Malcolm Bocking

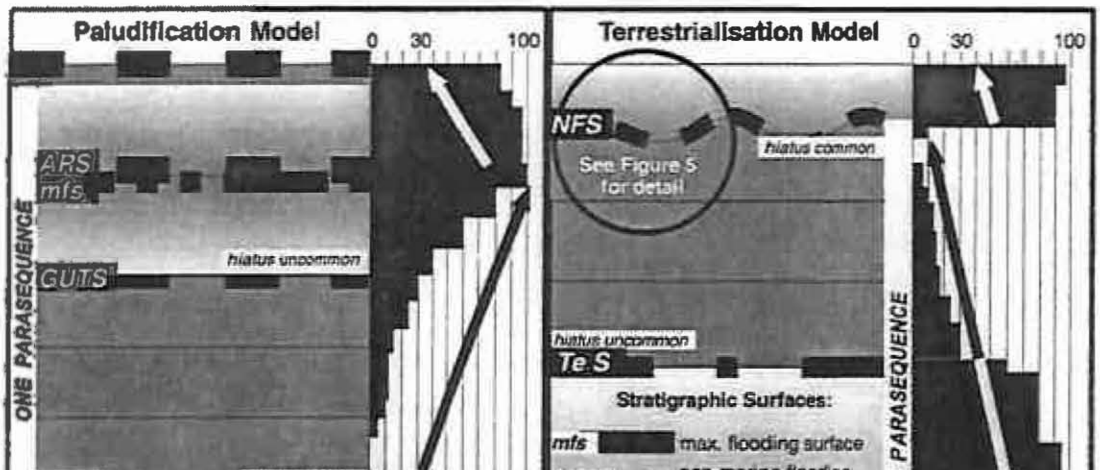
THIRTY THIRD NEWCASTLE SYMPOSIUM

on

ADVANCES IN THE STUDY OF THE SYDNEY BASIN

JULY 30 - AUGUST 1, 1999

NEWCASTLE NSW AUSTRALIA



DEPARTMENT OF GEOLOGY, *The* UNIVERSITY *of* NEWCASTLE

ISSN 0727-0097

It is recommended that reference to the whole or part of this volume be made in the following form:

DIESSEL, C., SWIFT, E.K. & FRANCIS, S. 1999. *Proceedings of the 33rd Newcastle Symposium, "Advances in the Study of the Sydney Basin"*, The University of Newcastle.

The UNIVERSITY *of* NEWCASTLE

Callaghan, New South Wales, 2308

DEPARTMENT OF GEOLOGY

Publication No. 858

Cover:
Two sequence-stratigraphy models of coal-bearing parasequences.

The UNIVERSITY *of* NEWCASTLE
AUSTRALIA

PROCEEDINGS OF THE THIRTY THIRD NEWCASTLE SYMPOSIUM

on

"ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

edited by C Diessel, E Swift & S Francis
***The* University *of* Newcastle**

July 30 - August 1 1999
NEWCASTLE NSW 2308 AUSTRALIA

CLAUS DIESSEL
CONVENER

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

PREFACE

Welcome to the Newcastle Symposium! Have I not written this many times before? It sounds like a blast from the past, and I would not have thought that after having retired from official duties for seven years now, I would be dragged away from Mozart, Puccini and my microscope to convene another Symposium. But here I am, hoping to remember old tasks and trying to learn new ones, because many things have changed since the last time I did this job.

Of course budgets have always been tight, but in the past we could operate a slush fund within the Geology Department, which allowed us to handle the Symposium's finances ourselves. Now every cent has to pass along a convoluted route through the University's administrative services, which makes it all rather cumbersome. Years ago, the phrase "economic rationalism" was something one associated Canberra with but not the seats of learning. Now this paradigm affects even the Newcastle Symposium which has to pay for the use of all campus facilities including our own building. So, please, be patient when the morning and afternoon teas in the foyer of the Geology building are a bit crowded, our old venue in the foyer of the Great Hall would have cost you more in registration fees.

Tight University budgets are also the main reason for my convenership this year. In common with other departments around campus, the Geology Department operates on a shoestring and is inadequately staffed; so much so that when Ron Boyd, the current more or less permanent convener, went on study leave this year, the Symposium seemed doomed. However, this did not go down well with some of our regular patrons whose persuasive arguments led to the present arrangement.

