only by a few kilometres to the S. The plot for the TPs of the Mittagong River (M), at 2050ft, is between the wadden and river lines. If adjusted to the L_w line, the C_w would be about 2-7km², which is topographically feasible. Other swamps are roughly circled.

Please note that my 'wadden(lagoonal)-type palaeomorphs' have such small (tidal=total) catchment areas in relation to their large forms, that in most cases preposterously large 'hyper-pluvial river catchment areas' would be needed to provide the discharge producing such large channels. This can be read from the graph, but a table which summarises the values of L to C, for which there was no room, has been added to the draft 'Times Atlas and TPs' article. Many of the examples there could not possibly be of fluvial origin; those in the present paper which plot close to the L_w lines could be fluvial if one is to accept Dury's 'theory'. I myself can only envisage a tidal origin for the latter, but would class them as 'estuarine, not 'wadden', as their total catchment is larger, and would imply land with a rain-fed river draining into an estuary, 'the tidal mouth of a river'. Values for L to C can be compared on the separate table (handout), and will confirm that many TPs (wadden-type) would require much bigger catchments than is reasonable.

Figure 3 is a segment from the Moss Vale 1:100 000 Nat. Top. Map, sheet no. 8928, 1975, showing an area on the waterparting between the Shoalhaven and Wollondilly systems, not reached by the rejuvenation so obvious for the main rivers. The valleys of Barbers Creek (Shoalhaven) and its opposing Uringalla Creek (Wollondilly) are shallow and have some valley meanders. It is the same for Paddys River. The rejuvenation of the Shoalhaven gorge in the far south is very striking, and contrasts strongly with the 'mature' landscape around the waterparting, where remnants of Tertiary sediment with plant fossils, marked T, are found: a couple of small outcrops in Uringalla valley, at about 600m≈1968ft, another near Hanging Rock, and a larger one south of Wingello, at about 660m≈2160ft.

Note how the latter elevation agrees with that of the Quaternary, only shown as 'swamp' on Figure 2, along the Wingecarribee TPs, at from just under 2200 to 2300ft. On the geological map the Quaternary extends higher up and lower down on the valley floor. It would be worthwhile to have a re-investigation of all these sediments, also to check them for sedimentological evidence of tidal influence. (Cinnamomum flora is mentioned.) For an old-timer the very 'youthful' appearance of the rejuvenated gorge of the Shoalhaven River and the lower part of Barbers Creek, so close to the 'mature' waterparting suggests the old favourite: 'river capture', but let this not lead me astray.

The Cudgegong River has TPs at many points along its course. Some, as is often the case, show up because a reservoir makes the great meander shapes stand out (Mudgee 100 000 sheet). Near its headwaters, rejuvenation has not yet penetrated, and the great valley meanders are 'mature'. More TPs are found in the Sydbey Basin, but they are not as frequent as elsewhere. Some sriking TPS are found on the Nepean R. near Camden; see Figure 1. There are small TP 'ghosts' in many areas, but they have also not been unplotted.

W.F. GEYL

Discussion

For my work the 100 000 Nat. Top. Map has the disadvantage of its hill-shading interfering with my own shading between contours, which I have used for so long to bring out 'stepped surfaces' and now tidal palaeomorphs. See on Figure 11 how it shows up the 3.5km valley wavelength of Uringalla Creek, with $C_r \approx 56\text{km}^2$ $C_{pt} \approx 18\text{km}^2$. In this connection it must be noted that on the 1:100 000 map the detail of the 20m contours differs quite a bit from that of the 50-foot contours on the older 1" to 1 mile map, though the patterns are similar.

Note my frequent use of small scales for the figures; the great size of the features under discussion allows this. Some very suggestive shapes can be seen even in the Times Atlas (Compr. edition, 1967) on sheet 12, SE Australia, 1:5 000 000: the Neales, Frew and Finke rivers before they reach Lake Eyre, the Barcoo (Wilson, Kyabra) River, ditto; also sheet 13: Georgina, Diamantina. See also p. 70, NW France, 1:1 000 000: the Loire etc. (See 'Lyell unblemished'.)

That rivers can do important morphogenetic work under given circumtances is not denied. A glance at the effects of rejuvenation on the rivers flowing E from the Robertson plateau will make it obvious (Figure 2). Phillipson (1931; II-2, p. 163 etc.) used the idea of *'Erosionsterminante'*, not unlike the curve of the graded river of Davisians, related to the river's varying capacity to erode. If a new surface (in a humid climate) was gentle, the river would aggrade its course (given it had a supply of sediment from upstream); if the surface were steep, it would erode. On an irregular surface it would aggrade or erode according to its relation to the *Terminante*. Increase of discharge makes the it gentler (allows degradation), decrease: steeper (allows aggradation).

But in appropriate humid climates rivers today are not actively eroding over most of their courses; only in their steeper upper courses do they act like torrents and remove more rock than they deposit, and the same in special circumstances where part of the bed is abnormally steep. If climate change in- or de-creases overal discharge, the *Terminante* is respectively steepened or reduced, and the river will erode or aggrade to adjust to it. I do not think that Phillipson ascribed valley meanders with misfit streams to the effects of increased rainfall. Nor does Dury, as far as I am aware, in his many publications on his 'theory' of valley meanders and underfit streams, anywhere acknowledge Phillipson's prior recognition of the climatic factor *re* river erosion.

I have not found reference in Davis' writings to climate change having such an effect: he only considers change to arid or humid and v.v., or from temperate to glacial, or v.v.. Dury rightly regards the 'capture' explanation for misfit rivers as inadequate. For several generations the divisions of morphogenesis have been: fluvial, arid-aeolian, glacial, marine. Only recently have some textbooks begun to introduce an intermediate division on estuarine landforms.

Lyell recognised that rivers could erode, but thought that the landforms owed more to 'marine currents'. I have not read enough of his work to know how specific his arguments were, but the examples in my draft Lyell unblemished' (handout), first and foremost the Medway, shows he had reason, as do all the other examples.

TIDAL PALAEOMORPHS

Though Dury deserves credit for his painstaking work on his 'theory' of valley meanders, a problem which since the time of de la Bèche (1826) had so long confounded geologists/geomorphologists, he failed to produce actualist (or uniformitarian) evidence in its support. Moreover, when collecting his data for the relation of valley meander wavelength to river catchment, he ignored the many 'small' valley meanders I have classed as 'wadden(lagoonal)-type', with relatively even smaller catchments than for the examples he chose. His averaging of wavelengths seen to increase over a short distance is also open to question.

In judging between his 'theory' and my own hypothesis, the latter has the advantage of being fully actualistic: tidal palaeomorphs can be compared visually with tidal neomorphs on the maps, and morphometry (measurements; plots on regression graph) supports this. 'Double bends' and 'frog-legs' (elsewhere) 'flood prongs' (van Veen 1950, in Geyl 1976a) and other characteristic forms, often complex, of the tidal channels of today are replicated (preserved) in tidal palaeomorphs.

Note also that irregularities are easily explained by the dynamics of the tidal environment. With a small lowering of sea level, a new set of tidal meanders will be initiated, smaller than those in which they now develop. But even without change of sea level, deposition from tidal limit seaward will reduce discharges, and large meanders will be replaced by smaller ones; in some cases the earlier meanders will be preserved, in other cases eroded. Some tidal meanders will become deserted, and preserved. Whole tidal channels may be preserved, and then filled with fine sediment, by being cut off from the main stream, so that patterns of palaeomorphs on maps, and sedimentologically, can be complex.

The enormous specific discharges of tidal streams of today are a fact. My composite graph even shows the regression lines for Q to C for the Dutch tidal streams, and it can be seen how little catchment they need to rise above the 'Pardé-limit', the line based on momentary maximum river discharges the world over! And it is not Q_{mm} which determines channel width and so wavelength. Considering we all know that the land stands higher now than in the Cretaceous, and that the sea-shore must have touched every spot of what is now dry land, why has not more real attention been given to evidence indicating the presence of the sea's tidal margins? But my hypothesis of TPs, despite all my maps and graphs, has not turned the tide for thirty years.

What is now needed is that geomorphologists/geologists take notice of the hypothesis, and are aware of its implications. Then, when the occasion arises on their field trips, they may bring back sediment samples for testing. Fossils may still occasionally be found, but it seems more likely that sedimentological evidence will show that palaeo-tidal environments have existed in areas previously thought fluvial, but now become suspect through the recognition of tidal palaeomorphs. I missed out on sedimentology, and later never had the courage or the encouragement to take it on. I am much impressed by what is done in that field (L. de Boer et al., 1988), but also remember Baulig's warning (1935, p.23).

All-out fluvialism has held things up far too long. Down with it!

* * * * * * * *

TIDAL PALAEOMORPHS

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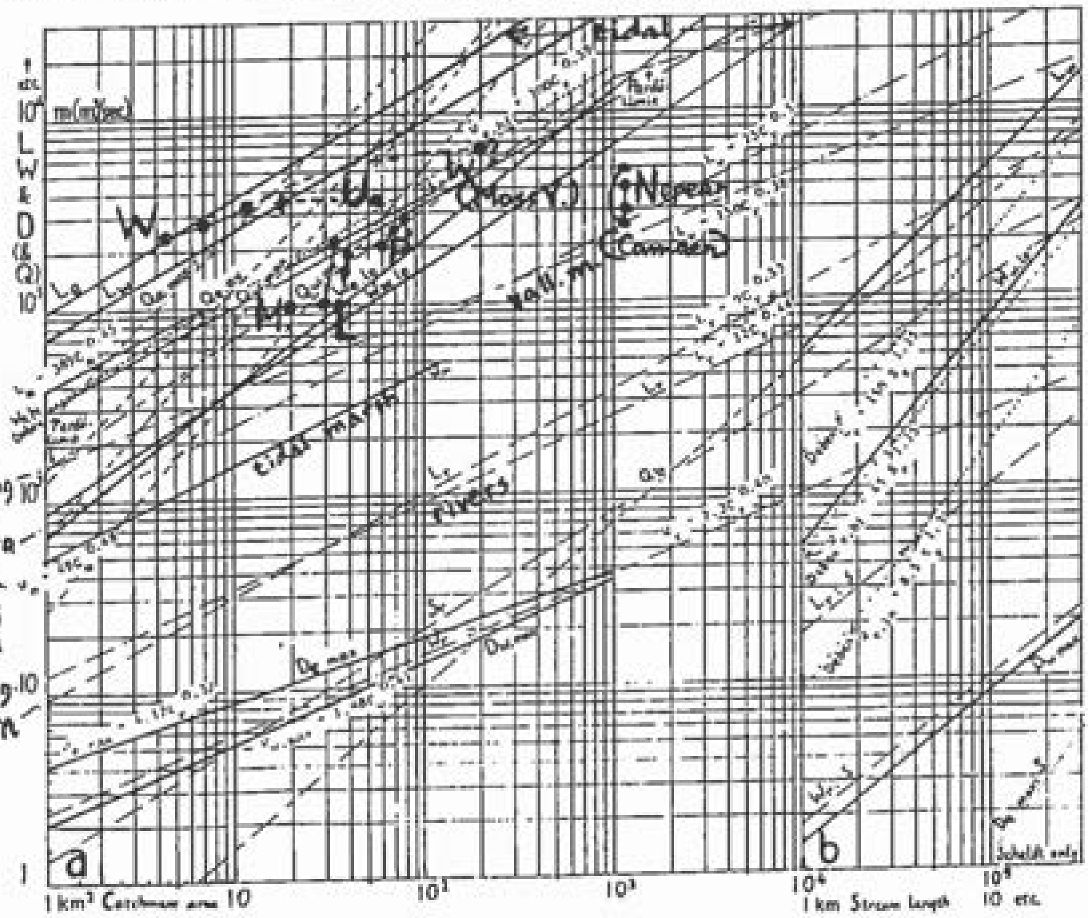
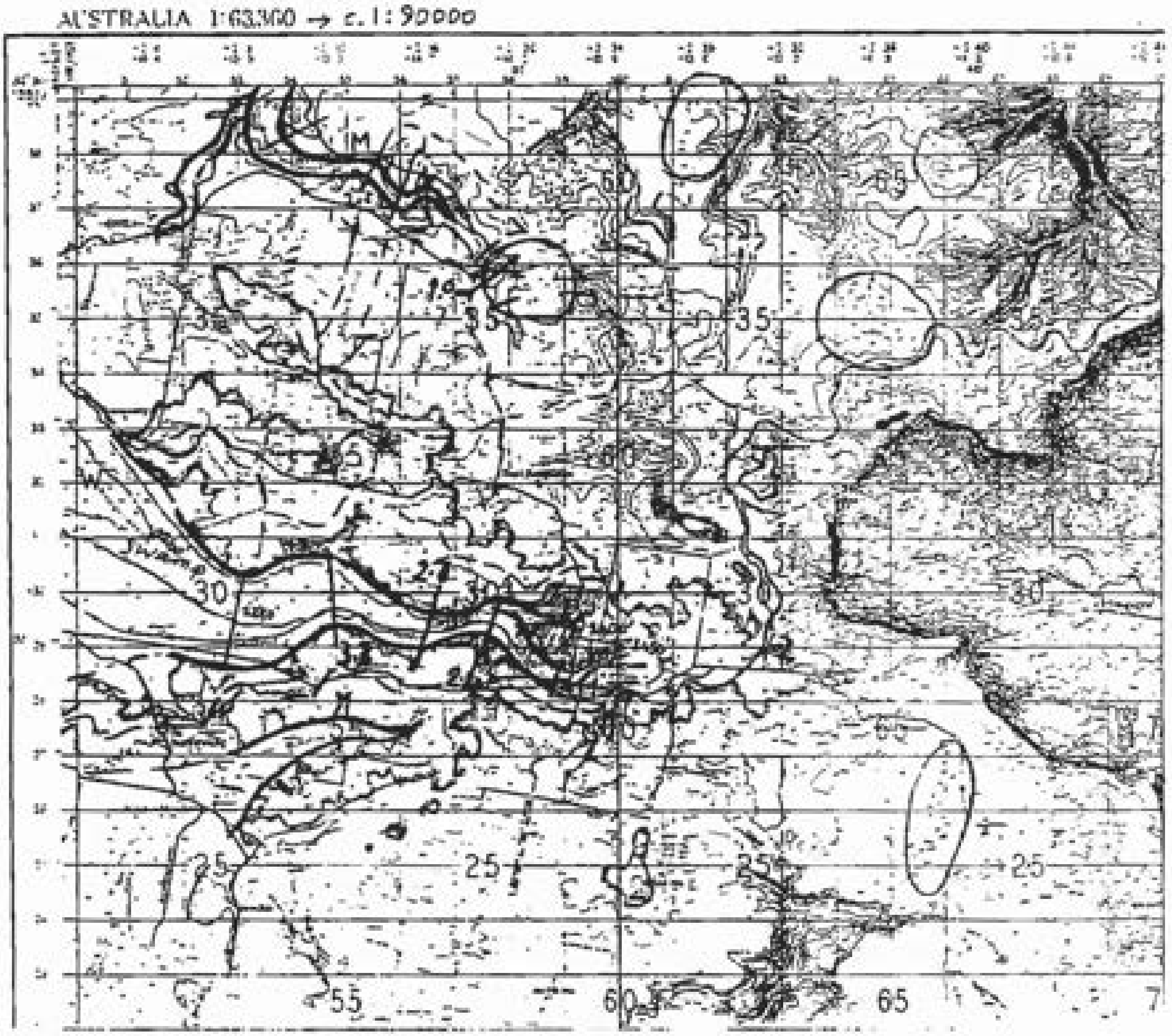
Figure 1. Morphometric graph for comparison of data on suspected tidal palaeomorphs (valley meanders) with regression lines for various stream parameters to catchment area. See other publications. Only the part for Catchment here used to plot $L_{v(st)}$ to C_r. See Key to symbols, next page.



