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TWENTY FIFTH NEWCASTLE SYMPOSIUM

on

"ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

12th to 14th APRIL, 1991

NEWCASTLE, NSW AUSTRALIA

DEPARTMENT OF GEOLOGY, THE UNIVERSITY OF NEWCASTLE, NSW 2308

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C.F.K. DIESSEL
CONVENOR

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

PREFACE

On 12th to 14th April, 1991, the University of Newcastle will once again be host to the "Newcastle Symposium on Advances in the Study of the Sydney Basin". This year's Symposium will be the 25th consecutive gathering of geologists from industry, academia and various research organisations, which makes it the most consistent annual function in Australia's geological conference calendar.

The first "Newcastle Symposium", as it is generally known, was held in 1965 in order to mark the transfer of the Geology Department from the rather cramped Tighes Hill site to the present building on the then newly-established Shortland campus. The success of this first meeting of some 60 geologists working in the Sydney Basin was such that at the end of the two day gathering, an invitation was issued to assemble in Newcastle again in the following year. Since then, the invitation has been repeated many times, and the Symposium has developed into an important vehicle for the exchange of scientific and technical information.

In spite of its growth in national status, the Symposium has retained the essential elements which assured its initial success. Most important among these is the relaxed atmosphere. It is true that any gathering of some 200 people from many parts of Australia requires a certain structure, however, most participants see the Symposium more as a workshop in which new ideas are aired, hypotheses are tested, and interesting geological observations are discussed before they find their way into national and international scientific journals in a much more polished form.

Although the conduct of the Symposium is not entirely informal, formality is low key and kept to a minimum. The planning and organisation of all events are carried out on a voluntary basis by members of the Geology Department. This has the added advantage, for the Symposium of still being affordable at a time when many other conferences have priced themselves out of the financial reach of potential participants.

Finally, let us not forget that the Symposium does not consist entirely of work. Once again, the Graduate Society of the Department of Geology caps the Friday excursion with a sheep roast, and the usual dinner takes place on Saturday night. In addition, there are tea and lunch breaks for people to meet each other, there are trade exhibitions, poster papers to view and other events that make the Newcastle Symposium not only a scientific forum but also an enjoyable social gathering.

Welcome to the 25th!

Claus F. K. Diessel
Convener

FOREWORD

Welcome to the 25th Newcastle Symposium on "Advances in the Study of the Sydney Basin". Despite the recession, support for this Symposium has been very strong, with 37 papers and numerous posters being offered, covering a wide variety of topics.

The Keynote Speaker is Mr Geoffrey Sharrock, Executive Director of Bayswater Colliery Company, who will be speaking on "Current issues in the Coal Industry", a topic of very great interest to us all.

The Excursion this year will concentrate on the Newcastle Coal Measures, fresh outcrops of which have been exposed in road cuts at Swansea and Seahampton. Engineering, structural and sedimentological aspects will be examined and discussed.

The Sheep Roast has again been organised by the Geology Graduates' Society and will be held in the University Union on the Friday evening, commencing at 6:30pm. It provides delegates with the opportunity to enjoy each other's company, exchange gossip – scientific and otherwise, and to partake of the excellent fare that is provided. On Saturday evening, delegates can renew acquaintances at the Dinner in the University Union. Something a little different has been organised by Claus Diessel for this occasion.

Late in 1990, Ian Plimer announced his intention to take up the Chair in the Department of Geology at Melbourne University. During the six years as Head and Professor of this Department, Ian made significant changes to the course structures, gave the Department a higher profile and fought a number of battles with the creationists. Many challenges will confront him in his new position – these he will take on with relish and we wish him well with them.

It is unlikely that the Chair will be filled, nor any additional staff appointed in the near future because of the severe budgetary constraints which currently prevail in the University. Hopefully, this will change in 1992 because increasing numbers of students are enrolling in geology courses, placing ever increasing burdens on our small number of staff, resulting in less time for the preparation of lectures and practicals, and for research. Only with additional staff can the Department remain as productive in research as in the past and provide the balanced degree course our students need to compete on the open market with graduates from other universities.

Claus Diessel, with the able assistance of Geraldene MacKenzie and staff, are to be thanked for their tremendous efforts in organising this, the Silver Anniversary of the Newcastle Symposium.

Robin Offler
Head of Department

PROGRAM

25th NEWCASTLE SYMPOSIUM

"ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

FRIDAY	**12 APRIL 1991**
12:30 - 17:30 **EXCURSION**	NEW OUTCROPS IN THE NEWCASTLE COAL MEASURES *Claus Diessel (Ncle University), Chris Francis (RTA), Konrad Moelle (ICR), Steve Summerell (RTA)* New road cuts in the Newcastle area have revealed interesting natural and mining induced structures in the Newcastle Coal Measures. The excursion will visit localities near Swansea and Seahampton, respectively, in order to discuss the origin of some of the phenomena and inspect the remedial measures taken in order to secure the road works. *Because access is restricted, there will be only one bus with a maximum of 65 participants.*
18:30 - 23:00	**UNIVERSITY OF NEWCASTLE GRADUATES' SOCIETY SHEEP ROAST**

SATURDAY	**13 APRIL 1991**	
08:30 - 09:00	**REGISTRATION** - Foyer of the Geology Department	
09:00 - 09:05 **Lecture Theatre B01**	**WELCOME** by the Head of the Geology Department, Associate Professor Robin Offler	
09:05 - 09:10	**OPENING** of the 25th NEWCASTLE SYMPOSIUM by the Vice Chancellor of the University of Newcastle, Professor Keith Morgan	
TECHNICAL SESSION 1	**LECTURE THEATRE B01** **Chair**	**David Branagan, Sydney University**
09:10 - 09:40	*Alan Day* *Sydney Univ.*	Geological interpretation of a gravity survey of the Newcastle region, with special reference to the 1989 Newcastle Earthquake.
09:40 - 10:10	*Mark Colwell* *ACIRL*	Demonstrating compatibility between residential development and longwall mining.
10:10 - 10:50	**MORNING TEA**	in the FOYER OF THE GREAT HALL
10:50 - 11:20	*Eric Lohe* *CSIRO*	An overview of the structural fabrics of the Sydney Basin and a comparison with the Bowen Basin.
11:20 - 12:00	*Geoffrey Sharrock* *Bayswater Colliery*	***** KEYNOTE ADDRESS ***** Current issues in the Coal Industry
12:00 - 12:20	DISCUSSION	
12:20 - 12:25	CHAIR	SUMMARY & VOTE OF THANKS
12:30 - 13:45	**LUNCH**	in the UNIVERSITY UNION

SATURDAY	13 APRIL 1991	
TECHNICAL SESSION 2A	LECTURE THEATRE E01 Chair	 Robin Offler, University of Newcastle
13:45 - 14:15	*Richard Evans & Albert Migliucci UNSW*	Evolution of the Sydney Basin during the Permian as a Foreland Basin to the Currarong and New England Orogens.
14:15 - 14:45	*David Briggs University of Melbourne*	Correlation charts for the Permian of the Sydney-Bowen Basin and the New England Orogen.
14:45 - 15:15	*John Roberts UNSW*	Calibration of the Carboniferous and Early Permian of the Southern New England Orogen by SHRIMP ion micro-probe zircon analyses.
15:15 - 15:45	AFTERNOON TEA	in the Foyer of the GREAT HALL
15:45 - 16:15	*Stirling Shaw Macquarie University*	Late Permian and Triassic igneous activity in the New England Batholith and contemporaneous tephra in the Sydney and Gunnedah Basins.
16:15 - 16:45	*Michael Vickers Univ. New England*	The Werrie Volcanics, Wingen NSW: geology, geochemistry and tectonic significance.
16:45 - 17:15	*Evan Leitch Univ. Technology Sydney*	Early Permian volcanism and Early Permian facies belts at the base of the Gunnedah Basin, in the northern Sydney Basin, and in the southern part of the New England fold belt.
17:15 - 17:45	*Bill Morris*	The Coffs Harbour Block - not an accretionary prism.
17:45 - 17:50	CHAIR	SUMMARY & VOTE OF THANKS
19:00 FOR 19:30	SYMPOSIUM DINNER	at the UNIVERSITY UNION

SATURDAY	13 APRIL 1991	
TECHNICAL SESSION 2B	LECTURE THEATRE B01 Chair	 Andrew Williams, FAI Mining
13:45 - 14:15	*Ivan Mumme CSIRO - Lucas Hts*	The effect of earthquakes on underground openings.
14:15 - 14:45	*Peter Willey ACIRL*	Alternative ways of analysing and displaying subsidence data.
14:45 - 15:15	*John Hanes BHP - Figtree*	Some challenges facing geologists in underground coal mining.
15:15 - 15:45	AFTERNOON TEA	in the Foyer of the GREAT HALL
15:45 - 16:15	*Rod Doyle BHP - Figtree*	Appin & Tower collieries in-seam rim surveys.
16:15 - 16:45	*Scott Thompson METS Pty Ltd*	Practical applications of the radio imaging method (RIM) from boreholes.
16:45 - 17:15	*Wayne Stasinowsky Mining Geophysics P/L*	Seismic resolution and small fault detection limits.
17:15 - 17:45	*Phil Schmidt CSIRO*	Orientation of drill core using palaeomagnetism in coal exploration.
17:45 - 17:50	CHAIR	SUMMARY & VOTE OF THANKS
19:00 FOR 19:30	SYMPOSIUM DINNER	at the UNIVERSITY UNION

SUNDAY	14 APRIL 1991	
TECHNICAL SESSION 3A	LECTURE THEATRE E01 Chair	 Brian Engel, University of Newcastle
09:00 - 09:30	*Albert Migliucci & Richard Evans UNSW*	Clay models of the northern Sydney Basin and southern Tamworth Belt, NSW.
09:30 - 10:00	*Victor Tadros Dept. Mins. & Energy*	Utility of coal seams as sequence boundaries in the non-marine Upper Black Jack Formation, Gunnedah Basin.
10:00 - 10:30	*Simon McDonald & Greg Skilbeck, U.T.S.*	Marine facies and their distribution, Permian Porcupine and Watermark Formations, Gunnedah Basin.
10:30 - 11:00	**MORNING TEA**	in the Foyer of the GREAT HALL
11:00 - 11:30	*Edwin Willey Univ. Coll. Sthn. Qld*	The geology of the Mt View — Mt Bright Inlier and adjacent rocks, Pokolbin, NSW.
11:30 - 12:00	*Jochen Kassan & Chris Fielding Univ Qld*	Triassic depositional environments in the south-west Bowen Basin.
12:00 - 12:30	*David Branagan Univ. Sydney*	Geology of the Pyrmont-Ultimo area, Sydney.
12:30 - 13:00	*Colin Murray-Wallace Univ Newcastle*	Quaternary correlations using amino acid racemisation : the Sydney Basin province in a global context.
13:00 - 13:05	CHAIR	SUMMARY & VOTE OF THANKS
13:05 - 14:15	**LUNCH**	in the UNIVERSITY UNION

SUNDAY	14 APRIL, 1991	
TECHNICAL SESSION 3B	LECTURE THEATRE B01 Chair	 Philip Seccombe, University of Newcastle
09:00 - 09:30	*Peter Flood Univ New England*	Natural zeolite exploration using the "Geoautoclave process" model for their formation.
09:30 - 10.00	*Bill Fraser UNSW Oatley*	Geological control of the spatial distribution of Aboriginal sites in the Royal National Park, NSW — initial findings.
10:00 - 10:30	*Phillip Hitchcock D.J.Douglas & Partners*	The electrical conductivity probe : a new tool for groundwater contamination and salinity measurement.
10:30 - 11:00	**MORNING TEA**	in the Foyer of the GREAT HALL
11:00 - 11:30	*Gang Li & K. Moelle, Univ. Newcastle*	Fracture behaviour of sandstones — a comparison of samples from the Sydney and Bowen Basins.
11:30 - 12:00	*Richard Evans UNSW*	Early Permian palaeogeography of the southern Sydney Basin
12:00 - 12:30	*Bülent Agrali Austen & Butta Ltd*	From bore cores and strip samples to coal processing plant scheduling — a practical approach.
12:30 - 13:00	*Andrew Falkner & Chris Fielding, Univ Qld*	Applications of sedimentology to longwall underground coal mining.
13:00 - 13:05	CHAIR	SUMMARY & VOTE OF THANKS
13:05 - 14:15	**LUNCH**	in the UNIVERSITY UNION

SUNDAY	14 APRIL, 1991	
TECHNICAL SESSION 3C	LECTURE THEATRE G04 (Geology Building) Chair	 Tom Callcott
09:00 - 09:30	*Geoff Taylor* *RSES/ANU*	Reflections on reflectance.
09:30 - 10:00	*Ron Wilkins et al.* *CSIRO*	The suppression of vitrinite reflectance in the Greta and Pelton coals : a fluorescence alteration study.
10:00 - 10:30	*John Wilmshurst* *CSIRO*	A new instrumental method for the assessment of coking coal.
10:30 - 11:00	MORNING TEA	in the Foyer of the GREAT HALL
11:00 - 11:30	*Judy Bailey* *Univ. Newcastle*	Combustion characteristics and char evolution of vitrinite and inertinite-rich coal concentrates.
11:30 - 12:00	*Michelle Smyth* *CSIRO*	Coal petrology, natural fractures and methane drainage of Sydney Basin coals.
12:00 - 12:30	*Claus Diessel* *Univ. Newcastle*	The 1991 ICCP Ring Analysis — an interesting comparison of two coals and their cokes.
12:30 - 13:00		Discussion of the 1991 Ring Analysis
13:00 - 13:05	CHAIR	SUMMARY & VOTE OF THANKS
13:05 - 14:15	LUNCH	in the UNIVERSITY UNION

GEOLOGICAL INTERPRETATION OF A GRAVITY SURVEY OF THE NEWCASTLE REGION, WITH SPECIAL REFERENCE TO THE 1989 EARTHQUAKE

A.A. DAY
University of Sydney

INTRODUCTION

The Newcastle earthquake on 28 December, 1989, emanated from a focus 11.5 km below the Boolaroo-Cockle Creek area (McCue et al, 1990). Only one aftershock was recorded, frustrating the hope that it might be possible to identify the active crustal fracture from the distribution of aftershocks. Earthquakes had previously occurred in the region in 1837-41, 1868 and 1925. The seismological and geological presumptions that faulting was responsible for these earthquakes and that the causative stress-field must have persisted for possibly several million years, imply that cumulative displacement amounting to some hundreds of metres may have affected one or more "marker" horizons. If any such marker had a distinctive density and lay within about the top three kilometres of the crust, it should be possible to detect its displacement by a steep fault from the characteristic "bipolar" gravity signature of a fault. A marker horizon of distinctive density which immediately suggests itself is the Lochinvar Formation, composed largely of basic volcanics. A less easily detectible marker might also be provided by the presumed Carboniferous bedrock surface underlying the Lochinvar Formation.

The only published gravity data in the Newcastle region were about ten values obtained by the BMR in the course of its Australia-wide helicopter-borne survey (BMR 1:500,000 Gravity Maps). To the west, there was a regional gravity net along some of the main roads across the Lochinvar Dome observed and discussed by Ali Nalaye in the 1970s (Nalaye, 1977). The author therefore undertook a detailed gravity survey of the region.

THE GRAVITY SURVEY

The gravity survey was commenced seven days after the earthquake, and initially concentrated on the inner metropolitan area of Newcastle where the greatest damage had occurred and where preliminary seismological studies suggested the epicentre lay. In March 1990 revised epicentres were available and the gravity survey was extended to the west and south. As the major gravity anomaly features of the region came to light additional work was done to increase the station density, and readings were taken north of the Hunter River estuary in the hope that additional light might be shed on some of the more difficult problems of interpretation which had emerged. In all, about 1400 gravity stations were occupied. The results from about 1100 of these are discussed in this paper.

The Bouguer anomalies are based on the BMR's "Isogal-84" system, absolute values being derived from the BMR stations Sydney-A and Wahroonga-CS2 (Wellman et al, 1985). Density adopted for the Bouguer reduction was 2400 kg/m^3. Terrain corrections on the Hammer system were applied when required (amounting to 60 g.u. for stations on the

Sugarloaf Range). Anomalies are expressed in $\mu m/s^2$, referred to for convenience as "gravity units" or g.u.

From density values for relevant lithologies, the bulk densities of strata in the area are estimated to be: Carboniferous, 2600; Lochinvar Formation, 2700; all other Permian, 2400; Quaternary, 1800 kg/m^3. In the discussions of anomalies these densities are expressed relative to the "all other Permian" (being the dominant volume) as +200, +300, 0, and -600, respectively.

PRINCIPAL GRAVITY ANOMALY FEATURES OF THE NEWCASTLE REGION

To facilitate their discussion, the principal anomaly features are named as follows:

The Coastal Gravity Gradient essentially paralleling the coast and expressed in a coastward increase of about 20 g.u. in anomalies.

The Cockle Creek Gravity Gradient which extends 20 km north-northwesterly from Warner's Bay towards Heddon Greta, and involves a decrease of about 40 g.u. to its west side.

The Fassifern - Heddon Greta Gravity Trough which lies between the Cockle Creek Gradient and less continuous gravity gradients to the west, near Mulbring and Awaba.

The Windy Hill - Islington Gravity Ridge identified by a chain of individual anomalies 3 to 5 g.u. above the surrounding values.

The Sandgate - Mayfield Gravity Ridge similar to the preceding ridge, but less extensive.

REGIONAL CHARACTER OF GRAVITY PROFILES ACROSS THE NEWCASTLE REGION

The anomalies found are all positive and range from minimum vales of 176 g.u. to a maximum of 283 g.u., a range of nearly 110 g.u. The average value, about 230 g.u. suggests that the crust may be slightly thinner than standard, and/or possesses a slightly greater bulk density than standard. The latter is supported by the seismic refraction results of Finlayson and McCracken (1981).

Because Newcastle is situated close to the northeastern limit of the preserved part of the Sydney Basin, where the Permian and Carboniferous geology at depth may be reasonably accurately predicted, it appears useful to compare anomaly profiles with the Sydney region (Figure 1; author's own data). The profiles are keyed to the presumed eastern limit of continental crust defined by the foot of the continental slope. The Coastal Gradient in the Newcastle region comprises about 50 g.u. eastward from Toronto, and only 20 g.u. or so, near Newcastle City (with slight fluctuations possibly due to the Delta Syncline structure in the Newcastle Coal Measures). The rise in the gradient at Sydney exceeds 400 g.u.. It is clear in Figure 1 that the Toronto and Sydney gradients both commence at about 120km distance inland from the continental margin,the gradient at Newcastle being less well sampled due to the wide continental shelf.

Inland, the general level of the Newcastle anomalies is similar to the maximum reached by the gravity high in the western Sydney district. Since a regional level of 240 g.u. in the west of the Newcastle region is associated with thick Lochinvar Formation basic volcanics (e.g. East Maitland No. 1 intersection: 1000m) it appears that the western Sydney gravity high may also be due, at least in part, to the presence of thick Lochinvar volcanics at depth. A detailed discussion of this point is inappropriate here, but the author's intepretation of the origin of the western Sydney gravity high differs somewhat from that expounded by the late Dr. Ifti Qureshi (Qureshi, 1984, and earlier papers).

The similarity of the descending western boundary gradients is interesting, but probably coincidental, because the gradient west of Sydney passes well to the west of the Newcastle example (BMR 1:500,000 Gravity Maps).

THE COCKLE CREEK GRAVITY GRADIENT

The gradient in the vicinity of Argenton and Edgeworth reaches 9 g.u. per km., and has a range of 42 to 45 g.u. Application of Smith's rule (Smith 1959) leads to an estimate of the maximum depth of the causative density contrast as 3 km. Trial fitting of curves calculated for a model involving a near-vertical fault displacing the Carboniferous basement shows that this displacement must be close to 500 m, eastern block up. Introducing a similar fault displacement in the Lochinvar layer, assumed 800m thick, helps to improve the fit to the observed profile, but the best fit is only obtained with the Carboniferous basement in the upthrown block at a depth of 1000m (or less), i.e. only 200m of "all other Permian" is allowed for, meaning the Maitland Group and Tomago Coal Measures are essentially missing. If the thickness of the Lochinvar layer is halved, its contribution to the fit is halved and the basement must be raised, leading to much the same conclusion but allowing a thickness of not more than 200m of Permian strata beneath the Newcastle Coal Measures. The supposition of a substantial thickness of coal (50m or more, in the Dempsey Formation?) preserved on the western block would assist in explaining the gravity gradient.

That there were in excess of 2000m of Rutherford to Tomago strata deposited in this area is implicit in all published isopach and depositional environment reconstructions (e.g. Mayne et al 1974). Thus the gravity interpretation implies uplift and substantial erosion of the block east of the Cockle Creek Gravity Gradient prior to the deposition of the Waratah Sandstone.

A less plausible alternative interpretation would require a near-vertical density boundarywithin the Carboniferous basement whereby dense mafic lithologies not seen in outcrop are supposed to underlie the eastern block; there are no magnetic anomalies in the area which could justify this supposition. A seismic reflection study is required to provide independent evidence of the deep structure.

In the vicinity of Warners Bay the Cockle Creek Gravity Gradient veers south-southwestwards and joins the Coastal Gradient. Additional work planned for the Swansea-Wangi area may determine whether the deep structure proceeds under the continental shelf or parallels the central Macquarie Syncline.

THE FASSIFERN - HEDDON GRETA GRAVITY TROUGH

The trough reaches a minimum in the Killingworth area, with a subsidiary minimum near the former O'Donnelltown. There is a broad correspondence with the axis of the northern Macquarie Syncline as mapped by Branagan and Johnson (1970) (or in greater detail by Branagan, 1962). But the agreement is not exact, for example the axis of the Syncline cuts obliquely across the gravity contours around Toronto and passes east of the Killingworth minimum. Moreover the syncline deepens steadily south-southeastwards from the Great Sugarloaf area, whereas the gravity anomalies have their minimum at Killingworth and then rise gently to the south-southeast. Lastly, the Gravity Trough extends west to Mulbring and Freeman's Waterhole, 3 to 4 km beyond the western limb of the Syncline.

At Fassifern the axis of the Macquarie Syncline is 300m below sea-level. Assuming that this depth has been achieved by an equal amount of sag in the Carboniferous basement, the gravity effect of the Newcastle Coal Measures is about 22 g.u. The Gravity Trough is here about 35 g.u. below the top of the bounding gradient (at 230g.u.). Thus the thickness of

Newcastle Coal Measures in the Syncline is insufficient to explain the whole amount of the Gravity Trough, and the lateral extent of the two structures is significantly different.

An important feature of the Gravity Trough is that it extends to Heddon Greta, and perhaps further northwest. Thus, in geological terms, the Trough extends beyond the boundaries of the Newcastle and Tomago Coal Measures, crosses the Buchanan Monocline obliquely and reaches the Greta Coal Measures outcrop. This relationship suggests that there is a belt of locally thicker Early Permian strata beneath the younger rocks. In their synopsis of the Rutherford and Farley Formations, Mayne et al (1974, Fig. 14) postulate a thick section extending south-eastwards through the present area. It appears reasonable to conclude that the 12 to 20 g.u. of the Fassifern - Heddon Greta Gravity Trough not explained by the Newcastle Coal Measures in the Macquarie Syncline arise from the thickened Rutherford & Farley Formations below. Since the gravity trend follows Surveyor's Creek, and no name for the sedimentary trough is known to the author to exist, it is suggested it be called *The Surveyor's Creek Trough*.

BEARING OF THE GRAVITY ANOMALIES ON THE EARTHQUAKE'S POSITION AND MECHANISM

The foregoing analysis shows that there is probably a major near-vertical fault of Permian age underlying the Cockle Creek area. The epicentres of the earthquake and its aftershock published by McCue et al (1990) fall either side of Cockle Creek, between the Stockton Borehole Mine and Boolaroo, about 2 km west of the interpreted fault trace. McCue et al's focal mechanism solution indicates that the principal movement at the focus was thrusting along either a fault-plane dipping 75 degrees toward 060 degrees, or a fault-plane dipping 32 toward 190 degrees (these planes are orthogonal, following the principles of the widely adopted "double-couple" model of the focal mechanism). The former, steep, thrust if continued to the ground surface would outcrop between Booragul and Fennel Bay. The latter, shallow angle, thrust would outcrop near Woodberry. However, as far as the author is aware, no evidence of ground fracturing has been discovered, neither has any significant change in ground elevation been identified.The strike of the steeper-dipping fault plane in the focal mechanism solution agrees to within 10 degrees with the trend required for the fault interpreted from the gravity anomalies. It is therefore suggested that the earthquake (and its antecedent in 1925) originated in the Permian fault which had been re-activated in the Cainozoic, perhaps during the documented passage of eastern Australia over a sea-floor spreading centre in the Late Tertiary.

GRAVITY GRADIENT ASSOCIATED WITH THE BUCHANAN MONOCLINE

In mapping the northwestern extent of the Fassifern - Heddon Greta Gravity Trough, two profiles were obtained across the Buchanan Monocline. The gravity anomaly variation across the monocline outcrop clearly resembles that of a buried thrust dipping west at about 45 degrees and displacing the dense Lochinvar Formation. This conclusion supports that put forward by Blayden many years ago (e.g. Blayden 1971).

EVIDENCE FOR DEEP QUATERNARY EROSION CHANNELS NEAR HEXHAM

A gravity profile with stations at about 200-metre intervals was obtained across the low-lying area near Hexham. Readings were obtained with some difficulty due to the constant heavy vibration caused in the springy alluvium by unceasing truck traffic. Two localised lows were found, 10 and 12 g.u. below an estimated regional value for bedrock. The results are shown in Fig. 2. Galloway (1965) and others have presented evidence that the Pleistocene course of the Hunter River passed to the sea *north* of the Tomago high ground. The discovery of <u>two</u> 40 to 50m deep channels at Hexham is interpreted to indicate that the northwestern one carried the Blue Gum Creek drainage and the southeastern one carried the Ironbark Creek drainage, as shown in the Figure. Since the anomaly minimum over the southeastern channel is lower than that over the other channel, it is possible that the southern channel is the deeper, perhaps due to some part of the Blue Gum Creek drainage also being carried through it.

BROAD, SMALL AMPLITUDE HIGH NEAR AWABA

This anomaly is only discernible on the anomaly map as a loop in the 200-g.u. contour due to the accident that the anomalies increase somewhat irregularly from about 198 to 203 g.u. The high has a range of 5 to 6 g.u. It is perhaps significant that a 7 km-long, northerly trending dyke traverses the area (Bryan, 1966). A dyke of such length could have associated with it as feeder a deeply buried sill, which could explain the gravity anomaly. The author carried out magnetometer traverses in an attempt to locate this dyke, but without success. It would be interesting to see whether structure contours in the Awaba State Mine area reveal any local arching of the strata produced by the inferred sill.

THE WINDY HILL - ISLINGTON AND SANDGATE - MAYFIELD GRAVITY RIDGES

In the northeastern segment of the area anomaly gradients are sufficiently low to reveal a degree of fine structure in the anomalies. Locally high values, about 3 to 5 g.u. above the general anomaly level, occur in two readily identifiable, slightly curved belts trending approximately southeast.The two anomaly ridges evidently reflect the presence of elongated strips of rock having a density slightly greater than that of the adjacent material. However, because the amplitude of the two ridges is small it is impossible to deduce the depths or attitudes of the causative bodies. The anomaly ridges may identify the upper edges of thin (100 to 200m) sheets such as clusters of basaltic dykes, or buried sills; although they do not bear any obvious relationship to the abundant post-Permian dykes in the region. Just possible is a derivation from the eroded sub-crops of lava sheets within the Lochinvar Formation assuming an episode of folding and subsequent erosion prior to deposition of the Dempsey Formation. Also just possible is a derivation from thrust faulting of dense layers at depth.

SPECULATION ON EVIDENCE FOR A SOUTHERLY EXTENSION OF THE WILLIAMS RIVER FAULT

Perusal of the The disposition of the anomaly features in the northwestern part of the anomaly map suggests the speculation that the anomaly pattern in the northwestern segment is displaced dextrally with respect to the southeastern segment. A straight line can be drawn between the two suggested segments, as shown on Figure 3, and a sinistral displacement of 1.5km appears to place the two anomaly patterns in a simpler relationship to one another. In addition to the broader features, it may be noted that a local anomaly high occurs near Leneghans Flat, and, given the sinistral restoration suggested, this high then aligns with the Windy Hill - Islington Gravity Ridge to the southeast.

In isolation, proposal of this line of displacement would be difficult to justify, but its northeasterly trend passes through the buried deep channel of the Pleistocene Blue Gum Creek discussed above, extrapolates along a deeply eroded segment of the Hunter River's Pleistocene channel, passes just west of Raymond Terrace and is approximately on line with the Williams River Fault. The relative motion of the western block on the Williams River Fault, essentially dip-slip, has produced in the dipping Carboniferous strata a dextral displacement of outcrop pattern comparable with that discerned in the gravity anomalies.

If the supposed line of displacement is accepted as a fault (whether dip-, oblique- or strike-slip being undetermined) its activity must have occurred after the Surveyor's Creek Trough had developed and prior to the Tomago Coal Measures deposition, i.e. in the mid-Permian (?early in the D1 deformation phase of Collins (1990)).

SUMMARY OF GEOLOGICAL EVENTS DEDUCED IN THIS PAPER

EARLY PERMIAN - "Surveyors Creek Trough" active in Rutherford and probably Farley time.

MID PERMIAN - Eastward under-thrusting produces Buchanan Monocline which deforms northwestern margin of Surveyors Creek Trough.
NNW-trending near-vertical fault accompanies uplift of Minmi - Warners Bay block by 500m; deep erosion of top of block.

MID to EARLY LATE PERMIAN - NNE-trending faulting possibly an extension of and associated with a phase of movement on the Williams River Fault; cuts Surveyors Creek Trough.

QUATERNARY - Erosion of two deep stream channels near Hexham, probably by Blue Gum and Ironbark Creeks flowing north to join the Hunter River north of Tomago.

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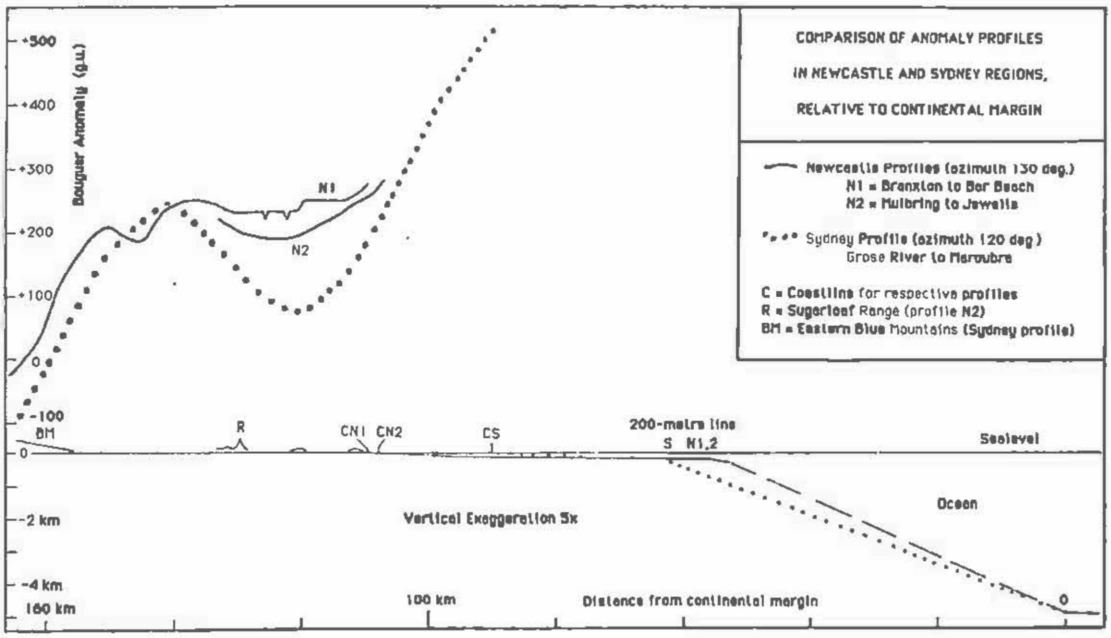

FIGURE 1. Comparison of gravity profiles in Newcastle and Sydney regions perpendicular to the continental margin.

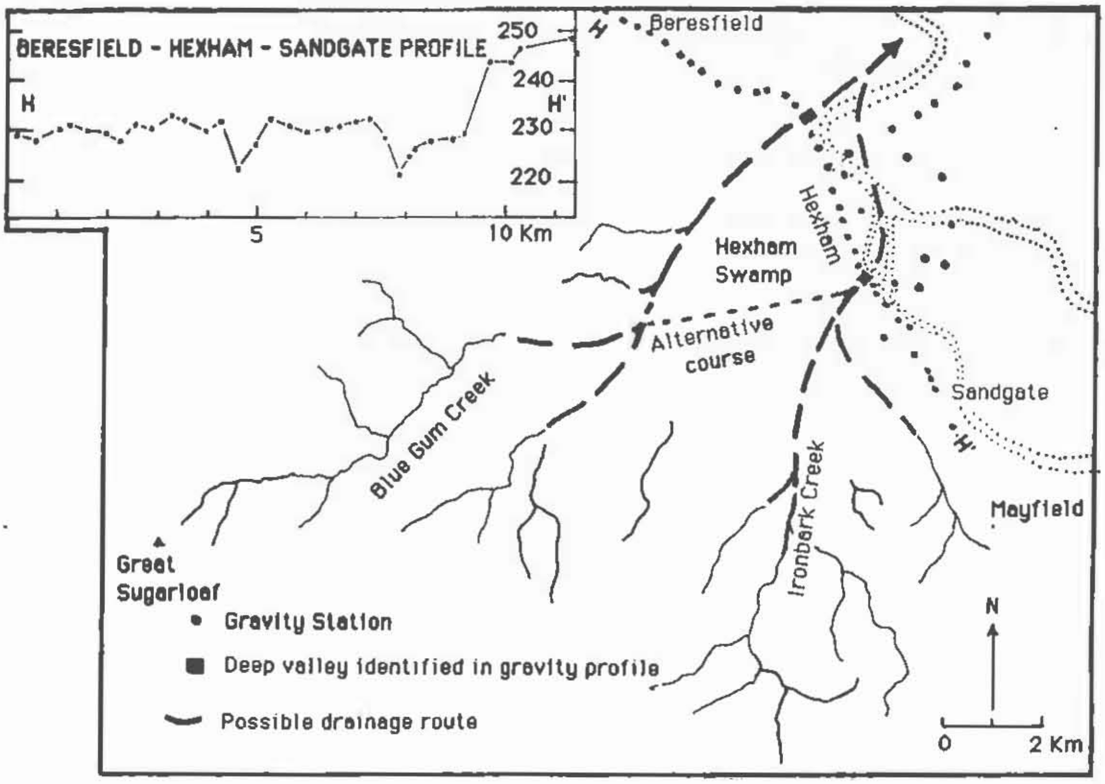

FIGURE 2. Beresfield - Sandgate gravity profile identifying two deeply eroded channels beneath the modern alluvium near Hexham.

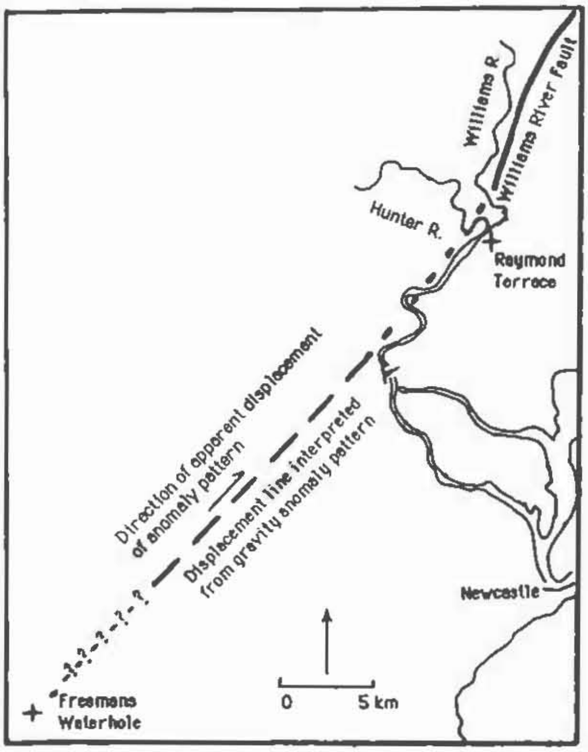

FIGURE 3. Displacement line interpreted in anomaly pattern and its possible connection with the Williams River Fault. The highly speculative extension southwest towards Freeman's Waterhole is to question a possible association with thrusting in that area reported by Moelle and Branagan at the 1988 Symposium.

IMPROVING THE COMPATIBILITY BETWEEN LONGWALL COAL MINING AND RESIDENTIAL DEVELOPMENT

R.W. SEEDSMAN & M. COLWELL
ACIRL Ltd, Corrimal

1. INTRODUCTION

ACIRL are acting as project managers for a NERDDC, NSW Coal Association, and Mine Subsidence Board project to develop and demonstrate means by which there can be greater compatibility between underground coal mining and surface land use for residential purposes. This greater compatibility should allow the degree of coal sterilisation to be minimised. Support to the project is being provided by Elcom, Newcom, and BHP Collieries, FAI Mining, and the Department of Minerals and Energy. The three major objectives of the project are:

(i) Develop and demonstrate new and more appropriate designs, techniques, and materials for structures subject to subsidence.

(ii) Demonstrate the effects of mine subsidence on conventional and and new housing designs

(iii) Provide comprehensive, well documented evidence to all intersested parties.

2. WYEE EXPERIMENTAL SITE

This stage (the first) of the project was carried out over Longwall 4 at Wyee State Mine between July and October 1989. Longwall 4 was 250 m wide and extracted 3.1 m of the Fassifern Seam at a depth of 200 to 210 m below the surface. Total pillar extraction had previously taken place in the Great Northern Seam which is approximately 39 m above the longwall panel. Maximum subsidence over Longwall 4 was recorded to be 1.9 m. Maximum compressive strains of 6 mm/m (longitudinal) and 6 mm/m (lateral) were recorded. Maximum tensile strains of 2 mm/m (longitudinal) and 5.4 mm/m (lateral) were also measured.

Two test walls, built in July 1989, to simulate typical brick veneer residential construction were monitored before, during, and after the face passed underneath the site. One wall was constructed on a conventional concrete strip footing, the other on an experimental footing designed to protect the structure from ground strains due to mine subsidence. The walls were built parallel to, and straddling, the panel centre line. Extensive surveying of surface stations, using conventional survey techniques as well as strain triangles, was carried out to determine the pattern of ground movement.

The test walls showed no response during the tensile phase, however a near vertical crack (approximately mid-way along the length) in both walls developed above the damp course during the compression phase. After the trial, the footings were excavated and it was found that a near vertical crack had developed along the full length of the unprotected footing and that this crack extended vertically one and a half brick courses upwards.

The brick walls above the dampcourse failed in bending. It would appear that the cracking occurred at a much lesser degree of footing curvature (1 in 3000 approximately) than the values expected from the literature which are closer to 1 in 1000. The inference is that the brick/mortar combination used was unusually brittle and that consideration should be given to the development of more flexible mortar.

Calculations show that the failure of the unprotected wall footing in tension cannot be explained by the bending strains measured. It is probable that tension was introduced into the footing during the relaxation of the compression strains, and that the footing failed from this cause.

3. WEST WALLSEND SITE

For the 2nd stage of the project a conventional brick veneer house was constructed on the centre line of Longwall 3, West Wallsend Colliery. The aim is to demonstrate to all interested parties, and especially the general public, the effects of longwall mining on residential dwellings.

Longwall 3 was 134 m wide and extracted 2.3 m of the Borehole Seam at a depth of 200 m. During the last complete survey (7th December 1990) with the longwall face approximately 500 m past the house the maximum recorded subsidence near the house was 300 mm. The maximum recorded compression and tensile strains were 2.6 mm/m and 2.9 mm/m respectively.

However the maximum tensile strain was not recorded during the anticipated tensile phase of the subsidence wave (ie as the face approaches the house), it being less than 0.5 mm/m. The strain of 2.9 mm/m was recorded when the face was approximately 710 m past the house site (21/12/90). It is thought that soil shrinkage is the cause of this increase in tensile strain. This belief is further reinforced due to the general relaxation of compressive strain around the house.

Only superficial damage to the house has been recorded. Two doors jammed and a join between two plaster sheets opened. Externally some minor cracking of the brickwork, concrete pathways and garden edges has been observed.

Soil conditions at the site have been classified as Extremely Reactive. (As 2870 - 1986). Monitoring will continue to determine the effects of soil movements on the house.

4. EXPERIMENTAL CONCRETE SLAB

An ideal footing system for brick veneer dwellings in subsidence areas would be isolated from ground strains, unaffected by ground curvature, able to be relevelled, and have little if any additional cost associated with it. After an extensive review of options, the "Pod Lok" system for concrete slab construction has been identified as having great potential. The system uses a series of box formers and spacers to build a slab on a sand base above the ground surface.

Modifications to the "Pod Lok" design and the design of jacking points for relevelling have been conducted. A trial slab (8 m x 8 m) was cast on a 37 mm/m slope to test the design assumptions and trial the jacking system. This slab has since been successfully relevelled.

5. FUTURE WORK

The final stage of the project will involve the construction and undermining of a brick veneer/concrete slab dwelling which incorporates features to allow it to be relevelled. Both structural and minor, but still critical, detailing techniques will be demonstrated. Subsidence levels will be in excess of those set down in the Smith/Clough report - viz, 600 mm subsidence.

6. ACKNOWLEDGEMENTS

Lee Appleyard and Associates and Coffey and Partners International are acting as structural and foundation engineering consultants respectively to the project. The West Wallsend house was founded by the Mine Subsidence Board. The majority of funds are provided by NERDDC Project No 1355. The support offered by local coal mining companies and local government is gratefully acknowledged.

AN OVERVIEW OF THE STRUCTURAL FABRICS OF THE SYDNEY BASIN, AND A COMPARISON WITH THE BOWEN BASIN

E.M. LOHE & T.P.T. McLENNAN
CSIRO Division of Geomechanics

INTRODUCTION

The Sydney Basin represents the southern section of the Sydney-Gunnedah-Bowen Basin system, a major depositional feature containing dominantly Early Permian to mid-Triassic sediments and volcanics. The basinal sequence has been affected by a variety of post-depositional deformations, principally expressed by episodes of faulting. The purpose of this study is to review the general characteristics of these structures, to define their regional distribution and significance, and to identify, if possible, a sequence of tectonic events relative to each other, and some indication of their geological ages.

It is necessary to acknowledge that numerous workers have collected structural data in the Sydney Basin, and have provided evidence for, and suggestions about the sequence of structural events and their possible origins, so we are not necessarily proposing concepts which are entirely new. However, the CSIRO study on the structure and mining conditions of the Sydney Basin coalfields and other recent studies have provided much additional structural data, so it is timely to undertake an overview the post-depositional deformational history of the basin.

SUMMARY OF REGIONAL STRUCTURAL FABRICS

Newcastle Coalfield

The Newcastle Coalfield is characterised by a series of broadly N-S to NNW trending gentle folds, which are, from east to west, the Macquarie Syncline, an anticline in the vicinity of Morisset and Awaba, the Yarramalong Syncline, and the Kulnura Anticline (Crapp & Nolan 1975). They plunge gently to the south, and dips on the limbs are generally about 3-4°. A set of folds with east-west axes, and forming shallow dome-and-basin structures, is also present, especially in the northern section of the coalfield (Crapp & Nolan 1975).

Normal Faults

NW to NNW trending normal faults are the dominant fault type in the Newcastle Coalfield. They typically have steep dips, and vertical displacements mostly less than 6m, but reaching 15m (Crapp & Nolan 1975). N to NNE trending normal faults represent the other major type of normal faulting. These faults are less frequent than the NW-trending faults, and commonly appear to be confined to fairly discrete zones up to 1km wide, e.g. in the Chain Valley-Wallarah area. Normal faults oriented WNW also occur in the Newcastle Coalfield.

Thrust Faults

Thrust faults and bedding-parallel shearing have been identified in a number of area in the Newcastle Coalfield, although in comparison to the normal faulting they are generally relatively minor in both occurrence and deformational effects. Thrusts have been identified in a number of orientations: a). N-NNE, e.g. in Gretley have a number of NNE-trending thrusts with senses of displacements to both east and west. Similar thrusts occur in the Wallsend North open pit to the north of Gretley Colliery; b) NW-trending thrusts; c). ENE-trending thrusts, e.g. Freemans Waterholes, Pelton/Ellalong Colliery (Moelle &

Branagan 1988), and WNW-trending thrusts (e.g. Gretley Colliery).

Dykes

Dyke swarms trending NW to NNW are a characteristic feature of the Newcastle Coalfield. That is, they are parallel or sub-parallel to the major normal fault set. Dykes are also parallel to the NNE and WNW fault orientations, and in some areas appear to be concentrated in zones of faulting. The dykes of the Newcastle Coalfield are generally considered to be mostly Early Tertiary (e.g. Rickwood 1985).

Sydney Region

A variety of structural features have been identified in the Triassic rocks of the Sydney region, principally the Hawkesbury Sandstone and Wianamatta Group. It is marked by gentle folding with NNE to NE axial trends (Branagan et al. 1988), and by normal, reverse, and some strike-slip faults. Most faults occur in fairly discrete zones of deformation (Norman & Branagan 1984). Normal faults occur in a number of orientations, but faults trending NW, N-NNE, and NE appear to be the most common (Norman & Branagan 1984; Branagan 1985). Thrust faults occur in the Sydney region in a number of orientations, ranging from NW, N-NNE, and NE, with some occasional more E-W oriented thrusts. Most are low-angle or bedding-parallel structures (Branagan et al. 1988). Available information suggests that the N-NNE structures are probably the most important. Branagan et al. (1988) correlate their development with the formation of the NNE-trending folds. The Sydney region is also characterised by sub-vertical NNE-trending shear zones, which parallel an important joint direction (Norman & Branagan 1984). The dominant movement appears to be strike-slip, although some normal and reverse displacements may also be present. The shear zones are relatively late structures, and apparently postdate the normal and thrust faulting.

Southern Coalfield

The Southern Coalfield is located over the Woronora Plateau of the Sydney Basin. The plateau is bounded to the east by the coastal escarpment, and to the west and south by the Nepean Fault and Nepean Monocline. The gross structural distribution of the sedimentary sequences of the Southern Coalfield has been attributed to a broad, N-S orientated syncline with its axis running south from Camden, (Wilson 1975). As well, a series of minor anticlinal-synclinal folds with axes trending NW on the eastern side of the coalfield. The folds are gentle - regional dips are generally less than 2°, although dips of 5° or more have occasionally been encountered. Although faulting is generally not intense, the Southern Coalfield is characterised by three main fault orientations - NW-SE, N-S to NNE-SSW, WNW-WSE to WSW-ENE (Wilson 1975; Shepherd 1990). As well, some NE trending faults have also been identified.

Normal Faults

NW-NNW trending faults dominate the structural fabric of the Southern Coalfield. They are normal, dip-slip faults which may have been modified by some later oblique movement (Shepherd 1990). They dip both to the NE and SW, and may form graben structures. The larger faults are up to 10km in length, and have throws of up to 75m. The major NW-trending faults commonly form major colliery boundaries. Monoclinal structures are associated with these faults in the southern and western parts of the coalfield. Several N-S to NNE-SSW trending zones, containing a large number of normal faults with throws of up to 9m, occur in the Southern Coalfield. One of these zones, trending NNE, passes through Coal Cliff and Metropolitan Collieries, and correlates with the Helensburgh Lineament of Mauger et al. (1984). The apparent displacement of these zones across some major NW-trending faults identified by Shepherd (1990) suggests that the movement on the NW-trending faults postdates the N-S to NNE-SSW fault zones. There is also commonly evidence of two phases of movement on these faults - an early dip-slip motion, and a later oblique-slip motion (Shepherd (1990). The normal faults are the result of brittle failure of well consolidated, compacted sediments, and appear to have displaced the Triassic as well as the Permian sequences.

Strike-slip Faults

Strike-slip faults, also referred to as "shear zones" occur in a number of orientations, but principally WNW and N-NNE. In the Southern Coalfield they are notable for their association with coal outbursts (Marshall et al. 1980). A component of vertical displacement, up to 2m, has also occurred on some faults. The faults are typically vertical to sub-vertical in orientation, but there is also clear evidence of strike-slip reactivation of inclined normal faults. The WNW faults occur in clusters as in West Cliff and Metropolitan Collieries, and also as widely spaced individual faults. The sense of displacement on these faults has not been unequivocally determined Structures associated with the faults (Marshall et al. 1980), may be Riedel (or additive shears), or tension gashes. Either way, they strongly suggest that the maximum compressive stress at the time of deformation was orientated NE-SW to ENE-WSW, and that strike-slip motion was in most cases sinistral.

Thrust Faults

Thrust faults are a minor structural feature in the Southern Coalfield. Some NNE-trending thrusts have been identified. Stone rolls which are characteristic of certain parts of the coalfield typically trend north-west. Agrali (1987) concluded that they represented compressional structures of tectonic origin, and possibly developed during the Late Triassic Hunter Thrust compression.

Dykes and sills

Dykes are sub-parallel to faults in the Southern Coalfield, and occur at about the same frequency (Wilson 1975). They are oriented NW, WNW, and NNE to NE. Sills also occur in the coalfield. The intrusions are predominantly Jurassic and Early Tertiary in age (Carr & Facer 1980).

Western Coalfield

The Western Coalfield occupies the Blue Mountains Plateau, which is bounded on its eastern side by the Lapstone Monocline-Nepean Fault system. The Permo-Triassic basinal sequence generally dips very gently to the east, at 1-2°, but reaches 4° in the Glen Davis area (Morris 1975). Published data on the fault systems in the Western coalfields has been presented by Shepherd et al. (1981). Normal, reverse, and strike-slip faults occur in the Western Coalfield, of which normal faults are the most common. The Lapstone Monocline -Nepean Fault system is a regionally significant structural feature, and is also discussed briefly below.

Normal Faults

Normal faults and fault zones are mostly approximately meridional in orientation, and include NNW, N-S and NNE trends. Shepherd et al. (1981) indicate that N-S to NNE-SSW trending faults and joints occur in discrete zones. Some more NW-trending normal faults (e.g. in Clarence Colliery), and NE-trending faults (e.g. Invincible Colliery) also occur. The normal faults generally do not have large throws, in the <1 to 5m range, but some larger throws have been recorded. The normal faults show some evidence of having been reactivated by later deformation Rise-to-the-fault bedding in the footwall adjacent to the fault planes, flexures in the hanging wall, and small-scale asymmetrical folds are all indicative of compressional deformation, probably post-dating the normal faulting event.

Thrust and Reverse Faults

Thrust faults at present are largely known from mine workings in the Lithgow seam, e.g. in Invincible Colliery (Shepherd et al. 1981). They typically strike NNE, and dip both east and west. Throws on reverse and thrust faults are generally not large. Low-angle thrusts are the most common type. Deformation of normal fault planes in proximity to the thrust faults in Invincible Colliery (Shepherd et al. 1981) strongly suggests that the thrust faults post-date the normal faults.

Strike-slip Faults

Minor strike-slip faults, which are characterised by well-developed gouge zones, occur in zones in the Western Coalfield. They are developed in a number of different orientations. One group of strike-slip faults is oriented NW to NNW, for example in Cullen Bullen, Old Invincible, Grose Valley, and Newcom Collieries (Shepherd et al. 1981). The sense of movement of most of these faults has not been clearly determined. In some cases sub-horizontal slickensides overprint the dip-slip slickensides on normal faults (Shepherd et al. 1981), indicating strike-slip reactivation of the normal faults. Strike-slip motion on NE-trending faults in Invincible Colliery represents reactivation of NE-trending normal faults, and displacements are small.

Lapstone Structural Complex

The Lapstone Structural Complex (Branagan & Pedram (1990), essentially separates the Blue Mountains Plateau from the topographically lower Cumberland Plain to the east It incorporates the Lapstone Monocline and associated faults in the northern section, and the Nepean Fault system in the southern section. The complex was originally thought to have been dominated by normal faulting (Branagan 1969, 1975), but further work showed that other faulting styles are also present, including high-angle reverse, low-angle thrust, and strike-slip faults (Branagan & Pedram 1982, 1990). Branagan & Pedram (1990) note that small-scale thrust faults are common throughout the region. In the North Lapstone Monocline region, in the Grose Valley, Burralow Creek, and Paterson Hill areas, there is evidence of considerable tectonic disturbance, including a series of monoclines, warps, faults, and anticlinal structures. Herbert's (1989) interpretation of AGL Sydney Ltd seismic data taken largely across the southern Nepean Fault section of the complex appears to indicate that moderately to steeply dipping reverse faults are the dominant type of structure in most of the complex. Most of the reverse faults are apparently dipping to the west, and therefore indicate a dominantly west-over-east sense of tectonic transport.

Available field data suggest, however, that many of the faults are fairly complicated structures. Major faults that occur in the complex which have been interpreted as normal faults are typically steep or nearly vertical, and beds adjacent to them are commonly steeply dipping or are, interestingly, overturned in some cases (e.g. Hawkesbury Lookout, Kurrajong Faults) in zones up to 100m or more. The features associated with these faults may well have originated during compressive tectonism, as Herbert (1989) proposed. On the other hand, some of the deformational effects now observed could have resulted from reactivation and reversal of pre-existing normal faults and associated drag structures. This can result in inversion of structures, steepening of some fault planes, oversteepening of dragged beds, and generation of fold structures.

Hunter Coalfield

The Hunter Coalfield occupies the NW-trending belt of Permian coal-bearing rocks which crop out to the west of the Lochinvar Anticline between the Carboniferous sequences of the New England Fold Belt to the north, and the relatively flat-lying Triassic cover sequence to the south. The NE margin of the coalfield is presently defined by the Hunter Thrust system, which forms the leading edge of the thrust terrane of the New England Fold Belt. The regional structural fabric of the Hunter Coalfield is characterised by a series of N-NW trending fold structures (anticlines, synclines, and monoclines) with associated meridional normal faults (Mayne et al. 1974). which are recognised as having been active to varying degrees during sedimentation in the Permian, and possibly also the Triassic (Beckett 1988). The meridionally trending faults are interpreted as basement structures which led to the formation of basement-controlled fault-blocks such as the Lochinvar Anticline (Rawlings & Moelle 1982).

Normal Faults

Normal faults in the Hunter Coalfield occur in a number of orientations - broadly N-S, NW to WNW, E-W, and NE-SW. The meridional normal faults typically occur on the flanks of the regional anticlines, e.g. the Muswellbrook, Loder, and Lochinvar Anticlines, and include faults with large throws of up to 200m. Normal faults in other orientations also generally occur in discrete zones or clusters with a horst-and-graben configuration. For example, NW-trending normal faults occur at the southern end of the Muswellbrook Anticline, and in the Drayton Mine area. E-W trending faults occur in a zone in the Mt. Arthur North area, and in the Drayton Mine East Pit. NE-trending faults are present in a distinctive zone extending across the coalfield from at least Hunter Valley No.1 Mine to Swamp Creek Mine in the north. The relative ages of the normal fault systems is difficult to determine because of a lack of overprinting criteria.

Thrust Faults

Not surprisingly, the Permo-Triassic sequences of the Hunter Coalfield region have been affected by compressional tectonism related to the Hunter Thrust system. This is expressed by a number of large thrust faults with broadly NW orientations in the Permian footwall rocks of the main thrust, including the Aberdeen, Hebden, and West Brook Faults. As well, NW-trending thrusts with dominantly NE over SW senses of tectonic transport have also been identified in various mine leaseholdings, e.g. in Muswellbrook Colliery, Drayton Mine, and Hunter Valley No.1.

Similar thrusts can occasionally be detected in the Triassic sediments to the south of the coalfield. A NE-dipping, WNW-trending thrust in Triassic rocks was described near Broke (Moelle & Sutherland 1977). There is also some evidence for more east-west compression and thrusting in the Muswellbrook area. Thrusts with NE to ENE orientations also occur in the Hunter Coalfield, although they appear to be relatively minor occurrences.

DISCUSSION

Eastern Sydney Basin

When viewed together on a regional scale, the sections which constitute the eastern side of the Sydney Basin, namely the Newcastle and Southern Coalfields, and the intervening Sydney region, display a number of similarities in terms of their structural fabrics, and related features. They include:

- NW-NNW trending normal faults. They are generally larger structures in the Southern Coalfield than in the Newcastle region. In the Southern Coalfield the NW-trending faults intersect the Triassic cover, and are therefore Late Triassic or younger in age.

- N-NNE trending normal faults, which typically occur in discrete zones with horst-and-graben faulting in both the Southern and Newcastle Coalfields, and also in the Sydney region. In terms of age they also postdate the Triassic sediments, but may slightly predate the NW-trending normal faults.

- Minor NE-trending normal faults occur throughout the region. Their age relative to the other normal fault systems is unclear, but Norman & Creasey (1985) suggest that they predate the NW-trending dykes.

- Dykes which mostly parallel the NW-NNW, N-NNE normal faults, and sills are a prominent feature of the eastern Sydney Basin.

- N-NNE trending thrust faults occur in both the Newcastle and Southern Coalfields, and in the Sydney region. NNE-trending folding is also present in the Sydney region. NW oriented thrust faults and localised stone rolls occur in the eastern part of the Sydney Basin, but do not appear to be common. Broadly E-W thrusts, with both WNW and ENE trends, and E-W folds are also present, but are relatively uncommon.

Certain timing relationships allow a possible sequence of events to be established. Several episodes of igneous intrusion have been defined in the Sydney Basin (Carr & Facer 1980; Embleton et al. 1985; Branagan 1985), including a Jurassic phase (143 - 207my BP), and an Early Tertiary phase (Oligocene-Eocene - 26-58my BP). It is generally considered that most dykes in the Newcastle and Southern Coalfields and the Sydney region are Early Tertiary (Oligocene-Eocene) in age (e.g. Rickwood 1985), although this is not clear-cut from the available dating. However, it is assumed here that most of the dykes are Tertiary. The normal fault systems which are parallel to the dyke swarms are considered to be broadly contemporaneous i.e., Early Tertiary, and in fact indicate the same principal extension direction of NE-SE to ENE-WSW. The generation of the dykes has been correlated with the Early Tertiary Tasman Sea rifting (e.g. Facer & Carr 1979; Carr & Facer 1980), which was active from 80-60my BP (Hayes & Ringis 1973; Weissel & Hayes 1977).

If the NW-NNW trending faults and dykes are largely Early Tertiary in age, then it likely that the N-NNE trending normal faults and dykes are considered to be essentially the same age. They are broadly parallel to the Tasman Sea rift margin, now the south-eastern Australian continental margin. The Tasman Sea rifting is interesting in that the principal direction of extension, as indicated by the magnetic-anomaly and transform-fault patterns (Weissel & Hayes 1977; Johnson & Veevers 1984), is approximately NE-SW to ENE-WSW. That is, the orientation of the prominent NW-NNW trending fault/dyke systems of the eastern Sydney Basin is orthogonal to, and consistent with the principal extension direction during Early Tertiary rifting. The rift margin and the N-NNE-trending faults and dykes are, however, oblique to the principal extension direction, and are in a conjugate position to the NW-trending faults and dykes. The timing of dyke formation and structural relationships suggest that the N-NNE-trending faults were initiated before the NW-NNW trending faults and the episode of dyke intrusion. Both NW and NNE structures possibly represent reactivated basement structures, or structures which may have been initiated during somewhat earlier extensional tectonism, for example in the Jurassic.

The eastern on-shore section of the Sydney Basin is therefore interpreted as having undergone a significant episode of extension and igneous activity in the Early Tertiary.
In the northern Newcastle Coalfield, the NW-trending thrust faults predate the NW-trending normal faults (e.g. in Gretley Colliery a NW-trending thrust is displaced by a NW-trending normal fault). These faults are therefore pre-Early Tertiary, and their orientation suggests that they can be correlated with Late Triassic Hunter Thrust deformation. The NE-trending normal faults, although they are uncommon, also appear to predate the NW-trending faults and dyke (e.g. Norman & Creasey 1985). However, from evidence in the Hunter Coalfield, probably post-date the Hunter Thrust tectonism, and may be Jurassic.

N-NNE trending thrust faults clearly displace, and therefore post-date the NW normal faults. They are considered to represent a compressional event with an E-W to WNW-ESE principal compression direction. As well, NNE-trending folds in the Sydney region are correlated with this event, and it is possible that the gentle, broadly meridional regional folds of the Newcastle Coalfield represent the same compression, or were accentuated by it. If the NW-faults are Early Tertiary in age, then the NNE-trending structures indicate that compressional tectonism has occurred in the eastern Sydney Basin since that time, probably in the mid- to late Tertiary. The timing of more E-W oriented thrusts and folds in the Newcastle Coalfield is unclear, but as discussed later, they are possibly related to Tertiary N-S compression.

Strike-slip faults, which are mostly NW-WNW or N-NNE in orientation also post-date the normal faulting episodes, and are therefore also interpreted as being indicative of post-Early Tertiary compressional tectonism. The direction of the principal compressive stresses is difficult to determine for many of these faults, as their sense of displacement is unknown. WNW-trending strike-slip faults in the Southern Coalfield are possibly sinistral, and suggest a NW-SE or WNW-ESE direction of compression.

North-western Sydney Basin

As in the eastern Sydney Basin, it would be useful to have some geological events in the Hunter Coalfield region, such as phases of deformation, which can be dated with reasonable certainty, and provide key fixed points to which other events can be related. In the north-eastern part of the basin, however, this has proved to be rather difficult. It is generally assumed that the major movement on the Hunter Thrust system is Late Triassic, and on the basis of deformations seen elsewhere in eastern Australia, e.g. in the Bowen Basin, this is probably a reasonable assumption. However, the actual situation may be somewhat more complicated than this. Intrusions in the Hunter Coalfield have been dated as both Jurassic and Tertiary (Embleton et al. 1985). NE-trending dykes are taken to be Tertiary (Beckett 1988). A NE-trending dyke is displaced by thrusting in Muswellbrook Colliery. This indicates that post-Triassic thrusting has also occurred in the north-western Sydney Basin, and is therefore either post-Jurassic or post-Early Tertiary, depending on what date is accepted for the dykes. An earlier thrusting event certainly exists. The NE-trending zone of normal faulting which passes between Hunter Valley No. 1 and Swamp Creek Mine (McLennan & Lohe 1990), is considered to post-date the broadly NW-trending Hebden Thrust adjacent to the Swamp Creek Mine. A large NE-trending dyke occurs adjacent to the faulted zone, and it is inferred that both may be related to the same extensional event. A pre-Tertiary (or pre-Jurassic?) thrusting event has therefore occurred, with essentially NE-SW directed compression, and is therefore correlated with the well-known Late Triassic compressive tectonism.

As already noted, thrusting post-dating the dykes occurs in the north-western Sydney Basin. If the dykes are Early Tertiary, then this event possibly correlates with the E-W to WNW-ESE directed compressional tectonism postulated to have occurred in the eastern part of the Sydney Basin after the Early Tertiary normal faulting and intrusive activity correlated with the Tasman Sea rifting. It is therefore perhaps significant that although most of the Hunter-related thrusting displays a NE-to-SW sense of tectonic transport, there is some evidence for E-W to WNW-ESE directed compression as well, e.g. in the Muswellbrook area, which may be related to this late phase of tectonism.

The relative timing of NW-SE, N-S, and E-W normal faults, and how they relate to the major thrusting events is not readily defined, as timing relationships are not easily obtained. NW-trending faults in the Muswellbrook area are clearly cut and reactivated by thrusts, but if there are in fact both Late Triassic and Tertiary thrusting events, then it is necessary to determine which events have overprinted the NW-trending normal faults. Field evidence indicates that they have certainly been reactivated and displaced by approximately E-W directed compression, but it is not clear at present whether earlier (Triassic) thrusting has also affected them. It is tempting to correlate the NW-trending faults with the NW-trending faults in the eastern part of the basin, which are postulated to be largely Early Tertiary in age, but further work needs to be done to resolve this problem. Meridional normal faults, which occur on the flanks of the regional anticlines and monoclines are likely to have had relatively long histories of activity. The latest, and most obvious movements on these faults, however, displace well lithified sediments, and are probably no older than the Late Triassic, and could well be younger. There is some evidence to suggest that they pre-date thrusting, but as was discussed earlier, if than one episode of thrusting has occurred, then relative timing of these events needs to be clarified. The timing of E-W normal faults has not been determined as yet.

Western Sydney Basin

Clear indications of the age of faulting events in the Western Coalfield are difficult to obtain. The normal faulting is evidently the earliest phase of post-depositional deformation. Shepherd & Huntington (1981) proposed that the origin of much of the normal faulting, especially within fault and joint swarms, to the west of the Lapstone structure, represented extensional tectonism which may be correlated with the Early Tertiary Tasman Sea rifting. They further suggested that the orientation of many of the faults was determined by basement discontinuities. As discussed below, the normal faulting is therefore correlated with Early Tertiary deformation in the Lapstone Structural Complex.

Post-extensional compressive deformation resulted in thrusting, particularly on NNE-trending faults, and is ascribed to approximately E-W compression (Shepherd et al. 1981). At least some of the strike-slip deformation is assigned to the same compression. The orientation of the thrust structures strongly suggests that they correlate with the post-Early Tertiary compressional tectonism proposed for other parts of the basin.

Lapstone Structural Complex

The Lapstone Structural Complex is a prominent feature of the Sydney Basin, so that any overview of the structural fabrics of the basin, and their relationship to each other needs to take some account of it. The complex seems to have had a long history of activity. It appears to coincide with a "hinge" in the Sydney Basin sequence, which thickens to the east. Branagan (1975) therefore suggested that the Lapstone feature was active already in the Permian. Harrington & Brakel (1981), on the basis of isopach, structural-contour patterns, and lithofacies data, postulated that a major basement fault was present beneath the complex. The Lapstone structure also coincides with north-south gravity gradient, culminating in a gravity high to the east of it (Qureshi 1984; Leaman 1990). The gravity data may indicate the presence of structures in the basement coinciding with the Lapstone structure.

The tectonism which essentially gives the Lapstone Structural Complex its present configuration has affected the Triassic basinal sequence is clearly at least Late Triassic in age, if not younger, but little agreement exists about the exact timing of deformational events in the Lapstone complex. Branagan (1975) has suggested that the present configuration is largely due to Tertiary events related to the Tasman Sea rifting. Laterization of Tertiary gravels in the area may be Early Miocene (Bishop et al. 1982), so that the gravels could be Early Tertiary in age, and the main deformations may date from that time (Branagan & Pedram 1990). Herbert (1989) suggested that the deformation of the Lapstone Monocline is essentially related to one event, probably the Late Triassic Hunter Thrust-related compression.

However, conclusions reached earlier about the structural histories of other parts of the Sydney Basin may provide some useful information regarding the formation of the Lapstone complex. It is suggested that the present structural configuration of the Lapstone complex was generated in the Early Tertiary during extensional tectonism related to the Tasman Sea rifting, as proposed by Branagan and others. It is considered to have resulted in the formation of a series of meridional normal faults and monoclines, possibly localised by older basement structures, and also produced the prominent escarpment which marks the boundary between the Blue Mountains Plateau and the Cumberland Plain to the east.

As noted earlier, the existence of a post-Early Tertiary, broadly E-W compressional event, resulting N-NNE trending thrusts and folds, is postulated to have occurred in the Sydney Basin. This event, which is identifiable in the Western Coalfield to the west of the Lapstone structure, is suggested as the deformation which has generated the compressional features such as reverse faults and low-angle thrusts described by Herbert (1989) and Branagan & Pedram (1990). The dominant direction of tectonic transport seems to have been west over east. The monoclinal fold structures have probably been accentuated by the compression, and normal faults reactivated and inverted, and steepened. Drag folding adjacent to originally normal is likely to have been compressed and also accentuated by reverse movement, resulting oversteepening and even overturning of beds. The Late Triassic Hunter Thrust compressional event is probably too early to have generated the Lapstone thrusting.

An interesting sidelight of the E-W compressional deformation is that detachment of the relatively thin Permo-Triassic basinal sequence could have occurred on a decollement at or near the sediment-basement contact as a result of thrusting. If this did occur, then it is likely that pre-existing normal faults originally passing into the basement would be disconnected at or near the base of the basinal sediments, and could be very difficult to detect seismically in the basement. The thrust and reverse faults would, of course, mostly ramp up from the decollement, and not appear in the basement. Other late-stage compression, which produced strike-slip faulting in the Southern and Western Coalfields, may also have reactivated structures the Lapstone complex by strike-slip and oblique faulting.

COMMENTS

The above discussion suggests that is possible to define a number of post-depositional tectonic events which hare regionally significant in the Sydney Basin. They are:

1. Late Triassic compression related to a major movement of the Hunter Thrust. The effects of this deformation are essentially seen in the northern parts of the basin.

2. Jurassic dyke and sill intrusion (143-207my BP), which may have been accompanied by an episode of extensional tectonism resulting in normal faulting. However, it is difficult to ascribe definitely any particular faulting to such an event.

3. Early Tertiary extensional tectonism, essentially related to the Tasman Sea rifting. This resulted in NW-NNW and NNE trending normal faulting in the eastern parts of the basin, and associated Early Tertiary dyke and sill emplacement (Eocene-Oligocene). In the central and western basin, the present configuration of the Lapstone Structural Complex is considered to have been initiated by normal faulting and monoclinal folding in the Early Tertiary. Normal faulting in the Western Coalfield, and also the Hunter Coalfield is postulated to be related to this event as well.

4. Post-extensional, broadly E-W compressional tectonism, possibly mid-Tertiary (?Miocene) in age, which produced broadly N-NNE trending thrust and reverse faulting, and folding. This event can be identified over most of the basin. Reverse and thrust faulting in the Lapstone complex is correlated with this event. Strike-slip faulting is some areas may have been generated during this event.

5. Some evidence exists for other late-stage compressional events, e.g. resulting in strike-slip deformation, and broadly E-W oriented thrusts anad folds. Their ages relative to other events are difficult to determine, but the E-W structures may be Tertiary (see below).

In general terms, the post-depositional structural fabric of the Sydney Basin is dominated by normal faulting, much of which is probably Tertiary in age, but which may include a Jurassic event as well. Certainly, much of the normal faulting is inferred to have post-dated the major Late Triassic movement on the Hunter Thrust system. The role of relatively long-standing structures in localising the Post-depositional structures cannot be ignored, e.g., along the flanks of the regional anticlines in the northern Sydney Basin. However, the latest movements which are now seen on these structures are post-depositional, and are likely to be Tertiary in many cases.

Perhaps one of the more interesting aspects of this overview is the definition of a phase of post-Early Tertiary compressional tectonism in the Sydney Basin. It is interesting to note that N-NNE trending folds and thrusts occur in the Southern New England Fold Belt immediately to the north of the Sydney Basin. Collins (1990) assigned these structures to Permian tectonic events, but if the existence of a regional E-W mid-Tertiary compression is correct, then some of these structures could possibly be Tertiary, or have been reactivated in the Tertiary.

Compressive deformations which are probably Tertiary are known elsewhere in eastern Australia. Extensional tectonism in the Eromanga Basin has been correlated with the Early Tertiary Tasman Sea rifting (e.g. Hoffmann 1989), and was followed by two compressive deformations - a N-S compression which is considered to be a response to Australian-Pacific plate interactions in the middle Oligocene-Miocene, and a final E-W compression, which is tentatively dated as Miocene-Holocene. The E-W compression in the Sydney Basin region could be correlated to the latter compressional event. Interestingly, there is an indication of weak N-S compression in the Sydney Basin as well, e.g. in the northern Newcastle Coalfield, giving rise to broadly E-W thrusts and folds. It may also be Tertiary.

THE BOWEN BASIN

The Bowen Basin, which constitutes the northern section of the Bowen-Sydney Basin system, provides some interesting comparisons with the Sydney Basin. Post-depositional structures affecting the Bowen Basin sequences are dominated by thrust faults and folds oriented NNW to NW (e.g. Dickins & Malone 1873; Hobbs 1985; Hammond 1988). The degree of deformation ranges from intense penetrative folding and thrusting in the Folded Zone on the eastern side of the basin, to relatively basin-and-dome foldiong, and low-angle thrusts running parallel to bedding for considerable distances on the Collinsville Shelf in the west. Most thrusts are easterly dipping, and display an E-over-W sense of tectonic transport. The age of this thrusting is considered to be largely Late Triassic, but earlier Permian compressional tectonism has been detected, and Late Cretaceous or Tertiary compressions are also present.

Normal faults do occur, e.g. NE-trending faults in the German Creek area, but they do not appear to be a major part of the structural fabric of the basin. Some Tertiary normal faulting is evident in the Formation of the Duaringa Basin, which contains largely late Eocene sediments (Day et al. 1983). The normal faulting which dominates the Sydney Basin, is clearly not as well developed in the Bowen Basin. This is undoubtedly a function of the fact that the Bowen Basin region is not as immediately adjacent to the Late Cretaceous-Early Tertiary rift systems as the Sydney Basin is. However, both show evidence of relatively late compressional tectonism, which may be pertinent to the compressional stress regimes observed in much of eastern Australia at the present time.

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EVOLUTION OF THE SYDNEY BASIN DURING THE PERMIAN AS A FORELAND BASIN TO THE CURRARONG AND NEW ENGLAND OROGENS

P.R. EVANS[1] & A. MIGLIUCCI[2]
[1] School of Mines & Centre for Petroleum Engineering, UNSW
[2] Sagasco Resources Ltd, Adelaide

INTRODUCTION

The Sydney Basin contains up to 6000 m of Permian and Triassic strata (Mayne et al. 1974) overlying Ordovician-Carboniferous of the Lachlan Fold Belt (Leaman 1990). The Permian is thicker adjacent to the Hunter Fault, but also thickens eastwards towards the continental shelf. The basin is widely referred to as a foreland basin to the New England Orogen or Fold Belt (eg. Scheibner 1989). There is little agreement, however, on the time and manner of basin initiation.

The concept that the "Currarong Orogen" existed during the Late Palaeozoic and Early Mesozoic to the east of the Sydney Basin was mooted by Jones et al. (1984). The existence and likely extent of the Currarong Orogen are uncertain because of the lack of definitive information from below the continental shelf, and because rifting during the Cretaceous has probably caused the bulk of the complex to become part of the Lord Howe Rise (Shaw 1990).

The stratigraphy of the Sydney Basin requires the presence of the Currarong Orogen throughout the Permian, because loading of the crust was principally to the east, and to a lesser extent by the New England Orogen to the north.

PERMIAN DEPOSITIONAL CYCLES

Jones et al. (1984) confined their observations and comments to the Upper Permian and Triassic. However, the entire Permian is divisible into six coarsening upwards cycles, each of which is thought to represent a stage of encroachment of the Currarong Orogen onto the craton.

CYCLE 1: Lochinvar Formation and Wasp Head Formation

The Lochinvar Formation is up to 835 m of a coarsening upwrards marine facies with interbedded basalts. McClung (1980) reconstructed the palaeogeography of the northern Sydney Basin during Lochinvar time, suggesting that deposition was largely within a NW-SE trending depression, with elevated ground to the SW, and a NW-SE trending high of Carboniferous rocks to the north. Elevation of the high (Migliucci & Evans 1991) and the coarsening upwards facies are regarded as evidence of the first compressive pulse to create the foreland basin.

The correlative Wasp Head Formation in the southern Sydney Basin is a shoreline transgressive facies regarded as part of Cycle 1.

CYCLE 2: Rutherford Formation - Greta Coal Measures

Cycle 2 includes up to 1100 m of section in the north, consisting of the Rutherford and Farley Formations and the Greta Coal Measures. Deposition was most rapid along the northern flank and to the east of the present basin, trends that were maintained throughout the Permian.

The Rutherford Formation was deposited below wave base, but not necessarily in very deep water. The Farley Formation, coarsening upwards and with a northerly source area, represents nearshore deposition close to or above wave base.

The Greta Coal Measures at the top of Cycle 2 are confined to a lobe up to 480 m thick (Mayne et al. 1974), deposited by a humid alluvial fan delta sourced to the north of the Hunter Fault. Coal seams around the flanks of the Lochinvar Anticline deteriorate and split away from both flanks of the anticline (=Kulnura Arch; Mayne et al. 1974), indicating growth of the structure during deposition (Britten et al. 1975).

The Pebbley Beach Formation in the south was largely deposited either below wave base or in a tidal regime (Gostin & Herbert 1973, Stutchbury 1989). The Yadboro Conglomerate and the intervening 'Jindelara facies' (Evans et al. 1983) are partial correlatives deposited by an alluvial fan delta confined by the Talaterang Low and progressively drowned by the advancing sea.

The Snapper Point Formation, correlative of the Greta Coal Measures, extends across the Sydney Basin (Mayne et al. 1974), as an overall westward transgressive facies that overlapped the Pebbley Beach Formation and onto basement. Most of the formation was derived largely from the western margin of the basin, for example through the fluvial system that deposited the Tallong Conglomerate (Szabados 1990). The type Clyde Coal Measures are products of embayment swamps on the flanks of the rising Snapper Point sea.

CYCLE 3: Branxton Formation/Wandrawandrian Siltstone & Muree/Nowra Sandstone

The Branxton Formation of pebbly silty sandstone and sandy siltstone with conglomeratic horizons is over 900 m thick and largely a shelfal facies (McClung 1980). A increase northwards of the sand/shale ratio and the presence of coal and carbonaceous matter indicates the proximity of peat swamps and presumably a coastal margin facies. Maximum development of the Muree Sandstone is in the northeast, where it is up to 160 m thick and coincident with the more sandy and thicker sector of the underlying Branxton Formation. The source of the Muree Sandstone was localized to northeast of the

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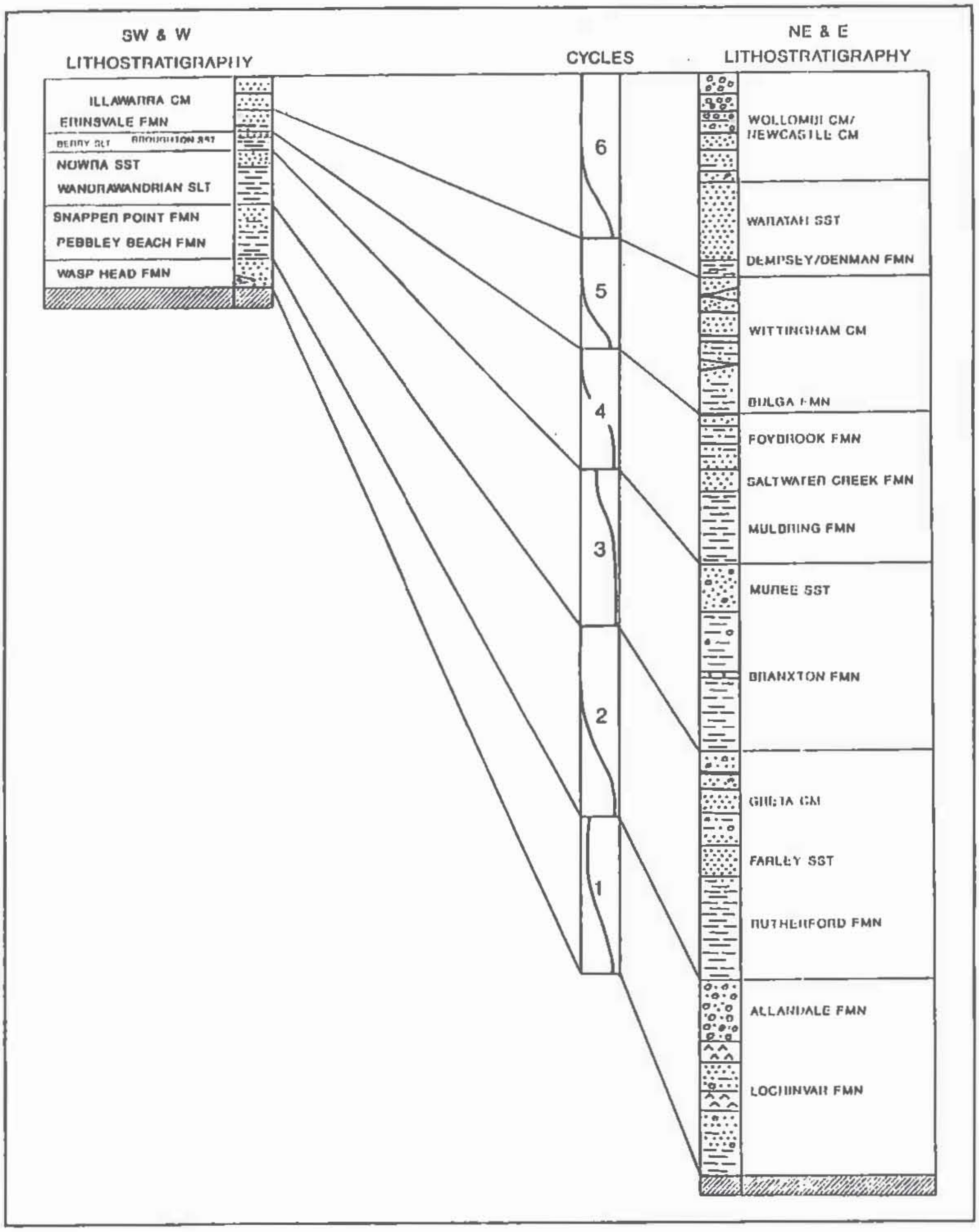

Fig. 1 Representative stratigraphic columns through the Permian of the Sydney Basin illustrating the six foreland cycles and correlative craton margin sequences. Vertical scale proportionate to stratigraphic thicknesses.

basin. McClung (1980) concluded that Hunter Fault was active during deposition of the formation.