So here we are ready to go, slightly down in numbers but with a full and interesting program which covers a wide range of geological topics. In lieu of a keynote address, the 33rd Newcastle Symposium will host the inaugural Kenneth George Mosher Memorial Lecture. This new annual lecture in honour of the former Chief Geologist of the Joint Coal Board has been created by the New South Wales Coalfield Geology Council to be given in conjunction with the Newcastle Symposium. The choice of the Newcastle Symposium as a venue for this important new lecture series is deeply gratifying to us and indicates the high regard the coal-geological community has for our work. The inaugural lecture on the life and work of Ken Mosher will be given be Brian Vitnell. We are honoured to have Mrs Mosher with us for the occasion.

Another highlight will be the core display on Friday in and around the core shed of the Geology Department, which offers a detailed comparison of the Newcastle Coal Measures and their stratigraphic correlatives in the Upper Hunter Valley and the Gunnedah Basin. The display takes the form of an extended poster paper put together by Jeff Beckkett and his colleagues, and is a unique opportunity to gain insight into the uppermost Permian rocks outside the Newcastle Coalfield.

Finally, I am looking forward to seeing many old and new friends and colleagues again, and wish you an enjoyable time in Newcastle.

Claus F.K. Diessel
Convener, 33rd Newcastle Symposium

FOREWORD

Welcome to Newcastle and another Newcastle Symposium! This is a Symposium that might not have happened, except for the enthusiasm and tenacity of Claus Diessel, who came out of a well-earned retirement from the Convener's job to organise this year's program. Ron Boyd has been a major driving force behind the Symposium for the last few years. With Ron in Calgary for the year on an outside studies program and severe staff shortages in the Department, we owe Claus our gratitude for his efforts in preserving the annual tradition of our major geological conference.

Since the functions for this year's Symposium are being held close to, or within the Department you will see that substantial changes have taken place in the Geology building over the last year. Externally, the appearance of the building is unchanged, but close to $750 000 has been spent on refurbishing the interior, including the upgrade and re-design of laboratories, the provision of better teaching facilities , major improvements in electrical and computer services, and a general facelift for rooms and passageways. The loading dock and rear access has been redesigned, with the emphasis on improving the link to our new rock and core library and logging facility in the old garage. Those of you who have observed the core display will realise the value of the core logging area, which has already become an extremely important resource for teaching and research. The finished result of all this reorganisation looks good and functions well, but belies the huge upheaval during renovations, when every room in the department had to be emptied and the contents and occupants relocated as work progressed through the building.

On staff matters, we welcome Elaine Swift as Administrative Assistant in the Department, replacing Judi Winwood-Smith while Judi is on leave in Samoa for the year. Elaine has tackled her new role with much energy and initiative and appears to have survived her first Symposium unfazed! The achievements of two other staff members deserve recognition. First, it is very pleasing to note that Bill Collins has been promoted to Associate Professor. This is an excellent achievement for Bill, and is particularly meritorious since only a few applications were successful in the last round. For the first time, awards have been made to the general staff and I am delighted that Richard Bale was singled out for an award, highlighting his huge contribution to technical work in the Department over many years.

Finally, it is great to note that a baby boom has struck the Department in the space of about six months! Leading off the charge were Kev Ruming and Sue with the arrival of Jemima, closely followed by no less than twins (Emma and Harry) for the Collins household (and Bill was always telling us how busy he was even before this event). Judy Bailey produced another young lad (Tim) earlier this year, followed by the arrival of Stuart from Jennifer Wadsworth and Tim Rolph. Balance is now restored to the age profile of the Department!