The following figures are xerocopies from the maps used, with some shading, and TPs outlined; this gives the feel of the map work better.

Figure 2. Tidal palaeomorphs of the Robertson Plateau, NSW. RASC 1945, Kiama topo map sheet, 8/439, 1" to Im, reduced to c. 1:125 000, 1000-yard grid, 50ft c.i. Wingecarribee (W) valley meanders outlined along 2400ft contour, with valley floor to below 2300ft; Tertiary basalt on interfluves. L_v=2.4, 2.7, 3.3km, as marked, to $C_r \approx 4.5$, 7, 13km². Mittagong R. (M) ditto at c. 2000ft, L_v=1 (gap), 1.05, 2.1km, $C_r \approx 20$, 30, 32km². From geol. map, areas of Quaternary sediment (swamp on topo. map) roughly circled. Note steep (Illawarra) scarp to east; coast only 20km away. Asymmetrical divide! Some VM 'ghosts' also outlined. 100 000 topo. map also helpful. **See Key for symbols, letter code, below.**



SYMBOLS used in text and figures

Parameters	*Suffixes*			
R: radius of curvature	e:	estuary	pt:	palaeotidal
L: meander wavelength	w:	wadden	.av:	average
W: channel width	m:	marsh	.max:	maximum
D: channel depth	t:	tidal, undiff^d	.lw:	low water
C: catchment area	r:	river	.hw:	high water
S: stream length	v:	valley	b:	bankfull
Q: discharge	p:	palaeo	2.3:	mean annual flood
			mm:	momentary maximum

Figure 3. The 'mature' Shoalhaven-Wollondilly waterparting, 1:100 000 Div. Nat. Map. topo map, 1975, reduced to c. 1:132 000, 20m c.i., 1km grid. Some areas of Tertiary sediment with plant fossils (Geological map, Wollongong sheet) are roughly circled and marked 'T'; many basalt remnants. The C(ol) between Barbers Creek (B), Shoalhaven tributary much rejuvenated only a few km downstream, and Uringalla Creek (U), tributary to the only slightly rejuvenated Wollondilly, is between 600 & 620m, which elevation is shaded; interference from hillshading. One striking flat-floored VM of the Uringalla has L_v=3.5km, C_r≈56km²; (if wadden TP, C_w≈18km²). Values marked, also for Long Swamp (L) and Paddys River (P); and Barbers Ck. too? See Figure 1 for plots; previous page for Key.

CAVES, DOLOMITE, PYRITE, ARAGONITE & GYPSUM : THE KARST LEGACY OF THE SYDNEY & TASMANIA BASINS

R.A.L. OSBORNE
Centre for Mathematics & Science Teacher Education,
Sydney University

INTRODUCTION

Studies in the U.S. and U.K. have indicated that sulfuric acid derived from basinal fluids and from the oxidation of pyrite plays a significant role in the development of extensive, highly decorated limestone caves. Hill (1987) proposed that Carlsbad Cavern in New Mexico, renown for its size and for the presence of exquisite gypsum, aragonite and sulfur deposits, formed by the reaction of acidic sulfurous brines, rather than carbonic acid rich groundwater, with the limestone. A similar origin has been proposed for the adjacent, highly decorated and still incompletely explored Lechuguilla Cave (Cahill, 1991). Lowe (1992) has suggested that sulfuric acid produced by the oxidation of pyrite is an important agent in the initial solution of limestone caves

Palaeokarst deposits containing secondary dolomite and pyrite are found in many of the Lower Palaeozoic limestones of the Lachlan Fold Belt along the south western margin of the Sydney Basin in New South Wales. Similar deposits occur in Tasmania where the Ordovician Gordon Limestone is overlain by Permian sediments of the Tasmania Basin, similar to those of the Sydney Basin.

Dolomite and pyrite bearing palaeokarst deposits form the substrata on which many of the more spectacular aragonite speleothems have formed and are the source of sulfate for gypsum deposits in these caves (Osborne, 1993).

It has been proposed that the palaeokarst sediments are of early Permian age (Osborne & Branagan, 1985, Osborne, 1991) and represent the initial stages of Sydney Basin deposition. It is suggested here that the dolomite and pyrite were emplaced by fluids from the overlying basinal strata permeating through the palaeokarst sediments which would have been much more permeable than the dense Lower Palaeozoic limestones in which the palaeokarst features and the modern caves have developed.

RELATIONSHIP TO THE SYDNEY AND TASMANIA BASINS

Some of Australia's largest , best known and best decorated caves, are developed in limestones overlain by or adjacent to Permian basinal sediments. In New South Wales Billys Creek , Bungonia, Church Creek, Colong and Jenolan Caves along with some small caves in the Mudgee District are developed in Lower Palaeozoic Limestones in close proximity to, or directly overlain by, remnants of the Sydney Basin. In Tasmania Exit Cave is developed where the Ordovician Gordon Limestone is overlain sediments of the Lower Parmeener Group and the important karst areas of the Florentine

Valley and Mole Creek are, or have in the past been, overlain by strata of the Tasmania Basin.

HOST FOR THE DOLOMITE AND PYRITE

Dolomite and Pyrite have been found deposited in fractures in the limestone and emplaced in carbonate and siliceous palaeokarst deposits at Billys Creek, Bungonia, Colong, Jenolan Caves in New South Wales and at Ida Bay in Tasmania. Four principal facies of palaeokarst sediment; Laminated & Graded Bedded Carbonate, Crinoidal, Limestone Breccia and Terrigenous Clastic, have been identified at these localities and all have been found hosting secondary dolomite and pyrite.

MODE OF EMPLACEMENT

Petrographic evidence indicates that both the dolomite and the pyrite are secondary. The secondary nature of the dolomite is clearly visible in specimens of coarse crinoidal limestone from Bungonia . Pyrite occurs both as cubes and as framboids suggesting a relatively low temperature of emplacement. At Ida Bay pyrite framboids have been found replacing the matrix of limestone breccias.

The Lune River Quarry at Ida Bay has exposed a 100m section through the Gordon Limestone and the palaeokarst features developed in it. In this quarry the frequency of palaeokarst features and associated pyrite and dolomite mineralisation decreases with depth, suggesting that the dolomite and pyrite were emplaced from above after the palaeokarst sediments were deposited. Observations at localities in New South Wales are also consistent with the dolomite and pyrite being emplaced from above after deposition of the palaeokarst sediments.

THE KARST LEGACY OF THE SYDNEY AND TASMANIA BASINS

Cave Structures

Recent work at Jenolan caves (Osborne,1993) has shown that many of the present cave passages are inherited form the Palaeozoic and have been exhumed by the oxidation of pyrite in palaeokarst sediments that formerly filled them. There is increasing evidence that this is also the case at Colong Caves in New South Wales and at Exit Cave in Tasmania. Apart from resulting in the exhumation of filled caves sulfuric acid released from the weathering pyrite is likely to play a role in the excavation of new caves in the limestone. This may, in part, account for the large size of Exit Cave which is developed downstream of a weathering pyrite deposit.

Gypsum, formed from the reaction of sulfuric acid from the weathered pyrite and limestone, is a powerful agent of crystal wedging in limestone. Large areas of breakdown in Exit Cave result from crystal wedging by gypsum. Gypsum crystal wedging also occurs at Jenolan Caves and is implicated in the development of large breakdown chambers such as the Exhibition Chamber in Lucas Cave.

Speleothems

Jenolan Caves is renown for its aragonite helictites . Osborne (1993) proposed that dolomitic palaeokarst deposits were the source of magnesium needed for the deposition of aragonite rather than calcite at Jenolan. Thus features such as the Furze Bush, the Arabesque and the helictites in Ribbon Cave, all of which have grown on a dolomitic palaeokarst substrate, are the legacy of basinal fluids from the Sydney Basin acting on palaeokarst deposits. A similar relationship is seen between sulfate deposits and pyrite bearing palaeokarst at Jenolan.

Some of the most significant features of Exit Cave in Tasmania are the group of gypsum deposits known as Edies Treasure which owe their origin to the weathering of pyrite deposited by basinal fluids of the Tasmania Basin.

CONCLUSION

Studies in both New South Wales and Tasmania indicate that Permo-Triassic Basins have played a significant role in the development and mineralisation of caves in underlying Lower Palaeozoic limestones. This relationship has been demonstrated at Jenolan in New South.Wales and at Exit Cave in Tasmania. Work in progress is refining knowledge of the relationship between karst and Permian cover at Jenolan Caves and it is planned to expand the work to examine other at karst areas in New South Wales (Colong, Church Creek) and Tasmania (Florentine Valley, Mole Creek).

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THE CORRELATION OF THE EXTENT OF REACTIVE CLAY SOILS TO THEIR GEOLOGY IN THE NORTHERN LAKE MACQUARIE & NEWCASTLE REGION

M.R. TAYLOR
NSW Dept of School Education

INTRODUCTION:

'Reactive' or 'expansive' clays are commonly found within the sediments of the Lake Macquarie and Newcastle soils. Possible damage to lightly loaded structures, such as dwellings, as a result of differential soil movement is dependent upon a number of interactive factors operating. These include temperature fluctuations, soil moisture content, the clay proportion within the soil, clay types present, water table level, slope steepness, drainage, footing design and the integrity of the footing. Because of the variability of these factors it becomes difficult to predict with any certainty how a particular site will behave in an engineering capacity. Australian Standard AS 2870 offers guidance on the "Design of Residential Slabs and Footings" but its reliance on a regular regional geology makes it less useful in areas which have variable geological strata outcropping, such as found in the northern Lake Macquarie and Newcastle region. Whilst the geology of this region is well known, the link between it and the reactive clays of the region have not been closely examined. This study (Taylor, 1993a) looks at the correlation between the reactive clays and the local geology, as well as other factors in the northern Lake Macquarie and Newcastle region.

CLAYS AND CLAY MINERALS:

Clays are important constituents of soils, exerting a dominating influence on soil structure. They are colloidal particles whose size are less than 2 microns. Chemically they are almost essentially composed of hydrous alumino-silicate. They form in three major environments - the weathering, the sedimentary, and the digenetic/hydrothermal environment (Hall, 1987). They can be 'inherited' and altered during the fulfilment of the rock cycle.

Clay minerals are mostly restricted to phyllosilicate clays, of which there are 4 basic groups - **kaolinite, montmorillonite, illite** and **chlorite**. Their origin is unclear but an inherited detrital origin or an 'in situ' authigenic origin is possible (Evans, 1992). Authigenesis may have occurred by alteration of inherited clays through transformation processes, or by direct precipitation from solution or crystallization (Sehgal *et al*, 1974), through the weathering of primary and secondary minerals.

The nature of the Newcastle - Lake Macquarie soils is one of association with the weathering of the various sedimentary rock strata that are ubiquitous within our study area. The type of clay minerals that are dominant (70 to 100%) are the phyllosilicates of **kaolinite** and **illite** (Lambert and Moelle, 1986) which are common alteration products of sandstones and conglomerates (Millot, 1970). These particular clay minerals' atomic structures do not accommodate the number of water molecules that are characteristic of the more 'reactive' or expansive clay minerals. **Montmorillonite** clay minerals are capable of swelling when immersed in water and as such they are capable of causing the soil to 'heave' or swell, or even shrink when the climatic conditions are hot and dry. This group of clay minerals are known to form from the alteration of volcanic ashes ie. tuffs or tuffaceous sandstones (Grim and Güven, 1978).

Within the study area the Newcastle Coal Measures contain some 21 coal seams, and associated with almost all of them is a claystone layer, often immediately above and below the coal seam. Tuffs and claystones represent 19% of the sedimentary layers in the Newcastle Coal Measures (Diessel, 1980, Table 6.1) and as these claystone layers are tuffaceous in origin, it would be reasonable to assume that they have sourced the 'reactive' clays.

The formation of the kaolinite and illite clay minerals stems originally from the weathering and later erosion of primary aluminosilicate minerals (feldspars and biotite mica), readily derived from the granites and basalts during deposition of the sediment into the northern end of the Sydney Basin, of which our study area forms part of. However as the basin formed during the Permian Period (some 250 million years ago) it is more likely that the bulk of the present clays are of authigenic origin, having been developed during or after deposition, as described by Velde (1984). The environmental and climatic conditions predicated the types of clays formed, once the primary minerals had completed weathering and erosion had resulted.

SURFACE GEOLOGY MAP:

Map 1 shows the surface geology of the study area, and is redrawn from a map of Pryor and Mursa (1968). The areal limit of the map is to the north of the Waratah Sandstone Formation (arbitrarily taken as the basal unit of the Newcastle Coal Measures). From the map it can be seen that there is a northwest-southeast trend of outcropping strata, with the northern most strata being the oldest. The southern and western flanks are mostly covered by Triassic Narrabeen Group strata, namely the Munmorah Conglomerate.

Claystones are found throughout the Newcastle Coal Measures, often closely associated with coal seams. There are some 8 named Tuff Members, all are considered significant in an engineering sense, mostly in their capacity to cause problems through swelling. Each of the four geological Sub-Groups have claystones which form swelling clays, with some of the problematical ones having been identified as montmorillonites (Edwards, 1985; Seedsman, 1986; Rigby and Moelle, 1986; Lambert and Moelle, 1986). The claystones represent 19% of the strata, with kaolinites and illites making up nearly 80% of the clay mineralogy and montmorillonite 10% (data from upper portion of the Newcastle Coal Measures).

SOIL CLASSIFICATION:

The NSW Department of Conservation and Land Management (*CALM)* prepare soil maps drawn on the basis of '**soil landscapes**'. Northcote (1978) defines 'soil landscapes' as:

> *"natural areas of land of recognisable and specifiable topographies and soils, that are capable of presentation on maps, and can be described by concise statements".*

Some nine soil landscapes were recognised in the study area, namely, *residual, colluvial, erosional, alluvial, estuarine, beach, aeolian, swamp* and *undisturbed.*

PHYSICAL TEST DATA:

A major part of this study was to collate specific physical test indices of clay soils and compare their areal distribution with other parameters such as soil type distribution and surface geology.

REACTIVE SOILS OF NEWCASTLE AND LAKE MACQUARIE:

Data was collected mainly from 2 Newcastle Geotechnical Engineering companies whose physical testing laboratories had results covering much of the study area, although concentrated where suburban development had required their services.

PHYSICAL TESTING DETERMINANTS - 'I_{SS}' and 'Ys' VALUES.

The most reliable indicator of site reactivity, and the best indicator of ground movement (Cameron, 1989) is the **shrink-swell test** (I_{SS}), as defined by AS2870 - *1990* (as amended). This laboratory test determines the physical characteristics of the sample, in particular the *shrinking* and *swelling strain*. When it is considered in conjunction with other physical parameters such as *soil suction*, *thickness* of the clay layer, as well as the depth of the *cracking zone* of a soil, the **'maximum free surface movement'** (Ys) of the soil can be calculated and a **site classification** assigned. These two parameters (**Iss % and Ys mm**) can therefore be used as a measure of the reactivity of the soil. Local geotechnical engineering firms use these measures and their test results have provided some 580 Iss values which have formed the basis of this study.

Shrink-swell test data from 262 sites were examined, and the highest I_{SS}% values at each location (ie. peak value) were recorded (see Table 1) and plotted onto a 1:100 000 map overlay. The I_{SS}% values were arbitrarily coded into 5 shrink-swell 'I_{SS} percentile' ranges. The reactivity ranges were:

0 - 2.0% (*stable*); 2.1 - 3.5% (*medium*); 3.6 - 5.0% (*high*);
5.1 - 6.5% (*very high*); >6.5% (*extremely high*)

TABLE 1: PEAK SHRINK-SWELL (Iss%) VALUES AND SURFACE GEOLOGY FORMATIONS.