The Wandrawandrian Siltstone, up to 200 m thick, rapidly succeeds but does not overstep the Snapper Point Formation in the south, being limited by a basement hinge at the meridian of the Lapstone Monocline. It was deposited below wave base, passing eastwards into deeper water with an increasing palaeoslope. Mass sliding at Warden Head, Ulladulla, transported a semiconsolidated block of the formation from the west to the east. The regressive-transgressive Nowra Sandstone (McKelvey & McClung 1972) conformably succeeds the Wandrawandrian Siltstone, but is of limited extent, forming an elongate shoal up to 80 m thick (Herbert 1980b).

Cycle 3 thickens to the east and shallows upwards to the wave- or at least storm wave-base levels of the Nowra and Muree Sandstones, but does not terminate in a thick non-marine facies.

CYCLE 4: Mulbring Siltstone - basal Vane Subgroup of Wittingham Coal Measures/lower Tomago Coal Measures

The Mulbring Siltstone rapidly succeeding the Muree Sandstone was deposited over a broad area and represents widespread deepening of the basin and deposition largely below wave base. There is no transitional shallow water transgressive facies on top of the Muree Sandstone, but after all, little of that formation ever emerged above sea level. The Berry Siltstone in the south is a siltstone in the east, but to the west includes interbeds of sandstone comparable to the Nowra Sandstone (Mayne et al. 1974; Walker 1980). Perhaps the regression/transgression conglomerate within the Nowra Sandstone (McKelvey & McClung 1972) is a more appropriate boundary for the base of this cycle on the western flank of the basin.

The Kulnura Arch was active; all Cycle 4 formations thin towards the arch, but generally thicken to the east.

Cycle 4 concludes with shallow marine and the sandy shoreface facies of the Saltwater Creek Formation and delta plain facies of the Foybrook Formation and the lower half of the Wallis Creek Formation of the Tomago Coal Measures east of the Lochinvar Anticline where over 600 m of firstly beach then delta plain facies were deposited (Beckett & MacDonald 1984).

To the south the Berry Siltstone is succeeded by the Broughton Sandstone and the Pheasants Nest Formation at the base of the Illawarra Coal Measures. These were deltaic and fluvial sequences derived from the craton to the west, although much of the Broughton Sandstone is composed of locally derived volcanic detritus from the shoshonitic Gerringong Volcanics.

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CYCLE 5: Bulga Formation (Kulnura Marine Tongue) - Malabar Formation

The next cycle commenced with the final marine incursion across the bulk of the basin, that includes the Bulga Formation (Kulnura Marine Tongue), the upper Wallis Creek Formation of the Tomago Coal Measures, and the Erins Vale Formation of the Illawarra Coal Measures. Marine facies are succeeded by deltaic facies of the remainder of the Whittingham Coal Measures and correlatives, that spread south parallel to the axis of the present basin (Bowman 1980).

As well as continued movement of the Kulnura Arch, structures to the northwest began to form during Cycle 5, controlling deposition of the Whittingham Coal Measures (Britten et al. 1975).

CYCLE 6: Uppermost Tomago, Newcastle, Wollombi & Upper Illawarra Coal Measures

The Dempsey Formation (marine, prodelta facies), the Waratah Sandstone (barrier island, shoreface facies), and the Newcastle Coal Measures, a humid alluvial fan complex sourced from the northeast (Diessel 1980), form coarsening upwards sequence that merges southwards with the delta complex of the upper Illawarra Coal Measures (Herbert 1980a). The depocentre must be east of the present coastline (Branagan & Johnson 1970).

The Kulnura Arch was distinctly emergent at this time; its growth affected the distribution of coal seams during deposition of the Wollombi and Newcastle Coal Measures. Continued pressures from the ESE generated three significant structural zones: 1) the en echelon anticlinal structures with meridional axes adjacent to the Hunter Fault west of the Lochinvar Anticline; 2) folds trending NNE-SSW along the eastern flank of the basin, including the Lochinvar Anticline and Macquarie Syncline in the north and the onshore Dural Anticline and offshore Sea Lion structure in the south; 3) the Lapstone Monocline. Zone 1) is the product of transpressional slip (Carey & Osborne 1939; Migliucci & Evans 1991). Zone 2) and the eastward slope of basement are the end result of long-acting compressive stress from the ESE, and crustal load induced by the Currarong Orogen. The Lapstone Monocline, a near-surface expression of a backthrust, probably with some sinistral slip, assumed its present form during the Triassic (Herbert 1989, Pickett & Bishop (in press).

DISCUSSION

The sedimentary deeps in the upper Hunter Valley, are ascribed to crustal loading by the southern Tamworth Belt, and to the load of sediments originating from both the north and northeast. The Currarong and New England Orogens would have been linked to the northeast of Newcastle, as if there was a kink in the orogenic front. As the supracrustal plate overrode the western plate, the northeast corner of the lower plate suffered the greatest degree of flexure and received the greatest quantity of sediment.

Stress was imposed in pulses along essentially the same vector throughout the Permian, and it could well have continued at least until the Late Triassic (Evans & Roberts 1980).

There are corollaries to this model. For example, the point of inflexion at Murrurundi, between the Hunter Fault (bordering the Sydney Basin) and the Mooki Fault (flanking the Gunnedah Basin) is at the distal end of the southern Tamworth Belt uplift. The more northerly strike of the Mooki Fault and the marked change in structural styles east of the inflexion indicate that the Tamworth Belt north of Murrurundi is the product of more convergent foreland thrusting than experienced along the Hunter Fault and by the southern Tamworth Belt.

Another corollary is that the complex of faults at the southern extension of the Peel Fault and including the Manning Fault complex, from north of the Barrington Granite to the coast south of Taree, is parallel to and likely to have a similar sinistral strike-slip component to that of the Hunter Fault, as surmised by Roberts & Engel (1987) and Collins (1990).

Finally, it is tempting to speculate on the relationship between the western bounding fault to the Currarong Orogen to the subsequent fault that controlled assymetric spreading of the Tasman Sea during the Late Cretaceous (Jongsma & Mutter 1978). Perhaps the latter was created by reactivation of the original frontal fault of the Currarong Orogen, a reverse of the process of change from a passive to a compressional continental margin envisaged for example by Price (1981) during evolution of the western margin of the North American craton (Fig.). Accepting the reconstruction by Shaw (1990) of the opening of the Tasman Sea, the highly tectonized core of the Currarong Orogen should now be part of the Dampier Ridge and Lord Howe Rise, and it is unlikely that "the other half of the Sydney Basin" (Carey 1969) is preserved thereon. Recent seismic surveys of the Dampier Ridge and Lord Howe Rise did not locate obvious evidence of there being such a remnant (Whitworth & Willcox 1985, Colwell & Coffin 1987).

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CORRELATION CHARTS FOR THE PERMIAN OF THE SYDNEY-BOWEN BASIN AND NEW ENGLAND OROGEN

D.J.C. BRIGGS
University of Melbourne

The Permian System of the Sydney-Bowen Basin and New England Orogen comprises a very large number of stratigraphic units, reflecting a wide variety of original sedimentary environments and a complex history of tectonic, eustatic and climatic events. In order to investigate the time relationships of these units, a comprehensive compilation has been prepared of available information relevant to time control. This includes palaeontological information (including taxonomic work by the writer as well as macrofaunal, macrofloral, microfaunal and microfloral records by others), radiometric dates, and lithostratigraphic evidence for correlation or time relationships. As a geographical framework for this database, the region has been subdivided into 16 latitudinal bands, each corresponding to one set of laterally adjoining 1:250 000 Sheet areas, and each of these bands has been subdivided into from three to eighteen structural domains.

This data compilation has been used to draw up the 16 correlation charts in the accompanying poster; three of these are included in this abstract. The charts use an updated version of the biostratigraphic framework described by Briggs (1989), which integrates a set of successive brachiopod range zones with the palynological zones of Price. The relative durations of the Permian stages follow the time scale of Ross and Ross (1987).

The oldest zone considered here is the *Lyonia* n. sp. Zone (corresponding approximately to palynological zone PP1.2). This zone is regarded as Asselian because its correlatives in Western Australia lie stratigraphically below an Early Tastubian ammonoid fauna (Figure 1). Radiometric data obtained by Roberts (this volume) indicates that some units in eastern Australia below the *Lyonia* n. sp. Zone are also Permian, or at least younger than the type Carboniferous in Europe. This implies that the *Lyonia* n. sp. Zone corresponds to only the Late Asselian, rather than the whole of the Asselian as I have previously assumed (e.g. Briggs, 1989). No attempt will been made here to discuss correlations of earlier Asselian units, which have not been studied in detail by the writer.

The set of correlation charts in the accompanying poster represent only one possible interpretation of the data compilation amassed to date. Many details of the correlations are equivocal from available data, and some changes are likely as new data is collected. Nevertheless a number of points of relevance to the history of the tectonic development of eastern Australia can be made at this point.

1. Sydney-Bowen Basin system:

The Sydney-Bowen Basin is now thought to have begun with an extensional phase prior to later sag and foreland basin phases (Murray, 1990b). In the main eastern axis of the system, the Taroom Trough-Gunnedah-Sydney Basin, this extensional phase appears to have involved incipient rifting, leading to the emplacement of intrusions and volcanics now associated with the Meandarra Gravity Ridge (Murray, 1990b). These volcanics seem to be mostly Sakmarian in age, although the precise time of onset of volcanism in the Gunnedah and Bowen Basins is poorly constrained. Late Asselian, generally glacigene deposits occur locally in the Sydney Basin, stratigraphically lower than the volcanic units, but laterally extensive sediment accumulation, like the volcanism, did not begin until the Sakmarian.

The transition to a compressional setting seems to occur in the main eastern axis of the system at about the top of the *warwicki* Zone (mid-Artinskian), as this level is followed by an influx of coarse detritus from the New England Orogen in the Greta Coal Measures of the lower Hunter Valley and (more controversially) in the Maules Creek Formation in the north-eastern Gunnedah Basin. In the Denison Trough the Sakmarian extensional phase is separated from the onset of compression in the Kungurian by a basin sag phase (Ziolkowski and Taylor, 1985).

Indications of contemporaneous volcanic activity become prominent in the Sydney Basin and eastern Bowen Basin from the Ufimian. An intensely tuffaceous interval has been recognized throughout the Sydney-Bowen Basin at essentially correlative levels just below the top of PP5 (Kaloola Member, upper Newcastle Coal Measures etc.).

There are strong indications that transgressive pulses in the Sydney Bowen Basin system can be widely correlated throughout the system, suggesting that they are primarily associated with eustatic fluctuations. One prominent transgression in basal PP5 in the Sydney-Gunnedah Basin (the Speldon/Kulnura/Bulga/Archerfield transgression) seems to correspond to the Ingelara/Maria transgression of the Bowen Basin, while a later pair of sharp trangressive pulses before a markedly regressive interval (Dempsey + Shortland, upper Wilton + Bargo, "false Denman" + Denman etc.) seems to occupy about the same level within PP5.0.2-3 as the Peawaddy + basal Black Alley transgressive pulses of the Bowen Basin. Both these events seem to be recognizeable in the coastal onlap curve of Ross and Ross (1987).

2. Yarrol-Tamworth belt:

The Yarrol-Tamworth belt is used here for the zone between the Hunter-Mooki-Goondiwindi-Burunga Fault system in the west and the Yarrol-Peel Fault system to the east. Sequences on the western/southern side of the belt (e.g. Prospect Creek, Werrie, Stroud-Gloucester and Myall Synclines) are generally closely allied to those of the adjacent Sydney-Bowen Basin. Most of these show stratigraphic breaks in the mid-Permian (Figs 2,4), generally without marked angularity. Sequences on the eastern/northern side of the belt are mainly Early Permian, but Late Permian sequences, unconformable on deformed Early Permian, are preserved only in the far north of the belt.

The shift to a compressional setting was accompanied in the Yarrol-Tamworth Belt by the development of thick andesitic volcanics in the late Artinskian (*E. preovalis* Zone), suggesting the resumption of plate convergence and subduction. Remnants of these include the Owl Gully Volcanics and equivalents of the Yarrol Block, the so-called "Camboon Andesite" of the Prospect Creek Syncline and Gogango Overfolded Zone, and the "Lizzie Creek Volcanics" of the Connors Arch area, these last two being entirely younger than units of the same name in the Bowen Basin. The "Plumbago Creek beds" and correlatives in the Drake area (Coastal-Tablelands belt) are also contemporaneous.

3. Coastal-Tablelands belt:

The term "Coastal-Tablelands belt" (after two of its components, the Coastal Block and Tablelands Complex) is used here for the region between the Yarrol-Peel Fault system in the west and the Gympie belt in the east. Permian sequences in this region are unconformable on a basement of deformed Devonian-Early Carboniferous subduction complex (intruded by Late Carboniferous granitoids), and little deformed, mostly Carboniferous shelf sediments. Various authors have attempted to explain the presence of the latter in the Coastal-Tablelands belt by tectonic emplacement. Onlapping Permian sequences demonstrate that if these were tectonically emplaced, this occurrred before *Lyonia* n. sp. Zone time.

Permian sediments are preserved mainly in the southern part of the Coastal-Tablelands belt, where continental extension in the Late Asselian, resulted in the accumulation of the thick "pebbly mudstone" deposits of the lower parts of the Manning Group and their northern equivalent, the Silver Spur beds. Undated "pebbly mudstones" recorded from the "Amamoor beds" and their equivalents (e.g. Murray, 1990a) possibly represent a northern continuation of this sequence.

Mid-Permian tectonism in the Coastal-Tablelands belt is widely indicated by angular breaks between Early Permian sediments and relatively undeformed mid- to Late Permian volcanics. The age of this deformation is constrained by the age of the deformed Early Permian sediments, which range up to the *E. warwicki* Zone in the west (Silver Spur Beds) and up to the late *E. preovalis* zone in the east (Plumbago Creek beds and equivalents, and the Yessabah Limestone-Warbro Formation). Conglomeratic and in part terrestrial sediments of Artinskian to early Kungurian age occur scattered throughout the western part of the Coastal-Tablelands belt, and probably reflect contemporaneous tectonic movement. These sequences include the "Swamp Oak Beds" near Emmaville (?*E. warwicki* Zone correlative), the Dummy Creek Conglomerate, Bodonga Beds, Ashford Coal Measures (?Stage 4), Wallaby beds (upper *E. preovalis* Zone) and lower Eight Mile Creek/Rhyolite Range Beds (*E. maxwelli* -*E.* n. sp. A Zone correlatives). One effect of the early stages of this movement was to cause an eastward shift in the main depocentre in the belt, so that shallow marine sediments of the *E. warwicki* to upper *E. preovalis Zone* were deposited unconformably on the Carboniferous in the Parrabel Anticline and Emu Creek areas.

The completion of mid-Permian movement is harder to date, but presumably largely predates most of the mid- to late Permian volcanic sequences, which are locally tilted, but apparently not folded.

Resumption of arc volcanism in the late Kungurian is dated by marine faunas in the basal Emmaville Volcanics near Glenmore and the lower part of the upper, volcanic unit of the Rhyolite Range Beds. Marine faunas from the Warwick-Drake area suggest that volcanism continued there until immediately after *E. ovalis* Zone time. The final phase of Permian volcanism in the region, represented by the Dundee Rhyodacite and co-magmatic plutons of the Moonbi Suite, therefore must be closely contemporaneous with the intensely tuffaceous interval in the Late Permian of the Sydney-Bowen Basin.

4. Gympie Belt:

The term "Gympie belt" is used here for rocks of the Gympie Group s. str., excluding Carboniferous, probable subduction-complex rocks also included in the Gympie terrane by various authors. Correlations of the Permian sequence shown in Figure 4 are based on my own studies, and differ from those of Waterhouse and Balfe (1987).

The Highbury Volcanics/Mant Basalt on geochemical and lithological grounds are regarded as representing an immature island arc (Murray, 1990a). Dacitic volcanics in the overlying Rammutt Formation, marking the terminal phase of the arc, are dated by marine faunas in the higher parts of the Rammutt Formation correlative of the *Bandoproductus* n. sp. Zone and *E. warwicki* Zone. The termination of arc volcanism thus coincides in time with the termination of extensional volcanism in the Sydney-Bowen Basin, and immediately precedes the onset of late Artinskian arc volcanism in the Yarrol-Tamworth belt. The time of initiation of Gympie arc volcanism is not palaeontologically constrained, but could feasibly have followed the termination of Carboniferous arc volcanism in eastern Australia.

The South Curra/Gigoomgan Limestone contains faunas of the upper *E. preovalis* Zone at its base and of the *E.* n. sp. F Zone at its top. Accumulation of a relatively small thickness of limestone over such a prolonged interval of time is consistent with accumulation on a submerged, extinct island arc remote from terrigenous sediment input. If this is the case then the sudden but conformable transition to probable turbidites of the Late Permian Tamaree/Teebar Formation indicates arrival of the arc at the trench on the continental margin. Following collision with the continent, Early to Middle Triassic trench sediments (Traveston/Brooweena Formations) accumulated unconformably over the seaward side of the arc terrane, and in part were contemporaneously deformed (forming the Kin Kin beds) prior to the intrusion of the Goomboorian Diorite around 240 Ma. Dating the accretion of the Gympie arc as late Late Permian rather than Triassic (cf. Murray, 1990a) suggests that the collision may have contributed to contemporaneous events in the New England Orogen, including deformation of the Rocksberg Greenstone and of the Nambucca Block, emplacement of the Marlborough Block, and westward overthrusting along the Hunter-Mooki and related fault systems.

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BRACHIOPOD ZONES	APP ZONES	PERTH BASIN	CARNARVON BASIN	CANNING BASIN	AMMONOID AGES
Bando-productus n. sp.	2.2(3b)			3 Nura Nura Member	3. STERLITA-MAKIAN
Strophalosia subcircularis	2.1 (3a)	Fossil Cliff 2 Member 2? Woolaga Lst	CALLYTHARRA FORMATION 2?	CAROLYN FORMATION	2. LATE TASTUBIAN
Tomiopsis elongata		HOLMWOOD SHALE 1	CARRANDIBBY FORMATION	WINIFRED FORMATION	1. EARLY TASTUBIAN
Lyonia n. sp.	1.2 (U2)	NANGETTY FORMATION	LYONS FORMATION	BETTY FORMATION	

Figure 1. Correlation of eastern Australian Early Permian zones with three standard Western Australian sections containing ammonoids. The correlation is supported by a number of macrofaunal links, and also appears to be closely consistent with palynological data from the Canning Basin (as summarized by Lehmann, 1986, Figure 4). Ammonoid ages are based on the comparisons made by Glenister and Furnish (1961) and Glenister, Windle and Furnish (1973).

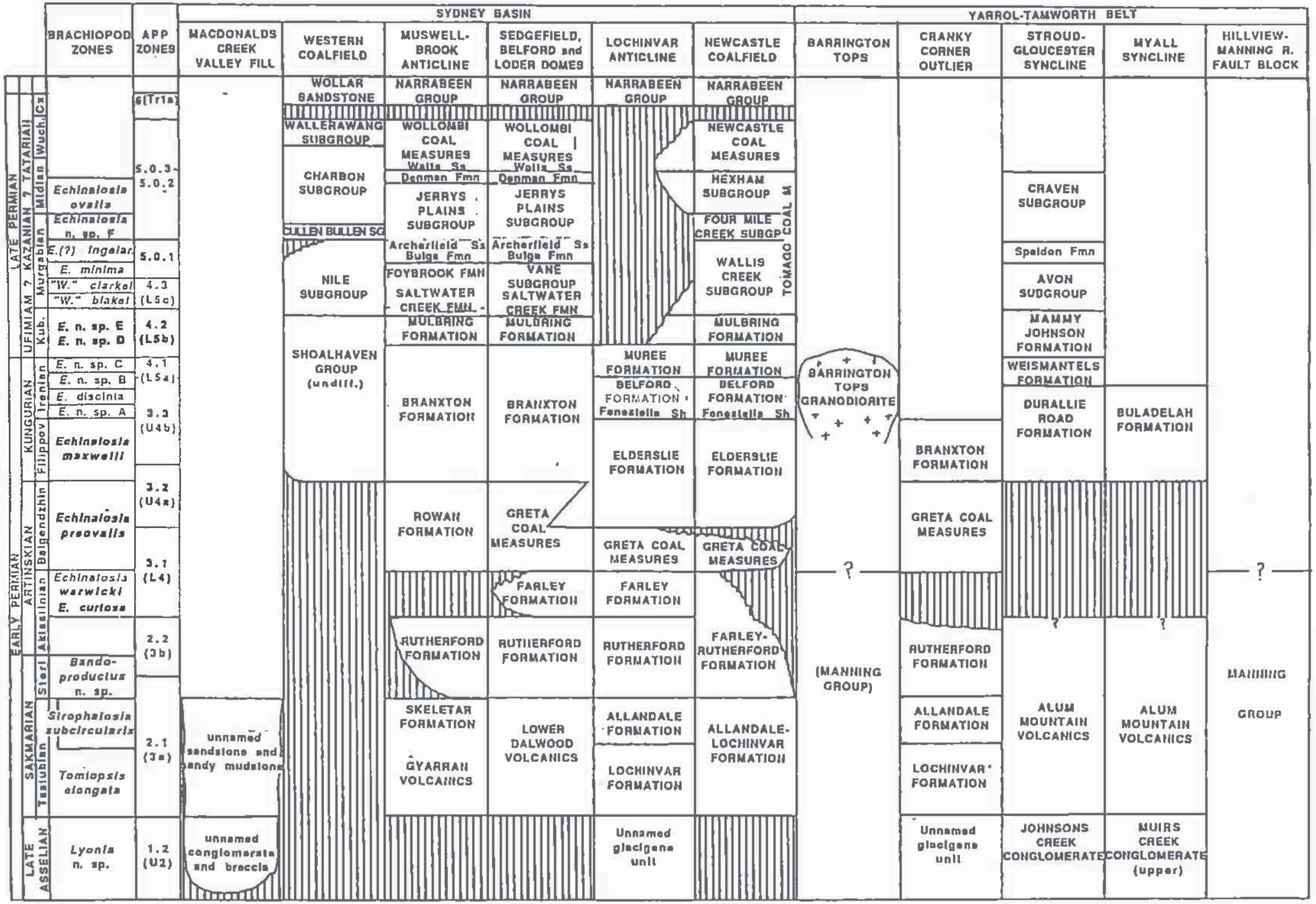

Figure 2. 32°00'S - 33°00'S: Permian units of the DUBBO, SINGLETON and NEWCASTLE 1:250 000 Sheet areas. Bracketed units are not known from the region specified, but occur in closely adjacent areas.

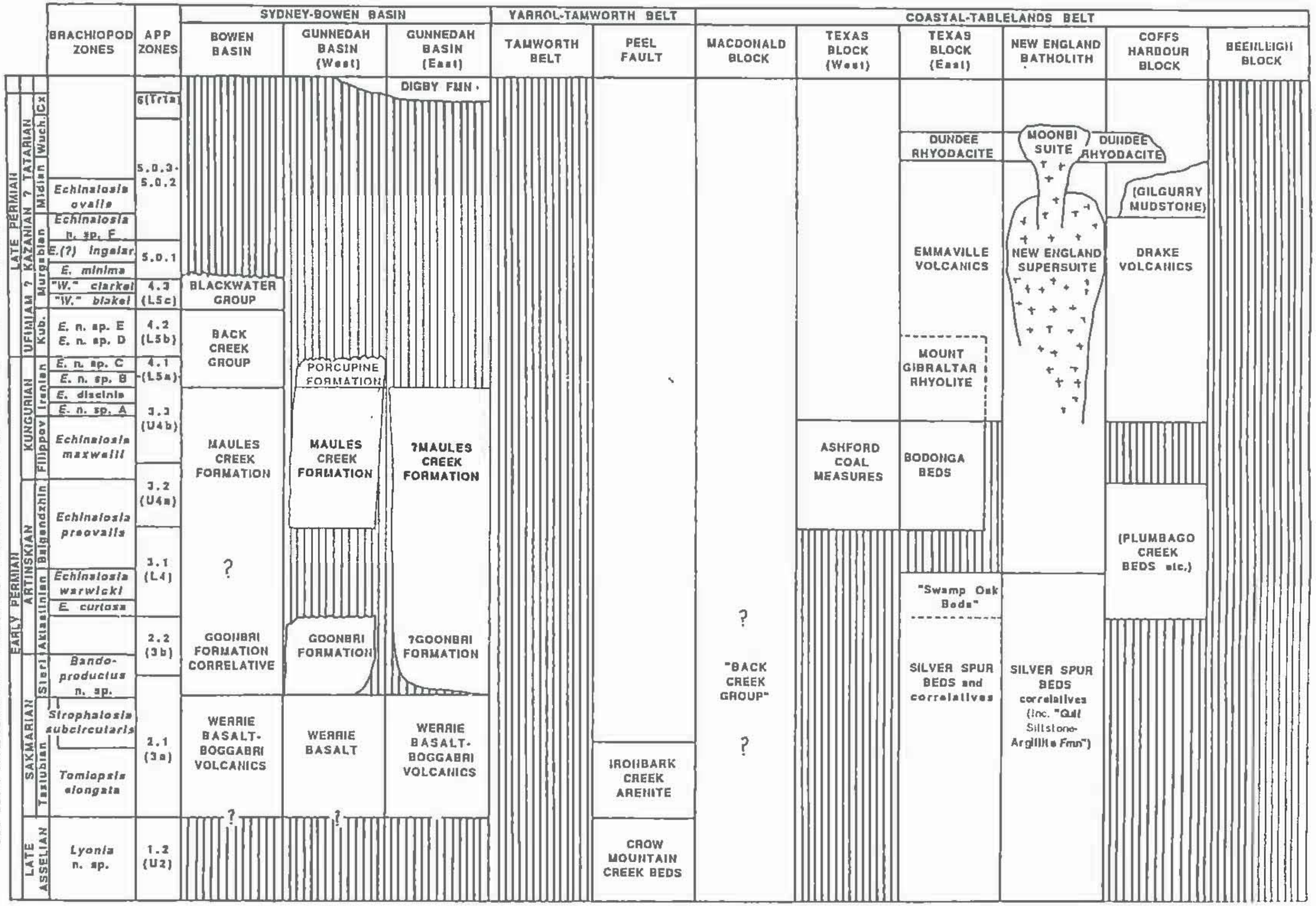

Figure 3. 29°00'S - 30°00'S: Permian units of the MOREE, INVERELL, GRAFTON and MACLEAN 1:250 000 Sheet areas. Bracketed units occur in closely adjacent areas.

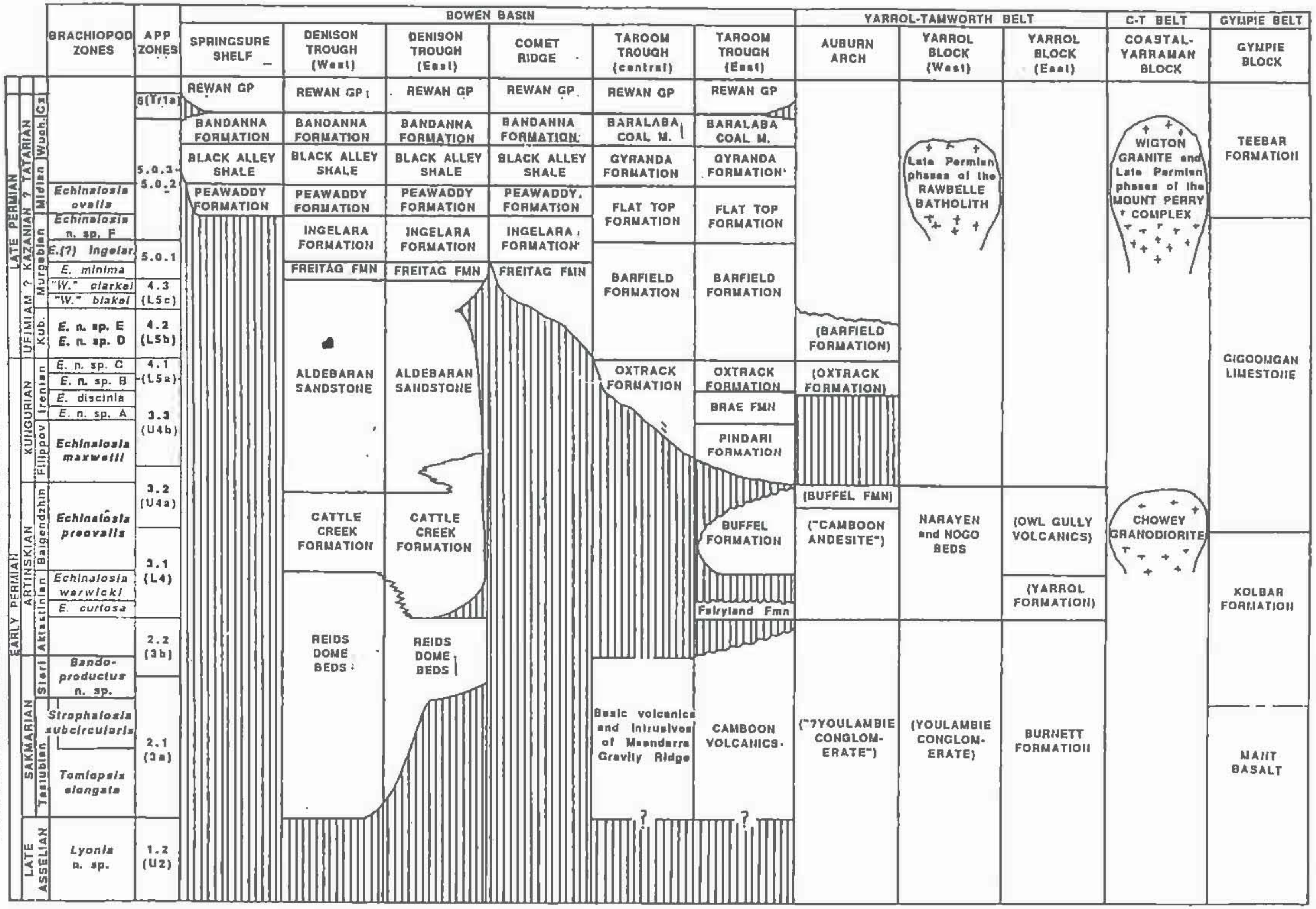

Figure 4. 25°00'S - 26°00'S: Permian units of the EDDYSTONE, TAROOM, MUNDUBBERA and MARYBOROUGH 1:250 000 Sheet areas. Bracketed units occur in closely adjacent areas.

CALIBRATION OF THE CARBONIFEROUS AND EARLY PERMIAN OF THE SOUTHERN NEW ENGLAND OROGEN BY SHRIMP ION MICROPROBE ZIRCON ANALYSES

J. ROBERTS[1], J.C. CLAOUE-LONG[2] & P.J. JONES[3]
[1] **University of New South Wales**
[2] **Australian National University**
[3] **Bureau of Mineral Resources, Canberra**

INTRODUCTION

Volcanics interbedded within Carboniferous-Early Permian marine and non-marine successions within the southern New England Orogen (SNEO) have been dated by SHRIMP ion microprobe U-Pb zircon analyses. The aims of the project include: 1) calibrating the eastern Australian Early Carboniferous biozones which are cosmopolitan in nature and can be correlated with type sections in Europe, providing more accurate information on the age of stratotype sections; 2) dating the Late Carboniferous Gondwanan cold water marine assemblages which are endemic to Australia and South America and cannot be correlated with those from elsewhere; 3) determination of the temporal extent of the Late Carboniferous glaciation; and 4) assessment of the age relationships between Late Carboniferous sequences of the SNEO and the Early Permian of the Sydney Basin and adjacent regions.

The stratigraphic succession utilised in this project is located within the Rouchel, Gresford and Myall Blocks of the SNEO in the northern Hunter Valley and Myall districts of NSW (Roberts & Engel, 1987; Roberts et al., in press). It was chosen because of frequent interfingering between volcanogenic non-marine and fossiliferous marine rocks. The andesitic and dacitic ignimbrites, rhyolite and tuff analysed are either biostratigraphically constrained by fossils, located in stratigraphic positions controlling minimum or maximum ages for fossiliferous marine strata, or have an important geological and/or stratigraphic significance. The stratigraphic locations and ages of successfully dated samples are given in Fig. 1.

The SHRIMP zircon data are at a preliminary stage of interpretation and final ages with appropriate uncertainties will not be presented here. The purpose of this abstract is to present our interim assessment of consequences for the timing of events, some of which are so major as to merit further work.

RESULTS

1. Tuffs from the Kingsfield Formation at the base of the succession, which contain the conodont *Siphonodella sulcata* and are overlain by units with the *S. crenulata* Zone, have an age of 355.8±5.6 Ma (Claoue-Long et al., in press a). This date is within error of the 353.2±4 Ma age for a bentonite, from within the *sulcata* Zone in the Hasselbachtal stratotype, used to redefine the age of the Carboniferous-Devonian boundary (Claoue-Long et al., in press a); the system boundary is taken at the base of the *sulcata* Zone.

2. Volcanics from the non-marine Waverley and Isismurra Formations provide an indication of age for the *Schellwienella burlingtonensis* Zone and a maximum age for the *Orthotetes australis* Zone. The Kurra Keith Tongue of the Isismurra Formation has an age of around 345 Ma and provides an approximate minimum age for the *burlingtonensis* Zone. Conodonts of the *Scaliognathus anchoralis* Zone in the upper part of the *burlingtonensis* Zone enable this to be used as an estimate for the Belgian Tn3c-V1a. An unnamed pyroxene andesite within non-marine Waverley Formation sediments intertonguing with the Dangarfield Formation (*burlingtonensis* Zone) provides a less well defined constraint of around ~350 Ma for the maximum age of the zone

3. The Gilmore Volcanics Group and Nerong Volcanics are used to constrain the ages of the *Delepinea aspinosa* and *Rhipidomella fortimuscula* Zones. The Martins Creek Ignimbrite Member underlies marine sediments (Chichester Formation) containing the *fortimuscula* Zone (note that there are possible *fortimuscula* fossils beneath the ignimbrite south Dungog) and overlies units containing the *aspinosa* Zone. The Nerong Volcanics similarly overlie units with *aspinosa* (Conger Formation) and either upper *aspinosa* or *fortimuscula* Zone assemblages (Boolambayte Formation; Roberts et al., in press). The Lambs Valley Ignimbrite Member overlies sediments containing the *fortimusucula* Zone and provides a minimum age for that zone. Foraminifera from the upper *aspinosa* Zone belonging to zones 13-15 of Mamet (Roberts, 1975) are of V2b-V3b age, and ammonoids from the *fortimuscula* Zone (Campbell et al., 1983) are now considered to be B2-P1 (=V3b) in age (after Riley, 1990). The V3b lies within the range 340-330 Ma.

4. The Paterson Volcanics have an important stratigraphic position beneath the glacial Seaham Formation and also signal the beginning of the Kiaman Magnetic Interval. The volcanics were dated from two separate localities and have an age of around 330 Ma, which is late Visean rather than Westphalian, as indicated from previous K-Ar dates (Roberts et al., in press).

5. Two volcanics within the Seaham Formation have yielded Namurian and Westphalian ages, but units at the top of the formation contain zircons which have been obviously recycled; the upper limit on the glaciation has not been determined.

6. Rhyolites from the upper part of the Booral Formation and the McInnes Formation provide a minimum age of around 285 Ma for the *Levipustula levis* Zone and an even younger age for the overlying non-marine units

7. Rhyolite from the Alum Mountain Volcanics dates the incoming of the *Glossopteris* flora and Stage 3a Microflora at around 275 Ma.

GEOLOGICAL CONSEQUENCES

1. The major geological consequence of the new dates concerns the usage of 'Late Carboniferous' and 'Permian' in eastern Australia and most of Gondwana. The top of the Stephanian Stage in Europe is around 300 Ma (Lippolt & Hess, 1985) or 295 Ma (Jones, 1988) in age, and is overlain by the Autunian, the basal Permian unit in Europe. On the basis of palaeobotanical evidence, the Autunian is equated with the Asselian in USSR (Rausa-Chernousova et al., 1979), the base of which is currently favoured as the defined base of the Permian System. Provided these ages and corelations are correct, the upper part of the *Levipustula levis* Zone (upper Booral Formation) and the overlying McInnes Formation, Koolanock Sandstone, and Johnsons

and Muirs Creek Conglomerates are Permian and not Late Carboniferous as previously indicated. The interval of time assigned to the 'Permian' Period in eastern Australia is therefore quite short (~25 Ma), extending from around 275 Ma to the beginning of the Triassic (around 251 Ma; Claoue-Long et al., in press b); this age is compatible with that of 256±4 for the Awaba Tuff from 50 m below the top of the Newcastle Coal Measures in the Sydney Basin (Gulson et al., 1990).

2. If these indications are confirmed, the *Nothorhacopteris* flora in eastern Australia (e.g. in the McInnes Formation) extends into the Permian, and that the incoming of the *Glossopteris* flora and the Stage 3a Microflora, which some authors (e.g. Balme, 1980) have been taken to indicate the beginning of the Permian, took place some 20 Ma after the commencement of that period and is consistent with Early Permian faunal dating of pre-Stage 3 palynofloras elsewhere in Australia (Foster & Waterhouse, 1988). The first appearance of the *Nothorhacopteris* flora is also older than previously suspected because dates from the Paterson Volcanics confine the Mt Johnstone Formation to well within the Visean, probably the late V3b or earliest V3c.

3. The duration of the *L. levis* Zone, from near the base of the Namurian (~325 Ma) to about 285 Ma is approximately equal to the duration of the entire Early Carboniferous and far longer than that of the 'Permian' Period in eastern Australia. This requires testing with further work. Support for the new interpretation is provided by the co-incidence of the cold water fauna with onshore deposition of the glacial Seaham Formation and widespread glaciation throughout Australia (Powell & Veevers, 1984).

4. The major outburst of Carboniferous volcanogenic activity and deposition of volcanogenic sediments took place in the Visean and now includes the Paterson Volcanics and Mt Johnstone Formation. The prominent disconformity beneath the latter unit, previously regarded as having tectonic significance, is best interpreted as a brief but widespread uplift within the volcanic arc.

5. Changes in the correlation of non-marine units (Fig. 1) mean that most Late Carboniferous macro- and microfloral zones require substantial revision. For example, the 'enriched *Nothorhacopteris*' flora recorded from the Mt Johnstone Formation (now Visean) and the McInnes Formation (now Permian) was regarded as significant for correlation (see Morris, 1985, fig. 42); it may have been climatically controlled. The *Potonieisporites* Assemblage of Helby (1969), from just above a tuff dated as Westphalian in the Seaham Formation at Paterson, is older than the *Diatomozonotriletes birkheadensis* Assemblage (previously assigned to the *Spelaeotriletes ybertii* Assemblage) in the McInnes Formation; this apparent reversal of the succession of palynofloras is probably the result of changes in the criteria used for zonal recognition (e.g. the first appearance of monosaccate pollen, which originally defined the base of the *Potonieisporites* Assemblage of Helby, was later taken by Kemp et al., 1977 to define the base of the *Spelaeotriletes yberti* Assemblage, or its equivalent in eastern Australia.

6. The late Visean age of the Paterson Volcanics now requires the Kiaman Magnetic Interval to commence at that time rather than in the Westphalian as suggested by K-Ar ages (Roberts et al., in press).

7. The age of the base of the Carboniferous Period (353.2±4) is younger than the previous ages of 363 Ma (Harland et al., 1990) and 360+5-10 Ma (Odin, 1982).

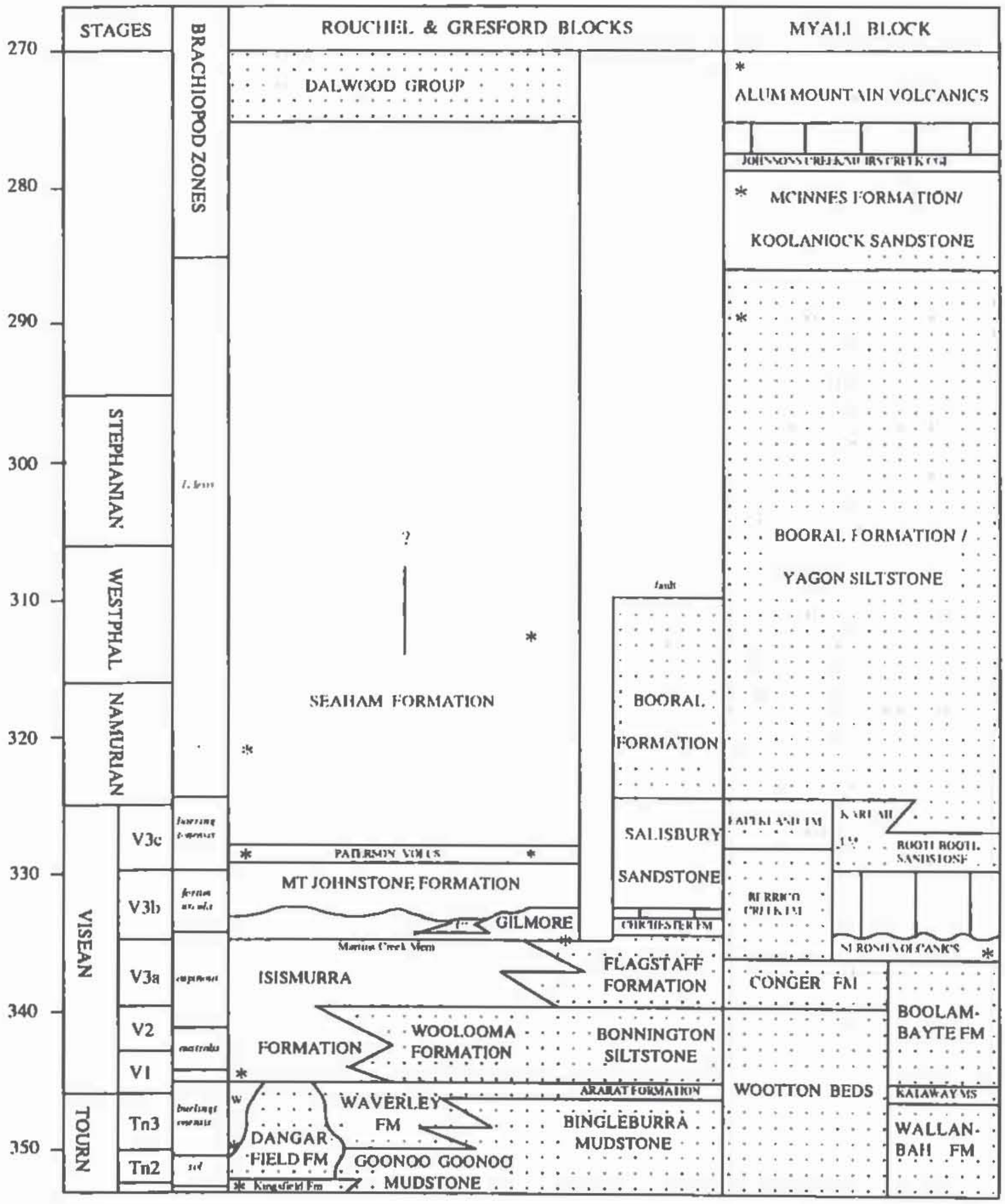

Figure 1. Preliminary correlation chart of Carboniferous and Early Permian units of the southern New England Orogen based on biostratigraphic information and new data from zircon analyses. Marine rocks stippled.

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LATE PERMIAN AND TRIASSIC IGNEOUS ACTIVITY IN THE NEW ENGLAND BATHOLITH AND CONTEMPORANEOUS TEPHRA IN THE SYDNEY AND GUNNEDAH BASINS

S.E. SHAW, P.J. CONAGHAN & R.H. FLOOD
Macquarie University

INTRODUCTION

Although the New England Batholith has a history that spans some 80 Ma, it formed principally as the result of two major intrusive events: the first during the latest Carboniferous and earliest Permian generated the S-type Hillgrove and Bundarra Plutonic Suites; and the second during the Late Permian and Triassic (Shaw & Flood 1981) when as much as 66% of the Batholith was emplaced. Igneous activity between these two events was responsible for emplacement of plutons at Barrington Tops (269-265 Ma, Roberts & Engel 1987), Balala (275 Ma biotite Rb/Sr, Shaw unpublished) and possibly elsewhere, but appears to have been minor. Many of the Late Permian and Triassic granitoids were emplaced at relatively shallow levels and were accompanied by extensive volcanism, now preserved as silicic tephra-fall and tephra-flow material both within the New England Fold Belt and the adjacent Sydney and Gunnedah Basins.

For much of the Permian and Triassic, the Sydney and Gunnedah Basins, as sectors of the Gondwanan foreland Sydney-Bowen Basin, received sediments that were either quartz-rich and craton-derived from the west, or labile and orogen-derived from the east. Late Permian deposition in the Sydney and Gunnedah Basins is dominated by a large piedmont wedge of labile sediments comprising volcanolithic silts and sands, conglomerates, tephra/tuffaceous-claystone and coal. The abundance of tephra units in the Upper Permian coal measures of both the Sydney and Gunnedah Basins has already been argued by various authors (e.g. Brownlow 1979; Byrnes 1982b; Jones et al. 1984, 1987; and Diessel 1985) as evidence of coeval volcanism in the New England Orogen.

We present new biotite Rb/Sr age data that refine previous age estimates of Late Permian and Triassic igneous activity in the New England Batholith. The distribution of the data is discussed in relation to centres of igneous activity within the Batholith, and to the contemporaneous development of tephra/tuffaçeous-claystone units within the Sydney and Gunnedah Basins

LATE PERMIAN AND TRIASSIC IGNEOUS ACTIVITY

Plutons of this age occupy the central, northern and eastern parts of the Batholith. They comprise the Moonbi, Uralla and Clarence River Plutonic Suites (Shaw & Flood 1981), leucocratic and other plutons of the Mole and Stanthorpe areas and a series of discrete Triassic plutons including the Round Mountain Leucoadamellite and others east of the main Batholith between the latitudes of Coffs Harbour and Port

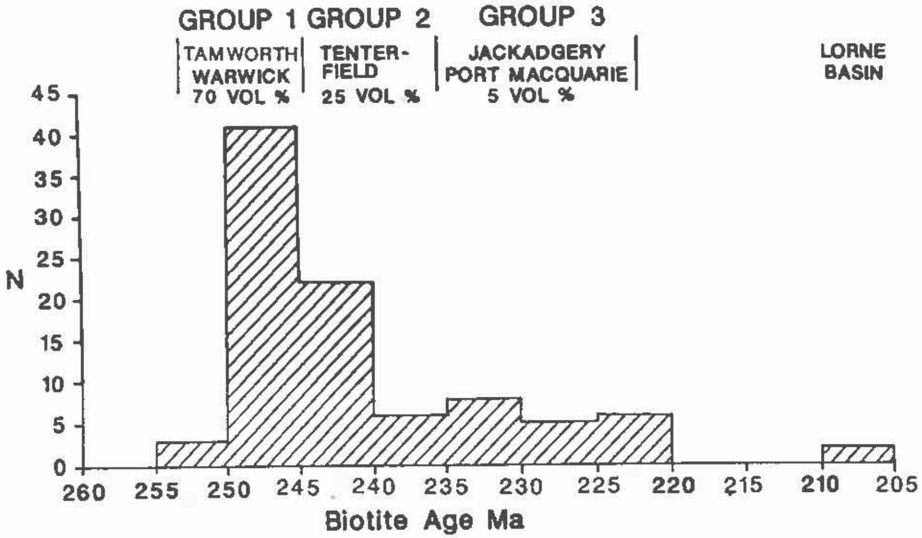
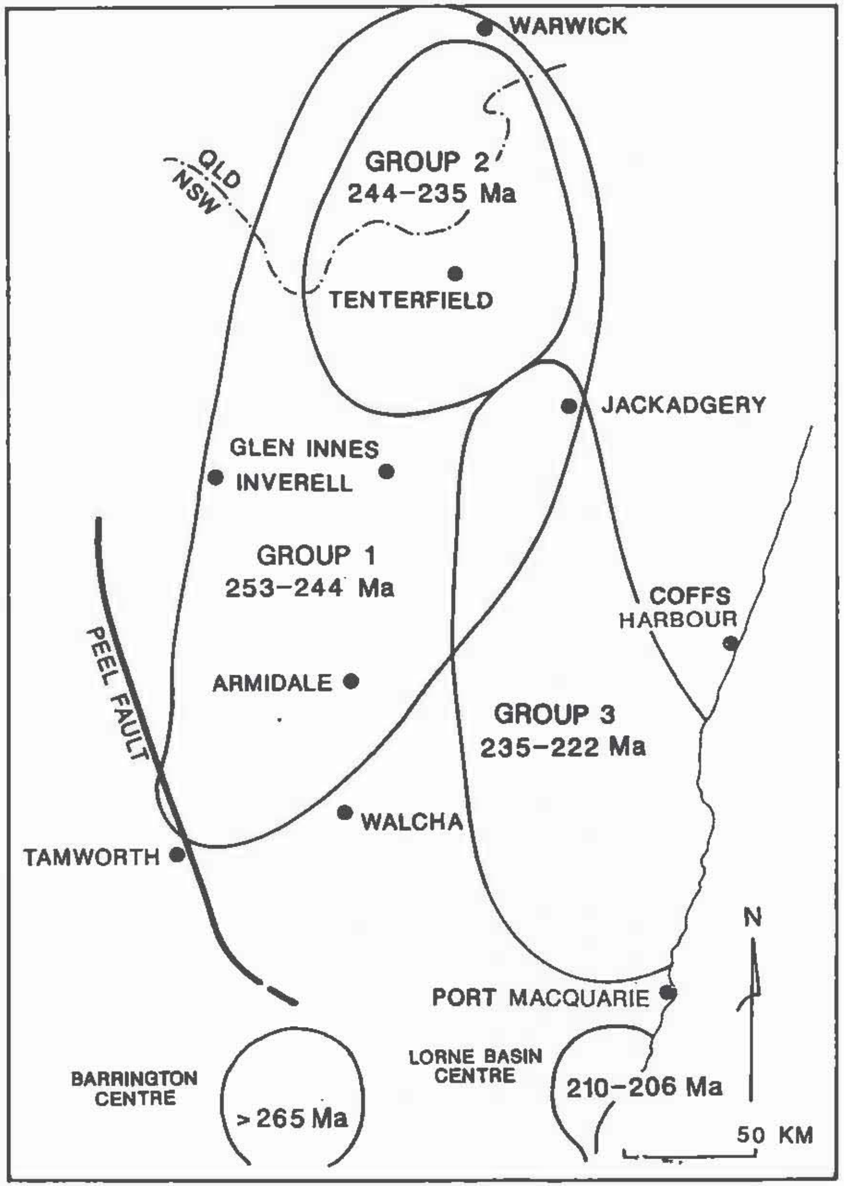
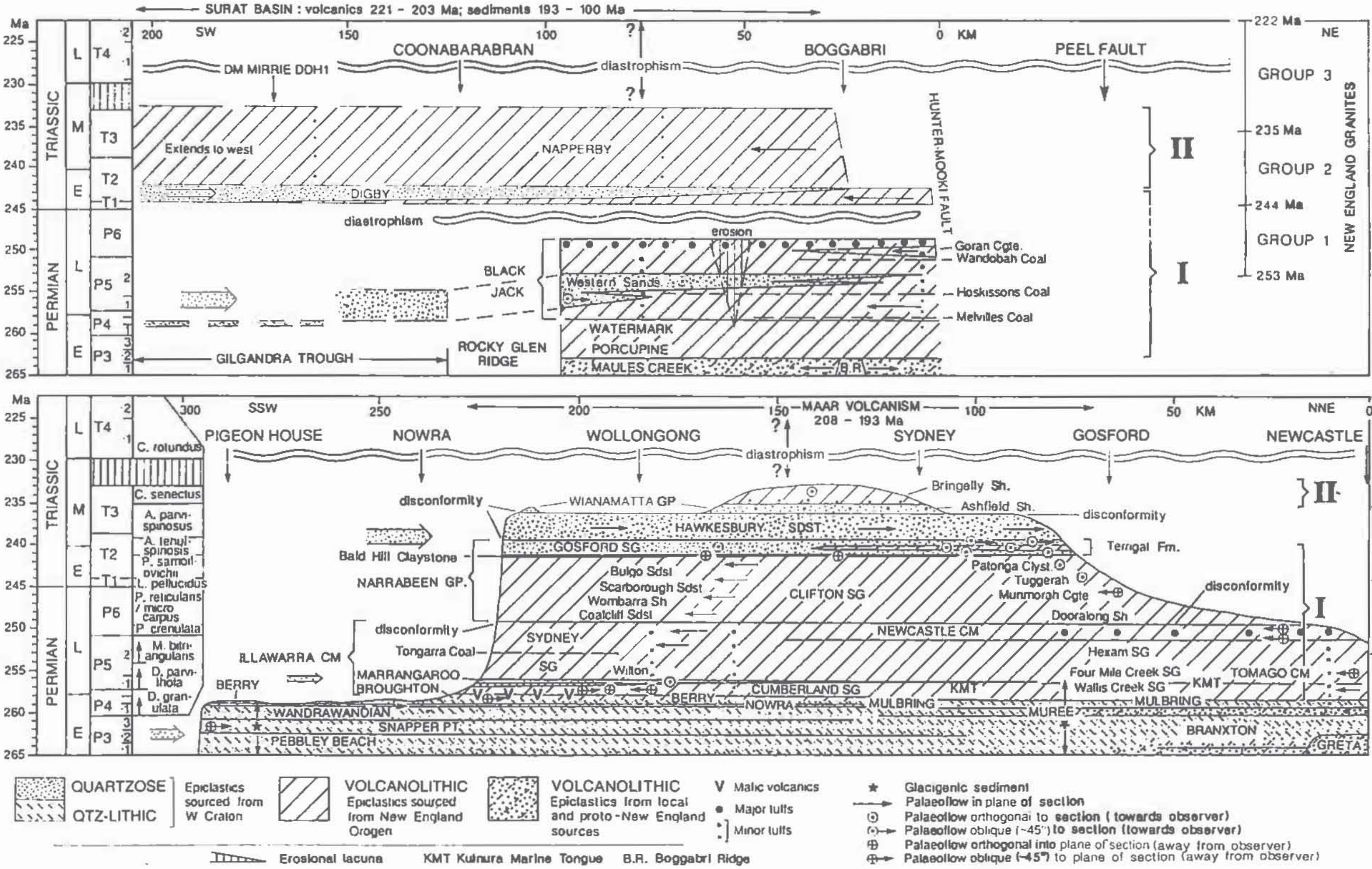


Fig. 1. (above) Histogram of 93 biotite Rb/Sr age determinations from the New England Batholith. Subdivision of the ages according to centres of igneous activity.

Fig. 2. (right) Schematic representation of centres of igneous activity of Late Permian and Triassic granitoids by age groupings. Older Bundarra and Hillgrove Plutonic Suites are not included.

Fig. 3. (facing page) Time-space transects of the Gunnedah and Sydney Basins. Modified from Veevers & Powell (in prep.). Geological time-scale from Palmer (1983). Palynostratigraphic units and index forms from Price et al. (1985) calibrated against stratigraphy of the Sydney and Gunnedah Basins by Veevers (unpubl.). I and II refer to pulses of volcanolithic sediment from the New England Orogen.




SURAT BASIN : volcanics 221 - 203 Ma; sediments 193 - 100 Ma
Ma
SW
NE
KM
222 Ma
COONABARABRAN
BOGGABRI
PEEL FAULT
DM MIRRIE DDH1
diastrophism
GROUP 3
TRIASSIC
PERMIAN
HUNTER-MOOKI FAULT
Extends to west
NAPPERBY
II
235 Ma
GROUP 2
NEW ENGLAND GRANITES
DIGBY
244 Ma
diastrophism
erosion
GROUP 1
Goran Cgte.
Wandobah Coal
BLACK JACK
Western Sands
I
253 Ma
Hoskissons Coal
Melvilles Coal
WATERMARK
PORCUPINE
MAULES CREEK
B.R.
GILGANDRA TROUGH
ROCKY GLEN RIDGE
SSW
NNE
MAAR VOLCANISM 208 - 193 Ma
PIGEON HOUSE
NOWRA
WOLLONGONG
SYDNEY
GOSFORD
NEWCASTLE
C. rotundus
C. senectus
A. parvispinosus
A. tenuispinosis
P. samoilovichii
L. pellucidus
P. reticulans / microcarpus
P. crenulata
M. bitriangulans
D. parvithola
D. granulata
disconformity
WIANAMATTA GP
Bringelly Sh.
Ashfield Sh.
HAWKESBURY SDST.
GOSFORD SG
Terrigal Fm.
Bald Hill Claystone
Patonga Clyst.
NARRABEEN GP.
Bulgo Sdst
Scarborough Sdst
Wombarra Sh
Coalcliff Sdst
CLIFTON SG
Tuggerah
Munmorah Cgte
Dooralong Sh
NEWCASTLE CM
ILLAWARRA CM
Tongarra Coal
SYDNEY SG
Hexam SG
Four Mile Creek SG
Walls Creek SG
KMT
TOMAGO CM
MARRANGAROO
BROUGHTON
Wilton
BERRY
CUMBERLAND SG
NOWRA
MULBRING
MUREE
WANDRAWANDIAN
SNAPPER PT.
PEBBLEY BEACH
BRANXTON
GRETA
QUARTZOSE
QTZ-LITHIC
Epiclastics sourced from W Craton
VOLCANOLITHIC Epiclastics sourced from New England Orogen
VOLCANOLITHIC Epiclastics from local and proto-New England sources
V Mafic volcanics
Major tuffs
Minor tuffs
Glacigenic sediment
Palaeoflow in plane of section
Palaeoflow orthogonal to section (towards observer)
Palaeoflow oblique (~45°) to section (towards observer)
Palaeoflow orthogonal into plane of section (away from observer)
Palaeoflow oblique (~45°) to plane of section (away from observer)
Erosional lacuna
KMT Kulnura Marine Tongue
B.R. Boggabri Ridge

Macquarie. Within the Batholith proper, there are extensive areas of eroded silicic ignimbrite, tephra-fall, epiclastic material and minor lava flows presently mapped separately under several stratigraphic names. Mapping of the Emmaville Volcanics and overlying Dundee Rhyodacite ignimbrite (Shaw & Flood 1988; M^c Phie 1986) has shown they are relatively thin (less than 2 km thick) essentially flat-lying deposits forming the preserved remnants of structural basins (caldera?). Other volcanics, some of which form the erupted parts of high-level plutons, occur at Uralla-Kentucky (Flood 1971), Wandsworth, Drake and Werrikimbie in the Hastings Block.

AGE RESULTS

As part of a regional Rb/Sr age-dating programme in the New England Batholith, we have been systematically dating separated biotite from undeformed granitoids and those volcanic units that contain unaltered biotite. Isotope analyses were conducted at the Centre of Isotope Studies, C.S.I.R.O. North Ryde. Biotite ages were calculated using host-rock data where available, or otherwise estimates of host-rock initial ratios. Age uncertainties (at the 95% confidence level) were calculated as 0.5% (or +/- 1 Ma for Late Permian ages). However, replicate analyses of coarse-grained biotites (>100 microns) for 0.1 g sample sizes, commonly show age differences of up to 4 Ma that indicate isotopic inhomogeneities between samples. While these differences could be eliminated by grinding the biotite more finely, it does show that geological variations exceed analytical precision and that realistic Rb/Sr biotite age estimates are no better than +/- 2%.

A histogram of 93 new biotite age determinations from the New England Batholith (Fig. 1) indicates more or less continuous igneous activity from 253-222 Ma with the initial period between 253-244 Ma accounting for an estimated 70% of the total Late Permian and Triassic activity.

Examination of the spatial relationships of the granitoids with respect to their ages and compositional groupings suggests that the centre or locus of igneous activity changed with time. Three igneous centres or groups of temporally-related intrusions can be recognized and their broad geographic distributions are outlined in Fig. 2.

Group 1. 253-244 Ma: Granitoids of the central Batholith, forming a broad NNE-trending belt between Tamworth and Warwick. They include the Moonbi, Uralla and Clarence River Plutonic Suites, the Greymare Granodiorite west of Warwick and an adamellite pluton near Texas. Contemporary extrusives include the Terrible Vale tufficites near Uralla (Flood 1971), volcanics near Wandsworth, the Drake Volcanics and the Dundee Rhyodacite ignimbrite. The Emmaville Volcanics, underlying the Dundee Rhyodacite ignimbrite are included since they appear conformable with the Dundee and are no older than Fauna IV age (Olgers 1974). The distribution of some of these plutonic rocks (e.g. the Moonbi and Uralla Plutonic Suites) within an elongate NNE zone, and the association of extensive coeval volcanics, preserved partly as caldera-fill, indicate that igneous activity probably took place in a rift or graben structure similar to the Taupo Volcanic Zone, the Rio Grande Rift or the Oslo Rift. Preserved volcanic rocks are mainly rhyolite and rhyodacite ash-flow and ash-fall material containing abundant glass matrix (now devitrified) marked by shard shapes, broken phenocrysts of plagioclase, coarse biotite and beta-form quartz. Hornblende and pyroxene are less abundant in rhyodacite tephra and orthoclase more common in rhyolite tephra.

Group 2. 244-235 Ma: Mainly large leucocratic granitoids of the northern Batholith centered around Tenterfield. They include the Mole, Stanthorpe, Bolivia Range, Billyrimba, Mackenzie, Nonnington, Mt Jonblee and Petries Sugarloaf plutons. They occur within the belt of Group 1 granitoids, and as argued by Shaw & Flood (1981), "have resulted from low degrees of 'dry' partial melting of an I-type source region that had undergone an earlier melting event". We are not aware of volcanic rocks associated with these granitoids.

Group 3. 235-222 Ma: Widely separated plutons of the eastern Batholith found within a poorly defined SSE-trending zone between Jackadgery and Port Macquarie. They include the Round Mountain, Dandahra Creek, Carrai, Botumburra plutons, small granitoids near the coast between Valla and South West Rocks, and the Gundle group plutons. Contemporary extrusives include the dacite and rhyolite caldera complex at Cockawambeeba (forming the Werrikimbe Volcanics) some 20 km west of the Gundle plutons. The compositions of Group 3 plutons are quite diverse, varying from leucogranites to I-type hornblende-biotite granodiorites. Rhyolite and biotite-dacite tephra are found only in association with the Cockawambeeba caldera.

MAIN PATTERNS OF SEDIMENT PROVENANCE IN THE SYDNEY AND GUNNEDAH BASINS

Provenance relationships in the Sydney and Gunnedah Basins are depicted on time-space sections (Fig. 3) oriented orthogonally to the regional trend of the onshore segment of the New England Fold Belt as defined by the Hunter-Mooki Thrust System. In the case of the Sydney Basin, the line of the section runs parallel to the coast and is inferred to lie no more than a few tens of kilometers west of the proposed southern or offshore extension of the New England Orogen (Jones et al. 1984, 1987; Brakel 1984). Early Permian sedimentation in the precursor Sydney and Gunnedah Basins predated the main phase of development of the New England Orogen and was dominated by influx of quartz-lithic detritus from the craton on the west and by the accumulation of volcanolithic detritus from local extensional-phase volcanics (i.e., Werrie Basalt, Boggabri Volcanics etc.) and proto-New England sources on the east.

As a result of progressive large-scale deformation and magmatic activity ('Hunter-Bowen Orogeny') in the Orogen (Roberts & Engel 1987; Collins 1990), two major pulses of volcanogenic sediment were deposited within the Sydney and Gunnedah Basins (Pulses I and II in Fig. 3). These volcanolithic sediments are characterised by dispersal patterns directed either away from the New England Orogen or parallel to its western margin and contain major tephra deposits, the sedimentary characteristics of which indicate derivation from the New England Orogen. These volcanolithic sediment pulses are equivalent to the megacycles described by Conaghan et al. (1982) and Jones et al. (1984) and contain the main record of preserved tephra deposits.

Pulse I in the Sydney Basin comprises the Upper Permian coal measures and the Narrabeen Group and Pulse II comprises the upper two-thirds of the Middle Triassic Wianamatta Group (specifically the Minchinbury Sandstone and Bringelly Shale). These two volcanogenic sediment pulses in the Sydney Basin are separated by the craton-derived Hawkesbury Sandstone and Ashfield Shale, thought to represent an interval of relative tectonic quiescence in the southern New England Orogen. In the Gunnedah Basin Pulses I and II are separated by the upper, quartzose phase of the Digby Formation. In the northern and central Gunnedah Basin on erosional lacuna occurs within the upper part of Pulse I.

TEPHRA DEPOSITS IN THE SYDNEY AND GUNNEDAH BASINS

Patterns of tephra development in the Sydney and Gunnedah Basins are generally the same, both in terms of stratigraphic positioning and frequency of occurrence. They differ, however, in the nature of the beds (i.e. tephra-flow versus tephra- fall, and thickness) a consequence of distance from source. In the Sydney Basin, the first appearance of tephra is at the top of the Wandrawandian Siltstone (in the south) and the Mulbring Siltstone (in the north) (Fig. 3). These tephra units, many less than 10 mm thick, increase in thickness and frequency in an irregular pattern upwards throughout the Tomago Coal Measures and correlatives and culminate in the Newcastle Coal Measures and correlatives with very thick units (up to 25 m; Diessel 1985), some of which are surge and tephra-flow deposits. They contain bentonitic clays and have a mineralogy of quartz, biotite and feldspar (Diessel 1985). The thickness and bedding characteristics of some of these tephra units (e.g. Nobbys Tuff and Reids Mistake Tuff) suggest that they are at relatively close to moderate distances from the eruptive sources (McDonnell 1983; Diessel 1985; Mushenko 1985).

In the Gunnedah Basin, tephra first appears in the Watermark Formation as rare thin air-fall beds (max. 10-15 cm). Rare tephra beds of similar thickness are present in the lower part of the Black Jack Formation but from the Wandabah Coal Member upwards, tephra abundance increases dramatically, forming an interbedded tephra-coal sequence that culminates in the Tuffaceous Stony Coal Facies (Byrnes 1982b; Tadros 1986; Tadros pers. comm. 1991). Individual tephra beds are up to 5 m thick but more commonly 30-40 cm thick. The distal nature of these tephra units is reflected in their fine grainsize and the presence of biotite flakes as much as 1.2 mm across. The distances to probable Group I (Emmaville- or Dundee-related ?) source vents are of the order of 100 km. On the time-space diagram (Fig. 3), the indicated interval from the Wandabah Coal Member to the eroded top of the Black Jack Formation is 251-248 Ma (and possibly younger because of the missing sequence), corresponding well with the radiometric age peak of Group I granitoids (249-246 Ma). As biotite radiometric data record pluton cooling ages, rather than ages of intrusion or extrusion, the age discrepancies are minor and are in the direction to be expected.

The disappearance of tephra above the Upper Permian coal measures of the Sydney Basin is not considered to be due to non-preservation, as suitable low-energy (including lacustrine) environments conducive to their preservation are a feature of parts of the overlying succession, i.e. Narrabeen group. In the Gunnedah Basin, however, the top of the Upper Permian coal measure succession was eroded during latest Permian diastrophism and it is therefore difficult to assess whether tephra deposits were present in the section that has been removed. The reconstructed palynostratigraphic age of the interval of peak tephra influx in both the Sydney and Gunnedah Basins is much the same (i.e., Upper 5c-basal Tr1a palynostratigraphic zones in the older terminology; Gunnedah Basin 251-248 Ma and Sydney Basin 251-249 Ma).

Younger tephra deposits in the Sydney Basin are presently known only from the Middle Triassic Wianamatta Group. The first occurrence is in the base of the Ashfield Shale and consists of a thin white tuff a few mm thick (Byrnes 1982a). A second tephra unit is found in the base of the overlying Bringelly Shale (Cobbitty Claystone Bed) and contains grains of quartz, apatite, zircon, garnet (?), muscovite (?) and alkali feldspar (Byrnes 1974), suggesting a rhyolitic source. These Wianamatta Group tephras correspond in age to the boundary between the Group 1 and Group 2 granitoids (Fig. 3). In the Gunnedah Basin, thin beds of pelletal flint-clayrock, interpreted by us to be tuffs, occur within the Napperby (previously Wallingarah) Formation (Higgins & Loughnan 1973) though there are presently few data on their stratigraphic and geographic extent.

CONCLUSIONS

New age-data for biotite from the New England Batholith show a period of magmatic activity from 253-222 Ma with a major magmatic pulse, Group 1, between 253-244 Ma, accounting for 70% of the total Late Permian-Triassic igneous activity.

The ages, distribution of plutons and compositions can, on a first order basis, be subdivided into 3 groups. The location of magmatic centres of each group changed with time, although magmatic activity appears to have been continuous. Granitoids of similar compositional type may be present in more than one group.

The Group 1 magmatic pulse, the most major of the Batholith, was accompanied by rhyolitic and rhyodacitic tephra that, judging from the extensive remnants still preserved in the Batholith, must have been considerable at the time of eruption and must have had profound effects in adjacent sedimentary basins. From the time-space diagram (Fig. 3), the reconstructed palynostratigraphic time interval for preserved peak tephra deposits in the Sydney and Gunnedah Basins are 251-248 and 251-249 Ma respectively, corresponding well with Group 1 ages.

There is no satisfactory explanation of the presence of tephra deposits (although lithologically insignificant, Diessel 1980) in the lower Tomago Coal Measures and correlatives, unless they were derived from a source other than New England, as they appear too old to have been derived from the Group 1 plutons. However, there are strong arguments (Diessel 1980,1985; Jones et al. 1984, 1987) from thickness and onshore dispersal patterns of proximal tephra deposits and alluvial-fan conglomerates in the Newcastle Coal Measures, that the New England Orogen continued east of and then southerly parallel to the present coast ("offshore southern sector" Jones et al., 1987; "Currarong Orogen" Jones et al., 1984; "Northumberland Ridge" Brakel 1984). This postulated offshore segment of the Orogen must have been the source for the lower Tomago (and correlative) Coal Measure tephra deposits, as well as the centre for latite extrusives in the southern Sydney Basin (Jones et al. 1984, 1987).

Zircon U/Pb ages from tuffaceous units in the Tomago and Newcastle Coal Measures (Gulson et al. 1990) are older than the ages expected from the palynostratigraphic scale (Fig. 3) and the culmination of tephra abundance in both the Sydney and Gunnedah Basins. Our data suggest a close relationship between the major period of igneous activity (Group 1 plutonism) and the abundance of tephra. There is also a reasonable correspondence of our age data to the time-scale of the Sydney and Gunnedah Basins as calibrated by Veevers (unpubl.).

The area of Group 1 granitoids extends from Tamworth to Warwick and it can be assumed on the basis of similar granitoid compositions, that volcanic rocks such as those found at Emmaville-Dundee were a feature of the zone. The effects from such outpourings would not only be recognised in the adjacent Sydney and Gunnedah Basins as ash-fall and ash-flow deposits, where contemporaneous depositional environments allowed for their preservation, but as a significant component of reworked juvenile sediment influx to the Sydney and Gunnedah Basins (Conaghan et al. 1982, Jones et al., 1984). By analogy with the Taupo Volcanic Zone, positioned as it is within a graben structure, and at low elevations, and providing vast volumes of vocanolithic material, there may not be a strong argument for the New England Orogen to have been associated with significant uplift during intrusion (cf. Roberts & Engel, 1987).

The erosional lacuna within the upper part of volcanolithic sediment Pulse I increases in temporal significance northwards from the southern Gunnedah Basin to the Narrabri Ridge and declines northwards from there in the Bowen Basin (Etheridge 1987). This regional pattern is mirrored by the northward shift of the centre of magmatic activity between the Group 1 and Group 2 plutons. Tephra deposits related to the latter phase of Group 3 plutonism might be expected to occur in the Clarence Basin to the northeast.

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THE WERRIE VOLCANICS, WINGEN NSW : GEOLOGY, GEOCHEMISTRY AND TECTONIC SIGNIFICANCE

M.D. VICKERS
University of New England

INTRODUCTION

Volcanic rocks outcrop in a stratigraphic position at or near the base of the Sydney Basin in a number of areas, and are a key to deciphering the late Palaeozoic evolution of Eastern Australian (eg Leitch, 1969, 1974; Scheibner, 1973). With a strike length of at least 90km, and thickness of up to 2000m, the Early Permian Werrie Volcanics (WV) (eg Manser, 1968 for review) take this near-basal position at the Basin's northeastern margin. The WV overlie the fluvial Temi Fm, which onlaps the Late Carboniferous continental margin Currabubula Fm which is dominated by calc-alkaline volcanic arc derived sediments (McPhie 1987) and calc-alkaline lavas (Wilkinson, 1971).

Several tectonic models for the evolution of New England and the Sydney Basin include the WV in their discussions (eg Brownlow, 1982; Leitch 1969, 1974; Roberts and Engel, 1987; Scheibner, 1973). These rocks have been cited along with the silicic Boggabri, Gunnedah and Warrigundi volcanics as evidence for bimodal rift-related volcanism (eg Roberts and Engel, 1987; Scheibner, 1973). The models are hampered by a lack of detailed petrogenetic studies, because although they cover about 500 km^2, the generally pervasively zeolitized WV weather readily and outcrop very poorly (eg Manser, 1968).

Presented here are the results of a study of the WV near its southernmost extremity, east of Wingen in the Upper Hunter Valley. Local topographic relief of 500 m provides some relatively fresh exposures of these volcanics. Particular questions addressed are:

- Can any lithological variation be mapped within the WV and if so, could a source be indicated? [Benson et al (1920) proposed the Warrigundi Volcanic Complex near Currabubula as the source for the WV. This is supported by Flood et al, (1988).]

- Is the WV a continuation of the Late Carboniferous calc-alkali volcanism, or is it chemically distinct? [Leitch (1974) and Leitch et al (1988) have suggested that they represent a continuation of the same volcanic episode.]

- What is the tectonic setting for the WV? [Leitch, (1974) suggested that the end of Early Permian volcanism was a result of cessation of subduction. Scheibner (1973) Roberts and Engel (1987) and Murray et al (1989) have suggested that they represent a rift setting.]

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GEOLOGY

Lithotypes: Six primary lithotypes of the WV (lavas, block lavas, pyroclastics, ignimbrites, intrusives and fluvial sediments) are recognised east of Wingen. Both basaltic and benmoreitic subtypes of each lithotype exist. Strong zeolite alteration is very common in these rocks, although benmoreite lavas can be relatively fresh locally. Some WV related intrusives are also relatively fresh, although the majority are highly zeolitized.

Stratigraphy and volcanic facies: A broad stratigraphy of four lithotype associations exists within the Temi Fm and WV:

- Upper Middle WV: Benmoreitic pyroclastic/epiclastic association
- Lower Middle WV: Benmoreite lava/block lava association
- Lower WV: Basaltic lava/pyroclastic/epiclastic/intrusive association
- Temi Formation (base of Permian): Fluvial to basaltic epiclastic association.

A volcanic facies model is constructed for the area, based on the recognition of these lithotype associations. Initially, basaltic volcanics prograded over the fluvially dominated Temi Fm, which has increased mafic clast input near its top. A thick, basaltic lava-dominated lower WV in the south gives way northwards to basaltic pyroclastic-dominated sections. These lithotypes are facies variants and the presence of pyroclastics indicates proximity to source. Some of the intrusives within the lower basaltic rocks may be volcanic feeders. Up section, mafic volcanics are swamped by more silicic volcanics. Rapid vertical and lateral lithological variations indicate that a stratovolcanic core-flank is exposed.

MINERAL CHEMISTRY

The WV are 2- and 3-pyroxene-bearing rocks, and hence have a sub-alkaline character. This character is not supported by "ideal" site substitutions in cpx, nor by whole-rock geochemistry.

Pyroxenes: The nomenclature used for pyroxenes is that of Morimoto (1989). Pyroxene analyses were recalculated on the basis of 4 cations to take into account Fe^{3+}, using the method of Ryburn et al (1976).

The cpx in the WV basalt (R66126) is diopside, only slightly more Wo-rich than the augite in the silicic WV extrusives (R66198, R66201) and the WV dolerite (R66174). None are titanian (using Morimoto's [1989] criterion: Ti > 0.100 atoms per 6 oxygens). Rims and cores in R66201 vary little in composition, suggesting that the activities of Ca, Fe and Mg remained relatively constant during the crystallization of these phenocrysts. To completely fill "ideal" sites, all WV cpx have Al apportioned and many also have Fe^{3+} apportioned into tetrahedral sites. Substitution of Al and Fe^{3+} for Si is unusual in sub-alkaline cpx (R J Arculus, pers comm) and suggests significant silica undersaturation in the melt.

Phenocrystal enstatite ($Wo_3En_{75}Fs_{22}$) occurs in R66198 (benmoreite) along with augite phenocrysts and microlites. Pigeonite ($Wo_{12}En_{53}Fs_{35}$) and enstatite ($Wo_2En_{57}Fs_{41}$) occur as inclusions in feldspars in R66174 (dolerite), which also contains groundmass augite microlites.

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Table 1 Representative mineral analyses

R. No	R66128	R66174	R66174	R66174	R66188	R66189	R66201	R66281
Rock type	basalt	dolerite	dolerite	dolerite	benmoreite	benmoreite	andesite	andesite
Lithotype	lava	intrusive	intrusive	intrusive	lava	lava	lava	lava
Analysis No.	072	202	203	204	260	154	039	042
Mineral	diopside	augite	pigeonite	enstatite	enstatite	augite	augite	augite
Grain type	phenocryst	microlite	microlite	microlite	phenocryst	phenocryst	phenocryst	phenocryst
Comments	core		incl'n in plag	incl'n in plag	core	core	core I	rim 1
T.S. colour	green	green	green	green	green	green	green	green
Oxide (Wt%)								
SiO2	48 00	51.94	43.28	41.22	53.83	51.37	51.98	52.30
TiO2	0.99	1.08	0.22	<0 .13	0.30	0.71	0.20	0.22
Al2O3	5 75	2.04	10 60	12,33	1.36	2.34	1.18	1.58
Cr2O3	0.24	< 0 13	< 0 13	< 0.13	<0 .12	< 0 13	< 0.13	< 0.13
FeO	6.98	9.76	20.35	23.56	14.81	8 24	10.06	10.32
MnO	< 0.13	< 0.13	< 0 13	< 0 13	0 55	0.32	0.42	0.43
MgO	15.00	14.88	17.80	15 67	27.84	16.04	14.82	14.44
CaO	23.25	21 00	5.50	1.10	1.36	21.93	22.18	21.00
Na2O	< 0.20	0.52	< 0.21	< 0.21	< 0.20	0.29	< 0.20	< 0.20
TOTAL	101.19	101.22	97.55	98.88	100.04	101.24	100.61	100.29

R. No	R66174
Rock type	dolerite
Lithotype	intrusive
Analysis No.	205
Mineral	olivine
Grain type	incl'n in plag
Comments	
Oxide (Wt%)	
SiO2	39 63
FeO	27 04
MnO	0.57
NiO	<0.18
MgO	30 77
Total	98.01

R. No	R66174
Rock type	dolerite
Lithotype	intrusive
Analysis No.	209
Mineral	Plag
Grain type	microlite
Comments	core
Oxide (Wt%)	
SiO2	55.39
Al2O3	28.01
Fe2O3	0.90
CaO	10.88
BaO	0 30
K2O	0.49
Na2O	4.72
TOTAL	100.87

Feldspars: Plagioclase in the WV rocks is mainly labradorite, but compositions from An_{78} to An_{44} were obtained by microprobe analysis. There is no appreciable difference between cores and rims. No K-rich feldspars occur.