Phil Seccombe
Associate Professor
Head, Department of Geology

NEWCASTLE SYMPOSIUM PROGRAM

"ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

Friday	**30 July 1999**	
0.900 - 17.30	Illustrated display of bore cores for the purpose of comparing the Newcastle Coal Measures with the stratigraphically equivalent Wollombi Coal Measures in the Upper Hunter Valley and Gunnedah Basin. The display is in the form of an extended poster paper presented by J. Beckett, M. Creech, J. Maloney, W. Pratt, D. Stevenson and L. Wiles, under the title: *Newcastle to Narrabri - One basin, one stratigraphy.* Venue: core library of the Department of Geology. Morning and Afternoon teas are provided. Lunch facilities are available in the University Union. An introduction to the display will be given at 10.00 by Mr J. Beckett.	
18.30	**ICEBREAKER SHEEP ROAST in the UNIVERSITY SHORTLAND UNION**	
Saturday	**31 July 1999**	
08.30 - 09.00	**REGISTRATION** - Foyer of the Geology Building	
TECHNICAL SESSION 1	LECTURE THEATRE - STH *Chair* R Offler	
09.00 - 09.10	WELCOME by the Head of the Geology Department, Associate Professor Philip Seccombe	
09.10 - 09.35	*Mr J Enever* *CSIRO Petroleum* *Dr W Gale*	The Contemporary Stress Field in the Newcastle Coal Measures
09.35 - 10.00	*Mr T Jones* *AGSO*	Reducing the Risk from Hunter Earthquakes: the Newcastle '99 project
10.00 - 10.25	*Mr M Ives* *PowerCoal*	Environmental Management in Exploration
10.25 - 11.00	**MORNING TEA in the FOYER of the Geology Building**	
11.00 - 11.20	*Prof C Diessel* *The University of Newcastle*	Particulate UFO's and IFO's in Newcastle's air
11.20 - 11.45	*Mr R Othman &* *A/Prof Colin R Ward* *University of NSW*	Stratigraphic Correlations in the Southern Bowen and Northern Gunnedah Basins Northern NSW
11.45 - 12.10	*Dr D Branagan* *University of Sydney*	Beyond the Northern Boundary: The early years of New England geology
12.10 - 12.40	***Mr B Vitnell*** ***Coal Geologist (retired)***	**The Coalfield Geology Council of NSW - Kenneth George Mosher Inaugural Memorial Lecture**
12.40 - 12.45	*CHAIR*	VOTE OF THANKS
12.45 - 13.50	**LUNCH in the UNIVERSITY SHORTLAND UNION**	

Saturday	31 July 1999	
TECHNICAL SESSION 2	LECTURE THEATRE - PG08 (Main theatre in Physics Building) *Chair* D Branagan	
13.50 - 14.15	*Dr P Carr & Dr B Jones University of Wollongong*	Lava tubes, lobes and sheets: emplacement of the Late Permian, marginal basin Blow Hole flow, Southern Sydney Basin
14.15 - 14.45	*Mr J Brownlow & Mr R Arculus NSW Dept Mineral Resources*	Composition and Origin of the Early Permian Boggabri Volcanics, Gunnedah Basin, NSW
14.45 - 15.15	*Mr S Morton Coffey Geosciences*	Some trends noted in the Nerong Volcanics North of Karuah
15.15 - 15.45	**AFTERNOON TEA in the FOYER of the Geology Building**	
15.45 - 16.15	*Dr P Hatherly et al. CSIRO*	The influence of coal measure gas on seismic exploration data in the Southern Sydney Basin
16.15 - 16.45	*Dr J Esterle CSIRO Explor.& Mining*	Effect of Comminution Energy on Rosin Rammler Distributions for Coal
16.45 - 17.15	*Mr A Van Heeswijck Eurydesma Geological Services*	Evidence of rifting in the Northern Sydney Basin.
17.15 - 17.45	*Mr T Harrington & A/Prof R Offler The University of Newcastle*	New insights into the deformation history of the Hunter Coalfield
17.45 - 17.50	*CHAIR*	VOTE OF THANKS
Saturday	31 July 1999	
TECHNICAL SESSION 3	LECTURE THEATRE - STH *Chair* C Bacon	
13.50 - 14.15	*Mr R Gwyther et al. CSIRO*	Rock Mass Deformation Monitoring
14.15 - 14.45	*Dr Gang Li Coffey Geosciences*	Direct Observation of Longwall Caving within the Overburden
14.45 - 15.15	*Dr B Agrali Bullant Associates*	Roof Rolls, Clay Dykes and related features in the Bulli Seam, Burragorang Valley Mines, NSW
15.15 - 15.45	**AFTERNOON TEA in the FOYER of the Geology Building**	
15.45 - 16.15	*Mr D Stevenson Dept of Mineral Resources*	The Wollombi Coal Measures
16.15 - 16.45	*Ms W Kramer et al. The University of Newcastle*	Correlation of tuffs in the Newcastle and Wollombi coal measures based on geochemical fingerprinting
16.45 - 17.15	*Dr H Zwingmann University of Wollongong*	K/Ar dating of authigenic clays related to igneous intrusions in Hunter Valley Coals
17.15 - 17.45	*Dr L Gurba University of NSW & Mr C Weber, Pacific Power*	Influence of igneous intrusions on coalbed methane potential, Gunnedah Basin, NSW
17.45 - 17.50	*CHAIR*	VOTE OF THANKS
19.00 for 19.30	**SYMPOSIUM DINNER in the UNIVERSITY SHORTLAND UNION**	