GEOLOGICAL GROUP	GEOLOGICAL SUB GROUP	GEOLOGICAL FORMATIONS	PERCENTILE 0-2.0%	RANGE 2.1-3.5%	OF Iss 3.6-5.0%	VALUES 5.1-6.5%	>6.5%
		Alluvium	18.6%	21.5%	45.7%	11.4%	2.9%
NARRABEEN		Munmorah Conglomerate	50.0%	12.5%	25.0%	12.5%	
NEWCASTLE COAL MEASURES	MOON ISLAND	Catherine Hill Bay	41.7%	8.3%	41.7%	8.3%	
		Eleebana	6.2%	50.0%	31.4%	6.2%	6.2%
	BOOLAROO	Croudace Bay, Reid's Mistake, Warners Bay/ Mount Hutton	3.8% 15.0%	23.1% 25.0%	42.3% 10.0%	30.8% 45.0%	5.0%
	ADAMSTOWN	Tickhole	30.0%	30.0%	20.0%	20.0%	
		Kahibah	11.1%	33.3%	44.5%		11.1%
		Glebe	27.3%	9.1%	45.4%	18.2%	
		Kotara	20.0%	6.7%	46.6%	26.7%	
	LAMBTON	Shepherds Hill	25.0%	37.5%	25.0%		12.5%
		Bar Beach	36.8%	47.4%	5.3%	10.5%	
		Bogey Hole	25.0%	25.0%	50.0%		
		Tighes Hill	11.1%	33.3%	44.5%	11.1%	
		Waratah Sandstone	4.0%	24.0%	32.0%	36.0%	4.0%

SITE CLASSIFICATION MAP USING (Ys) VALUES:

Sites (261) that have been classified using the maximum "free surface movement" (Ys mm) values were plotted onto map. The Ys mm values were graded into four AS2870 groupings, namely,

S	<20 mm	slightly reactive
M	20 mm - 40 mm	moderately reactive
H	>40 mm - 70 mm	highly reactive
E	>70 mm	extremely reactive

which represent *site classifications*. Again an attempt was made to establish correlations between the site classification and the subcropping of geologic formations as well as soil classifications. The results proved similar to the peak shrink/swell values.

RESULTS OF THE DETERMINED CORRELATIONS:

When the *peak shrink-swell* (I_{ss}%) data was applied to the geology map of the Newcastle Coal Measures (see Table 1), a set of graphs were able to be constructed. These graphs showed quiet clearly that a strong correlation exists between the Geological Sub-Groups and an increase in the reactivity of overlying soils, particularly in the centre two Sub-Groups (*Boolaroo & Adamstown)* of the Newcastle Coal Measures (NCM). The *Waratah Sandstone* underlying the NCM showed a very high reactivity. The overlying *Quaternary Sediments* derived from streams and creeks also displayed high reactivity (see Fig. 1).

Figure 2 shows the correlation between the *maximum free surface movement (Ys mm) values* and the Geological Sub-Groups of the Newcastle Coal Measures.

Figure 3 shows the plot of the soil reactivity indicators (I_{ss} and Ys) for the Geological Sub-Groups. The two lines are almost parallel for the two indicators. This highlights the high reactivity of the central and lower Sub-Groups of the NCM. Perhaps almost as important is that it demonstrates that the 'peak shrink-swell' values are by themselves adequate indicators of a soils reactivity!

When the *peak shrink-swell* and the *maximum free surface movement* data were applied to the soil landscape map of the study region, there appeared to be little or no correlation between the soil reactivity and soil landscapes. There were some rudimentary topographic control, suggesting that steep slopes had lower soil reactivity while flatter areas (no doubt where clays are deposited and accumulate) showed higher soil reactivity.

CASE STUDY - MOUNT HUTTON AND ELEEBANA FORMATIONS:

Soils from a new subdivision in Crescent Road, Charlestown was examined by a local Geotechnical Engineering firm and the subsequent physical testing showed very high shrink-swell values:- *7.6%*, *6.5%*, *5.8%*, *8.2%*, *3.8%*, and *6.3%*. These values would cause the site to be classified as either a **H** (highly reactive) or **E** (extremely reactive). This area is situated on the *Mount Hutton Formation* (lowest formation of the Boolaroo Sub-Group of the NCM). Field samples were taken from this *Formation* to see if these reactive clays were widespread. Map 2 shows the sampling sites. Clays from the *Eleebana Formation* were also taken for comparison. The samples were subjected to XRD to identify the clay minerals present.

X-RAY DIFFRACTION RESULTS:

The results (Taylor, 1993b) found that the dominant mineral identified was **Quartz** in all samples. In the *Mount Hutton Form.* **Kaolinite** was the common accessory clay mineral in all samples, while **Smectite** (the group whichincludes **Montmorillonite**) was found in all samples either as a trace or accessory mineral. Trace amounts of the clay mineral **Illite**, as well as **Feldspar** and **Anatase** were identified. In the *Eleebana Form.*, again **Quartz** was dominant with **Kaolinite** present in accessory or trace amounts. **Smectite** was found in two samples in accessory quantity. Again **Anatase** and **Feldspar** were identified in trace amounts.

REACTIVE SOILS OF NEWCASTLE AND LAKE MACQUARIE:

CONCLUSIONS:

This study has confirmed that the nature of the Newcastle Coal Measures and its influence on a soils reactivity is complex. There are few, if any, obvious controls that can be used to identify a likely reactive soil site. Experience and a widespread database appear the best guidelines that can be of use by local geotechnical engineering firms. The many influences affecting soils, more or less confirm the need for site specific data on which to make engineering decisions.

Notwithstanding these limitations, this study has concluded the following:

1. that the shrink/swell (Iss %) value is a good indicator to use as a judge of a soils reactivity (when applied in accordance with AS2870 guidelines) and that a Iss % value greater than 3.6% represents a site with a relatively 'high' reactivity;
2. by taking the 'peak' Iss % value the calculated 'maximum free surface movement' value can be estimated, and hence a site classification can be quickly estimated;
3. that there is a correlation existing between soil reactivity and the surface geology;
4. that there is little or no correlation existing between soil reactivity and 'soil landscapes';
5. that weathered tuffs and claystones (8 named Tuff Members) often associated with coal seams appear to be a prime source of reactive clay minerals, as soils associated with these strata or at least found above them are sites of reactive clay minerals, eg. montmorillonite and kaolinites;
6. that there is a clearly defined increase in the reactivity of clays coming from the 'middle' Boolaroo and Adamstown Formations of the Newcastle Coal Measures;
7. that the Waratah Sandstone underlying the Newcastle Coal Measures, as well as the Quaternary age alluvium associated with streams, swamps and floodplains also contain a high proportion of reactive clays;
8. that a map can be prepared with broad zones to show the extremes of soil reactivity. Such a map has been prepared as a result of this study (see Map 3) which demonstrates the control of reactive soil sites by the surface geology.

ACKNOWLEDGMENTS:

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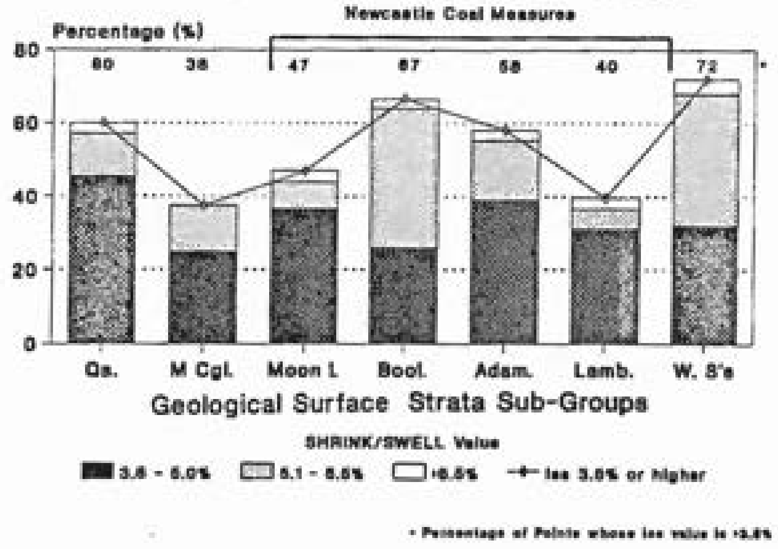


FIGURE 1. Reactive Clays-Newcastle/Lake Macquarie
Peak SHRINK/SWELL (Iss%) Values

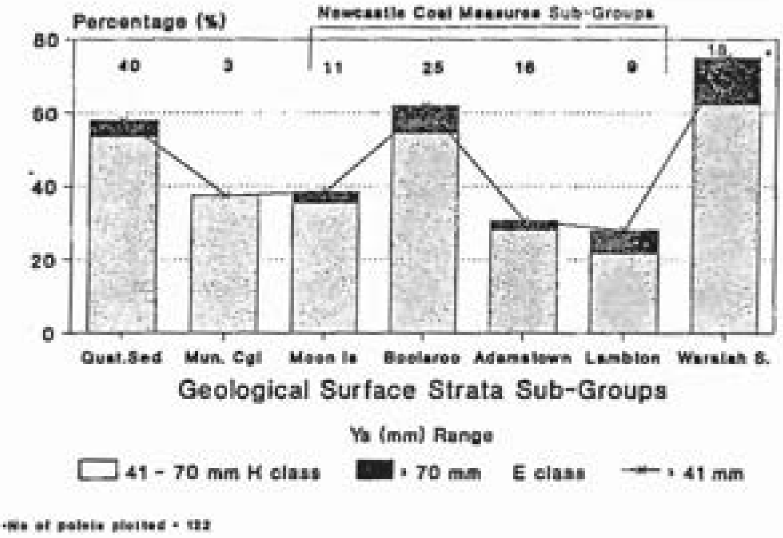


FIGURE 2. Reactive Clays-Newcastle/Lake Macquarie
'FREE SURFACE MOVEMENT (Ys mm) Values

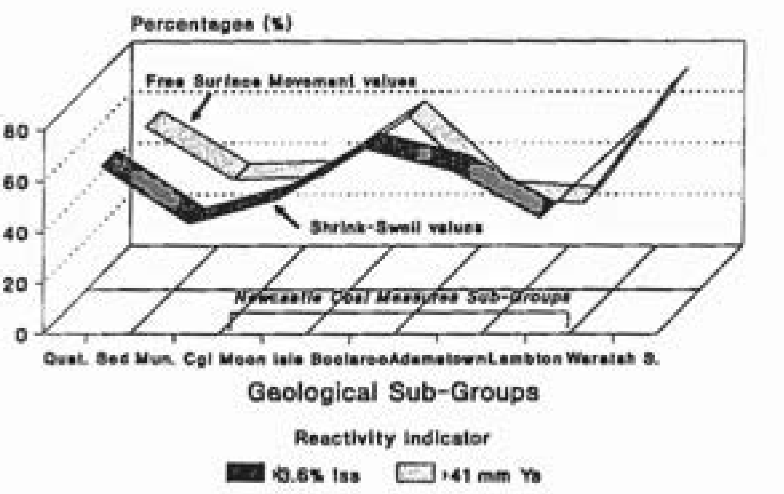
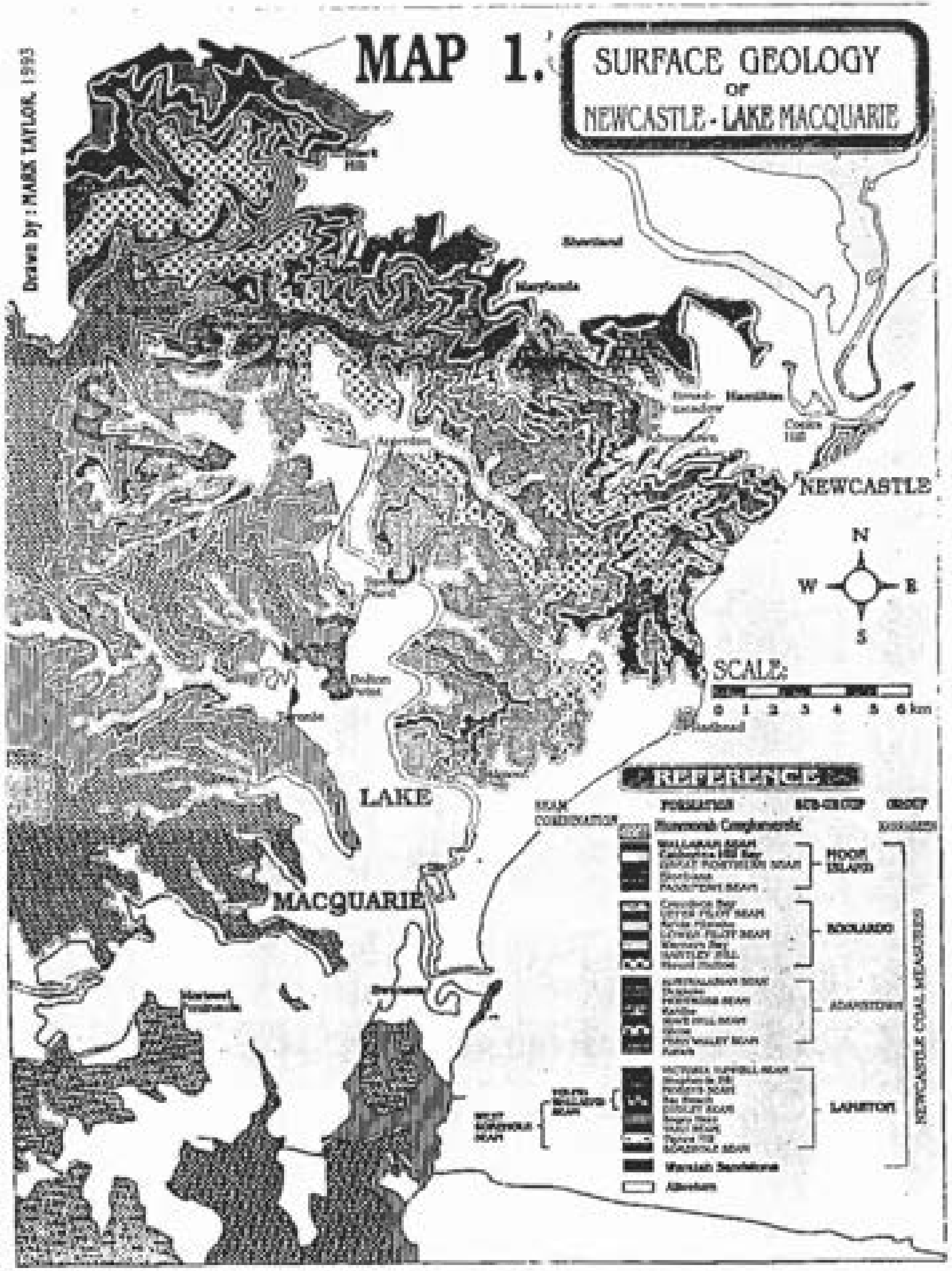