Olivine: An Fo_{68} inclusion (evidently protected from alteration by its plagioclase phenocryst host) in R66174, a dolerite is the sole WV olivine analysis.

GEOCHEMISTRY

The geochemistry of the WV (Table 2) is compared to the Late Carboniferous Volcanics (McPhie, 1987 and Wilkinson, 1971) and Boggabri Volcanics (J W Brownlow, unpublished data).

Major Elements: On a volatile-free basis, extrusive WV rocks fall into the trachybasalt, basaltic andesite, "basaltic rocks", benmoreite and trachyte "benmoreitic rocks" fields, using the IUGS recommended "TAS" scheme of Le Maitre, (1989). With one exception, all the WV volcanics analysed plot in the silica-saturated fields (Fig. 1). The basalt from the Boggabri volcanics falls into the same group as the WV basaltic rocks. Currabubula Fm rocks generally plot in the silica-oversaturated fields.

On Harker-type major element oxide variation diagrams using SiO_2 and MgO, there are insufficient WV data points in these diagrams to be able to generate an informed discussion about the source and processes or any possible differences between the suites.

Trace Elements: The WV have a chemical signature that is distinct from the volcanics in the Currabubula Fm. Sr, Zr, V, Mn, P and Ti are much higher and Rb and Ba are much lower in the WV than the Late Carboniferous volcanics. Nb is strongly depleted in both suites (WV: 3-8 μg/g)

Table 3 Geochemical data - WV - whole rock analyses

Oxides - wt% trace elements - µg/g <[number] = below [detection limit]

UNE No.	R66124	R66125	R66126	R66191	R66192	R66196	R66168	R66140	R66171	R66176	R66174	R66182	R66194	R66143
Rock type	basalt	basalt	basalt	benmoreite	benmoreite	benmoreite	benmoreite	benmoreite	andesite	andesite clast	dolerite	dolerite	dolerite	dolerite
Lithotype	lava	lava	lava	lava	lava	lava	lava	lava	ignimbrite	fluvial cong.	intrusive	intrusive	intrusive	intrusive
Comments	altered	altered	altered	fresh	fresh	fresh	altered	altered	altered	altered	altered	altered	altered	altered
SiO2	45.07	48.86	50.29	59.71	61.82	58.87	61.11	61.74	61.60	51.55	48.36	55.43	48.97	42.36
TiO2	1.46	1.42	1.28	1.16	1.20	1.59	1.20	1.22	0.61	0.55	1.58	1.79	1.53	1.87
Al2O3	17.30	16.93	16.71	15.50	18.03	16.00	15.96	16.35	16.74	14.27	16.37	17.86	18.64	17.15
Fe2O3	9.18	9.17	9.75	2.92	3.70	3.95	4.66	5.15	5.02	4.13	4.78	6.00	8.26	12.07
FeO	0.10	0.04	0.41	2.97	2.50	2.63	2.08	0.68	0.13	0.74	3.90	1.13	1.13	1.81
MnO	0.15	0.13	0.11	0.19	0.12	0.20	0.15	0.11	0.11	0.29	0.17	0.13	0.09	0.16
MgO	4.56	5.80	4.58	1.63	1.59	2.31	1.38	1.11	1.07	1.50	4.37	2.26	3.77	6.49
CaO	8.94	7.74	7.17	4.01	4.31	5.46	4.03	3.05	3.25	10.56	10.54	5.97	8.89	5.31
Na2O	3.32	3.93	3.11	5.26	5.46	5.20	5.23	5.79	6.90	5.19	3.57	4.79	4.12	3.32
K2O	0.95	1.23	1.15	1.52	1.57	1.42	1.54	1.80	1.58	1.33	0.71	1.02	0.81	0.92
P2O5	0.53	0.51	0.56	0.47	0.48	0.71	0.48	0.49	0.24	0.23	0.44	0.42	0.82	0.74
S	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
H2O-	1.47	2.23	2.41	0.97	0.96	1.20	0.66	0.56	0.55	0.64	1.02	1.00	2.01	3.16
LOI	6.94	2.20	2.53	1.18	0.81	1.20	1.42	1.74	2.42	9.24	2.33	2.23	1.57	4.89
TOTAL	100.15	100.17	100.02	97.47	100.53	100.53	100.08	99.39	100.21	100.42	100.13	98.91	100.19	100.05
Nb	7	8	4	7	7	7	7	7	5	2	4	3	8	7
Zr	154	152	157	339	359	284	357	370	110	79	118	170	158	197
Y	22	22	25	54	56	50	53	61	10	8	22	36	29	31
Sr	528	952	1345	454	489	690	469	433	469	546	980	560	994	684
Rb	10	14	11	17	19	18	19	19	16	12	8	9	4	8
Th	4	<3	4	<3	<3	3	<3	3	<3	<3	<3	<3	<3	<3
Pb	9	4	6	11	10	8	10	11	5	7	4	3	6	8
As	7	10	11	8	9	9	9	12	21	24	32	64	14	13
U	<2	<2	2	<2	<2	2	<2	<2	1	0	<2	<2	2	2
Ga	18	18	16	22	20	20	19	21	16	11	18	18	18	23
Zn	84	83	90	100	103	104	111	119	71	48	89	100	89	90
Cu	44	31	40	5	5	2	2	7	13	5	53	49	35	35
Ni	96	97	55	3	3	4	5	5	17	17	36	51	59	146
Mn	1099	948	795	1347	848	1416	1071	797	804	2424	1172	1039	847	1204
Cr	193	202	164	7	6	3	4	2	30	24	110	94	134	232
Ce	46	44	60	60	61	58	66	60	26	20	33	36	58	82
Nd	30	30	40	39	44	43	42	48	17	16	24	30	38	38
Ba	313	474	495	482	455	501	450	486	445	540	321	351	531	443
V	174	121	144	38	39	98	38	45	60	73	241	220	241	233
La	19	20	29	24	24	25	27	21	12	13	20	16	23	26
Sc	29	28	24	15	16	20	18	19	8	17	36	23	31	34
Fe2O3*	9.29	9.21	10.21	6.23	6.48	6.87	6.97	5.91	5.17	4.95	9.11	7.28	9.52	14.09
FeO*	8.36	8.29	9.19	5.6	5.83	6.18	6.27	5.31	4.65	4.45	8.2	6.53	8.56	12.67
Ti/100	88	85	76	69	72	95	72	73	37	33	95	107	91	112
Y/Nb	3.14	3.67	6.25	7.71	8	7.14	7.57	8.71	2	4	5.5	12	3.63	4.43
Y.3	66	66	75	162	168	150	159	183	30	24	66	108	87	93

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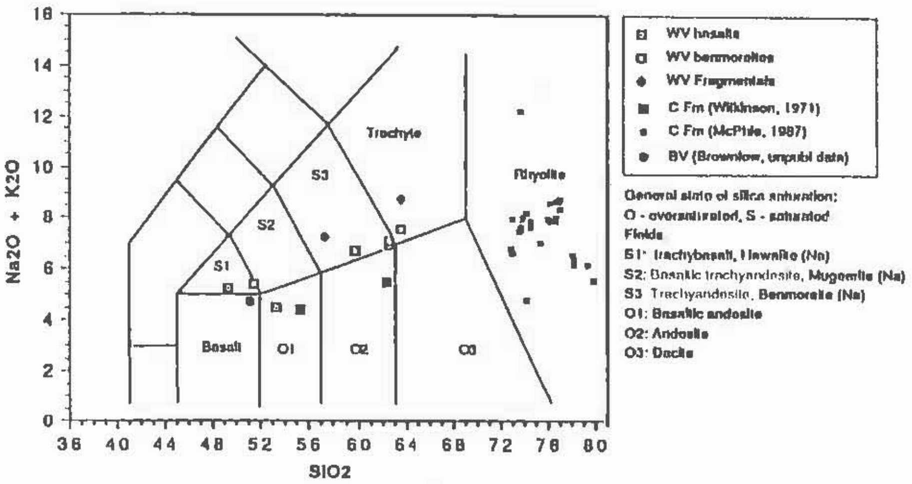

Fig. 1. TAS classification of rocks from the WV, Currabubula Fm and Boggabri Volcanics.

DISCUSSION

The WV are an unusual and distinctive group of igneous rocks which show both alkaline character (eg high Ti and Zr, the presence of benmoreites) and sub-alkaline characteristics (low Nb, 2- and 3-pyroxene bearing). Benmoreites are not common rocks, and rarely occur outside alkaline suites world-wide. They tend to be minor components in rift-related and hot-spot volcanic suites.

Using Pearce and Cann's (1973) Ti/100-Zr-Y*3 diagram, the WV basaltic rocks plot on the line dividing the fields of within plate and calc-alkaline basalts. On their Ti-Zr diagram, the basalts plot outside but between the fields containing calc-alkaline basalts and ocean floor basalts. The basalts have Y/Nb ratios of ≈3-6, which indicate a tholeiitic character.

Of particular interest is the high-Ti/low-Nb concentrations, consistent across the WV suite. The decoupling of these elements is most unusual in igneous rocks (R J Arculus, pers comm) and a literature search for modern or ancient analogues was fruitless. Until this problem is solved, a thorough classification of the WV and an understanding of its tectonic setting may prove to be elusive.

The single analysis of a basalt from the Boggabri Volcanics (on a similar stratigraphic level, about 170 km NW of Wingen and also probably Early Permian) has a similar chemical signature. Flood et al (1988) state that the Warrigundi Volcanics (located between Boggabri and Wingen), although calc-alkaline in nature, have an unusual chemical signature, with particular respect to their high TiO_2 contents. This suggests that the petrogenetic processes and/or sources that produced the WV in the Early Permian were active on a regional scale.

CONCLUSIONS

The WV at Wingen contains basalts and benmoreites both as lavas and pyroclastics. The volcanic facies indicate a local stratovolcano core-flank within the pile, as a source for the rocks. The suite is chemically distinct from the volcanics in the Late Carboniferous Currabubula Fm and shows both alkalic and subalkalic characteristics. The WV is unusual both in mineralogy and chemistry and does not appear to have a modern or ancient analogue. In particular, the Ti, Nb and Zr concentrations in these rocks are not easily explicable in term of source and/or process. It is concluded that the WV may represent a tectonic environment that has not previously been recognised. This enigmatic system appears to have been active on a regional scale and holds the key to our understanding of the early evolution of the Sydney Basin.

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EARLY PERMIAN VOLCANISM AND EARLY PERMIAN FACIES BELTS AT THE BASE OF THE GUNNEDAH BASIN, IN THE NORTHERN SYDNEY BASIN AND IN THE SOUTHERN PART OF THE NEW ENGLAND FOLD BELT

E.C. LEITCH & C.G. SKILBECK
University of Technology, Sydney

INTRODUCTION

This paper derives from investigations we have undertaken of the early Permian volcanic rocks of the Gunnedah Basin and adjacent parts of the southern New England Fold Belt. It is principally concerned with the nature of the volcanic activity, and the palaeogeographic significance of these rocks, but we have attempted to extend our results into the northern Sydney Basin and nearby southeastern parts of the New England Fold Belt, and to outline an early Permian palaeogeography of this region.

In this account the term 'early Permian' is used loosely, to refer to that part of the Permian prior to the onset of deposition of the Greta Coal Measures and correlatives.

EARLY PERMIAN VOLCANISM AT THE BASE OF THE GUNNEDAH BASIN

Stratigraphic framework

Most of the floor of the Gunnedah Basin comprises volcanic rocks of early Permian age. Silicic, intermediate and mafic rocks are present and, on the basis of intersections at the bottom of Department of Minerals and Energy drill holes, the distribution of two contrasting units can be mapped (Fig. 1). The unit dominated by silicic rocks is termed the **Boggabri Volcanics** typical members of which are flow-banded rhyolite and ignimbrite that outcrop north of Boggabri (McPhie 1984). Drill holes northeast and northwest of Boggabri intersected similar rocks which are also present in a belt 15 - 50 km wide, and at least 180 km long, beneath the western part of the Basin. Mafic rocks are the major component of the Werrie Basalt, which includes uncommon andesite and dacite. This unit was first described from the Werrie Syncline, east of the Mooki Thrust. Within the Gunnedah Basin area it outcrops east of Narrabri and at Gunnedah, and has been intersected widely in drill holes in the central and eastern parts of the Basin.

Both the Boggabri Volcanics and the Werrie Basalt are of early Permian age. The relationship between the two units is unestablished but limited information from uncored oil exploration holes and regional correlations (McPhie 1984) supports earlier suggestions that the Boggabri Volcanics are the older, although the

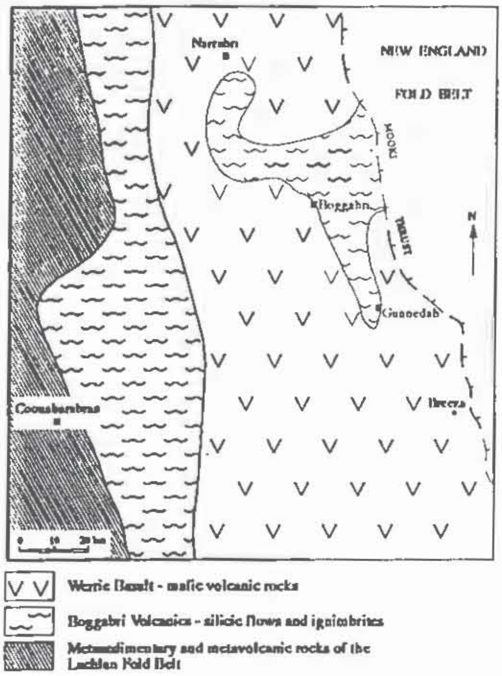

Figure 1: Distribution of major rock units on the floor of the Gunnedah Basin.

occurrence of uncommon silicic rocks in the Werrie Basalt (Leitch *et al.*, 1988; Flood *et al.*, 1988) complicates discussion. In Eulah 1 basalt and andesite in the upper part of the hole overlies ignimbritic dacite, the contact being marked by a thin horizon of claystone.

The top of the volcanic assemblage is everywhere erosional, with the upper part of the mafic volcanics in particular showing evidence of deep weathering. All rock types are commonly overlain by little-transported ill-sorted conglomerate or breccia (eg. Leard Formation).

Boggabri Volcanics Volcanism

Most drill core recovered from the Boggabri Volcanics comprises ash flow tuffs. The degree of flattening of lithic clasts and pseudomorphically replaced glass shards indicates that these range from unwelded to densely welded. Individual flow units, the boundaries of which are defined by abrupt changes in clast and/or phenocryst content or breccia zones, range from 1 to at least 50 metres thick with most between 5 and 35 metres. McPhie (1984) recorded flow units up to about 100 metres thick in outcrop near Boggabri. No difference in either clast size or flow thickness has been noted between the western belt of Boggabri Volcanics and those found between Gunnedah and Narrabri.

Ash fall tuffs are rare; a two meter interval of thinly bedded tuffs in Girrawillie-Bulga 1 includes probable ash fall deposits, and accretionary lapilli tuff occurs near Boggabri (McPhie 1984). McPhie also recorded the presence of plant-bearing mudstone near the top of the volcanic sequence in the latter area but no epiclastic rocks have been identified from core.

Coherent lavas with flow layering are common in outcrop but were only intersected in one drill hole (Tullamullen 1) in which the layering is contorted and the flow rocks are associated with autoclastic breccia.

Overall the character of the silicic rocks suggests that they accumulated relatively close to source. Thick ash flow units, reverse pumice grading, the absence of base-surge deposits, only rare ash-fall deposits and epiclastic rocks, and the presence of coherent flows, all accord with this conclusion. Evidence of widespread welding, the lack of internal weathered horizons, and the absence of significant reworking or of obviously marine rocks point to rapid subaerial accumulation.

EARLY PERMIAN VOLCANISM AND FACIES BELTS

Werrie Basalt Volcanism

Most of the Werrie Basalt comprises sheet flows that have thicknesses of between about 1 and 32 metres. Individual flows have a highly amygdular upper part which grades down into progressively more massive and coarser grained basalt. Amygdules increase in size and abundance again towards the base of flows which are in some places marked by thin horizons of close-packed autoclastic breccia. Thicker (up to 7 meters) breccias of similar character are probably block flows.

The 28 meters of dolerite drilled in Howes Hill 1, unconformably overlain by Permian clastic rock (Maules Creek Formation), is considered to be an intrusive phase of the Werrie Basalt; elsewhere rocks of doleritic texture grade out into amygdular rocks and are interpreted as slowly cooled flow interiors.

Basaltic ash fall tuffs, tentatively identified in intervals about 0.5 meters thick in Emerald Hill 1 and Eulah 1, are the only evidence of pyroclastic activity. Epiclastic intervals are equally rare, a (scattered ferruginous and clayey horizons, probably products of weathering during periods of quiescence.

Werrie Basalt volcanic activity was quietly effusive in a subaerial environment as indicated by the absence of pillow structures, aquagene tuffs or intercalated marine sedimenSUW mited palynological data (McMinn, 1982). The rarity of other than flow rocks points to broad shield structures as the dominant volcanic form.

CORRELATIVE VOLCANIC ACTIVITY IMMEDIATELY EAST OF THE MOOKI THRUST

The oldest Permian unit from the western part of the New England Fold Belt, the Temi Formation, is a terrestrial clastic sequence, largely of silicic volcanic provenance, and including ash fall tuffs. McPhie (1984) suggested the general correlation of this unit with the Boggabri Volcanics noting the evidence of 'remote, silicic volcanic activity' in the latter (a correlation which thus suggests perhaps several tens of kilometres of overthrusting on the Mooki).

The Werrie Basalt conformably overlies the Temi Formation in the westernmost New England Fold Belt (western Tamworth Belt). For the most part it is of similar character to the mafic sections further west although a central volcanic complex with abundant intermediate and silicic rocks has been identified by Flood *et al.* (1988) north of Werris Creek.

Subaerial volcanism is indicated for most of the Werrie Basalt in western New England, but to the northeast of Murrurundi Hanlon (1948) mapped basalt flows low in the Werrie Basalt that are intercalated with sandstones containing an earliest Permian marine fauna (Runnegar, 1970), suggesting an eastern transition into a marine environment.

EVIDENCE FOR CONTEMPORANEOUS VOLCANISM IN MARINE EARLY PERMIAN SEQUENCES CLOSE TO THE PEEL FAULT

Early Permian clastic sequences occur in the eastern Tamworth Belt in the upper Barnard River, within the Peel Fault System at Hanging Rock, Attunga Creek and Woodsreef, and east of the Peel Fault at Mulla Creek and in the upper Barnard River region (Leitch, 1988). These sequences include redeposited rocks

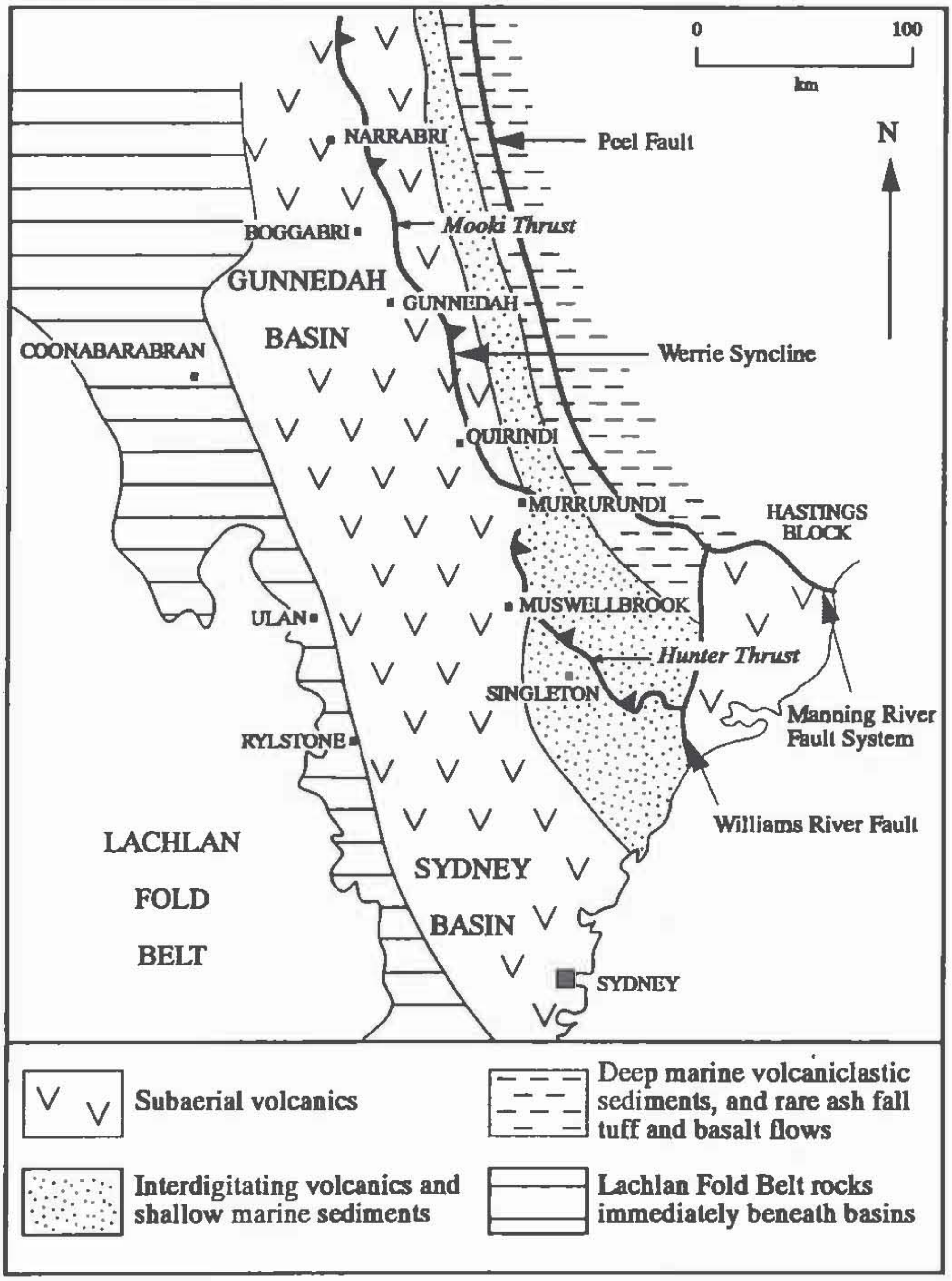

FIGURE 2: Distribution of early Permian (pre-Stage 3b) facies belts.

and are probably of moderately deep water origin. Lithofeldspathic sandstones, probably the product of the reworking of silicic ash, are common and at Attunga Creek little modified feldspathic crystal tuffs occur. The most likely source for the contemporaneous volcaniclastic components is the Boggabri volcanism. Basalt and basalt breccia intercalated in the Attunga Creek sequence is probably a distal phase of the Werrie volcanism.

EARLY PERMIAN FACIES BELTS IN THE GUNNEDAH BASIN AND CENTRAL WESTERN NEW ENGLAND

The foregoing account indicates the presence of three approximately north-south trending early Permian facies belts in central western New England (Fig. 2). In the west is a belt of subaerial silicic and mafic volcanic rocks. The earlier activity was dominantly silicic and confined to the west, with an eastern zone of derived clastics, whereas later, mainly mafic, activity extended further east. The central belt, least well preserved, comprises intercalated mafic volcanics and marine sedimentary rocks. The eastern belt is dominantly marine sedimentary rocks but includes a large silicic volcaniclastic component, silicic ash fall tuff, and uncommon intercalated mafic volcanics. It is noteworthy that the boundaries between these belts do not coincide with major tectonic structures. The western belt occurs on both sides of the Mooki Thrust, and the eastern belt straddles the Peel Fault.

EXTENSION OF THE FACIES BELTS INTO THE NORTHERN SYDNEY BASIN AND SOUTHEASTERN NEW ENGLAND

The facies belts can be traced to the south into the Sydney Basin and the southeastern part of the New England Fold Belt. The belt of subaerial volcanics is represented in outcrop by the Gyarran Volcanics around Muswellbrook and by silicic and mafic rocks intersected in deep drill holes extending south to Kirkam 1, some 70 km westsouthwest of Sydney (see summary in Bradley *et al.*, 1985). Volcanic rocks derived from this belt are found in a diatreme north of Wisemans Ferry where they are associated with fragments of quartzose greywacke of Lachlan Fold Belt character (O'Reilly, 1990) suggesting that the early Permian volcanics lie on a basement of Lachlan Fold Belt rocks in the west.

Intercalated mostly mafic volcanics and shallow water sedimentary rocks characterise the older part of the early Permian Dalwood Group in the lower Hunter Valley and correlative units in the Cranky Corner Basin north of the Hunter Thrust. These strata are considered an extension of the central facies belt defined further north.

Mostly deeper marine early Permian rocks are restricted to the area north of the Manning River Fault System where a very thick sequence of clastic rocks accumulated, but primary volcanic rocks are absent. (Recent investigations indicate that the lavas reported from Mayer's Kywong Beds (see Leitch, 1988) are part of the Alum Mountain Volcanics). The dominant provenance of these rocks is silicic volcanic and silicic ash-fall tuffs occur rarely.

THE SIGNIFICANCE OF THE ALUM MOUNTAIN VOLCANICS

The facies distribution so far outlined is complicated east of the Williams River Fault by the presence of the subaerial Alum Mountain Volcanics. These comprise a compositionally diverse suite of early Permian rocks, ranging from basalt to rhyolite that are both overlain and underlain by non-marine strata (Helby *et al.*, 1986; Leitch *et al.*, 1988). They thus show the attributes of the western facies belt but lie well to its northeast. There are several possible explanations for their seemingly anomalous location.

The region east of the Williams River Fault may have remained emergent during the early Permian, forming a large volcanic island (Fig. 3A). Alternatively the western facies belt may have bifurcated south of Murrurundi, with an emergent ridge of volcanics extending continuously east to this region. In this latter case the central facies belt would not have been continuous from Murrurundi to the lower Hunter Valley but would have flanked the ridge on either side (Fig. 3B). A third possibility is that the whole of the block east of the Williams River Fault was moved north in post-Alum Mountain times from an initial position along the western belt (Fig. 3C). The minimum required displacement is of the order of 150 km, of similar sense and comparable scale to other movements in southern New England implied by Leitch's (1988, Fig. 3) reconstruction of earliest Permian relationships.

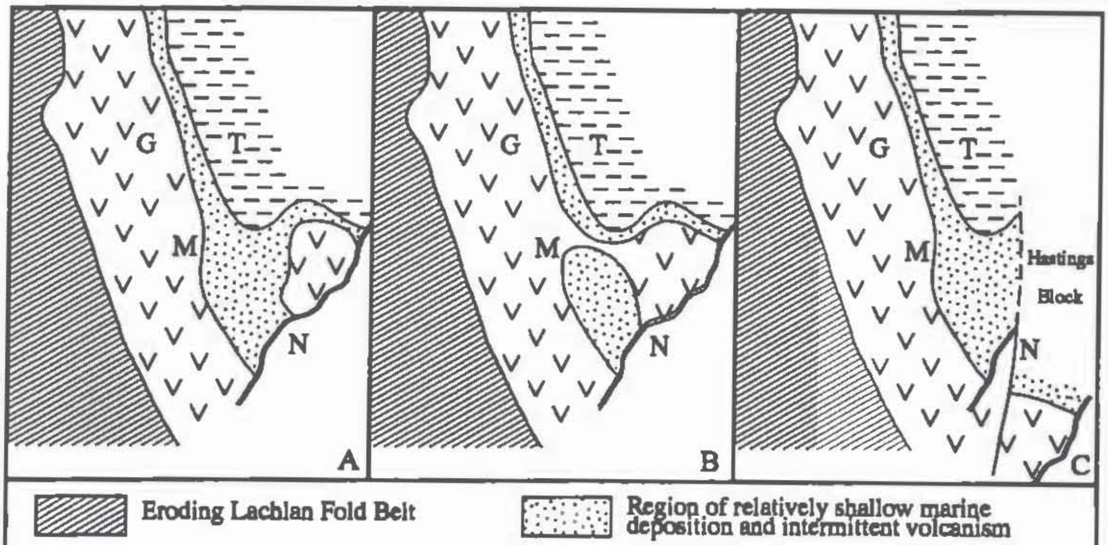

FIGURE 3: Alternative interpretations of early Permian (pre-Stage 3b) palaeogeography. G - Gunnedah, M - Muswellbrook, N - Newcastle, T - Tamworth.

DISCUSSION

Increasing knowledge of the nature and distribution of early Permian rocks in the Sydney and Gunnedah Basins and the southern parts of the New England Fold Belt places increasing constraints on reconstructions of the palaeogeography of this period. A number of major questions remain, however. For example, was the Sydney Basin separated from the basin in which the early Permian rocks of southern New England accumulated (the Barnard Basin) by either an active volcanic ridge, or a "basement" ridge (McClung, 1986), or are the Sydney Basin rocks of this age the more marginal deposits and the Barnard Basin rocks the deeper water deposits of the same basin? By Greta Coal Measures time there was a clear northern limit to the Sydney Basin but did the uplift, implied by the change in depositional style at this time, herald the end of deposition in the Barnard Basin? What is the movement history of the Williams River Fault and the Manning Fault System and to what extent has post-early Permian displacements on these structures disrupted earlier palaeogeographic patterns? How much foreshortening has occurred across the Mooki and Hunter Thrusts; does the apparent pinning of these structures north of Wingen and near Paterson imply only modest displacements or are there transfer structures in these areas that have taken up major movement? Until these questions are answered no definitive early Permian palinspastic palaeogeographic reconstruction will emerge.

Reconstructions like those of Figure 3 also suffer from portraying an interval of time over which considerable changes in palaeogeography may have occurred. Improvements in the dating and correlation of rocks aggregated here as 'early Permian' would lead to a more accurate set of reconstructions.

ACKNOWLEDGEMENTS

We extend our thanks to Mrs Leighonie Green who drafted the diagrams.

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THE COFFS HARBOUR BLOCK – NOT AN ACCRETIONARY PRISM

W. MORRIS
Medowle

It is very difficult if not impossible to prove that an area of ancient rocks was formed as part of an accretionary prism. Even in the case of the southern uplands of Scotland, which is the best known and probably the best documented example of ancient rocks for which an accretionary prism origin has been claimed, a fierce controversy still rages over whether or not this is correct. (McKerrow 1987, Murphy and Hutton, 1986).

Fergusson (1982a, 1982b, 1984) produced a number of papers on the geology and structure of the North West portion of the Coffs Harbour block and concluded by claiming that they formed part of a Late Palaeozoic accretionary prism, active until the Late Carboniferous.

As the generally accepted interpretation of New England envisages a volcanic arc, forearc basin and subduction complex, from West to East, an accretionary prism would be expected to face eastward. Instead the accretionary prism suggested by Fergusson faced South West. Flood and Fergusson (1982) and Fergusson and Flood (1984) then invoked a large scale Z-shaped megafold to explain the "incorrect" facing direction of the accretionary prism and in Murray et al (1987) suggested major strike slip faulting such that the Coffs Harbour block had been originally deposited in the vicinity of Rockhampton.

In Table 1 is shown a list of characteristics which may be present in an accretionary prism together with their described presence or absence in three suggested accretionary prisms.

THE COFFS HARBOUR BLOCK - NOT AN ACCRETIONARY PRISM

Table 1. Characteristics of accretionary prism

Characteristic Karig & Sharman 1975 Crook 1980 Leggett 1987	Southern Uplands of Scotland Leggett 1987	Woolomin and Cockburn Formations SE of Tamworth Cawood 1982	Coffs Harbour Block Ferguson 1982a, 1982b, 1984 1985
deposited between arc (or forearc) and trench	+	+	?
toe of prism facing ocean-ward, rear of prism faces towards arc	+	+	?
consists of repeated packets of oceanic sediments	+	+	-
characteristic sequence of basal basalt, chert and argillite overlain by turbidite	+	+	possible in Gundahl Complex
packets fault bounded top and base	+	+	-
packets hundreds of metres to 1-2 km thick	+	+	-
folds and faults near toe roughly horizontal becoming rotated towards vertical near rear	+	-	-
strata young towards arc	+	+	+
repeated packets young towards toe (oceanward)	+	?	?

From Table 1 it is apparent that the proposed accretionary prism origin for the Coffs Harbour block was based on very few of the characteristics listed for accretionary prisms. In fact it depends crucially on the claimed opposite younging directions of the individual strata and Fergusson's proposed "tectonostratigraphic units". In Fergusson (1982b, 1984) these tectonostratigraphic units were stated to young to the south west in the following way.

Willowie Creek beds	? Siluro Devonian
Gundahl complex	? Early Carboniferous
Coffs Harbour beds	? Late Carboniferous

Although all three ages were questioned by Fergusson as shown above, there has been no further discussion for or against these ages.

In the case of the Willowie Creek beds, the suggested age is acceptable, but as no structural evidence could be determined in this unit that supported its presumed accretionary prism origin (Fergusson, 1984), it does not seem reasonable to include it in the accretionary prism.

Also Fergusson (1988) reported chemical analyses on altered volcanics of "general basaltic and andesitic composition" from the Willowie Creek beds. Although he stated that the results "do not show any consistency", six out of eight results fell in the "Arc lavas" field. This suggests that the Willowie Creek beds are better considered as part of the arc, forearc or backarc, rather than part of an accretionary prism.

In the case of the Gundahl complex, the suggested ?Early Carboniferous age was based on the presence in the melange of ooid-bearing greywackes. Even accepting a possible Tournaisian or Visean age for these, as suggested by Fergusson (1984) and others, this does not make the Gundahl complex Early Carboniferous. The age is simply younger than the age of the greywackes. This could be Early Carboniferous, Late Carboniferous, Permian or even Triassic.

In the case of the Coffs Harbour beds, Fergusson (1982, 1984) suggested a ?Late Carboniferous age. This was based on a comparison of the petrography of the greywackes with the Late Carboniferous sequence of the northern Tamworth Belt. Fergusson (1984) then stated "a Late Carboniferous age is at least compatible for the greywackes of the Coffs Harbour beds". However, it is illogical to correlate the Coffs Harbour beds with the Northern Tamworth Belt, as Fergusson and Flood (1982) and Murray et al (1987) claim that the Coffs Harbour beds were deposited in Queensland, roughly in the vicinity of Rockhampton and only transported to their present position as part of the "z-shaped megafold" in the Early Permian. Recent estimates of the age of the Coffs Harbour beds by Flood and Aitchison (1988) states, "Radiolaria indicate a Late Devonian to Early Carboniferous age". This is for the Anaiwan Terrane which comprises the earlier named Sandon and Coffs Harbour associations (Korsch, 1977).

These thick turbidite associations are best interpreted as the proximal (Sandon) and distal (Coffs Harbour) facies of an oceanic basin fill. This is supported by :

(a) The geographic occurrence of the two associations, which is the Sandon association in the west and the Coffs Harbour association in the east.

(b) The Sandon association being a sandy turbidite sequence, while the Coffs Harbour association consists of thick argillite units coarsening upwards by increasing proportions of greywacke beds.

(c) The two associations having a common provenance (Korsch, 1984).

(d) Finally, the recent amalgamation of the two associations as the Anaiwan Terrane with a common Late Devonian to Early Carboniferous age (Aitchison and Flood, 1988) confirms this interpretation.

In a later map, Fergusson (1988) shows the Coffs Harbour beds in the North West portion of the Coffs Harbour block subdivided into Coramba beds and Brooklana beds. If this map is extended further south, the Moombil beds can also be shown (see Fig. 1). Korsch (1981) refers to the stratigraphy of the Coffs Harbour Block as consisting of the Moombil beds, Brooklana beds and Coramba beds in ascending order. He also refers to his subdivision of the Coramba beds into petrographic subunits A B C D, again in ascending order. All these units and subunits young to the North East, that is, the opposite direction to Fergusson's suggested younging directions.

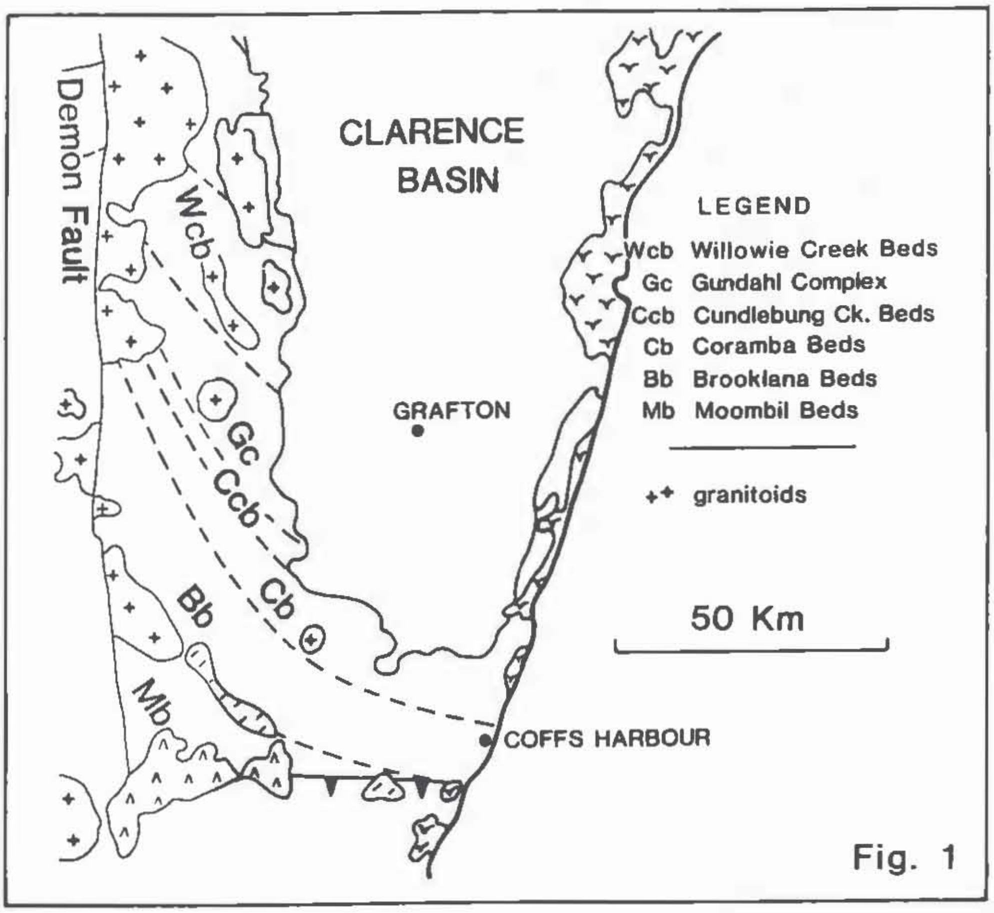

Fig. 1

Also shown on this map is the Cundlebung Creek beds. This unit is between the Coramba beds and the Gundahl Complex. Fergusson (1984) made no comment of the age of this unit but simply included it in his Coffs Harbour beds as part of that "tectonostratigraphic unit". The Cundlebung Creek beds are described as "black grey, massive and laminated argillite with rare greywacke, breccia and chert".

The Coramba beds, which are adjacent to the Cundlebung Creek beds, are a greywacke dominated unit, unlike the massive argillites of the Cundelbung Creek beds and the latter should be correlated on lithology with the Moombil beds. Similarly the Gundahl complex with a massive argillite matrix should also be correlated with the Moombil beds. Thus it is suggested that the Cundlebung Creek beds and the Gundahl complex are a repeated sequence of Moombil beds (probably repeated by thrust faulting) which comprise undeformed and markedly deformed segments. In this suggested repeat Moombil beds sequence, again the younging direction is to the North East as the Cundlebung Creek beds (undeformed Moombil beds) are of probable Late Devonian age while, as discussed earlier, the Gundahl complex is post Early Carboniferous age.

In contrast to the disagreement over younging directions in the stratigraphic and tectonostratigraphic units both Korsch (1981) and Fergusson (1982) report that the individual strata have a regional younging direction to the North East. From the earlier discussion of younging directions in the stratigraphic units it is therefore concluded that <u>the strata and the stratigraphic units</u> young to the North East and that Fergusson's claimed younging directions for his "tectonostratigraphic units" are incorrect.

Table 2. lists determined ages for rocks of the Sandon and Coffs Harbour associations. Although relatively few in number, none indicate a Late Carboniferous age for either association and the radiometric ages (particularly) are considerably older (mainly Devonian).

THE COFFS HARBOUR BLOCK - NOT AN ACCRETIONARY PRISM

Table 2. Determined ages of the Sandon and Coffs Harbour Associations			
Sandon Association		**Coffs Harbour Association**	
Palaeontology	**Radiometric**	**Palaeontology**	**Radiometric**
Late Devonian – Early Carboniferous Korsch (1977) Anaiwan Terrane* Late Devonian – Early Carboniferous (Fammenian – Tournaisian) Flood and Aitchison (1988)	Limbri, 389 ± 17 (Early Devonian) Shaw and Flood (1982)	Anaiwan Terrane,* Late Devonian – Early Carboniferous (Fammenian – Tournaisian) Flood and Aitchison (1988) Texas area, Visean limestones Flood and Fergusson (1985)	Wongibinda, 387 ± 12 (Early-Middle Devonian) Moona Plains, 351 ± 9 Tournaisian – Visean Boundary Sandon and Coffs Harbour Associations, Average value 375my (Base of Late Devonian) Hensel et al (1985) Metamorphic age > 318 ± 8 (Namurian) Graham and Korsch (1985)

* Anaiwan Terrane = combined Sandon and Coffs Harbour Associations

The Visean limestones in the Texas area (see Table 2) were interpreted as olistoliths by Korsch and Harrington (1981). They favoured this interpretation to explain the presence of older rocks in a younger sequence (the Coffs Harbour association, assumed to be Late Carboniferous). The limestones were more likely deposited in situ, as was the Ashford limestone of the same age which occurs 15km to the North West. These limestones record the shallowing of the Sandon and Coffs Harbour associations basin in the Texas area and indicate that the age of the two associations is older than Visean.

In conclusion, it follows from the younging directions that the Coffs Harbour Block does not consist of an accretionary prism facing South West. Also from the ages listed it is apparent that the Coffs Harbour Block consists mainly of rocks that are Devonian to Early Carboniferous in age. Without the Late Carboniferous accretionary prism facing South West the Z shaped megafold and major strike slip movement is not necessary to correct the facing direction. It also makes Oroclinal bending unnecessary as a process for the formation of New England.

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THE EFFECT OF EARTHQUAKES ON UNDERGROUND OPENINGS

I. MUMME
CSIRO Division of Coal & Energy Technology

ABSTRACT

This paper discusses the probable behaviour of underground workings, including the Newcastle area, due to the dynamic effect of local earthquakes. To do this it was necessary to examine the basic mechanisms controlling the passage of seismic waves through the ground as they induce transient stresses that are superimposed on the existing insitu stresses within the rock matrix enclosing the underground openings.

From these studies, as well as from a review of relevant literature, it is concluded that unless a seismic event occurs close to an underground working, the induced transient stresses generated would be small with respect to the excavation stresses because high stress waves are rapidly attenuated in their passage through the rocks. Further, although an adjacent earthquake may generate high accelerations, it is limited in the maximum amount of stress it can generate.

Although it is expected that there will be a reduction in peak ground motions with depth from the free surface, there are still questions to be answered. For example, what is the actual specific nature of underground seismic motions resulting from a local earthquake? Such information is hindered by the lack of data and by the fact that most rocks at depth form inhomogeneous and discontinuous media.

INTRODUCTION

The mechanisms for seismic damage to underground openings are significantly different from those of a surface structure, but since most experience of the effects of earthquakes have been gained on the surface of the earth, we will address the surface evidence of earthquakes, and then look at the underground evidence.

Earthquakes damage man made surface structures in a variety of ways. At least 5 factors, structural and natural, strongly influence damage to structures, namely:

(1) The strength of the earthquake waves that reach the surface. In this regard, the magnitude of the horizontal component is especially critical in that few structures provide safety against horizontal shaking.

(2) Duration of the earthquake ground motions. It is the accumulating effect of a series of tremors that is the usual cause of wall collapse. The main tremor may substantially weaken many buildings, but less intense after shocks may cause collapse.

(3) Geological foundation. To many engineers and insurance experts this is the most important factor in earthquake damage. Studies have shown that damage to buildings on soft ground to be more extensive than to buildings on hard ground. For example, Mexico City suffered as a result of the September 1985 earthquake which occurred 400 km away, because of the soft lake bed subsoil of the city.

Thus strengths and elastic properties of rocks, and soil, affect the response of sites to earthquakes.

(4) Building Design. The necessary design strength of structure in resistance to both horizontal and vertical ground motions can be accomplished by adequate bracing and structural continuity, and

(5) Proximity to the fault, or fault zone. Structures resting directly on the fault zone are obviously precariously located if there is movement along the fault. Otherwise damage is not necessarily a function of distance from the fault.

Any structure straddling such a fault including tunnels crossing the fault would be sheared apart by the high stresses that are necessary to shift such much earth and rock. Although surface fault displacements are primarily confined to active plate margins, they do occur in intraplate situations, and Australia is no exception.

Apart from damage to structures, residual impressions at the surface include subsidence, landslides, slumping, fissuring, liquefaction and so.

In many instances these impressions indicate local instability of geological formations. In general they indicate the potential for earthquakes to generate permanent changes in geological formations near extensive free surfaces. At Newcastle, the seismic damage from tectonic earthquake results from relatively deep seated earthquakes in the region.

BACKGROUND INFORMATION. Although there is not a large amount or experience with regard to the seismic behaviour of underground openings, it is an essential first step to examine the performance of tunnels. To this regard, data on the seismic stability and behaviour of shallow underground workings are well summarized in a paper by Dowding and Rozan (1978).

Damage to tunnels was found to be generally manifested in one or more of the following forms:

(1) damage from earthquake induced ground failure such as liquefaction or landslides at tunnel portals,

(2) damage from fault displacement, and

(3) damage from ground "shaking", or ground vibration. Damage due to ground failure and fault displacement can usually be avoided by prudent siting. This leaves only seismic motions as a concern.

These studies compared calculated accelerations at the ground surface with tunnel damage and show that the tunnels are less susceptible to damage than surface structures.

Peak accelerations at the surface of less than 0.2 g did not damage the tunnels; between 0.2 g and 0.5 g damage was only minor (eg. small scale cracking in concrete lined tunnels), however above 0.5 g damage became significant. The observed damage was also compared with modified mercalli (MM) intensity level for aboveground structures. The "NO damage Zone", with accelerations up to 0.5 g is equivalent to MM VII-IX. Therefore, at peak surface accelerations that normally would result in heavy damage to above ground structures MM VIII-IX there is only minor damage to tunnels.

Some earlier work on the effect of depth on seismic motion performed by Duke and Lees (1959) showed the following results:

(1) at short periods, surface displacements are larger than underground ones.

(2) the ratio of surface to underground displacement depends on the type of ground. It is greater for alluvium than for weathered rock and may reach a value of least 10.

(3) For wave periods over one second, the ratio becomes comparatively small, approaching 1 as the period increases.

(4) There is a particular average period of incoming waves for which a given type of ground will provide a maximum ratio of surface to underground displacement. If the average period of incoming waves is not approximately equal to this particular period, the ratio will be significantly smaller. The oldest underground works are of course mines, and Stevens (1977) has compiled reports concerning the effects of earthquakes on underground mines.

The many reports of earthquake shaking show tunnels stand up well under seismic shaking. However, many reports indicate that solid rock tunnels are susceptible to changes in hydrological conditions ie. there are reports of tunnel flooding. This strongly suggests that although there may have been no apparent damage to the structure, there is a probability in an increase in fracture density in the rocks surrounding the tunnels.

As a result of a literature review involving damage from earthquakes to tunnels, mines, and wells and damage (rock bursts) from mining operations, Pratt et al. (1978) came to the following conclusions.

(1) there are very few data on damage in the subsurface due to earthquake. This fact itself attests to the lessened effect of earthquakes in the subsurface because mines exist in areas where strong earthquakes have done extensive surface damage.

(2) more damage is reported in shallow tunnels near the surface than in deep mines.

(3) in mines and tunnels, large displacements occur primarily along preexisting faults and fractures or at the surface entrance to these facilities, and

(4) data indicate vertical structures such as wells and shafts are less susceptible to damage than surface facilities.

EARTHQUAKE DAMAGE TO UNDERGROUND WORKINGS IN NEWCASTLE AREA

Key findings of a study conducted by the joint coal board, Singleton, are as follows (Rynn, 1990):

(1) Ingress of water - major effects at Lambton, minor effects at West Wallsend, Newvale No. 2, Gretley, and Teralba.

(2) Spalling of ribs - Ellalong, West Wallsend Teralba (longwall)

(3) Wall of roof - Gretley, Teralba (longwall)

(4) Mainroads - Moonee

(5) Return airways - Moonee

(6) Conveyor belt roads - Gretley

(7) Drift installations - Teralba

(8) Shaft installations - Teralba

The approximate epicentral distances of the affect coal mines are Teralba, near the epicentre; West Wallsend 5 km; Gretley, 8 km) Lamfton, 10 km; Moonee, 25 km; Newvale No. 2, 30 km, Ellalong, 30 km. By examining the basic mechanisms of the progression of seismic motion from the principles of wave generation and propagation to wave interaction with an underground opening, it can be shown that the induced bulk movement of the host rock only causes relatively low stresses with respect to the excavation stresses because high stress wave motions are rapidly attenuated in travelling through the rock. Further, although an earthquake may generate extremely high accelerations, it is limited in the maximum amount of stress it can create.

CONCLUSIONS:

In conclusion, the following conclusions may be drawn from available information.

(1) damage can be expected underground if fault displacement occurs through the underground opening.

(2) Seismic data favours reduction of amplitude with depth; and

(3) the frequency content of earthquake motions is important to the stability of the underground openings.

(4) Flooding as a result of enlargement or interconnection of fractures may occur.

(5) The intensity of shaking and severity of damage appears to diminish with increasing rock quality.

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ALTERNATIVE WAYS OF DISPLAYING AND ANALYSING SUBSIDENCE DATA

P. WILLEY
ACIRL, North Ryde

Abstract

A method for three dimensional display and manipulation of subsidence data on a workstation is described. Three methods for the prediction of subsidence in Australia are outlined including profile functions, influence functions and "SUBSID", a computer program based on a frictionless laminated beam model. A method for the prediction of ground strains, tilts and curvatures from the shape of the subsidence trough is outlined. The construction and use of subsidence development curves is briefly described.

Introduction

Expansion of underground coal mines and urban areas has led to a conflict of land use. Those who wish to mine coal are finding that they are restricted in their activities by the presence of surface structures and those who own or operate surface structures are reluctant to allow them to be affected by subsidence. At present the approach is that large blocks of coal must be left under sensitive surface structures such as dams, railway lines and transmission towers. Less sensitive structures such as homes and commercial premises have restrictions placed on their design in order to minimise subsidence damage. Claims for any damage that does occur are made to the Mine Subsidence Board who determine their validity.

The present approach involves using the "worst case" view of surface deformations both as input to structural design and as a restriction on the extent of mine workings. In order to remedy this situation for the benefit of both coal miners and surface land users subsidence researchers must do three things:

1. Improve our precision in predicting mining induced subsidence especially with regard the location and magnitude of differential surface deformations.

2. Determine tolerances of various existing structures to ground deformations.

3. Design structures to either tolerate ground deformation or be easily rectified when subsidence has ceased.

ACIRL has been attempting to address these issues in two, NERDDP-funded research projects. In one project housing structures are being designed, built and tested to accommodate movements due to subsidence. The other project involves various methods of back analysis of subsidence data is being used to develop more accurate prediction methods. This paper is an outline of some of the major findings of the latter project.

3-D Graphical Data Base

In order to fully understand the nature of the surface deformations involved in the subsidence process it is helpful to be able to view the progress of the subsidence wave. A three-dimensional graphical data base has been developed on a Silicon Graphics workstation to allows easy visualisation and manipulation of subsidence data. Patterns of vertical subsidence, tilts, curvatures and strains can easily be determined. All that is required for input is the survey date, a list of peg numbers, and the X, Y and Z co-ordinates. The data can be viewed from any angle by selecting movement options and moving the "mouse". A zoom option allows detailed examination of selected areas. "Animation" shows the progress of the subsidence trough and the movements of individual pegs and allows easy recognition of survey errors. A "QUERY" option shows the co-ordinates and survey date for each point on the screen. This display can be laid over a mine plan showing face positions. Output may include subsidence contours, strain rosettes and tilt vectors. Another useful display involves the drawing of vectors from the original peg position to the position on a particular survey date. The vectors show how the pegs are "drawn" toward the void left by mining. The display allows easy comparison between predicted ground movements and actual field measurements.

Prediction of Subsidence Using Profile Functions

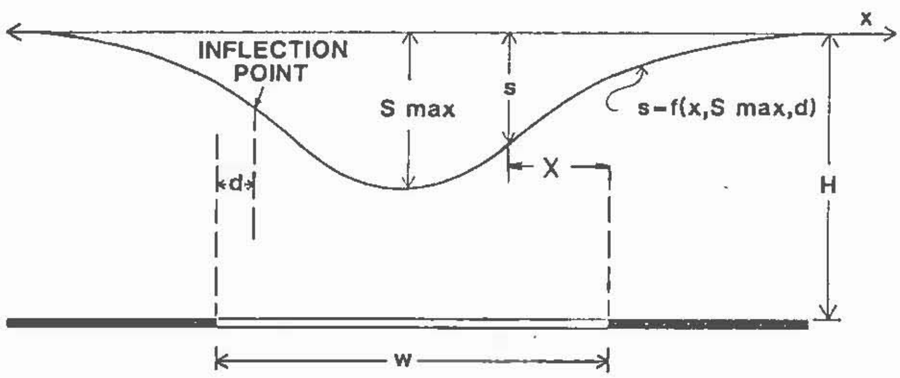
Profile functions have been widely used in a number of countries to predict subsidence (Whittaker and Reddish, 1989). The shape and magnitude of the subsidence profile may be approximated by fitting a curve to the measured data. The curves are mathematical functions of the form $s = f(x, Smax, d)$ where s = subsidence at a point, x = distance of that point from the ribside, Smax = maximum subsidence, d = position of inflection point relative to the ribside (see Figure 1). Many profile functions also include the concept of "radius of influence" or "angle of draw". Salamon (1989) suggests that this is unnecessary because the area of influence can be limited by the use of asymptotic functions. In super-critical panels Smax is a function of the extracted seam thickness (Brauner, 1973). In sub-critical panels Smax is a function of W/H where W = width of extraction and H = depth of extraction and must be determined empirically. The value of d must also be derived empirically and is also related to the W/H ratio (width/height). See for example Figure 16 in Holla, 1985. The UK

Subsidence Engineers Handbook (National Coal Board. 1975) states that the point of inflection migrates towards the panel centre as W/H increases and this causes the shape of the subsidence profile to change.

Once the various parameters have been determined empirically then curves based on these parameters can be fitted to measured data. Rather than matching a curve to the vertical subsidence data it is easier and just as valid to match a curve to the measured tilts. If the half-profile curve is roughly symmetrical about the inflection point then the curve for the first derivative will be a Gaussian or Bell-shaped curve of the form $T(x) = e^{p(x)}$ where p(x) is a quadratic polynomial. ACIRL is currently matching curves of this form to field data.

Advantages in using profile functions include: the subsidence profile can be determined quickly on a computer; the shape of the whole profile can be determined instead of just a few points; given the shape of the profile estimates of the magnitudes and location of the likely tilts, strains and curvatures can be calculated. Disadvantages include: difficulty in gaining accurate results for "greenfields" areas; small errors in subsidence lead to larger errors in tilt, curvature and strain; the shape of the profile may be effected by parameters not included in the function.

FIGURE 1



PROFILE FUNCTION NOMENCLATURE

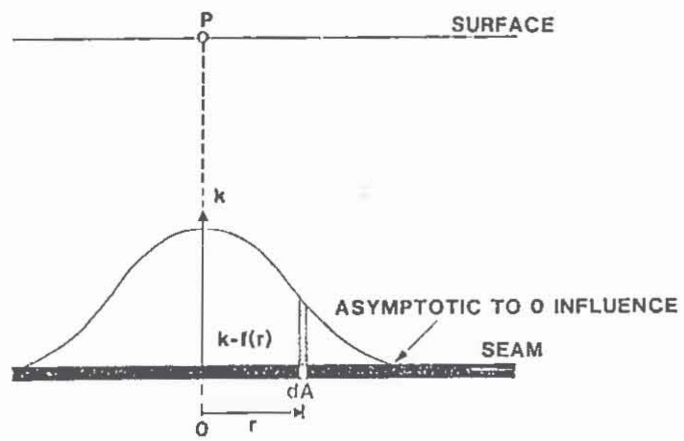
Prediction of Subsidence Using Influence Functions

The influence function method is another method for subsidence prediction that is being refined by ACIRL for use in Australia. The basis of the influence function method, as described in Brauner. 1973. is outlined below.

The influence of an infinitesimal area of coal extraction. dA. on the subsidence of a point P can be written k = f(r) where r = the horizontal distance of P from the element dA (see Figure 2). Note that the influence curve is the shape and size of the subsidence trough that would result at the surface from the extraction of element dA. In this sense the influence function can be viewed as a profile function for extraction of element dA. The sum of the influence of a series of elements gives the subsidence trough as illustrated in Figure 3. The function f(r) is at its maximum when r = 0 and tends towards 0 when r becomes sufficiently large because the function is asymptotic to zero.

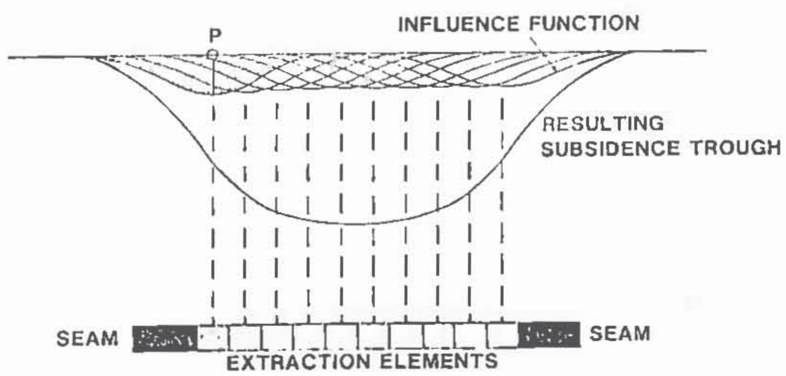
The function f(r) is assumed to be the same for a given geology and is independent of mine layout. ACIRL has been investigating functions that best fit the measured data with reasonable results.

FIGURE 2



INFLUENCE OF ELEMENT dA ON POINT P.

FIGURE 3



SUPERPOSITION OF INFINITESIMAL INFLUENCES TO PRODUCE SUBSIDENCE TROUGH, BASED ON BRÄUNER (1973)

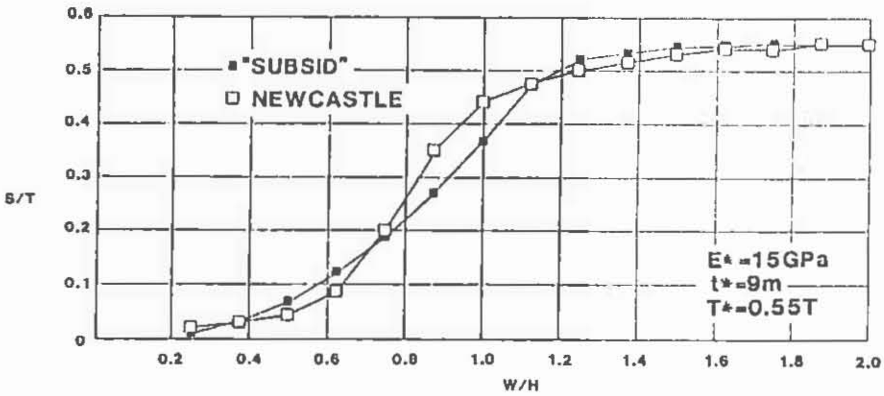
DISPLAYING & ANALYSING SUBSIDENCE DATA

Prediction of Subsidence Using a Friction-less Laminated Beam Model

"SUBSID" is a computer program for subsidence prediction based on a friction-less laminated beam model of strata behaviour. "The model is based on the idealisation that a horizontally stratified rock mass can be modelled as a pile of horizontal thin plates," (of equal thickness and elastic modulus) "where the interfaces between the plates are friction-less and thus free to slide" (School of Mines, UNSW, 1990). The model's potential as a predictive tool can be demonstrated by Figure 4 where predictions of Smax are plotted against those of Holla (1987). Here, it is apparent that using a laminate thickness (t*) of 9m, an elastic modulus (E*) of 15GPa, and a modified seam thickness (T*) of 0.55 x actual seam thickness (T), the "SUBSID" curve closely matches the empirical curve for the Newcastle Coalfield. Different parameter values may be used in an attempt to match the models outcome with empirical data from other areas. Also, to ensure that the curve "flattens out" at the value of maximum possible subsidence the seam thickness must be reduced by multiplying by the subsidence factor which in Newcastle's case is 0.55. This is valid because actual convergence of the lowest beam is limited by bulking in the goaf. It is hoped that actual values of E and t estimated from borehole data can be correlated with values of E* and t* derived from the curve fitting.

ACIRL is currently working on further calibration and refinement of the model which is proving to be a simple and accurate means of subsidence prediction. The program may prove to be particularly useful in "greenfields" areas where empirical techniques cannot be applied with confidence. A three-dimensional version of the program is being developed by coupling it with ACIRL's displacement discontinuity program "THREED".

FIGURE 4



"SUBSID" Results vs. Newcastle Coalfield Empirical Subsidence Curve (after Holla, 1987)

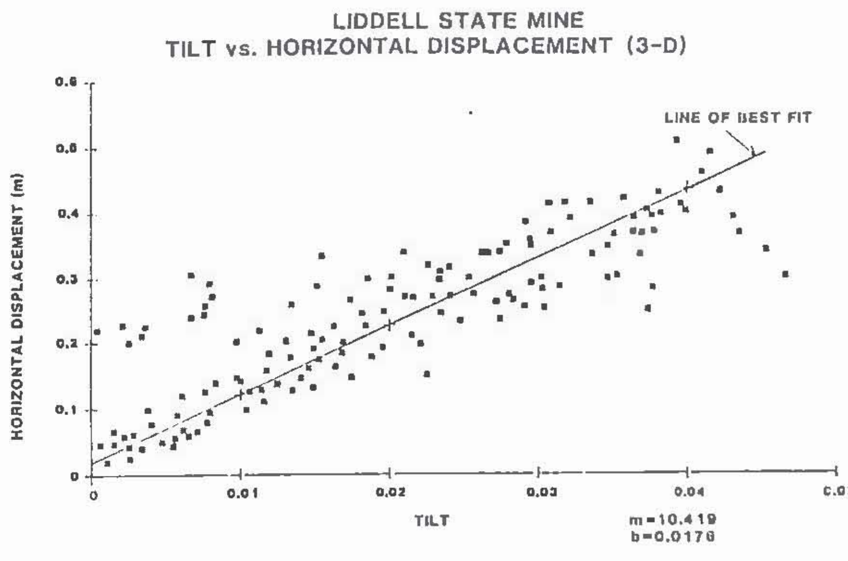
PETER WILLEY

Prediction of Ground Strains and other Destructive Deformations

Of primary concern to the subsidence engineer is the ability to predict with some degree of confidence the magnitudes, locations and orientations of ground deformations that may be detrimental to surface structures. Prediction of tilts and curvatures can be made simply by taking the first and second derivative of the subsidence profiles predicted by the above methods. Using 3-D analysis the likely location and orientation of these deformations in relation to the subsidence trough can also be determined. Plans displaying the various deformations can thus be produced to give structural engineers a basis for design. It should be noted here that small errors in the prediction of vertical subsidence will produce larger errors in predictions based on the first and second derivatives of the subsidence profile.

It has been shown that a relationship exists between the magnitude of curvature and strain (for example, National Coal Board, 1975). Salamon (1989) states that "the assumption that the horizontal displacement is proportional to the tilt is equivalent to the postulate that the horizontal strain is proportional to the curvature". Correlations between horizontal displacement and tilt have recently been completed by ACIRL and show that the relationship is linear with a slope of between 6m and 11m (remembering that tilts are dimensionless and horizontal displacements have units of length). Correlations vary less within a particular locality. Figure 5 shows a good correlation for data collected at Liddell State Mine. Correlations between the orientations of tilts and displacements also show promising results.

FIGURE 5

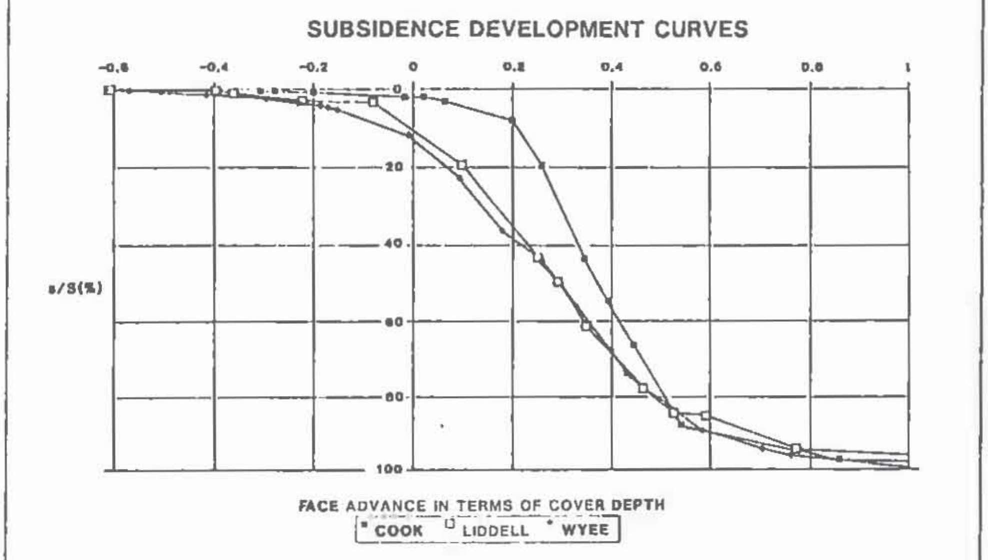


DISPLAYING & ANALYSING SUBSIDENCE DATA

Subsidence Development Curves

Subsidence development curves are a simple means of displaying the progress of subsidence at a surface point over an advancing panel. Figure 6 shows a comparison of subsidence development curves from three mines. The x-axis is the face position relative to the point normalised by dividing by the depth to the seam. The y-axis is the subsidence at the point normalised by dividing by the maximum subsidence experienced by that point. Subsidence development curves may be used to indicate when a surface installation will begin to be effected by subsidence and when subsidence has finished and as a comparison between sites to see how quickly subsidence occurs. They may also prove helpful to educate the public on the rate of subsidence.

FIGURE 6



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SOME CHALLENGES FACING GEOLOGISTS IN UNDERGROUND COAL MINING

J. HANES
BHP Steel Collieries Dlvn., Figtree

Abstract

The paper summarises some of the problems facing underground coal mining which geologists can help to solve. It also provides a look at a few innovative solutions that have been applied by BHP's geologists to help solve exploration and mining problems. With the contracting economic sphere coal mining companies and their geologists need to become smarter using their brains and geo-logic to solve some of the challenges that face them.

Introduction

Coal mining is a multi-skilled activity. Although it has been dominated by the mining engineer in the past, it is now becoming more dominated by economic situations and the problems to be solved quite often require a different application of logic than that which the average engineer has inherited and a different approach.

Because of his training, the mining engineer usually sees things in black and white with no shades of grey. The geologist, either by training or by nature, seems to have a more inquisitive nature and doesn't necessarily accept what he sees or take it at face value. He is more inclined to ask "why?" rather just "how do I fix it?".

The solutions to many of the problems facing underground coal mining will be found in the field or in the mine, not in the text books or in past practices. What is a problem to a narrow minded geologist or engineer is a challenge to an open minded one. To maintain their jobs in the coal industry as conditions become tight, the geologist must look for the challenges with possible geological components and apply his/her thoughts and logic processes to those challenges which have the largest cost impact on mining. By doing this the pro-active geologist will win recognition, save his company a lot of money and maintain his job. The reactive geologist who waits to be called upon to help collect information on a problem will find himself out of work.

Some of the challenges facing geologists in premining investigations include the age old problems of prediction of roof and floor behaviour, caving characteristics, support requirements, water and gas and redefinition of coal resources in terms of potential productivity and cost of mining with various mining systems and resultant economic values of insitu coal.

JOHN HANES

Some of the geological challenges facing underground coal mining include how to handle the ever increasing amounts of gas, predicting small scale structures which effect longwall mining, mine orientation and methodologies to best manage the high lateral stress fields in Australia, minimisation of contamination of run-of-mine coal and probably many others with a lower impact on mining. As well as these, are the challenges associated with the need to protect the environment from mining effects, from exploration and from liberation of gasses into the atmosphere and minimisation of deleterious effects of urban developments encroaching on prime coal reserves. This paper summarises some of the above challenges which are most applicable to BHP's Collieries on the Southern Coalfield.

Gas

Gas emissions into the mine can cause major costly delays at the coal face and safety hazards due to the potential for outbursting from development faces and ignitions resulting in explosions. Mining development in gassy coals of low permeability can encounter high gas pressure gradients at the face resulting in occasional outbursts or nuisance value gas emissions which slow production. On the Southern Coalfield where these problems are more severe than in the Newcastle area, predrainage by longholes has assisted greatly. At Leichhardt Colliery in Central Queensland, predrainage techniques were not as successful with drainage holes requiring in excess of one to two months before any effect could be noticed.

Gas emissions on longwall faces from underlying or overlying gas sources represent major problems and BHP is conducting comprehensive research at its mines into methods to minimise the effects of such emissions. Maddocks (1991) and Williams (1991a) summarised the problems associated with these types of emissions at Appin and Tahmoor Collieries respectively in the Southern Coalfield. In these two cases much of the problem gas originated in the Wongawilli seam which underlies the mined Bulli seam. For several years holes have been drilled from the working seam down to the Wongawilli seam in an attempt to drain the gas or at least capture the gas during mining. The holes are inclined somewhere between 15° and 25°. Many trials have been made of different inclinations and different orientations of the boreholes. The boreholes at Appin have typically produced low flows of gas. However, some of the holes have produced large volumes. Production from the holes typically does not start until after the longwall face has passed over them. Geo-logic was applied to this gas problem last year. The big question was "Why do some of the holes produce really good gas flows whereas most of them are very poor producers?" (based on the assumption that high gas flows represent good capture of gas and therefore represent the best potential for solving the gas-out problems). The exercise described by Maddocks (1991) involved probing of each of the boreholes in a longwall with PVC tubing to assess how much of the hole was open and available for free gas drainage. The work revealed that the majority of the holes were cut off under the rib line of the longwall after the longwall passed. The highly producing holes remained open to the Wongawilli seam. Maddocks reported that the open length of borehole was a function of stress concentration and mining strain in the floor before the advancing longwall and he showed it had a cyclic pattern. As the open hole produced more gas it was concluded that something had to be done to keep the holes open. A trial was conducted using slotted drill rods inserted into some holes to see if gas production could be increased. There was some fear that strata movement would be sufficient to close even the drill rods. In practice, the holes which were cased with drill rods produced more gas than their associated uncased holes. A major trial is now being conducted with casing of boreholes along a full longwall block to assess its value. In this case geo-logic has provided an explanation for an observed phenomenon and indicated the engineering solution to the problem. Only time will tell if increased gas capture by downholes will reduce time lost on the longwall face due to gas-outs.

In the Southern Coalfield the 200 m thick Bulgo Sandstone formation lies approximately 100 m above the Bulli seam. The Bulgo contains reservoirs of natural gas which have a very low permeability in the virgin state but which, on undermining, emit large volumes of gas often into the mine ventilation. This gas contains up to 2% ethane and has a characteristic odour. A similar situation is faced by miners in the Newcastle area where the working seam is overlain by coal seams. BHP have drilled boreholes into the Bulgo Sandstone and completed the holes with slotted casing to allow drainage of the gas to the surface upon undermining by longwall. These wells typically reach peak flow after the longwall has past approximately 70 m beyond the borehole. As well as presenting a hazard to mining, Bulgo gas represents a valuable resource.

At Westcliff Colliery Kembla Coal and Coke have attempted to drain gas from the goaf by the use of gob wells (R. Lama Pers. Com.). These holes were drilled to within 10 m of the coal seam and cased through the Bulgo with slotted casing in the lower part of the hole beneath the Bulgo and grouted casing above the base of the Bulgo. The first of these holes produced large volumes of gas when the longwall was located approximately 50 m from the hole (i.e. prior to undermining). Other holes in the same trial met with mixed success.

Geo-logic indicates that the gob holes and the Bulgo holes are affected at different times by the advancing destressed zone associated with the longwall goaf and gas flow is associated with different mechanisms of dewatering. There is a great potential to remove much of the excess gas which threatens longwall mining via a combination of boreholes drilled into the overlying strata from the surface. However, geo-logic and engineering know-how must be applied to firstly understand then to solve many of the challenges facing this technology.

Predrainage of gas from problem seams is the ideal. However, in our relatively impermeable, highly stressed coals, predrainage is not an easy matter. Boreholes drilled into the Wongawilli seam prior to mining produce very low gas flows. The challenge is to make these boreholes extract more of the Wongawilli seam gas than they currently do. In the United States hydrofraccing from surface boreholes is used to increase gas production. However, the United States conditions of vertical maximum stress and permeabilities one or two orders of magnitude greater than in Australia with the added benefit of taxation concessions makes the technology more applicable and more profitable in the United States than it would appear to be in Australia. However, hydrofraccing must be trialled in our conditions to determine if it will work and if it will work profitably. Other options to predrain underlying seams include longhole drilling (Williams 1991,a) with dewatering of these holes and possibly with hydrofracturing.

<u>Structures</u>

The accurate prediction of face- and longwall-stopping structures ahead of mining development is critical for economical extraction of coal. Structures with throws as small as a half a seam thickness can stop a longwall and cause considerable delays. Prediction methods vary from the simple geological tools of projecting known intersections, to the more complex tools of drilling, surface geophysics, the use of radio waves, satellite imagery, etc. However, most of these are coarse in structural resolution.

In the Southern Coalfield where drilling costs around $60,000 to $70,000 per bore surface seismic is now extensively used for prediction of structures. In the twelve and a half years of use of high resolution seismic in Australia there have been only a few modifications. The conventional equipment used is bulky and requires 4WD landcruiser vehicles for its transport and involves many difficulties where access is poor in rough terrain. It cannot be used in damp environments such as swamps and it requires delays while equipment is dried out after rain. The dynamic range of the equipment appears to be limited, thereby limiting resolution. To obtain best quality data, refraction surveys are required prior to design of shothole depths. The system has therefore many draw backs in the application of high resolution seismic in areas of rough terrain or environmentally sensitive areas and the results with resolutions of the order of 6 m to 10 m are not good enough for confident longwall design although they are adequate for picking pit stopping faults. The costs of surveys using this equipment are high varying from around $15,000 to $20,000 per line kilometre.

The challenge to improve data quality with less environmental impact and at a lower cost has been taken up by BHP's geologists and research geophysicists who are currently designing a system which will be far more applicable to our conditions than conventional equipment.

When a conventional high resolution seismic survey is completed, several months pass before results are available from the data processing laboratories. Coal surveys represent small change to the laboratories and are slotted in between oil field processing runs. Such delays are unacceptable and it is a challenge to improve processing turn around perhaps by development of a specialised coal seismic processing facility. Some work has been done (Hatherly and Poole, 1990) in the use of a work station for fast processing of 3D seismic and this system could be adopted for more routine seismic processing. Much exciting work is now being done in image processing and there is potential for use of these systems for better and more innovative processing of seismic data.

In the mines, smaller structures can be detected using geophysical techniques such as RIM and in-seam seismic. However, they must be discriminately used where they are applicable. They cannot be applied everywhere and pre-data must be collected and evaluated prior to the design of full scale surveys. There are challenges in this area to improve understanding of applicability and interpretation.

Whenever the geologist uses remote sensing techniques to predict structures the miner can take one of two extreme actions. One action is to completely avoid an area of predicted structure. The other is to mine it anyway just to see if the geologist is right. Some mines can become inoperable if the miners believe every line on a plan is a fault. Some mines won't operate profitably if they keep developing roadways to prove the geologist right or wrong. Although the continuous miner is probably one of the best tools for proving predictions of structures it is not the most cost efficient tool. Although beset with its own problems, inseam drilling has much to offer for structural assessments and validation of structures predicted from remote sensing tools. The technique has problems (Williams, 1991b) with surveying of the hole and costs. However, these challenges should be met and solved to provide the coal industry with a useful, physical testing tool for structural assessments. Along with the longhole drilling, equipment for geophysical logging of the holes must be improved.

GEOLOGICAL CHALLENGES

Environmental Impact

Surface exploration work necessarily has an impact on the environment. In times passed, gaining access to a drill site or preparation of seismic lines involved the use of a bulldozer scraping away the surface soil to provide tracks which could easily be traversed by heavy equipment and 4WD landcruisers. The community is now more environmentally sensitive and demands that exploration work has minimal impact. Much of BHP's coal exploration work is conducted in either Water Board catchment area or over local farmlands, both environmentally sensitive areas. Tracks for drill rig access are still driven with heavy equipment but the blade is not allowed to touch the soil. Low scrub is pushed, large trees are avoided. The access tracks are not to the standard that they used to be and occasionally tyres are staked. However, evidence of the presence of a track soon disappears. Seismic surveys are now being introduced with hand clearing or very light equipment clearing in timbered country and slashing of grass in pastured country. The tracks are kept to a minimum width. To minimise compaction of the land under the tracks, movement of 4WD conventional landcruiser vehicles is minimised and most movement of surveyors, stemming gravel, etc. is conducted using wide-tyred, low weight, 4WD motor cycles. With the development of a light weight, portable seismic system most of the work can be done using these 4WD motor bikes and the need for any heavier vehicles will be obviated.

On the Southern Coalfield the area surrounding Campbelltown, Camden, Menangle, Appin, and Wilton, is planned for urban development in the ever expanding metropolis of Sydney. Under this land lies a magnificent resource of some of New South Wales' best coking coal with associated large resources of natural gas. The management of the State's energy resources and provision of land for housing appear to be in conflict. At current rates urban development will ensure that the land overlying the coal and gas resources is occupied prior to mining. To remove the gas from the coal and the overlying strata prior to mining will have to involve hydrofracced wells, draining gas for very long periods of time (up to 10 - 20 years). This will, of necessity, involve co-existence of urban development and gas drainage plants.

Gas Recovery and Utilisation

Although the technology and incentives for surface extraction of coal seam gas exists in the United States, the different ground conditions in Australia will make gas extraction technically difficult and expensive. There is a challenge to our Governments to ensure that the financial incentives to develop a gas industry based on coal seam gas are available and there is assistance to develop appropriate Australian technology. Even so, regular predrainage of gas from these coals will only commence in the 2000 to 2020 period because of the lead times for technology development and capital requirements. If urban development prevents surface drainage, a means of better gas capture from underground will have to be developed, but this will be very expensive and has the potential to be far less efficient, thus causing extra hazards for mining.

The huge volumes of gas to be extracted from the ground will also have to be utilised. Methods of extraction to minimise contamination of the gas have to be improved. The challenges in this area are obvious and the financial rewards to the State and Country are potentially high.