Sunday	1 August 1999	
TECHNICAL SESSION 4	LECTURE THEATRE STH *Chair* P Seccombe	
09.05 - 09.30	*Dr L Gurba* *& Colin Ward* *University of NSW*	Coalification pattern of the Gunnedah Basin, NSW
09.30 - 09.55	*Dr A Hutton* *University of Wollongong* *Mr R Doyle* *Shell Coal Australia*	Carbonate speciation in Wynn Seam coal
09.55 - 10.20	*Mr P McClelland* *Ultramag Geophysics*	Airborne vs ground magnetics for intrusion delineation in the Hunter
10.20 - 10.45	*Prof C. Diessel* *et al.* *The University of Newcastle*	New significant surfaces in onshore sequence stratigraphy
10.45 - 11.15	**MORNING TEA in the FOYER of the Geology Building**	
11.15 - 11.40	*Mr H Kahraman* *CSIRO*	A review of coal quality prediction from geophysical logs
11.40 - 12.05	*Dr J Esterle* *CSIRO*	Controls on Phosphorous Variability at the Minescale
12.05 - 12.30	*Ms A Golab* *University of Wollongong*	Ionic and Sulphur Isotope Composition of Illawarra Rainfall
12.30 - 12.55	*Mrs V Hatje* *University of Sydney*	Trace Metal Distribution in Port Jackson Estuary, Sydney
12.55 - 13.00	*CHAIR*	VOTE OF THANKS
13.00 - 14.00	**LUNCH in the UNIVERSITY SHORTLAND UNION**	
14.15 - 16.00	Standards Association MN/1/5/1 Coal Petrology Working Group Meeting	

VISITOR PARKING INFORMATION

Visitors are required to park in General car-parking areas, not Staff, Reserved or Service Vehicle parking areas.

Visitors who park a motor vehicle (including a motor cycle) on the Callaghan Campus are required to pay a motor vehicle entry fee.

Fees apply Monday to Friday, between the hours of 8 am and 5.30 pm throughout the year, but NOT on weekends.

Single day entry permits may be purchased from coin operated vending machines, which are located at entrances and all major car parks on the Callaghan campus (shown on plan overleaf). The cost of a daily permit is $1.

The permit MUST be clearly displayed on the dashboard of the car. Failure to pay the prescribed fee or parking other than in a General parking bay may result in a $60 fine.

THE CONTEMPORARY STRESS FIELD IN THE NEWCASTLE COAL MEASURES

J Enever

CSIRO Petroleum, PO Box 3000 Glen Waverley, Vic 3150

INTRODUCTION

In a previous Sydney Basin Symposium (Enever et al, 1997) the regional stress field of the Sydney Basin was discussed with reference to a large number of direct measurements summarised through the agency of the Sydney Basin Stress Map (NSW, DMR 1997). In a subsequent publication (Enever et al 1998), a more detailed summary of the information available for the Hunter Valley region was presented. This current paper concentrates on the data available for the Newcastle Coal Measures. Data in this case has been obtained from a combination of hydraulic fracturing conducted in surface holes and overcoring conducted from underground openings (Enever & Walton, 1995)for coal mining and coal bed methane exploration. The measurements reported were concentrated in the Newcastle Coal Measure rocks. A few data points were obtained from sediments overlying the Newcastle Coal Measures, and from the underlying Tomago Coal Measures.