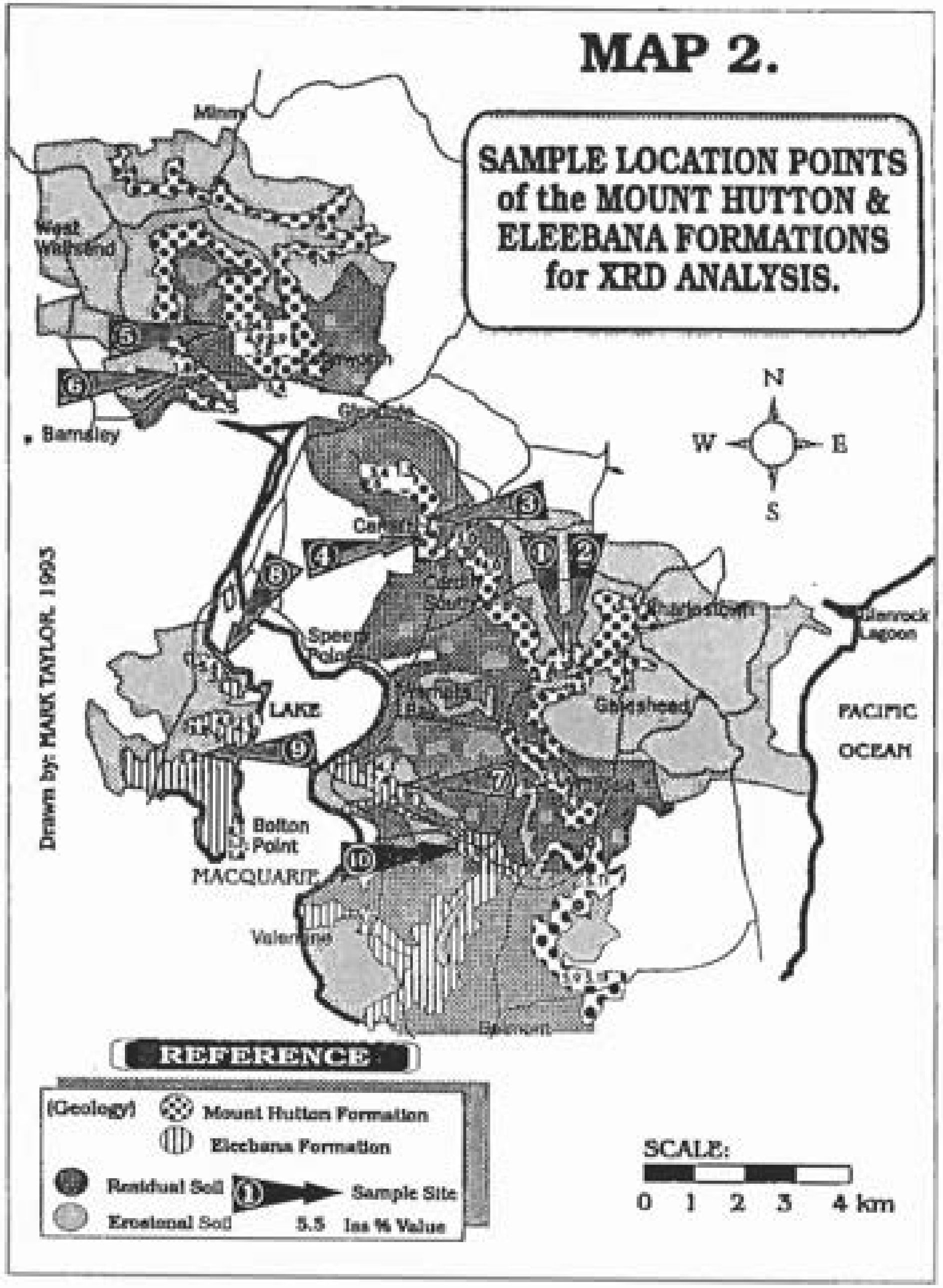
FIGURE 3. Reactive Clays- Newcastle/Lake Macquarie
SURFACE GEOLOGY & REACTIVITY INDICATORS



MAP 1.

SURFACE GEOLOGY OF NEWCASTLE - LAKE MACQUARIE

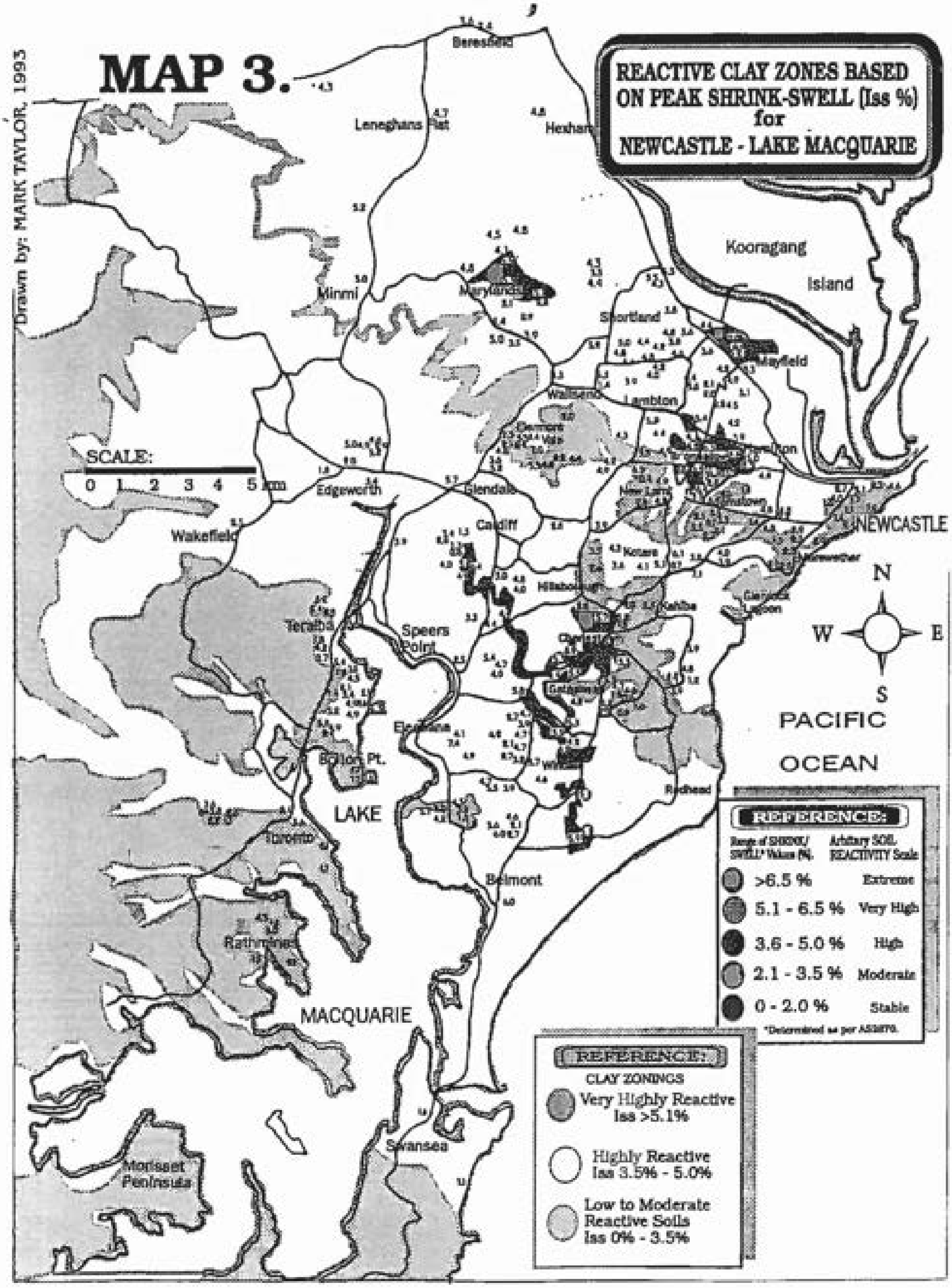
Drawn by : MARK TAYLOR, 1993



MAP 2.

SAMPLE LOCATION POINTS of the MOUNT HUTTON & ELEEBANA FORMATIONS for XRD ANALYSIS.

Drawn by: MARK TAYLOR, 1993


MAP 3.
REACTIVE CLAY ZONES BASED ON PEAK SHRINK-SWELL (Iss %) for NEWCASTLE - LAKE MACQUARIE
Drawn by: MARK TAYLOR, 1993
SCALE:
0 1 2 3 4 5 km
Beresfield
Leneghans Flat
Hexham
Kooragang
Island
Minmi
Maryland
Shortland
Mayfield
Wallsend
Lambton
Cameron Park
Edgeworth
Glendale
New Lambton
NEWCASTLE
Wakefield
Cardiff
Kotara
Merewether
Hillsborough
Adamstown
Garden Lagoon
Teralba
Speers Point
Charlestown
N
W
E
S
PACIFIC
OCEAN
Boolaroo
Booragul
Warners Bay
Bolton Pt.
Redhead
LAKE
Toronto
Belmont
Rathmines
MACQUARIE
Swansea
Morisset Peninsula
REFERENCE:
Range of SHRINK/SWELL* Values (%)
Arbitary SOIL REACTIVITY Scale
>6.5 % Extreme
5.1 - 6.5 % Very High
3.6 - 5.0 % High
2.1 - 3.5 % Moderate
0 - 2.0 % Stable
*Determined as per AS2870.
REFERENCE:
CLAY ZONINGS
Very Highly Reactive Iss >5.1%
Highly Reactive Iss 3.5% - 5.0%
Low to Moderate Reactive Soils Iss 0% - 3.5%

REGIONAL STUDY OF CARBONATE MINERALS IN THE BARALABA COAL MEASURES

J.H. PATTERSON, J.F. CORCORAN & K.M. KINEALY
CSIRO Division of Coal & Energy Technology, N. Ryde

ABSTRACT

Scanning electron microscope and electron microprobe data are presented for the carbonate minerals found in the Baralaba Coal Measures, south-east Bowen Basin. The chemical compositions of these phases have been determined in the coal seams intersected in six boreholes, along strike from Baralaba to Theodore South. Four main modes of occurrence of carbonates were observed : calcite in cleats and infills in coal, siderite nodules in claystone and coal, magnesian siderite as infills in coal and ankerite in cleats and infills in coal. Regional and stratigraphic variability in carbonates is discussed. The occurrence of these carbonate types reflect the local conditions during diagenesis and maturation of the coal.

INTRODUCTION

Carbonate minerals have been associated with slagging in conventional pulverised fuel power stations (Kent and Champion, 1964 and Wibberley and Wall, 1982). Changes in the amounts of these minerals often account for variability in ash fusion temperatures (Kent and Champion, 1964) and ash compositions (Shibaoka, 1970). In recent years a renewal of interest in coal gasification in entrained flow gasifiers, for use in integrated gasification-combined cycle (IGCC) power plants, has led to the characterisation of carbonate minerals in Australian bituminous coals (Patterson et al. 1992a, b and 1994). This work revealed unexpected variability in the composition of ankeritic and sideritic carbonates and raised the possibility that the four compositional types of siderite observed might be indicators of depositional environment. It is generally considered that siderite nodules are syngenetic and formed very early in diagenesis whereas calcite and ankerite cleat and vein infillings are epigenetic and only formed after coal compaction and much later in maturation (Kemezys and Taylor, 1964 and Ward, 1978 and 1986).

A series of reference boreholes along the south eastern boundary of the Bowen Basin, from Baralaba to Theodore South, provided the opportunity to examine carbonate minerals in a number of seams and localities. A geochemical study of the inorganic constituents in these same boreholes was available (Shibaoka, 1970) and seam correlations throughout the area are well established (Svenson et al. 1975). This paper reports the results of scanning electron microscopy and microprobe analyses of the carbonate minerals observed throughout the Baralaba Coal Measures.

EXPERIMENTAL PROCEDURES

The carbonate minerals occurring in coal and claystone particles were studied using scanning electron microscopy and electron microprobe analyses as previously described (Patterson et al

1992a, b). Samples were selected on the basis of the petrographic analyses of the various core sections, as reported in CSIRO Location Reports. Polished grain samples from these original studies were repolished to provide fresh surfaces for analysis. This enabled an effective coverage of the main carbonate minerals present by seam in each of the selected boreholes. The locations of the boreholes examined are shown in Figure 1 and information on the seams examined is given in Table 1. A total of 6 locations and 67 samples provided a good coverage of the major seams within the Baralaba Coal Measures from Baralaba to Theodore South.

RESULTS AND DISCUSSION

The compositional ranges of the carbonate minerals observed in the Baralaba Coal Measures are given in Figure 2 and are very similar to those previously reported for Queensland and New South Wales coals (Patterson et al 1982b). Variability in the composition of sideritic carbonates for the six boreholes is shown in Figure 3 and scanning electron microscope photographs of the main carbonate types and associations are given in Figure 4. The five carbonate types observed were calcite, ankerite, siderite, calcian siderite and magnesian siderite as discussed below.

Calcite - Calcite was observed in many samples and in all localities and seams (excepting for borehole No. 1294). As found for other Australian coals, the calcite was predominantly cleat material and was essentially pure $CaCO_3$ with only minor substitution of calcium by iron and magnesium (Figures 2 and 4a). Some calcite infills were observed in coal (probably in inertinite) as shown in Figure 4c. The present work therefore confirms that calcite in the Baralaba Coal Measures is epigenitic in origin. It is considered that calcite and ankerite occurring in cleats, veins and infills in Australian coals were formed by precipitation from percolating waters, after the coal has been compacted and undergone most of its maturation (Kemezys and Taylor, 1964).

The chemical analyses given in the original CSIRO location reports, reveal large variations in inorganic carbon content due to variability in the amounts of carbonate minerals (Shibaoka 1970). Shibaoka examined trends in total carbonate minerals with stratigraphy for most of the boreholes included in the present study. A good correlation was demonstrated between the total iron, calcium and magnesium in the ash, and the inorganic carbon of the coal. The majority of these elements in the coal are present as carbonates. It was also demonstrated that in the Moura-Theodore district, the coal seams immediately below the Rewan Formation or the Kia-Ora conglomerate were richer in inorganic carbon (and hence carbonates), with the exception of seams intersected in borehole NS33 (Shibaoka, 1970). Moreover, when the inorganic carbon content of the top seams is high, the ash has higher CaO content and lower MgO and Fe_2O_3 contents. Thus calcite cleat infilling is generally greater in the upper seams, strongly suggesting that calcium containing solutions percolated down from the overlying rocks.

Increased total carbonate content in the coal leads to ashes with lower silica ratios ($100SiO_2/SiO_2+CaO+MgO+Fe_2O_3$) and generally lower ash fusion temperatures. A silica ratio of < 70 and a flow temperature < 1400°C (reducing conditions) are considered as desirable for coal use in slagging gasifiers (Patterson et al 1994). Thus the carbonate rich upper seams would appear most prospective for usage in IGCC power plants. It could even be feasible to market seams immediately below the Rewan Formation for IGCC and the other coal seams for conventional power generation.

Ankerite - This phase was observed as a minor component in the samples examined from Moura (NS33) and the Reid and Dirty seams at Baralaba. It was rarely observed in the samples examined from the other boreholes. The ankerite occurred as infillings, mainly in cleats and veins in the coal (Figure 4e) and is therefore considered to be epigenetic and to have formed later in coal maturation. The chemical composition appears to be slightly less variable than for ankerite observed in other Queensland coals, although this may only reflect limited sampling. It would seem that ankerite is of restricted occurrence relative to calcite and sideritic carbonates and is therefore of lesser importance in the Baralaba Coal Measures.

Sideritic Carbonates - Iron carbonate minerals were observed in all the localities examined, but not in all the seams at each locality. Indeed, there was considerable variability in the amounts of siderite observed with stratigraphic depth and no clear trends were established for particular seams. It seems likely that all seams contain siderite but the type and amount is variable from sample to sample. Sideritic carbonates can become more important in coals which have not been subject to cleat infilling by calcite (as discussed earlier). This is particularly well illustrated by the results for Moura C seam in borehole No 1294 (Figure 3c). At this location siderite was the only carbonate mineral observed. However, C seam samples from adjacent borehole NS33 (Figure 1) contain some calcite and ankerite cleat infilling.