JOHN HANES

Coal Quality

Although much work has been traditionally done in the field of coal quality, there are still many challenges which, if successfully met, can improve coal industry profitability. Three challenges which BHP's geologists are investigating in the belief that they have the highest potential for improved profitability are run of mine coal ash control, coal size degradation control and washability predictions. A recent trial ROM ash control project at Cordeaux Colliery used Coalscan ash monitoring data as a basis for preparation of statistical control charts of ROM ash versus seam ash. This highlighted the amount of contamination in the product and steps were immediately taken to train the longwall operators in minimising contamination. This project has aroused much interest amongst BHP's mines as each 0.1 m thickness of stone contamination in a 2,000 m x 250 m longwall block represents 125,000 tonnes of stone which has to be cut, transported to the washery, washed and disposed of. Coal size degradation through mining and transporting out of the mine and through the washplant increases the amount of coal fines to be handled in the washplant and in a coke oven. A 1% decrease in coal fines production in the system can result in a cost saving of nearly $1 per tonne of coal. The age old problem of predicting coal washability parameters and washplant output from borecores and strip samples still presents a challenge which is being continually addressed.

Stress, Roof Support etc.

Many of the challenges associated with measurement and prediction of stress directions, orientation of roadways to minimise stress effects and roof support that existed 10 years ago have been met and partly solved (Gale et al, 1989). The major challenges facing coal mining geologists in this area include those associated with improving development advance rates for longwall gate roads. The increased support density required in stressed roadways slows advance. Design of mine layouts and support methods to maximise advance rates requires understanding of the geological environment and geotechnical engineering of support.

Conclusions

The proactive geologist who is prepared to take a helicopter view of the problems facing the Coal Industry will find many challenges of a geological flavour to which he can apply geo-logic to find a solution which could save his industry money and pay his salary. Innovation and practical application are required to solve many of our problems. The challenges to be concentrated on firstly are the ones with greatest potential financial return. The challenges involved with the sharing of resources between mining and community have to be overcome and a means of co-existence developed. Government incentive is required for the Country to develop a coal seam gas industry which can supply the community's needs while reducing environmental threats.

GEOLOGICAL CHALLENGES

Acknowledgements

The continuing and patient support of BHP Steel International Group - Collieries Division for research into mining problems and development of technologies necessary for meeting the challenges that face mining and exploration helps keep BHP's Collieries working. It also makes the author's work enjoyable and rewarding. Permission to publish this paper is appreciated.

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APPIN AND TOWER COLLIERIES IN-SEAM RIM SURVEYS

R. DOYLE
BHP Steel Collieries Divn., Figtree

SUMMARY

BHP Illawarra Collieries have successfully undertaken 4 RIM tests, 2 each at Appin and Tower Collieries. This paper outlines the purpose of the tests and the results. The purpose of this paper is simply to promote a useful and successful exploration tool to the coal industry.

INTRODUCTION

The Coal Mining industry is undergoing a continuing rationalization in its strive for more economic and efficient production. In 1985 BHP Illawarra Collieries operated 9 collieries producing an annual output of 6 million tonnes p.a. By 1992 only 4 collieries will be operating but will be producing 8 million tonnes p.a.

Because of this dependency on fewer operating mines the greater is the importance placed on high level accurate geological interpretations. Good information is worth paying for! BHP's Technical Services Department, Geology Section has instigated a pro-active approach to in-seam exploration. In the past 12 months a total of 4 RIM tests have been performed in BHP mines using METS Pty Ltd.

The Radio Imaging Method (RIM) is an electromagnetic geophysical technique which defines the variation of attenuation response in coal. Structures such as faults or joints give a higher, or anomalous reading above average attenuation rates. The technique can only be used in transmission. It can be shot from roadway to roadway or, from borehole to borehole. The radio wave is confined to the seam by the roof and floor rocks allowing easy transmission of the signal to the receiver.

TEST 1: TOWER COLLIERY LONGWALL 4

Tower Colliery extracts coal from the Bulli seam which varies in seam thickness from 2.1 to 2.8 m over the length of the longwall block. The width of the longwall is 100 metres. The purpose of the tests was twofold: firstly, to determine the accuracy and reliability of the method, and secondly to give "clean coal" results in an area of concern. Normal underground mapping techniques were considered sufficient to determine the location of structure prior to the tests. It was hoped that RIM would provide confirmation of directions and size of the known faults within the longwall block. Prior knowledge of structure would also give us confidence if the technique confirmed this data.

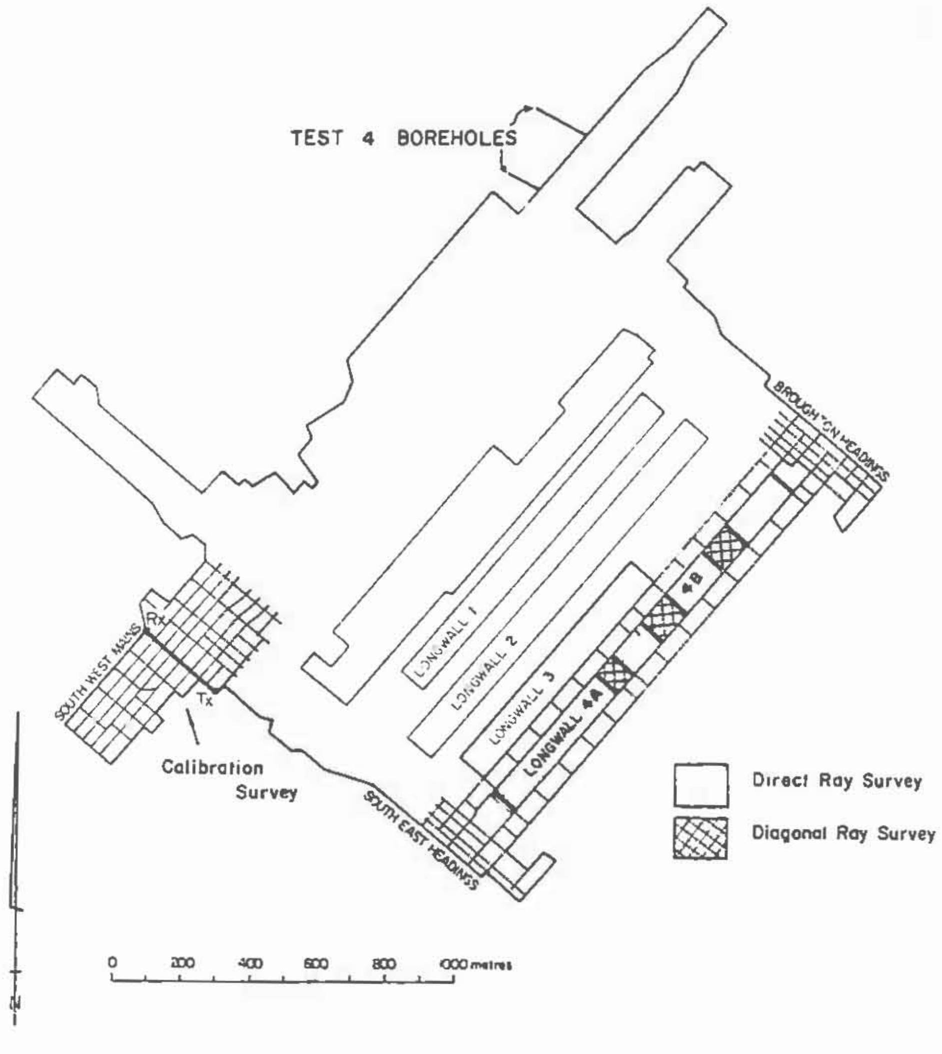

Figure 1, shows Tower Colliery workings including the layout of Tests 1 and 4, and the Calibration Survey.

The Direct Ray Path Survey was shot from points of similar distance on either side of the longwall along the full length of the longwall. Reflecting metre markings were located on the roof to allow both maingate and tailgate parties to be certain of the exact location at all times. During the Direct Ray Path Survey anomalous zones were distinguished by the varying attenuation rates. Figure 2, shows the results of the Direct Ray Path Survey.

The Direct Ray Path Survey highlighted 7 anomalies. Of these, 3 were considered major features (A, B & C). Anomalies B & C were faults that were mapped prior to the survey; while Anomaly A had not been previously recorded in the workings. The most critical aspect of this survey was the "Clear Coal" designation between Anomalies B & C.

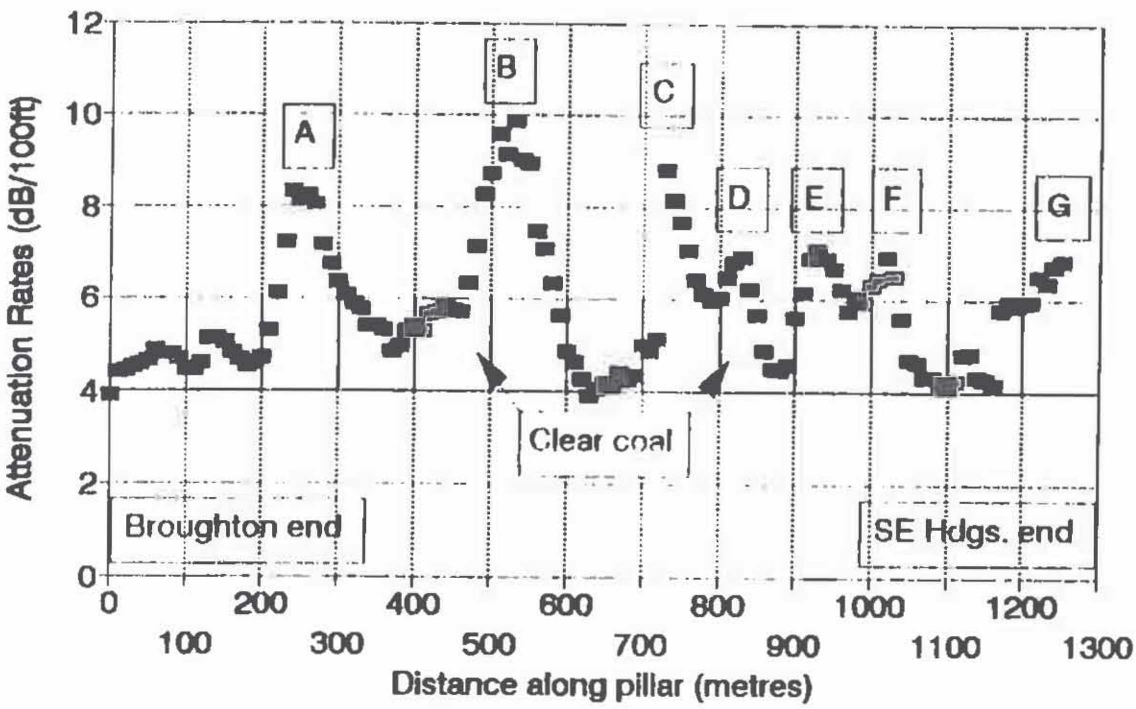

Figure 2, showing results of the Direct Ray Path Survey

During a methane drainage drilling programme, four holes from one location intersected stone. A mining decision was made to investigate these stone intersections by using the most successful exploration tool available - a continuous miner. A "stub heading" some 30 m long was driven across the longwall block - no hazards were intersected.

Had the RIM survey been conducted prior to the driveage of the stub heading, considerable costs could have been saved and any problems that may have occurred by taking a longwall through the stub would have been avoided. The survey gave good, clear anomalies on the structures that we knew were present and therefore increased our confidence in the "clear coal" report, in the area of concern.

Anomaly C was a significant hazard to longwall mining and the decision to remove the longwall equipment and reinstall it into Longwall 4B had already been made - the question was where to place it. RIM gave Mine Management the confidence to install the face so that it would extract coal on both sides of the "stub heading" area. This saved some 50,000 tonnes of prime Bulli seam coal from being sterilized. The cost of the survey, some $6,400, would have been recovered with 1 shear on the longwall. The value of this survey technique cannot be understated.

Anomalies G, F, E and D were considered real, but of a nature that would not cause an impediment to longwall mining. Anomaly G represented the tail end of a dyke and was represented by a zone of jointing. Constant production rates occurred over Longwall 4 highlighting and confirming the prediction of the RIM survey - that these anomalies would not impede mining. At the time of writing Longwall 4B is still producing coal, and Anomaly A, a strike slip fault has not been intersected by the longwall.

Following the Direct Ray Path Survey a Calibration Survey was conducted. The purpose of this aspect of the survey was to establish how well the radio waves are transmitted over distance in the Bulli Coal at Tower Colliery. The results were excellent proving up the distance to a possible 500 m with realistic resolution of geological features to 300 m.

Following these two surveys Scott Thomson (METS) processed the data overnight and planned 3 individual Tomographic Surveys to highlight the major anomalies located during the Direct Ray Path Survey. Day 2 saw the conduct of the tomographic surveys. Figure 3a shows the ray paths of Anomaly C, while Figure 3b shows the tomographic image. The darkened area represents the trace of the fault plane which can be seen to bifurcate. These results fitted in with the expected geology, in that the fault projected across the block, decreasing in throw. The results of the tomographic survey enhanced the accuracy of the Direct Survey predictions.

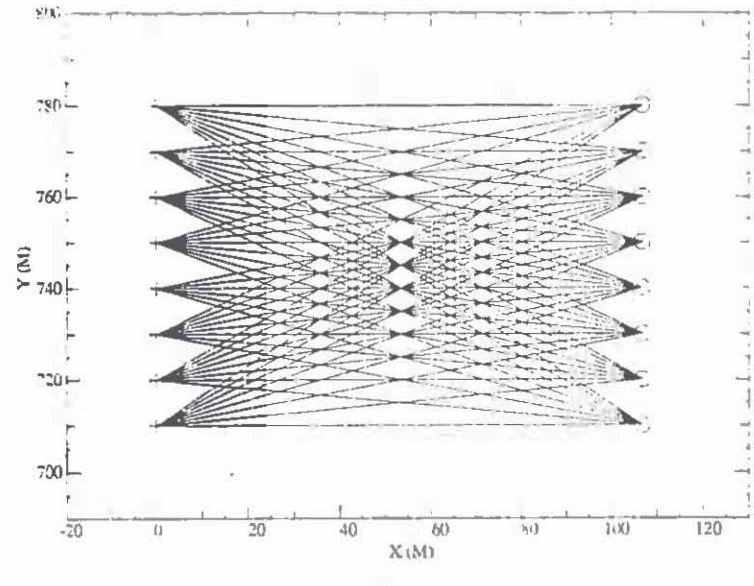

Figure 3a. Detail of Ray Paths for the Tomographic Survey, covering Anomaly C.

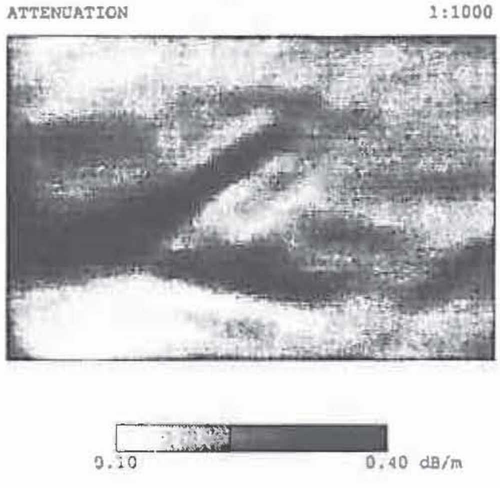

Figure 3b Tomographic Image of Anomaly C.

APPIN AND TOWER COLLIERIES IN-SEAM RIM SURVEYS

TEST 2 - APPIN COLLIERY - LONGWALL 20

Following the success at Tower a specific problem was highlighted at Appin Colliery. A fault was located on one side of Longwall 20 and not on the other.

Figure 4 shows the results of the 2 surveys at Appin Colliery. Ray Williams of GeoGAS Pty Ltd was contracted by METS to conduct this survey. The purpose of the survey was to trial the method and hopefully determine the extent and location of the fault to assist in mine planning. Depending on the results of the survey the mine management was planning to drift through the fault cutting the floor using the shearer. Therefore additional information about the fault was sought.

From underground mapping the fault plane had a relatively straight trace with a throw adjacent to Longwall 20 of 1.5 m. What the fault did inside the 200 m longwall block was uncertain. A calibration survey was also conducted at Appin Colliery and determined similar properties to those of Tower Colliery - both mines working the Bulli seam. A Diagonal Ray Survey was conducted to highlight this zone.

The results of the survey indicated an unusual arcuate fault trace, stating that the fault would diminish to a position of 120 m within the block and that it would occur as an en-echelon type feature. This result was not postulated prior to the survey. But because of the success of the surveys at Tower and the confidence in both the method and the people conducting the technique - the results were accepted. Mine management gave the go ahead for traversing the fault zone with the shearer and mining engineers proceeded to plan how to grade down this fault zone. Had this survey not been conducted the uncertainty of mining through this hazard would have been very large. At production levels of 10,000 tonnes per day, delays due to uncertain geological conditions are costly.

TEST 3: APPIN COLLIERY 21

Longwall 21 also contained a fault of 2.3 m throw adjacent to the wall. Logistically it was a very similar problem to the previous test. A Direct Ray survey was conducted followed by a Diagonal Ray Path Survey of two anomalous areas within Longwall 21.

The location, extent and trace of the fault are shown in Figure 4. Fault A was predicted to increase in fault magnitude and/or high water content prior to dying out. While the prediction of Fault B was to trend some 180 m across the block, decreasing in magnitude all the way. As well as this there were "clear coal" zones recognised.

Mining decisions were made to remove the longwall equipment prior to approaching Fault A due to an increase in throw and the possibility of poor roof conditions associated with the curvilinear fault plane. A number of reasons contributed to the decision, to avoid the area between Faults A and B and the longwall is to be reinstalled outbye of Fault B. RIM assisted in this decision making process.

TEST 4 - TOWER COLLIERY N.E. INTAKES

A NERDDC funded test was trialled at Tower Colliery. Peter Hatherly of ACIRL coordinated the project which involved utilising pre-existing methane drainage holes to a depth in-seam of 165 m.

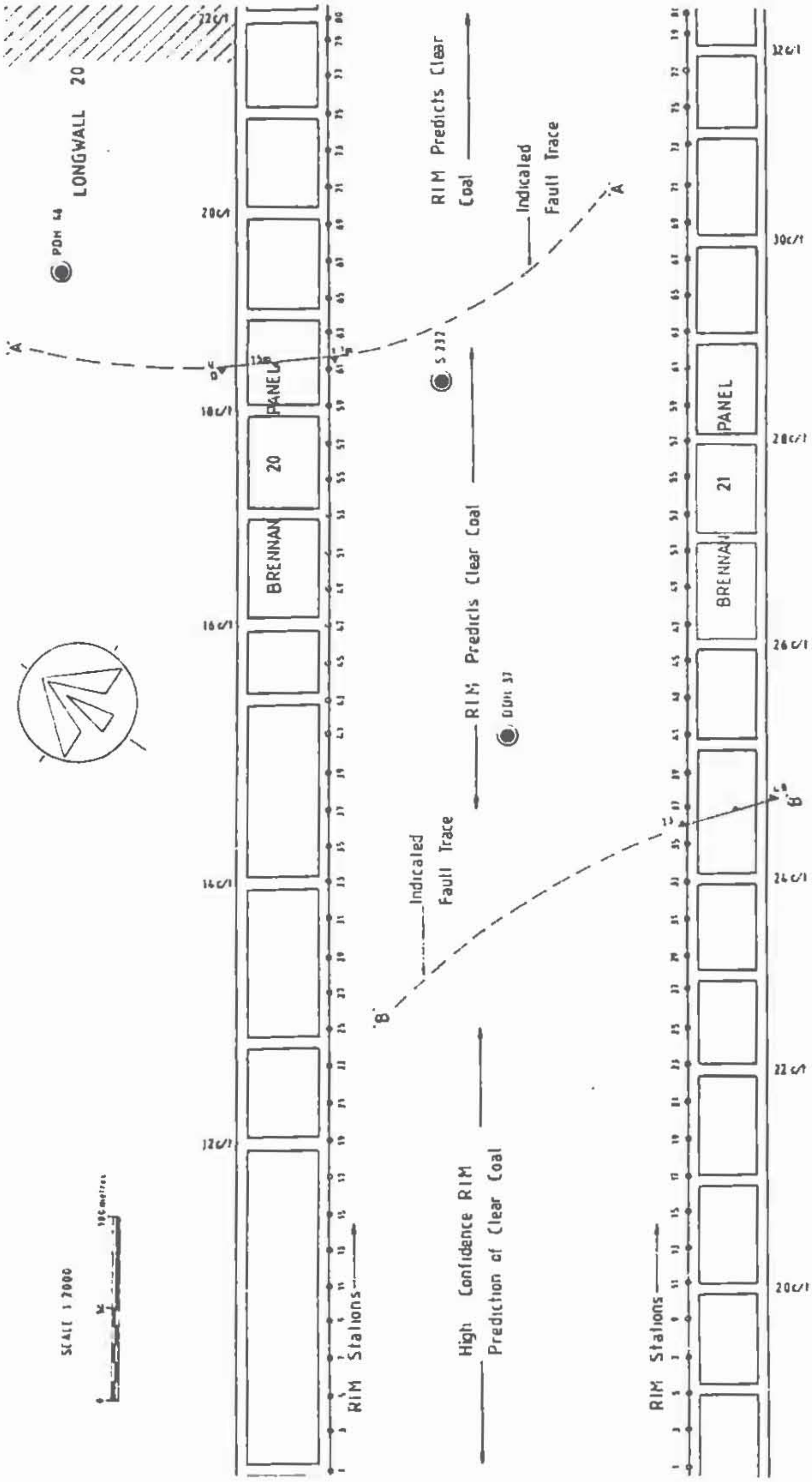

Figure 4: Appin Colliery, Longwall 20 and 21
showing RIM layout and fault traces

The survey involved a pulley/winch operated system of inserting and removing the transmitter and receiver in the boreholes. The holes are shown in Figure 1. Antistatic and flame retardant plastic pipes were installed in the holes to facilitate sliding of the transmitter and receiver. Due to crushing in some of the holes it was only possibly to insert the pipe in the transmitter hole to a depth of 106 m, while the receiver pipeline was inserted to the full depth of 165 m. A distance of 200 m separated the two boreholes and the area covered by the survey was over virgin coal. A major fault has been picked up by surface high resolution seismic and its tail should be in the vicinity of the test site. The purpose of this test was twofold, to determine if the fault was present in the area and secondly to test the technique in in-seam horizontal boreholes.

No anomalies were located. The importance of this work lies more in the fact that the technique can be demonstrated to be effective in the search for features in virgin coal conditions. For example, this technique could now be conducted in advance of longwall development. The results of such a survey technique could have serious implications on mine development.

Hence this trial test at Tower Colliery was deemed a successful operation. The first of its magnitude in an underground mining operation in Australia.

CONCLUSION

The purpose of this paper is simply to inform. Four RIM tests have been conducted at Appin and Tower Collieries, they have all been successful. The results of the tests have been confirmed by prior underground mapping and by longwall mining of those areas tested. The results are providing a data base for BHP to gain more confidence in the technique, this confidence has been put to the test already and will no doubt be put to the test in the future.

The role of in-seam exploration will gain more importance with time, and Geologists must "come up with the goods" if mines are to become more efficient and more economical.

ACKNOWLEDGEMENTS

The author wishes to thank BHP Collieries Division for permission to present this paper. The management and workforce at both Appin and Tower Collieries provided excellent support during the surveys, in particular the survey crews.

I am grateful to Paul Maddocks, Scott Thomson and Ray Williams for their major roles during the surveys.

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PRACTICAL APPLICATIONS OF THE RIM TECHNIQUE FROM BOREHOLES

S. THOMPSON
METS Pty Ltd, Maitland

ABSTRACT

The Radio Imaging Method (RIM) has been used in Australian longwall mining operations for detecting geological anomalies from underground roadways (RIM I). RIM II utilises the same concept in borehole applications. This paper describes the performance of RIM II from vertical boreholes at a number of Australian coal mining sites. Targets include abandoned workings, faults and intrusions. The applicability of the technique to evaluating seam continuity is discussed. It is suggested that RIM II may play an important role in conjunction with drilling programs to target areas of structural complexity and to establish areas of 'clear coal' and thereby reduce the number of holes that need to be drilled.

1 INTRODUCTION

The Radio Imaging Method (RIM) is an electromagnetic geophysical technique which uses medium frequency (50 - 520 kHz) radio waves to evaluate subsurface geology.

RIM relies on propagating radio waves through layered strata, such as a coal seam. The resulting EM wave signal will attenuate (lose strength) as a direct response to variation in the conductivity of the strata.

In-mine RIM (RIM I) has been successfully conducted on a commercial basis since 1988 by METS Pty. Ltd., mainly in longwall mining operations in NSW and Queensland. It was recognised that the sensitivity of RIM to geological structure could be applied to best advantage by getting 'ahead of the face'. For this reason, recent research in RIM has been geared to borehole application from either horizontal or vertical holes.

SCOTT THOMSON

This paper will describe the results of RIM II borehole trials utilising VMD (vertical magnetic dipole) antennas, which took place in January 1991, as part of NERDDC project No. 1209, managed by the Australian Coal Industry Research Laboratories (ACIRL). The technique was tested in abandoned mine search, and geological structure definition.

The field trials were conducted by METS Pty. Ltd. in conjunction with staff from ACIRL, CSIRO Division of Radiophysics and STOLAR Inc. of the USA. Participants in the trial were FAI Mining, Pacific Coal, Coal Resources of Queensland and Novacoal Australia.

2 APPROACH

The approach at each trial site was to firstly define the variation in attenuation response in areas of clear ground. This would enable significance to be attached to values lying outside the range of attenuations for normal coal. This is achieved by ray paths in 'clear coal'. The clear coal results at varying transmitter to receiver separations enables a RIM 'C factor' to be calculated. This is unique for seam and location and is analogous to the C factor used in RIM I in-mine surveys (Thomson et al, 1990). The 'C factor' is then used to calculate attenuation rates.

RIM measurements were then undertaken from borehole to borehole across the area of interest. The Transmitter (Tx) was lowered down a borehole to mid-seam position. The Receiver (Rx) was then lowered to a corresponding position in a nearby borehole. This enabled a transmission survey to take place. Signal amplitude and phase were recorded for each cross-hole interval.

Comparison of the calculated attenuation rate (the rate of signal decay) at various cross-hole intervals enabled inferences to be made about the intervening geology.

3 ABANDONED WORKINGS SEARCH

At Teralba Colliery, the target was abandoned workings with a section of 3m, extracted from a geological seam height of 4.5 - 5m in the Great Northern Seam.

Results:

Cross-hole surveying indicated a considerable disparity in attenuation rates for the various borehole to borehole intervals (figure 1).

Ray paths postulated to be affected by workings had attenuation rates up to 85 dB/100m. This compared with designated 'clear coal' of < 50 dB/100m. In plan the RIM results support the location of the workings contained in the historical records (figure 2).

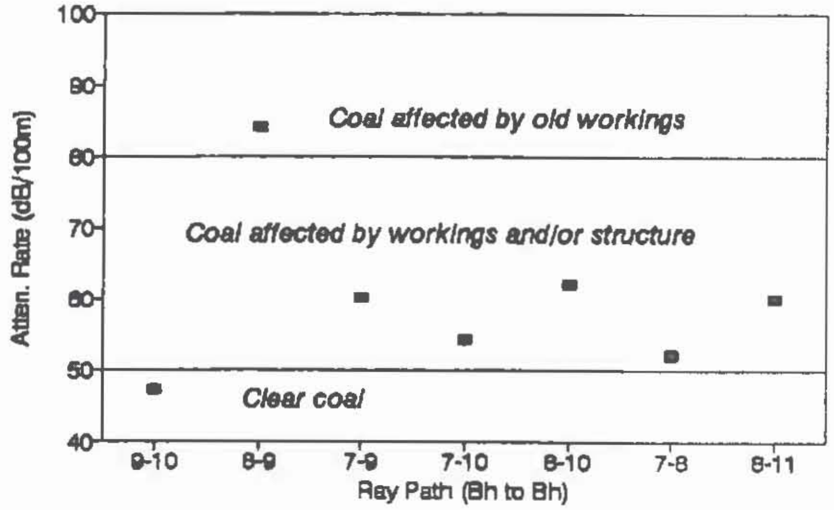
With the exception of path 8 to 11 (which may be affected by a geological structure), the attenuation rates were found to be consistent with the hypothesised extent of old workings intersected on the cross-hole ray path. The greater the area of workings between the holes, the higher the attenuation rate.

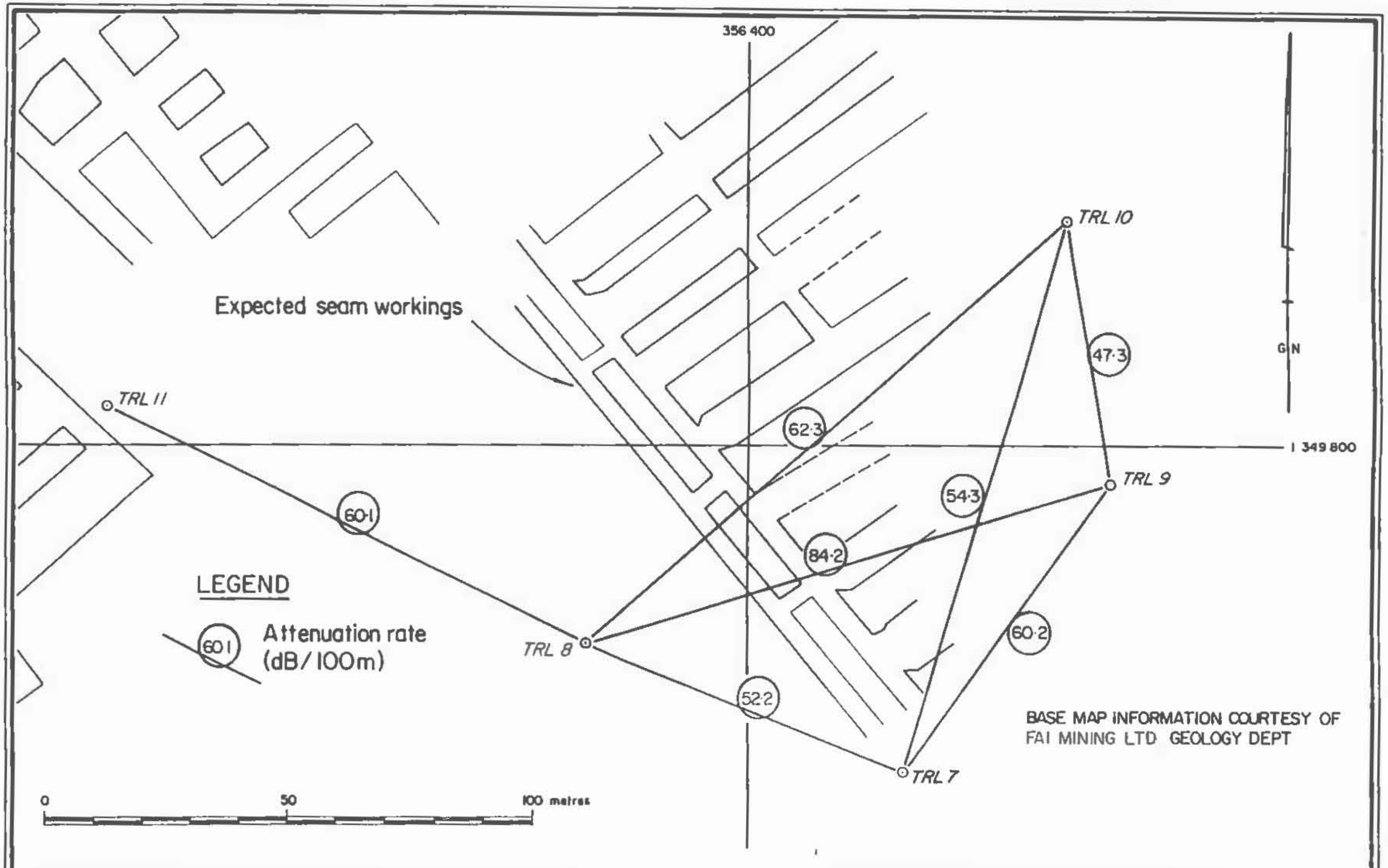
Conclusions:

The RIM II survey at Teralba Colliery illustrated the role that the technique can play in increasing confidence in the location of abandoned mine workings. RIM II proved to be a useful adjunct to boreholes as it operates in the horizontal plane of the seam and increases the 'zone of influence' of vertical boreholes.

In the future RIM II may be used to influence target selection in drilling for abandoned workings, and ultimately, reduce the number of holes that need to be drilled.

Fig. 1 Teralba Colliery
Attenuation Rate Contrast





TERALBA COLLIERY RIM SYSTEM II TRIAL RAY PATH ANALYSIS Fig. 2

4 GEOLOGICAL DISTURBANCES

4.1 Intrusions - Maules Creek

Novacoal's Maules Creek deposit has been extensively drilled. Until recently, it was considered virtually devoid of igneous intrusions in the proposed open cut area. The recent drilling program identified an area where seams had clearly been heat affected. The RIM II survey was conducted to attempt to define the limits of the intrusion in the major economic horizon, the Braymont Seam.

A surface magnetometer survey of the area had been conducted previously. Two discrete anomalies were identified.

Results:

Ray paths affected by the intrusion had attenuation rates up to 77.6 dB/100m. This compares with 'clear coal' attenuation rates of 10-20 dB/100m. The attenuation rates for the various ray paths are presented in figure 3.

By examining the various cross-hole ray path attenuation rates it was possible to deduce the orientation and likely extent of the intrusion (in plan).

Conclusions:

The RIM survey indicated that in the Braymont Seam, the extent of the intrusion was larger than that indicated by the surface magnetometer survey, and more linear with a well-developed strike. In addition, on the basis of attenuation rates, the intrusion appeared to be larger to the south-west of the magnetometer anomalies.

The evidence of the drill hole cuttings, the RIM survey and the magnetometer survey provided strong evidence that the intrusion is a dyke of variable thickness (likely to be up to 5 metres thick) orientated north-east to south-west.

At Maules Creek, the RIM II survey enabled a geological interpretation of the target horizon to take place. This is not possible with routine surface based geophysical methods, which may be affected by noise and surface effects.

Fig. 3 Maules Creek, Braymont Seam
Attenuation Comparison

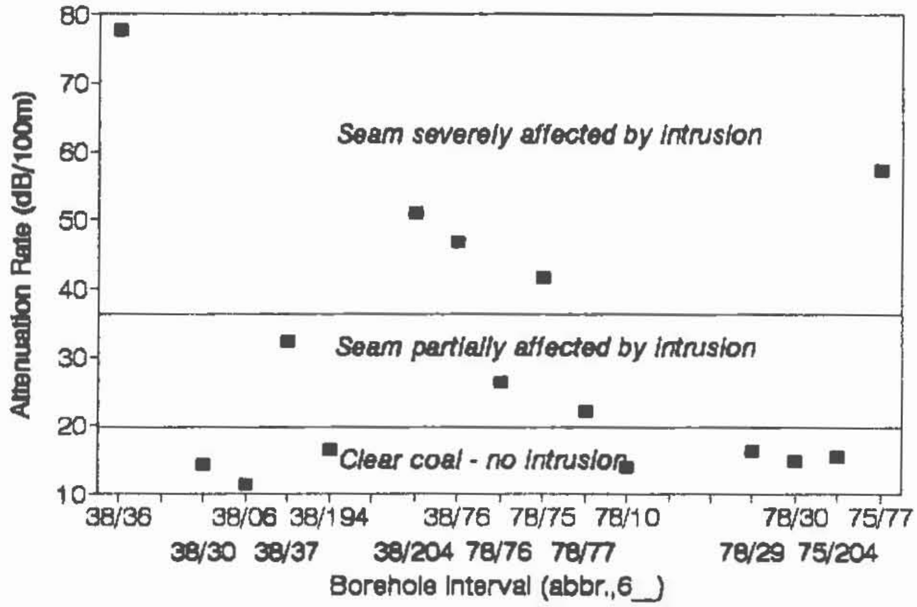
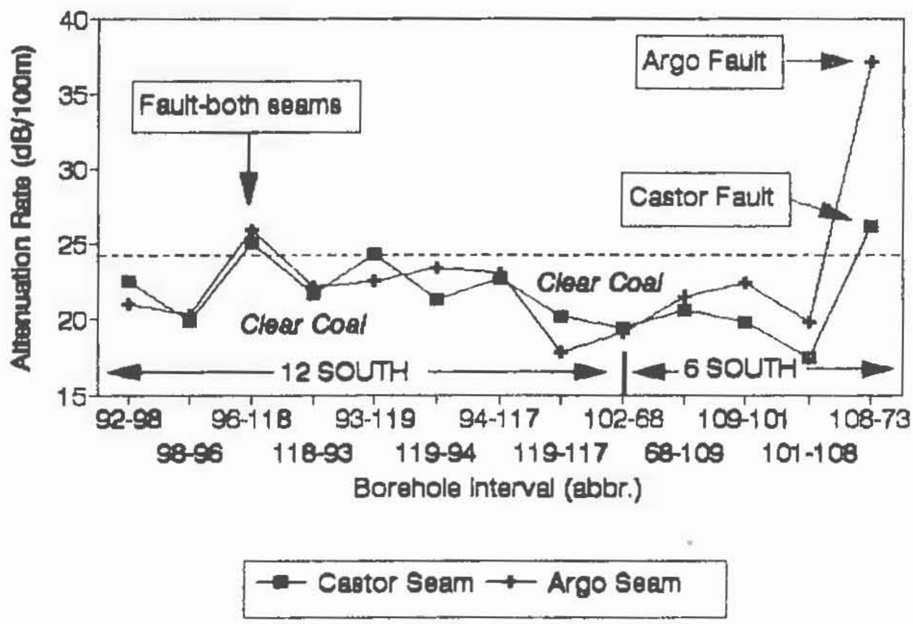


Fig. 4 Cook Colliery
Attenuation Comparison



4.2 Faults - Cook

At Cook Colliery boreholes are spaced at less than 50 m centres through geologically complex areas. The close spacing enabled RIM from boreholes to be evaluated in a succession of cross-holes, most of which remained in clear coal. Some however, were affected by seam disruption of an unspecified nature.

Results:

A 'normal' attenuation rate for coal (signifying the path is clear of geological problems) was found to be less than 24 dB/100m for both the Castor and Argo Seams (figure 4).

Ray paths affected by faulting had attenuation rates up to 37.1 dB/100m. Relative to 'clear coal' this is a high rate of signal attenuation and probably indicates a significant disruption to the seam (full-face fault?).

Generally, the attenuation response of faulting was much lower (25-26 dB/100m). This more subtle response to faulting probably reflects the magnitude of the structures themselves (ie. the faults are less than full seam throw). Nevertheless, it appears that RIM II borehole to borehole may only be sensitive to the major structures.

Conclusions:

RIM appeared to provide a high confidence prediction of clear coal between boreholes. It is difficult to ascertain the nature of geological discontinuities from RIM alone, nevertheless the magnitude of the signal loss is likely to be proportional to the size of the discontinuity.

RIM clearly has a role at Cook in reducing the need for 'blanket' close borehole spacing by proving 'clear coal' where appropriate. RIM can be used in conjunction with drilling to ensure the appropriate areas are targeted for exploration.

5 CONCLUSIONS

The RIM II trials illustrated the technique has a role to play in establishing seam continuity between boreholes. The targets of abandoned workings, intrusions and faults were all successfully distinguished from clear coal.

RIM II in conjunction with surface boreholes is likely to find a niche in the exploration scene for those operations where the target coal is not too deep (thereby enabling relatively close borehole spacing). There is no role for RIM in operations with 1 km borehole grids.

A drilling program may be driven by RIM survey results. Clear coal areas can be established early in the program, then geologically disturbed zones can be targeted for further investigation. RIM has the capacity to make exploration planning 'smarter' and to reduce the number of holes that need to be drilled.

An essential feature of RIM II is its ability to target the economic horizon. This makes it superior to most surface based remote sensing methods as it is not influenced by 'noise' effects or non-target horizon anomalies.

6 ACKNOWLEDGEMENTS

I would like to thank the respective management and staff of FAI Mining Ltd., Novacoal Australia Ltd. and Coal Resources of Queensland Ltd. for their permission to publish results from RIM work at their mines.

The following individuals played an important role in the trial program: Gary Boese (Stolar Inc.), Patrick Mackenzie (UNSW), Jeanne Young (CSIRO), Andy Williams and Michael Creech (FAI), Chris Lauritzen (Novacoal) and Derek Deevey (CRQ).

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SEISMIC RESOLUTION AND SMALL FAULT DETECTION LIMITS

W.D. STASINOWSKY
Mining Geophysics Pty Ltd, Mt Ommaney, Qld

ABSTRACT

Seismic resolution not only depends on the properties of the seismic pulse and the geology through which it is transmitted, but also on processing the data and the skill of the interpreter. In terms of interpretation, resolution also depends on the spatial coverage, i.e. lines close or far, the presence of multiple tie lines or a 3–D survey.

To maximise the resolution of seismic reflection in terms of small fault detection, it is necessary to not only understand the physical constraints but also the interpretive constraints.

INTRODUCTION

The object of seismic reflection (or any other geophysical technique), is to provide an interpretation of the information in terms of a geological model to aid mine planning. In terms of seismic reflection applied to coal mining, this essentially means interpreting the positions and throws of faults in the survey area.

To help understand the limits of seismic reflection in terms of small fault detection, it is necessary to not only understand the physical constraints but also the interpretive constraints.

DEFINITION OF RESOLUTION

Before looking at what affects resolution, it is necessary to define what we mean by resolution.

The resolution is defined here to mean the smallest vertical displacement that has a high confidence of always being interpreted as a fault. Thus faults at or greater than the resolution would have a high confidence of always being detected.

SINGLE TRACE (or 1D) RESOLUTION

Seismic sections are composed of traces. These are traditionally thought of as ray traces which are composed of straight line segments. In reality, this is slightly misleading, since the wave form expands as a hemispherical pulse. This pulse is composed of alternating zones of compression and rarefaction of the particles in the ground (see figure 1). Ray traces drawn normal to the hemisphere are used as a representation of this motion.

When the pulse intersects an interface, some of the energy is reflected back. However, the reflection does not originate from a single point, but rather from an area (see figure 2). In physics, this is generally taken to be the area of the first Fresnel zone. In the Southern Coalfields, a reflection from say 500 m could be coming from an area 20–30 m wide.

If the feature of interest varies over the reflection area, the response will be some average of this area. This is important if short strike length faults are being sought.

The ability to resolve individual interfaces is a 1D resolution problem and depends on the frequency content of the reflection wavelet. Although the pulse travelling in the ground is not an ideal wavelet, processing is usually fairly successful at converting the trace into a series of wavelets.

As seen in figure 3, two interfaces 10 m apart will not be resolved by a 50 Hz wavelet but will be by 100 Hz.

For reflections off coal seams, the two interfaces act differently. A pulse going from a faster to a slower layer will be reflected back with a negative pulse. Thus the coal seam reflection generates a good reflection at both 50 and 100 Hz (see figure 4).

In real data, the wavelet can vary over very short distances as seen in figure 5. The three zones are each about 150 m wide but show vastly different wavelets.

SECTION (or 2D) RESOLUTION

A fault cannot be interpreted from a single trace. The minimum requirement is to generate a section of sufficient length.

For high resolution work, the station separation needs to be closer than the first Fresnel zone so that the reflection areas overlap.

SEISMIC RESOLUTION

The resolution of the section depends not only on the single trace resolution but on the continuity of the events and the signal-to-noise ratio. If the signal-to-noise ratio decreases, the section will be less able to be reliably interpreted even if the frequency content doesn't change. Conversely, if the signal-to noise and continuity are very good, the resolution may be as good as a quarter wavelength or better. This far exceeds the theoretical limit of the single trace resolution.

Processing is another factor which can affect the section resolution. If confidence in the processing is reduced due to possibilities of say cycle skip, the confidence in the section to be interpreted will also be reduced. This will in effect, reduce the resolution of the section (as defined).

One of the biggest problems with detecting small faults is the diffractions generated off any abrupt interface change. If a fault were to terminate a coal seam by sharply faulting it below the depth of interest, the resulting section would show a diffraction extending past the point of termination (see figure 6).

When diffractions are coupled with small displacements, it is sometimes difficult to determine whether the level change was due to a fault or a monocline (see figure 7). It then becomes essential to have geological input to limit the possibilities.

Figures 8 and 9 are included as an example of the smallest resolution gained so far in the Southern Coalfields from the surface. They show a 3–6 m fault evident on three reflection events. The variation in the throw depends not only on the error of estimating the time difference in the throw, but also in possible velocity variations.

SPATIAL (or 3D) RESOLUTION

Spatial Resolution depends on the proximity of adjacent sections and their similarity, i.e. continuity between sections. The closer the adjacent sections and the more tie lines, the higher the resulting confidence of interpretation.

The highest spatial resolution is gained by using a 3D survey. However, because of the cost, 3D surveys often have less fold or are compromised in other ways. This tends to reduce the overall resolution by lowering the 1D and 2D resolution components of the survey.

In areas of short strike length features, 3D surveys have proved very effective. Care should be taken to design enough fold in the area of interest to allow the extra potential of the 3D survey to succeed.

TOTAL RESOLUTION

Ultimately, after the 1D, 2D and 3D components have been maximised, the resolution depends on the interpreter's skill in determining what is real and what is not. Thus the resolution as defined as the resolving power of the interpretation, is subjective depending on several factors.

Given that the process if interpretive, the resolution will depend on the geological information, e.g. the continuity of structures. If they are long relative to the line separation then the confidence increases. If there is a good supply of geological information, the interpreter can have greater confidence and the total resolution is increased.

CONCLUSIONS

The resolution is defined here to mean the smallest vertical displacement that has a high confidence of always being interpreted as a fault.

The resolution of any seismic survey depends on (in order of importance):

- The physical parameters including frequency content of the trace and signal-to-noise ratio.
- Processing
- The skill of the interpreter.
- The supply of geological information.
- Coverage

ACKNOWLEDGMENTS

The author wishes to thank the following people and organisations for their help and for permission to present relevant data:

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Peter Hatherly of ACIRL
Phil Harman of BHP Exploration
Harvey Holmes of the University of New South Wales
John Anderson of KCC Tahmoor

SEISMIC RESOLUTION

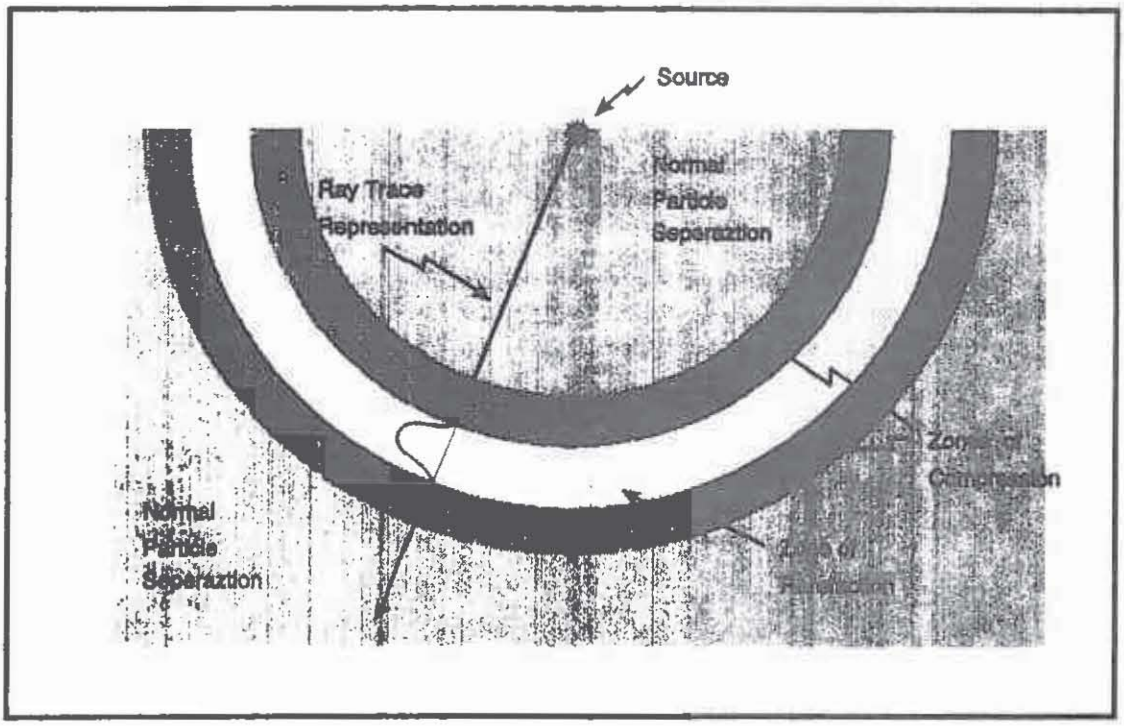

Figure 1 Seismic Pulse

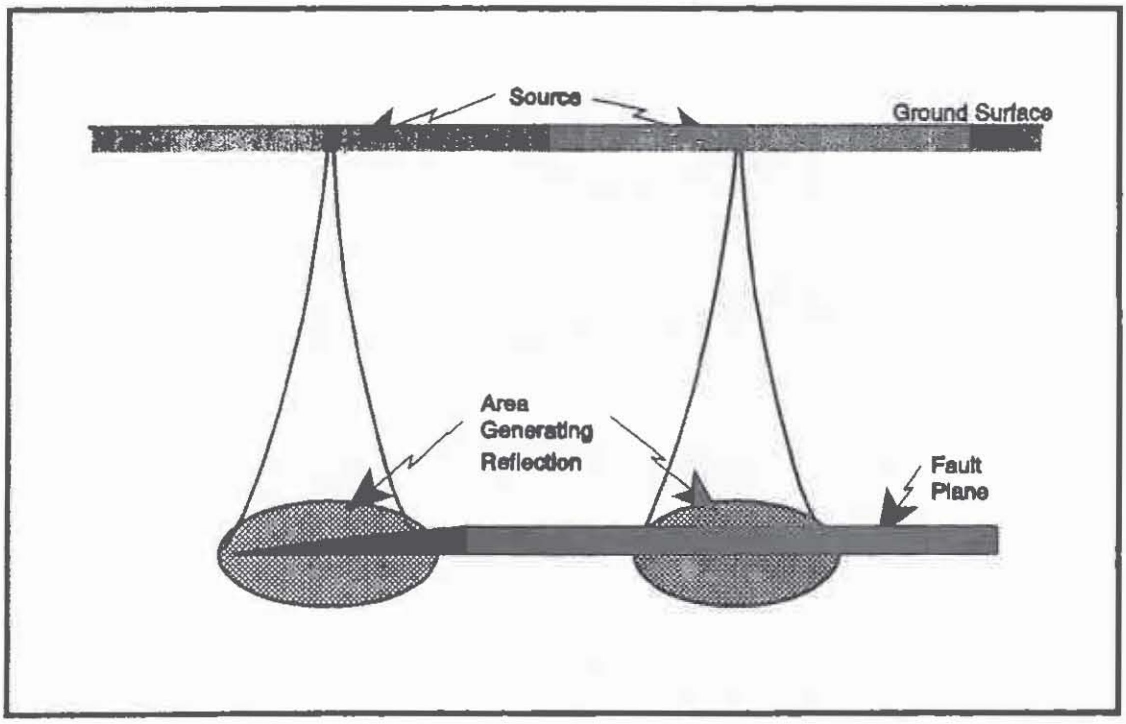

Figure 2 Reflection Area

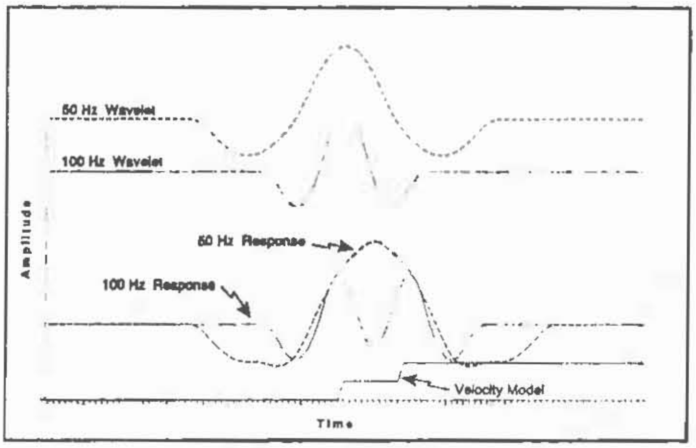

Figure 3
Reflection From
Two Interfaces

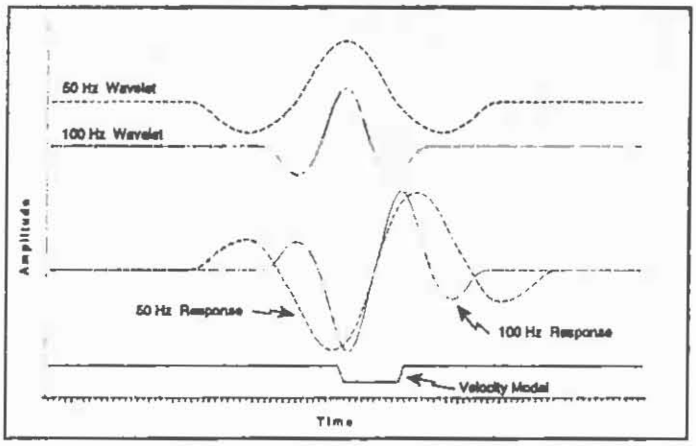

Figure 4
Reflection From
Coal Seam

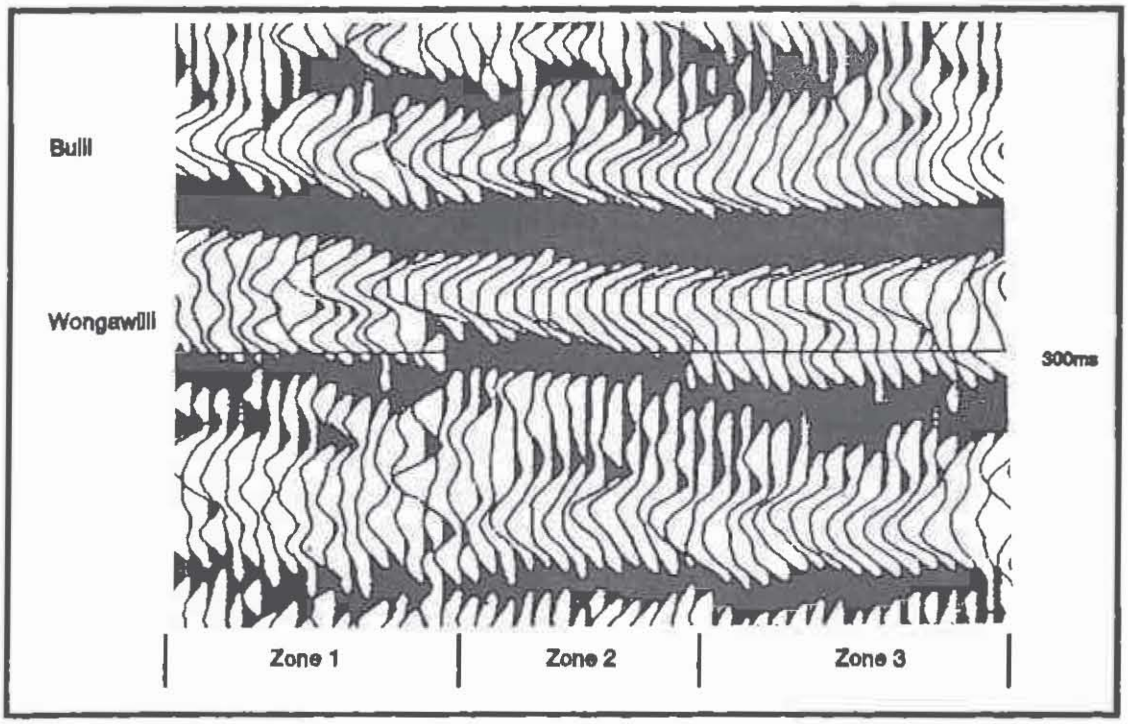

Figure 5 Pulse Variation Along Bulli Reflection

SEISMIC RESOLUTION

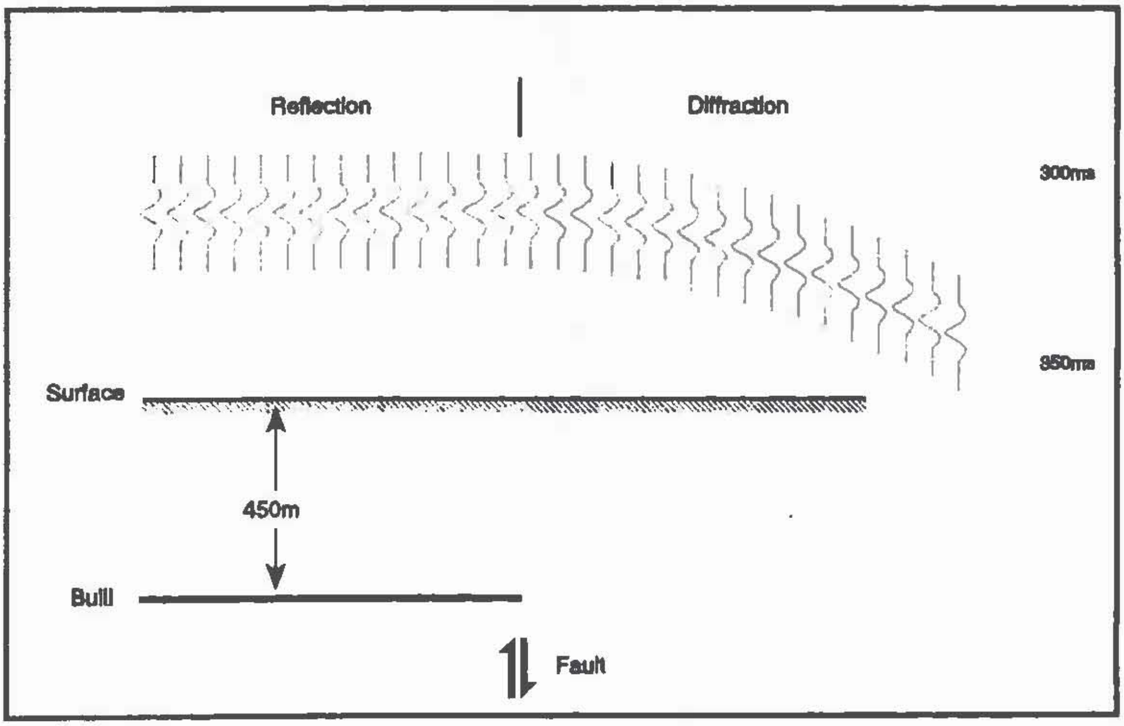

Figure 6 Diffraction – Typical of Southern Coalfields

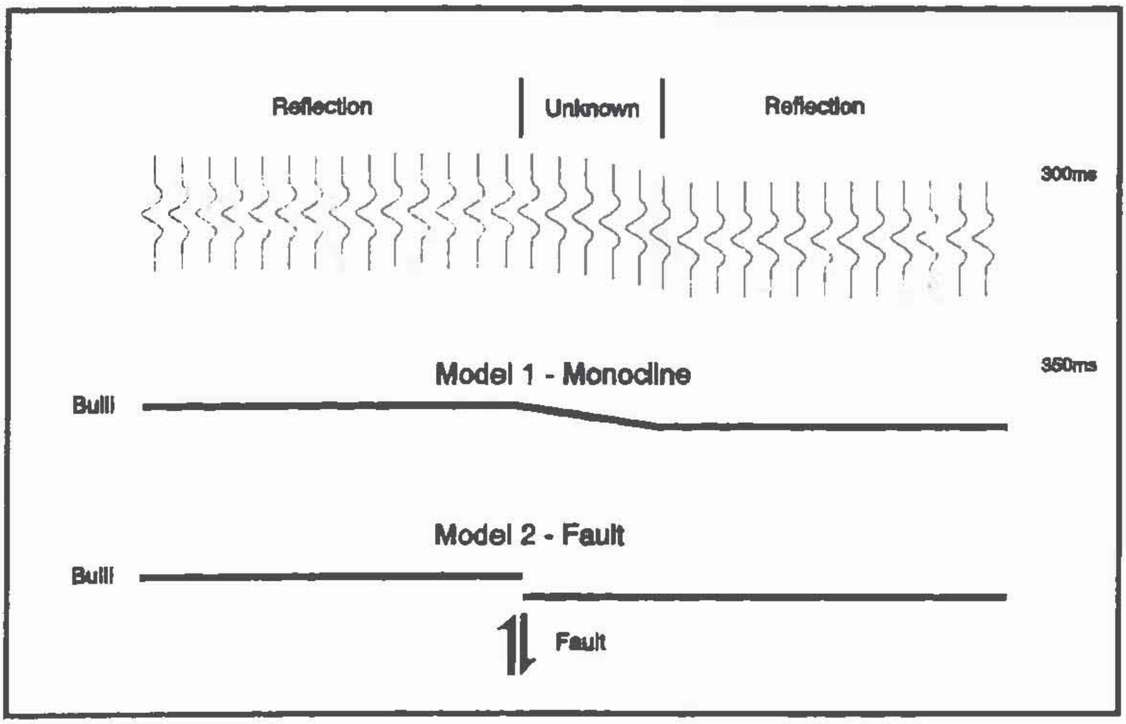

Figure 7 Level Change and Possible Diffraction

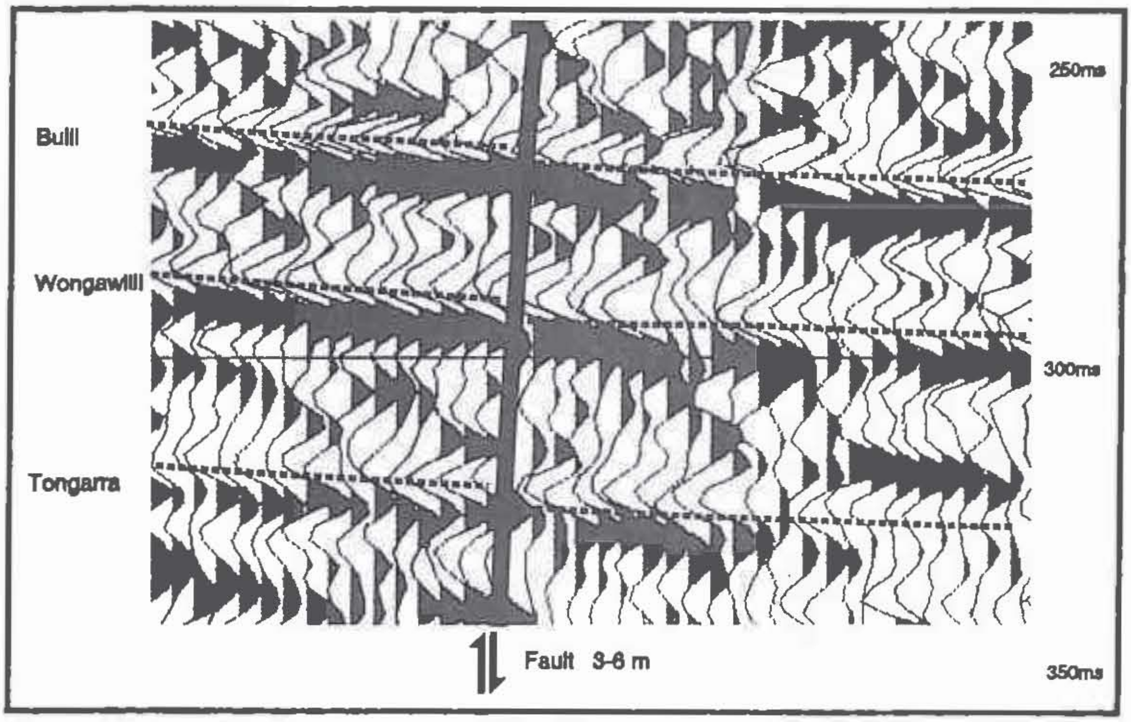

Figure 8 High Resolution - 3–6m Fault at 450m Depth

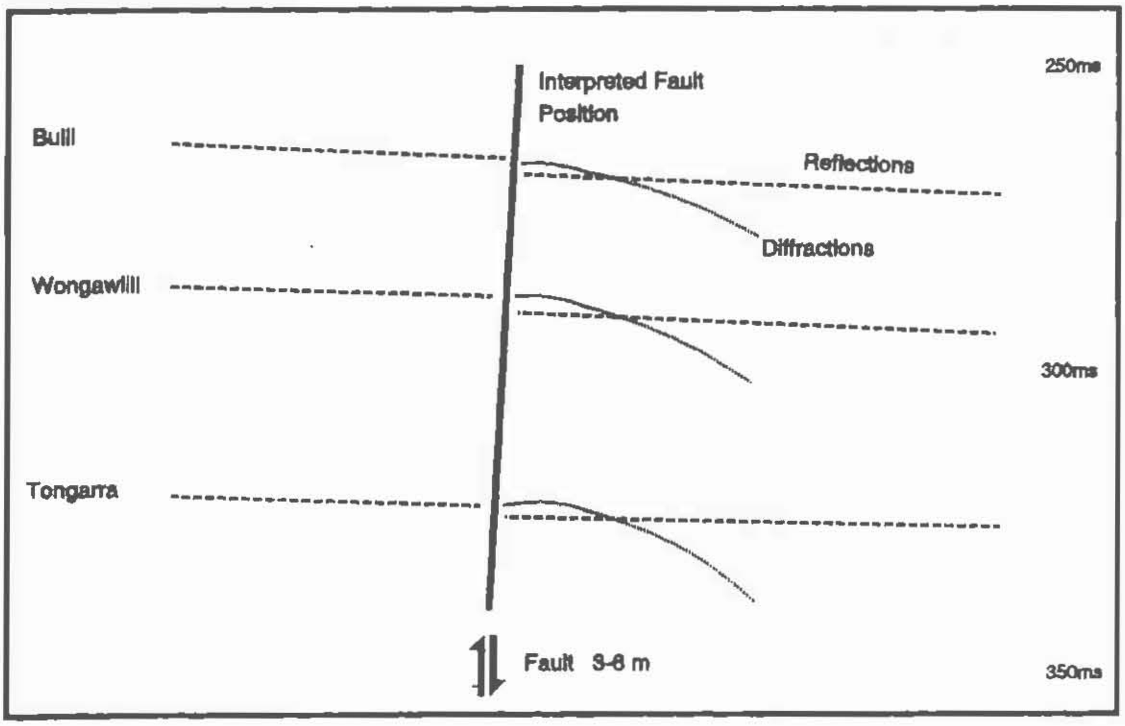

Figure 9 Interpreted Model of Figure 8

ORIENTATION OF DRILL CORE USING PALAEO-MAGNETISM IN COAL EXPLORATION

P.W. SCHMIDT[1] & J.C. ANDERSON[2]
[1] CSIRO Divn. Exploration Geoscience
[2] Kembla Coal & Coke

ROCK MAGNETISM

The CSIRO Rock Magnetism group has been studying the magnetic properties of Australian rocks for about fifteen years. One of their most exciting and probably most esoteric discoveries was of a ubiquitous magnetic overprint throughout the Sydney Basin and the coastal region to the South. From the thermal properties of the overprints it was estimated that rocks now outcropping at the surface had been elevated to about 200°C during the Mid Cretaceous, implying that a thick blanket of sediments has since been eroded. This was correlated to events leading up to continental rifting and the formation of the Tasman Sea. It has now been shown that this thermal effect is a common precursor to rifting and overprinting is a typical signature of "passive margins".

BORE CORE ORIENTATION

The knowledge of this magnetic overprint layed dormant until recently when the question arose of orienting diamond drill cores of Sydney Basin sedimentary rocks from the Tahmoor area using their natural remanent magnetisation (NRM). It was suggested that the orientation of the core could be determined by measuring the direction of its NRM, and aligning it with the previously determined NRM of the local rock units - provided that the rocks possess a measurable NRM. Previous measurements were on igneous rocks and red beds, and it was not known if coal measures were suitable.

To test the magnetic properties of the coal measures, samples were taken of sandstone and mudstone in the Tahmoor Colliery from the Bulli seam roof, from the wall of the drift, and from drill core. These results showed that they do possess a measurable NRM, and that it corresponds to a Mid Cretaceous direction. Most importantly, the direction is not affected by the process of drilling.

An important difference between the colliery rocks and the other Sydney Basin rocks studied is that the colliery rocks contain only the one (Mid Cretaceous) magnetic direction, whereas the other rocks contain more than one direction. In the other rocks it proved possible to erase the overprint, using palaeomagnetic "cleaning" techniques, to uncover an older magnetisation related to the formation of the rocks. The total natural remanent magnetisation (NRM) of these other rocks is therefore the vector resultant of two magnetisations, which often occur in varying ratios. The directions of the NRMs can be very scattered, as in the Milton Monzonite (Fig. 1). The Hornsby

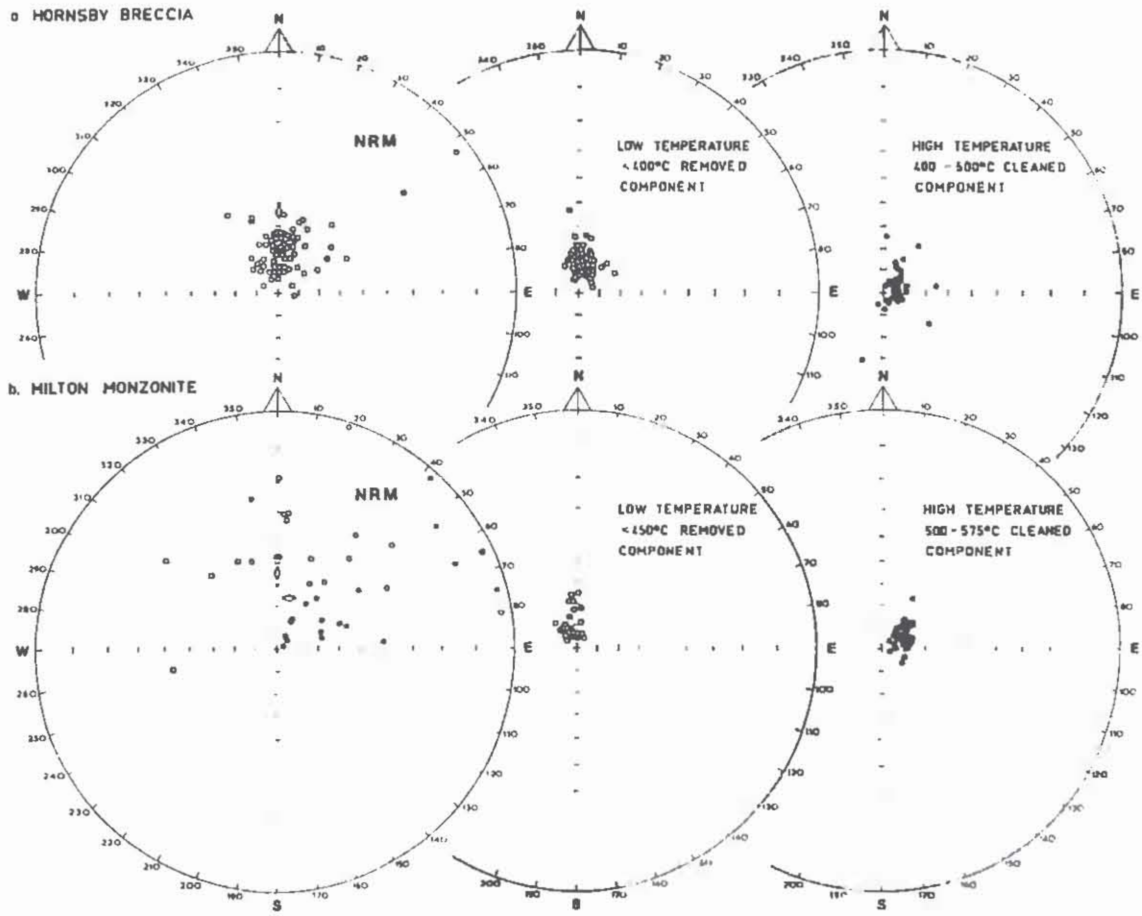

FIGURE 1 - PALAEOMAGNETIC DIRECTIONS
Open symbols are upward directed, while closed symbols are downward.

Breccia, on the other hand, is almost completely overprinted so the NRM directions are close to the overprint directions, being only a little scattered by varying but small contributions from underlying older magnetisations. Because the colliery sediments are completely overprinted, their NRM directions do not change significantly with palaeomagnetic "cleaning". This is an important property of the sedimentary rock for use in drill core orientation because, over at least a local area, the rocks have a consistent magnetic direction.

BORE CORE MAGNETOMETER

A portable horizontal spinner magnetometer interfaced to a computer has been constructed for KCC to automatically orient drill core. This magnetometer measures the horizontal component only of the NRM, however that is sufficient to orient the core for most practical purposes.

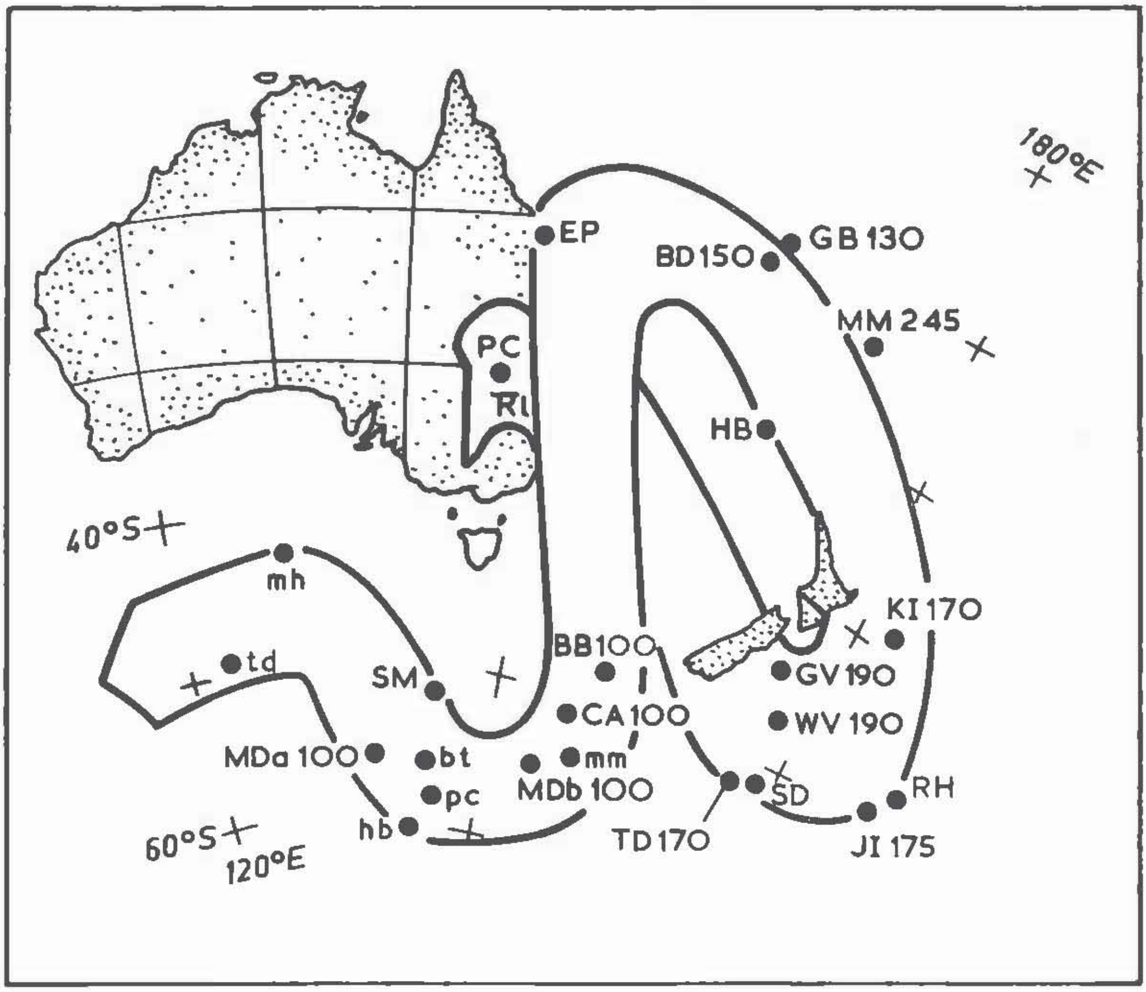

FIGURE 2 - MESOZOIC APPARENT POLAR WANDER PATH
Large symbols are primary poles while small symbols are overprints.

USES FOR ORIENTED CORE

The additional data that can be gained by orienting core is well known; examples in coal exploration include:

- orienting fractures and faults
- orienting cleat direction
- orienting principal stress directions (when coupled with strain relaxation measurements)
- orienting sediment transport directions from cross bedding.

Some advantages of using NRM to orient core, compared with other methods, are:

- it is cheap and fast
- it requires no special drilling equipment or techniques
- it can be applied to existing core material.

The orienting technique could also be applied to core obtained for any other purpose, such as petroleum exploration, mineral exploration and geotechnical investigations - provided that the rocks are suitably magnetized.

FUTURE INVESTIGATIONS

The concept of orienting bore core using its NRM warrants further investigation. Samples could be taken from throughout the Sydney and Bowen Basins (and elsewhere) to determine basinal NRM directions. Different stratigraphic levels should be sampled at each location.

The Mesozoic apparent polar wander path (Fig. 2) is based on rocks ranging in age from Early Triassic (Patonga Claystone) through to Mid Cretaceous (Mount Dromedary Complex) and shows considerable structure which should allow fairly good age estimates for events which cause the overprints.

A collection of case studies from orienting bore core using its NRM will evaluate the reliability of using the method, and will establish the practical uses of the method.

CLAY MODELS OF THE NORTHERN SYDNEY BASIN AND SOUTHERN TAMWORTH BELT, NSW

A. MIGLIUCCI[1] & P.R. EVANS[2]
[1] Sagasco Resources Ltd, Adelaide
[2] School of Mines & Centre for Petroleum Engineering, UNSW

SUMMARY

Clay models support proposals that structuring of the NE Sydney Basin and the the southern Tamworth Belt was due to progressive crustal compression vectored from the ESE. They imply that the New England and Currarong Orogens were coupled, and that the Hunter Fault and related structures were created at an offset in the orogenic front.

INTRODUCTION

The Hunter Fault, marking the northeastern boundary of the Permian-Triassic of the Sydney Basin with the Carboniferous of the southern New England Fold Belt, is traceable from Murrurundi in the north to East Maitland in the lower Hunter Valley. The fault does not continue beyond East Maitland, or in geological terms to the east of the Lochinvar Anticline, where Permian formations rest directly and unconformably upon the Carboniferous. If, as suggested by Carey & Osborne (1939), there has been sinistral strike-slip motion in the vicinity of the Hunter Fault, the strain from which is reflected in deformation of both the Permian and the Carboniferous, it is likely that the Lochinvar Anticline took up the movement at the southeastern end of the fault, as if the crust east of the anticline is coupled to the New England Block.

CLAY MODELS

Benson (1976) tested this proposition with a clay model (Fig. 1) that indeed reproduced the main structures northwest of the Lochinvar Anticline, but that differed from the field data, having no upthrust block to the north. Benson's model was based on shaped thin metal plates below a block of clay and sliding upon a fixed board, the sliding plate representing the overriding crust, similar to models created, by Cloos (1955) and Wilcox et al. (1973). Migliucci (1990) repeated the experiment, but with a thick-edged upper plate, representing pre-existing high blocks to the east and north (Fig. 2). The model was designed to simulate sinistral transpression along the southern Hunter Fault. On this occasion, different but compatible structures developed, not so much resembling shallow structures within the Hunter Valley, but major structures involving basement.

The differences in model behaviour are attributed to differences in the thickness and viscosity of the clay caused by differences in water content. Benson created his model in a watery clay that could be assumed to represent relatively plastic basin fill; Migliucci employed a stiff clay with a lower water content that could be thought of as resembling basement rather than the basin fill. The upper plate of Benson's model was cut into an L-shape, whereas in Migliucci's model the leading edge of the upper plate was cut at 45°.

COMPARISON OF MODELS WITH GEOLOGY

Benson's model (Fig. 1) developed the en echelon anticlines that characterize the Permian of the upper Hunter Valley west of the Lochinvar Anticline as well as splays of faults at the termination of the Hunter Fault that compare with the associations between the Lennoxton and Greta Faults. The detachment developed between the lower plate and the deforming clay would be equivalent to the thrust flat identified by Glen & Beckett (1989) as necessary to accommodate folding in the Permian to the south of the Hunter Fault.