THE TECTONIC SETTING OF THE NEWCASTLE COAL MEASURES

Current thinking regarding the tectonic setting of the Newcastle Coal Field suggests that the latest stage (probably Tertiary) tectonic event leading to structural development in the coal measure sediments was an episode of compression with three separate discernible orientations (Lohe et al 1992):

- northeast – southwest
- approximately east-west
- broadly north-south

These compressional events are credited with thrust related reactivation of earlier normal faulting, in turn thought to be controlled by even earlier basement structures.

The absence of any obvious extensional event since the time of the compressions outlined above would suggest the prospect of the residual impact of these being left in the contemporary stress field measureable in the sediments today.

Figure 1 summarises all orientational data from in-situ stress measurements in the coal measure rocks (excluding coal) readily available to the author. Figure 1 is primarily based on hydraulic fracture data, from tests conducted in any given hole over a depth window, with each individual test being considered as a separate data point. Limited overcoring data is included in Figure 1. In the case of the overcoring data, measurements at any site were conducted at essentially the same depth below surface.

Figure 1 suggests a primarily bi-modal stress field orientation (approximately NE and ENE) with additional secondary clusters around NNE and SE-SSE. Superimposed on Figure 1 is the approximate stress field orientation in the basement rocks attributed to the Newcastle Earthquake. In general terms, the orientational distribution in Figure 1 reflects the phases of compression postulated above from the tectonic history of the region, with the addition of a SE-SSE component.

Figure 2 is a similar compilation of orientational data for the Hunter Valley region (Enever et al 1998). Figure 2 also suggests an essentially bi-modal horizontal stress field orientation, with one predominant orientation (just E of NE) overlapping the predominant orientations in Figure 1. The strong orientational cluster around SE in Figure 2 is, however, not reflected in Figure 1.

Figure 3 summarises the horizontal stress field orientational data on a site by site basis. In each case the predominant stress field orientation is shown, as well as any clear secondary stress field orientation where one exists. In some cases the results from individual holes are aggregated, while, in other cases, the results from a number of holes in close proximity have been combined to allow selection of a predominant stress field orientation for a relatively small area.

Scrutiny of Figure 3 suggests a possible pattern of stress field orientation underlying the overall distribution summarised in Figure 1:

- a tendency for the N - NE oriented stress vectors to approximately align with the local trend of the Macquarie Syncline.
- a pervasive ENE trending stress field orientation, not obviously related to the local structural fabric, but approximately consistent with the orientation of a major transform fault system postulated to impact the Sydney Basin (Schiebner et al, 1993).

While it is by no means clear if the N-NE orientation is a reflection of the impact of "local structure" or an artifact of the regional compression postulated to have impacted the northern Sydney Basin (see above), it can probably be reasonably suggested that the ENE orientation most likely reflects the impact of regional compression. In this context, it is of interest that the N-NE data was collected at relatively shallow depth (above approximately 400m), while some (but not all) of the ENE data was collected below 600 metres depth.