Figure 2 shows that three compositional siderite types were observed : siderite, magnesian siderite and calcian siderite. These are consistent with those observed more widely in Australian bituminous coals (Patterson et al. 1992a, b and 1994). Siderite compositions observed at the six locations are shown in Figure 3 and the forms and associations found are discussed below.

It can be seen that siderite was observed in all localities (Figure 3) whereas occurrences of magnesian and calcian siderite are confined to the north at Baralaba and to the south of Theodore. Betwen Moura (No 1294) and Theodore (NS27) siderite predominates. Only minor differences were observed in the average compositions of siderite from the different localities. The structural formulae determined for each locality are given in Table 2. There are subtle differences in chemical composition and these may well reflect pore fluid composition at the time and location of crystallisation. However, for practical purposes the composition of siderite would appear to be constant throughout the Baralaba Coal Measures. As previously observed for Australian coals, the magnesian siderites are more variable in composition and it is not meaningful to average the data. The compositions range up to 30% substitution of iron by magnesium (Figures 3a, f). Calcian siderite was only observed in one sample from borehole NS14 (Figure 3c).

During the SEM and microprobe examinations attempts were made to record the form (nodular or infilling) and associations of the sideritic carbonates. This is best discussed separately for each locality from north to south. For borehole NS24, magnesian siderite and siderite predominate (Figure 3a and Table 2). Siderite occurs as nodules in claystone particles within the upper seams (Cameron and Reid). Magnesian siderite occurs in the lower seams, as nodules (in claystone and coal), as a massive band (Dawson seam) and also as infilling in coal (Unnamed seam). The nodular siderite and magnesian siderite are thought to be syngenetic in origin whereas the magnesian siderite infilling appears to be epigenetic (Figure 4f). Thus at Baralaba there is evidence of changes in siderite type and associations with stratigraphic depth.

Borehole No. 1294 sampled the Moura C seam and siderite was the only carbonate observed. It mainly occurred as nodules in coal and claystone particles, with lesser massive siderite of possible epigenetic origin. The composition of the siderite was the same regardless of form or association (Figure 3c). Siderite was again observed in Moura borehole NS33 as nodules and grains in the coal, and was of similar composition throughout (Figure 3e). Comparable nodules in coal or claystone particles were also observed in the Nipan 2 and 8 seams from borehole NS45 (Figure 3b) and in the Nipan 2, 4/5 and 6 seams at Theodore boreholes NS27 and 47R (Figure 3d). It would thus appear that siderite in the central region from Moura to Theodore is dominantly syngenetic in origin and may well reflect the depositional conditions early in diagenesis of the coal.

The chemical composition of the siderite is essentially constant in this central region (Table 2) suggesting that a stable depositional environment prevailed throughout the various cycles of coal seam formation. Magnesian siderite was only observed in the Nipan 3/4 seam in the Theodore borehole (Figure 3d) and was of different origin. It occurred as infillings in the coal (Figure 4f) and is therefore considered to have crystallised much later during maturation of the coal.

At Theodore South, the results are more similar to those at Baralaba in the north (compare Figures 3a and 3f) excepting for the occurrence of some calcian siderite (Figure 3f). However, as before siderite occurs as nodules in claystone (Figure 4b) and the magnesian siderite occurs as infillings in coal (Figure 4f). Calcian siderite was only observed in the one sample from the Nipan 4/5 seam and occurred as infillings in the coal.

From our results there are two dominant compositional siderite types in the Baralaba Coal Measures, siderite and magnesian siderite. There are also four main modes of occurrence, nodules in claystone (Figure 4b), nodules in coal (Figure 4d), infillings in the coal (Figure 4f) and as massive sideritic bands within the sequence. As indicated earlier the siderite and magnesian siderite nodules are considered to have formed early in diagenesis, whereas the magnesian siderite infilling is thought to have occurred much later during maturation.

CONCLUSIONS

A number of links have been demonstrated between carbonate type and depositional environment during diagenesis and maturation of the coal in the Baralaba Coal Measures:

1. Nodular siderite in claystone and coal may reflect conditions early in diagenesis. It is syngenetic in origin and occurs in variable amounts throughout the sections examined. Minor compositional variations between siderites probably reflect the composition of pore fluids at the particular location and time of crystallisation.
2. Magnesian siderite and the calcian siderite commonly occur as infillings in the coal. They are considered to be epigenetic in origin and formed at a later stage during maturation of the coal. This mainly occurred at Baralaba and to the south of Theodore.
3. Ankerite is a minor component in coals from Baralaba and Moura and occurs as epigenetic cleat and vein infillings in the coal.
4. Epigenetic calcite, in cleats and veins in the coal, was observed in all localities to varying extents, generally with a tendency to be enriched in coal seams immediately below the Rewan Formation or Kia Ora conglomerate. This is considered to reflect percolation of calcium-containing solutions from the rocks above, much later in diagenesis after the coal has been compacted and undergone most of its maturation.

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Table 1 Boreholes and Seams examined

Borehole	CSIRO LR No.	Locality	No. of Samples	Seams examined
NS24	343	Baralaba	12	Moody, Boyd, Cameron, Reid, Doubtful, Dawson, Dunstan, Double, Unamed and Dirty
No 1294	346	Moura	6	C
NS33	360	Moura	14	A,B,C,D and E
NS45	367	Nipan	12	Nipan 1-11
NS27 and NS47R	384	Theodore	13	Nipan 2-8
NS14	371	Theodore South	10	Nipan 4-10

Table 2 Structural Formulae for Siderites

Locality	Structural Formula
Baralaba	$Fe_{0.85}\,Ca_{0.06}\,Mg_{0.06}\,Mn_{0.03}\,CO_3$
Moura (No. 1294)	$Fe_{0.91}\,Ca_{0.03}\,Mg_{0.01}\,Mn_{0.05}\,CO_3$
Moura (NS33)	$Fe_{0.87}\,Ca_{0.07}\,Mg_{0.03}\,Mn_{0.03}\,CO_3$
Nipan	$Fe_{0.91}\,Ca_{0.05}\,Mg_{0.03}\,Mn_{0.01}\,CO_3$
Theodore	$Fe_{0.89}\,Ca_{0.05}\,Mg_{0.02}\,Mn_{0.02}CO_3$
Theodore South	$Fe_{0.88}\,Ca_{0.04}\,Mg_{0.06}\,Mn_{0.02}\,CO_3$

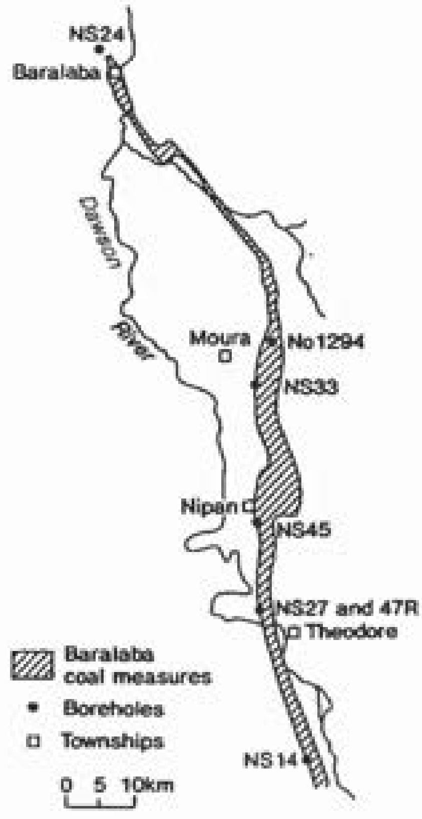


Figure 1 Locations of boreholes examined

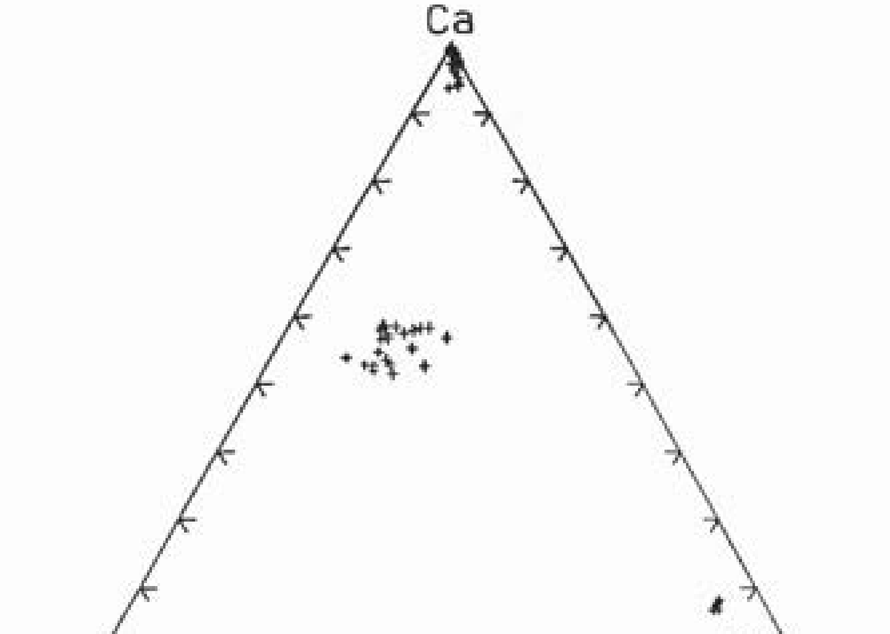


Figure 2 Compositions of carbonates in the Baralaba Coal Measures

CARBONATES IN THE BARALABA COAL MEASURES

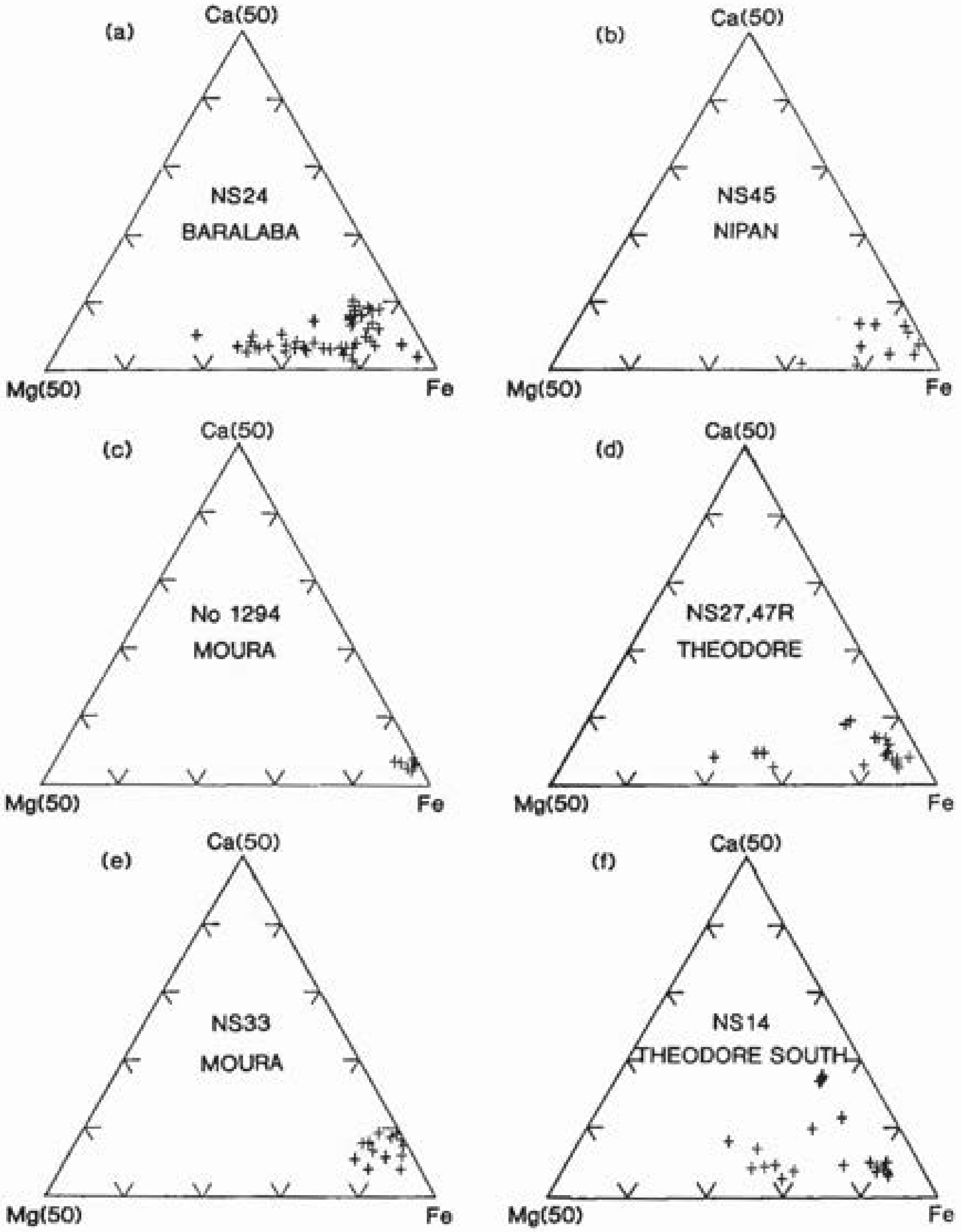
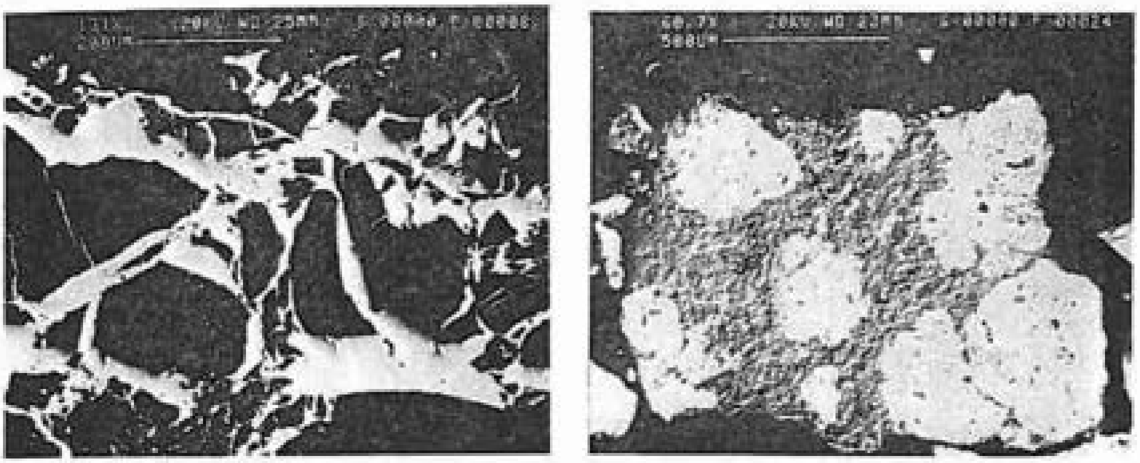
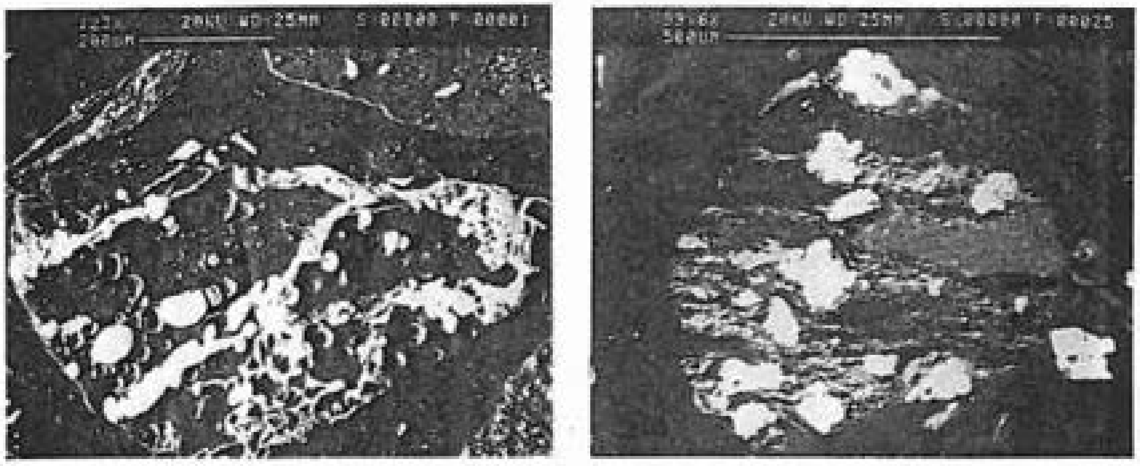