In Migliucci's model a distinct uplift developed above and at the re-entrant between the edge of the directly convergent and oblique convergent margin (Fig. 2). Assuming north as indicated, the high was bounded by a thrust fault along the southwestern flank and a back-thrust along the northeastern margin. As deformation progressed a series of minor folds with intervening sharp synclines grew parallel to the margins of the uplift. A set of subparallel synthetic fractures extended across and westwards from the high.

The Hunter Fault is represented in this model by the thrust zone to the southwest of the main high. The high in turn resembles the Carboniferous high to the north of the Hunter Fault, comprising the Rouchel and Gresford Blocks but not the Myall Block (Roberts & Engel 1987). Folds along the margin of the uplift adjacent to the southwestern thrust front bring to mind the synclines in the Carboniferous Basin Belt (Voisey 1959). The eastern flank of the high corresponds to the Williams River Fault. East-directed thrusts and associated synclines on the eastern flank of the high correspond to the position of the Gloucester Syncline (Lennox & Wilcock 1985).

Migliucci's model suggests nothing about the relationship between the Carboniferous of the Rouchel and Gresford Blocks and the Lower Permian to the north of the Manning Fault Complex, other than pointing to the fault complex as the margin of the growing Carboniferous high. The northwestern end of the model's upper plate was not shaped to suitably reflect extension of the Hunter Fault to the north of Murrurundi as the Mooki Fault. However, the northwestern end of the high may represent the change in structural styles at this location where the Hunter-Mooki Fault assumes a more northerly trend.

The W-E synthetic fractures created above the lower plate have no directly observed equivalents in the Hunter Valley, but they bring to mind the W-E boundaries between structural zones across the upper

Hunter Valley identified by Glen & Beckett (1989). Neither model provides an explanation of the N-S trending and related fractures that characterize the Rouchel and Gresford Blocks (Roberts & Engel 1987). However, Carey & Osborne (1939), distinguishing between extensional and antithetic strike-slip faults in this zone, provided the most plausible explanation of these fault systems that is compatible with the current proposal. Some clay models of strike-slip structures develop numerous antithetic fractures, but large scale forms of such structures are not common in nature (Wilcox et al. 1973). In the present case, the upper plate is rigid and the clay cake is homogenous, whereas crust below the Carboniferous was likely to be complexly dislocated during deformation and the lithologies of the Carboniferous are varied.

DISCUSSION

The clay models demonstrate the effect of oblique convergence of two crustal blocks; convergence in terms of the northern Sydney Basin and southern Tamworth Belt, occurring from the ESE towards the WNW. In many respects the models confirm the analyses of the structural grain and regional strain by Carey & Osborne (1939), Glen & Beckett (1989), and Collins (1990). In particular they emphasise that deformation of the northern Sydney Basin and southern Tamworth Belt was caused by the translation of a crustal block from the ESE, and that convergence of the New England Block from the north was not the prime cause of these structures.

The models imply that a crustal block to the east of the Sydney Basin was coupled to the New England Block. Jones et al. (1984) conceived of the presence of "the Currarong Orogen", to the east of the Sydney Basin. The front of the New England - Currarong Orogen was not straight. Presumably it lay to the east of the present coastline of NSW adjacent to the Sydney Basin, but was offset to the WNW along a fracture parallel to the southern Hunter Fault, then turned northwards at Murrurundi. A more recent parallel to such an offset in an orogenic front is to be seen in the Rocky Mountains in the vicinity of the Canadian/US border, where the Lewis Thrust and related foothill front trends to the SE for some 200 km, in contrast to the general NNW-SSE of the orogenic front (Carey 1976, fig. 162).

The Currarong and New England Orogens would have been linked to the northeast of Newcastle, and the Hunter Fault was largely a sinistral transpressive boundary.

The time of movement(s) cannot be determined from these models. Nevertheless, the models are consistent with the proposal that block convergence from the ESE continued episodically (Evans & Migliucci 1991). The duration of the Hunter Orogeny need not be defined, for example, just as Middle Permian (Leitch 1974); or Late Permian (Collins 1990), but as a prolonged phase of orogeny, that continued in a series of pulses from virtually the beginning of the Permian until the Late Triassic.

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CLAY MODELS NORTHERN SYDNEY BASIN...

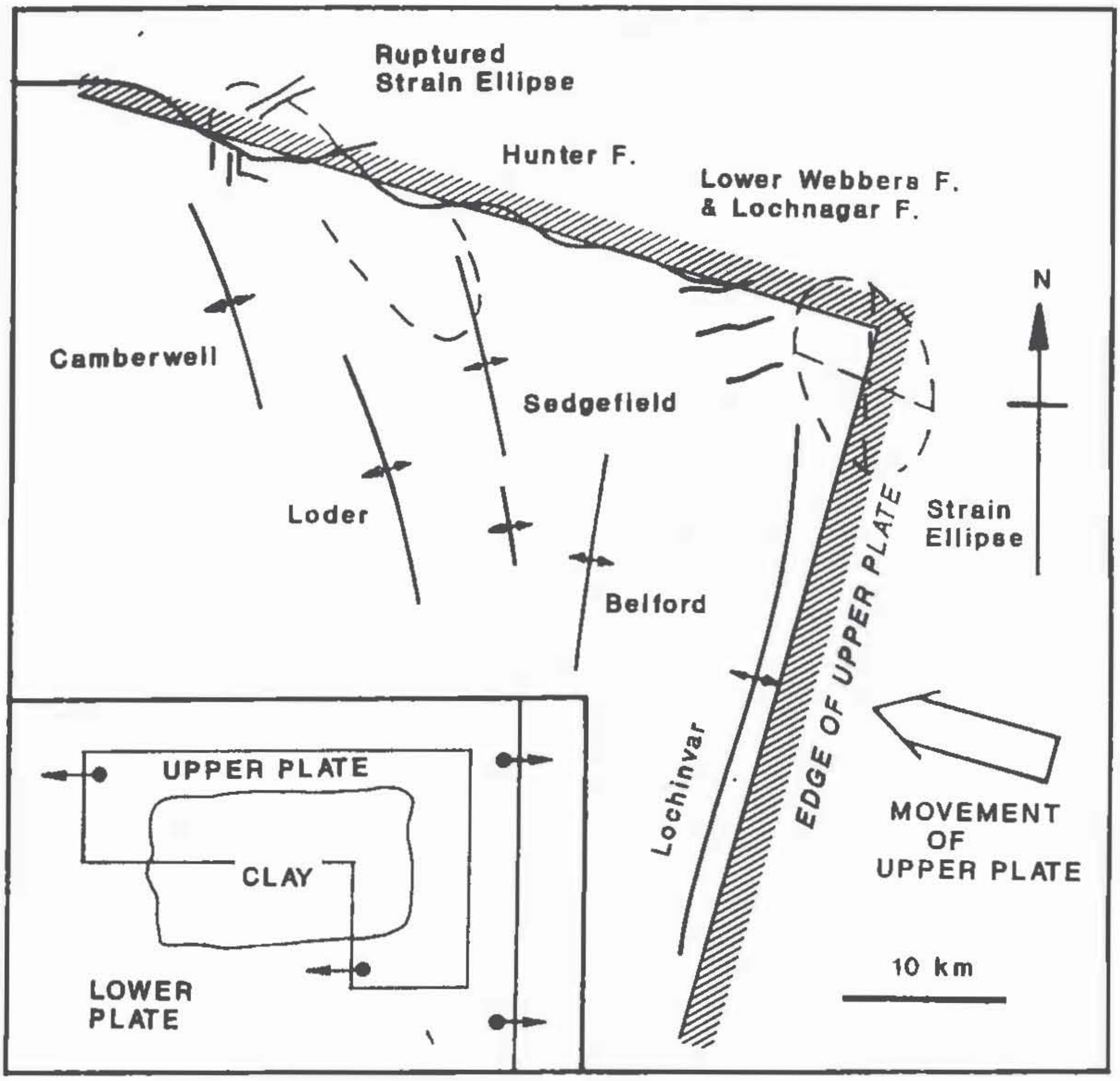

Fig.1 Main structures (folds and ruptures) created by Benson (1976) in a clay model of the northern Sydney Basin. Fold axes are identified with actual structures in the Hunter Valley region. After Benson (1976, fig. 51b). Inset shows arrangement of plates and clay.

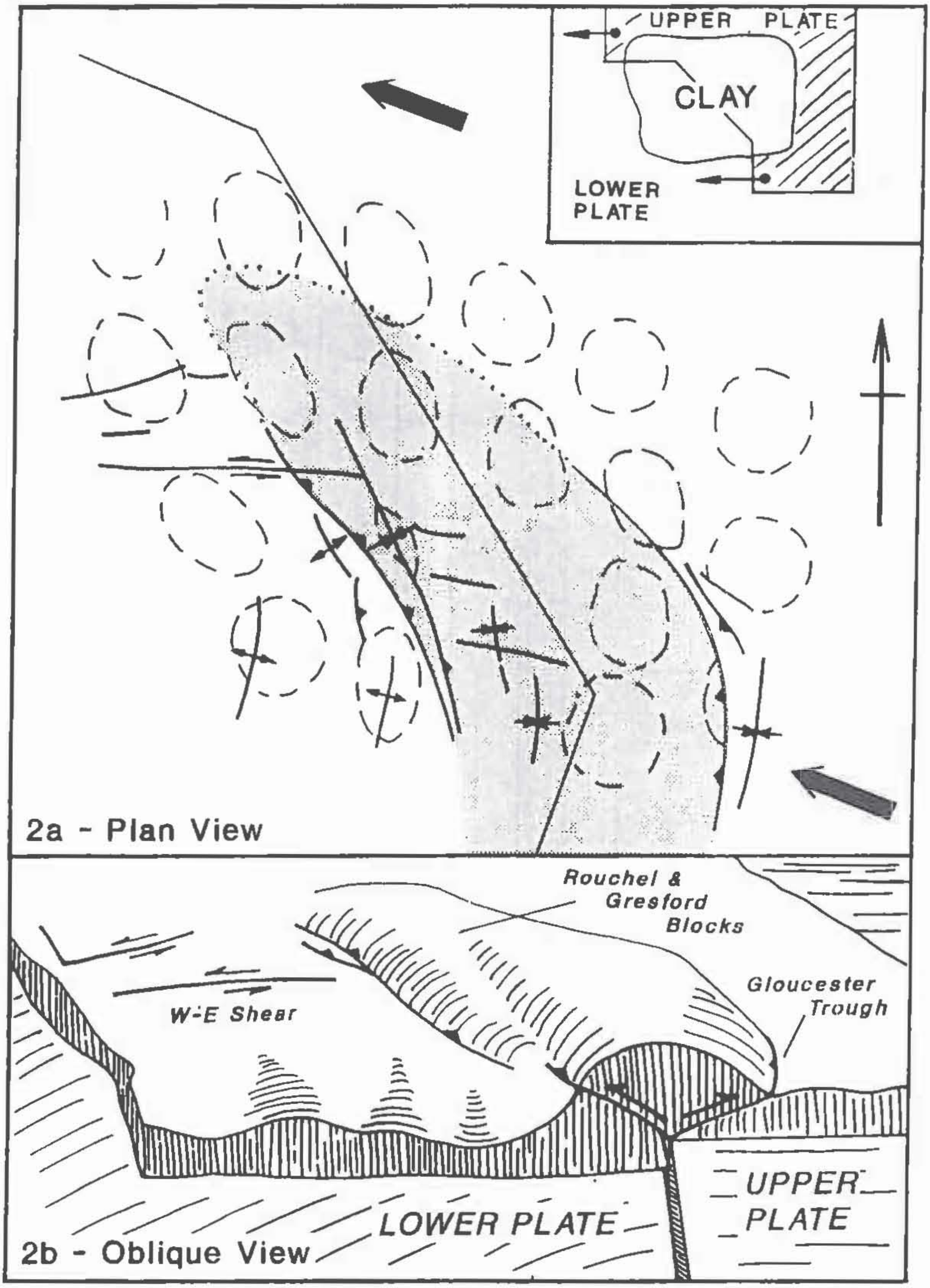

Fig.2 Structures created by Migliucci (1990) in a clay model of the northern Sydney Basin and southern Tamworth Belt.

UTILITY OF COAL SEAMS AS SEQUENCE BOUNDARIES IN THE NON-MARINE UPPER BLACK JACK FORMATION, GUNNEDAH BASIN

N.Z. TADROS[1] & D.S. HAMILTON[2]
[1] NSW Department of Minerals & Energy
[2] Bureau of Economic Geology, University of Texas at Austin, USA

INTRODUCTION

Concepts of sequence stratigraphy have dominated sedimentary basin analysis over the past decade, and one of the basic challenges has been determining the bounding surface between genetic stratigraphic packages. The concepts were developed in marginal marine basins where successive progradational episodes are separated by onlapping marine shales which can form easily recognized and regionally correlatable sequence boundaries. In non-marine aggradational basins however, the absence of marine intercalations necessitates different criteria for sequence recognition.

COAL SEAMS AS SEQUENCE BOUNDARIES

Non-marine aggradational basins comprise large complexes of stratigraphic sequences. Defining sequence boundaries and establishing a genetic stratigraphic framework for the basin can be difficult. However, there are some obvious bounding surfaces in non-marine basins. Subaerial erosional unconformities provide one type of boundary. More subtle, conformable bounding surfaces are also present, an example being coal seams of regional extent, which allow subdivision of terrestrial basin-fill into genetic units of common tectonic, climatic and paleogeographic origin (Hamilton and Tadros 1990).

Coal seams of regional extent are the product of prolific peat growth and preservation during periods of negligible clastic accumulation and can define times of relative stability (slow, steady subsidence) between episodes of major reorganisation in basin tectonics or climate. They can, therefore, represent significant sequence boundaries and have considerable utility in defining a basin's genetic stratigraphic framework.

Coal seams of subregional extent, although not representing sequence boundaries, have time significance locally and may be useful in subdivision within the larger genetic stratigraphic packages.

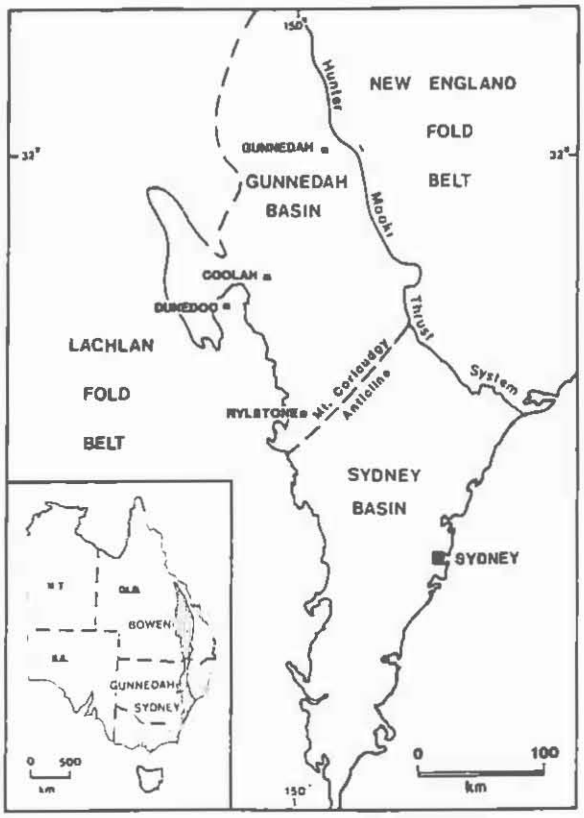

Fig.1 Location and structural setting, Gunnedah Basin.

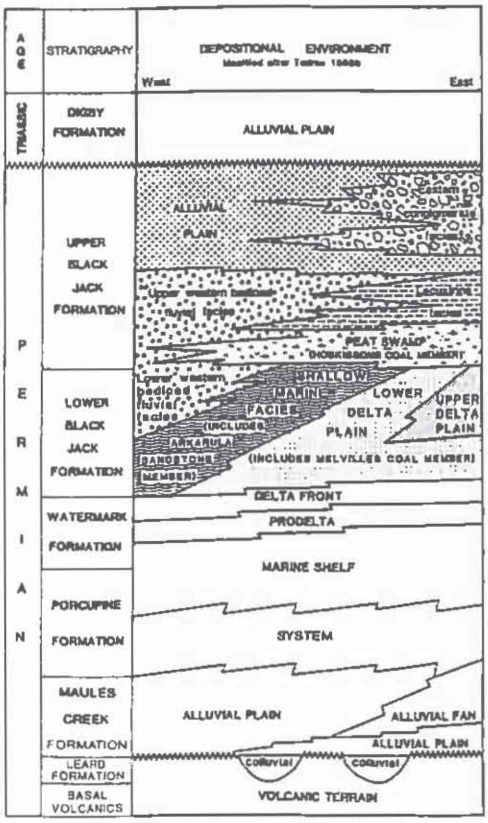

Fig.2 Stratigraphy & depositional environments.

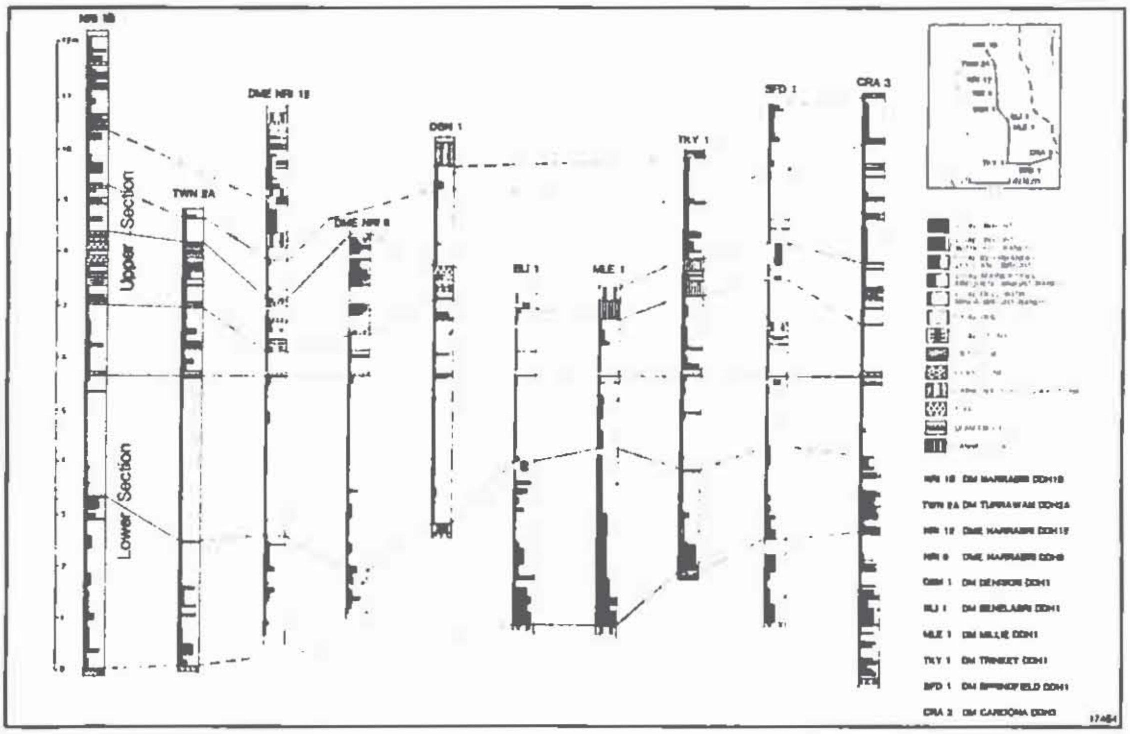

Fig.3. Hoskissons seam lithotype profile,nort-south(-east) section (from Tadros,1988a).

SEQUENCE BOUNDARIES- AN EXAMPLE FROM THE GUNNEDAH BASIN
Examples of regionally extensive coal beds that form sequence boundaries occur within the Upper Permian section of the Gunnedah Basin.

Basin Setting and Sratigraphy

The Gunnedah Basin occupies a foreland setting between the New England Fold Belt (NEFB) and Lachlan Fold Belt (LFB) which represented the orogen and craton respectively during the Late Permian and Triassic (Fig.1). During discrete episodes throughout the basin's history, these two elements supplied sediments of distinctly different composition; the NEFB supplied volcanic-lithic detritus while the LFB shed quartzose sediments.

The basin sequence is characterised by two coal-bearing formations, the Early Permian Maules Creek and Late Permian Black Jack Formation (BJF). These are separated by the marine Porcupine and Watermark Formations. The Permian strata are unconformably overlain by Triassic fluvial and lacustrine deposits of the Digby and Napperby Formations.

This paper focusses on the upper part of the BJF since it is a non-marine sequence and contains coals of regional and sub-regional extent. The top of the upper BJF is marked by an erosional unconformity, and the base of the sequence is defined at the Hoskissons seam. This seam separates the fluvial-lacustrine upper BJ deposits from the deltaic and shallow-marine systems of the lower BJF. Fig.2 shows the early interpretations of the upper BJ deposition and although only schematic, it gives an idea of the understanding of the sequence prior to the correlation and analysis of the coals. Tadros (1986a,b) recognized easterly and westerly-derived fluvial facies based on sediment composition. He also recognized widespread lacustrine and pyroclastic-rich floodplain facies from analysis of drill core. But it was not until thorough analysis of the coals were undertaken that the distribution and boundaries of different depositional systems could be mapped.

Hoskissons Seam

The Hoskissons seam is regionally extensive and represents a significant period of non-deposition of terrigenous clastics over all but the basin periphery. Quartzose channel fills disrupt the seam along the western basin margin and and volcanic-lithic sediments split the seam over a narrow zone in the northeast. The seam has correlatives of regional extent in the Sydney Basin to the south (Hunt et al. 1986). Correlation of the Hoskissons seam is extremly reliable for two reasons: 1) The seam has characteristic macroscopic lithotype and maceral composition profiles; both can be traced throughout the basin (Tadros 1988a) (Fig.3). Typically, the seam consists of two sections separated by a 0.1 m persistent tuff or tuffaceous claystone marker (Fig3).

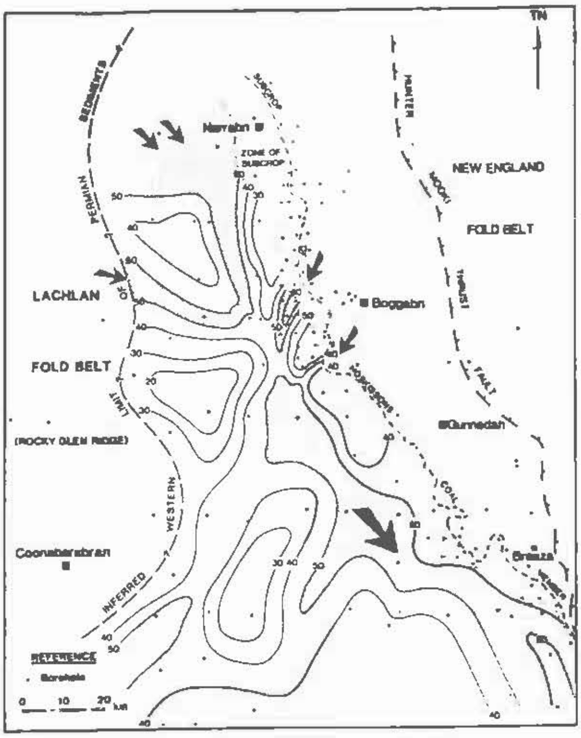

Fig.4 Percentage sandstone upper BJF. (from Tadros, in prep.).

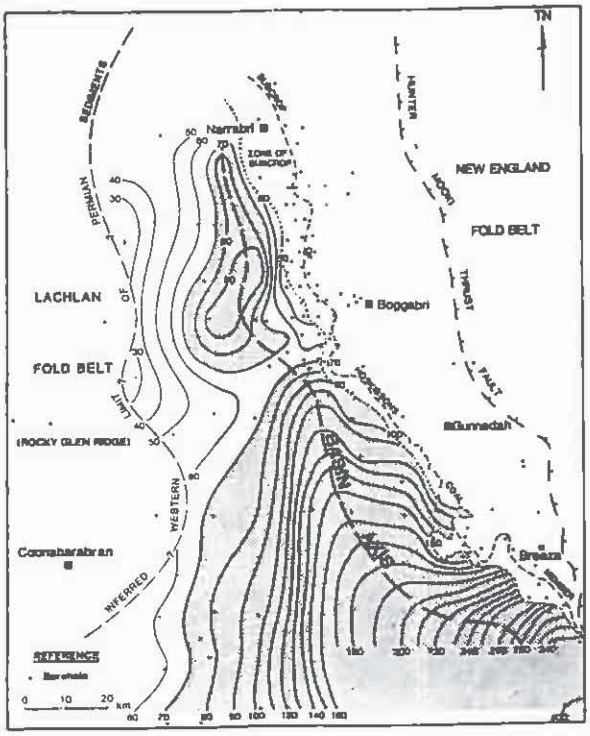

Fig.5 Isopachs, upper BJF showing basin axis. (from Tadros, in prep.).

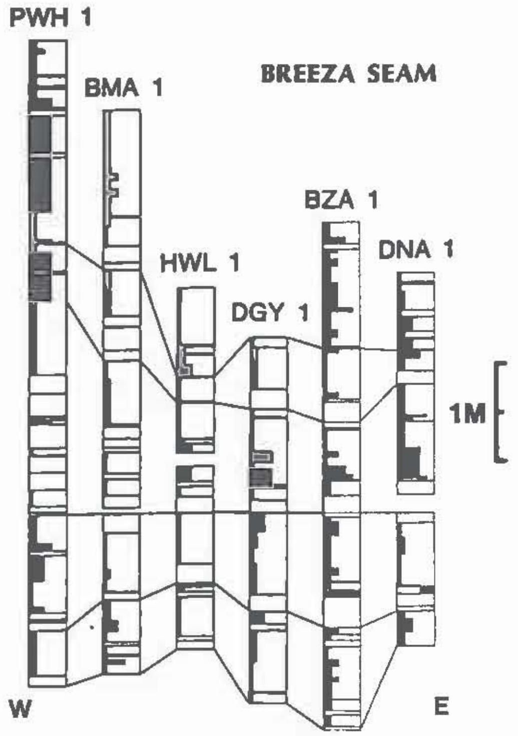

Fig.6 Breeza seam lithotype profile, EW section.

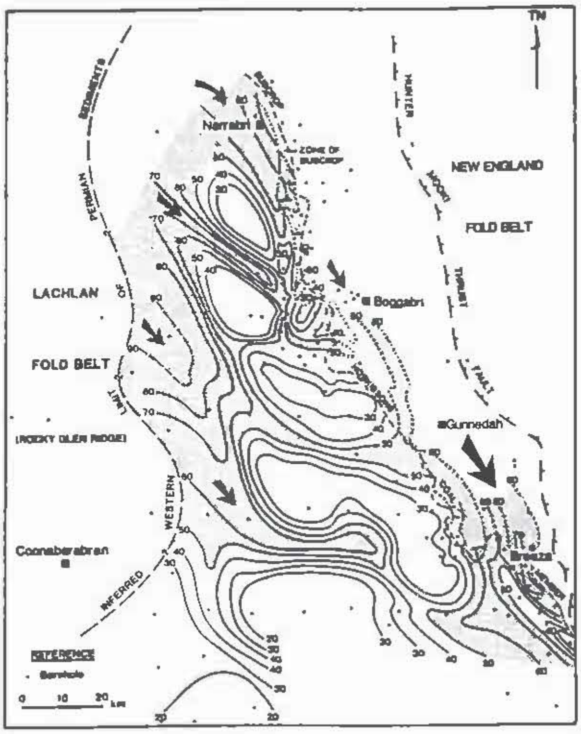

Fig.7 Percent. ss. western fluvial system, southern half = Hoskissons-Breeza interval.(Tadros in prep.).

The lower section consists of two major plies: interlayered dull and bright coal at the base with a tendency for upward decrease in brightness,overlain by dull coal with a few thin bright layers associated with thin carbonaceous claystone and tuff layers. The upper section, consists of three major plies; dull coal at the base,interlayered carbonaceous claystone, tuff, and dull and bright coal in the middle, and interlayered dull and bright coal at the top with carbonaceous claystone and tuff layers grouped towards the top.

2) The seam is petrographically unique in the Permian Gunnedah and Sydney Basins (Hunt et al. 1986). It is inertinite-rich with a high proportion of inertodetrinite and the liptinite content is significantly higher than that of most Australian coals (Tadros 1988b).

The seam makes an excellent sequence boundary between major episodes of tectonic reorganization and sedimentation. It closely overlies a palynological zone boundary marked by the first appearance of Dulhuntyspora parvithola, and within the resolution of the Permian palynological zones, accumulation of the Hoskissons peat commenced approximately synchronously across the basin and accumulated as a nearly continuous blanket over most of the Sydney-Gunnedah Basin (Hunt et al., 1986) during a period of tectonic stability.

Upper Black Jack Sequence

Percentage sandstone map for the upper BJ sequence (Fig.4) is a composite of both east and west fluvial systems and illustrates the major depositional elements. A southeasterly trending axial channel complex is joined by tributaries from both the east and west. There are also well defined interchannel areas. An isopach map of the upper BJF (Fig.5) shows the area of maximum subsidence to the southeast. The location of the axial channel complex is largely structurally controlled.

Coal seams in the upper BJ sequence are less extensive than the Hoskissons seam and will be discussed to illustrate their value in dividing the basin-fill. In the northern part of the basin, the coals were not laterally extensive and were restricted to the interchannel areas. Coal seams could not be correlated across the fluvial axes. More rapid subsidence in the southeastern part of the basin probably caused the rivers in the north to incise their own channels and remain fixed in position through time, thus confining peat accumulation to interchannel ponds. Coals in the southern part of the basin in contrast, were more laterally extensive and this provided an opportunity to map the fluvial systems between the seams.

Hoskissons - Breeza Seam Sequence

Three correlated seams are present within the Hoskissons-Breeza seam sequence: the Caroona seam at the base that has limited coverage in the southeastern corner of the basin,

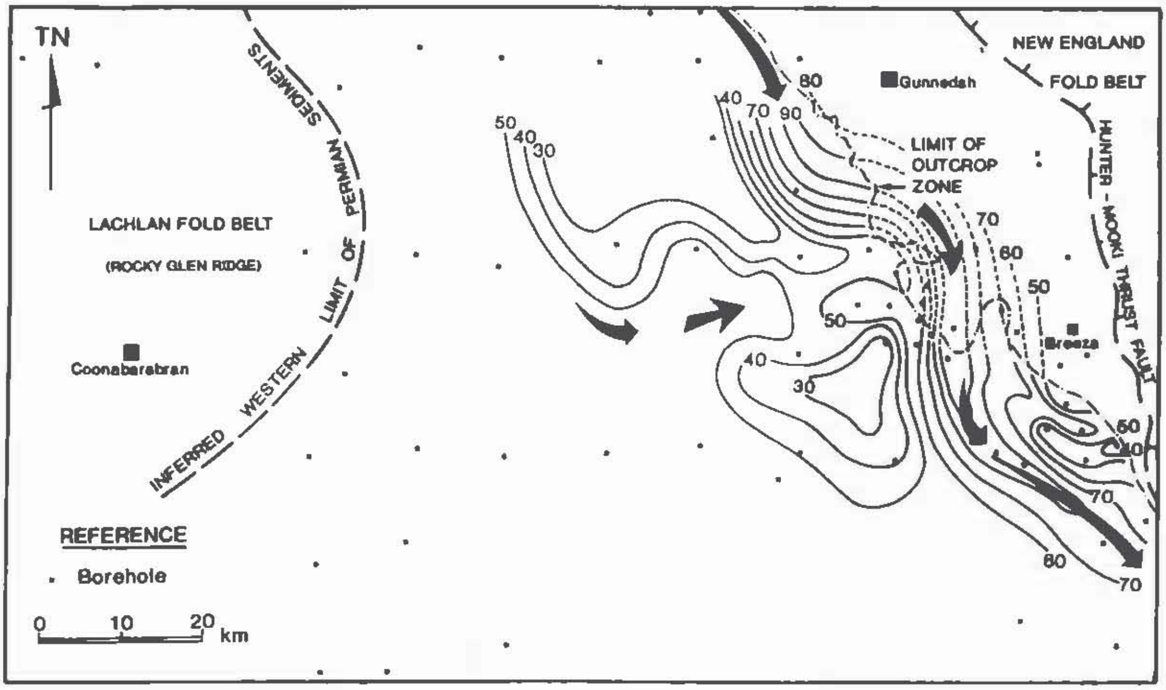

Fig.8. Percentage sandstone between Howes Hill/Hoskissons and Breeza seams.(modified from Tadros in prep.).

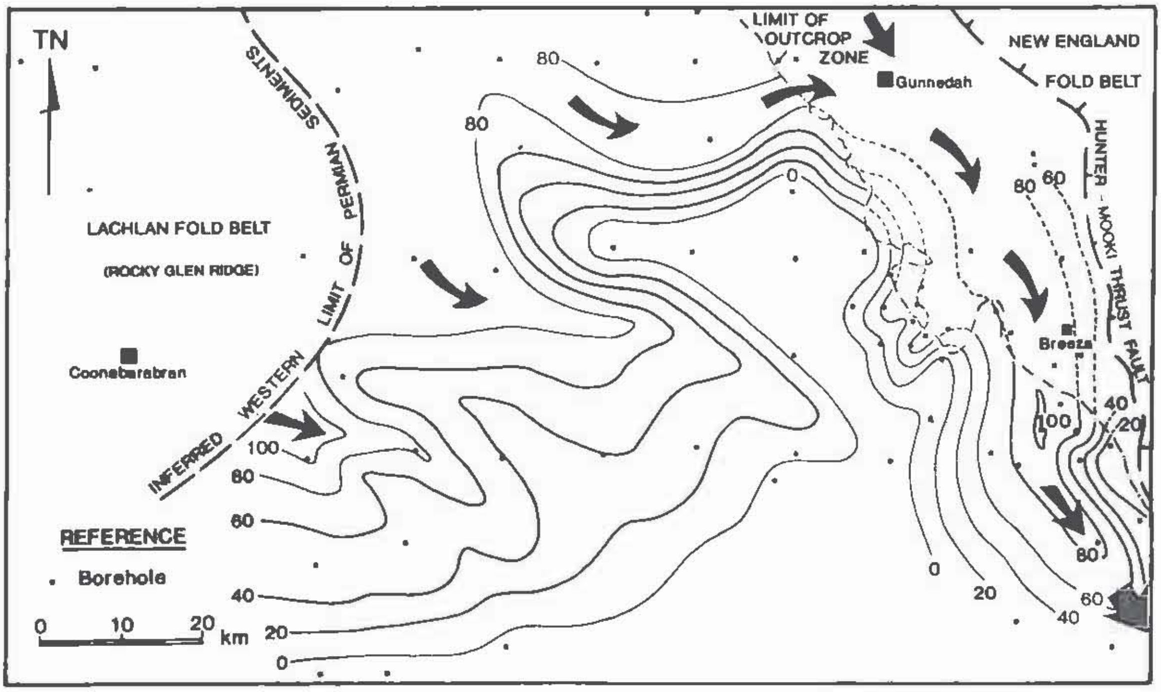

Fig.9. Percentage sandstone between the Howes Hill/Hoskissons and Breeza seams (from Tadros in prep.).

the Howes Hill seam in the middle extending over the southeastern corner of the basin, and the Breeza seam at the top that has regional coverage over much of the southern basin area and forms a significant sequence boundary.

The Breeza seam occurs at an average of 45 m above the Hoskissons seam. The Breeza seam has a characteristic brightness profile that can be divided into 5 discrete sections separated by persistent tuffaceous claystone layers. The two lowermost sections consist of dull coal with minor bright layers, and there is a tendency for increased brightness towards the west. This section is mostly dull coal with minor bright layers, and the top part of the seam has intermediate dull to bright layered coal.

Correlation of the upper BJ coals has indicated that the Breeza seam marks the boundary between the quartz-rich (western fluvial-lacustrine systems, Tadros 1986a,b) and the volcanic-lithic sediments (eastern fluvial system, Tadros 1986b). The percentage sandstone map (Fig.7) for the quartz-rich sequence (Hoskissons-Breeza seams) shows a prominent fluvial pattern with southeasterly flowing contributary streams that emanated from the LFB in the west and joined a trunk channel complex flowing south and southwesterly along the basin axis.

The sub-regional Caroona and Howes Hill seams also have time significance and have been used to map lithofacies intervals within the Hoskissons-Breeza genetic stratigraphic sequence. The percentage sandstone map for the interval between the Caroona and Howes Hill seams (Fig.8) defines a southeast-trending quartzose sand body which represents the axial channel complex of the western bed-load fluvial system. The percentage sandstone map for the interval between the Howes Hill and Breeza seams (Fig.9) shows that the axial channel complex has shifted further to the east and there are some small tributaries flowing from the southern part of the LFB.

Breeza Seam - Top of BJF Sequence

Sediments in this sequence are volcanic-lithic, sourced from the NEFB. The top of the Breeza seam forms the lower sequence boundary. The upper boundary is defined by the Permo-Triassic unconformity. The percentage sandstone map for this sequence (Fig.10) shows a strong fluvial pattern with southwesterly flowing contributary streams that emanated from the NEFB in the east and joined major trunk channel complexes flowing southeasterly and southwesterly over areas of greater subsidence.

Sub-regional Clift, Springfield and Doona seams have been correlated within this sequence. The seams are generally confined to the east and central parts of the basin area Correlation was increasingly difficult westward and upwards

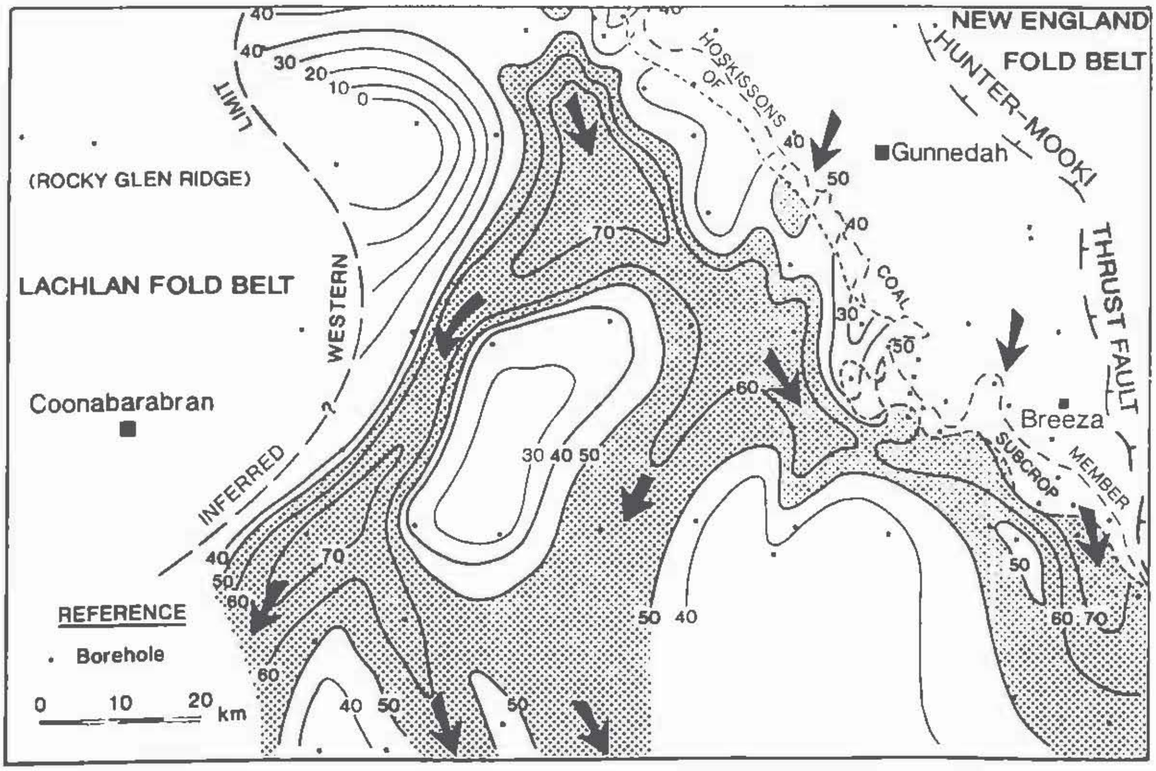

Fig.10. Percentage sandstone, eastern fluvial system, between top of the Breeza seam and top of BJF. (modified from Tadros, in prep.).

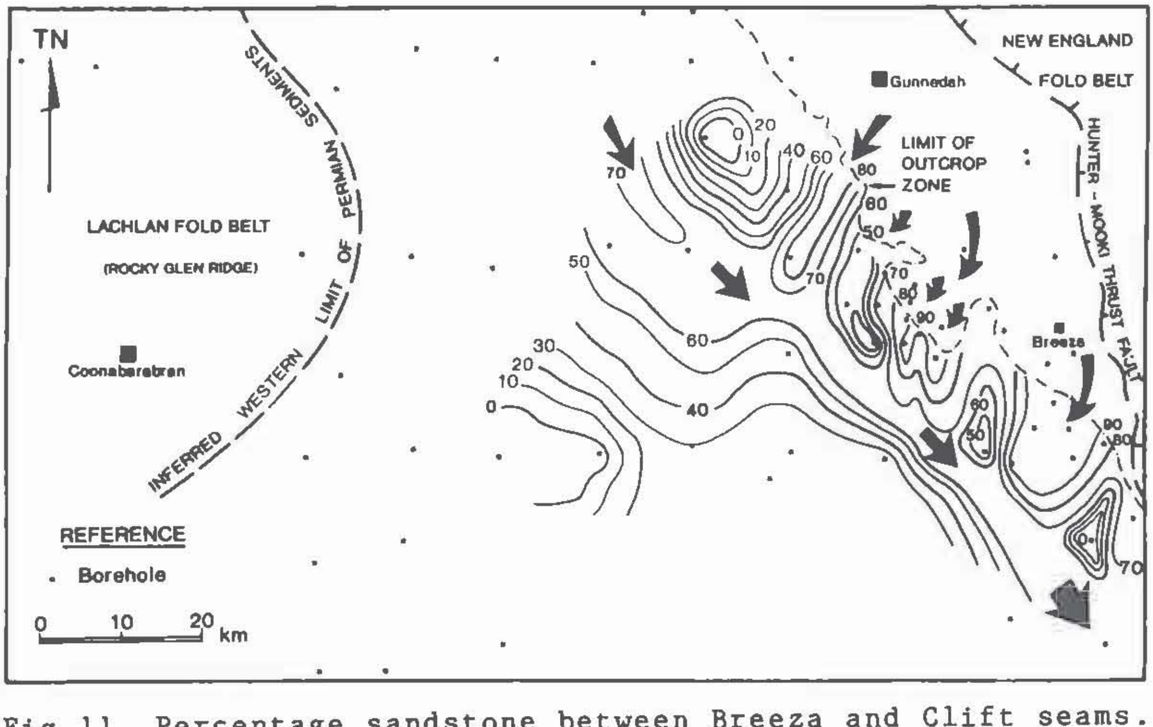

Fig.11. Percentage sandstone between Breeza and Clift seams. (modified from Tadros, in prep.).

as a result of loss of seam character caused by large amounts of tuff and tuffaceous sediments.

The percentage standstone map for the interval between the Breeza and Clift seams (Fig.11) shows a major change in the sequence. The axial channel complex shifted to the southwest and there are well defined tributaries emanating from the northeast. Composition of the sediment has changed dramatically also. There is a transition along the axial drainage where quartzose and volcanic-lithic sediments are mixed but towards the top of this sequence the volcanic-lithic sediments become dominant.

The Clift-Springfield-Doona-top of BJF intervals (Figs. 12,13) are characterised by southwestward migration of the eastern fluvial system with time. The axial channel complex has moved basinward, and there is a prominent tributary pattern with well developed interchannel areas.

CONCLUSIONS

Coal seams of regional extent such as the Hoskissons and Breeza seams formed during periods of negligible clastic accumulation and can define times of relative stability between major episodes of tectonic reorganisation and sedimentation. They can, therefore, represent significant sequence boundaries and allow subdivision of terrestrial basin-fill into genetic stratigraphic units of common tectonic, climatic and paleogeographic origin.

Coal seams of sub-regional extent such as the Caroona, Howes Hill, Clift and Springfield seams have time significance and are useful in subdividing larger genetic strategraphic sequences into lithofacies intervals, which, in the case of the Gunnedah Basin, allowed mapping the evolution of the fluvial systems.

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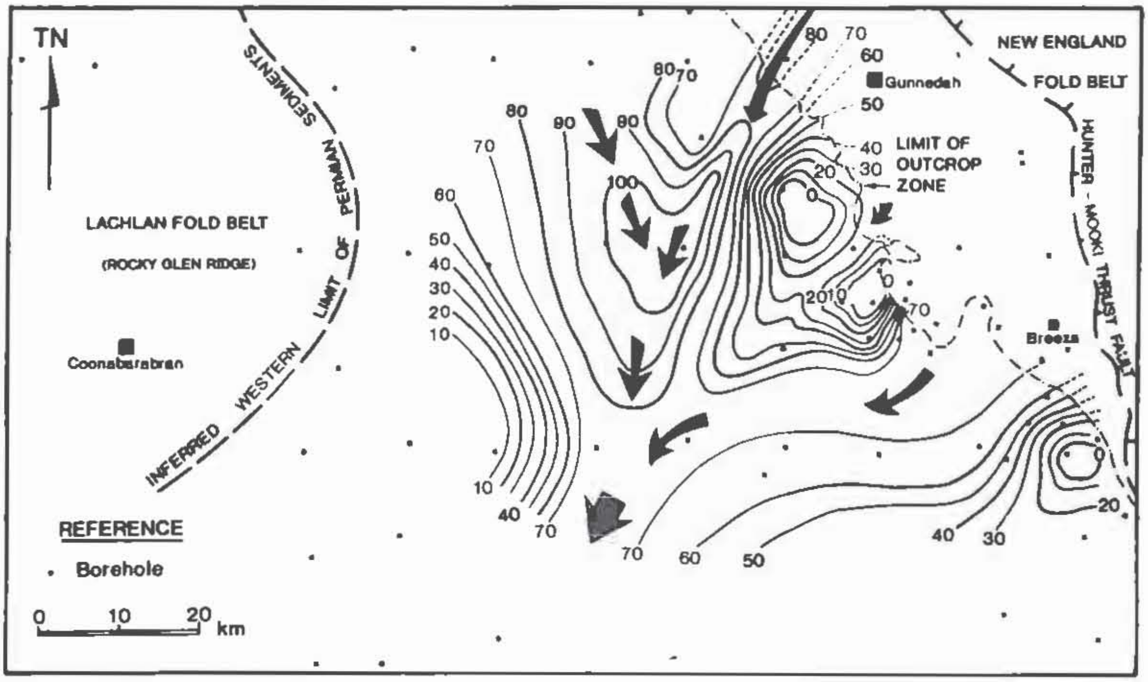

Fig.12. Percentage sandstone between the Clift and Springfield seams (modified from Tadros, in prep.).

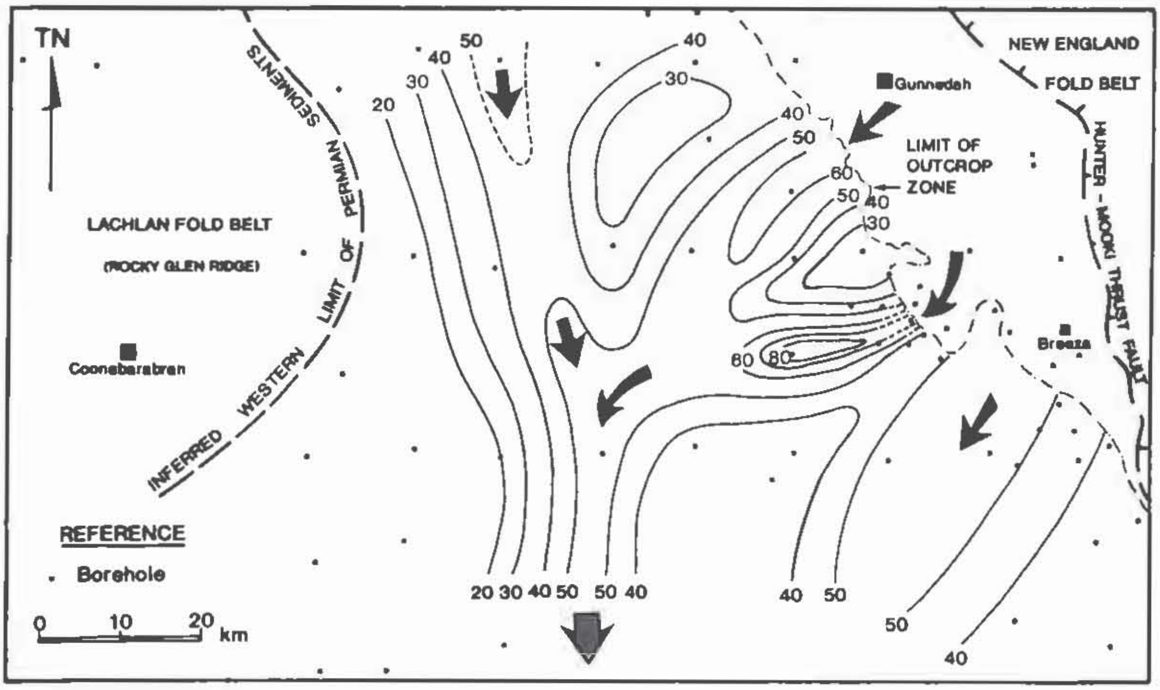

Fig.13. Percentage sandstonebetween the Springfield seam and top of the BJF (modified from Tadros, in prep.).

MARINE FACIES AND THEIR DISTRIBUTION, PERMIAN PORCUPINE AND WATERMARK FORMATIONS, GUNNEDAH BASIN

S.J. McDONALD & C.G. SKILBECK
University of Technology, Sydney

1. INTRODUCTION

Recent studies of facies in Permian strata of the Gunnedah Basin (Fig. 1) have concentrated on the coal-bearing Maules Creek (Thomson, 1986) and Black Jack (Hamilton, 1987) Formations (Fig. 2). Stratigraphically between these two units lie the marine Porcupine and Watermark Formations which have received only cursory treatment as part of wider studies (Beckett *et al.*, 1983; Hamilton and Beckett, 1984; Tadros, 1988).

In this paper we present a preliminary report on continuing detailed facies analysis of the Porcupine and lower Watermark Formations. The study is based mainly on examination of drill core from the 35 NSW Department of Mines and Energy (DME) boreholes that have penetrated these units, supplemented by cuttings and geophysical logs from 5 petroleum exploration wells (Fig. 3). Most of the latter are located in the northwestern part of the basin. The basin area is approximately 14,700 km^2, giving an average well density of one per 370 km^2.

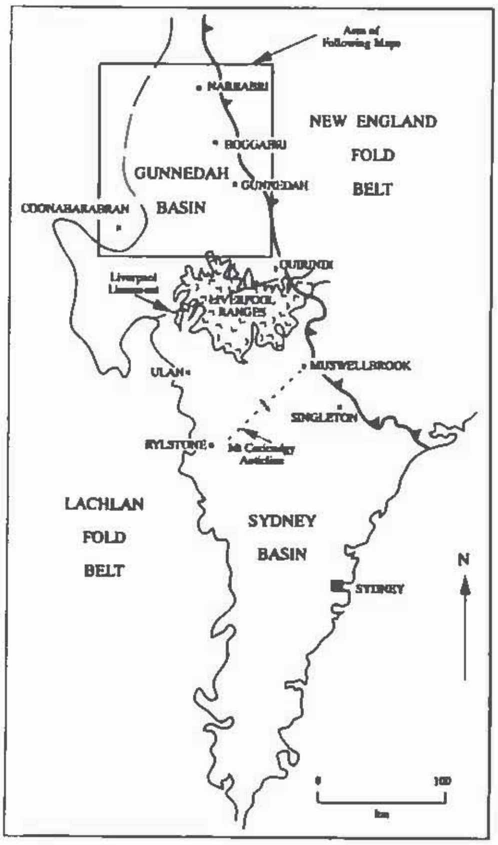

Figure 1: Location Map

2. STRATIGRAPHY (Fig. 2)

Following DME coal exploration drilling that began in 1981, the stratigraphy of the Gunnedah Basin was reviewed by Beckett *et al.* (1983). On the basis of cores, they indicated the characteristic lithologies of the Porcupine Formation to be poorly-sorted sandstone, siltstone and conglomerate with pervasive bioturbation. The unit overlies the Maules Creek Formation in the central part of the Basin and unconformably overlies volcanic basement along the margins (Fig. 4).

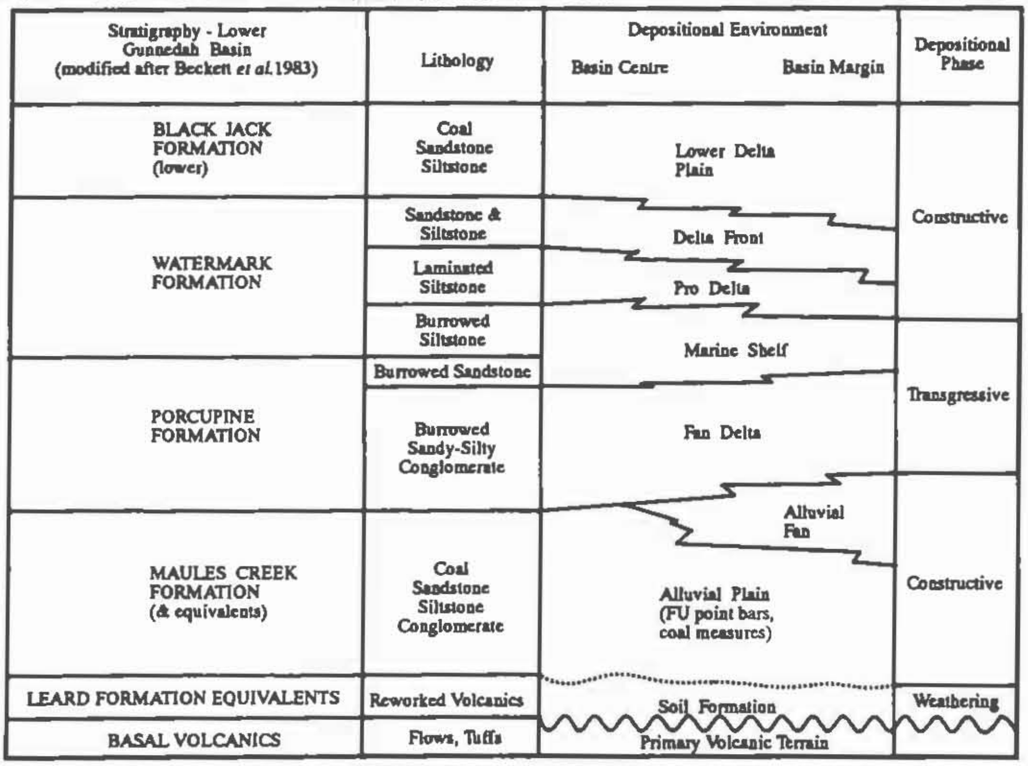

FIGURE 2: Stratigraphy of the lower part of the Gunnedah Basin and depositional environments (modified from Beckett *et al.*, 1983).

The base of the Porcupine is diachronous, ranging from Permian upper stage 4 in the more eastern occurrences to lower stage 5 in the west (McMinn, 1991, pers. comm.), and its contact with the Maules Creek Formations is complex. On the basis of work by Manser (1965) and Evans (1967), Runnegar (1970) proposed that a regional disconformity marked the base of the Porcupine, even where the underlying Maules Creek Formation is present (e.g. Bohena 1), and subsequent drilling along the western margin seemed to confirm this hypothesis (Bourke and Hawke, 1977). However, drilling in the central and southern parts of the basin has partly disproved this relationship. In this region Beckett *et al.* (1983) reported interfingering of the Porcupine and Maules Creek Formation, and the sequence of microfloras in this part of the section is complete. However, towards the north and west at least part of the section is missing (McDonald, *in prep.*).

The Watermark Formation gradationally overlies the Porcupine at all locations where both are present, and ranges in age from upper stage 4 at Quirindi 1 (Morgan, 1976a,b) to stage 5 in the north (McDonald, *in prep.*). It consists in its lower parts of a massive to bioturbated dark grey to black siltstone containing sporadic pebbles. This sequence is gradationally overlain by laminated siltstone, that becomes progressively sandier up section, heralding regression that culminated in the deposition of the Black Jack Formation.

3. SEDIMENTOLOGY

We recognise six facies within the Porcupine-lower Watermark interval. They are described below and their vertical distribution in selected wells is shown in Fig. 5. A possible sedimentologic model follows.

MARINE FACIES, PORCUPINE/WATERMARK FORMATIONS, GUNNEDAH

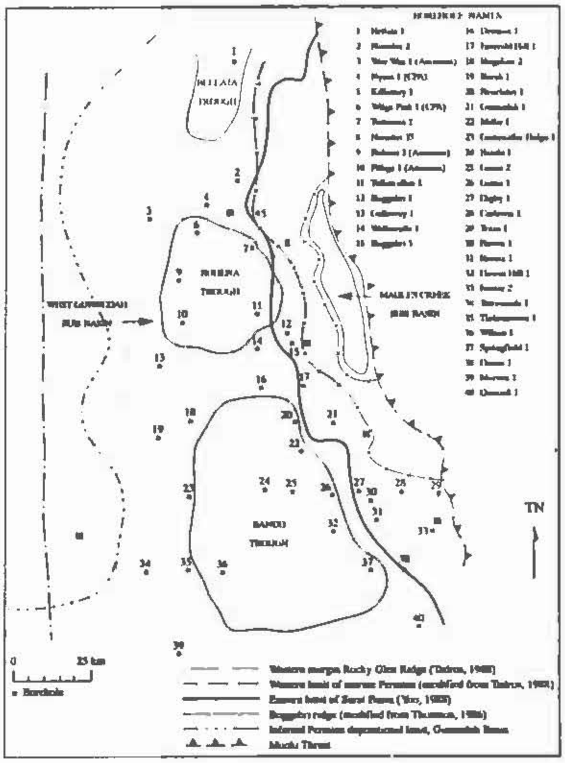

FIGURE 3: Boundaries, structural divisions and borehole location.

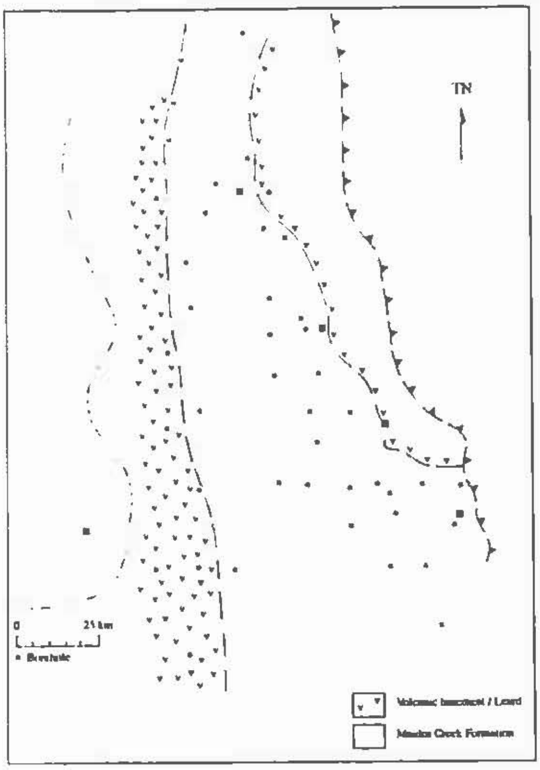

FIGURE 4: Subcrop on base Porcupine Formation.

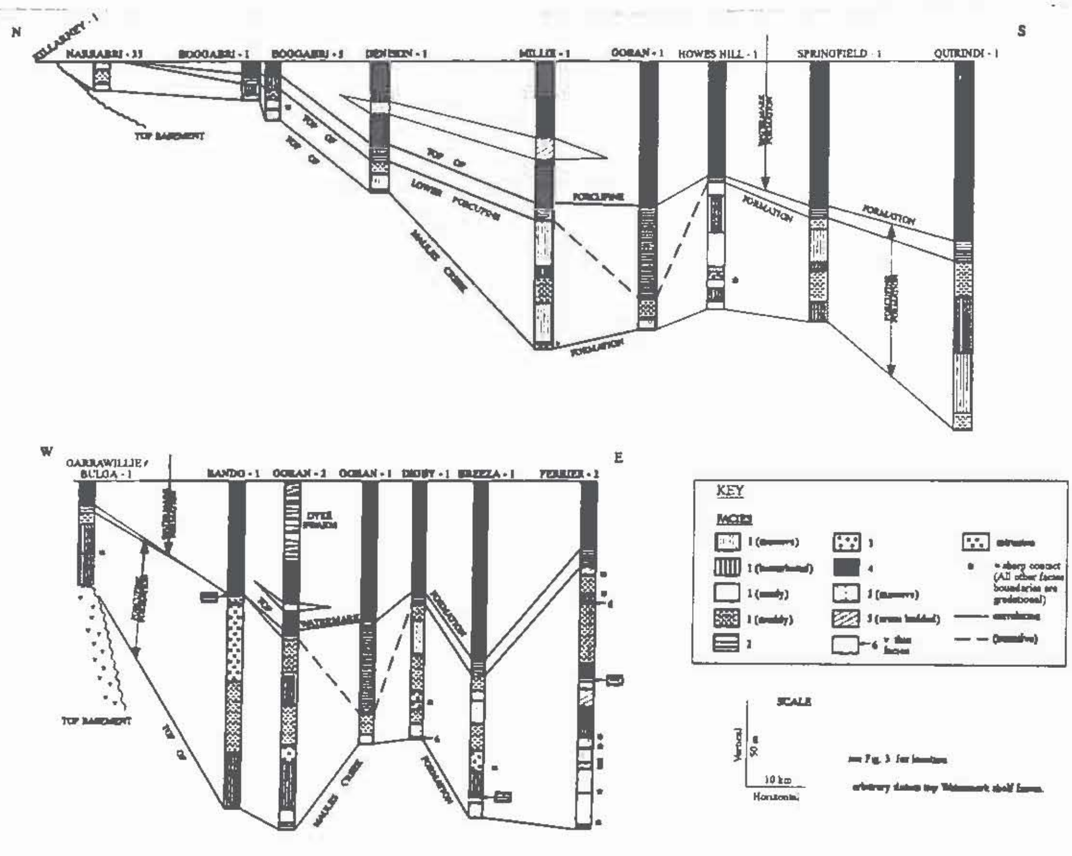

FIGURE 5: Facies and stratigraphic correlation in the Porcupine and Watermark Formations.

DESCRIPTION:

Facies 1: Facies 1 comprises massive paraconglomerate with an unsorted or very poorly sorted sandstone and mudstone matrix. Abundant clasts are mostly silicic volcanics, but near the western margin of the basin quartzite clasts are also present. Clast size ranges from granule to pebble. Four varieties of paraconglomerate are recognised: 1) massive, with unsorted sandstone/mudstone matrix, 2) massive with dominantly sandy matrix, 3) massive with dominantly muddy matrix, and 4) conglomerate with a pervasively bioturbated matrix and containing *Cruziana* and *Zoophycus*. These varieties are gradationally interstratified on scales ranging from less than one metre up to 40m, and occur individually in association with other facies. Together they make up most of the volume of the Porcupine Formation. Specimens RU08, RU09, LU14 and LU18 of Ward *et al.*, (1986) are indistinguishable from the rocks of this facies. Depositional sedimentary structures are characteristically absent. Some beds show crude upward fining, but only rarely are unequivocal contacts between sedimentation units preserved making it difficult to relate vertical trends to depositional processes.

Facies 2: The typical lithology of facies 2 is a homogeneous mixture of sandstone and mudstone, with rare clasts and indistinct lamination. The mixing of sand and silt is attributed to biological activity, with *Zoophycus* found sporadically throughout. This facies most commonly occurs at the top of the Porcupine Formation (herein called the "Transition Facies") where it grades into the overlying Watermark Formation. In this position it is gradationally interstratified with underlying facies 1 or 3 and overlying facies 4 in beds from 0.5 to 55m in thickness. LU24 of Ward *et al.* (1986) closely resembles rocks of this facies.

Facies 3: Orthoconglomerate similar to RU02 of Ward *et al.* (1986) comprises this facies. Clasts are identical to those of facies 1, but the matrix is a structureless, moderately sorted, lithic sandstone. These rocks are rare, occurring in layers from 1 to 12m thick gradationally interstratified with facies 1 or 5. In Digby 1 a 4m thick bed of facies 3 is erosionally overlain by a 6m thick bed of the facies.

Facies 4: Massive to bioturbated mudstone, in places sandy, and with rare clasts, makes up most of the lower part of the Watermark Formation. *Zoophycus* is present. Uncommon sandstone occurs in wispy laminae. The majority of clasts are widely dispersed but, in rare occurrences, clasts are concentrated into indistinct layers. LU17 of Ward *et al.* (1986) is comparable to rocks in this facies.

Facies 5: Rare occurrences of moderately- to well-sorted, massive and cross-bedded lithic sandstone and pebbly lithic sandstone comprise this facies. Most beds are gradationally bounded, but a few have erosional basal contacts. Beds are up to 14m thick. AR05, 06, 07 and 18 of Ward *et al.* (1986) are representative.

Facies 6: Heterolithic sandstone and mudstone, in gradationally bounded beds from 0.5 to 11m thick, form a very minor component of the Porcupine Formation. Two varieties are present; horizontally interstratified and laminated sandstone and mudstone (AR19 of Ward *et al.*, 1986), and ripple cross-laminated sandstone and mudstone (LA07 of Ward *et al.*, 1986).

INTERPRETATION:

A periglacial fan delta system retreating under the influence of marine transgression is the favoured depositional model for the Porcupine-Lower Watermark sequence (Beckett *et al.*, 1983; Hamilton and Beckett, 1984), but this has yet to be tested by detailed analysis.

The rarity of depositional sedimentary structures and identifiable sedimentation boundaries in facies 1, the principal component of the Porcupine, means that the accepted method of facies interpretation by process identification cannot be used. Previous workers have invoked mass movement and/or glacial action (e.g. McClung, 1980; Hamilton, 1985) to explain the deposition of facies 1, but neither interpretation can account for bioturbated units in excess of 35m thick.

Any model for the deposition of the Porcupine-lower Watermark interval, and interpretation of the constituent facies must incorporate the following:

a) A marine origin (based on fossil content, see Russell (1981) for summary).
b) An overall upward fining sequence (Fig. 6).
c) The presence of a conglomeratic interval stratigraphically between underlying non-marine alluvial plain sediments (Maules Creek Formation) and overlying marine siltstone of the Watermark Formation.
d) Thick (30-40m) beds of massive and bioturbated paraconglomerate.
e) The presence of intermediate to deep-water ichnofacies (*Zoophycus*) and the absence of shallow water ichnofacies.
f) Overall younging and thinning of the stratigraphic interval (Fig. 7) towards the west, as well as the appearance of a disconformity at the base of the interval, in this direction.
g) Upward reduction in clast content, without reducing in the size of the coarse-tail of the clast population.

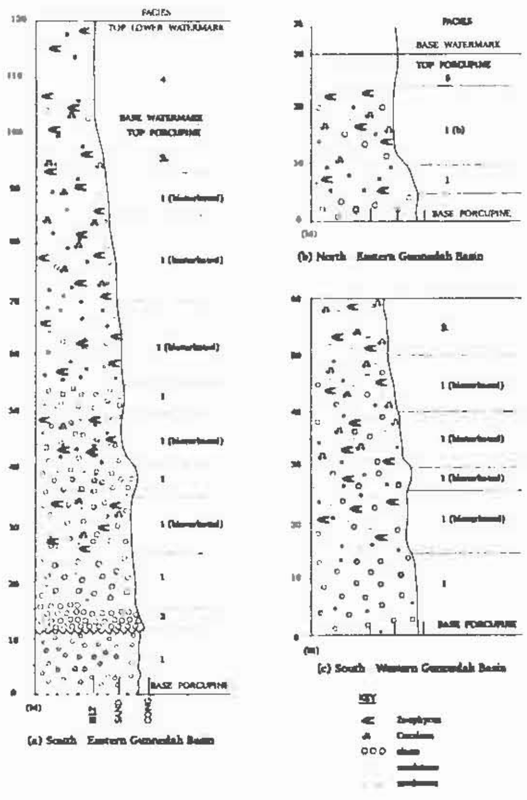

FIGURE 6: Idealised facies sequences.

MODEL:

We agree that a transgressive fan delta is the best general model to explain the first three characters listed above, but a more detailed explanation is required to incorporate all features noted. For example, f) contradicts the simple transgression implied by b), and e) is inconsistent with a depocentre that gradually deepens.

Figure 8 shows the distribution of facies at the base of the Porcupine Formation, divided into those of upper stage 4 and those of lower stage 5 age. This shows an initial lobe of coarse-grained sediment (predominantly facies 1) proximal to the Boggabri Ridge, fringed by a belt of finer-grained rocks (facies 5, 6 and the mudstone-matrix variety of facies 1).

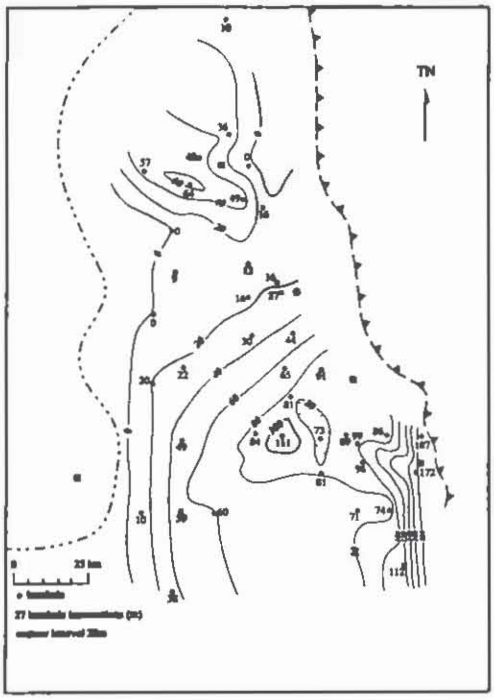

FIGURE 7: Isopach map of the Porcupine Formation.

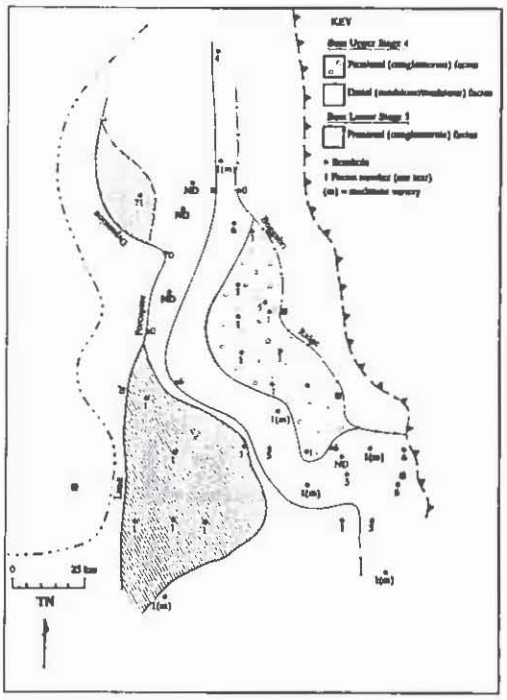

FIGURE 8: Basal facies distribution for the Porcupine Formation.

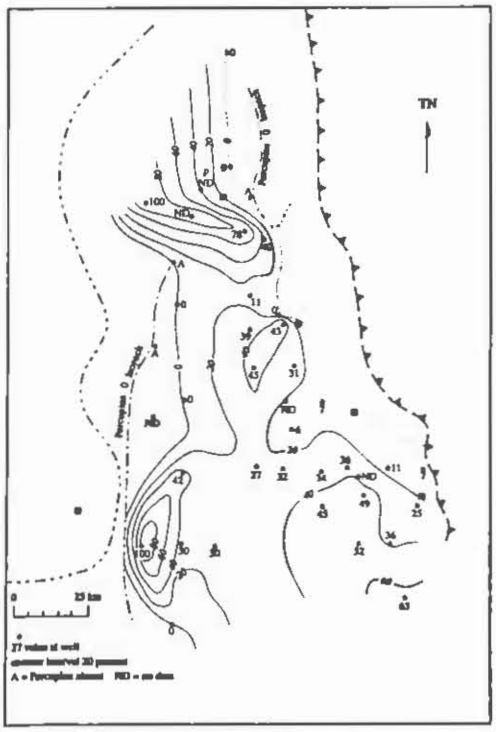

FIGURE 9: Percent conglomerate in the Porcupine Formation.

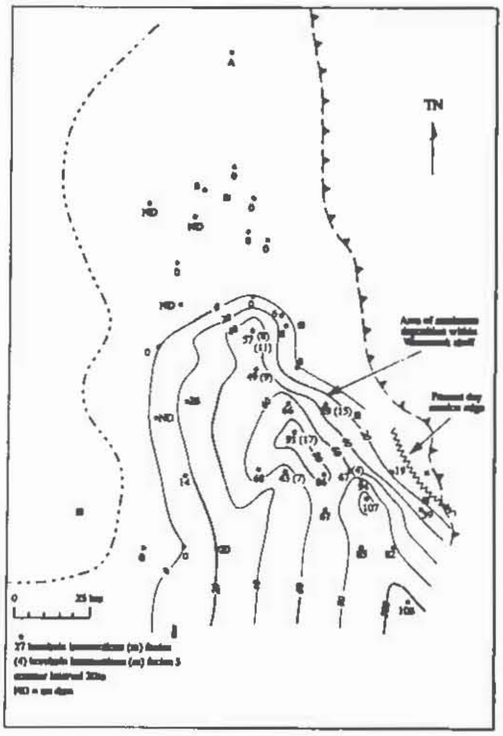

FIGURE 10: Isopach map of the lower Watermark Formation.

Comparison between Figure 8 and Figure 9 shows that the locus of conglomerate deposition thereafter prograded, as a linear belt, towards the southwest, leaving behind a belt of thick, finer-grained (mainly sandy) sediment. Evidence for this has largely been eroded from the Maules Creek Sub-Basin (Fig. 3), but still exists in outcrop at Gunnedah (Hanlon, 1949) and in the Deriah Forest area (Hill, 1986).

By lower stage 5 times, basinal marine conditions had been established in the east, whereas clastic progradation from the area of the Rocky Glen Ridge (Yoo, 1988) in the west had commenced (Fig. 8). The latter, in concert with the disconformity along the western margin, suggests uplift and erosion of the ridge at this time. Figure 10 shows that the lower Watermark marine environment was not as extensive in the west and north as the underlying fan delta, but that it extended further south.

The model that we feel best incorporates d) and e) above, and Fig. 9 is one in which the fan delta system developed adjacent to a fault escarpment, the western wall of which was at least initially, continuously subsiding. Coarse-grained sediment was delivered to a marine environment which lacked a significant shallow water component, and prograded irregularly by large-scale Gilbert delta-type foreset accretion similar to that described by Postma and Cruickshank (1988) and Prior and Bornhold (1988) for Quaternary Norwegian fan deltas. The typical large-scale, low angle structures expected would be difficult to identify in core. Each increment of sediment is delivered to the slope break of the fan delta either by mass movement or traction processes, and is accreted to the foreset, most probably by gravitational remobilisation. If the sediment supply is intermittent, as in most fan deltas (Galloway and Hobday, 1983), then ample opportunity would exist for biological reworking of the increments to form the bioturbated variety of facies 1. We suggest that the water depth adjacent to the escarpment approximates or exceeds the maximum foreset height, that is, the maximum thickness of continuous sequences of the facies. Non-bioturbated varieties of facies 1 are either foresets accreted so rapidly that there was insufficient time for bioturbation, or are remobilised bioturbated beds.

Facies 2 accumulated under similar conditions, but in a region removed from the supply of clasts. Facies 3 represents rarely preserved, reworked marine transgressive (*cf* Clifton, 1981), or channel-fill lag. The lower Watermark Formation comprises mostly Facies 4 which accumulated mainly from suspension in the latter stages of transgression. The clast component of this facies was transported by ice rafting, accounting for g) above. Massive and cross-bedded sandstones (facies 5) accumulated in a shallow marine environment. The cross-bedded variety most probably formed offshore bars. The depositional mode of massive sandstones is more difficult to interpret; they possibly represent grainflow deposits remobilised from previously winnowed, shallow marine sandstone. Facies 6 accumulated in a shallow marine environment where traction currents and suspension deposition alternated.

Fan deltas where debris flow processes dominate over traction flow are characteristic of semi-arid regions with abundant clay. Galloway and Hobday (1983, p.27) cited volcaniclastic and glacial terrains as common environments of this type of deposition. The Porcupine-lower Watermark interval is unique among ancient fan deltas in that its deposits are almost entirely devoid of depositional sedimentary structures, and it lacks a reworked, shallow marine periphery.

4. ACKNOWLEDGEMENTS

We would like thank Professor Evan Leitch for his critical review and vast improvement of this manuscript, and Mrs Leighonie Green who drafted the diagrams under considerable duress.

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THE GEOLOGY OF THE MOUNT VIEW - MOUNT BRIGHT INLIER AND ADJACENT ROCKS, POKOLBIN, NSW

E.C. WILLEY
University College of Southern Queensland

INTRODUCTION

The Pokolbin Inliers lie on the western flank of the Lochinvar Anticline in the north of the Sydney Basin. They comprise two relatively discrete outcrops, the larger Mount View-Mount Bright inlier in the south and the smaller Drake's Hill and Hungerford Hill inliers in the north (See Fig. 1).

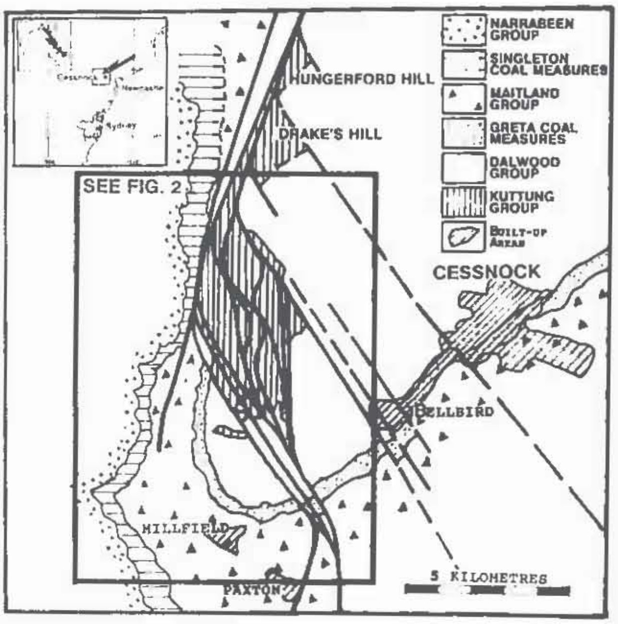

Figure 1. Location Map.

The earliest geological study of the inliers and overlying strata (David 1907) indicated that the stratigraphic succession was interrupted by periods of tectonism - an interpretation followed by subsequent workers in the region generally. It is not proposed to change this interpretation; however, detail presented permits a better understanding of the relationship between stratigraphy and tectonism at least in the Pokolbin area.

AMG followed by six digits refers to grid reference of the Australian Map Grid.

STRATIGRAPHY

Introduction.

The rocks in the area range in age from early Carboniferous to early Triassic. Adequate descriptions of most rock units in the area are already available (Packham 1969), so no details are provided except where necessary. The distribution of outcrop of units is shown in Figure 2.

Basement (?).

Mount View Range Granodiorite (Brakel 1972). Browne & Walkom (1911) and Brakel (1972) reported rhyolites and tuffs (= Mt Bright Rhyolitic Ignimbrite Member (Brakel 1972)) containing pebbles of granodiorite, interpreting a nonconformity between the granodiorite and the Kuttung Group. These pebbles have doubtful significance, since diverse granite-derived clastics occur throughout the Kuttung. This contact is interpreted as faulted.