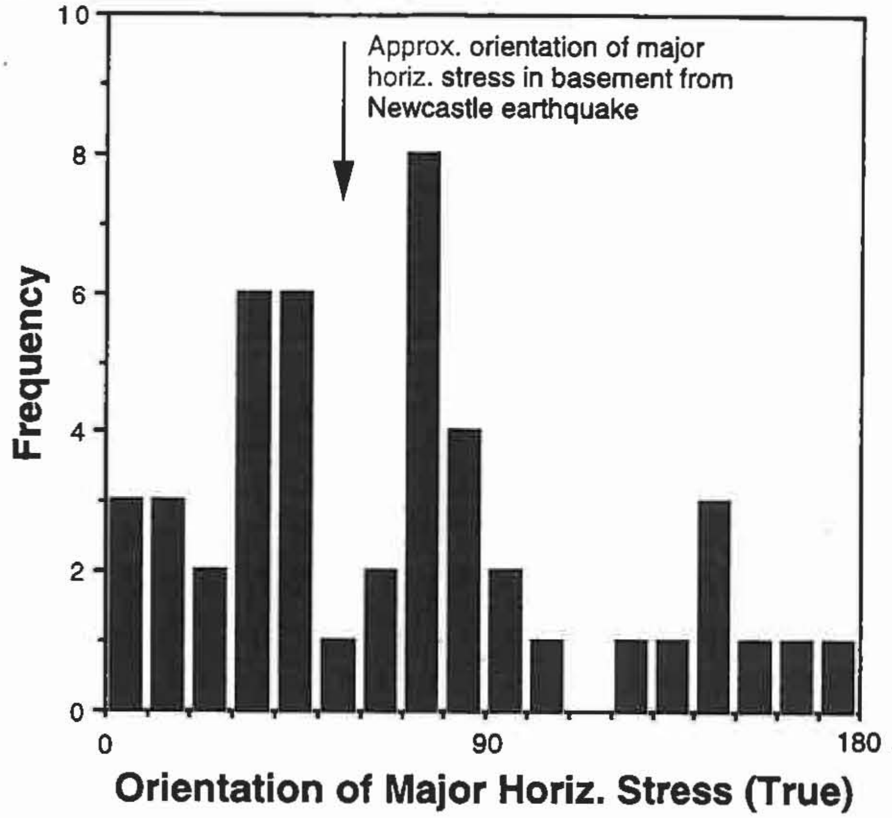

Fig. 1 Summary of horizontal stress field orientational data for Newcastle Coal Measures