Figure 3 Compositional ranges for siderites at different locations



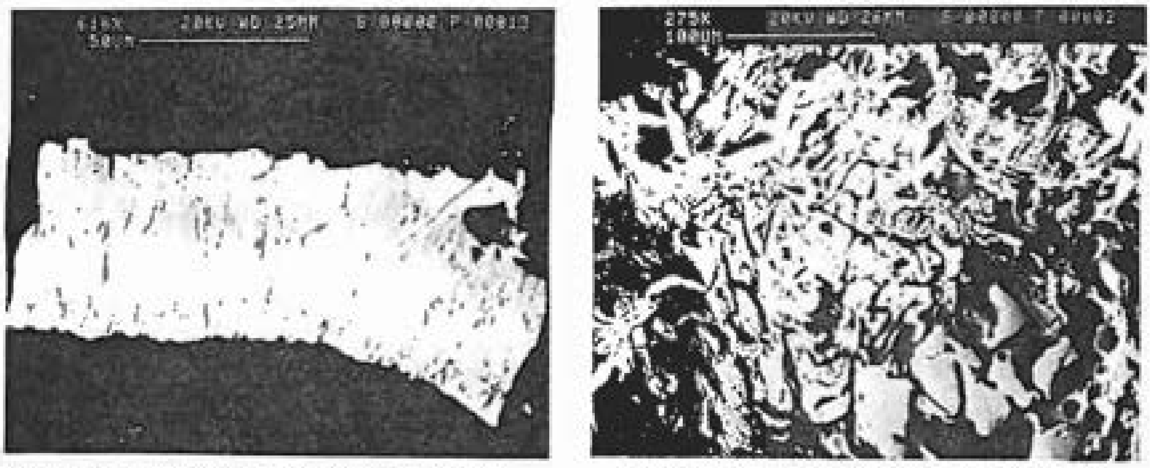
(a) Calcite cleats (bright) in coal

(b) Siderite nodules (bright) in kaolinitic claystone



(c) Calcite infilling (bright) in coal

(d) Siderite nodules (bright) and illitic clay (grey) in mineralised coal.



(e) Ankerite cleat with minor siderite along bottom edge

(f) Mg-siderite (top) and calcite (bottom) infilling in coal

Figure 4 Scanning Electron Microscope Photographs of Carbonates

MINERALISATION & CONTROLS ON GOLD DEPOSITION, COPELAND GOLDFIELD

J.H. GIBSON & P.K. SECCOMBE
Dept. of Geology, The University of Newcastle

ABSTRACT

In the Copeland Gold District, gold-bearing epithermal veins were formed within transpressive fracture systems as a result of sinistral movement on the Manning Fault. These veins contain a simple sulphide mineralogy consisting principally of pyrite (py) and arsenopyrite (asp). Lead and sulphur isotope data indicate that mineralising fluids were magmatic; isotopic signatures for lead are similar to data from the Barrington Tops granodiorite. Gold deposition occurred when ponded fluids, reduced by pyritisation and demethanation, driven by a 'suction pump' phenomenon, as described by Sibson (1992) mixed with upwelling magmatic fluids at the time of faulting.

INTRODUCTION

The Copeland Gold District, which lies approximately 10km west of Gloucester or 125km due north of Newcastle, produced 163kg of alluvial gold and 1,954kg of lode gold between the years 1876 to 1956. Only a small and spasmodic production has been recorded after 1887. The district is situated in the southern portion of the New England Fold Belt, with the mines occurring almost exclusively within the Upper Devonian Bowman Beds of the Tamworth Group. The origin of the Copeland deposits is intriguing, as they are hosted exclusively by sediments of low metamorphic grade, which demonstrate low strain. However, the deposits do not conform to the style of gold-quartz veins formed in more deformed metasedimentary sequences elsewhere (e.g., Hill End, NSW; Ballarat, Vic.) but show features characteristic of epithermal mineralisation. Poor exposure of abandoned mines, poor outcrop and difficult terrain compound the problem. This contribution utilises lead and sulphur isotopic data and studies of dispersed organic matter (DOM) in vein material and hostrocks to argue for an epithermal origin of the Copeland gold deposits. Factors considered important in vein formation include a magmatic source of metals and fluid, structural control during transpressive deformation associated with movement of the Manning Fault and fluid-rock interaction involving pyritic and carbonaceous rock units of Devonian age.

SEDIMENTOLOGY & STRUCTURE

Sedimentology

The hostrocks comprise a sequence of marine strata of unknown thickness, assigned to the Bowman Beds of Devonian age. Two contrasting rock types are evident:

1) A sequence of black-coloured, rarely fossiliferous (Leptophloeum *australe*, and radiolaria) rocks, which consist of texturally immature, medium-grained sandstones and coarse-grained siltstones. These rocks are finely laminated, contain abundant organic material and pyrite, lack sedimentary structures other than dewatering and slump features, and indicate deposition in a deep marine environment.

2) Pale blue-grey to greenish-coloured, poorly sorted sediments, which range from immature granule conglomerates to medium-grained, volcano-clastic sandstones. These units are characterised by highly variable bed thicknesses and are interbedded with the dark-coloured sandstones and siltstones described above. The rocks contain little or no carbonaceous material or pyrite. Beds contain rare ripples and typically reveal an erosional base, above which boulder to granule mud clasts are commonly found. These rocks are interpreted as mass-flow units resulting from the destabilisation of pyroclastic material deposited in a shelf environment.

Structure

The structural style of the area can be accounted for by deformation operating during two of the four tectonic stages (Collins, 1991) of the Hunter-Bowen Orogeny (265-250Ma):

1) D_1, an east-west compressional event, which produced an upright anticline of large amplitude (F_1) with a N-trending, sub-horizontal axis.

2) D_4, a period of sinistral movement on the Manning Fault and related faults further south, which produced a transpressive deformation event (Wilcox *et al.*, 1973; Ramsay & Huber, 1987; Bartlett *et al.*, 1981).

ORIGIN OF ORE-FORMING FLUIDS

Sulphur and lead isotopic studies undertaken on minerals separated from veins and wallrock provide important constraints on the nature and the possible source of the hydrothermal fluids.

$\delta^{34}S$ of Sulphides

Sulphides from the veins and hydrothermally altered wallrock (mullock) adjacent to the veins have been analysed (Table 1), together with samples of unaltered host rock. The narrow range ($\delta^{34}S$ = -1.8 to 3.4 per mil) in isotopic composition for vein and wallrock samples is indicative of a single source of sulphur. Further, since Ohmoto (1986) contends that the $\delta^{34}S$ composition of sulphur derived from the mantle should not extend beyond the range -3 to 2 per mil, this suggests that the source of the sulphur responsible for mineralisation in the Copeland Gold District has a mantle signature.

Table 1 Sulphur isotopic composition of sulphides, Copeland goldfield

$\delta^{34}S$ values (per mil)

COPELAND GOLDFIELD

Sample type	**No. of samples**	**Mean Value**	**Std. Deviation**
Veins	17	1.0	1.29
Altered wallrock	12	-0.4	0.79
Country rock			
pyrite	4	-7.4	
pyrrhotite	2	1.6	

Mineral pairs

$\delta^{34}S$ values (per mil)

Mine	**Pyrite**	**Arsenopyrite**	**Variation** ($\delta^{34}S_{py}-\delta^{34}S_{asp}$ per mil)
Golden Crystal	-0.9	-0.3	-0.6
Golden Consul	1.2	0.6	0.6
Golden Consul (mullock)	1.1	0.8	0.3

The negative signature of the pyrite extracted from the whole rock samples (mean $\delta^{34}S = -7.4$ per mil) lies in the range in isotopic composition for sulphides encountered in modern sedimentary environments (-5 to -35 per mil; Stanton, 1972), and is consistent with a syn-sedimentary origin for pyrite in the country rocks involving biogenic sulphur produced during the consumption of organic matter within unconsolidated sediments.

The limited variation in isotopic composition between mineral pairs (pyrite and arsenopyrite) and between similar minerals within mullock and veins taken from the same mine (Golden Consul, pyrite and arsenopyrite; Table 1) suggests that the source of sulphur remained constant throughout deposition. Data obtained by us on the isotopic composition of arsenopyrite in other ore-forming environments indicate that it typically gives a similar $\delta^{34}S$ value to coexisting pyrite. We reach a similar conclusion for the Copeland data.

Lead Isotopes

Lead isotope analysis of 16 pyrite samples taken from 11 mineralised veins were undertaken at the Centre for isotope Studies, CSIRO Division of Exploration and Mining, Sydney. The Copeland lead isotope data lie well below the crustal growth curve (Fig. 1) and overlap closely the field of analyses from the Barrington Tops granodiorite (Hensen *et al.*, 1993). These authors contend that the low isotopic values for lead, coupled with low initial $^{87}Sr/^{86}Sr$ ratios (0.70375) and high ε_{Nd} values (5.6 to 7.8) are indicative of a mantle signature for the Barrington Tops granodiorite.

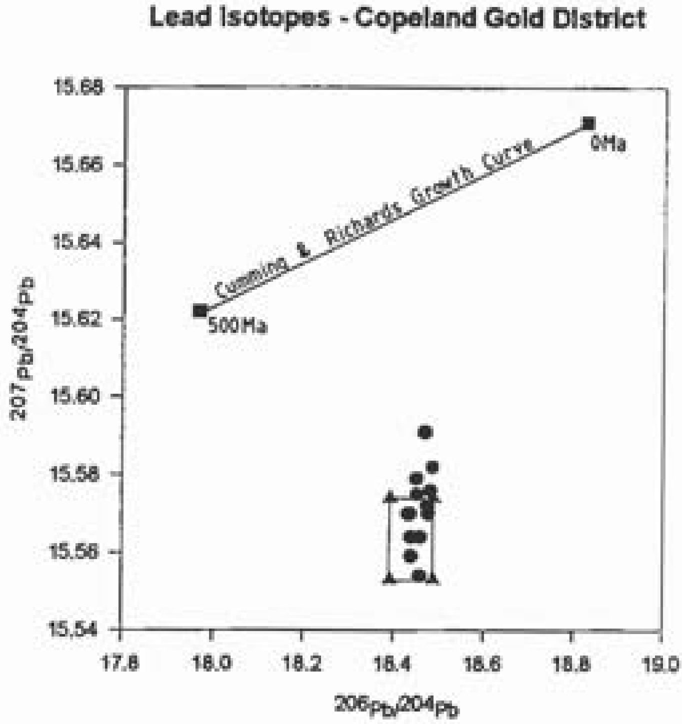


Figure 1
Lead isotope ratio diagram for pyrite samples (filled circles) from the Copeland Gold District. Filled squares indicate positions on the Cumming & Richards growth curve for 500Ma and the present. Filled triangles represent the maximum/minimum values of data from the Barrington Tops pyroxene granodiorite (Hensen *et al.*, 1993).

Of six analyses of vein pyrite from the Copeland samples, 5 lie within the field of the Barrington Tops granodiorite, and one plots just beyond the granodiorite field. Pyrite taken from altered wallrock give greater variation, with only two of five values confined to the granodiorite field. This suggests some small degree of contamination from the Devonian country rocks to the mantle-lead signature.

The lead and sulphur isotopic data point strongly towards a magmatic source for components of the Copeland veins. Further, the lead isotopic analyses favour the mantle-derived, Barrington Tops granodiorite or a buried, generically related equivalent as the source of metal and fluid responsible for the hydrothermal activity and mineralisation at Copeland.

CONDITIONS OF MINERALISATION

Mineralisation styles in the veins and their alteration halos are simple, consisting dominantly of quartz and minor (late) calcite, accompanied by rare sericite and chlorite. The principal sulphide minerals are pyrite and arsenopyrite, together with rare chalcopyrite, pyrrhotite and sphalerite. Gold, in hand specimen, has a sub-millimetre to decimetre grain-size, which at its maximum, is larger than that of any other sulphides encountered.

Vein growth has been attained in two paragenetic stages, which appear to have been influenced by a fall in temperature over the life of the hydrothermal event.

COPELAND GOLDFIELD

Stage 1 - 350-225°C

An upper temperature limit for this first paragenetic stage of vein development is constrained by reflectance measurements made on DOM particles from breccia fragments preserved within some veins. A lower temperature limit is constrained by the pyrrhotite-pyrite- arsenopyrite association, as detailed by Heinrich and Eadington (1986). The following reactions are important in discussing this mineral assemblage:

Pyrrhotite: Amorphous FeS --> mackinawite --> pyrrhotite

$$Fe_{++} + H_2S = FeS + 2H^+ \text{ (Schoonen \& Barnes, 1991)} \qquad (1)$$

Arsenopyrite: Two paths of formation are suggested:

$$2H_3AsO_3 + H_2S + 2H^+ + Fe^{++} = 2FeAsS + 6H_2O \qquad (2)$$

$$2H_3AsO_3 + 2FeS_{am} = 2FeAsS + 3H_2O \qquad (3)$$

Pyrite (minor): $Fe^{++} + 2S = FeS_2$ (4)

Minor pyrite could form above 300°C, with nucleation of FeS_2, but nucleation would be improbable from 300-250°C and chemically untenable without a mono-sulphide precursor below 250^{oC} (Schoonen & Barnes 1991). Major gold deposition would not be accomplished at this stage, as the formation of arsenopyrite (equation 2) would act as a buffer consuming H^+, which is the main depositional mechanism for gold deposition.

Stage 2 - 200-150°C

The upper limit is constrained by the cessation of arsenopyrite deposition, and the homogenisation temperature of primary fluid inclusions confined to late-formed quartz (195°-205°C). The lower temperature is defined by homogenisation temperatures of secondary fluid inclusions in healed fractures from the same samples of quartz. The major stage of deposition of gold and calcite is late; both minerals are associated with the growth of vugh quartz and both are found with rare pyrite as late-stage cavity infill. The following reaction is significant:

Pyrite: Amorphous FeS --> mackinawite --> pyrrhotite --> pyrite

$$FeS + H_2S = FeS_2 + H_{2(g)} \qquad (5)$$

Arsenopyrite: Minor arsenopyrite may form below 220°C, with deposition ceasing at 200°C if aqueous H_3AsO_3 sustains an activity of 10^{-4} m.

Boundary conditions for fluid composition for stages 1 and 2 of the paragenesis are likely to be: pH range = 4-6; log fO_2 range = -35 to -45. Under these conditions, arsenic is likely to be transported as the H_3AsO_3 form (Heinrich and Eadington, 1986) and for solutions where sulphur is present principally as the aqueous H_2S species, gold would be carried as the $HAu(HS)_2$ complex (Hayashi and Ohmoto, 1991).