Kuttung Group

Conglomerates and interbedded acid and intermediate volcanics and indications of periglacial environments are characteristic of the group. The conglomerates are very diverse, permitting the recognition of several distinctive horizons. The lower unit contains a variety of granite clasts up to block size, as well as hypabyssal, volcanic and some metamorphic clasts. The middle part has a volcanic provenance, traceable to the interbedded volcanics. The uppermost part contains inter alia clasts of a distinctive quartz-orthoclase-porphyry, which is restricted to this part of the sequence (Browne & Dun 1924, David 1950). Sandstones and red, purple and brown green mudstones occur. The mudstones contain Rhacopteris fronds.

Vineyard Lookout Formation (redefined; after Brakel 1972) (See Fig. 3). It is proposed that the Vineyard Lookout Volcanic Agglomerate Member (Brakel 1972) be excluded from the Pokolbin Hills Volcanics, and together with underlying strata be raised to formation status. The type section containing approximately 900 metres of dominantly coarse-grained sedimentary rocks with interbedded volcanic rocks is defined from AMG 386678 to AMG 378665. The unit is dominated by conglomerates with clasts of volcanic rocks similar to the interbedded volcanics, together with a wide range of granitic, hypabyssal and some metamorphic (quartzites) rock types. Clasts are moderately to poorly sorted, and range up to block size. Sandstones and red siltstones and mudstones occur. The interbedded volcanics include at least three horizons of trachytic flow tuff, two acid flow tuffs and near the top of the unit a trachytic block tuff. The base of the unit is not seen; the top is overlain by the Pokolbin Hills Volcanics (as redefined below). The eastern boundary of the outcrop of this unit is faulted against the Mt Bright Rhyolitic Ignimbrite Member. The unit is probably correlatable, in part, with the Mt Johnstone Fm.

Pokolbin Hills Volcanics (redefined; after Brakel 1972) (See Fig. 3). By exclusion of strata placed in the Vineyard Lookout Fm (see above), this unit becomes roughly conterminous with the three other members placed by Brakel (1972) in the unit. The Matthews Gap Dacitic Tuff Member (approx. 85m, oldest), the Flying Fox Gully Trachyandesite Member (approx. 40m) and the Mt Bright Rhyolitic Ignimbrite Member (at least 450m, youngest) together with intercalated sedimentary rocks chiefly derived from these volcanics, Mt VIEW - Mt BRIGHT INLIERS

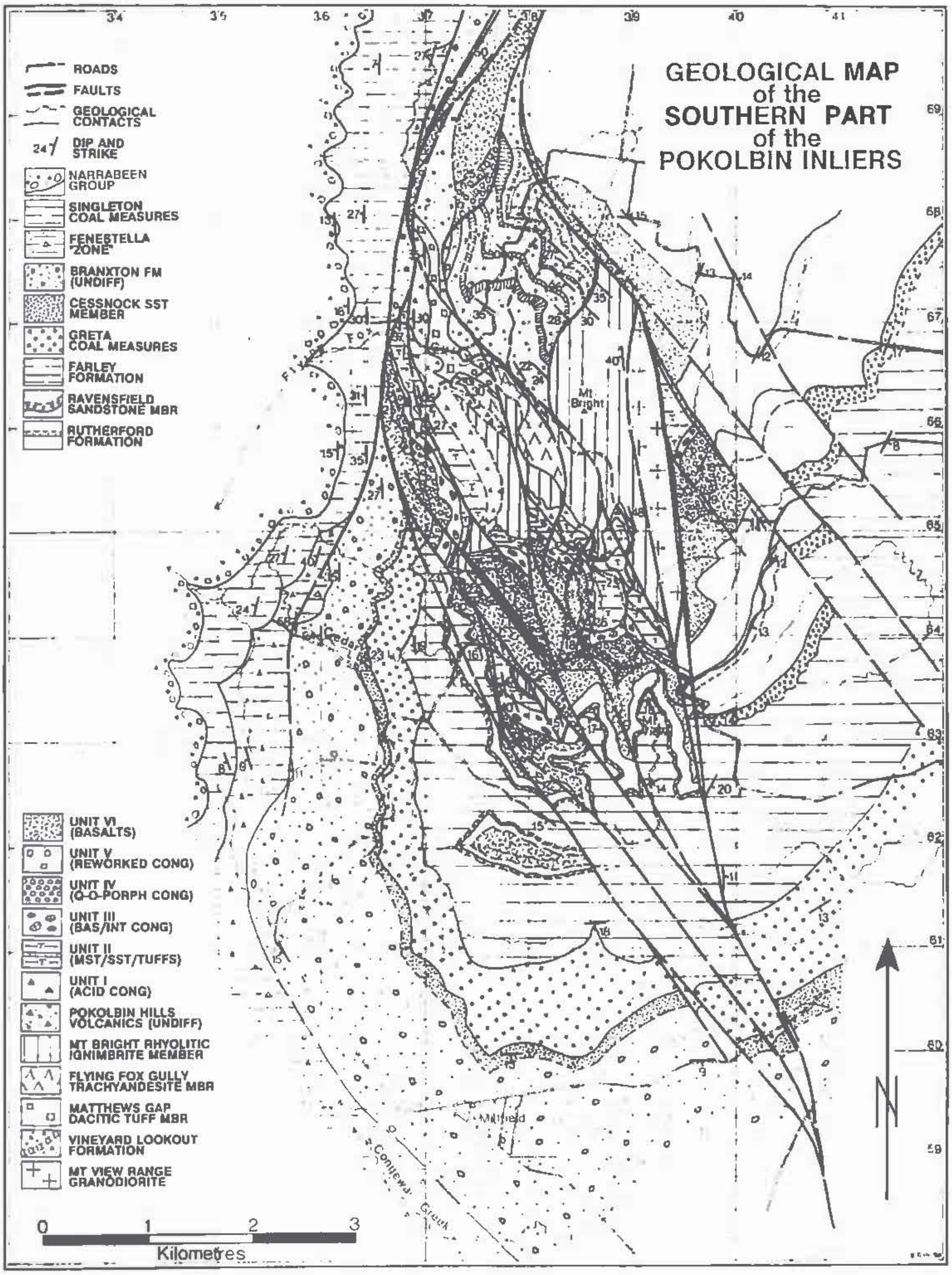

Figure 2. Geological map of the Mt View - Mt Bright area.

comprise the redefined Pokolbin Hills Volcanics. Because of faulting parallel to strike, it is difficult to assign a type section, however, all three members are developed from AMG 375664 to AMG 385664, and indicate that their stratigraphic order is the reverse of that given by Brakel (1972). All three members are significant feature formers. Total thickness of the formation is difficult to establish, due partly to faults parallel to strike and partly to the lenticular nature of the members. It must be at least 450m thick but may not exceed 500m. Radiometric dating (Gulson et al. 1990) supports time correlation of this unit with the Paterson Volcanics.

Units I, II and III. These beds have been recognised previously, being grouped in the Seaham Fm (Brakel 1972).
Unit I. This unit might be included in the Pokolbin Hills Volcanics, being composed of rudites and arenites derived chiefly from the underlying volcanics. The rudites are poorly sorted orthoconglomerates and orthobreccias, and locally are monomictic with blocks up to 0.9m across. It is diachronous, and occurs above the Matthews Gap Dacitic Tuff Member and the Mount Bright Rhyolitic Ignimbrite Member. Above the former, it is approximately 30m thick; above the latter, it is commonly 2-5m thick.
Unit II. This consists of 70m to 80m of red and purple mudstones and shales, with siltstones and sandstones and thin conglomerates. Fine-grained lithologies can be varved and contain dropped pebbles. Clasts of distinctive trachytic flow tuff occur amongst other rock types as erratics. About 20m of basic tuffs occur in this unit in the southwest.

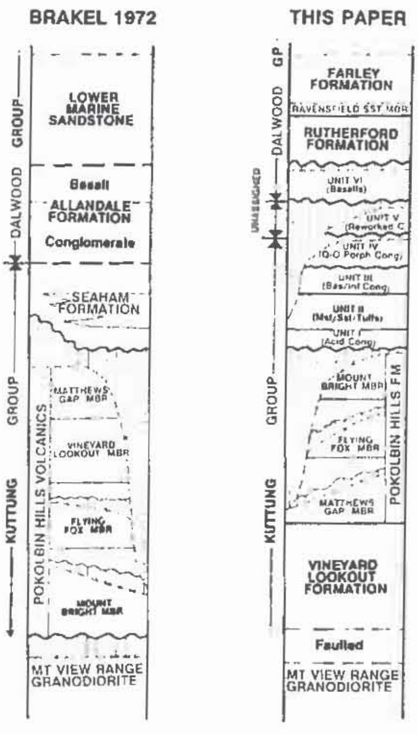

Figure 3. Comparison of Units.

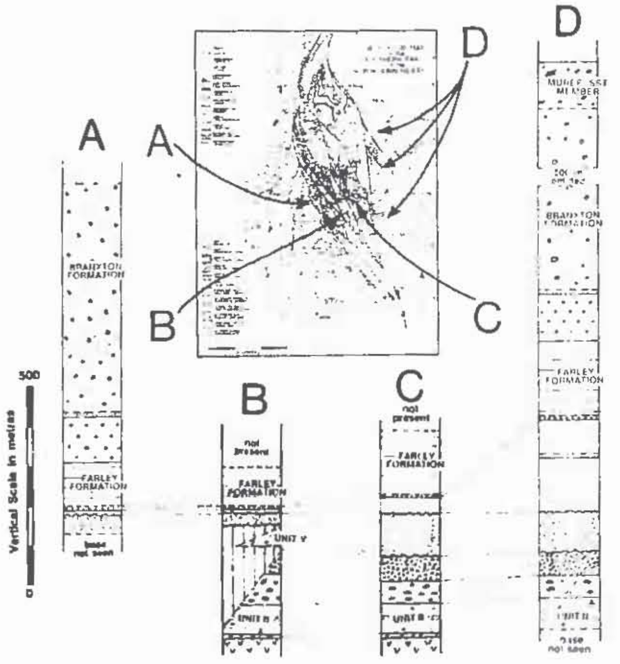

Figure 4. Stratigraphic thicknesses across area.

Mt VIEW - Mt BRIGHT INLIERS

Unit III. The Unit II are overlain conformably by a 50-65 metres of red-brown sandstones and conglomerates. The conglomerates contain subangular to moderately rounded pebbles of intermediate and basic volcanic rocks ranging up to 200mm in diameter. Sandstones are moderately to well sorted and massive. A conglomerate (10m) containing almost exclusively subangular to subrounded clasts of andesitic crystal flow tuff up to 0.5m across occurs at AMG 380633.

Unit IV. The lithologies of Unit IV are virtually identical to those of Unit III, the distinctions being provenance and colour. Unit IV has a mixed provenance including volcanic and hypabyssal rocks, quartzites and a distinctive quartz-orthoclase-porphyry not encountered in underlying strata. Granite clasts are absent. The interbedded sandstones and the matrix to the conglomerate are pale brown. This unit is about 60-80 metres thick.

Unassigned Unit.

Unit V. This unit produces no exposure, but is expressed by outcrop of dark brown-black soils with occasional resistant pebbles, including the quartz-orthoclase porphyry of Unit IV and frequent occurrences of the trachytic flow tuff, only seen in Unit II. This style of outcrop occurs at AMG 380628 and possibly at AMG 384635, but is often absent between Unit IV and Unit VI outcrops. The outcrop appears to represent sandstones and conglomerates derived from the underlying strata at least down to Unit II. It is assumed to be unconformable on older units. Its thickness may be 50 to 60m.

Dalwood Group.

Unit VI. This unit comprises basalts and basic volcanics, and includes the contemporaneous and "intrusive" basalts of David (1907). It is a persistent unit and usually overlies Unit IV. However, at AMG 380628, the unit rest on the rocks of either (a) Units I to IV (and even the Mt Bright Rhyolitic Ignimbrite Member) with marked angular unconformity or (b) Unit V which overlie this unconformity surface. It is 35m to 80m thick, and is interpreted to be part of the Lochinvar Fm. It is overlain by the Rutherford Fm.

Rutherford Formation. This contains dominantly fine-grained often calcareous sedimentary rocks, with occasional thin sandstones, limestones, basic volcanics and rare conglomerates. Marine fossils are common, and exposure is poor. The unit displays great variation in thickness across the area (see Figure 4), which appears to be delimited by N-S and NW-SE faults. In the east, it is estimated at 180m. Immediately west of the faults at AMG 395635, it is 30-40m thick. In the fault blocks between AMG 374645 and AMG 385625, it thins to about 10m. Further west, it thickens to about 25m. Sandstones and conglomerates are more common in thinner sequences. At AMG 373643, it is 9m thick, with 0.80 metre of conglomerate and pebbly sandstone at its base resting on fresh basalt.

Farley Formation. The Farley Fm consists of fine- to medium-grained sandstones, siltstones and shales with occasional conglomerate. Its base is marked by a thin persistent feature-forming sandstone - the Ravensfield Sandstone Member and its lateral equivalent. It comprises about 6m of well-sorted massive sandstones, but in the inliers, it is generally fossiliferous, bioturbated and poorly-sorted, containing many small pebbles. Although somewhat different from the type Ravensfield, its feature-forming character and its consistent position between the Rutherford and Farley outcrop suggest that it is a lateral facies of the Ravensfield Sandstone Member. The Farley Fm ranges in thickness from 200m in the east to 120m in the west.

Greta Coal Measures.

The Neath Sandstone (40m), Kurri Kurri Conglomerate (35m), Kitchener Fm (5m) and Paxton Fm (15m) occur in the Cedar Creek section (AMG 368638 to AMG 364637) and elsewhere in the area. The group displays freshwater deposition and a distinctive provenance including green chert pebbles. The Kitchener Fm is not exposed in Cedar Creek, but at AMG 366628, it consists of mudstones and shales, with no coal.

Maitland Group.

Only the lower part of the Branxton Fm (480m) is developed in the area. This unit commences with about 8 metres of Cessnock Sandstone Member. Brakel (1972) implied that the Muree Sandstone Member is present in the area, in which case its outcrop is marked by a prominent feature between AMG 366667 and AMG 358627, and the overlying mudstones and shales with abundant marine fossils and common erratics must represent the Mulbring Fm. However, this lithological description corresponds better to the Fenestella "Zone" as suggested by McClung (1980). This interpretation is preferred, although the thickness (220m) of the strata assigned to the Fenestella "Zone" is excessive. The upper part of the Maitland Group is missing, and the Singleton CM overlie the group unconformably.

Singleton Coal Measures.

Thin coals occur in a sequence of shales, sandstones and conglomerates at AMG 354645. Further north (AMG 364660), it comprises bleached sandstones, siltstones and shales, containing non-carbonised plant remains including Glossopteris and Vertebraria. Over 300m of strata are present.

Mt VIEW - Mt BRIGHT INLIERS

DISCUSSION.

Osborne (1949) did not identify the lithologies of Unit III, but assigned rocks of Unit IV to the Allandale Series, even though the type Allandale Fm has a basaltic provenance (Engel 1966). Brakel (1972) placed Unit III in the Seaham Fm and Unit IV in the Lower Dalwood Group, and described a transition between the units. However, the provenance of Unit IV is clearly typical of the top of the Seaham Fm (see also Browne & Dun 1924; David 1950) rather than of the lower Dalwood Group. Therefore, both provenance and the lack of stratigraphic break favour placing Unit IV in the Kuttung Group.

The first major development of basic volcanics in the region appears to herald the start of the Permian. Basic volcanics occurs in both the Lochinvar and Allandale Fms, and Unit VI correlate with either formations. Evidence presented below favours the correlation of Unit VI with the Lochinvar Fm. The boundary between the Kuttung and Dalwood Groups thus lies between Unit IV and Unit VI, but the group assignation of Unit V remains inconclusive.

Previous workers have described, often in general terms, major onlapping relationships between volcanics and conglomerates, etc.. In particular localities, this onlap appears to be a sedimentological response to the addition of a volcanic body onto a relatively flat riverine plain, rather than to tectonism. The instant development of local high relief by the eruption of a volcanic mass results in the mass shedding sediments until buried by onlapping sediments. This is more pronounced with acid bodies which have high aspect ratios. In addition, the reinterpretation presented here elliminates the major onlap - and the implied tectonism - proposed between the Mt Bright Rhyolitic Ignimbrite Member and the Vineyard Lookout Fm (Brakel 1972). Therefore, no significant tectonic activity appears necessary during the formation of the redefined Vineyard Lookout Fm and Pokolbin Hills Volcanics. Similar tectonic conditions persisted during the deposition of Unit I to IV as indicated by their relatively uniform thickness in different fault blocks (See Fig. 4). Therefore during the deposition of the Kuttung Group, the area appears to have been tectonically quiet.

The presence of an unconformable relationship beneath Unit VI (or possibly unit V) indicates that earthmovements occurred during the transition from the Kuttung to Dalwood Groups. The relationship between the units suggests that faulting occurred with tilting of strata within fault blocks. The erosion that occurred between the eruption of basalts of Unit VI and the Rutherford Fm suggests that uplift occurred in the area. The uplift in this area could have provided a source for the Allandale Fm conglomerates, favouring correlation of Unit VI with the Lochinvar Fm. The nature of this uplift is unclear but may be related to faulting.

The substantial thickness variation of the Rutherford Fm is fault controlled. Timing of fault movements relative to the deposition of the Rutherford Fm, however, cannot be specified. Reduction in thickness of the Farley Fm might be due to doming related to movement on faults. The Greta CM shows no reduction in thickness. The Branxton Fm/Singleton CM break and the thickness reduction in the Singleton CM and Narrabeen Group are related, in part, to syndepositional and postdepositional movements on faults.

In summary, in the Pokolbin area, tectonic activity was minimal during the deposition of the Kuttung. However, during the deposition of the Dalwood to Narrabeen Groups, fault related tectonism occurred. This activity appears to have been most pronounced during the deposition of the lower and middle Dalwood and the upper Maitland and Singleton.

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TRIASSIC DEPOSITIONAL ENVIRONMENTS IN THE SOUTHWEST BOWEN BASIN

J. KASSAN & C.R. FIELDING
University of Queensland

Introduction

Within the Bowen Basin and its southern subsurface continuation parts of the Triassic basin fill have proven hydrocarbon reservoir potential and are thus favourable targets for petroleum exploration.

This is particularly so for the quartzose Clematis Group of Early to Mid Triassic age. Previous studies of the Triassic succession in the Bowen Basin have focused either on stratigraphy or regional patterns of sediment dispersal (Dickins & Malone 1973, Jensen 1975). A few workers, notably Alcock (1970), Felton (1985) and Harris (1986), have attempted detailed facies analysis of individual formations and considered their regional setting.

This paper reports on a facies analysis of sediments from all three Triassic formations (Rewan Group, Clematis Group and Moolayember Fm.) in the southwest of the Bowen basin, an area of particularly good exposure and accessible well information. Data from government and petroleum exploration seismic lines, outcrop and drill core have been utilised in this study.

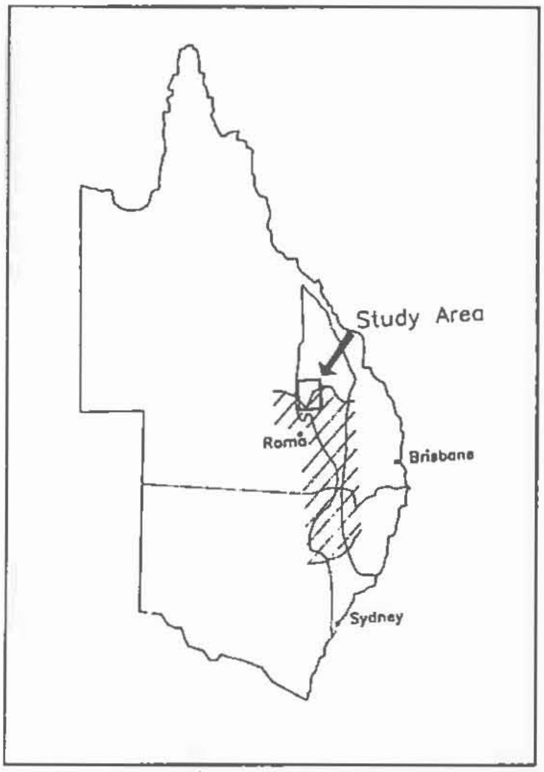

Figure 1 Location of Study Area

Study Area and Methods

Sediments of the Rewan Group, Clematis Group and Moolayember Fm. were studied at outcrop in an area ca. 100 km north of the township of Injune, Queensland (Fig. 1). Wherever possible, controlled orthogonal photomosaics were taken of laterally extensive outcrops on black and white film. These were later traced to delineate the external and internal geometry of sediment bodies. Vertical sedimentological sections were measured at accessible points along the outcrop to provide detailed information on lithology

and facilitate correlation between outcrop and drill core. Palaeocurrent directions were measured wherever possible and categorised according to the different current generated structures measured
Company and government seismic lines were utilised to determine possible structural controls on Triassic sediment accumulation in this area.

Rewan Group

Description

The volcanic lithic sediments of the Rewan Group have generally undergone intense diagenetic alteration, which greatly reduces porosity and permeability. With respect to hydrocarbon exploration this formation is therefore the least prospective, although locally it can provide reservoir facies. It has also been thought to form an important vertical permeability barrier which, where present, may prevent hydrocarbons generated in Permian sequences from reaching potential reservoirs higher in the stratigraphic succession. Furthermore a detailed study of the Rewan Group is hindered by the recessive nature of the sediments which results in sparsity of laterally continous exposure.

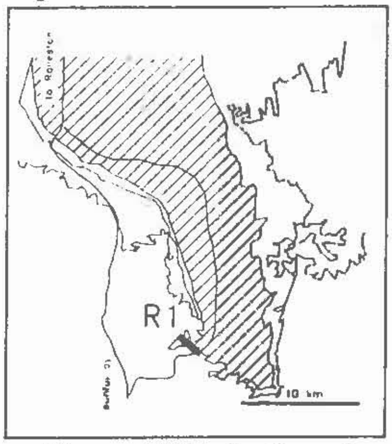

Figure 2 Distribution of Rewan Gp. (hatched).

In this study Rewan sediments of the Arcadia Fm. (Jensen 1975) were studied in a succession of roadcuts near Lonesome National Park (Locality R1 in Fig.2). Here, the lithology is dominated by reddish to chocolate brown siltstone, with interbedded, predominantly sharp bounded bodies of greenish grey, fine to medium grained volcanic lithic sandstone. The sandstones vary from friable to tightly cemented by quartz cement. Sandstone bodies are poorly interconnected or offset stacked and isolated by abundant fine grained sediments. Channel margins are characteristically sharp and erosive into abundant overbank muds or pre-existing channel fills. Palaeocurrent directions from these sediments indicate transport towards the northeast.

Sedimentary structures in the siltstones are mainly restricted to palaeosolic features (rootlet penetrated horizons and mottled light grey-reddish layers). Silts are interbedded with conspicuous light grey, poorly cemented coarse silt-very fine sand layers of 5-30 cm thickness. Structures are preserved very poorly in this labile lithology. Overall fine grained sediments dominate over coarser clastics.
Sedimentary structures in the sandstones are dominated by trough cross bedding, ripples and desiccation cracks. Trains of rip-up clasts occur at the bases of sandstone units. Coarse grained sediment bodies in the Arcadia Formation exhibit complex internal architecture with at least three major architectural elements (Fig.5):

* Inclined heterolithic stratified (IHS) units (alternate layers of sand and silt inclined at a shallow angle to the original horizontal)
* multi-storey, multi-lateral bodies composed of numerous nested thin lensoid beds.
* laterally extensive single storey sandbodies grading horizontally into overbank fines

Interpretation

The absence of marine fossils and the stratigraphic context of the unit (Fielding et al. 1990) strongly suggest a nonmarine environment of deposition. The depositional style is characterised by: 1.- the sedimentation of abundant fine grained material, 2.- poorly interconnected, current deposited sandstone bodies, 3.- evidence of temporary subaerial exposure, 4.- unimodal current directions. This points strongly to a fluvial depositional environment, conforming with results of Dickins and Malone (1973), Jensen (1975) and Harris (1986).

The dip directions of IHS units are at 45-90 degrees to the prevailing palaeocurrent direction and the IHS sets are therefore interpreted as lateral accretion surfaces on point bars of high sinuosity river channels.

The presence of poorly interconnected sandstone bodies implies episodic discharge and/or frequent and rapid channel avulsion. To account for the limited lateral extent of channel deposits, a strong element of vertical accretion has to be inferred. These characteristics are typically found in anastomosing rivers (Smith & Smith 1980). Schumm (1981) points out that change from one type of channel to another will depend on certain threshold values for slope and sediment supply. A meandering fluvial system that exists under conditions very close to the threshold may change rapidly and repeatedly to anastomosing and back reacting to relatively minor changes in sediment supply, slope or vegetation cover.

Based on the evidence presented above, the depositional environment proposed for the Arcadia Formation of the Rewan Group is a high sinuosity fluvial system, of meandering to anastomosing style, draining from a source area to the southeast of the study area and of acid volcanic provenance.

Clematis Group

Description

The quartzose sands of the Clematis Group and in partcular those near the top of this stratigraphic unit (Showgrounds Formation) form the primary Triassic exploration target in the Bowen Basin and its subsurface continuation. The change from volcanic lithic lithologies in Late Permian rocks and the Permo-Triassic Rewan Group to quartzose lithologies in the Clematis Group reflects a major change in provenance which is accompanied by a change in depositional style.

In stark contrast to the Rewan Group, sediments of the quartzose Clematis Group (Jensen 1975) outcrop extensively in the study area as high cliffs. Examination of outcrops was restricted to creek exposure, roadcuts and some smaller outcrops of limited lateral extent on the dip slope side of cuestas.

Sandbodies in the Expedition Sandstone are well connected, multistorey sheets, which are laterally continous for 100's of meters to kilometres and grade laterally into heterolithic strata (Fig.5).

Palaeocurrent data from this interval suggest initially transport towards the south, which higher up changes to northeasterly directions.

For the purpose of this study the rocks of the Clematis Group have been grouped into three major facies assemblages, labelled cA,cB and cC.

Facies Asssemblage cA

Thin bedded light grey siltstones/very fine sandstones with occasional interbedded thin layers and lenses of fine to medium quartzose sandstone, commonly exhibiting erosive bases and rip up clasts. Poorly preserved ripple cross lamination, rip-up clasts and horizontal lamination. The lateral extent of this facies could not be accurately determined due to its poor outcrop. It is suggested, however, that facies cA is neither very laterally extensive nor very common, as thick (> 2m) successions of siltstone are rare within the Clematis Gp.

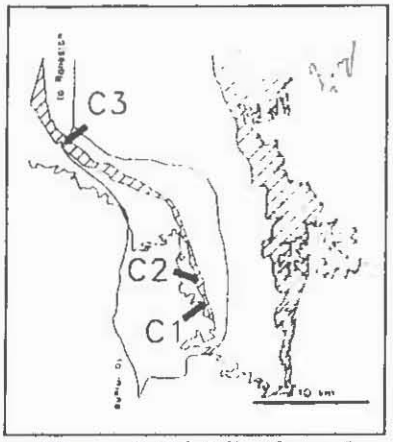

Figure 3 Distribution of Clematis Gp. (hatched).

Facies Assemblage cB

Sandstone beds 10-70 cm thick interbedded with light to medium grey siltstones of the same thickness. Ripple cross lamination, load casts, convolute bedding, trough cross stratification and horizontal stratification. Lithologies laterally extensive for hundreds of metres down dip, and tens of meters along strike, grade laterally into Facies cA on one side and Facies cC on the other.

Facies Assemblage cC

Major bodies of fine to coarse grained sandstone 4-10 metres thick. Internal architecture consists of a monotonous series of mutually intersecting lenticular sandstone bodies of 5-30m length and 1-5m height. Rare sandstone sheets of 1-3m thickness with a lateral extent larger than the outcrop (ca. 100-300m) and poorly defined internal architecture. Sandstones contain medium to large scale trough and tabular cross bedding and rip-up clasts. Granule and pebble bands are developed at erosive bases. At outcrops C1 and C2 (Fig.3) soft sediment deformation in form of dewatering structures is also very common. The general lack of fine grained material gives rise to multi-storey and multi-lateral sheets of several kilometres width, and tens of metres thickness.

Interpretation

Similar to the Rewan Group, the Clematis Group shows evidence of a continental depositional environment. The sediments of the Clematis Group are interpreted to have been deposited in low sinuosity fluvial systems, dominated by sandy bedload. Deposition took place mainly in the form of sandbars in poorly constrained channels (probably braided), which coalesced into several kilometre wide channel belts. Large to medium scale trough and planar cross beds in Facies cC represent individual barforms within these channels, while Facies cB is interpreted to represent channel or channel belt margin facies. Rare overbank deposits are represented by Facies cA. Discharge in these river systems may have been highly variable, as indication of erosion and reworking are common (pebble lags, erosive bases, rip-up clasts, slumping) In such an environment the preservation potential of overbank material and channel margins is low. On the basis of palaeohydraulic considerations Harris (1986) estimated the approximate bankfull channel width of Clematis channels to be around 300m. Here we suggest on the basis of field evidence that channelbelts were an order of magnitude wider (1-2 km) and graded laterally abruptly (over 10-50m) into overbank siltstones (Facies cA).

Moolayember Formation

Description

Alcock (1970) undertook a comprehensive study of the Moolayember Formation in the study area and concluded the depositional environment to be estuarine to fluvio-deltaic. Felton (1985) came to similar conclusions in an area 30 km south of the current study area. Both workers subdivided the formation into upper and lower members on the basis of facies assemblages. The reservoir potential of the formation is limited by diagenetic alteration of the unstable lithic component. The formation is generally recessive, but a succession of roadcuts and isolated creek exposure in this area allows detailed study of laterally extensive outcrops. Sediments of the Moolayember Formation were studied at outcrops M1 and M2 (Fig.4). Outcrops are composed of yellowish grey quartzo-lithic sandstones (ca.40% lithic component) interbedded with light grey to dark grey siltstones and very fine sandstones. The formation shows a change in sandbody geometry, from laterally extensive single storey sheets and rhythmically interbedded fine grained sediments near the lower formation boundary to laterally restricted, "ribbon-type" channel deposits higher up in the sequence (Fig.5). Current directions in the Moolayember are highly variable and locally bipolar (Alcock 1970).

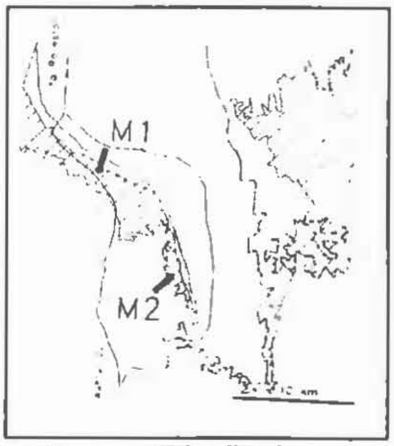

Figure 4 Distribution of Moolayember Fm. (hatched)

<u>Lower Moolayember</u>

fine sediments

Siltstones to very fine sandstones of the lower Moolayember Fm. exhibit abundant current ripples and lenticular and flaser bedding. In the subsurface the lowermost Moolayember is comprised of very dark grey, fine grained siltstone and claystone showing extensive signs of bioturbation (Snake Creek Mudstone) - this lithology does not crop out in the study area.

coarse sediments

Sandstones of the lower Moolayember Fm. contain abundant evidence of current action such as ripple cross lamination and trough cross bedding. Features of extensive reworking, such as rip-up clast conglomerates and erosive pebble lags are locally restricted. The most dominant feature is the great lateral extent of individual sandsheets which mostly do not exceed 20 cm thickness (Fig.5).

<u>Upper Moolayember</u>

Facies Assemblage mA

Dominantly siltstones and very fine sandstones; rootlet penetrated and ripple laminated in places; dominantly faintly laminated; occasional interbedded sharply bounded, massive sandstone beds up to 40 cm thick.

Facies Assemblage mB

Mounded (convex-up) heterolithic stratification dominated by siltstone and very fine sandstone; siltstones show poorly preserved rootlet penetration; thin (max 15 cm) sandstone sheets dip away from crest of convex feature and wedge out into laterally adjacent sediments.

Facies Assemblage mC
Complex heterolithic stratification, dominated by siltstone and very fine sandstone; bedding dips of thin sandstone sheets show a very wide range of direction of dip; adjacent beds exhibit same direction of dip which may be entirely different to the next "package" of strata; "packages" are mutually intersecting creating a complex picture (Fig. 5).
Facies Assemblage mD
Lenticular bodies of fine to medium, trough cross bedded sandstone and interbedded thin siltstone partings.

Interpretation
Lower Moolayember
Sediments of the lower Moolayember reflect deposition in a low energy environment as manifested by abundant fine grained sediments and the scarcity of erosive features. The depositional style is very much "layer cake" and is only occasionally interupted by strongly erosive events (mudflake conglomerates). An environment with a strong lacustrine component with reworking of fine grained material along shorelines or adjacent fluvial channels accomodates these features and is here suggested for the lower Moolayember.
Upper Moolayember
Outcrops along the Carnarvon Highway are confined to channel and overbank deposits of current deposited sands and associated fine grained material. Stepped channel margins indicate well consolidated substratum at the time of channel incision. Lateral accretion on point bar or alternate bar deposits is well evidenced by epsilon cross bedding preserved in one complete channel cross section. Channel width in this case is 60m. Channel margins are wide (ca. 20m) compared to the channel width, and show well developed levees, recognised as Facies Assemblage mB (Fig 5).

Conclusions

In the absence of marine micro and macro fossils and other evidence of marine influence, Triassic sedimentation in the study area has to be assumed to have been entirely non-marine. To the east and south of the study area, however, lateral equivalents of the strata studied here have been found to contain acritarchs and were considered restricted to near shore marine.
Depositional style and sandbody geometry show considerable variation throughout the Triassic. Similarly sediment dispersal patterns and provenance underwent several dramatic and abrupt changes during this time. This is summarised in Fig. 5.
The Bowen Basin forms part of the Permo-Triassic Bowen-Gunnedah-Sydney Basin Foreland Complex. Extensive tectonic activity in the Bowen Basin during the Triassic has been well documented for the eastern basin margin. Here large scale thrusting is evident in coal mine exposures and has recently been shown on deep seismic sections (Korsch et al. 1990). The study area lies in the western part of the basin, which traditionally has been considered an area of relative tectonic quiescence.
Seismic lines, however, clearly show a lower Triassic inversion of a pre-existing system of normal faults. Thickening of Triassic strata towards the downthrown side of these faults is also apparent. The abundant and spectacular softsediment deformation at section C1 and reorganisation of drainage during upper Clematis times in this area is

here interpreted as being seismically induced through fault activity concurrent with deposition of the sediments.

The influence of active tectonism on fluvial deposition is well known from a variety of foreland basins, including the modern Papuan Foreland Basin. From field evidence and by analogy with foreland basins worldwide, therefore, we propose that syndepositional tectonics form the largest single influence on the development of fluvial styles throughout the Triassic in the southwestern Bowen Basin.

Acknowledgements

The data presented here form part of an ongoing research project on the basinwide development of Triassic deposition. This work was undertaken with support from the Australian Research Council and the University of Queensland. Logistic support and the supply of data by AGL Petroleum is gratefully acknowledged.

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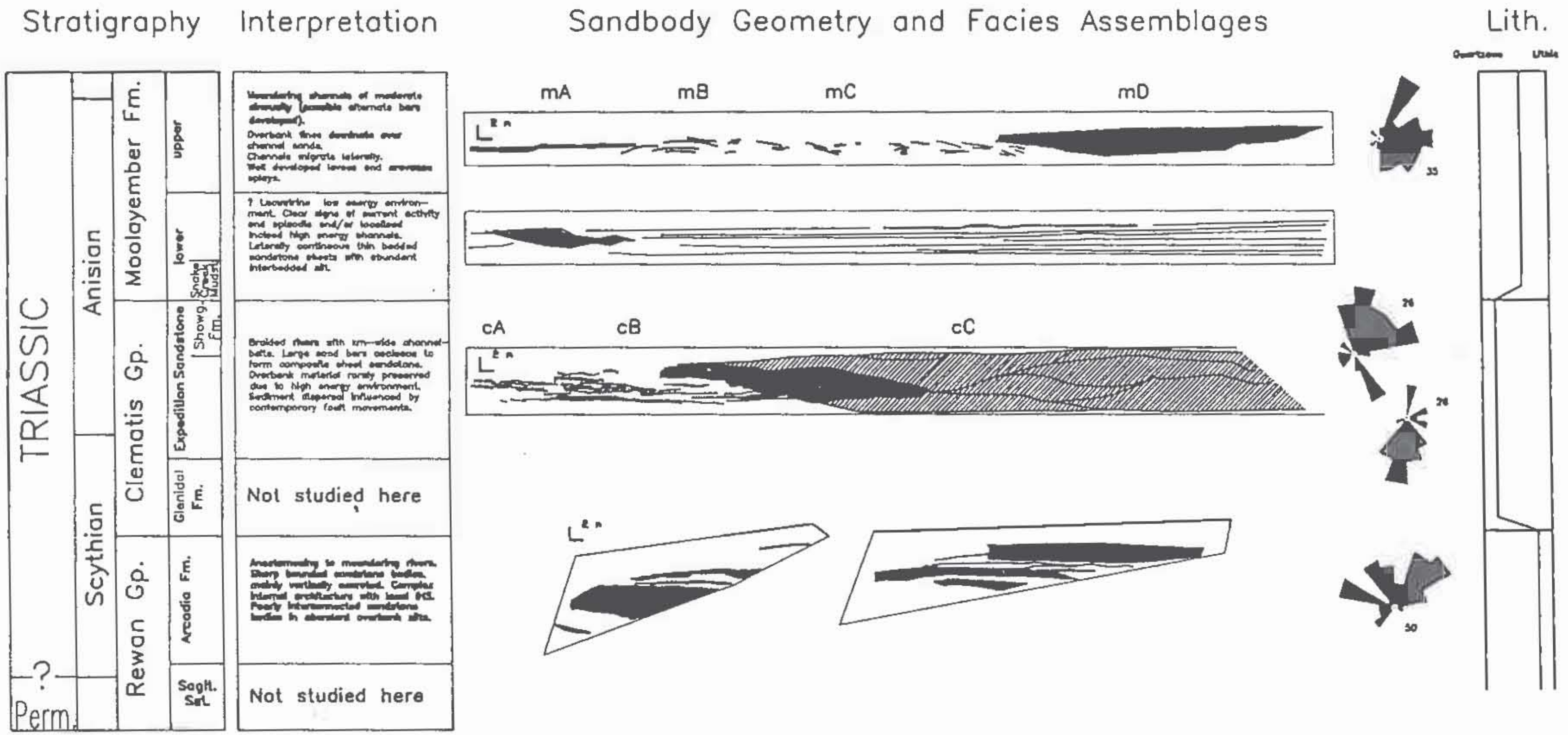

Figure 5 Summary of Stratigraphy and Depositional Environments in the Triassic of the Bowen Basin

GEOLOGY OF THE PYRMONT-ULTIMO AREA, SYDNEY

D.F. BRANAGAN
University of Sydney

INTRODUCTION

The Pyrmont area of inner Sydney (Figure 1) contains an interesting stratigraphic problem, not previously addressed, and several easily accessible structural features of the types described recently by Branagan (1977, 1985), Norman & Branagan (1984), Norman (1986), Branagan et al (1988), Mills et al (1989) Branagan & Mills(1990), and which have significance for both theoretical and practical reasons.

STRATIGRAPHY and BROAD STRUCTURE

The area is supposed to consist largely of Hawkesbury Sandstone, (Sydney 1: 100 000 map), but exposures in various excavations show that towards the south there is a variable thickness of Mittagong Formation and Ashfield Shale. While the Mittagong Formation was absent from the foundations of the University of Technology, it was 3m thick in the Prince Centre site in Thomas Street, near Quay Street (loc. D/9,Fig.1) with dips up to 8^{0}northeasterly. A similar thickness is exposed in the Paddy's Market site (loc. E/9), where the beds dip about the same amount easterly, and contain lens-like bodies about 15m in length and 2.5m thick. About 1m of what might be called Mittagong Formation was exposed in the Fig Street cutting, at an elevation of about 18m, overlain by 2.5m of Ashfield Shale (loc. C/6, Fig.1).

The top of the Hawkesbury Sandstone is close to 14 m in the railway cutting adjacent to Allen Street (loc. B/5, Fig.1), and 160m north, in the cutting below Pyrmont Bridge Road, the beds dip

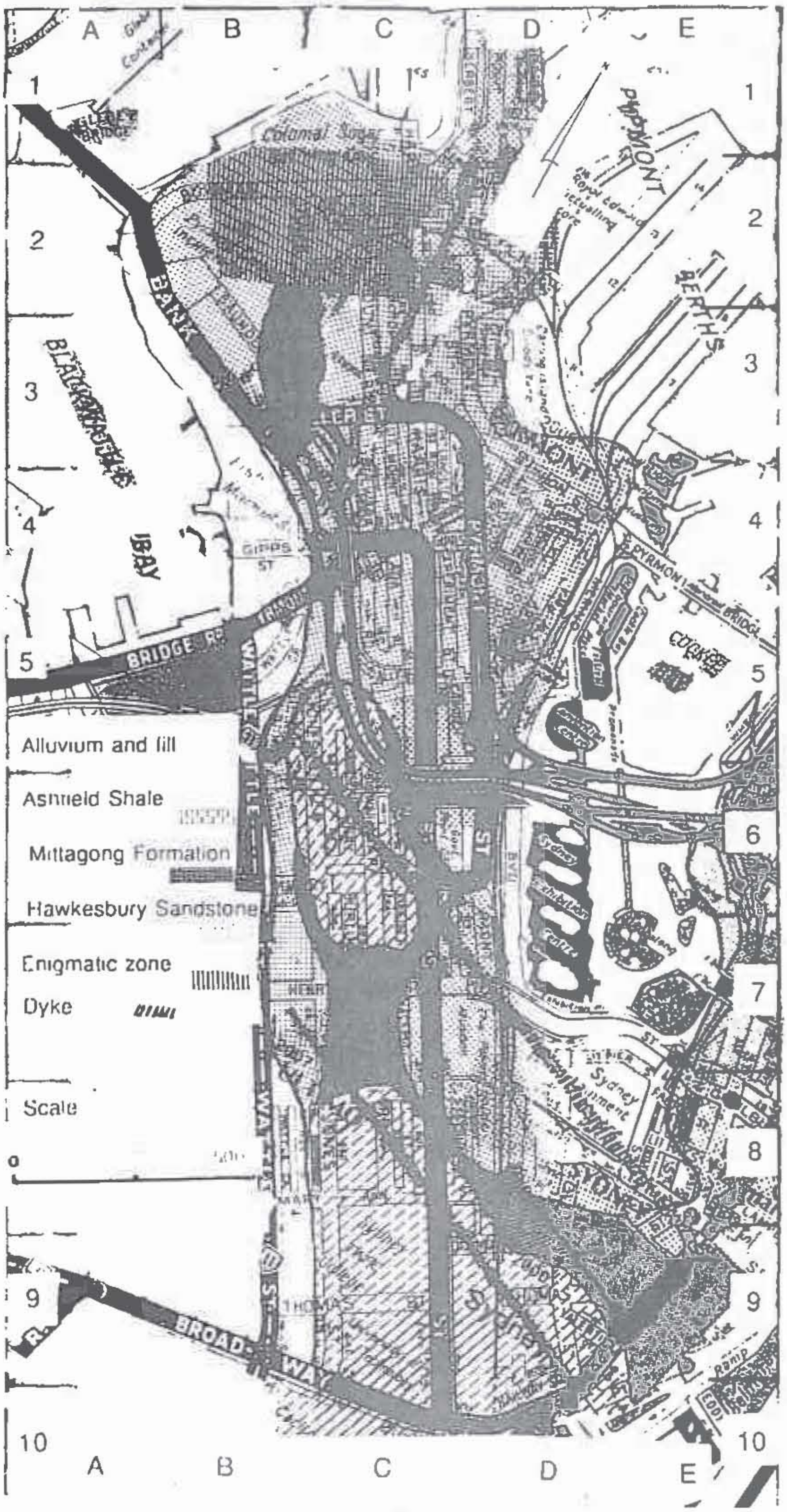

Figure 1 · Geology and Locality map-Pyrmont Ultimo area gently north (2%) before becoming horizontal. What appears to be Mittagong Formation in the road cutting on the corner of Saunders and Miller Streets, and the adjacent railway cutting (loc.B/3), at an elevation of 6m asl, could only be so if there is folding or faulting, as identified Hawkesbury Sandstone occurs just to the north i.e.south of Bowman Street (loc. B/2, Fig.1) at a considerably higher elevation, (up to 38m asl).

The relationships discussed are shown on the cross-section, figure 2. There is almost continuous outcrop along the railway, and observable faulting (see later), shows minimal vertical displacement. Consequently the apparent Mittagong Formation can only be seen as running directly into the Hawkesbury Sandstone (fig.2). Another interesting feature is the nature of the Hawkesbury Sandstone exposed on the cliff face above the railway tunnel (loc.BC/2,3). The rock occurs in regular beds, about 3m thick, and the grainsize is somewhat finer than in other localities.

This problem, the apparent intertonguing of the Mittagong Formation and the Hawkesbury Sandstone, has not been satisfactorily solved, but it is essentially a stratigraphic question, not a structural one, although on a broader scale Pyrmont forms the northeastern end of the Erskineville Low structure identified by Lovering (1954) (and see Branagan et al, 1988). Perhaps it involves two pulses of sedimentation of the Mittagong type.

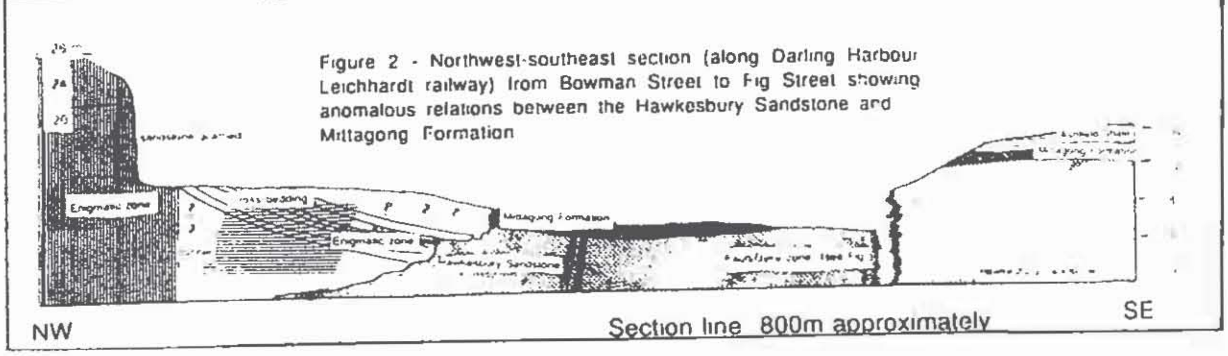

Figure 2 - Northwest-southeast section (along Darling Harbour Leichhardt railway) from Bowman Street to Fig Street showing anomalous relations between the Hawkesbury Sandstone and Mittagong Formation

DYKES

The area is cut by at least five dykes, three trending WNW, two NS. The most southerly of the three WNW dykes is persistent over several kms, (Rickwood, 1985). This dyke, about 5m wide, caused considerable trouble in the foundations of the Daily Mirror building in Kippax Street, in the 1960s, tilting the strata on both sides (Branagan,1969).

The second WNW dyke occurs 125m northerly, and was located about three years ago, in the Thomas Street site mentioned above. Here it was 2.5 m thick, and dipping nearly vertically. The intrusion had tilted the strata on the northern side over a distance of 3m, but there was minimal disturbance on the southern side of the dyke. It was variably weathered, with slight variations in hardness,and some iron banding, but was mostly soft clay. It passes under the Library of the University of Technology in Quay Street (loc. D/8,9, Fig.1). Rickwood (op. cit.) notes other occurrences. It has not been definitely traced northwest of Harris Street.

The third WNW dyke cut obliquely across the Fig Street site. This is the so-called 'Great Sydney Dyke' (Rickwood, 1985). It was 2m thick, giving a width of exposure of more than 3m on the sides of the cutting. The dyke was decomposed, consisting of soft wet clay. This material was excavated and replaced by concrete in both walls of the cutting, and restrained by cables taken back some 30m into the adjacent sandstone.

This dyke was previously located during construction of the William Henry Street Bridge (Branagan, 1969), when the foundations of one pier were placed on it, and at many other places, as recorded by Rickwood (op. cit.). More recently it was cut in the Entertainment Centre site, where it dipped about 70^{0} to the southwest; in the foundation excavations of the telephone exchange in Parker Street, and in the nearby Holland Stolte Sydney Centre, 477 Pitt Street site.

Despite such previous experience the same dyke was encountered, apparently unexpectedly, on the City Market Site site, 683 George Street (adjacent to Hay Street), because no provision had been made for its presence in the way of support, drainage etc., resulting in collapse of the footpath on George Street, and considerable delay in construction. The dyke cropping out in the Glebe Island container terminal is probably an extension of this dyke.

The more prominent north-south trending dyke, one of few with this direction in the Sydney region (Rickwood, 1985), crops out in the railway cutting near Jones Street (loc C/2, Fig.1), where it is 1m thick. It has been recently exposed during clearing on the north side of the adjacent small park in Cross Street, north of the cutting, can be sampled immediately adjacent to the wooden staircase linking the lower and upper parts of Mount Street (loc. C/3, Fig.1), and is seen also in the railway cutting near the fish markets (loc. BC/4, Fig.1).

A second NS trending dyke, about .5m wide, is exposed in the fish market railway cutting, about 64m east of the more prominent dyke.

STRUCTURES

Two areas of structural interest occur: (a) in Jones Bay Road (loc. D/1, Fig.1), and (b) in the fish market railway cutting (loc.BC/4, Fig1). The former site has been briefly described in Branagan & Packham (1970), where it is suggested that it may be the extension of the NS dyke mentioned above. This is by no means certain, as the clay material present in some nearly vertical fractures appears somewhat sandy, although it is closely in line with the last exposure of the dyke. However this zone of close-spaced jointing- a "shear zone", some 25m wide, in the Hawkesbury Sandstone, similar to those described by Norman and Branagan (1984) strikes 30^{0}.

Sub-horizontal strike slip is envisaged in this zone, but no evidence in the way of slickensides or slicken lines was found, although such evidence has been obtained at several sites on the Hornsby Plateau (Mills et al, 1989). The zone contains four small vertical displacements. This zone may correlate with one at Milsons Point (Norman & Branagan, 1984) to the north across the harbour. To the south, in the Darling Harbour railway cutting, there is little evidence of the zone, except possibly where the dyke occurs, but near the fish-markets it may resume significance.

The second structural zone in the fish market railway cutting , (Figure 3), is more interesting, but more difficult to interpret. There are, in fact, four structures of different type in close conjunction. The zone also includes the dyke outcrops.

The most westerly feature consists of several groups (.6 to 3m width) of close-spaced joints, over a total width of 15m, striking 10^{0}. Several small vertical displacements (6-12cms), easterly side up, can be observed.

Easterly of the Miller street bridge and west of the dyke are several distinct metre-wide subvertical zones of brecciated, recemented sandstone, labelled respectively Faults A and B (Figs.3, 4 &5). These are similar to zones recorded previously by Norman and Branagan (1984), and Branagan et al (1988) at Cammeray, Fullers Bridge, Brown's Road-Wahroonga and elsewhere, although the easterly of the structures (fault B) is somewhat narrower, steeper and more sharply defined. The orientation of the two fault zones is 33^{0}-35^{0}, and the fault B has a vertical displacement of about 50cms. The sandstone adjacent to fault A has been tilted somewhat on the southern side of the cutting during faulting.

24 metres east of the dyke is a wider zone exposed in a lower part of the cutting, although the most westerly portion is obscured by detritus. This is a zone of thrust faulting (Fig. 3, 6). It is marked at its exposed western end by several planes which vary in dip from 30^{0} to 65^{0} westerly before coalescing in a crushed zone and coinciding with a smooth bedding plane. Some 5m easterly the fault diverges from the bed and splits into two planes which steepen to about 600. At the two positions where the fault and the bed coalesce the adjacent beds are cut by numerous small tension faults, trending obliquely to the fault plane but with considerable variation, and dipping about 70^{0} northerly. At the easterly end, under the fault plane, drag folding has caused overturning of some beds.

There are some similarities between this fault and several described by Norman (1986) in the Ashfield Shale at St. Peters

Quarry. However it differs from many of the thrusts previously described in the Hawkesbury Sandstone, (see reference list), which often have crushed zones immediately adjacent. However, all told, the faulting in the Pyrmont area is once again illustrative of the application of quite sudden, short-term relatively strong forces applied to the Triassic rocks, prior to dyke intrusion.

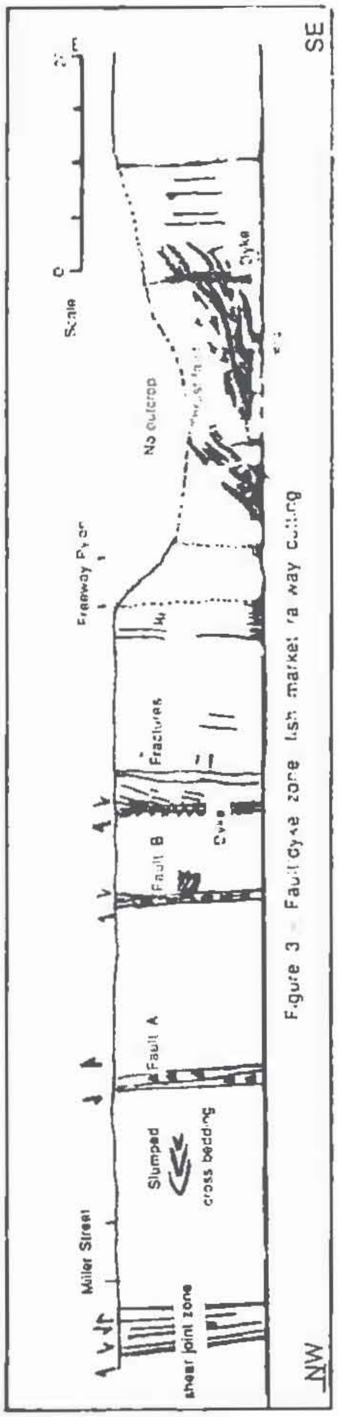

Figure 3 - Fault/Dyke zone fish market railway cutting

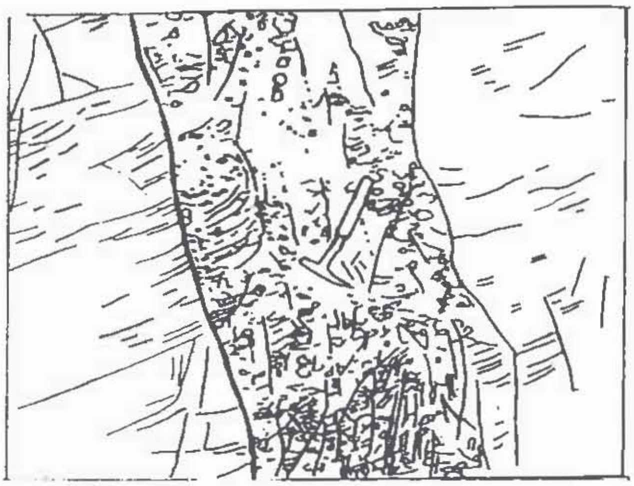

Figure 4 - Detail of Fault A, south side of railway cutting

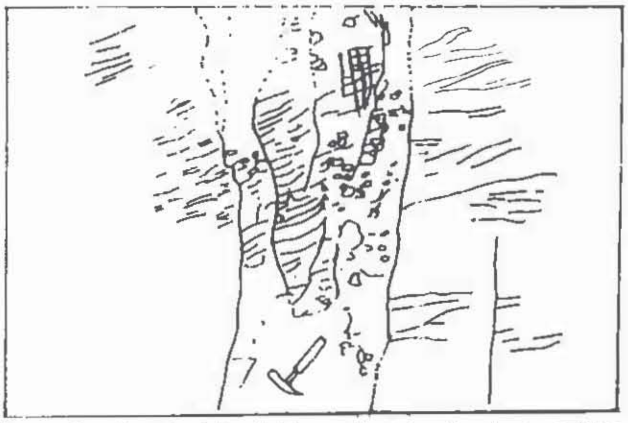

Figure 5 - Detail of Fault B, south side of railway cutting

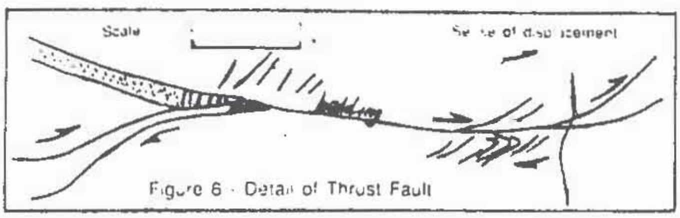

Figure 6 - Detail of Thrust Fault

D.F. BRANAGAN

CONCLUSIONS

Some re-evaluation of the Hawkesbury-Wianamatta boundary is called for. It was not a simple sharp break, but a more suble event in which initial topographic variation of the Hawkesbury Sandstone was significant, then changing patterns of erosion and sedimentation played a part, possibly with repititions of Mittagong type sedimentation, together with widespread, albeit slight tectonic activity. These matters seem to be particularly important in the Pyrmont-Ultimo area, where the Mittagong Formation makes a significant appearance.

After sedimentation ceased the Pyrmont area was subjected to one or more short, sharp periods of shear and compressional forces, forming zones of close-spaced jointing, possibly with sub-horizontal strike slip, and with minimal vertical movement, zones of crushing and brecciation, later recemented, and at least one zone of thrusting, essentially from west to east. North-South dyke intrusion post-dates the thrusting.

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QUATERNARY CORRELATIONS USING AMINO ACID RACEMISATION : THE SYDNEY BASIN PROVINCE IN A GLOBAL CONTEXT

C.V. MURRAY-WALLACE
University of Newcastle

INTRODUCTION

The application of amino acid racemisation reactions to the dating of Quaternary strata has undergone considerable development in recent years. Early studies were undertaken in restricted geographic settings and involved the assumption of uniform diagenetic temperature histories within small areas (Bada, 1972; Wehmiller, 1977). The influence of other parameters on racemisation were normalised, where possible, by analysis of specific fossil matrices (eg., molluscs, foraminifera, emu egg shells) that fulfilled the suitability criteria of racemisation studies (Wehmiller, 1984a). The calibration of amino acid racemisation data with isotopic dating methods (eg., radiocarbon, uranium-series disequilibrium and potassium-argon) were, and remain, an essential ingredient of this research (Murray-Wallace and Bourman, 1990).

Recognition of the strong dependence of reaction rate on temperature resulted in the application of amino acid racemisation data in studies of latitudinally, widely separated stratigraphic sequences (Kennedy *et al*, 1982; Wehmiller, 1982, 1984a, Hearty *et al*, 1986; Murray-Wallace and Kimber, 1987). Accordingly, fossils from regions characterised by higher diagenetic temperatures will display greater extents of racemisation than fossils of equivalent age from cooler regions. Calibration by isotopic dating methods, and biostratigraphic and geomorphologic evidence are critical to the successful application of this approach. Important developments from this research include : (1) quantification of the temperature dependence of amino acid racemisation reactions in carbonate fossils of Quaternary age, (2) provision of palaeoclimatic data (eg., modelling full glacial temperature reductions) that may then be related to the oxygen isotope record and (3) modelling latitudinal gradients of palaeotemperature.

More recently, amino acid data have been evaluated in a global context, in an effort to assess the utility of amino acid racemisation for stratigraphic correlation at a global scale (Hearty and Miller, 1987; Murray-Wallace *et al*, 1991). This paper examines critically, some of the central issues involved in applying amino acid racemisation reactions in global correlations and evaluates in a global context results for a last interglacial (oxygen isotope substage *5e*; 125,000 yr BP) estuarine sequence at Largs in the Sydney Basin).

THE RACEMISATION PROCESS

During diagenesis, amino acids and their precursor peptides may undergo numerous reactions including oxidation, decarboxylation, deamination, hydrolysis and racemisation (epimerisation). Following the death of an organism, the racemisation process involves the slow, albeit progressive, interconversion of L-amino acids to corresponding D-amino acids until equilibrium (racemic condition) is reached (ie, D/L = 1 for enantiomers and ~1.3 to 1.4 for diastereoisomers). Results from Arctic settings with contemporary mean annual temperatures (CMAT °C), typically in the range -7 to -12°C, indicate that this state is generally obtained within 10 Ma from the onset of racemisation (Wehmiller, 1982). In contrast, equilibrium is obtained significantly faster in temperate and tropical settings. At mid-latitude sites (eg, CMAT ~10°C) it takes approximately 2 Ma for isoleucine to attain equilibrium. In southern Australia (CMAT ~18°C) the effective upper limit of the method is approximately 600,000 years (Murray-Wallace and Kimber, 1989). A summary of the analytical methods routinely employed in amino acid racemisation studies is outlined by Murray-Wallace and Kimber (1990).

AMINOSTRATIGRAPHY OF LAST INTERGLACIAL COASTAL STRATA IN SOUTHERN AUSTRALIA

<u>Aminostratigraphy</u> is a chemo-stratigraphic method based on chrono-stratigraphic principles and involves the organisation of strata into chronostratigraphic units or <u>aminozones</u>. Lithostratigraphic and biostratigraphic evidence and isotopic dating methods are generally used to support these chronostratigraphically defined units. The term was introduced by Nelsen (1978).

The aminostratigraphy of last interglacial coastal sequences in southern Australia has been developed in the form of a predictive model that permits the relative dating of Quaternary fossiliferous strata based on the extent of amino acid racemisation and its relation to contemporary mean annual temperature (Figure 1).

Details of the lithostratigraphy of the last interglacial coastal strata sampled for this model are outlined by Murray-Wallace and Belperio (1991) and Murray-Wallace *et al*, (1991). The sampling strategy involved analyses on the hinge region of replicate specimens of well buried molluscs (>1 m). Species analysed include <u>Anadara trapezia</u>, <u>Katelysia rhytiphora</u>, <u>Katelysia scalarina</u>, <u>Glycymeris (Tucetilla) striatularis</u> and <u>Fulvia tenuicostata</u>. A "genus-effect" on racemisation (epimerisation) is not statistically significant in these taxa. .In addition to independent dating methods (ie, radiocarbon and uranium-series), lithostratigraphic, palaeontologic and geomorphologic evidence was used to calibrate the amino acid data (Figure 1).

Estuarine sediments associated with the "Inner Barrier" sequence of Thom *et al*, (1981) are exposed at Largs in the Hunter Valley, New South Wales. A last interglacial age was obtained by Murray-Wallace *et al*, (1988) from amino acid

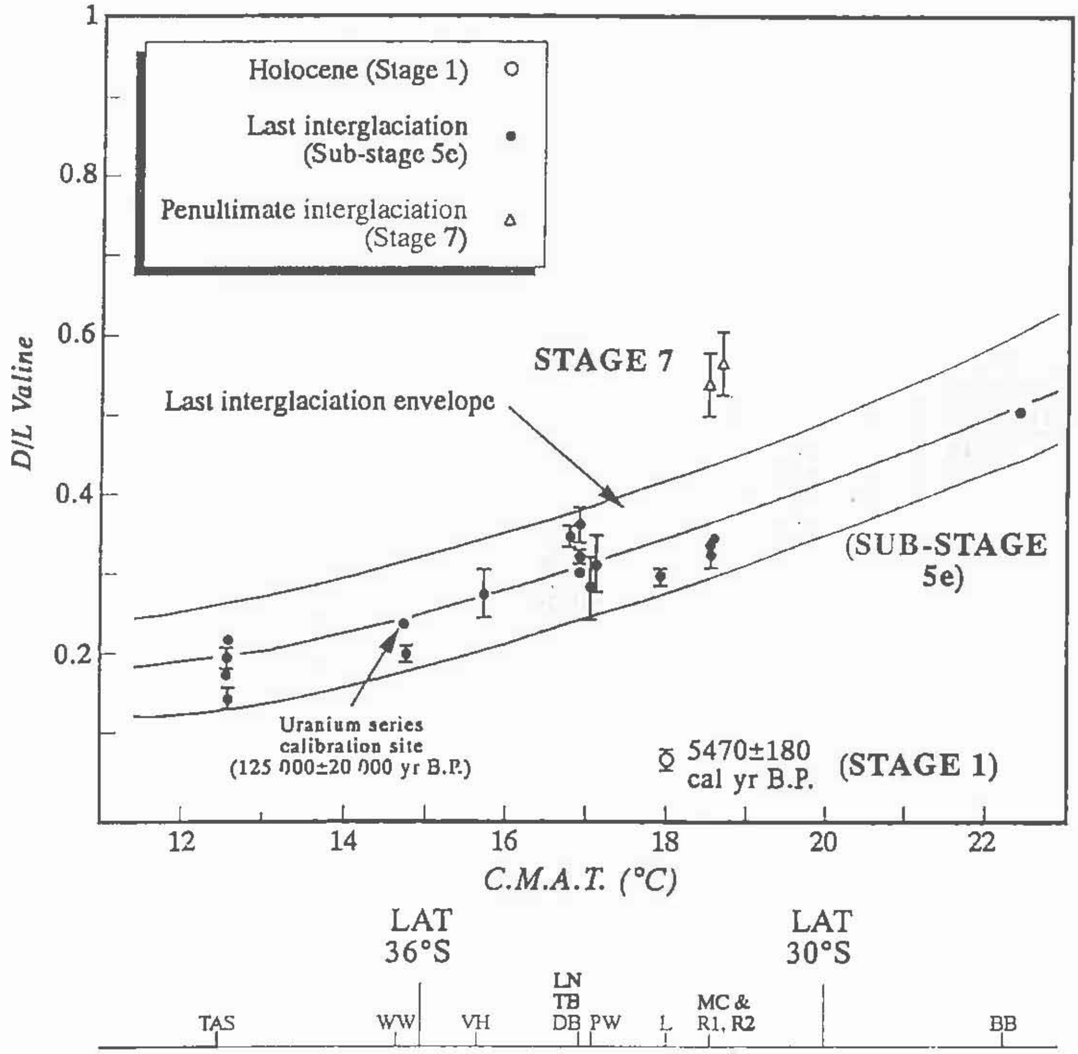

Figure 1. Extent of valine racemisation in last-interglacial (oxygen isotope substage *5e*) molluscan fossils plotted against contemporary mean annual temperature (CMAT°C). CMAT is a linear function of latitude for coastal sites in southern Australia within the latitudinal range 24°S to 43°S. Valine data for the penultimate interglaciation (Redcliff, northern Spencer Gulf, South Australia) are significantly different from the last interglaciation and plot above the envelope for the last interglacial data. In contrast, Holocene data plot below the envelope as indicated by a radiocarbon calibrated specimen of *Fulvia tenuicostata* from Smoky Bay, South Australia. Uranium-series calibration exists for the Woakwine Range (WW). Sample localities: TAS, Tasmania (viz., Montagu, Broadmeadows, Mowbray Swamp and Mary Ann Bay); WW, Woakwine Range, Mount Gambier Coastal Plain; VH, Victor Harbor, South Australia, DB and TB, Denial Bay and Tourville Bay, South Australia; PW and LN, Port Wakefield and Lake Newland, South Australia; L, Largs, New South Wales; MC, Minim Cove, Western Australia; R1, Redcliffe, Western Australia, R2, Redcliff, South Australia; and BB, Broadhurst Bight, Peron Peninsula, Shark Bay, Western Australia. (Source : Murray-Wallace *et al*, 1991).

racemisation analyses on specimens of Anadara trapezia. This strengthened the validity of a lithostratigraphic correlation made with uranium-series dated corals from the closely-related site at Grahamstown (Marshall and Thom, 1976). The sediments at Largs comprise shell-rich muddy sands at an elevation of +2 to +3 m AHD. Based on the mollusc species present, a water cover of 2m was inferred by Thom and Murray-Wallace (1988), suggesting a sea level within the proto-Hunter Estuary of approximately 4-5 m higher than present during the last interglaciation maximum.

The extent of racemisation for the amino acid valine in specimens of Anadara trapezia from Largs is in accord with the theoretically predicted exponential trend in the extent of racemisation against CMAT, for last interglacial molluscan fossils in southern Australia (Figure 1). Although CMAT represents a linear function of latitude, the extent of valine racemisation in the molluscan fossils within the latitude range of this study, is more closely approximated by an exponential function. This is attributed to the exponential effect of increasing temperature on racemisation rates. The error terms (1SD) represent intershell amino acid D/L ratio variation for sample replicates. The Anadara from the Largs deposit are clearly older than the Holocene specimen of Fulvia tenuicostata dated at 5470 ± 180 cal BP (CS-407) but younger than Anadara sp., of penultimate interglacial age from Redcliff, South Australia based on the extent of amino acid racemisation.

According to Wehmiller *et al*, (1988), assumptions implicit in this form of aminostratigraphic correlation include : (1) the present latitudinal temperature gradient model is an adequate model for the shape of former temperature gradients, (2) the non-linear racemisation kinetic model is appropriate for these studies, (3) the combination of temperature and kinetic models will predict smooth trends for isochronous D/L values versus latitude and (4) there is sufficient variation within local aminozone data sets to merit data averaging.

AMINOSTRATIGRAPHY AND GLOBAL CORRELATION

Sufficiently large data sets now exist to permit attempts at evaluating amino acid racemisation data from well-dated coastal sequences in a global context. Caution, however, should be exercised as the validity of global aminostratigraphic correlations rest heavily on: (1) rigorous interlaboratory comparisons of amino acid standards (eg, Wehmiller, 1984b): (2) due reference to the parameters that influence racemisation; (3) reliable calibration of amino acid data by isotopic dating methods in conjunction with geomorphologic, lithostratigraphic and palaeontologic evidence and (4) knowledge of the nature of racemisation kinetics in fossils.

Fossil molluscs of last interglacial age, independently established by uranium-series-dating, from northern and southern hemisphere sites with equivalent CMATs and comparable extents of racemisation points to the validity of global correlation (Murray-Wallace *et al*, 1991) using amino acid data (Figure 2).

Results for shells of last interglacial age (125,000 yr BP) for the amino acid isoleucine are depicted in Figure 2. These data conform to a similar exponential trend noted for the less extensively racemised amino acid, valine for the southern Australian data set (cf. Figure 1), and are in accord with isoleucine data for some

3000 shells compiled by Hearty and Miller (1987) from a range of locations in the Circum-Atlantic, Mediterranean and South Pacific.

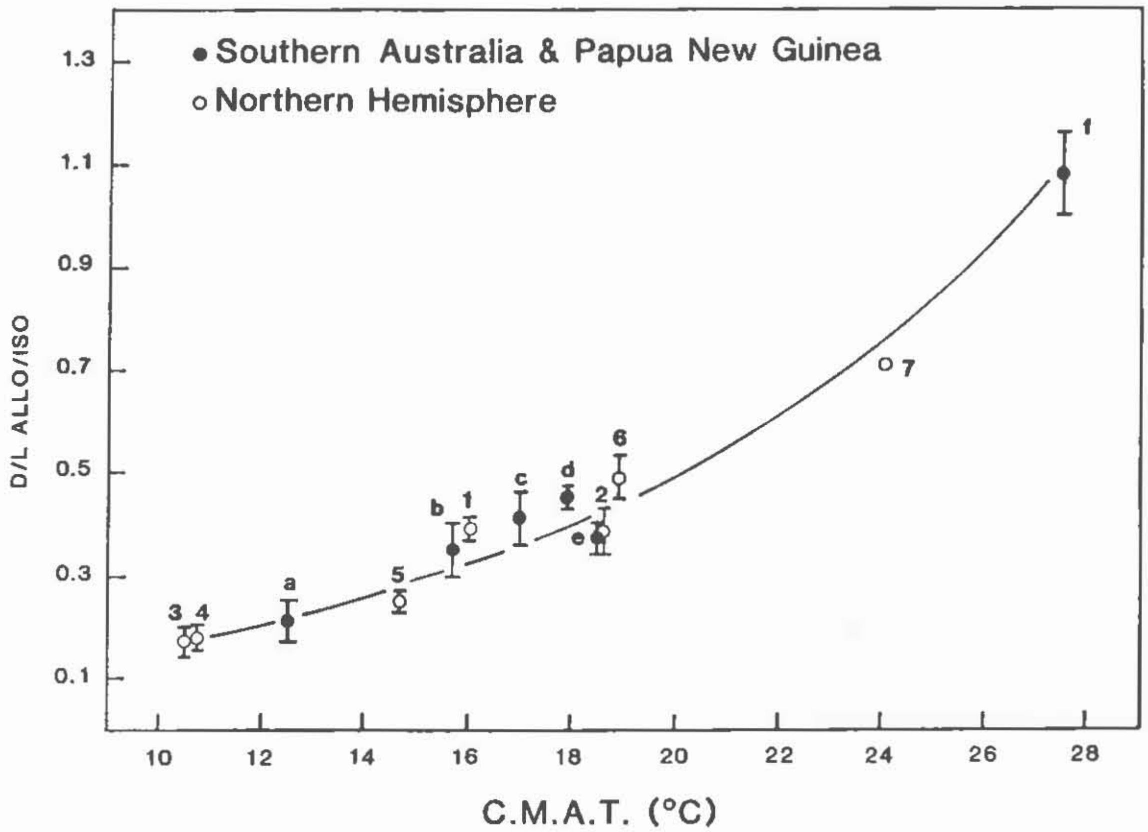

Figure 2. Extent of isoleucine epimerisation in last interglacial (oxygen isotope substage 5*e*) molluscan fossils plotted against CMAT for coastal sequences from Northern to Southern Hemispheres. Amino acid data from southern Australia and Papua New Guinea (Huon Peninsula) are represented by solid circles. Results from Northern Hemisphere localities indicated by open circles. Sample localities : 1. Latina, Italy (Hearty and Dai Pra, 1986); 2. Tunisia (Miller *et al*, 1986); 3. and 4. Netherlands (Miller and Mangerud, 1986); 5. Corsica (Hearty *et al*, 1986); 6. Tunisia (Hearty *et al*, 1986); 7. Florida (Mitterer, 1975). Southern Australia and Papua New Guinea sites include : a. Mary Ann Bay, Hobart; b. Victor Harbor, South Australia; c. Port Wakefield, South Australia; d. Largs, NSW; and e. Minim Cove, Perth. Isoleucine data for Tridacna gigas (the giant clam) are from late Pleistocene marine terraces on the Huon Peninsula, Papua New Guinea (Hearty and Aharon, 1988).

Two limitations presently confront global aminostratigraphic correlation. Frustratingly, many previous studies have been restricted to specific amino acids (principally isoleucine, aspartic acid and leucine), therefore hampering cross-correlation between different laboratories that report results for other amino acids. More fundamentally, however, not all deposits host fossils suitable for amino acid racemisation dating.

Future challenges in global aminostratigraphic correlation will involve : (1) extending the geographic coverage of amino and racemisation data, (2) improving the age resolving power (eg, around the substage *5e* isochron), (3) comparisons of latitudinal amino acid racemisation data sets with global oceanic/atmospheric temperature records and (4) a critical evaluation of Quaternary palaeoclimates in Australia.

CONCLUSIONS

Despite the complex of reactions amino acids and their precursor peptides undergo during diagenesis, and the initially surprising fact that amino acids survive in fossils for protracted periods, amino acid racemisation may be successfully applied in global correlation programs. The efficacy of this methodology is, however, dependent on calibration by other dating methods, interlaboratory comparisons of amino acid standards, due reference to the parameters that influence racemisation and a sound knowledge of the nature of racemisation kinetics in fossils.

ACKNOWLEDGEMENTS

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NATURAL ZEOLITE EXPLORATION USING THE "GEOAUTOCLAVE PROCESS" MODEL FOR THEIR FORMATION

P.G. FLOOD
University of New England

1. INTRODUCTION

The 1987 Information Package for Exploration and Development of Natural Zeolites in New South Wales (Department of Mineral Resources) together with the associated Proceeding of the Seminar on Natural Zeolites in New South Wales, provided the catalyst necessary to encourage exploration companies to examine the New South Wales Zeolite Province. Pecover (1987) has shown that the most widespread occurrences and highest concentration of zeolite minerals in eastern Australia are associated with acid to intermediate pyroclastic and epiclastic rocks within the continental to shallow marine Late Carboniferous sequence which extends 360 km from Newcastle in the south to near Gravesend in the north (Figure 1).

Exploration successes to date have been most encouraging. Development and exploitation of several recently discovered deposits appear likely. In late 1988 Mount Gipps Limited began mining at the "Escott" prospect near Werris Creek. This is the first such enterprise in the country; hitherto the mineral had been imported from the USA and Hungary. Export markets have been established in the Philippines and New Zealand. Early in 1989 a second company, International Mining Corporation NL, identified zeolite deposits of exploitable size at Cranky Corner, near Singleton (Roskill Information Services Ltd, 1990). In addition, several new exploration licences have been granted covering highly prospective areas within the southern portion of the zeolite province.

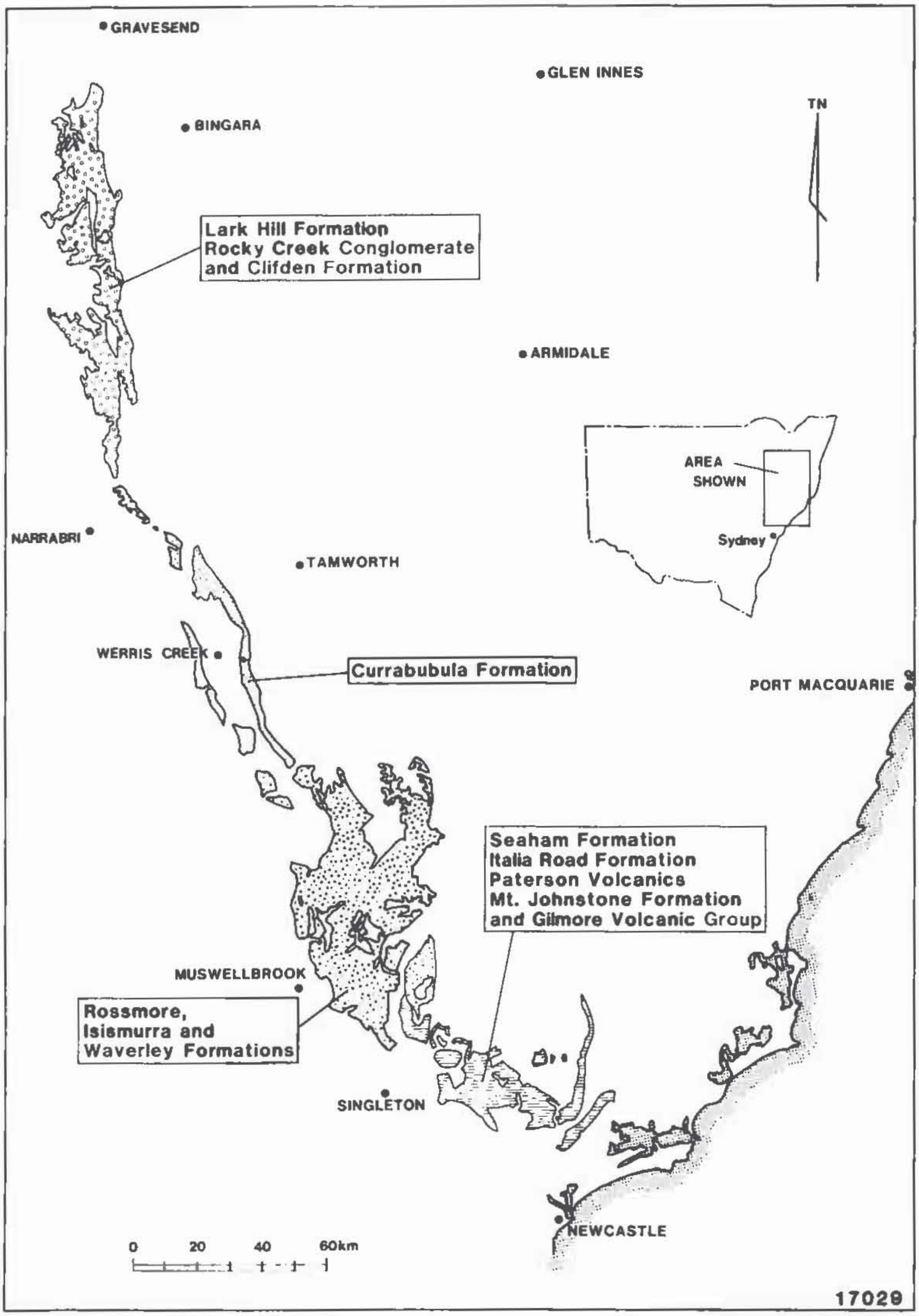

FIGURE 1 — NEW SOUTH WALES ZEOLITE PROVINCE

2. ZEOLITIZATION PROCESS

In situ alteration of vitric material can take place at or near ground surface and without the deep burial normally invoked (Coombs *et al.*, 1959) for zeolite formation (see Aleksiev and Djourova, 1988; Gude and Shepard, 1988; Levy and O'Neil, 1989; Senderov, 1988, Tsolis-Katagas and Katagas, 1990). Aleksiev and Djourova (p. 83) are of the opinion that most zeolitic rocks are the water facies of ignimbrites. This proposal is at variance with the normally accepted idea that zeolites are formed by the process of burial metamorphism (proposed mechanism in Japan and New Zealand).