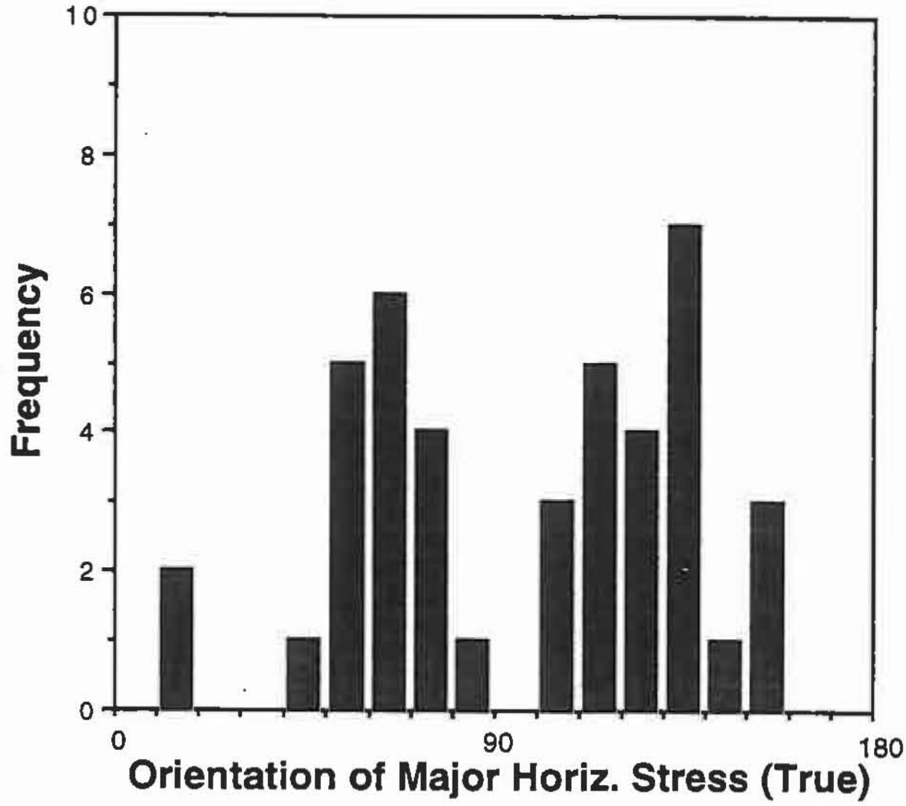

Fig. 2 Summary of horizontal stress field orientational data for Hunter Valley

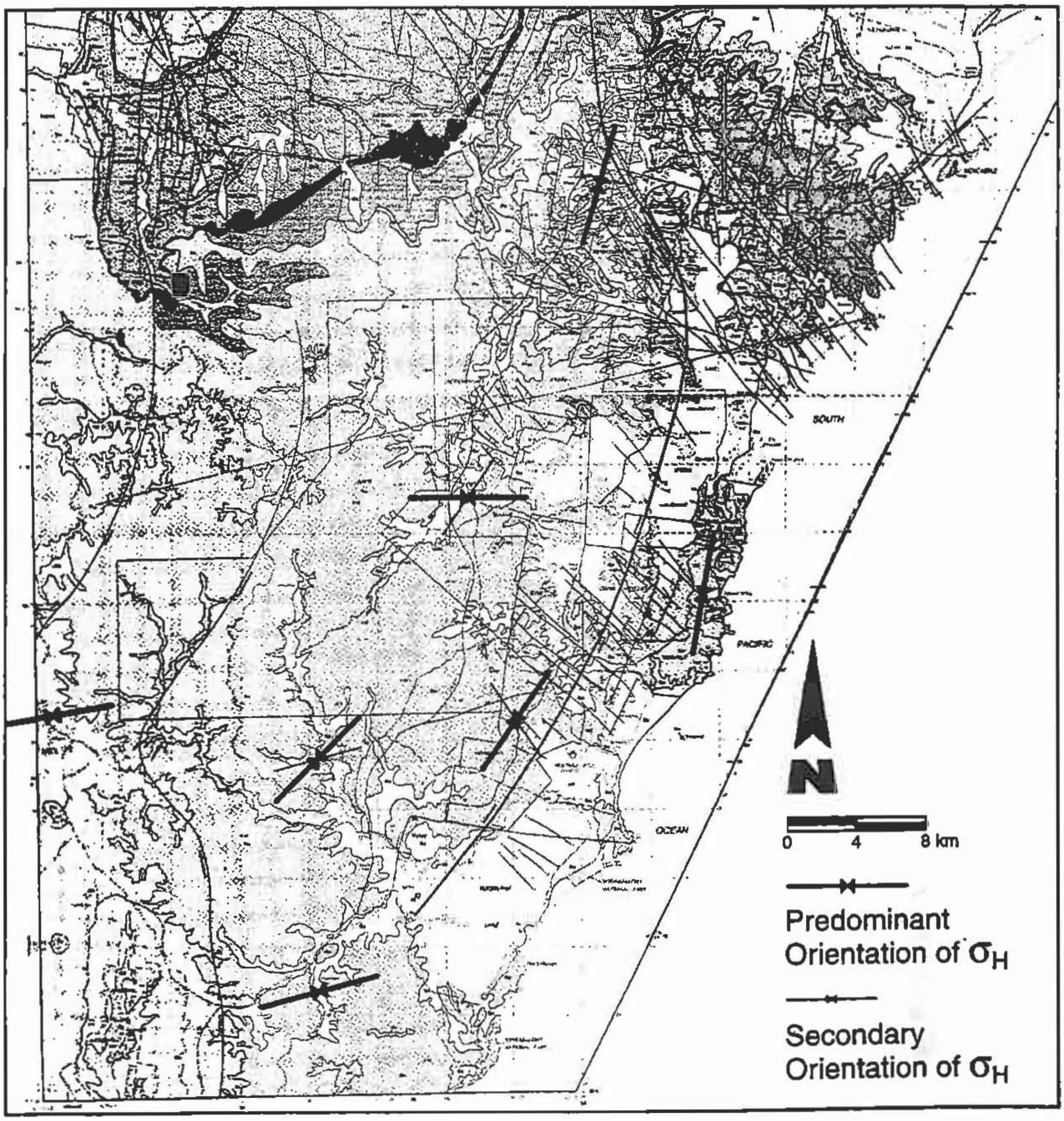

Fig. 3 Spatial trend of horizontal stress field orientation for Newcastle Coal Measures

Neither the N-NE nor the ENE orientation corresponds exactly with the implied stress field orientation in the basement rocks interpreted from the Newcastle Earthquake (Fig. 1). This may suggest that both measured stress field orientations have been influenced by the tectonic history rather than reflecting current tectonic processes. Alternatively, it might be that pre-existing structures at various scales are causing re-orientation of the current tectonic forces (as presumably represented by the earthquake focal plane solution).