Stage 3

This consists of surface weathering at ambient temperatures and thus will not be dealt with further.

GOLD DEPOSITION

The experimental data of Hayashi & Ohmoto (1991) show that between the temperatures of 250°-350°C, the solubility of gold in ore-forming fluids, in equilibrium with pyrite and/or pyrrhotite is typically between 0.1ppb to 1ppm. Dissolution and transport of gold as a bisulphide complex dominates over the formation and mobility of gold as a chloride complex, unless the fluid is H_2S poor, chloride-rich and has a pH below 4.5.

For mineralising conditions at Copeland, precipitation of gold could occur either by an increase in the activity of $_{H2(aq)}$, which may be triggered by reaction of the hydrothermal fluid with organic matter or ferrous iron-bearing minerals, and/or a decrease in the a_{H2S}, which may be generated by precipitation of sulphides or by mixing with H_2S-poor fluids. Simple changes in fluid temperature were shown to be an ineffectual depositional mechanism for gold from the bisulphide complex (Hayashi and Ohmoto, 1991). Thus, these chemical influences could explain why sediment-hosted gold deposits and metamorphic gold-quartz veins in slate-belts generally show an association with carbonaceous beds, volcaniclastic or igneous rocks and tectonism. Thick sequences of dominantly volcaniclastic sediments at Copeland would provide a ready source of ferrous iron to hydrothermal fluids involved in alteration reactions and so influence the precipitation of gold.

Carbonaceous Beds

Devonian DOM particles within the marine sediments would consist primarily of terrestrial and marine vegetal material. These DOM particles consist of the same macerals and undergo the same coalification processes that can lead to the progressive transformation from formation peat through coal to graphite within coal measures (Diessel & Offler, 1975), as products of firstly, by the process of bio-coalification and subsequently, by physico-chemical coalification (Diessel 1992).

Biochemical coalification within the carbonaceous sediments would commence with the biodegradation of the DOM particles at, or just below the sediment/water interface, generated by organisms that initiate decomposition, and would end with the polymerisation of humic colloids, in an essentially anoxic environment. Subsequent to biochemical coalification, the preserved vegetal and humic products commence physico-chemical coalification in response to a rise of temperature and pressure, initiated by post-depositional subsidence (Diessel, 1992).

Changes due to thermal cracking of the aliphatic and non-aromatic side chains release the effluent fluid end-members CO_2, H_2O and CH_4 (see Fig. 2), as aromatic clusters within the DOM particles grow and coalesce at the expense of the side-chains joining the aromatic clusters. CO_2 and H_2O evolve (decarboxylation) in the early stages of coalification and the hydrogen/carbon ratio of the remaining macerals remains constant until medium-volatile, bituminous coal grades (~80% C) are reached, after which the evolution of CH_4 becomes important (demethanation). With the virtual exhaustion of oxygen from the side-chains within the macerals at anthracite grade (~95% C), CH_4 dominates the effluent. This is accomplished by the emission of H_2 as the graphitising benzene rings break their hydrogen bonds, to form carbon crystallites.

Thus, until the DOM particles attain anthracite grade (about 350°C) there is little H_2-rich effluent produced to destabilise the hydrothermal fluids and cause precipitation of gold from soluble bisulphide complexes.

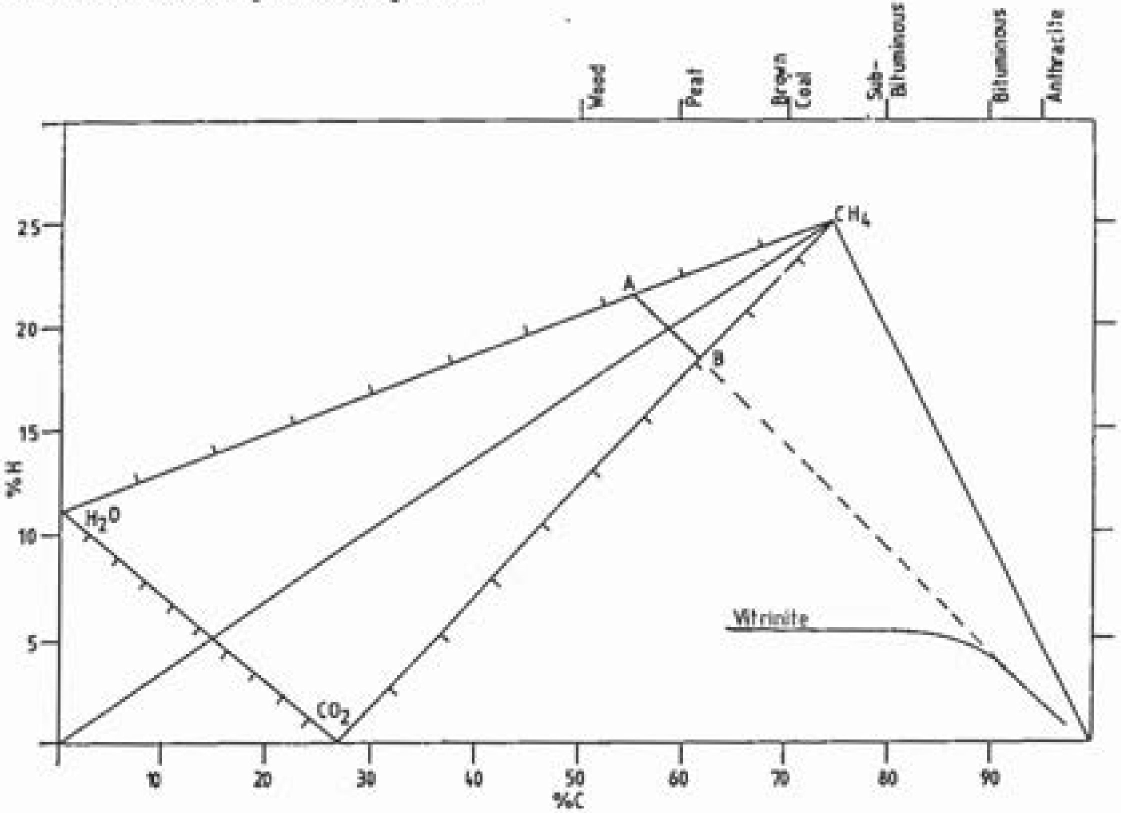


Figure 2
Seyler's Chart, modified after Diessel (1992). The triangle joining both extremities of the carbon scale together with CH_4 includes all organic compounds. The 'Effluent Triangle,' bounded by CO_2, H_2O and CH_4 contains all gases and fluids generated by coalification. The line A-B within the 'Effluent Triangle,' drawn tangential to the vitrinite curve (labelled) at 95% carbon indicates effluent by-products from coalification that would conform to the mixture 72% CH_4, 13% H_2O and 15% CO_2.

TECTONISM

It has been long recognised that gold-bearing quartz veins form within voids formed by faults and shear zones. Sibson (1992) cites Buckland, 1836; Hulin, 1925; Knopf, 1928 and McKinstry, 1948 as authors who paid attention to these structures within such deposits. Sibson (1992) further contends that this style of mineralisation primarily occurs as either epithermal deposits, originating in the shallow-brittle deformational zone (<1 to 2km depth) or as mesothermal mineralisation in the deeper brittle-ductile zone (≈ 10km crustal depth).

Brittle deformation features are identified from the structures developed in veins of the Copeland goldfield. These include recemented breccia veins, open space gangue fill and development of fault gouge and breccia; all of which are typical structures produced during multiple faulting within a seismogenically active crust (Sibson, 1992). Vein formation at Copeland was established within fault jogs linking *en echelon* fault segments or within fault bends under a prevailing transpressional deformation regime. Most auriferous veins opened during many episodes of incremental extension, as evidenced by high-dilation, hydrothermally cemented breccias containing clasts of wallrock or pre-existing vein material.

Prior to episodic fault movement, rocks adjacent to faults would have been dilated due to grain boundary opening and micro-cracking, together with the opening of extension fractures, to allow access of either hydrothermal or meteoric fluids (Ramsay & Huber 1987), providing hydrostatic pressure equalled or exceeded lithostatic pressure. At Copeland, lead and sulphur isotope data indicate show that ingressing fluids have a mantle signature and are therefore likely to have been derived from a cooling pluton of the same character as the Barrington Tops granodiorite, located beneath the goldfield. Our data cannot assess the role of meteoric fluids in the mineralising process, but their contribution may have been minimal.

Gold precipitation was effected by loss of H_2S by sulphidation reactions in the wallrocks (pyritisation) which also generated accompanying H_2 and aided gold reduction. Further reduction was accomplished during demethanation of meta-anthracite DOM particles as an ever-increasing fracture system exposed increasing surface area to the ingressing fluids.

Upon rupture, some local perturbations within the stress-field would favour extension (Segall and Pollard, 1980) within dilational jogs (Sibson, 1992) along non-planar faults. Openings would form faster than fluids could restore equilibrium within these voids, leading to a suctional force opposing the fault slip. Sibson (1992) contends that "Following rupture arrest, the lowered pressure is restored within the jog by inward fluid percolation from the surrounding rocks."

Thus, large volumes of fluids filled minor fractures adjacent to faults during dilation prior to fracture. These fluids would be reduced by pyritisation and demethanation reactions with the wallrocks and then were available, upon rupture, to be drawn into open conduits under reduced pressure to mingle with upwelling hydrothermal fluids. Rapid mixing of reduced fluids expelled from wallrocks with ore-bearing fluids rising through more open structures would cause gold-bisulphide complex destabilisation and deposition of gold, especially within carbonaceous strata. The association of coarse-grained, vugh-filling calcite with gold and quartz lends support to this process, since calcite precipitation is enhanced by a reduction in pressure, but not by a reduction in temperature (Holland and Malinin, 1979). Gold precipitation in the temperature range 150°-200°C at a late-stage of the vein paragenesis when mineral deposition was characterised by open-space textures, structural control of the deposits to breccia and fault zones and an apparent genetic relationship to an underlying intrusion all point towards the epithermal nature of the Copeland gold veins.

Biotite K/Ar ages for the Barrington Tops granodiorite in the range 262 to 269 Ma (Cooper *et al.*, 1963; Roberts and Engel, 1987) and a biotite Rb/Sr age of 262 Ma (Hensel *et al.*, 1985) permit the intrusion to be a source of hydrothermal activity for gold mineralisation during the Hunter-Bowen Orogeny (265-250 Ma), particularly as the intrusion post-dates D_1 folding (Collins, 1991). Recent U/Pb dating of zircons from the granodiorite (Kimbrough *et al.*, 1993) yields an average age of 281 Ma, taken as the age of early crystallisation of the pluton. The zircon and biotite ages appear compatible if typical pluton cooling rates are considered (20°-40°C per Ma; e.g., Mattinson, 1978), which suggest that hydrothermal activity developed late in the pluton's cooling history.

Further work in progress to test the concept of a magmatically driven, epithermal fluid system for mineralisation at Copeland will rely on analysing the trace element and lead isotope composition of the gold, and obtaining other stable isotope data (C, O, H isotopes) on vein and wallrock minerals.

CONCLUSIONS

Gold-bearing quartz veins of epithermal type in a low metamorphic grade turbidite succession of Devonian age at Copeland formed in fractures and shear zones induced by a transpressive deformation regime during the Hunter-Bowen Orogeny (265-250Ma). Near-zero per mil $\delta^{34}S$ values and a mantle signature for lead isotopic data for sulphides from veins and wallrock sulphides implicate the Barrington Tops granodiorite as a source of sulphur, metals and fluids in forming the Copeland gold veins. Magmatic fluids evolving from a granodioritic melt underlying the Copeland region invaded the host rock as a result of dilation prior to fracturing and became reduced due to sulphidation reactions in the wallrocks (pyritisation) and demethanation of meta-anthracite DOM particles exposed to ingressing fluids. Upon rupture, a relative drop in pressure in the fractures compared with the wallrocks allowed the reduced fluids to move into the fissures, thus permitting fluid mixing and precipitation of gold from upwelling ore fluids.

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VISCOSITY MEASUREMENTS ON MELTS FROM SOME NSW COAL ASHES

H.J. HURST, F.F NOVAK & J.H. PATTERSON
CSIRO Division of Coal & Energy Technology, N. Ryde

ABSTRACT

Viscosity versus temperature data are presented for four NSW coal ash melts with low ash flow temperatures and for fluxed mixtures of one coal ash with an ash flow temperature >1600°C. The experimental results are compared with model predictions based on the major components; silica , alumina, calcium oxide and iron oxide in the ashes, fluxed mixture or melts. Present models are unsatisfactory for many NSW coal ashes but can be adequate for ash fluxed with lime.

INTRODUCTION

The need for greater efficiency and reduction of greenhouse gas emissions in future power generation has led to increased interest in integrated gasification-combined cycle (IGCC) technologies. Major export coal customers and Australian utilities are proposing to use IGCC for the next generation of power plant installations, and it is generally considered that processes using entrained flow gasifiers, operated in a slagging mode, are the most appropriate for bituminous coals .

Under the high operating temperatures prevailing in entrained flow slagging gasifiers, the total ash content, the ash fusion temperatures, the chemical composition of the ash and the viscosity and flow characteristics of the molten slag are of great importance in coal selection. The molten slag must have a viscosity low enough to allow manageable slag flow at tapping temperatures. It is also desirable to avoid the inefficiency inherent in an excessively high slag temperature. These aspects are of particular concern for most NSW coals, which otherwise appear well suited for use in IGCC plants. The potential concern is the relatively high ash fusion temperatures, often >1500°C (under reducing conditions), associated with these coals. Such coals will require the the addition of flux and this may disadvantage them relative to other coals available to overseas customers. It is generally considered that the addition of fluxes will be necessary for coals with flow temperatures >1400°C. Molten slag viscosity versus temperature characteristics and the effect of fluxing agents (type and amount) become important factors in coal evaluation and selection for use in IGCC plants. This paper presents the initial results of work to establish the slag viscosity characteristics and response to fluxing agents of a range of Australian bituminous coals and compares the experimental results with model predictions based on the ash and melt compositions.

Pioneering work in slag viscosity measurement and the relationship of viscosity to successful slag tapping was carried out for USA coals[1,2] and was confirmed and extended by British workers[3-5]. For Australian bituminous coals the only published data is that of Boow[6], carried out almost thirty years ago. Overseas IGCC developers have tested a number of Australian coals but the results on slagging characteristics are proprietary. In recent years, the emphasis has been on the developement of models for the prediction of slag viscosity[7-9] and flux requirements[10].

However, the ash properties of Australian bituminous and sub-bituminous coals differ significantly from those of Northern Hemisphere coals and it is probable that the available predictive models for slagging behaviour will not be applicable. In particular, the silica content and silica to alumina ratios are much higher and the lime content much lower, in Australian coal ashes. Thus, the overall objectives of the present work are to obtain slag viscosity versus temperature data covering the range of ash/flux compositions for Australian coals, and from this to develop reliable methods for the prediction of slag viscosity and the type and amount of flux needed for adequate slag tapping from gasifiers using these coals.

EXPERIMENTAL

Coal Ash and Flux Mixtures

The overall strategy is to make viscosity measurements of melts covering the range of ash composition of NSW and Queensland bituminous coals. This preliminary study uses NSW coal ashes or fly ashes with ash flow temperatures comparable with the expected 1400-1500°C operating temperature range of a slagging entrained-flow gasifier. One coal sample with an ash flow temperature >1600°C was chosen for fluxing studies. Five coal samples were obtained from the CSIRO reference store of Australian coals, with one sample from the Gunnedah district, two from the Hunter and one each from the Newcastle and Western districts. Their properties are listed in Tables 1-2.