A different mode of formation, the "geoautoclave", a term introduced by Aleksiev and Djourova (1988), proposes that the generation of pyroclastic material, its transport, sedimentation and subsequent zeolitization are intimately interrelated. Pyroclastic material which had a temperature not lower than 800°-900°C at ejection, does not cool fully during transport. Thus, along with the charging of pyroclastic material into the water basin, also a vast amount of thermal energy are introduced. Owing to the rapid sedimentation and the thermal-insulation properties of pumice and volcanic glass, a considerable part of the thermal energy is preserved in the sediment. Pressure within the sediment pile continues to rise in response to the addition of further pyroclastics and the simultaneous increase in the temperature of the liquid phase in the sediments. A natural autoclave, vast in size, with laterally extensive similar P-T conditions, allows the zeolitization process to commence. The raised temperature and pressure create conditions whereby solutions of a suitable chemical composition and pH react with the volcanic glass.

3. EXPLORATION MODEL

The only site specific description of NSW zeolite occurrences is the work of Flood (1991) and Flood and Taylor (1991). In the Werrie Syncline zeolite occurrences appear to conform with the "geoautoclave" model.

An exploration model incorporating knowledge regarding the depositional setting and the "geoautoclave" process of zeolitization has been proposed by the author (Flood, 1991). The model (Figure 2) shows how the arc-flank to arc-fringe adjacent to ignimbritic centres is the best place to explore for natural zeolites. Large ?alkaline lakes serve as the repository for voluminous airfall tuffaceous material as well as providing the ideal chemical environment for pervasive alteration of silicic glass to zeolites.

Detailed stratigraphic mapping combined with comprehensive sedimentary environment analysis provides the key to delineating prospective areas within any zeolite province.

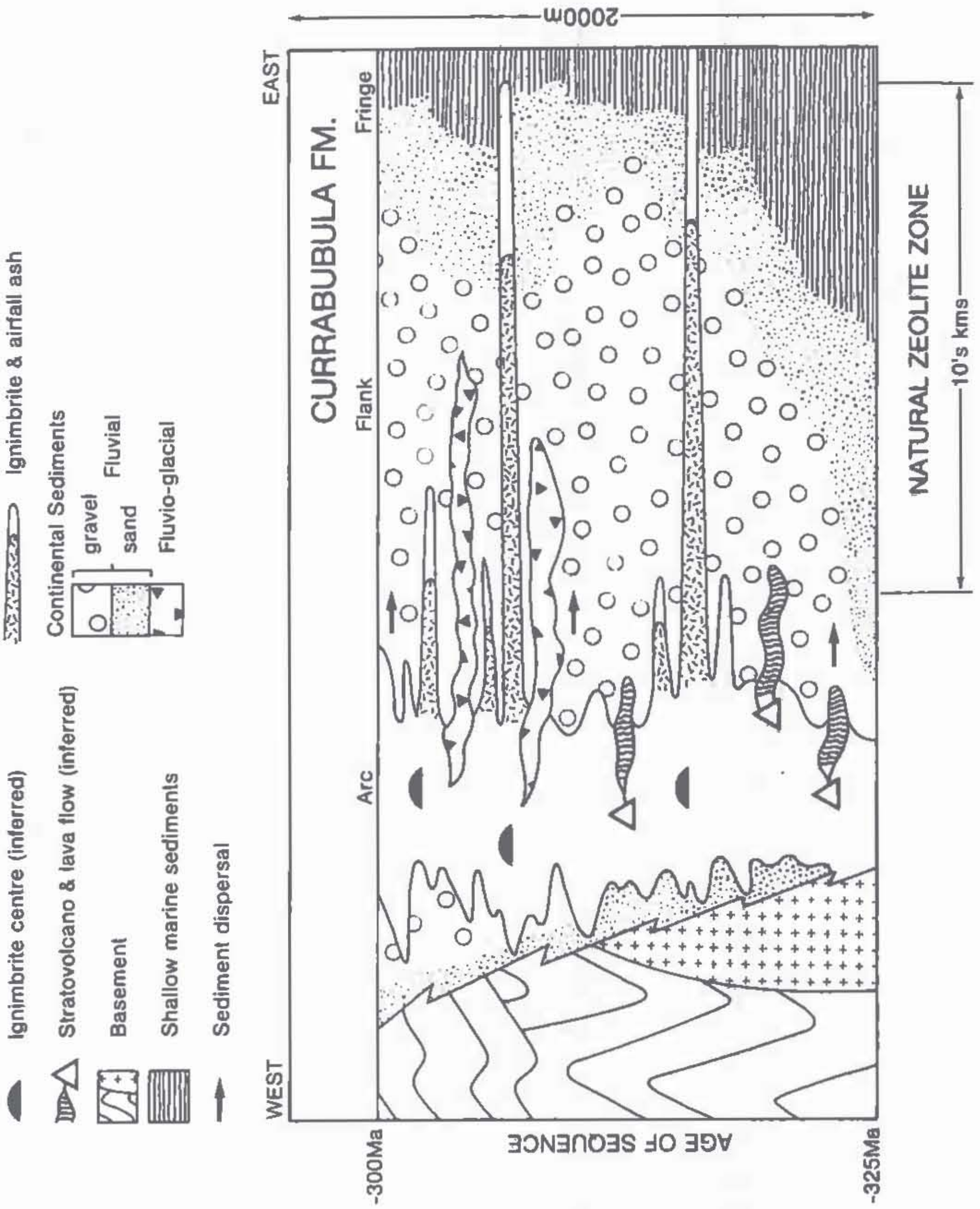

FIGURE 2 — THE "GEOAUTOCLAVE MODEL"

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THE GEOLOGICAL CONTROL OF THE SPATIAL DISTRIBUTION OF ABORIGINAL SITES IN THE ROYAL NATIONAL PARK – INITIAL FINDINGS

W.B. FRASER
University of New South Wales, Oatley Campus

INTRODUCTION

In the last decade it has become painfully obvious to anthropologists that aboriginal art in the form of rock engravings (petroglyphs), as well as the rock shelter (ochre and charcoal) drawings and hand stencils, have been weathering away at an accelerated pace. This acceleration seems to be mainly due to the increasing amounts of pollution in our modern industrial and throwaway society. Thus there is a great urgency to locate and record such priceless treasures before they are gone forever.

In the general literature on aboriginal culture and traditions, reference is made to the location factors common to aboriginal sites. These include such factors as height above the surrounding country, nearness to a fresh water supply, sunny north-east aspects and the presence of trees such as the cabbage tree fan-palm.

Brief mention is made of the fact that many sites are located along straight lines. Such lineations have been explained by recourse to such causes as "energy fields", various mystical forces and even extra-terrestial influences. Working briefly with archeologists involved in the "Aboriginal Living Sites Survey" (a Bicentennial project to locate and photograph the sites in the Royal National Park), the present author noticed the apparent close proximity of dyke type, structural features near three of the sites. These localities contained rock engravings and stone-axe grinding grooves.

THE RESEARCH DESIGN.

This study was thus designed to test: (a) the possible association of rock engraving sites with igneous intrusions and (b) the possible igneous control of the apparent linear distribution of such sites. The design is essentially a double blind investigation.

Stage one is to attempt to locate the dykes in the northern section of the Park, essentially without foreknowledge of the positions of aboriginal sites. (The author has visited only two sites in this area.) Superimposition of the locations of known sites in this section is then carried out in order to investigate the spatial correlation, if any, of the distribution of dykes and sites. (Statistical methods will later be applied to this task.) Finally, collaborative field investigation will be carried out by the author and archeologists of the Sites Survey team to test predictions of aboriginal sites arising from any correlations arising from this stage of the investigations. (This is the stage of operations now being commenced.)

Stage two will involve a geological mapping of the rest of the Park where sandstone occurs. Predictions will be then made as to the possible locations of aboriginal sites. These predictions will be then tested against known locations and others will be examined by the author and the archeologists for as yet undiscovered sites. (Note that this second stage of the investigation is also essentially "blind" in design.)

IGNEOUS INTRUSIVES.

The only igneous intrusives located with any degree of confidence in the northern section of the Royal National Park (north of a line joining Heathcote township with Little Marley) have been dykes. All intrusive material examined chemically has been of basaltic composition. No evidence of diatremes has so far been observed.

GEOLOGICAL CONTROL OF ABORIGINAL SITE LOCALITIES

Best exposures of basic dyke rock have been from the ocean coastline. The least weathered material comes from the rear wall of a deep chasm in the cliff face approximately two and a half kilometers south of Port Hacking Point or Jibbon. The locality is designated as "The Cobblers" on most maps (see Figure 1). All other recognisable igneous material is largely altered to clay minerals accompanied by various quantities of hydrated ferric oxide. Six such dykes have been identified in the Bundeena-Jibbon-Marley area close to the water's edge, although it is likely that the two dykes in the cliff above and on the rock platform at Bundeena ferry warf continue across Gunyah Bay to the east to the two dykes on the rock platform near the boatshed.

Eight clay samples from four of these dykes have been analysed by XRF and AA methods for major element oxides and trace elements respectively. A binary plot of zirconium (in ppm) against titanium dioxide (wt %) indicates a basaltic composition for all the samples.

No obvious green colouration in the clays have been noticed as in the Cowan dyke. Neither is there any clearly reciprocal relationship between the titanium and chromium values. X-ray diffraction analyses of these clay samples were being obtained at the time of writing to further elucidate the original basaltic mineralogy and possible tectonic conditions of formation.

DYKE IDENTIFICATION AND ASSOCIATED LANDFORMS.

Away from the coastline and the outer estuary of Port Hacking the incontrovertible identification of dykes is extremely difficult. The largest dyke in the area (mentioned above as containing the least weathered material) can be observed in the backwall of a very large chasm in the ocean cliff face (striking at approximately 117 degrees magnetic). Following this bearing to the West, one first encounters a linear strip of clay and iron oxide in the deep soil profile, sporadically bordered on each by resistant outcrops of sandstone. The latter exhibit quartz grains with obvious secondary growth crystal faces which glisten in the sunlight.

Then follows dense, low heath (burnt by recent fires) covering first a clay soil then consolidated sand dune material. Beyond this is a wide, elongated box valley (axis approx. 114 deg. magn.), which extends through swampy country then a narrow defile between tough sandstone outcrops, through to Bonnie Vale picnic and camping area. The surface expression, in Little Turriel Bay, across Port Hacking, is again sticky clay and iron oxide surrounded by semi-rainforest vegetation and large Angophora costata below a saddle depression and narrowing of the peninsula.

At Kirrawee in the railway station car park there is a narrow band of slightly sintered clay in the enclosing shales. Further to the west paralleling the south side of River Road leading to Woronora Bridge, there used to be a narrow gulley (now utilised for sewer pipes). Finally on the same bearing is the peculiar horseshoe bend of the Georges River in very resistant sandstone bedrock near Picnic Point. Overall a remarkable structural feature which is probably injected by igneous material over quite large distances. Because this dyke controls the major axis of Port Hacking, it is here proposed that it be named the "Port Hacking Dyke".

Rickwood (1985, p219) states that "...if pressure is adequate the lava may even be able to generate its own fractures." It would seem that this is the case with the Port hacking Dyke because its strike azimuth is approximately twenty degrees greater the roughly East-West (weak) local jointing direction.

The larger of the two dykes (within the sandstone hill) adjacent to the Bundeena ferry warf is notable for three features. Firstly it swells to a width of greater than two metres within the hill. Secondly it is bounded by prismatic jointed quartzite and thirdly the southern wallrock surface is in part slickensided. Large floaters of quartzite can be seen at the base of the cliff where the wave cut platform consists of less metamorphosed rock injected by copious quantities of hydrous iron oxides.

Further west and away from the coastline it is extremely to identify igneous intrusions with any high degree of confidence. Nevertheless for this study it was essential to attempt this task. Thus it was absolutely essential that the geological investigations be done without prior knowledge of the locations of the aboriginal sites. One week before the writing of this paper the spatial distribution of the sites was supplied to the author for comparison with the distribution of the (suspected) dykes.

The criteria listed below were utilised to locate the suspected igneous intrusions. Almost all of the western "intrusives" had strikes parallel to the major (roughly meridional) joint direction. The greatest concentration of these igneous bodies was near the point where the Hacking River changes its course from an East-West to a North-South direction upstream. It would appear that the major controlling influence in the estuary is the Port Hacking Dyke, while in the stream section from Bungoona Lookdown to Upper Peach Trees it is the (major) north-south jointing direction.

The criteria used for locating the dykes were:

(i) fresh igneous rock present;
(ii) weathered rock with relict igneous textures (e.g. ophitic) or structures (e.g. vesicular) present;
(iii) discordant tabular body of clay and iron oxides, the clay composition being high in titanium and/or chromium;
(iv) elongated depression or chasm with wallrock fractured and injected with hydous iron oxides;
(v) elongated depression or chasm with quartzite wallrock showing prismatic, jointing angled from the wall face;
(vi) elongated depression or chasm with wallrock exhibiting strong secondary regrowth quartz crystal faces;

N.B. Most of the above will be in elevated localities or surrounded by high sandstone wallrock with cross bedding very prominent in surface differential weathering. The vegetetation often includes tall Angophora costata, Banksia costata, Ceratopetalum gumifera, other semi rainforest species and the small pink flower ,Crowea saligna.

The above evidence criteria are arranged roughly in decreasing order of confidence for the recognition of dykes used so far. It is intended that these criteria will be refined as the study proceeds. It will be noted that no magnetic geophysical criteria have been included.

The aerial Total Magnetic Intensity Map - Wollongong/Pt Hacking at 1: 100 00 scale (S1 56-9, 9129) with sensitivity 0.1 nanoTeslas, has an average sample interval of 50 metres. Inspection indicates that only the Port Hacking dyke is evidenced as an appreciable anomoly in this area. Hand held proton magnetometers usually do not detect known dykes in this region, again apparently due to the deep surface weathering effects.

Prediction of dyke localities is best done by a combination of aerial stereographic photography and orthophoto maps on a scale of 1:4 000. The latter, however are only available for the urbanised fringes of the Park. No orthophoto maps of any scale are presently available for the Wattamola section. The dykes are often reflected in the contours as "double eye" patterns, representing double crowned hills

DYKE / ABORIGINAL SITE - MATCHING RESULTS

Only identified sites with rock engraved artworks and/or axe grinding grooves have been included in the aboriginal sites overlay. When superimposed on the geological map of suspected and confirmed dykes it was found that only four out of ten of the more extensive (confirmed or suspected) dykes were associated with two different sites. Thus it appears that the original "lineation" inference is not supported by strong evidence at this stage. Unless more sites are located along.the dykes, the hypothesis from inference (b) above must be rejected.

Instead it appears that most of the sites in this northern region are associated with individual (suspected) dykes. Only six of twenty sites are more than two hundred metres of a dyke structure and the immediate vicinity of four of these sites has not yet been visited by the author in the initial fieldwork.

CONCLUSIONS

From the initial results it would seem that dykes do not control the linear spatial distribution of aboriginal sites in the northern portion of the Royal National Park in New South Wales. Most sites containing rock engraving art and/or axe grinding grooves do appear to be closely associated with igneous dyke structures. Thus it would be extremely helpful to archeologists searching for such sites in sandstone regions to possess a detailed map showing igneous intrusions.

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W. B. FRASER

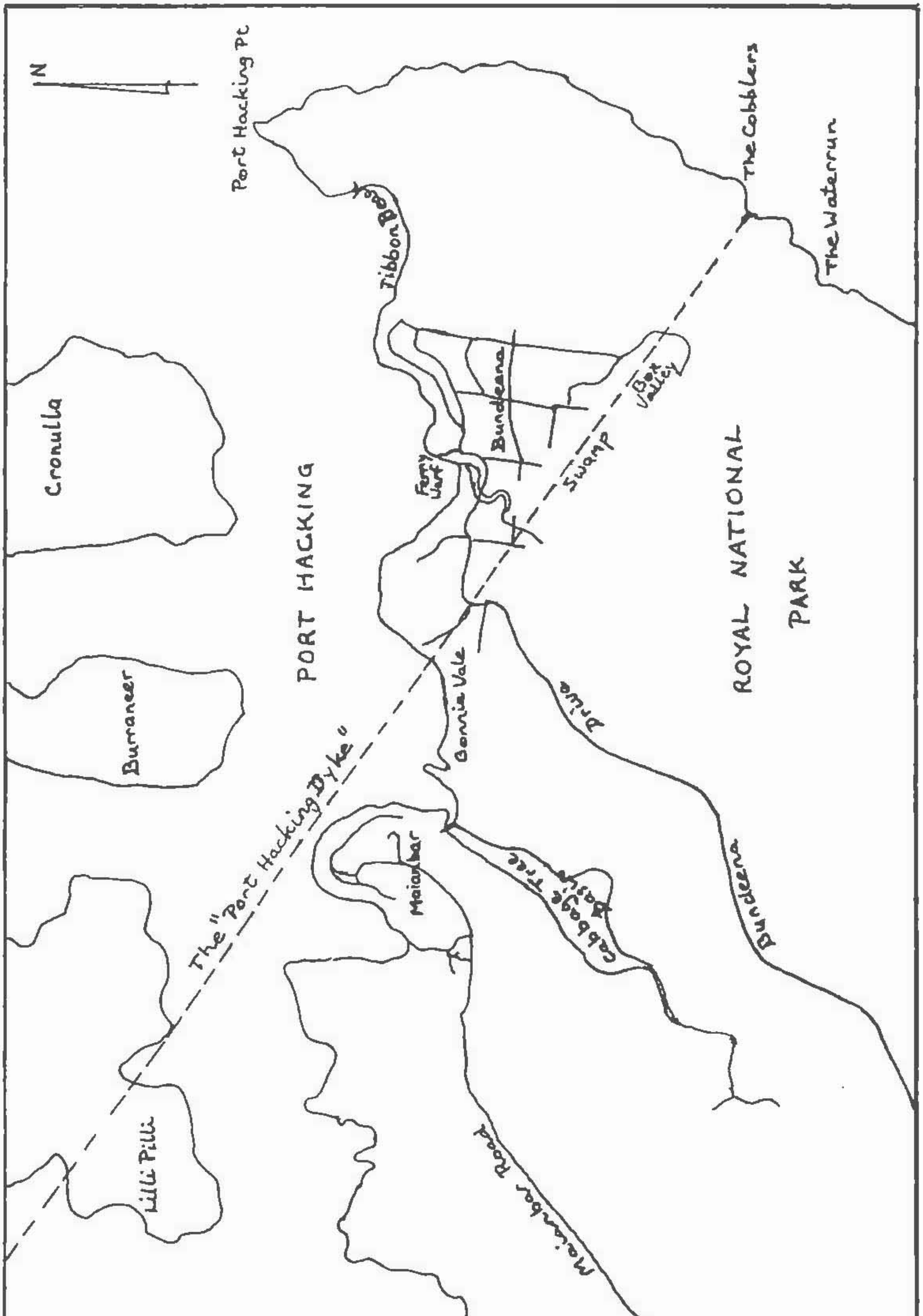

FIGURE 1 - LOCATION OF "PORT HACKING DYKE"

THE ELECTRICAL CONDUCTIVITY PROBE : A NEW TOOL FOR GROUNDWATER CONTAMINATION AND SALINITY MEASUREMENT

P.W. HITCHCOCK & R.J. CARR
D.J. Douglas & Partners Pty Ltd, Newcastle West

1.0 INTRODUCTION

The recently developed conductivity probe is able to take continuous readings of bulk conductivity (BC) with depth. The cone can either be used as a stand alone unit or in conjunction with the electric friction cone penetrometer test (CPT) which measures cone resistance and sleeve friction.

The combination of CPT and BC cone test allows assessment of the surface profile in terms of soil type and conductivity. As the bulk conductivity is a function of soil type, porosity, water content and composition, its definition is particularly useful in groundwater and pollution investigation work.

In this paper a case study of recent work at Astrolabe Park, Daceyville is presented. The BC probe was used in conjunction with offset resistivity soundings to define the geometry of a leachate plume emanating from a landfill and discharging into nearby environmentally sensitive wetlands.

2.0 EQUIPMENT DETAILS AND TEST METHODOLOGY

The testing procedure for the BC probe is the same as that used for the CPT. The equipment comprises a 35mm diameter cone which is attached to rods which are pushed continuously into the soil by hydraulic thrust, at a rate of 20 mm per second. The pushing rig is a 14 tonne ballasted truck (see photograph one).

The bulk conductivity is measured across two evenly spaced electrodes and results are recorded for every 20 mm of depth on a portable computer.

PHOTOGRAPH 1. Bulk Conductivity/CPT Truck Mounted Rig

3.0 CASE STUDY - ASTROLABE PARK
3.1 Background

Astrolabe Park is situated at Daceyville, Sydney and covers an area of some 8 hectares. From 1965 - 1972 the area was sand mined and backfilled with 'hard filling' (building rubble) and municipal waste. The resulting landfill was then landscaped and converted to parkland by 1975 (Hitchcock, 1991). Unfortunately the landfill is in close proximity to the Botany wetlands (see Figure 1.) which ultimately led to the detection of the pollution problem through a study of the pond water chemistry of this system (Butler, 1990).

The site is located in the Botany Basin the geological limits of which are defined where the unconsolidated Quaternary sediments abut the outcrop of the Triassic rocks (Wianamatta Group and Hawkesbury Sandstone) (Smart, 1974). These sediments can vary in thickness from a few metres to about 80 metres (Griffin, 1963). At Astrolabe Park these sediments reach a thickness of about 30 metres (Hitchcock, 1991) and comprise the main aquifer for the area. Apart from localised polluted areas the Botany Sands aquifer contains groundwater of good water quality which is extensively used for parkland irrigation and by industry.

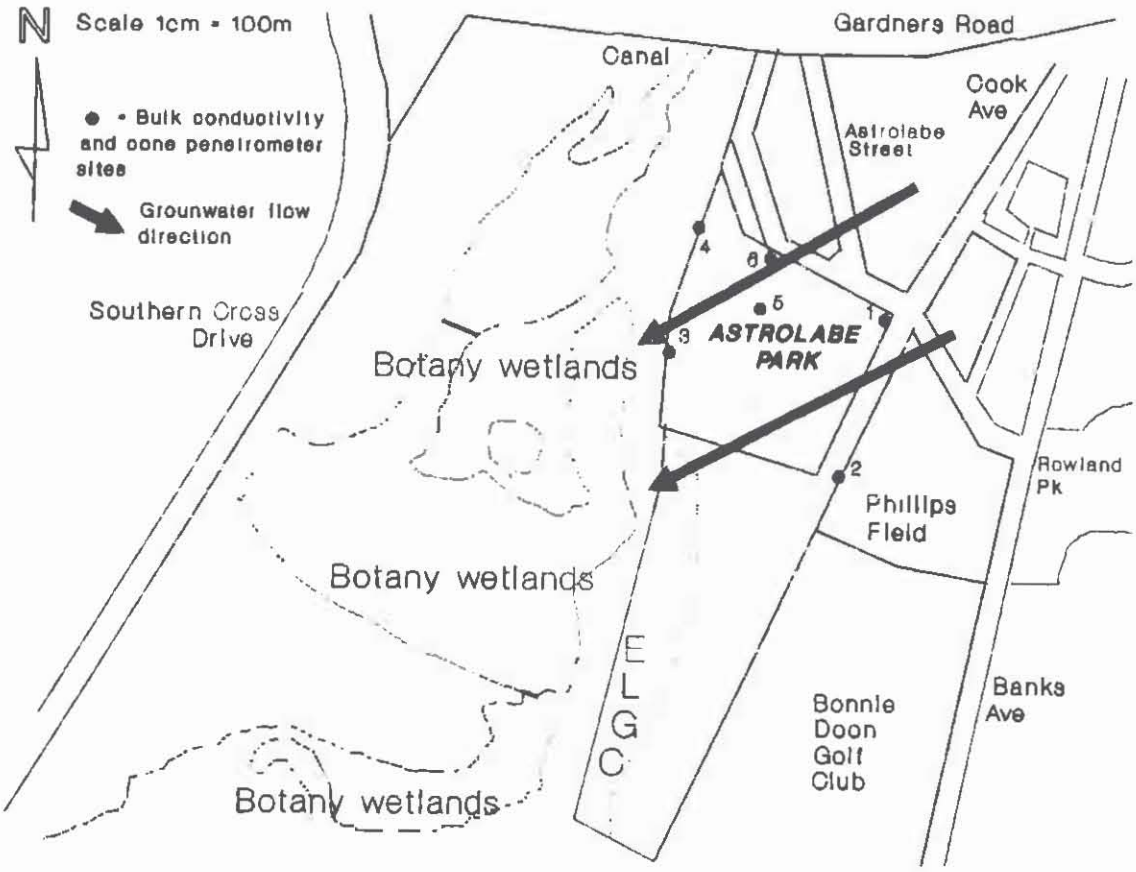

Figure 1. - Location of Astrolabe Park, Sydney

At Astrolabe Park the sediments are mainly comprised of sand of aeolian origin with minor thin layers (generally less than 0.3 metres) of organic clay and peat. These layers have a partial confining effect on the aquifer although in general the area can be thought of as unconfined. The water table is a maximum of 5 metres from the surface and mostly echoes the topography with the shallower groundwater found in the low lying areas adjacent to the wetlands. Groundwater flows from the north - east (see Figure 1.) through the landfill before discharging to the ponds of the wetlands (Hitchcock, 1991). A significant leachate plume is generated.

3.2 Bulk conductivity Testing and Resistivity Soundings.

A series of six conductivity probes with cone penetrometer (see Figure 1.) and 14 offset resistivity soundings using a wenner array were undertaken around Astrolabe Park.

The offset soundings were able to delineate that the aquifer resistance divides from an homogeneous reading indicative of 'clean groundwater' in the pre-landfill area into two zones of different resistivity both under the landfill and in post-landfill areas. The upper (lower resistive zone) is due to leachate contamination while the aquifer resistance below this was similar to that obtained for the pre-landfill groundwater (Hitchcock, 1991). The offset soundings therefore gave an homogeneous resistivity (or average) value for the leachate effected aquifer.

The bulk conductivity probe was able to further delineate the shape of the leachate plume by assessing lateral and vertical variations in resistivity. By conjunctive use of the CPT it was possible to assess whether the stratigraphic variations were due to changes in the soil strata (notably peat layers) or leachate contamination resulting from the landfill (see Figures 2. and 3.). High conductivity values obtained in sand strata are a result of leachate contamination while conductivity peaks in peat are either caused by the peat itself or a combined effect of peat and leachate (resulting in much higher values than peat alone, see Figure 3.).

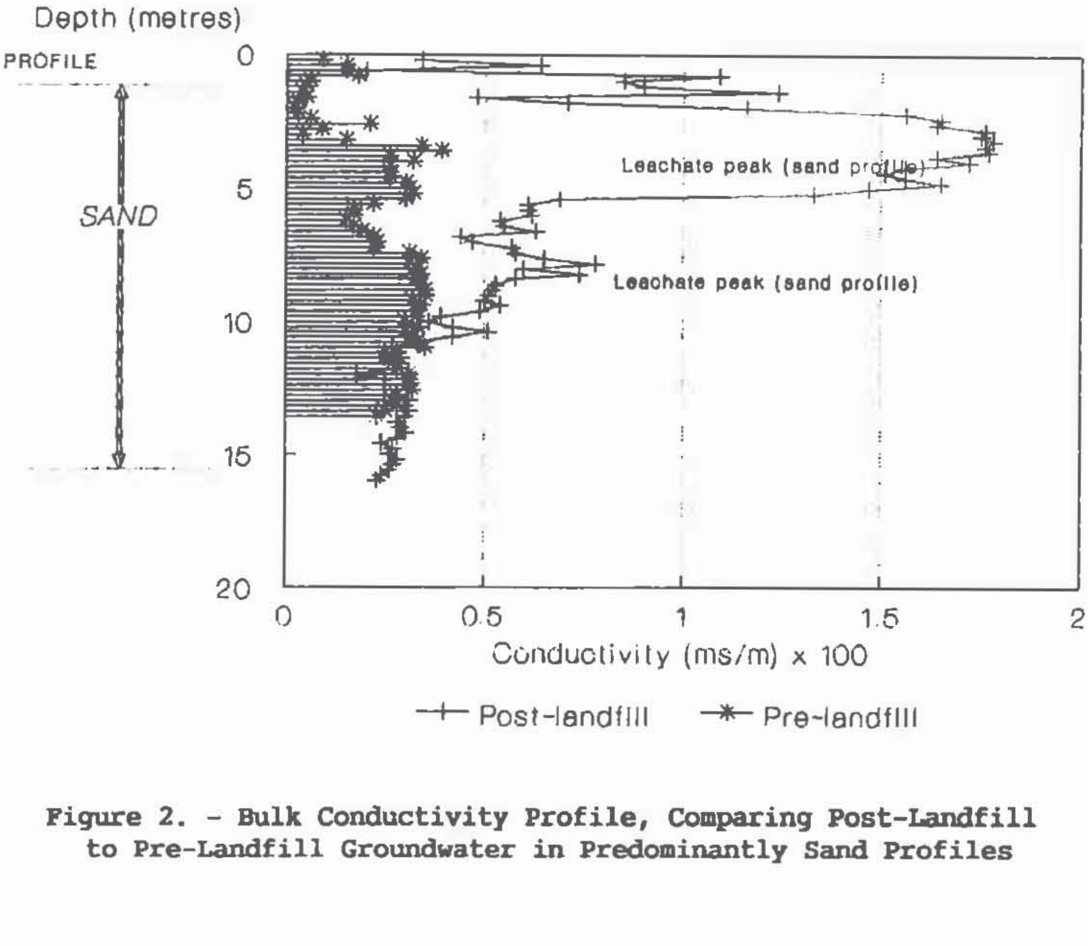

Figure 2. - Bulk Conductivity Profile, Comparing Post-Landfill to Pre-Landfill Groundwater in Predominantly Sand Profiles

Results from the testing indicated that the landfill is having a negative impact on the quality of the groundwater and that the leachate plume is located within the top six metres of the groundwater (see Figures 2. and 3.).

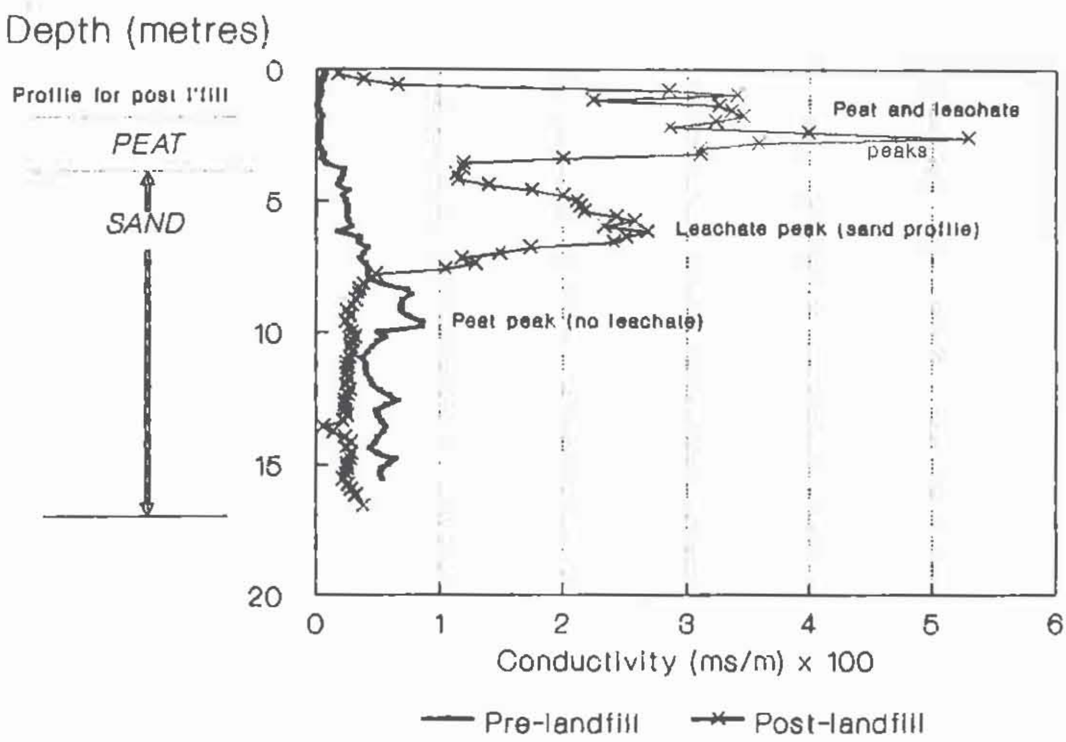

Figure 3. Bulk Conductivity Profiles Comparing Post-Landfill to Pre-Landfill Groundwater, Showing Peat Concentration.

4.0 CONCLUSIONS

The case study presented shows that the bulk conductivity probe is an extremely valuable tool for the identification of pollution plumes in unconsolidated sediments. Conjunctive use of the CPT can eliminate the problem of equivalence (eg. are variations in bulk resistivity/conductivity due to variations in clay content or fluid resistivity/conductivity) which as plagued the geophysicist since time began.

Use of the probe is not limited to studies of this kind. It has applications for dry land salinity assessment, salt water intrusion, dispersivity studies or it could be used as part of a monitoring programme for 'clean up' operations. In all of this work the cone can be used to target zones of interest so that expensive drilling and sampling costs can be minimised. As well as reducing drilling costs, the operation of the probe itself is very economical with an average output of 80 - 120 metres of vertical profiling per day.

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FRACTURE BEHAVIOUR OF SANDSTONES – A COMPARISON OF SAMPLES FROM THE SYDNEY AND BOWEN BASINS

G. LI[1] & K.H.R. MOELLE[2]
[1] University of Newcastle
[2] Institute of Coal Research

INTRODUCTION

The brittle fracture phenomenon found in rocks, though often masked by other geological processes, is fundamental for the understanding of many structural features and their formation processes (Pollard & Aydin, 1988). It is also of particular importance in the understanding of rock deformations relevant to engineering practices. The brittle fracture behaviour of sandstones, a rock type which is often associated with engineering activities, has been investigated. This paper compares the fracture parameters and crack propagation patterns of three fluvially deposited sandstones, and examines the relationship of the fracture behaviour of these rocks with their petrographical and petrological features. Several special fracturing aspects of brittle sandstones are also discussed.

EXPERIMENT PROCEDURES AND ROCKS TESTED

Three fluvially deposited fine-to-medium grained sandstones were tested in this study, namely the Upper Permian Barrier Spit Sandstone from the German Greek Formation, the Upper Permian Seahampton Sandstone from the Boolaroo Subgroup of the Newcastle Coal Measures, and the Triassic Wyong Sandstone from the Terrigal Formation of the Gosford Subgroup. The Barrier Spit Sandstone from the Bowen Basin differs distinctly from the other two sandstones of the Sydney Basin, mainly by its low porosity and strong cementation.

Standard chevron-notched short rod specimens (Ouchterlony, 1988) prepared from the 3 rocks were tested under monotonic, cyclic and sustained loading conditions with a MTS model 810.03 closed loop electro-hydraulic testing facility.

THE EXPERIMENTAL RESULTS

The fracture toughness

The study of fracture mechanics is concerned with the analysis of stress concentrations caused by sharp-tipped flaws, and with conditions for the propagation of these flaws. A measure of the tip stress field is the stress intensity factor K as the driving force of cracks. The critical value of K, often regarded as a material property, is called the fracture toughness, K_{IC}. When K reaches K_{IC}, catastrophic fracture growth occurs.

Table I presents the experimentally obtained fracture toughness values of the three sandstones, from which the following observations can be made:

(i) The variations of K_{IC} values are significant, this is due to the heterogeneity of the sandstones. The sensitivity of fracture propagation to material inhomogeneities is of special significance and concern for sandstones.

(ii) The average fracture toughness of of the Barrier Spit Sandstone is the highest among the 3 tested rocks, and is a result of its high density and very strong cementation.

Table I. The fracture toughness of the tested sandstones.

	Mean	Std. Dev.	Minimum	Maximum	Count
Seahampton Sandstone	770	404	187	1988	23
Wyong Sandstone	1460	404	1010	2350	32
Barrier Spit Sandstone	1590	346	1240	2115	7

Unit of K_{IC}: $KNM^{-1.5}$

The fracture energy

Crack propagation in rocks can also be evaluated by the energy balance concept, whereby the energy required for crack extension is assessed by the R-curve pertaining to a particular test material. R is defined as follows:

$$R = \frac{dW}{dA} \quad \text{.........(1)}$$

where A is the fracture surface area, R is the fracture resistance or energy required for crack growth and W is the total energy dissipated during fracture formation. For a brittle, linear elastic material, R is a constant; in other materials it is a function of the crack size.

The experimental results have shown that the Barrier Spit Sandstone varies again from the other two sandstones by showing a near constant R value with crack extension, indicating its extremely high degree of brittleness.

Subcritical crack propagation in the tested sandstones

It has been found that in all the 3 rocks, crack propagation occurred at fracture-tip stress intensities below their respective critical value, K_{Ic}, the subcritical crack growth value. In addition to this finding, several aspects of engineering significance have been identified:

(i) The described crack propagation is very sensitive to load cyclicity. A minute change of load fluctuations can demonstrably cause crack growth rates to vary by orders of magnitude.

(ii) Brittle sandstones are shown to be prone to fatigue damage analogous to that found in ductile metallic materials.

(iii) With a specified maximum stress intensity defining the load cycles, the Seahampton and Wyong Sandstone specimens are characterized by their exclusive dependency on load amplitude for crack propagation. Crack growth was immediately suppressed when the specimens were subjected to non-cyclic conditions. This finding suggests that rocks affected by cyclic loads, but assessed on the basis of results obtained from the commonly used monotonic or sustained loading tests, would most likely be susceptible to the risk of incurring "unexpected failures". This mechanical effect has not been widely recognized as yet.

(iv) The Barrier Spit Sandstone has demonstrated a very unusual crack propagation pattern. Fast crack growth has occurred under both cyclic and sustained loading conditions with the same maximum stress intensity, showing that this rock is susceptible to both fatigue and stress corrosion damage.

The great complexities of fracture behaviour of sandstones are underlined and demonstrated by the test results. A reliable prediction of rock failure and the successful design of engineering rock structures depend not only on the understanding of fatigue damage, but also on the identification of other possible classes of damage.

DISCUSSION

The dependence of fatigue crack extension on the crack-tip damage through microcrack generation

Under subcritical conditions, cracks in rocks propagate as a result of the formation of microcracks which progressively weaken the fracture resistance of the crack-tip region. The documented mechanisms for the crack-tip damage include stress corrosion, dissolution, diffusion, ion-exchange and microplasticity (Wiederhorn & Bolz,1970; Atkinson & Meredith,1987). These mechanisms, however, cannot account for the presently identified fatigue crack growth in brittle rocks. Consequently, there must be other unknown mechanisms responsible for the observed fatigue crack propagation

Based on SEM studies and on the assessment of statistical data of microcracks in the fracture-tip region (Li & Moelle, 1990), the kinematic responses of the clastic grains in the tested rocks have been investigated. This work has led to the identification of the cyclically intensified local rigid-body motions termed here "displacement reversals" as the principal mechanism responsible for the fracture-tip damage. More precisely, debonding, and microcracking in the fine particle aggregates including matrix, in altered products and in the argillaceous cement occur under the influence of the repeated differential movements to which the clasts are subjected by cyclic loading. These movements can be specified in two categories, namely, the local rigid-body translation and local rigid-body rotation. This damage mechanism differs from the documented mechanisms for subcritical crack growth by its purely mechanical nature, whereas those mentioned above involve chemical processes, with the exception of microplasticity.

Experimental results have shown that the effects of the identified damage mechanism intensify with increased amplitude of load cyclicity, but cease to operate under sustained loading conditions. Consequently, load cyclicity is the mechanism responsible for the observed fatigue crack propagation.

The nature and fabrics of sandstones with respect to the generation of local rigid-body motions as the identified fatigue damage mechanisms

A sandstone fabric can be effectively characterized by the following petrological features, that determine its mechanical and fracture behaviour patterns.

Firstly, by boundary conditions: generally, boundaries between different components or between clastic grains are frequently non-crystalline in nature, and are consequently weaker in sandstones than their equivalents in crystalline rocks, unless recrystallization during diagenesis was significant.

Secondly, sandstones are characterized by their pronounced inhomogeneity, created by the distinct differences between the constituent components, and also by the pervasive distribution of fine materials including matrix, cement and altered products which contain a high proportion (30% to 70%) of micropores in these fine aggregate components.

Finally, the proportion of original and secondary interparticle pores has a marked influence on the mechanical and fracture behaviour patterns of sandstones.

Local rigid-body motions can be considered as the systematical adjustments of discrete portions with different mechanical properties to stressing leading to inhomogeneous displacements. It is an inherent feature of the fabrics of the tested sandstones with the characteristics described above, that clastic components develop a misfit with adjacent grains when loaded under brittle conditions. It is thus obvious that local rigid-body motions must be involved. The relative movements of clastic grains can be facilitated with ease in the presence of the relatively weak boundaries, interparticle pores and especially by the pervasively distributed micropores in the matrix or in argillaceous cement and other altered products. Sandstones with such characteristics are, therefore, rather unique in this aspect and particularly prone to fatigue damage.

The above comments may not be applicable to all varieties of sandstones, especially not for those with substantial silica or carbonate cementation that may prevent or reduce the occurrence of local rigid-body motions of clastic grains. The recently tested Barrier Spit Sandstone distinguishes itself from the other two tested sandstones by its strong multi-phase cementation, and its extremely dense fabric with very little pore space . As a consequence, its demonstrated fracture behaviour, as discussed above, is very different from that of the two sandstones from the Sydney Basin.

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EARLY PERMIAN PALAEOGEOGRAPHY OF THE SOUTHERN SYDNEY BASIN

P.R. EVANS
The University of New South Wales

INTRODUCTION

Data from over 80 outcrop and borehole sections in and through the Lower Permian south of the Shoalhaven River between Marulan and Nowra have been assembled into a framework from which a new synthesis of the Early Permian evolution of the southern Sydney Basin has been derived. Four sequences are recognized, the distribution of which supports the proposition that the Sydney Basin was a foreland basin since early in the Permian (Evans & Migliucci 1991).

A continuing search for palynomorph-bearing strata in the Lower Permian has been under way at The University of New South Wales since 1978. A provisional report of this work was presented to the Newcastle Symposium in 1983. The Electricity Generating Authority of New South Wales (Elcom) undertook an evaluation of the region's coal potential during the early 1980s. In the process, Elcom drilled twelve, broadly spaced, continuously cored boreholes to basement. These boreholes, and recent field studies by Szabados (1990) in the Tallong area, and by Koellner (1990) in the upper reaches of Wandandian Creek and also in 1990 by students from The University of Wollongong have provided further information relevant to the palaeogeography of the region during the Early Permian.

The palynological data are limited by the regional maturation effects of post-depositional intrusions, by the usual oxidizing effects of prolonged weathering on outcrops, and, in marine facies, by the effects of partial digestion of the organic-walled fossils by bioturbation. Nevertheless, they are sufficient to provide a general biostratigraphic perspective from which the palaeogeography of the region may be viewed. The stratigraphy used was established by McElroy & Rose (1962) and Gostin & Herbert (1973). The palynological divisions used are based on units defined by Price (1983).

The general framework has been developed with the aid of the PC-based Golden Software Inc. graphics program "Surfer" and is presented in the form of computer generated maps and perspective block diagrams.

BASE-OF-PERMIAN UNCONFORMITY

The unconformity between basement and the Lower Permian presently dips to the east from an elevation in the west in excess of 1130 m (at Currockbilly Mountain) to depths of at least -500 m asl east of Nowra.

There are variations in this slope, however, at both local and regional scales. The Talaterang Low (McElroy & Rose 1962) is identifiable as a re-entrant in the regional slope affecting an elevation contrast of at least 500 m. There is no evidence that the Talaterang Low continues to depths below present sea level, but this may well be a function of available data. There is only one indirect data point in the likely eastward path of the depression, at Ulladulla, but it fits the regional slope rather than indicating the eastward extension of the Talaterang Low. The slope flatten eastwards below Jervis Bay. Below 400 m asl the average slope is about 30 m/km.

The size and scale of the Tallong Low (Herbert 1980) is not so obvious as that of the Talaterang Low. Fluctuations in the elevation of basement in the Tallong region are up to 100 m and plot as a series of isolated hills and valleys (Szabados 1990). Comparable variations in elevation are evident at the presumed downslope end of the Tallong Low, below Jervis Bay. There are, however, fewer points to indicate the true elevation of basement to the east of the Tallong Low than there are for the Talaterang Low.

Even more gently-sloping pre-Permian topography is evident in the vicinity of Nerriga, where variations in topographic elevation of the unconformity that define the Nadgengutta Low, are less than 100 m (Raine 1967).

A distinct basement "nose" is centred below the Sassafras Plateau and coincides with the drainage divide between the catchments of the Clyde River to the south and the tributaries to the Shoalhaven River to the north that incise the Yalwal Ramp.

EARLY PERMIAN STAGE 3a

The basal sequence Stage 3a includes the Wasp Head Formation and at least the basal Pebbley Beach Formation, and was created by the initial Early Permian transgression of basement. The westward extension of this sequence is limited, except within the Talaterang Low, where the Pigeon House Creek Siltstone and Yadboro Conglomerate and the 'Jindelara Sandstone' are preserved. The 'Jindelara Sandstone' (Seggie 1978) was formed in an essentially fluvial environment and includes the various outcrops of coal seams previously referred to the Clyde Coal Measures (but not the type Clyde Coal Measures).

EARLY PERMIAN STAGE 3b-4

Stage 3b-4 is the most widespread sequence in the southern Sydney Basin. It oversteps Stage 3a and includes lithofacies referred to the Snapper Point Formation, the 'Jindelara Sandstone' and the type section of the Clyde Coal Measures (Walker 1980), and the Tallong Conglomerate (Szabados 1990). The upper limit of the sequence approximates to the Stage 4/5 boundary and to the widespread deepening of the basin and rapid introduction of the Wandrawandian Siltstone. The present surface at the top of Stage 3b-4 dips to the east at about 20 m/km.

An isopach between the top of Stage 3-4 and basement provides an image of the slope on basement during deposition of the Snapper Point Formation. It removes post-depositional regional dip to the east that generally colours our views of the early development of the region. The regional slope on basement between Tallong and Nowra at that time was only about 6 m/km. As noted by Seggie (1978) the Talaterang Low was a broad valley to the northwest of Pigeon House Mountain. An island or shallow promontory of basement, which previously formed the northern flank of the Talaterang Low, survived during this period below the present Sassafras Plateau.

The type Clyde Coal Measures formed within the rentrant at the head of the Talaterang Low, on the flank of the Sassafras promontory.

The Tallong Conglomerate is viewed as a high energy fluvial facies that fed into the Snapper Point sea. The computer-generated isopach map indicates the likely development of a palaeovalley in basement to the southeast of Tallong, but the data points are sparse. In any case, the slope both down the centre of the valley and across its flanks were very gentle.

STAGE 5 - LOWER SEQUENCE

The final series of Lower Permian strata in the southern Sydney Basin includes the Wandrawandrian Siltstone, the Nowra Sandstone and the Berry Siltstone, all of which represent a lower section of Stage 5.

Wherever encountered the transition from the sandy facies of the Snapper Point Formation to the generally silty sequence of the Wandrawandian Siltstone is rapid, but conformable. The Wandrawandrian Siltstone does not extend as far west as the Snapper Point Formation. Its western limit was presumably a hinge line, west of which either limited deposition or a more sandy facies prevailed. Extension of the Wandrawandian Siltstone across so broad a tract to the east of the hinge line and the rapid transition from sandy facies of the Snapper Point Formation to the shaley facies of the Wandrawandian Siltstone indicates rapid deepening of the basin. The accompanying increase in slope is evidenced by the mass sliding towards the east seen in outcrops of the lower portions of the Wandrawandrian Siltstone at the coastal promontory of Wardens Head, Ulladulla.

A widespread conglomerate, about 1 m thick, at or towards the base of the Nowra Sandstone is a lag deposit marking the boundary between regression towards the top of the Wandrawandrian sequence and transgression as represented by the remainder of the formation (Herbert 1980; Runnegar 1980). It is thought here to be a significant boundary between two sequences, marking the end of a coarsening upwards cycle that commenced at the base of the Wandrawandrian Siltstone.

STAGE 5 - UPPER SEQUENCE

The typical Berry Formation (Rose 1966) to the north of Nowra consists of a monotonous shale and siltstone. Whereas Mayne et al. (1974) summarized the sand:shale ratio for the formation in the southern Sydney Basin as 1:4, Walker (1980) estimated the ratio to be 1:1 in the vicinity of the upper Clyde River. Outcrop samples from the sandy facies in the Tianjara and Sassafras regions provided Walker with fragments of Dulhuntyispora inornata, that signify the formation is no older than lower Stage 5c.

DISCUSSION

Apart from a possible N-S hinge line through the middle of the region, there is little evidence of fault control on sedimentation during the Early Permian.

The overall Permian history of the region is one of a westward advancing sea over a pre-existing undulating land surface, coupled with generally accelerated subsidence to the east. The original landscape was of a moderate elevation highland into which broad valleys had been eroded. If glaciations during the Carboniferous were responsible for this topography as is likely from more regional considerations, the resultant topography is suggestive of the glaciation being in the form of an upland ice field with escape glaciers grooving the flank of the highland, such as are found in parts of Iceland today. By Permian time, the landscape was relatively subdued and the valleys broad. The uplands were at a minimum elevation of 500 m asl, comparable to the elevation of the Southern Tablelands today.

The Talaterang valley provided a route for transport of sediment into the rising sea during Stage 3-4 time. An alluvial fan delta occupied and choked up this valley as time passed (Pigeon House Creek Siltstone - 'Jindelara Sandstone',) and extended into the rising sea.

The region of Currockbilly Mountain to the southwest of Ulladulla was still above sea level by the end of Stage 4 (Snapper Point Formation). For a while during Stage 4 an island or promontory extended eastward below the Sassafras Plateau.

The existence of this promontory that protected an embayment at the head of the Talaterang Low from the destructive forces of the sea, was probably responsible for the localised growth of the type Clyde River Coal Measure swamps.

During Stage 4 a high energy river system or fan delta (Tallong Conglomerate) debouched into the rising sea in the vicinity of Tallong, burying the local landscape, virtually at the top of the original Carboniferous highlands. The Tallong braid plain could have been a major feeder of coarser clastics to the Snapper Point sea. It is likely that high wave energies were sufficiently destructive and dispersive of the fluvial input.

Hinging of the basement early in Stage 5 time deepened the Wandrawandrian sea and induced a degree of local instability and slumping. This movement, which is attributed to continued crustal loading by the Currarong Orogen to the east also led to the maximum westward transgression (Berry Formation) before the seas became choked with an ever increasing input from the orogen and establishment of mainly non-marine depositional environments across much of the basin.

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FROM BORE CORES AND STRIP SAMPLES TO COAL PROCESSING PLANT SCHEDULING – A PRACTICAL APPROACH

B. AGRALI
Austen & Butta Ltd, Corrimal

INTRODUCTION

Despite an accelerated trend towards fully computerised prediction routines in most coal mines, especially for long-term forecasts, and for quality and economic assessments of new prospects, there are still a number of "grey" areas for short-term predictions in underground mines, particularly when the run-of-mine product (ROM) is a mixture of products with different quality and washability characteristics, and/or the coal processing plant (CPP) is geared to prepare a number of saleable products that have to comply with rather strict specifications.

The prediction method related in this paper is that used at the South Bulli Colliery operated by The Bellambi Coal Company in the Southern Coalfield of the Sydney Basin, N.S.W., where three distinct saleable products are prepared simultaneously: a low-ash coking coal (-45mm), and two thermal coal fractions (drewboy 125x45mm, and middlings 45x0.5mm), with current ash specifications standing at 9.5%, 12.5% and 15% respectively. The method has been developed, modified, and improved over the years in line with changes in product specifications, and alterations to the CPP.

The prediction routine involves numerous adjustments to all available laboratory analysis data, by the geologist and by the fuel technologist, owing to basic differences between laboratory and plant conditions.

MINE GEOLOGIST'S INPUT IN COAL PROCESSING

A mine geologist has a "natural" role to play in all aspects of a mine's life, starting even before the inception of a new mine (1), and including the ultimate, -processing-, stage. Data collected during exploration, and observations made by the geologist during actual mining thus provide a good basis for predicting the characteristics of the ROM, i.e. of the CPP feed (2, 3).

Having often personally sampled each one of the rock types included in the ROM, starting with coal, decided what analyses and tests would be needed, sent the samples to the laboratories of his choice, interpreted the results, and given -during the mine planning and actual mining stages- his advice on the nature of the coal and rocks to be mined, the geologist has a real responsibility rather than an occasional say in coal processing, and therefore must acquire a working knowledge of coal processing systems in addition to a thorough familiarisation with mining technology and mining practices, and perhaps even with some rudiments of economics (4).

SCOPE OF QUALITY PREDICTIONS

Some raw and washed coal characteristics do not vary too much over wide areas, whereas some others may vary over very short distances. Still some other characteristics are time-dependent, system-dependent, or operator-dependent. Slow-varying characteristics usually determine the long-term mining strategy, whereas some high-variability parameters are to be remedied by processing, if possible, and their variations predicted.

The main characteristics of a product that can be predicted are its size consist (which pre-determines the proportions of the ROM to be handled by various circuits), its yield at a given separating gravity (SG), and its ash content (which is controllable by adjusting the separating medium density in HM bath and cyclones). These are the three parameters that usually determine the viability of an operation, though the prediction of some additional characteristics may be required: e.g. the crucible swelling number (CSN) which can also be -theoretically- controlled. Ash control and the control of the CSN will directly affect the plant yield.

SCOPE OF QUANTITY PREDICTIONS

Production rates for various units (CM's and LW's) are set by the mine planning engineer, in line with their nominal capacity or the particular limitations of the operation whatever these may be, in terms of advance rates (m/shift, m/day, m/week) or tonnages (t/shift, t/day, t/week). In this last case the tonnages are ROM tonnages including extra-seam and in-seam dilutions and a percentage of moisture determined by experience. Projected combined tonnages of the ROM, including its average quality parameters are forecast using a simple spread sheet programme.

Extra-seam dilution may be considered in two distinct categories: 1) stone deliberately mined (direct discrepancy between actual seam thickness and the actual shearing height determined by necessity or by practice) and 2) stone mined due to its nature/geotechnical characteristics (euphemism for roof falls), which can be quantified only through a detailed underground and surface survey coupled with a long-term monitoring. Experience shows that dilution from roof rocks has a direct relationship with joint density for a given rock type, a given development direction, a given width of roadway, and a given set of support standards (5, 6).

The Bulli Seam in the South Bulli Colliery Holding has also a serious problem of in-seam dilution, owing to the occurrence of numerous floor- and roof rolls, clay dykes, and igneous intrusions. An accurate mapping of these features in development panels is the only basis for reliable predictions.

DATA SOURCES - ACCURACY, RELIABILITY, AND SUFFICIENCY CONCEPTS

Data used in quality predictions come from three main sources: bore cores (irregular grid owing to terrain configuration), mine strip samples (200m grid), and bulk ROM samples representing whole mine production or specific panels.

Owing to changes in analysis and test standards during various stages of exploration work, the geologist has to determine the correlatability of the available data through a careful assessment of their accuracy and reliability, and the sufficiency or otherwise of the data base for a desired level of precision in forecasts (7-9, 18-19).

BORE CORE DATA

Principles laid down by AS-2519 (10) complementing and condifying earlier work and recommendations by various researchers (11, 12, 13), and aiming to generate plant design and operation data from bore core analysis and test data are hardly applicable to slim cores obtained at depths of about 450m from the Bulli Seam which is known for the high variability of some of its quality parameters, and the expenditure needed for drilling large-diameter holes on a tight grid to this end could not be justified. Nevertheless a small number of such holes were recently drilled in assumedly strategic points of the Holding for the specific purpose of simulating ROM samples; laboratory work is still in progress on these samples which could possibly provide a basis for a direct adjustment of slim core data for better predictions. Meanwhile, for routine prediction purposes, slim core analysis data are adjusted so as to integrate these holes in our strip sample grid.

ADJUSTMENTS

Laboratory-determined data, based on dry screening and F/S analysis in organic liquids, do not provide a reliable basis for estimates of Plant results, as the treatment of raw coal through a CPP results in significant changes to the size and F/S characteristics of the feed material. Particle degradation and slimes production result in more material reporting to the fines section of the Plant. Because of the fact that in all preparation processes the efficiency of treating fines is less than that of coarse treatment, the actual clean coal yield is less than that suggested by laboratory data. However, a basis can be worked out for adjusting F/S results to actual CPP performance characteristics, as the discrepancy for a given SG is practically independent of coal type, but is a function of the equipment.

The geologist's predictions, after adjustment for CPP efficiency would be, -theoretically-, valid for a single product prepared at a constant SG, or with a constant ash content, but for 2 or 3 products there is very little that a geologist could estimate without an adequate knowledge of the various Plant circuits and/or without the hindsight of practical experience, which form two separate avenues for reliable predictions.

The first avenue is used by the fuel technologist who can work out empirical formulae for specific sets of circumstances as parts of a multi-step approach, by trying to fit a yield figure to each one of the geologist's washed ash figures on a number of ash/yield curves prepared for ROM bulk samples (14, 15). The final assessment of yields is then based on the assumption that the proportion of the 125mmx45mm fraction, going through the drewboy bath, and that of fines, going through the froth flotation circuit, are constant during a defined period, the only variable being the coking coal/middlings ratio representing approximately 66-67% of the Plant feed.

The second avenue is used by the geologist as a stop-gap prediction method when a number of alternative mining schedules are to be broadly investigated and compared. The method is simply based on comparing, for recently mined-out areas, what happened in the CPP to what the geologist would have predicted had he/she known the actual in-seam and extra-seam dilution ratios that were monitored, together with actual shearing heights in longwalls and development panels. Figs. 1-2 illustrate actual discrepancies between the geologist's 'idealised' predictions and the actual performance data of the CPP through a 15-month period prior to 1988, and a prediction table for the coking coal fraction, expressed as percentages of the CPP feed.

PREDICTION ROUTINE

For each characteristic to be predicted the routine for long-term scheduling (time unit: 1 year; periods of up to 25 years) involves the following steps:

1) Adjusting all available washability data for anticipated CPP performance at 1.50 SG (efficiency adjustment);

2) Adjusting borecore data to strip sample standards;

3) Preparing iso- maps, and superposing these to the projected development plan to determine average values for all panel-time blocks (until recently 'PLOTCALL' programme by Golden Software was used for this purpose, in conjunction with LOTUS 123;

4) Adjusting yield values for anticipated extra-seam dilution (LOTUS 123);

5) Combining panel-time block results on a yearly, weight averaged basis;

6) Adjusting results for actual SG's and/or for desired specifications (cf. Adjustments, last two paragraphs). Currently all long-term predictions are made through the use of the MINEX system by ESC, the geologist providing all the input data, and the fuel technologist carrying out the adjustments for the coking coal/thermal coal split.

For short-term predictions (time unit: 1 month; periods of up to 18 or 24 months), involving fully- or partly-developed longwall blocks, 'panel-time' blocks are replaced by 20 to 40m portions of the longwalls for which all quality data are available in reports prepared prior to the start of the units (16, 17). Extra-seam and in-seam dilution ratios are calculated as realistically as possible for short-term predictions, whereas uniform figures are adopted for long-term forecasts, based on the average values calculated over mined-out areas. Short-term predictions are still prepared partly using CP programmes and partly manually, due to the practical difficulty in entering a very large number of thickness- and structural data in the MINEX system.

ACCURACY OF PREDICTIONS

An absolute fit between predictions and actual CPP performance is practically unthinkable, especially for short-term forecasts (any close fit would be fortuitous), for the very simple reason that idealised production levels in various units can seldom be achieved over short periods, and all production units achieving their quotas on the dot, simultaneously, month after month, would hardly ever happen in underground coal mining. On the other hand, doubts will always exist on the representative value of all samples, the accuracy of laboratory determinations, the validity of generalising adjustment factors, the validity of some correlations (insufficient data density), etc. (18, 19).

Short-term predictions are consequently revised at regular intervals, taking into account actual advance rates in panels, and results from additional samples if any. All short- and long-term predictions should also incorporate some soundly defined margin of error.

ACKNOWLEDGEMENTS
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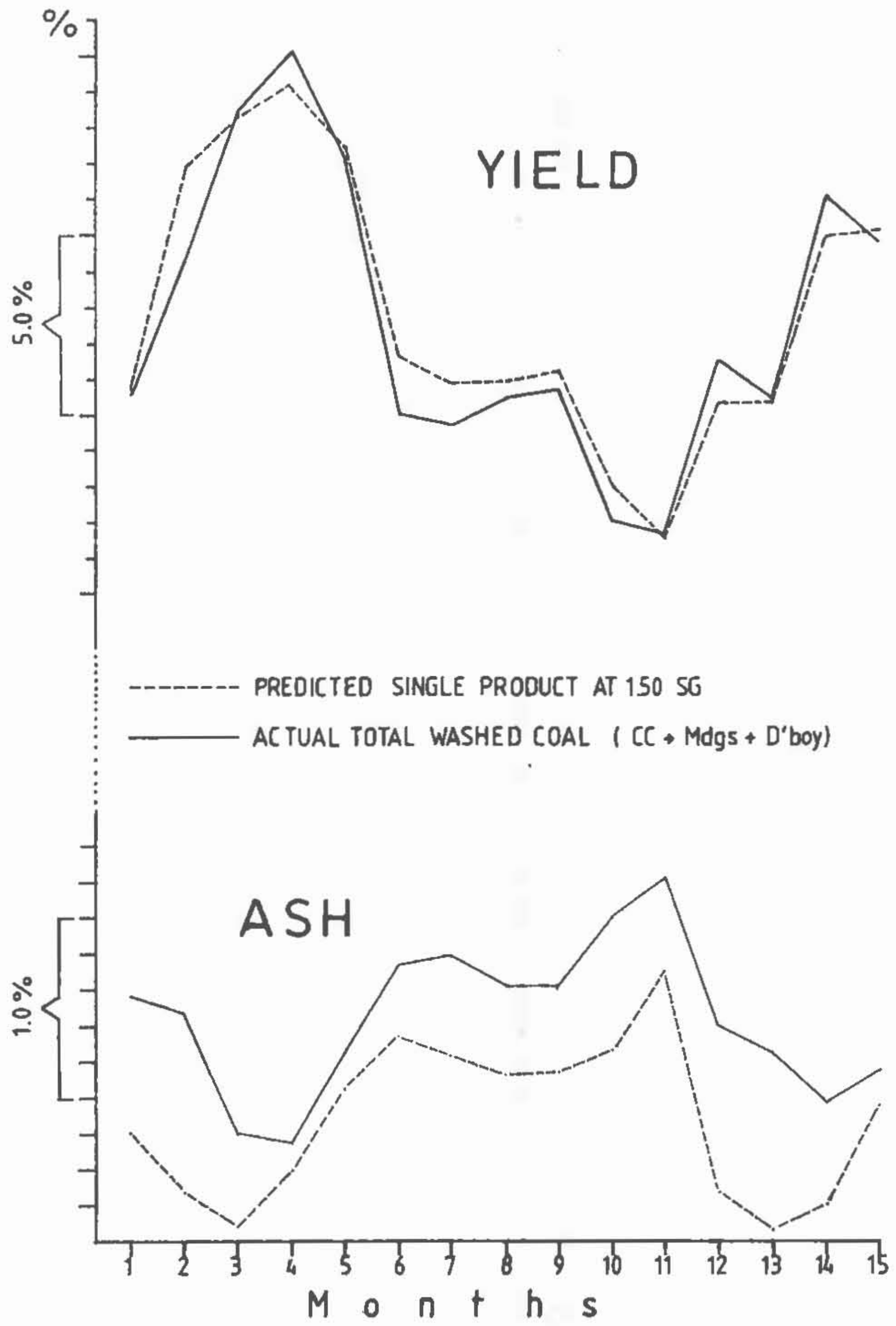

FIG. 1 Predicted yield and ash for a single product at 1.50 SG vs global yield and ash for actual product specifications.

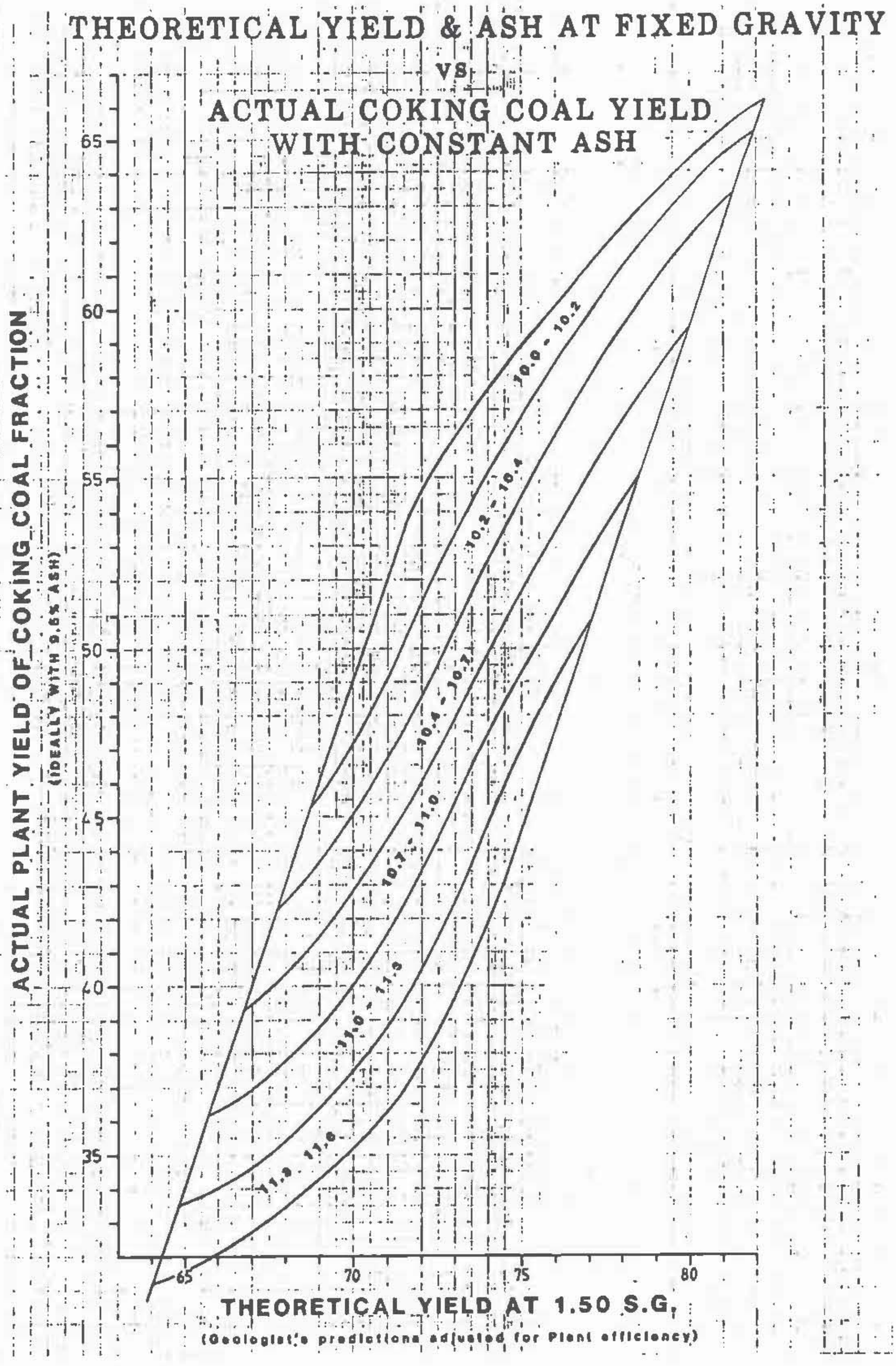
THEORETICAL YIELD & ASH AT FIXED GRAVITY
VS
ACTUAL COKING COAL YIELD
WITH CONSTANT ASH
ACTUAL PLANT YIELD OF COKING COAL FRACTION
(IDEALLY WITH 9.5% ASH)
65
60
55
50
45
40
35
10.0 - 10.2
10.2 - 10.4
10.4 - 10.7
10.7 - 11.0
11.0 - 11.3
11.3 - 11.6
65
70
75
80
THEORETICAL YIELD AT 1.50 S.G.
(Geologist's predictions adjusted for Plant efficiency)

FIG. 2

The paper "Applications of clastic sedimentation to the assessment of potential longwall underground coal mines" by A. Falkner & C. Fielding (pages 215-221) has been withdrawn.

In its place, the following paper will be given :

"It's just black, and they burn it" — A technologist's view of coal.

R.H. Sanders, Quality Coal Consulting Pty Ltd, Newcastle

REFLECTIONS ON REFLECTANCE

G.H. TAYLOR
RSES, Australian National University

INTRODUCTION

Reflectance of vitrinite is much used as a means of assessing the rank of coal and other naturally occurring organic matter, and for assessing the variation of rank with depth. This information is of great importance for coal assessment and utilization and for petroleum exploration. Reflectance has proved a useful parameter of rank - better than most others, but not perfect or universally reliable. In this paper some of the reasons for reflectance being a less than perfect parameter of rank are explored.

The relationship between depth and reflectance in an "ideal" sedimentary sequence would show measured values falling on a straight line or regular curve (depending upon the scales used). For these purposes, an "ideal" sequence means one formed through a regular accretion and burial of sediments of similar type, where the rocks have been uninfluenced by spasmodic igneous or tectonic events. Approximations to such ideal sequences do occur but, in general, extrinsic sources of variation are the norm. One of the useful contributions of reflectance is that the effects of these extrinsic influences can be detected and evaluated on the basis of deviations from ideality in the reflectance/depth curves.

Before we can evaluate extrinsic variations, we need to consider the consistency of the data concerned. This means that we need to consider the nature and source of intrinsic variations of reflectance - the variations within a single sample, in which all the organic matter must, since deposition, have experienced the same temperature and pressure conditions over the same time span. Reflectance measurements are made, of course, on vitrinite, and the Australian Standard on reflectance determination states "The rank of a coal seam is determined by measuring the maximum reflectance of the vitrinite sub-macerals gelocollinite and telocollinite, where identifiable" [1]. As is pointed out in the ICCP Glossary [2], it is not always possible to identify sub-macerals. Indeed, it is common experience that in the grain mounts of coal normally used to provide representative samples, it is not possible to do more than select vitrinite which appears to be reasonably uniform in appearance. There is even less chance of identifying the sub-macerals mentioned when samples of cuttings are being examined, since the vitrinite is commonly in small fragments, the affinity of which cannot be assessed. With cuttings there is also the chance of contamination of the sample by cavings or in some other way.

GEOFF TAYLOR

Many determinations of the reflectance of vitrinite have shown that, even after selecting appropriate areas for measurement, there is a substantial amount of variation in a single sample of coal. This variation - usually displayed as a histogram - is well known to those active in the field, although the usually quoted single value for the reflectance of a sample gives no hint of this variability. Some of the spread in values within a single sample has been attributed to variations in botanical origin and to conditions of deposition and preservation of plant material, and no doubt many of the reflectance variations can be traced back to these factors. However, we have comparatively little idea of the physical basis of the differences. Indeed, given the number of variables, we do not have a very clear idea of why reflectance works as well as it does.

REQUIRED CONDITIONS

For reflectance to be a valid means of assessing the degree of coalification at a single location and to be a valid basis for comparing the rank of widely separated coal samples, the two conditions below need to apply. (Obviously other conditions, to do with sampling, instrumentation, specimen preparation, measuring procedures and so on, need to apply also, but these cannot be considered here).

- 1. The material in all the microscope fields measured should be of the same or of very similar chemical constitution so that like is being compared with like. It would follow that refractive and absorption indices, on which the reflectance value depends, would also be nearly the same, other things being equal. (It is conventional wisdom among coal petrologists that the relationship between reflectance, refractive index and absorption index is described by the Fresnel-Beer equation. However, this relationship is really relevant only to non-diffusing media, and it is not hard to show that vitrinite is a diffusing medium).

It is certain on morphological grounds that a wide range of former plant materials are now preserved as vitrinite and that these have been subjected to varying degrees of gelification, oxidation and biodegradation before burial. Thus the humic matter at the time of deposition must have been quite variable, and these differences must persist to some degree during coalification. Also, it cannot be assumed that all the material recognized as vitrinite is indeed humic in character. For example, material referred to as "vitrinite-like" has been shown to be of degraded algal origin [3].

- 2. The physical state of the material (e.g. porosity) should be the same, so that materials are being compared in the same state of aggregation. To some extent, the physical state cannot be dissociated from the chemical state (e.g. moisture in coals of lower than bituminous rank).

Vitrinite is known to have a high internal porosity, much of which is extremely fine. However, relatively little information is available as to how this porosity is distributed and as to whether there are any significant differences in this respect between different vitrinite occurrences.

REFLECTIONS ON REFLECTANCE

ELECTRON MICROSCOPY

One way to assess at least some of the variability of the two kinds mentioned above is with transmission electron microscopy (TEM). With TEM, very thin sections ($< 0.1\mu m$) are used. High degrees of magnification and resolution can be obtained and the TEM images can be compared with those from reflected light microscopy. It has been found that, qualitatively, much of the of the variation in vitrinite reflectance can be understood in the light of TEM observations.

Material Variability

Much vitrinite which appears homogeneous in the light microscope can be seen with electron microscopy to be heterogeneous with respect to the types of organic matter present. This heterogeneity can be separated into two kinds: (1) where all the vitrinitic material is of humic nature, but with variations in the type of humic matter, and (2) where material other than humic matter is present in the vitrinite.

The most obvious differences within the humic matter are in the texture (see below). However, there are differences in the density of the TEM image which suggest differences in composition (Figure 1). The differences in types of humic matter may be enhanced for TEM with so-called 'electron staining' where solutions containing heavy metals are used to accentuate differences in texture or chemistry (Figure 2). The fact that the heavy metal compounds bind with varying strength to different occurrences of humic matter suggests differences in chemistry.

However, much vitrinite does not consist wholly of humic matter, but of mixtures of humic and other organic matter. The most common other matter visible with TEM is liptinite-like material, which may be fine shreds of actual liptinite (Figure 1), fine laminae of suberin (Figures 3 and 4), or the remains of microrganisms. The remains of microorganisms are commonly closely associated with humic matter in the form of aggregates of fine spheres; this association is the residue after biodegradation [4].

In a recent paper [5] it was shown that micrinite is comprised of aggregates of very fine spheres believed to be residual after the generation of hydrocarbons. Much of this very finely divided material (termed 'sub-micrinite' for purposes of discussion) does not occur in aggregates large enough to be seen as micrinite. Some of the dispersed sub-micrinite would be expected to affect the reflectance.

Another source of heterogeneity likely to affect optical properties is the occurrence of fine mineral matter. Several finely dispersed minerals have been observed with TEM, the most common being clay (Figure 5) and pyrite (Figure 3). When these minerals are present in a fine state of subdivision, they are usually also present in the sample as grains large enough to be visible with light microscopy.

Yet another source of heterogeneity is the presence of bitumen (Figure 6) - material which would be called exsudatinite if present on a scale large enough to be visible with light microscopy.

Textural variability

There are significant variations in texture between different occurrences of humic matter. Some humic matter appears compact (Figure 4) although commonly a very fine texture is visible with TEM. Other humic matter has a distinct fine granularity (Figure 7) and still other does not have a continuous structure, but is comprised of an aggregate of fine spheres (Figures 7 and 8). These varieties of humic matter may occur alone or in close association with one another, as in Figure 7; in the latter case there must be an averaging effect when such material is examined with the light microscope. Void space in humic matter is very evident in biodegraded material; this includes the cavities between fine spheres of humic matter (Figures 7 and 8). With increase in rank, these spheres pack more closely together so that in bituminous coals much of this void space has disappeared. There is also humic matter where biodegradation has left fine cavities following the removal of material by microorganisms (Figure 9). As well, there are cavities inherited from the vascular plant structure (Figure 9). The largest of the latter are visible with the light microscope; the smallest would only be seen with TEM.

DISCUSSION

Reflectance must be affected by a number of the factors mentioned. Variable void space means variation in the mass available to reflect light. However, there must also be substantial scattering of light by these finely porous materials, so that the amount of light returned to the objective must be diminished.

The presence of non-humic material would also be expected to diminish the apparent reflectance. This is partly because of light scattering and loss associated with the numerous interfaces, but partly because much of the non-humic material is liptinite-like matter which would be expected to have a low inherent reflectance. Variation in the nature of the humic matter itself seems likely to be a smaller, but probably still significant source of variability in reflectance. The effect of fine minerals may well vary. Where fine clay is present, the reflectance would be lowered for the same reasons as with liptinite-like material. However, where the mineral matter is pyrite, the scattering effect would reduce, but the reflectivity effect would increase, the observed reflectance.

A number of authors have suggested that the reflectance of vitrinite is diminished by the presence of oil impregnating the structure. This may indeed happen; however, we have not seen any evidence and there are reasons for caution in accepting that the explanation for the "suppression of reflectance" lies in oil impregnation on the scale of the finest pores in the vitrinite. The occurrence of bodies of bitumen is at least part of the reason for lowered reflectance in coals which have generated hydrocarbons.

In summary, TEM has revealed numerous sources of reflectance variability. Some of these have to do with differing porosity within humic matter and some to do with heterogeneity of material.

REFLECTIONS ON REFLECTANCE

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CAPTIONS TO FIGURES

All figures are TEM images of material identified as vitrinite by light microscopy. Microtome cutting marks (parallel striations) are evident on most micrographs and should be ignored.

1. Humic matter of variable density (medium grey) with numerous liptinite-like inclusions (pale grey to white). Sub-bituminous coal, Bass Strait.

2. Humic matter with very variable density after electron staining. The pale areas appear to be rich in liptinitic matter. Bituminous coal, Wandoan.

3. Sub-parallel laminae of suberin (A) in humic matter. The dark granular material (B) is fine pyrite. Sub-bituminous coal, Bass Strait.

4. Cell wall structures (arrowed) in "compact" humic matter. Brown coal, Yallourn.

5. Fine clay (arrows) dispersed in humic matter. Larger grains of clay (dark) at margin of field. Sub-bituminous coal, Bass Strait.

6. Irregularly shaped injections (pale) of bitumen into humic matter. Bituminous coal, Illinois.

7. Humic matter differing in texture: finely textured (A), granular (B) and aggregates of spheres (C). Sub-bituminous coal, Collie.

8. "Compact" cell wall humic matter surrounding cell lumens with aggregates of spheres (A) and biodegradation residue (B). Brown coal, Anglesea.

9. Vascular plant cell cavities (A) in "compact" humic matter with band of finely porous, biodegraded humic matter (B). Sub-bituminous coal, Bass Strait.

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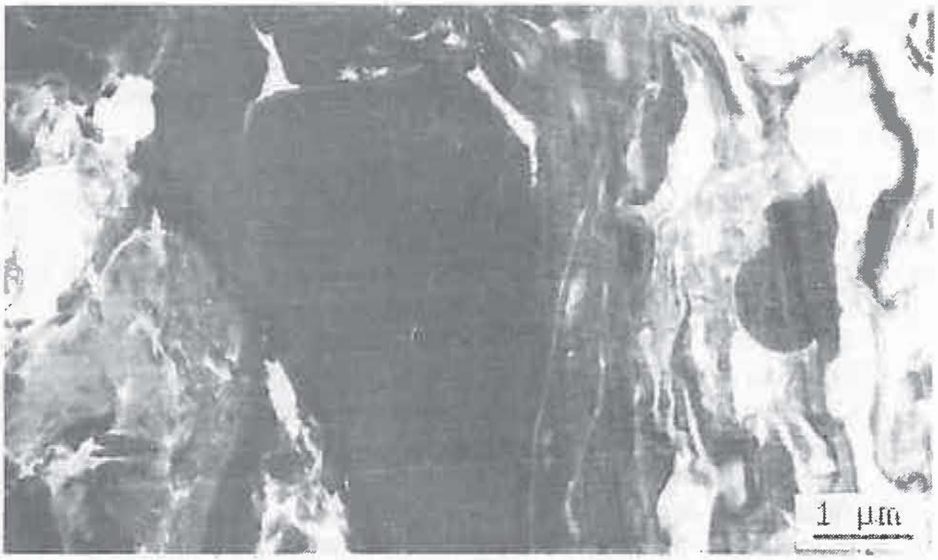

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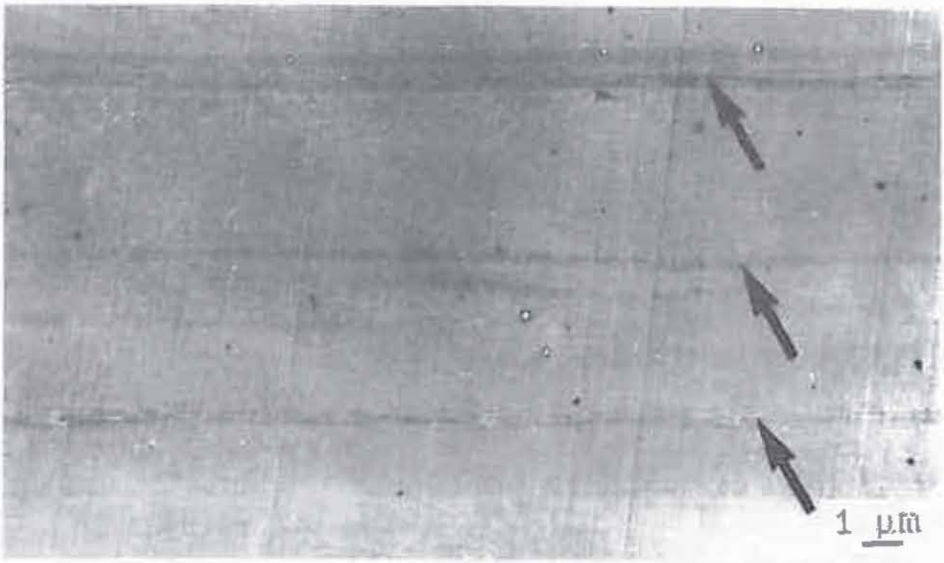

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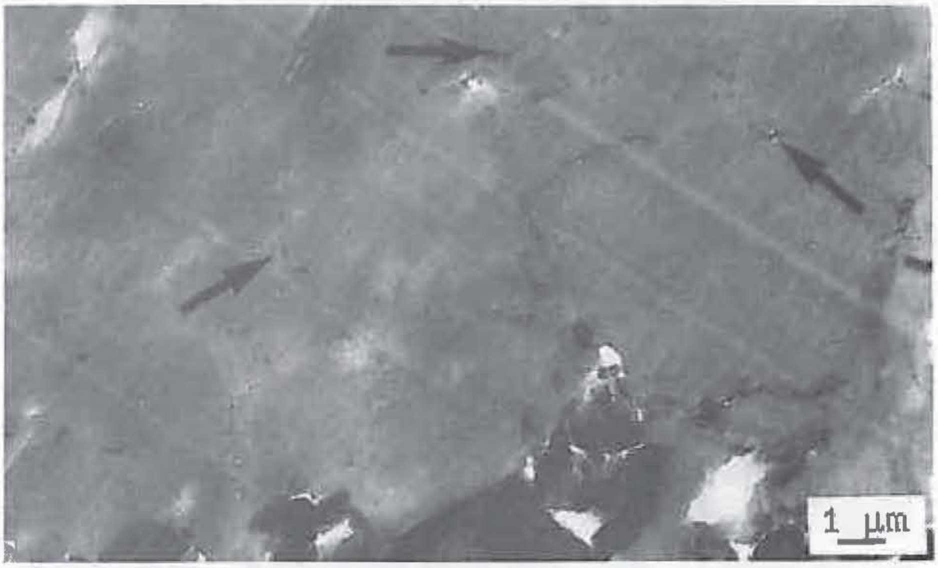

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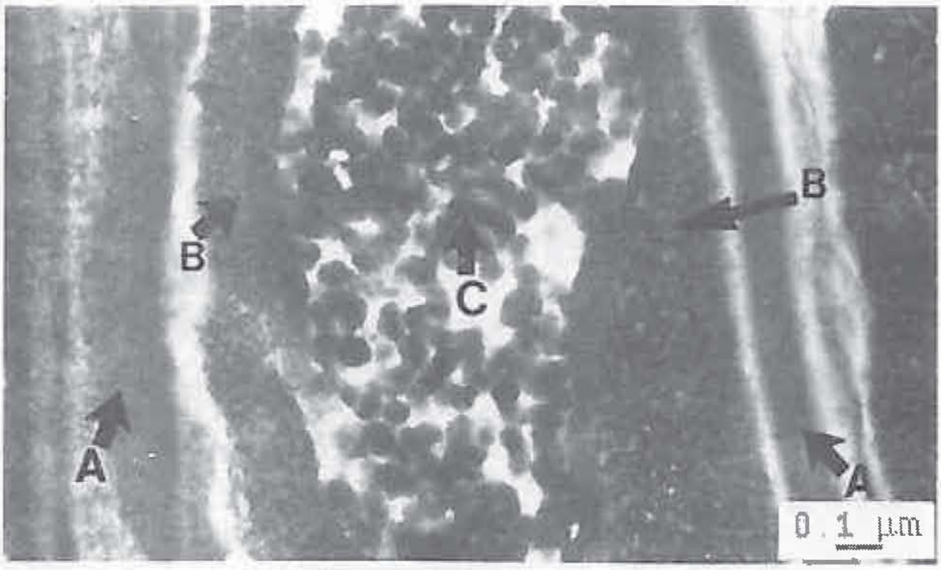

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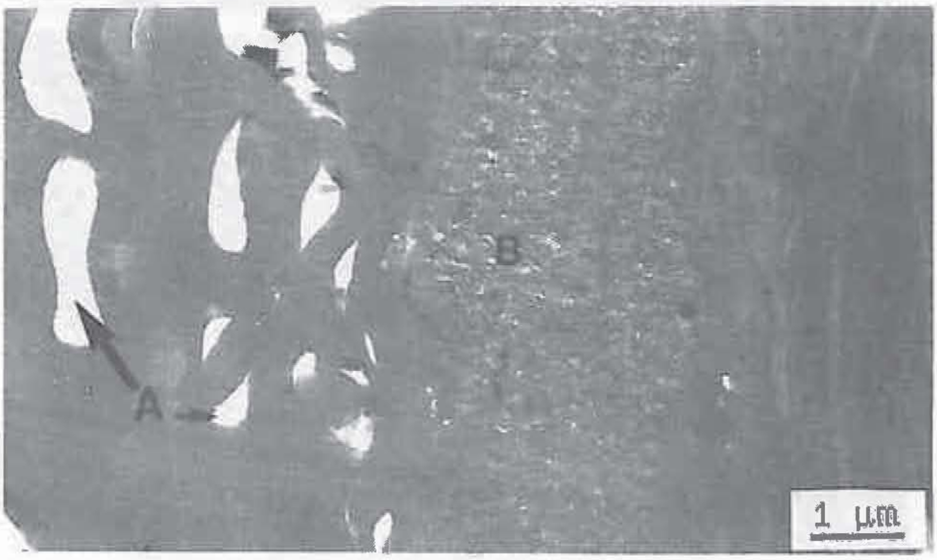

9

THE SUPPRESSION OF VITRINITE REFLECTANCE IN THE GRETA AND PELTON COALS : A FLUORESCENCE ALTERATION STUDY

R.W.T. WILKINS[1], N. ZHONG[2], M.V. ELLACOTT[1] & C.P. BUCKINGHAM[1]
[1] CSIRO, Division of Exploration Geoscience
[2] Jianghan Petroleum Institute, Jiangling, Hubei, P.R. China

The Greta-Pelton coals offer a classic example of suppression of vitrinite reflectance. Samples from these coals formed the basis of a multi-maceral fluorescence alteration study which was directed towards finding a method for identifying reflectance-suppressed vitrinite, and correcting for the effect.

Fluorescence measurements were made using the CSIRO laser Raman microprobe which doubles as an advanced fluorescence microscope. With the highly stable laser light source, the efficient optical system of the microprobe, and high sensitivity detectors, the capability of the instrument extends far beyond that of conventional fluorescence microscopes. With this apparatus it is easily possible to measure the fluorescence characteristics of all macerals, and even to obtain high resolution fluorescence images (Wilmshurst et al., this volume).

When a maceral is irradiated by U.V. or short wavelength visible monochromatic light, it will give rise to a broad fluorescence spectrum extending from the wavelength of the exciting radiation through much, or all of the visible region. If 488 nm argon ion laser radiation, for example, is used for excitation, the peak fluorescence is at about 625 nm, in the red. If a sequence of measurements is made at peak fluorescence while the maceral is being irradiated, it is observed that the intensity of fluorescence increases or decreases with time according to the type of maceral and its thermal maturity. In this way some hundreds of measurements can be obtained from a single 1-2 μm irradiation spot. Such measurements form the basis of a multi-parameter thermal maturity technique which has possibilities of wide application, especially in petroleum exploration.

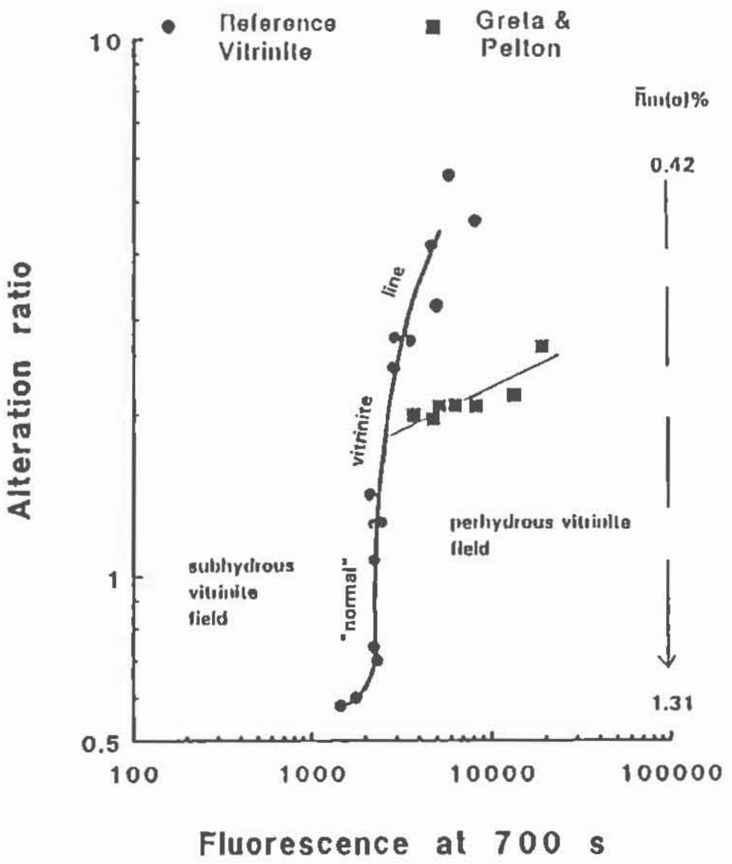

Fig. 1 Fluorescence alteration data on vitrinite from *Greta and Pelton* coal samples compared with vitrinite (telocollinite) from "normal" Australian coal.

If an index of the shape of the fluorescence alteration curve (the ratio of final to initial intensity) is plotted against final fluorescence intensity, a new and extremely useful diagram results. On this diagram (Fig. 1), "normal" vitrinite (telocollinite) plots close to a trend line, and perhydrous and subhydrous vitrinites plot in the fields respectively to the right and left of this line. Any vitrinite can therefore be classified by measurements taken from a single 1-2 μm spot. In general, liptinite and inertinite macerals also plot respectively to the right and left of the "normal" vitrinite trend line. Fluorescence alteration data on a range of macerals from a "normal" coal (Amberley, $\bar{R}m(o)\% = 0.54$) and a vitrinite reflectance-suppressed coal (Pelton $\bar{R}m(o)\% = 0.43$) are shown in Fig. 2. The special value of this type of plot results from the fact that whereas the fluorescence alteration ratio depends mainly on thermal maturity, the final fluorescence is mainly controlled by maceral type.

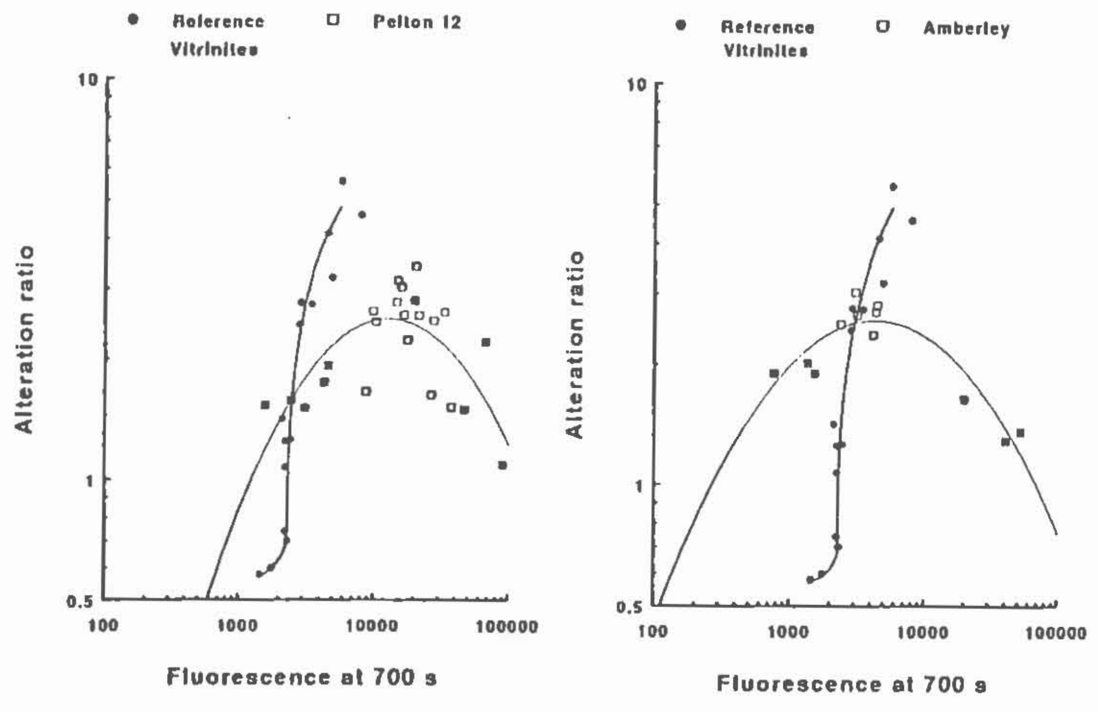

Fig 2 Fluorescence alteration data on a range of macerals from a "normal" coal (*Amberley*, $\bar{R}m(o)\%=0.54$) and a vitrinite suppressed coal (*Pelton*, $\bar{R}m(o)\%=0.43$). Shaded squares are liptinite and inertinite; unshaded squares are vitrinite.

The Greta-Pelton coals provide a good example of the use of fluorescence alteration data to evaluate vitrinite suppression effects. Samples taken from an 11 metre section through the two seams have been studied in detail by Diessel (1991). They are essentially iso-metamorphic, and would therefore be expected to have the same vitrinite reflectance. In fact, Diessel (1991) has shown that mean random telocollinite reflectance varies from 0.68% near the base of the Greta seam, to 0.43% near the top of the Pelton seam. Mean fluorescence alteration data for the telocollinite in these coals plot on Fig. 1, in the field to the right of the "normal" vitrinites. All are therefore anomalous, the extent of deviation from the "normal" vitrinite line being related to the extent of vitrinite reflectance suppression.

The data on the Greta and Pelton coals show that it is possible to derive an equivalent vitrinite reflectance directly from the fluorescence alteration ratio, which is little affected by suppression effects. A more extensive set of data from Australian, Chinese and New Zealand coals shows that if the suppression is extreme, and especially in coals of low rank, the best correction procedure is to make comparison with iso-metamorphic pairs of normal and reflectance-suppressed vitrinites of similar thermal maturity.

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A NEW INSTRUMENTAL METHOD FOR THE ASSESSMENT OF COKING COAL

J.R. WILMSHURST[1], C.F.K. DIESSEL[2], M.V. ELLACOTT[1], G HLADKY[1] & C.P. BUCKINGHAM[1]
[1] CSIRO, Division of Exploration Geoscience
[2] University of Newcastle

Introduction.

Observation and measurement of the fluorescence of a coal under irradiation with short wavelength visible light serves not only to highlight certain of the macerals, but has also been shown by Diessel to provide a basis for the assessment of its coking characteristics [Diessel and McHugh, 1986, Diessel et al, 1987, Diessel and Wolff-Fischer, 1987]. This method determines the fusible component of a coal by correlation with fluorescence intensity; the relationship between fluorescence intensity and fusibility is established by calibration against well studied reference coals. The manual measurement of the number of points sufficient to provide a realistic assessment, however, is both time consuming and tedious; an alternative approach lies in the use of the automated CSIRO laser Raman microprobe for the fluorescence measurements. The understanding and methodology necessary for this approach have come from the application of the microprobe to the examination of organic matter in petroleum exploration maturity-studies [Wilkins et al., 1990]. As a bonus, it appears that the fluorescence intensity of a maceral as determined by laser excitation, is less affected by incipient surface oxidation than if a conventional excitation source is employed.

Instrumentation and methodology.

The laser Raman microprobe, as used for the study of the fluorescence of carbonaceous materials, consists of a petrographic microscope, for examination and irradiation of the sample, tightly coupled to a sensitive high resolution spectrometer, the light source for irradiation being a small air-cooled argon laser operating in the blue at a wavelength of 488nm. The power delivered to the sample is typically some 0.5mW with a spot size dependent on the power of the microscope objective, but approximately 2μm in diameter for the X50 objective. The microscope stage is a precision x-y table driven by stepper motors and capable of 0.5μm steps in the x-y plane and with an active scanning area of 20 by 20mm. The system software allows for the scanning of an area, line by line, with selectable x and y step size and with variable fluorescence count time. The observation point can be reset, after fluorescence measurement, to any particular coordinate within the scan area.

The accumulated information is presented as an x-y 'map' in false color on a graphics terminal or plotter on the basis of the fluorescence intensity distribution or defined intensity boundaries, which could be set to represent the extent of the fusible macerals. The data can be analysed by two-dimensional image analysis techniques.

The results of preliminary fluorescence mapping of the sub-set of the two ICCP ring analysis coals [Bulli Seam (Wollondilly) BHP-CRL Y18610 and Seam A (Ruhr) BHP-CRL Y18611] will be presented.

In practice, the measurement of the fluorescence intensities, and the generation of the intensity map does not require the full capabilities of the Raman micro-probe and particularly its high spectral resolving power. Consequently, one of the authors [Wilmshurst] is developing a greatly simplified instrument , but one which retains the automation, laser excitation and high resolution x-y mapping features of the microprobe.

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COMBUSTION CHARACTERISTICS AND CHAR EVOLUTION OF VITRINITE AND INTERTINITE-RICH COAL CONCENTRATES

J. BAILEY
University of Newcastle

INTRODUCTION

Many attempts have been made to relate easily-measured coal characteristics to coal performance in combustion, pyrolysis and gasification (Oka et al. 1987; Crelling et al., 1988; Kalkreuth et al., 1990). Some basic parameters such as proximate volatile matter content, fuel ratio and mean vitrinite reflectance are useful in predicting coal performance in terms of a broad trend, but all such studies appear to discover exceptions and range limits within which these parameters are reliable.

The current study concerns the prediction of coal combustion performance. It is no surprise that the heterogeneous nature of coal, and the uniqueness of each coal-forming situation in terms of age, flora, physical and geochemical setting makes the first attempts at broad predictions somewhat unsatisfactory. While several workers have outlined the usefulness of rank-based predictions, increasingly it seems that the maceral makeup of the individual coal feed particles influence their combustion behaviour.

COAL	RANK (Rort %)	PURITY of VITRINITE CONCENTRATE (%)	PURITY of INERTINITE CONCENTRATE (%)
Bayswater	0.75	86.9	82.5
Coal 92	0.93	77.4	77.1
Curragh	1.23	94.6	87.2

Table 1: Rank and Purity of Coal Concentrates

EXPERIMENTAL PROCEDURE

In order to examine the relative effects of coal rank and coal petrographic composition on combustion performance, coals of three different ranks were examined, each in the form of a vitrinite-rich and an inertinite-rich concentrate. Each concentrate was analysed petrographically by maceral and microlithotype analysis, and chemically by proximate and ultimate chemical analyses. The coals were subjected to combustion testing in an Astro bench-scale furnace at five temperatures from 900° C to 1300° C, and the percentage burnout of the carbonaceous material calculated.

When pulverised coal particles are introduced into a furnace, they undergo rapid devolatilisation for a few milliseconds, then the remaining char burns heterogeneously during the remaining residence time in the furnace. In order to gain more detailed information about how the concentrates burn, an attempt was made to analyse not just the maceral composition of the individual coal particles, but also the appearance and physical characteristics of the high temperature devolatilised char particles produced by each fraction, which then proceed to "burnout". Char pyrolysed in nitrogen at 1500° C was statistically examined by computer image analysis for its combustion-related characteristics.

COALS EXAMINED

The three coals examined were Bayswater Seam from the Whittingham Coal Measures at Ravensworth, Coal 92 from the Gloucester Basin and Pollux Seam (Curragh) from the Rangal Coal Measures, Blackwater. These coal samples had mean random vitrinite reflectances from 0.75% to 1.23% as shown in Table 1, and so ranged from high volatile bituminous to medium volatile bituminous coal. Each coal was separated into a concentrate rich in vitrinite and a concentrate rich in inertinite, by handpicking. The concentrations ranged from 94.6% vitrinite for Curragh Bright coal to 77.4% vitrinite for Coal 92 Bright Banded coal, and from 87.2% inertinite for Curragh Dull coal to 77.1% inertinite for Coal 92 Dull coal. A concentrate of Curragh Fusain was also hand-picked and consisted of 87.2% inertinite, mainly of the highly reflecting type.

RESULTS

The analyses compare two main features of the three coals used:

1. The chars of the higher volatile, vitrinite-rich fraction of each coal are compared with the chars of the corresponding lower volatile or inertinite-rich fraction.

2. The chars from the bright or vitrinite-rich fractions from three coals of different ranks are compared, as are the chars from the dull or inertinite-rich fractions of three differnt rank coals.

COMBUSTION CHARACTERISTICS OF CHAR

Significant differences exist between the types of chars produced by end-member concentrates, both in their physical characteristics such as porosity and sphericity, and in their coke texture which is widely known in carbonisation to be responsible for differences in chemical reactivity.

Char Classification Methods

Quantitative characterisation of the chars includes the measurement by image analysis of parameters relevant to the oxygen diffusion rates and chemical reactivities of the chars. The parameters measured include porosity, sphericity, mean diameter, pore size distribution, char wall thickness, presence of large pores open to oxygen and coke texture. The char classification system used to characterise the chars produced by these concentrates has been detailed previously in FUEL (Bailey et al., 1990).

The char types produced by the lithotype concentrates from the Bayswater coal are presented in two histograms, Figures 1 and 2. The char type histograms show images of the dominant char type(s), along with the char codes (Bailey et al., 1990), which increase in order of greater density. The char types are shown as a percentage of the total population.

Char Type Results

High Vitrinite Concentrates

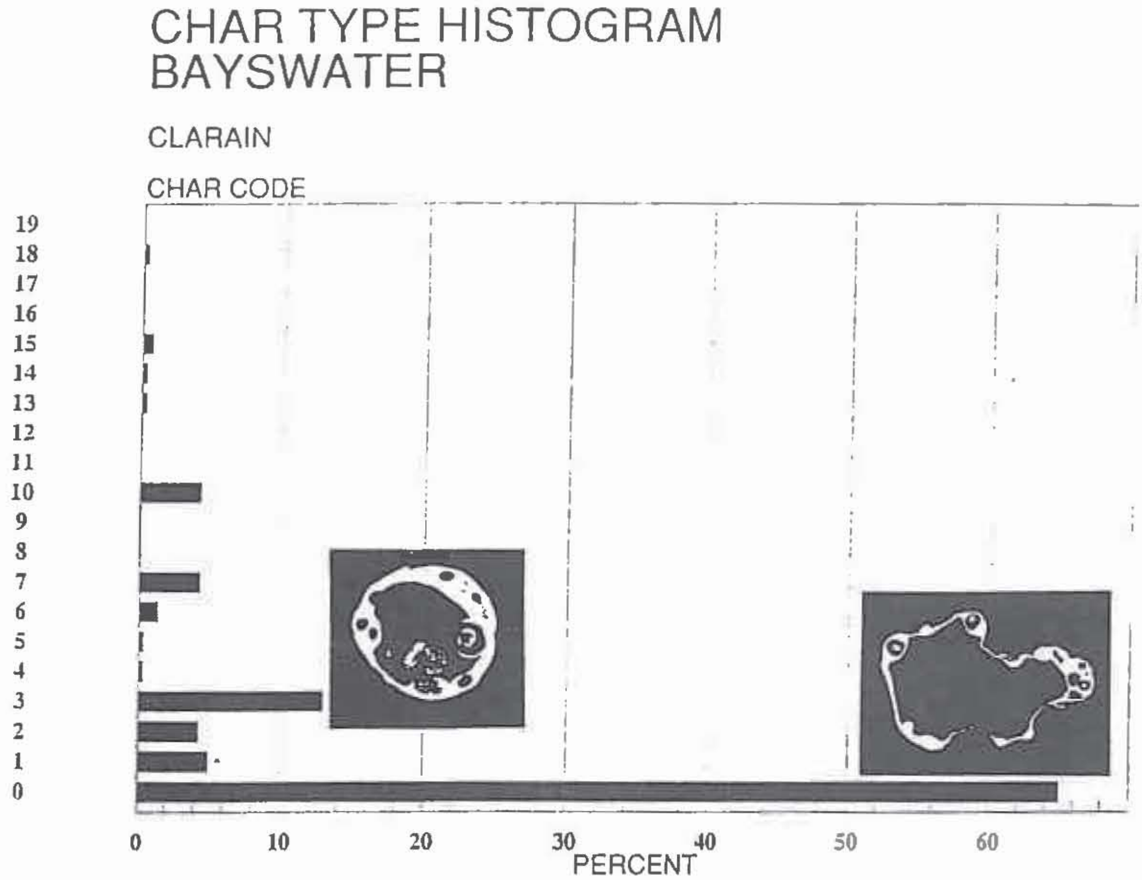
The high vitrinite fractions of all three coals produced four main char types.

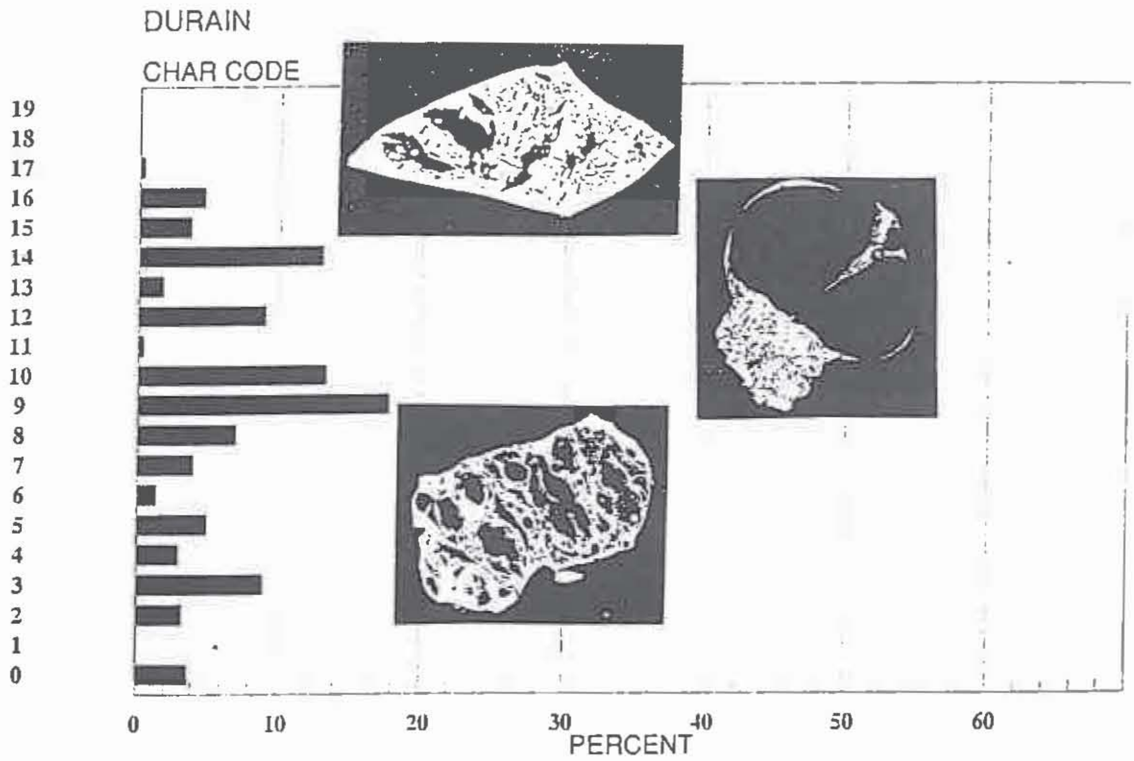
a) tenuispheres - thin-walled spheres
b) mixed porous - mixed character, > 50% porosity
c) crassispheres - thick-walled spheres
d) mesospheres - thick-walled chars of about 50% porosity

Even in the Curragh Bright fraction which had 95% purity, there were many mixed chars, thick-walled chars and some dense chars with less than 50% porosity. Lower rank coals like Bayswater are more likely to produce a more uniform char from the vitrinite fraction. Even Coal 92, at only high volatile bituminous A has a preponderance of thick-walled spheres and other high density chars. This means that the common tendency in the literature to assume that vitrinite-rich coal produces only thin-walled and uniform char is a gross simplification when considering coals of rank above hvb B.

High Inertinite Concentrates

The dull fractions of these coals produce a greater variety of char types than the vitrinite fractions. This is no doubt as a result of the greater variety of inertinite macerals than vitrinite macerals, which clearly appear to retain their individuality and to behave differently even under the extreme heating conditions of high temperature pyrolysis and combustion.





Figures 1 and 2: Histograms of Char Type for the Bayswater Chars

COMBUSTION CHARACTERISTICS OF CHAR

The inertinite-rich fractions produce chars dominated by four types:

a) mixed dense - partly dense chars with <50% porosity
b) crassinetworks - thick-walled chars with high internal surface area but limited access to oxygen
c) inertoids - thick-walled chars with <40% porosity
d) mixed porous - partly dense chars with >50% porosity

In general, these chars are thicker-walled and appear to provide less access for O_2 to their internal surface areas than most vitrinite chars. However, they are by no means solid and unreactive as is often assumed. Most of these chars develop from semifusinite and the lower reflecting inertinite macerals.

By comparison, the Curragh Fusain concentrate produced a high percentage of solid chars and char fragments. This high reflecting inertinite shows much less tendency to fuse but seems to undergo brittle splitting rather than plastic behaviour and devolatilisation.

Porosity

Overall the inertinite-rich fractions produced char of considerably lower porosity than high vitrinite char, with thicker walls and internal partitions. In all three cases the mean porosity of the inertinite-rich fraction is between 18 and 30% lower than that of the vitrinite-rich fraction.

There is a greater difference in porosity between the inertinite-rich and vitrinite-rich fractions in the lower rank coal in this study. The higher rank coals (Coal 92 and Curragh) have quite fusible inertinite and at the same time, lower volatile content in vitrinite, making both fractions more alike in porosity.

The porosity of the fusinite concentrate is far lower than for any other fraction, at about 28%, since it does not fuse to any great extent and undergoes very limited devolatilisation.

Sphericity

Mean sphericities of the particles range from about 0.53 to 0.66 for all fractions from all coals examined, except for the Curragh Fusain concentrate. This not only shows a significant departure from sphericity, but also a surprising uniformity. There is greater difference between the mean sphericities of vitrinite-rich and inertinite-rich fractions in lower rank coals, where the inertinite is less fusible and retains its angularity to a higher degree.

The sphericity of the fusinite concentrate was far lower than for any other fraction at 0.32, showing its tendency not to fuse or swell and to retain its elongate, angular appearance.

Mean Diameter

The mean diameters of the chars produced from the high vitrinite fractions are in all three cases greater than the mean diameters of the corresponding inertinite derived chars, probably as a result of swelling due to volatiles. All three inertinite-derived chars have similar mean diameters, ranging only from 54.8 to 59.4 µm, but these increase in order of rank. As coals approach coking rank, their inertinite becomes more fusible, so limited swelling may explain the slight increase in diameter.

The Bayswater vitrinite-derived char has the highest diameter of the three vitrinite-derived samples. The smaller than expected diameter for the Curragh vitrinite-derived charmay be due to rapid swelling followed by collapse as volatiles escape through the thin char walls.

Coke Texture

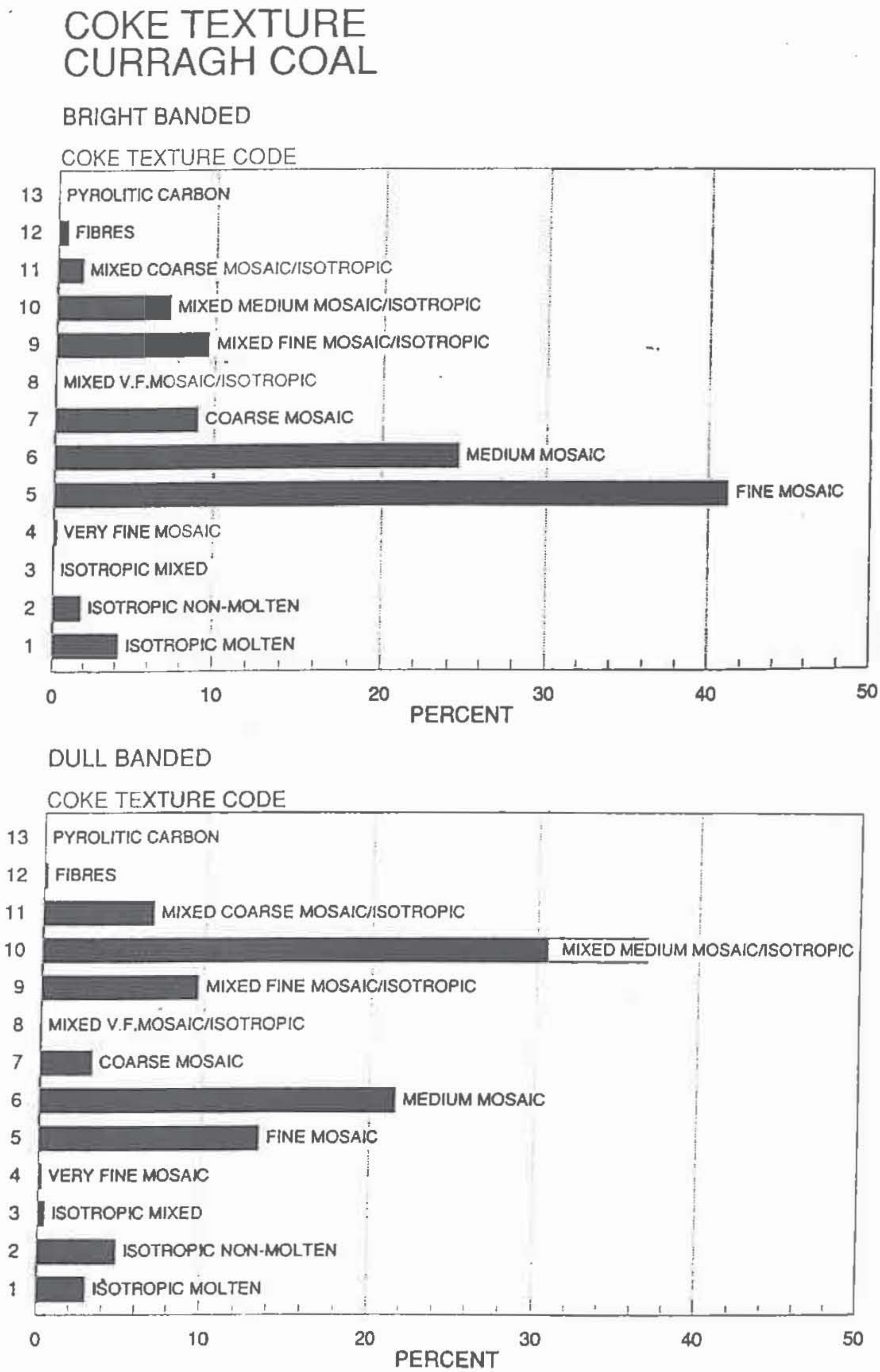
The coke textures used to classify the chars appear in Figures 3 and 4 on the histograms of coke texture for the Curragh coal fractions. Many of these terms are taken from standard ICCP and industry documents, but additional categories had to be added for the mixed chars. Unlike normal coking analyses, the particles were classified as a whole, not by one point on the particle. To account for chars with remnant isotropic inertinite sections the mixed categories 8 to 11 were added.

Coke texture was recorded in order to compare the state of devolatilisation and graphitisation of the chars from the various fractions, which has a bearing on the intrinsic chemical reactivity of the char material in carbonisation, and probably in combustion, though this is still to be proven.

In this study, greater anisotropy is developed in the chars as the coal concerned approaches coking rank. So although the heating rates and temperatures to which they have been exposed are far higher in combustion, similar trends are obtained to those for carbonisation.

The inertinite-rich fraction of all coals studied produced far more chars of mixed texture than the vitrinite-rich fraction, since some of the higher reflecting inertinite always retains its isotropic nature and result in particles with both anisotropic and isotropic texture.

If the isotropic char material is more reactive than highly anisotropic material in combustion with oxygen as it is shown to be in carbonisation, these textural differences may contribute to a better understanding of unpredictable burnout performances of some coal chars.



Figures 3 and 4: Histograms of Coke Texture for Curragh Chars

BURNOUT RESULTS

Burnout results corrected to 50 % excess air show that according to the laboratory scale testing, vitrinite concentrates do not necessarily produce a better burnout performance than inertinite concentrates.

It appears that the most clearcut example of higher vitrinite being associated with higher burnout is for the lowest rank coal tested, Bayswater coal. Coal 92 with mean random vitrinite reflectance of 0.93% shows consistently poorer burnout performance by its high vitrinite concentrate, than by its high inertinite concentrate above 950° C. Curragh high vitrinite concentrate shows better burnout than Curragh high inertinite up to 1100° C, but above this the burnout order seems to be reversed.

High reflecting inertinite contained in the Curragh Fusain concentrate shows a poorer burnout performance than the normal high inertinite Curragh concentrate at high temperature. Its better performance at lower temperatures may be partly due to the elongate narrow shapes of its coal particles, which may increase the diffusion rate of O_2 to the particles.

CONCLUSION

Significant differences have been found in the combustion-related characteristics of high temperature char produced from high vitrinite and high inertinite concentrates separated from three Australian coals. Differences in porosity, sphericity, char morphology, char size and coke texture are shown to result from differences in maceral composition, and also from changing rank when maceral composition is kept constant as far as possible.

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COAL PETROLOGY, NATURAL FRACTURES AND METHANE DRAINAGE OF SYDNEY BASIN COALS

M. SMYTH
CSIRO North Ryde Laboratories

INTRODUCTION

Prediction of natural fracturing behaviour and permeability of coal are vital to the economic exploitation of coalbed methane. The fracturing behaviour of a coal seam is related to its petrography: the frequency of fissures is highest in vitrites (Stach, 1982, p.345). The fact that 'cleat and minor jointing may be less well developed in Gondwana seams than in typical Carboniferous coal, a consequence of the comparatively few clean and thick vitrite layers in many such seams,' (ibid, p.181), may account for the lack of immediate success in the commercial exploitation of coalbed methane in the Sydney Basin.

With the lowering of pressure on a coal, methane stored on the internal surfaces desorbs and diffuses through the coal matrix into the natural fracture network of the coal. In the production of methane from coal, the gas must flow through the natural fracture network until it reaches a wellbore. If coals with high vitrite contents are most likely to have well developed natural fracture networks, knowledge of the abundance and distribution of vitrite and other microlithotypes in coals is necessary for prediction of likely flow paths.

NATURAL FRACTURES

The strength of coal microlithotypes depends on type and rank. The monomaceral microlithotypes, such as vitrite and semifusite have lower strengths than bi- and trimaceral microlithotypes (ibid, p.345). The liptinite-rich microlithotypes have the greatest strength (least likely to fracture), especially if the sporinite and cutinite contents are high, as the great toughness of these two macerals reduces the tendency for cracks to form (ibid, p.149).

Higher strengths of microlithotypes are also due to

1) poor development of bedding planes
2) thickness of heterogeneous layers in a seam
3) syngenetic mineral inclusions.

Therefore, sapropelic coals which are rich in liptinite macerals, with a high mineral content and low level of stratification, have the highest strength. These are followed by durites (with not too much included semifusinite) and then carbargilites, i.e. coal-clay mineral associations. Chalcedony and/or carbonate in fusinite cell lumens yields "hard fusite".

The frequency of fissures is highest in vitrites, and also some semifusites and fusites. Microlithotype strength can also be reduced by epigenetic minerals in cracks and fissures (ibid, p.345).

Given that all coals will fracture to some extent, it would be useful to establish typical densities of fracture networks and how interconnected they are in the various microlithotypes. Eventually such findings could be used to describe permeability, at least in a relative sense, for methane drainage.

COAL TYPE : HUNTER VALLEY SEAMS

Density contours have been drawn on plots of the microlithotype compositions of plies from seams in the Permian coal measures of the Hunter Valley. The highest value contours enclose the compositions of most commonly occurring types of coal. These compositional values have been described as "centres" and are listed in Tables 1 to 3.

The Lower Permian Greta Coal Measures, from the Maitland-Cessnock-Greta and Balmoral areas, may have some potential for methane drainage, at depth (Lohe, 1990). The most commonly occurring coal types are given in Table 1, and have compositions of 30-50% vitrite, 40-60% clarite plus intermediates (duroclarite and clarodurite) and 10% inertite plus durite. The clarite and intermediates-rich layers of the Greta Coal Measures coals could be

Table 1
Centres of density contours on microlithotype compositions of plies in Greta Coal Measures seams.
(Vitrite - Clarite + Intermediates - Inertite + Durite)

Seam	Major Centre
Greta	50-40-10
Homeville	30-60-10
Brougham Grasstrees Puxtrees (Thiess) Balmoral	30-60-10

expected to be relatively difficult to fracture, due to fine banding and high sporinite contents. The major fracturing direction is approximately parallel to the bedding and fine fractures (less than five micrometres) are virtually absent. Interconnected fractures, ten micrometres and wider, occur parallel, or at 45°, to the bedding. These, presumably, would provide pathways for the drainage of methane, as well as any fractures in the vitrite.

Coals in the Upper Permian Singleton Supergroup, listed in Table 2, have, on average, less than 10% clarite, which has been grouped with vitrite. Apart from the Bayswater seam, these coals have high vitrite plus clarite contents (65-90%), as their most commonly occurring coal types. Three of the seams include less vitrite plus clarite-rich plies throughout their thicknesses. The Bayswater seam, overall a low vitrite coal, comprises three commonly occurring types of coal through its profile, one of them with a moderate vitrite content.

Table 2
Centres of density contours on microlithotype compositions of plies in Singleton Supergroup seams.
(Vitrite + Clarite - Intermediates - Inertite + Durite)

Seam	Major Centre	Minor Centre	Minor Centre
Whybrow	90-05-05		
Wambo	80-10-10		
Blakefield			
Glen Munro	70-15-15		
Woodlands Hill			
Mt Arthur	80-10-10		
Piercefield	80-10-10		
Vaux	65-25-10		
Broonie/ Ravensworth	80-10-10	40-35-25	
Bayswater	20-40-40	50-30-20	05-05-90
Vere			
Pikes Gully	70-20-10		
Edderton			
Arties	80-10-10	50-30-20	
Edinglassie	75-15-10	55-30-15	
Liddell	75-15-10		
Ramrod Creek	70-20-10		
Barrett	70-20-10		

In the Newcastle Coal Measures, coals at the top of the sequence are inertite-rich, with plies having, commonly, compositions of 30-45% vitrite plus clarite, 20-30% intermediates (vitrinertite, duroclarite, clarodurite) and 35-50% inertite plus durite. The lower seams are vitrite-rich, with commonly occurring coal types of 70-85% vitrite plus clarite, 10-20% intermediates and 5-10% inertite plus durite (Table 3). The Rathluba seam from the Tomago Coal Measures is similar to these (Table 3).

Examples of the compositional spread of plies in the Hunter Valley coals are given in Figure 1.

Table 3
Centres of density contours on microlithotype compositions of plies in Newcastle and Tomago Coal Measures seams
(Vitrite + Clarite - Intermediates - Inertite + Durite)

Seam	Major Centre
Newcastle Coal Measures	
Wallarah	30-20-50
Great Northern	30-30-40
Fassifern	45-20-35
Upper Pilot	75-10-15
Victoria Tunnel	80-10-10
Young Wallsend	85-10-05
Borehole	70-20-10
Tomago Coal Measures	
Rathluba	80-10-10

PETROGRAPHY AND NATURAL FRACTURES

The vitrite-rich coals could be expected to have well developed, natural, fracture networks through most of their thicknesses, which should mean good permeability for methane drainage. However, many of these vitrite-rich seams contain numerous dirt bands which could interrupt the vertical interconnectedness of the finer fractures.

Intermediates-rich coals have far fewer fine and vertical natural fractures, although fractures parallel to the bedding may be useful for drainage.

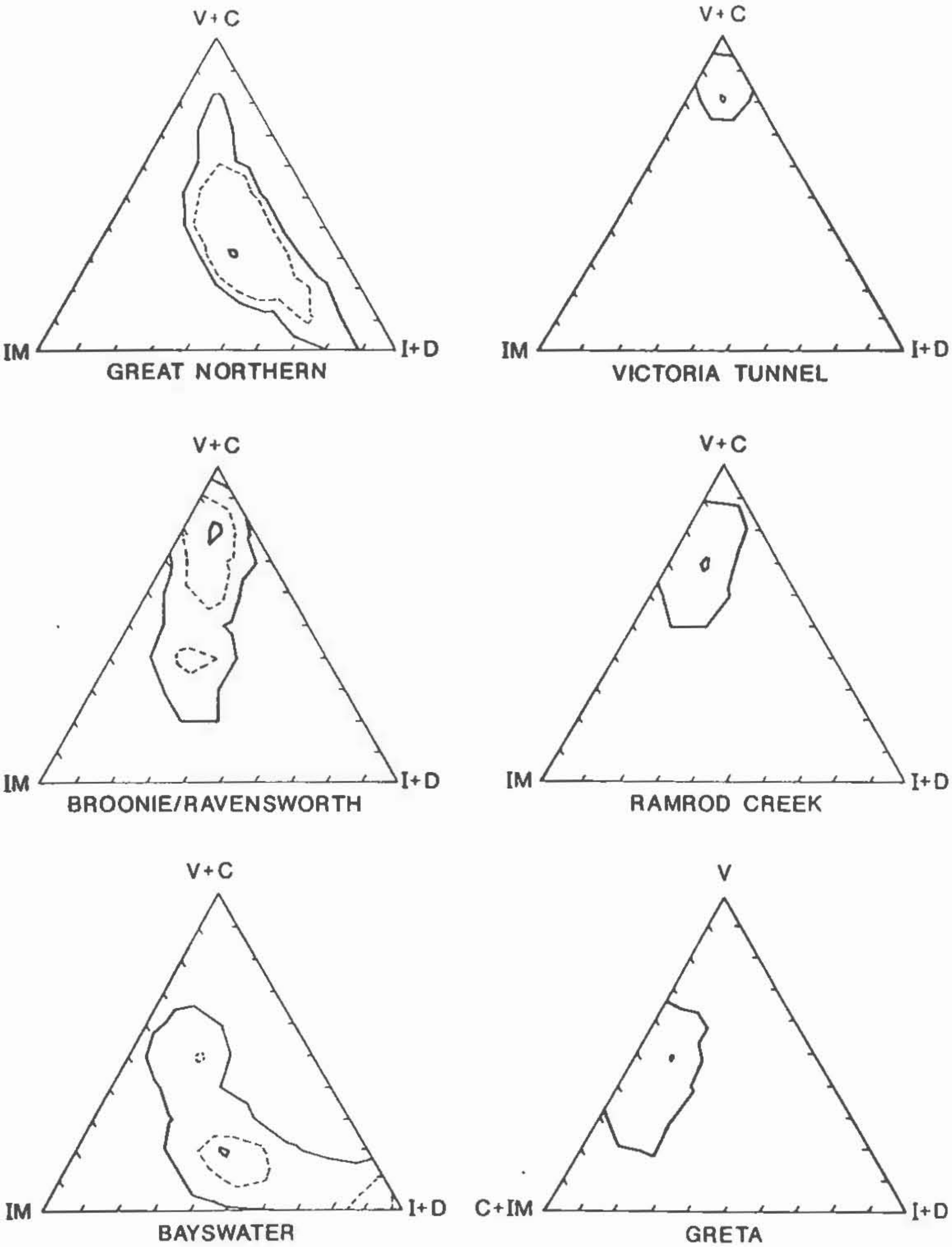

FIG.1 Spread of microlithotype compositions of plies in Permian seams from the Hunter Valley.

V=vitrite, C=clarite, IM=intermediates, I=inertite, D=durite

Inertite-rich coals also tend to lack fine fracture networks and commonly have fractures parallel to bedding. In such seams e.g. the Bayswater seam, the fracture patterns would vary throughout its thickness, depending on petrographic type. Drainage pathways may be effective in only selected parts of the seam.

Detailed knowledge of the petrology of a coal seam could be used to assess its relative suitability for the economic drainage of coalbed methane. In the Hunter Valley the large number of vitrite-rich seams suggest that, irrespective of dirt bands, the coal itself should be suitable for methane drainage.

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THE 1991 ICCP RING ANALYSIS – AN INTERESTING COMPARISON OF TWO COALS AND THEIR COKES

C.F.K. DIESSEL
University of Newcastle

At the meeting of ICCP Commission III held on 22nd February 1990 in Wollongong, NSW, it was decided to carry out a ring analysis on two coking coal samples of similar rank and with similarly high inertinite contents, one from the Ruhr Basin (Seam A), the other from Australia (Bulli Seam, Wollondilly Colliery). Participants in this ring analysis were asked to use their respective methods for assessing the proportion and extent of inertinite fusibility. Both coals were carbonised simultaneously in two separate containers in the BHP-CRL pilot coke oven in order to exclude any influence on inertinite behaviour by process variables. The coking conditions are listed in Table 1.

Table 1. Summary of the coking conditions and measured coke stability of the Bulli and Ruhr samples.

	Bulli	Ruhr
Coal Grind	85 % minus 3 mm	85 % minus 3 mm
Dry Bulk Density (Kg/m^3)	762	762
% Moisture of the Charges (ad)	8.5	8.5
Time to 900° in Oven Centre	12.9 hrs	
Total Coking Time	17.0 hrs	
Centre Temperature at Push	1065°	
Wall Temperature at Push	1115°	
Coke Yield *	77.1%	76.9%
Coke Stability JIS DI 30/50	13.7	24.0
JIS DI 30/15	93.1	92.3
JIS DI 150/50	3.3	6.8
JIS DI 150/15	80.7	81.2
ASTM **	53.9	54.5

* Calculated as *89.662 - 0.438 VM (db)* ** Calculated from JIS DI 150/15

A comparison of the two coals is given in Table 2. As expected, the Carboniferous Ruhr coal contains much more liptinite than the Bulli coal which is notably higher in ash (and mineral) content. The combined vitrinite and liptinite values are 47.8% for the Bulli coal and 47.2% for the Ruhr coal. Alternatively, the combined inertinite and mineral percentages are 52.2% and 52.8%, respectively, which demonstrates the considerable similarity of the two coals. Both samples are high volatile bituminous coals, although the Ruhr coal is marginally higher in rank as demonstrated by the volatile matter and vitrinite reflectance values listed in Table 1.

Table 2. Comparison of proximate (in % by mass) and petrographic (macerals in % by volume) analyses between the Bulli (Y18610) and Ruhr (Y18611) coal samples.

	Bulli (Y18610)	**Ruhr (Y18611)**	∂
Moisture (ad)	2.2	2.3	+0.1
Ash (ad)	8.1	3.1	-5.0
Volatile Matter (ad)	28.1 (31.3 daf)	28.4 (30.0 daf)	+0.3
Fixed Carbon (ad)	61.6 (68.7 daf)	66.2 (70.0 daf)	+0.6
Mean Random Telovitrinite Reflectance (%Rort)	0.95	1.00	+0.05
Telovitrinite	21.0	14.8	-6.2
Detrovitrinite	24.0	20.7	-3.2
VITRINITE	**45.0**	**35.5**	**-9.5**
Sporinite	2.2	9.8	+7.7
Cutinite	0.1	0.6	+0.5
Resinite	0.5	1.3	+0.8
LIPTINITE	**2.8**	**11.7**	**+8.9**
Micrinite	1.0	1.7	+0.7
Macrinite	4.5	5.0	+0.5
Semifusinite	20.1	22.6	+2.5
Fusinite	2.2	2.9	+0.7
Inertodetrinite	20.8	19.2	-1.6
INERTINITE	**48.6**	**51.4**	**+2.8**
MINERALS	**3.7**	**1.4**	**-2.3**

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Whole coal reflectograms of the two samples are illustrated in Figure 1. Apart from the more pronounced liptinite peak in the Ruhr coal the main differences between the two samples are the broader based vitrinite and inertinite reflectance distribution in the Bulli coal and its higher proportion of low reflecting inertinite. Both reflectograms have been

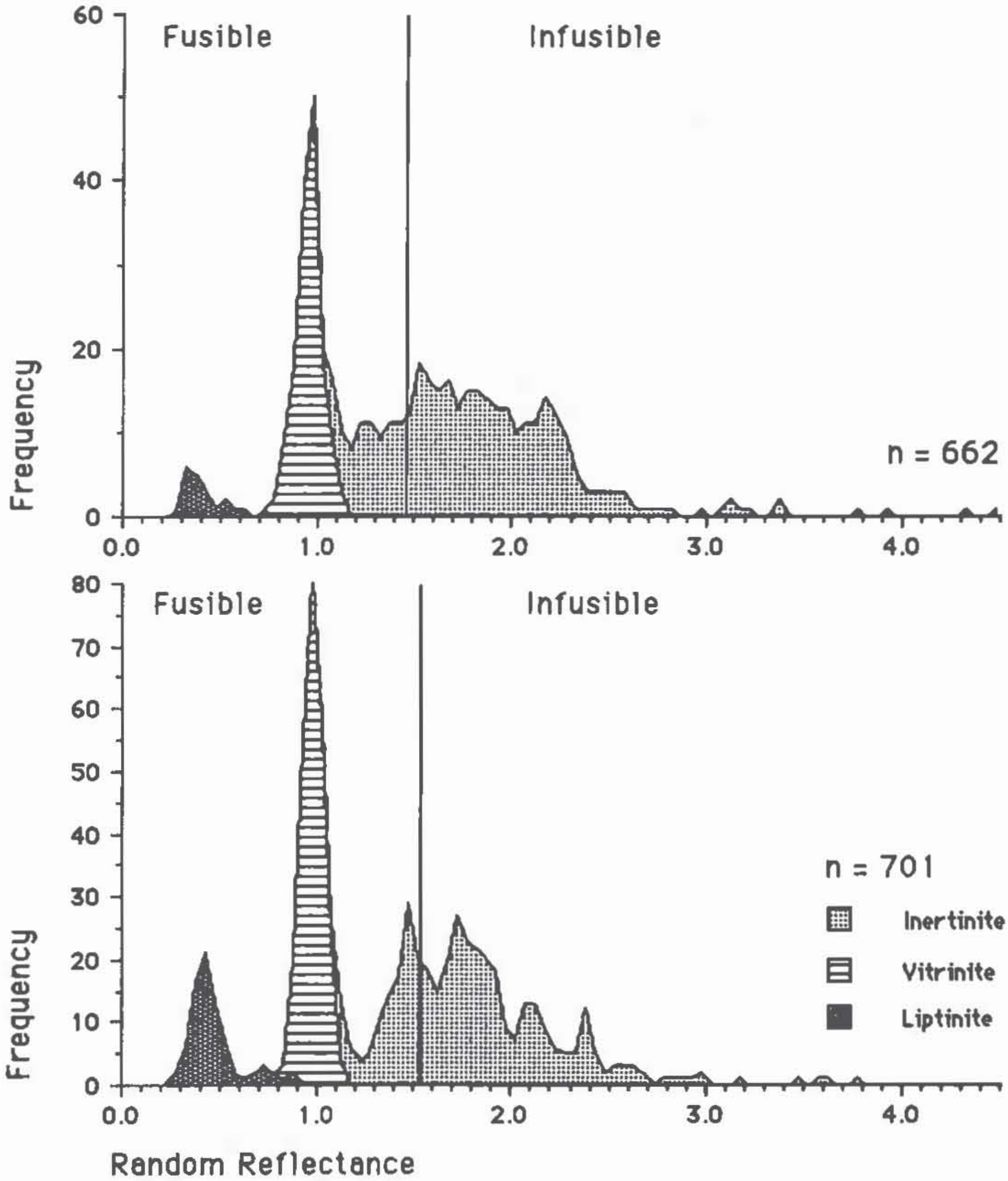

Figure 1. Whole coal reflectograms of the Bulli (top) and Ruhr (bottom) coals with fusibility limits according to Schapiro et al. (1961) and Schapiro and Gray (1964).

divided into a fusible and infusible portion by regarding 1/3 of semifusinite (+ macrinite) as being fusible in accordance with the Schapiro-Gray method. The respective ASTM coke stabilities were calculated to be 33 for the Bulli coal and 39 for the Ruhr coal. These figures compare poorly with the ASTM coke stabilities of 53.9 for the Bulli coal and 54.5 for the Ruhr coal listed in Table 1. The ASTM coke stability factors have been calculated

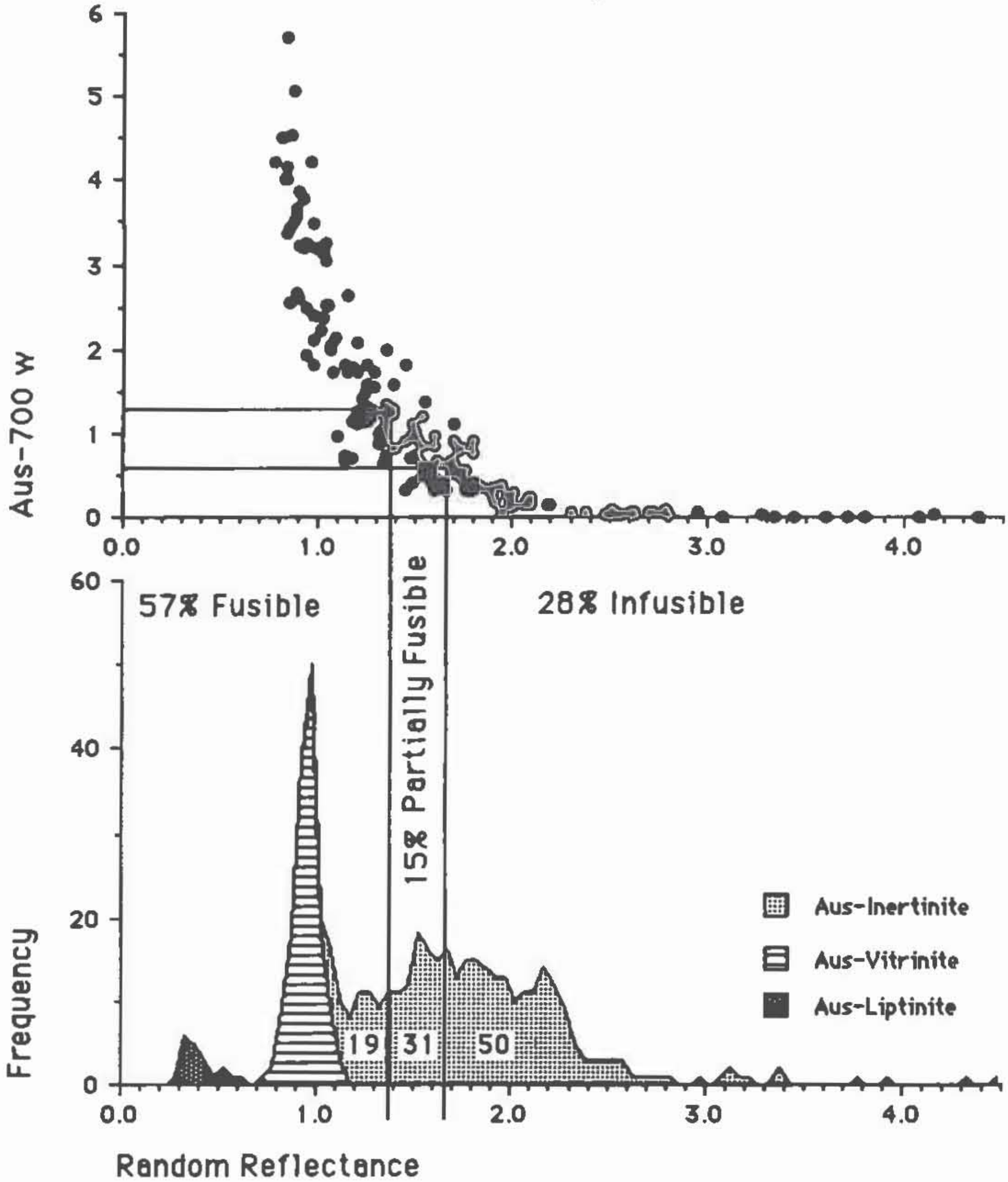

Figure 2. Whole coal reflectogram of the Bulli coal divided into fusible, partially fusible and infusible portions according to Equations [1] and [2]. The figures within the inertinite field are percentages normalised to inertinite = 100%. Projection of the fusibility boundaries to the superimposed fluorogram gives fluorescence cutoff values.

from the Japanese Drum Indices which, because of the small sample size, were the only stability indices actually determined on the coke made from the two coals.

Given that the failure to give correct estimates of coke stability indices in past ICCP ring analyses of Gondwana coals was generally due to an underestimation of the high degree of fusibility of many of their inertinite group macerals, the question of the degree of fusibility of inertinite has

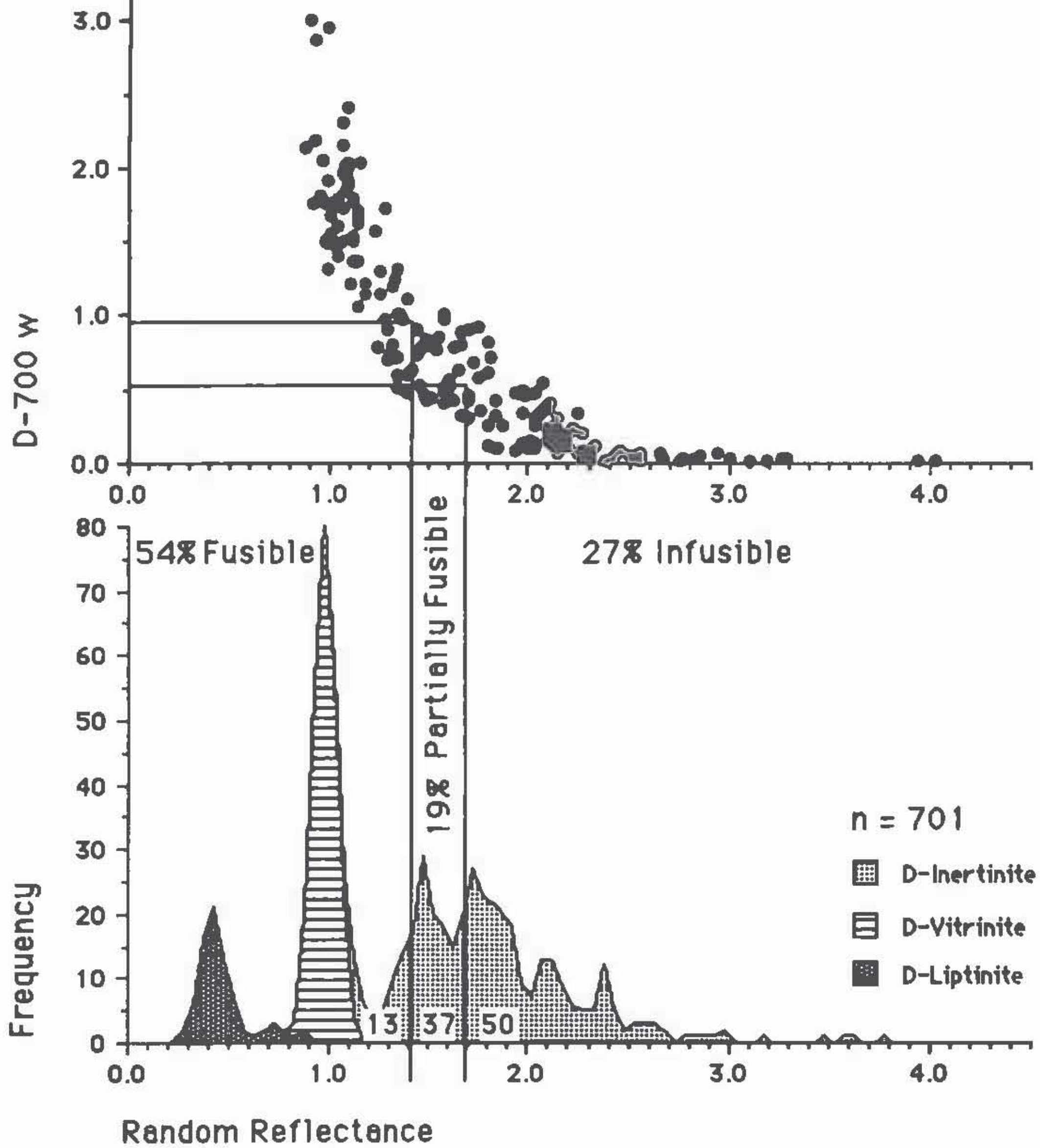

Figure 3. Whole coal reflectogram of the Ruhr coal divided into fusible, partially fusible and infusible portions according to Equations [1] and [2]. The figures within the inertinite field are percentages normalised to inertinite = 100%. Projection of the fusibility boundaries to the superimposed fluorogram gives fluorescence cutoff values.

received much attention in the past years which has led to the development of new diagnostic techniques. One of these divides the reflectogram into fusible (low reflectance), partially fusible (intermediate reflectance), and infusible (high reflectance) portions whose cutoff boundaries correspond to the rank of the feed coal (expressed as mean random telovitrinite reflectance measured in oil = Rort) as follows (after Diessel and Wolff-Fischer, 1986; and Diessel and Bailey, 1989):

Reflectance cutoff between fusible and partly fusible macerals

$$= 0.74 + 0.67 \text{ Rort} \qquad [1]$$

Reflectance cutoff between partly and non-fusible macerals

$$= 1.18 + 0.51 \text{ Rort} \qquad [2]$$

Table 3. Comparison of the microfabric of the cokes made from the Bulli and Ruhr coals, respectively.

Fabric Element		**Anisotropy Domain Size**	**Bulli**	**Ruhr**
a. Isotropic		submicroscopic	0.8	0.3
b. Incipient Anisotropic		< 0.5 µm	5.1	5.0
c. Circular Anisotropic	- fine	0.5 - 1.0 µm	39.3	39.0
d. " "	- medium	1.0 - 1.5 µm	3.4	7.2
e. " "	- coarse	1.5 - 2.0 µm	0.8	4.0
f. Lenticular Anisotropic*	-fine	2.0 - 5.0 µm	0.7	1.8
g. " "	- medium	5.0 - 10.0 µm	0.1	0.7
h. " "	- coarse	10.0 - 15.0 µm	0.6	0.8
i. Ribbon Anisotropic*	- fine	15.0 - 20.0 µm	-	-
j. " "	- medium	20.0 - 25.0 µm	-	-
k. " "	- coarse	>25.0 µm	-	-
l. Pyrolitic Carbon			0.4	0.2
m. Coke Matrix			**51.2**	**59.0**
n. Anisotropic (partially fused) Inertinite			18.7	13.8
o. Isotropic (unfused) Inertinite			26.1	25.5
p. Total Inertinite			**44.8**	**39.3**
q. Minerals			**4.0**	**1.7**

* Refers to maximum width.

When applied to the Bulli and Ruhr coals the two equations yield the fusibility limits illustrated in Figures 2 and 3, which confirm previous observations (Diessel, 1990) that in high and medium volatile bituminous coals in average only 50% of the inertinite is completely infusible. It appears now that this relationship is also true for Carboniferous coals.

In order to test the validity of the results obtained from the application of Equations [1] and [2], coal-to-coke mass balance calculations were carried out according to the method described by Diessel and Wolff-Fischer (1986 and 1987). This method takes into account the mass distribution of the various macerals and minerals contained in the feed coal. By applying empiric figures for devolatilisation during carbonization and for coke yield, the amount of unfused coke inclusions which would be expected, if all inertinite in the feed coal was truly infusible, is calculated. The proportion of fusible inertinite is the difference between the predicted amount of unfused inertinite in the coke and the invariably smaller amount of either unfused or partially fused inertinite actually determined in the coke by the microfabric analyses listed in Table 3.

The analysis results suggest that 16% of the inertinite contained in the Bulli coal fused completely, 35% fused partially and 49% remained inert. The respective figures predicted from Equations [1] and [2] and Figure 2 are 19%, 31% and 50%. In the Ruhr coal the mass balance calculations indicate that inertinite has contributed 19% to the fused coke matrix, 29% to partially fused coke, while 52% remained unfused. The respective figures predicted from Equations [1] and [2] and Figure 3 are 13%, 37% and 50%. Apart from the small variations in the proportion of fusible and partially fusible inertinite obtained by the two different analysis methods, these figures show that there is good agreement on the amount of infusible inertinite, which in both samples is approximately 1/2 of the total inertinite. The ASTM coke stabilities calculated on this basis are 55 for the Ruhr coal and 52 for the Bulli coal, which agrees well with the respective figures listed in Table 1.

Finally, attention is drawn to systematic differences in the fluorescence properties between the Bulli and Ruhr coals. In previous investigations of the carbonisation behaviour of Australian Permian and European Carboniferous coals (Diessel and McHugh, 1986; Diessel and Wolff-Fischer, 1986, 1987) Permian coals revealed consistently and significantly higher vitrinite fluorescence intensities than Carboniferous coals of the same rank. The two coals analysed in this study show the same trend, although extreme care was taken to avoid any differences in the timing and conduct of the sampling procedure and subsequent sample treatment. Histograms of microfluorescence measurements of telovitrinite are illustrated in Figures 4 and 5. In each of the illustrations three results

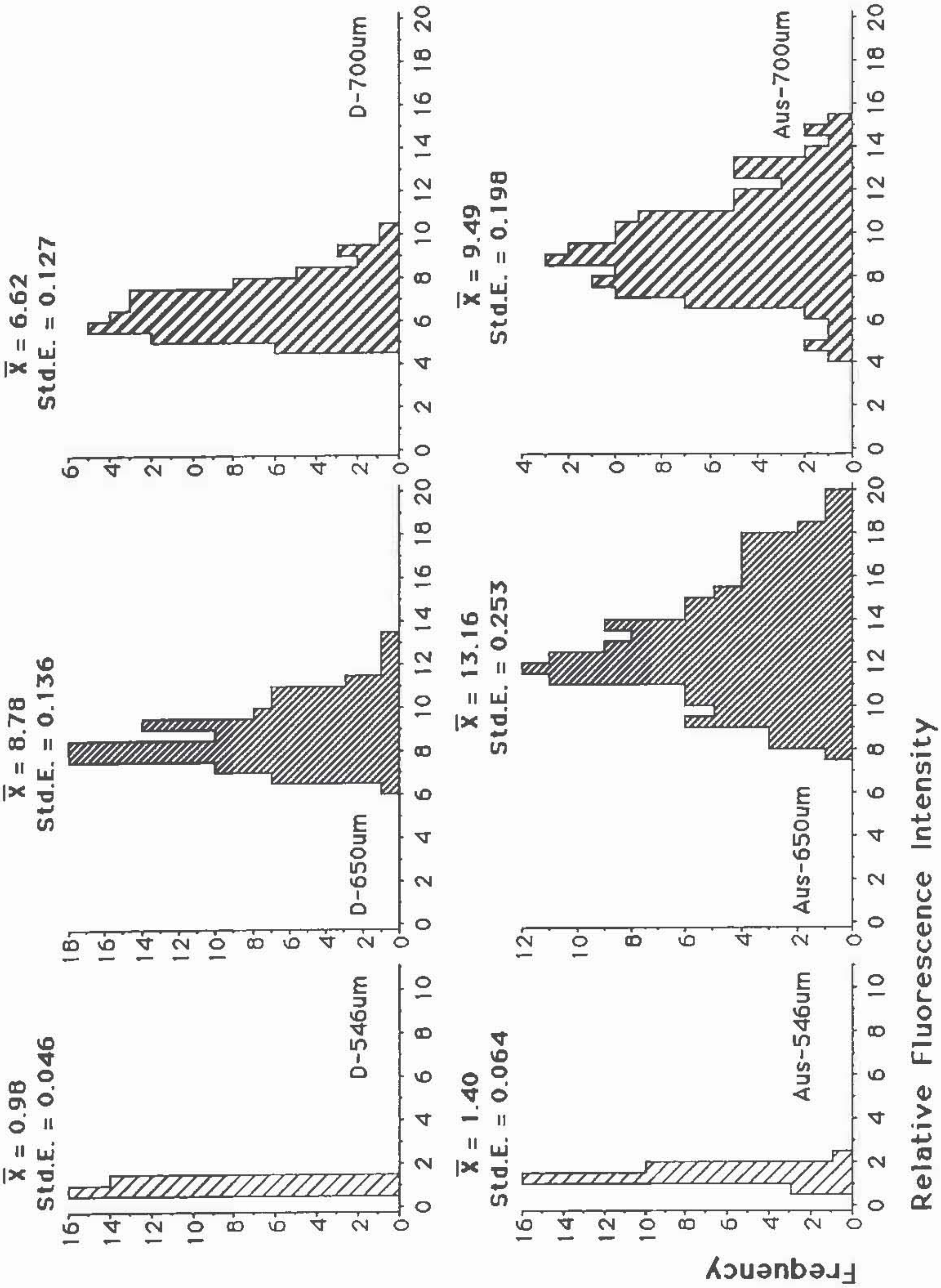

Figure 4. Comparison of the microfluorescence intensities of telovitrinite measured at 546 nm, 650 nm and 700 nm wavelength in the Ruhr (top) and Bulli (bottom) samples. Calibration was by unmasked uranyl-glass standard.

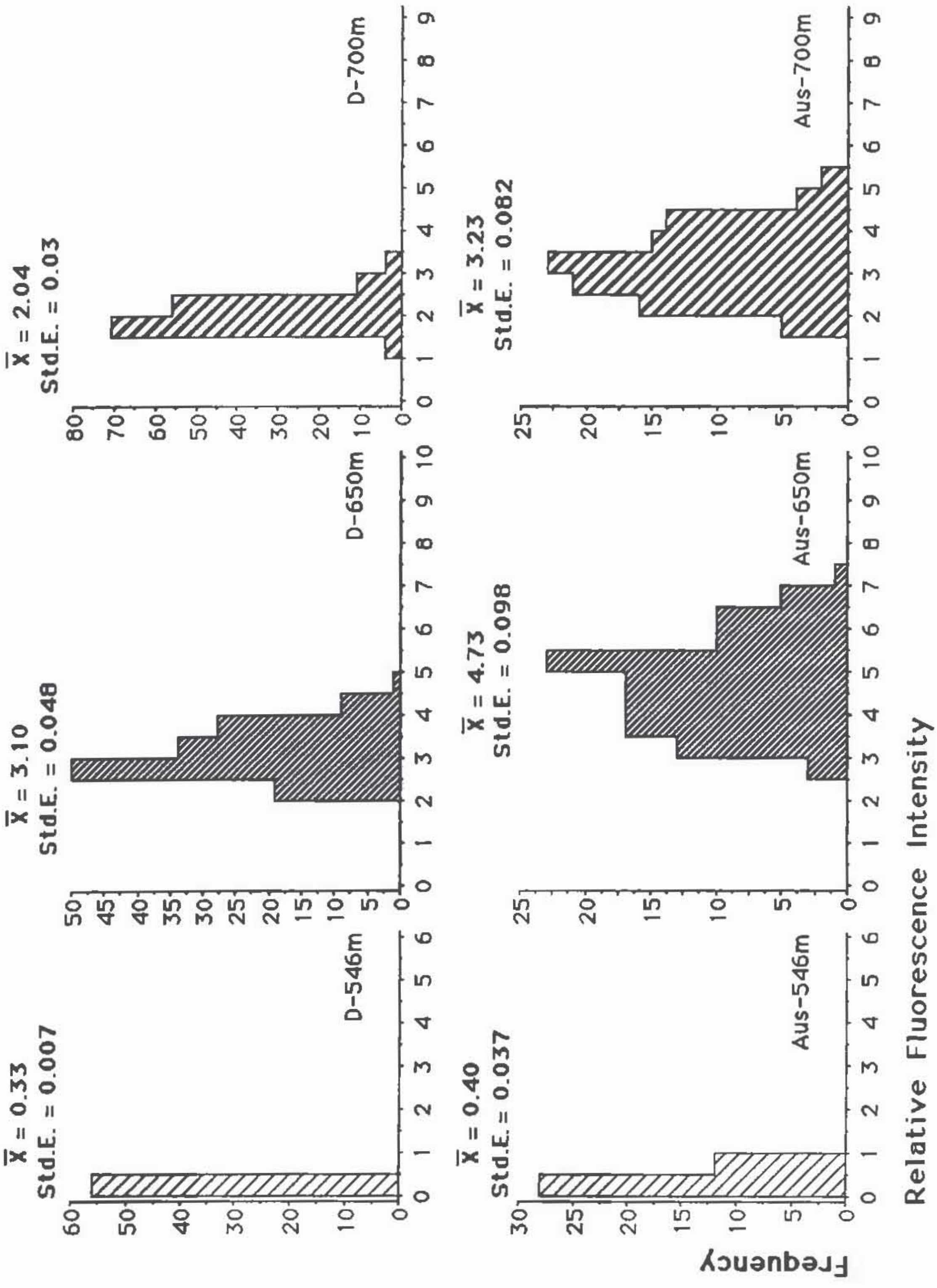

Figure 5. Comparison of the microfluorescence intensities of telovitrinite measured at 546 nm, 650 nm and 700 nm wavelength in the Ruhr (top) and Bulli (bottom) samples. Calibration was by masked uranyl-glass standard.

obtained at 546 nm, 650 nm and 700 nm wavelength are shown for both coals. In Figure 4 the fluorescence readings were calibrated against an unmasked uranyl-glass standard while in Figure 5 a masked uranyl-glass standard was used. The reasons for these differences are not known but, as shown in Figures 4 and 5, they are consistent in the longer wavelengths. They warrant a thorough investigation not only for reasons of scientific curiosity but also for commercial reasons in view of the link that appears to exist between fluorescence intensity and thermoplastic properties, as shown in Figures 2 and 3.

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