The ashes were prepared according to Australian Standard AS-1038.3-1989 and were pre-melted for the viscosity measurements. Table 1 gives the chemical composition in weight % for the major components of the ashes and the melts, the ash flow temperatures in a reducing atmosphere according to AS-1038.15-1987, and the silica/alumina, calcium oxide/alumina and ferric oxide/alumina ratios.

Four coal ash/calcium carbonate mixtures, (A=1/1, B=2/1, C=3/1 and D=5/1 by weight), were prepared using coal 5 and Unilab Laboratory reagent grade calcium carbonate. Table 2 gives the calculated compositions in weight % for the major components of the fluxed mixtures (on a calcium oxide basis) and analyses of the melts, the ash flow temperatures in reducing atmospheres and the oxide ratios.

Table 1

Coal Ash and Melt Compositions[#], Ash Flow Temperatures[*] and Oxide Ratios

	SiO_2	Al_2O_3	CaO	Fe_2O_3	Flow °C	S/A[+]	C/A	F/A
Ash 1	50.2	27.1	11.3	7.1	1380	1.85	0.23	0.54
Melt 1	46.2	25.1	11.2	6.4		1.84	0.24	0.54
Ash 2	45.5	27.7	11.1	2.8	1420	1.64	0.24	0.61
Melt 2	45.7	28.7	12.5	2.9		1.59	0.27	0.63
Ash 3	55.2	23	2.6	11.8	1400	2.4	0.05	0.42
Melt 3	53.7	22.6	2.9	12.9		2.38	0.05	0.42
Ash4	38.7	26	15	6.3	1360	1.49	0.39	0.67
Melt 4	39.2	27.8	15.1	6.4		1.41	0.39	0.71

Table 2

Fluxed Mixtures and Melt Compositions[#], Ash Flow Temperatures[*] and Oxide Ratios

	SiO_2	Al_2O_3	CaO	Fe_2O_3	Flow °C	S/A[+]	C/A	F/A
Ash 5	60	29	0.3	3.5	>1600	2.07	0.01	0.12
Mix A	38.4	18.6	36.1	2.2	1260	2.07	1.94	0.12
Melt A	39.9	19.6	37.2	1.1		2.04	1.9	0.06
Mix B	46.8	22.7	22.2	2.7	1410	2.07	0.98	0.12
Melt B	47.3	23.3	22.3	4.1		2.03	0.96	0.17
Mix C	50.5	24.5	16	2.9	1400	2.07	0.65	0.12
Melt C	52.5	26.2	17.1	0.6		2.01	0.65	0.02
Mix D	53.5	25.9	11.1	3.1	1400	2.07	0.43	0.12
Melt D	56.2	28.5	11.2	0.6		1.97	0.39	0.02

[*] Ash Fusion Temperatures by Carbon Consulting International Pty.Ltd., Newcastle.

[+] S = SiO_2, A = Al_2O_3, C = CaO, F = Fe_2O_3, [#] % w/w.

Viscosity Measurements

The viscosities were measured using a Haake-1700 high temperature rotational viscometer under a nitrogen atmosphere. Molybdenum rotors and crucibles were used for the the coal ash melts while graphite components were used for the fluxed mixtures. The melts were heated to about 100°C above the ash flow temperature, and viscosity measurements were taken at 30°C intervals while cooling until the melt recrystallized. The rotor speed, the torque on the rotor and the sample temperature , recorded with a type B thermocouple , were collected and processed by the Rotovisco Software.

RESULTS AND DISCUSSION

Composition

The sum of the weight percentages of the major components for the coal ashes (given in Table 1) approaches 100% , so that the equilibrium phase diagram for the quaternary silica/alumina/calcium oxide/iron oxide system should prove a reasonable model for their melt properties. Similarly, the values given in Table 2, where iron oxide is a minor component, show that the equilibrium phase diagram for the ternary silica/alumina/calcium oxide oxide system should model the fluxed mixtures.

An increase in weight percentages for the major components is observed from the ash to melt compositions due to the additional mass loss that occurs on heating the ash from the preparation temperature at 800°C to the ash melt temperature. One difference observed for the fluxing mixtures is the reduction, in weight per cent. of iron oxide, which separates out from the melt due to reduction to metallic iron by the graphite crucibles. Melt B did not show this behaviour, thought to be due contamination of the original sample by ferric oxide. Silica/alumina, iron oxide/alumina and calcium oxide/alumina ratios are shown in Table 1 for the ashes and melts and in Table 2 for the fluxing mixtures and melts. The small differences in the ratios for the ashes and melts and fluxed mixtures and their melts is due to the involatile nature of the major components, which means that the composition of the ashes and melts, when treated as a ternary or quaternary system, also alters little. Although predictions should be based on the melt compositions, the use of ash compositions should not lead to large errors.

Viscosity Measurements

The viscosity temperature relationships for the four coal ash melts are shown in Figure 1. The data may be fitted to an Arrhenius type expression. All display fluid behaviour over a wide temperature range and remain liquid below their ash flow temperatures (given in Table 1 and marked by arrows in Figure 1). These initial results serve to illustrate the range of slag viscosity values which can be encountered depending upon ash composition. The area for typical operating conditions for a slagging entrained-flow gasifier is defined by a temperature range of 1400-1500°C and by a viscosity value of 25Pa.s as the maximum value for satisfactory

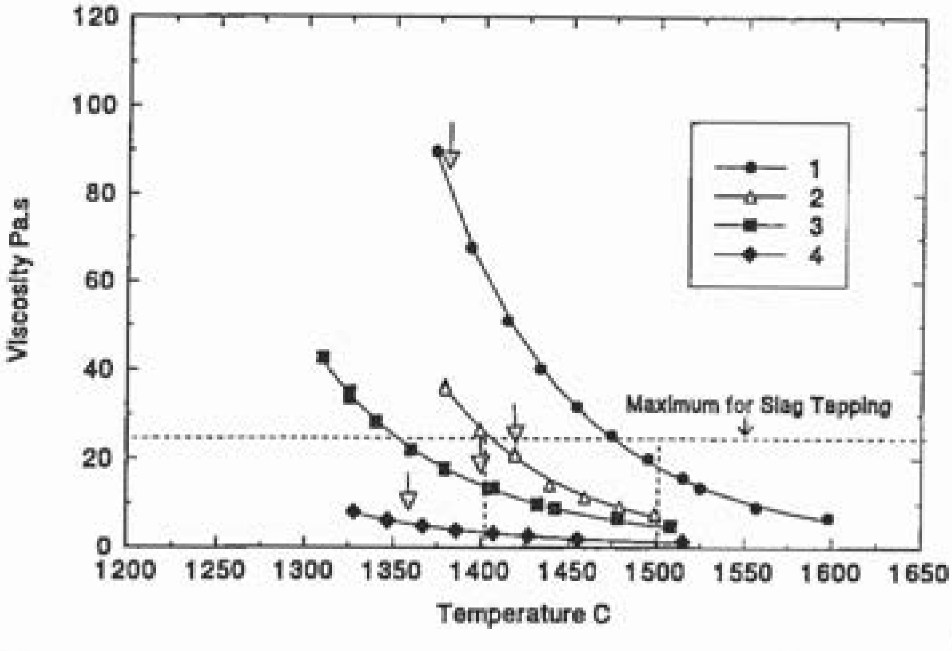

Figure 1 Viscosity-Temperature Relationships for Melts from Coal Ashes 1-4

slag tapping (dotted lines in Figures 1 and 2). Thus, it would be predicted that coal ash 1 would require a minimum temperature of 1475°C for slag tapping, whereas coal ash 3 might well be tappable at temperatures as low as 1350°C. If a tapping temperature of 1400°C were required for a particular gasifier, then coal ash 1 would need to be fluxed wheras the other three mav not.

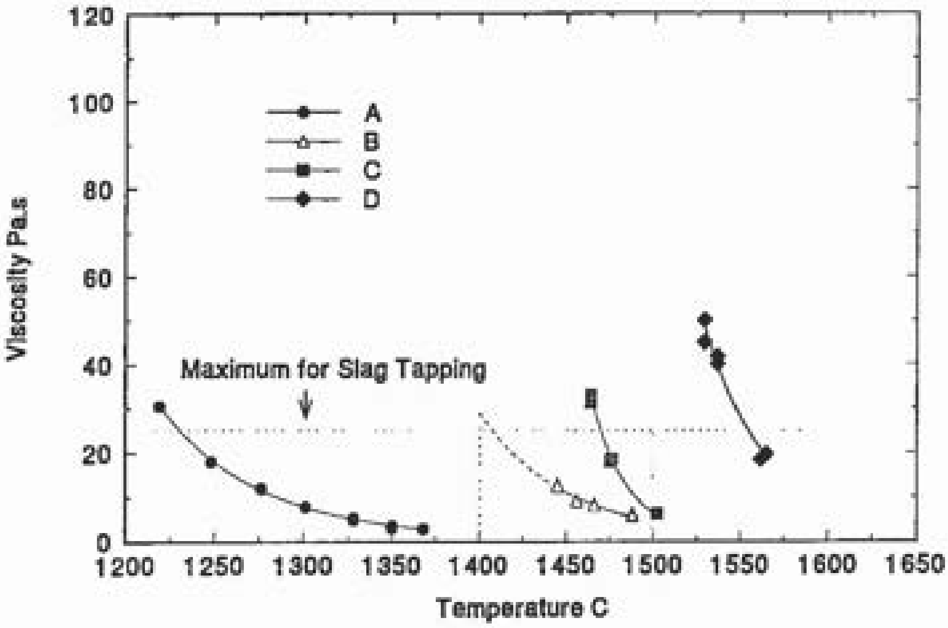

Figure 2 Viscosity-Temperature Relationships for Fluxed Mixtures from Coal Ash 5

The viscosity temperature relationships for the four mixtures of the Katoomba seam coal ash with calcium carbonate are shown in Figure 2. The data at higher temperatures were limited by the life time of the graphite crucibles, but illustrate the large changes in viscosity that occur with flux addition. From these results coal ash 5 would require an ash to flux ratio of between 2/1 and 1/1 for slag tapping at 1400°C. For this coal the ash content was 15.1%, and thus between 7.5% and 15.0% limestone (coal basis) would need to be added. If the tapping temperature could be increased to 1475°C then an ash to flux ratio of 3/1 (5% limestone on coal) might be possible.

VISCOSITY PREDICTIONS

The American[1,2] and British workers[3-5] proposed empirical viscosity relationships based on the chemical compositions of their coals. Since the silica to alumina ratio of Australian coals can often be much higher than those used in previous studies, it follows that viscosity prediction for the coal ash melts using these relations may be unreliable. Indeed, application of the British models[5,7] to ashes 1,2 and 3 leads to prediction of higher viscosity values than the actual data. A similar situation occurs for the viscosity prediction for fluxed coal ash melts, where the composition of the melts are different to the steel slags and glasses, on which the overseas models[8,9] are based. Predictions based on these models should be treated with some caution because of the extrapolations used, and this is stressed in software for the calculation of physico-chemical properties of slags[11].

In the present work, the Urbain model[9] has been modified using a least square fitting technique[12] of experimental viscosity measurements[13-14] of silica/alumina/calcium oxide melts at temperatures of 1450°C and 1500°C. The range compositions for the ternary system is silica (35-70 %w/w), alumina (0-25 %w/w) and calcium oxide (15-45 %w/w), which more closely resembles the compositions of fluxed Australian coal ashes. As in the simple Urbain model, iron oxide is considered as a fluxing agent.

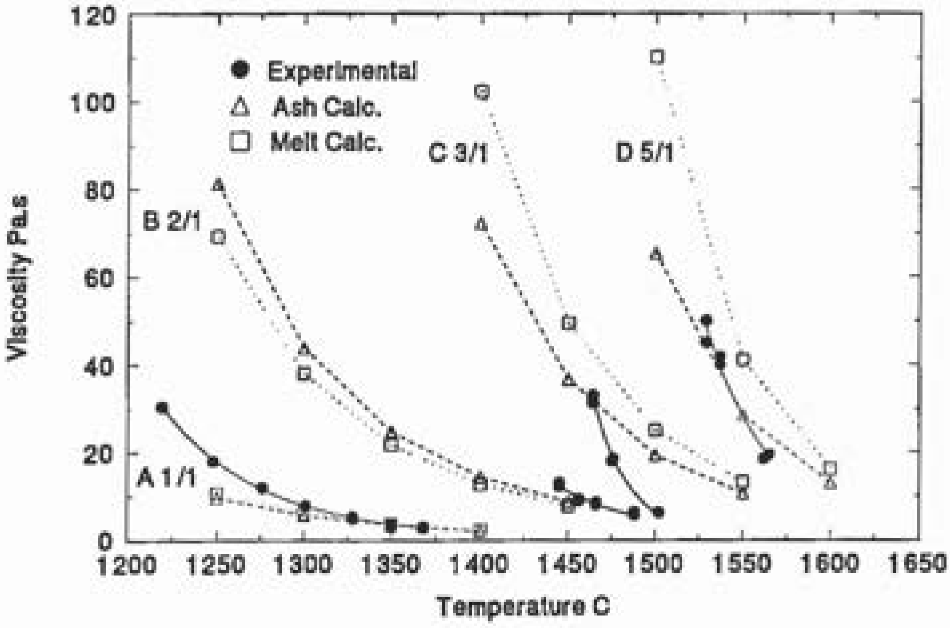

Figure 3 Experimental and Predicted Viscosities for Fluxing Mixtures

Examination of Tables 1 and 2 indicates that this model should not be used for the coal ash melts and strictly should only be applied to the fluxed melts A and B. The experimental data and the viscosity values predicted by the modified Urbain model from the fluxed mixture and the melt composition are shown in Figure 3. Better agreement is obtained for the two mixtures with higher flux, which have similar compositions to the model input data, whereas the mixtures with lower flux additions are outside the range of the data. The viscosity predictions made from the melt and ash compositions show some differences. Since these are small compared with the difference between the experimental and predicted values shown in Figure 3, viscosity predictions can be made using a composition calculated from calcium oxide addition to the coal ash composition.

The amount of fluxing agent used may also be calculated by consideration of the equilibrium phase diagrams for the ternary silica/alumina/calcium oxide system[10] where iron oxide is a minor component or for the quaternary silica/alumina/calcium oxide/iron oxide system[15]. The liquidus temperatures provide reasonable estimates for the ash flow temperatures, so that a composition for a flux mixture is chosen with a liquidus temperature close to the required operating temperature of the gasifier. The viscosity is then calculated to see whether it is suitable. This approach worked well in the present case but further results are needed on a range of ash compositions.

CONCLUSIONS

Although changes in chemical composition occur between the coal ashes and melts, the ratios of the major components remain unaltered. Thus, slagging predictions of ash fusion temperatures and viscosities can be made on the coal ash or slag compositions, as required.

Due to the complexity of the system, no completely satisfactory models are available for the prediction of coal ash slag viscosities. Although treatments based on the major components provide an indication, the effect of minor components cannot be discounted. The situation is more favourable for fluxing mixtures, where these effects are masked, and sensible estimates may be made from viscosity models based on equilibrium phase diagrams.

There is a need for a better predictive model for the viscosity of Australian coal ash melts, which often contain iron as a major component. The Urbain model treats iron oxide as a minor fluxing agent and hence is not applicable. Future work on a range of Australian coal ash melts should provide a data base to help rectify this.

This work suggests that reasonable predictions for slag viscosities and flux requirements may be made for the behaviour of fluxed mixtures in entrained flow gasifiers, using a modified Urbain model and equilibrium phase diagrams, respectively.

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