Figure 4 is an aggregated plot of stress field magnitude (normalised with respect to depth of cover) in relation to corresponding stress field orientation. Figure 4 reflects the essentially bi-modal stress field orientation discussed above. Unlike the situation in the Hunter Valley, where there appears to be a systematic change in magnitude with orientation (Enever, et al 1998), Figure 4 suggests a widely varying stress field magnitude, independent of orientation, both within a given site and from site to site. There does not appear to be any obvious systematic pattern to this behaviour, suggesting a high degree of sensitivity to local geological impacts.

Figure 5 shows the trend with depth of the major horizontal secondary principal stress magnitude for the aggregated data. Unlike some other regions of the Sydney Basin (Enever et al 1998, Enever, 1999), Figure 5 does not suggest any systematic trend with depth. As a general comment, the horizontal stress field in the Newcastle Coal Measures could be characterised from Figure 5 as extremely variable but of average high magnitude.

In Figure 6, corresponding values of σ_H and σ_h are plotted against each other. Figure 6 suggests a systematic pattern, with σ_H/σ_h being consistently around 1.5 for values of σ_H up to approximately 30MPa. At higher stress magnitudes, irregardless of depth, the data appears more scattered, with a different average ratio, closer to 2. This may well be an artifact of the measurement process. On face value, however, the suggestion is of a change in the nature of the stress field at higher magnitude.

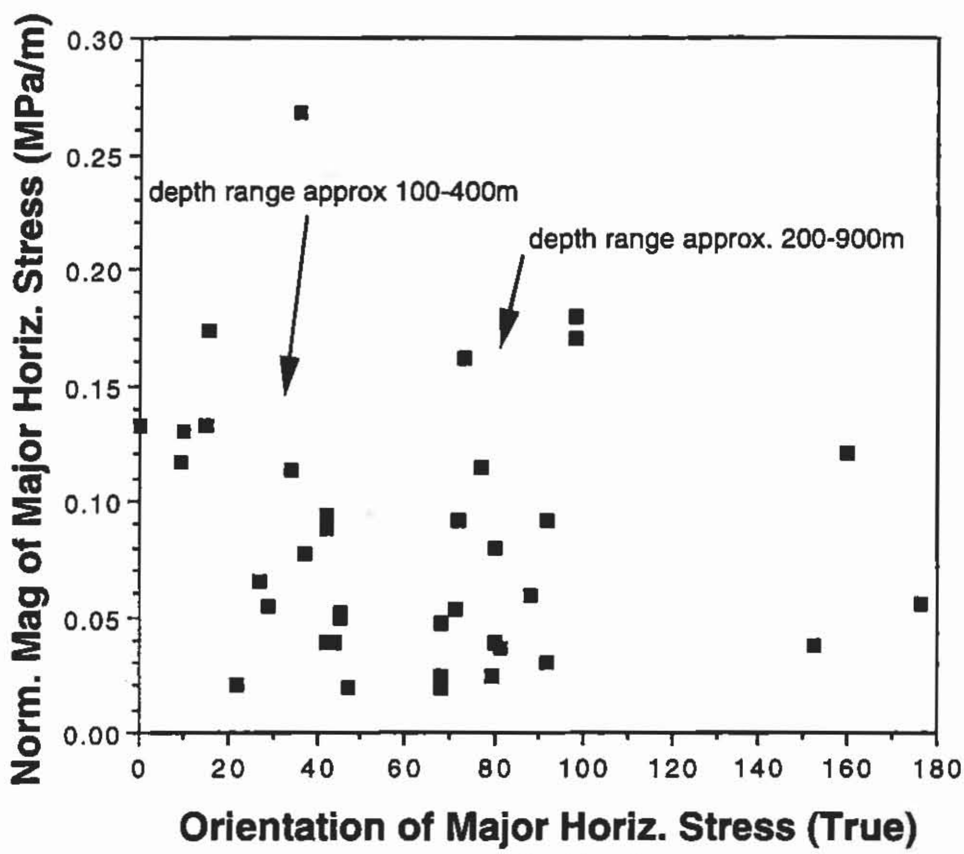

Fig. 4 Horizontal stress field magnitude versus orientation for Newcastle Coal Measures

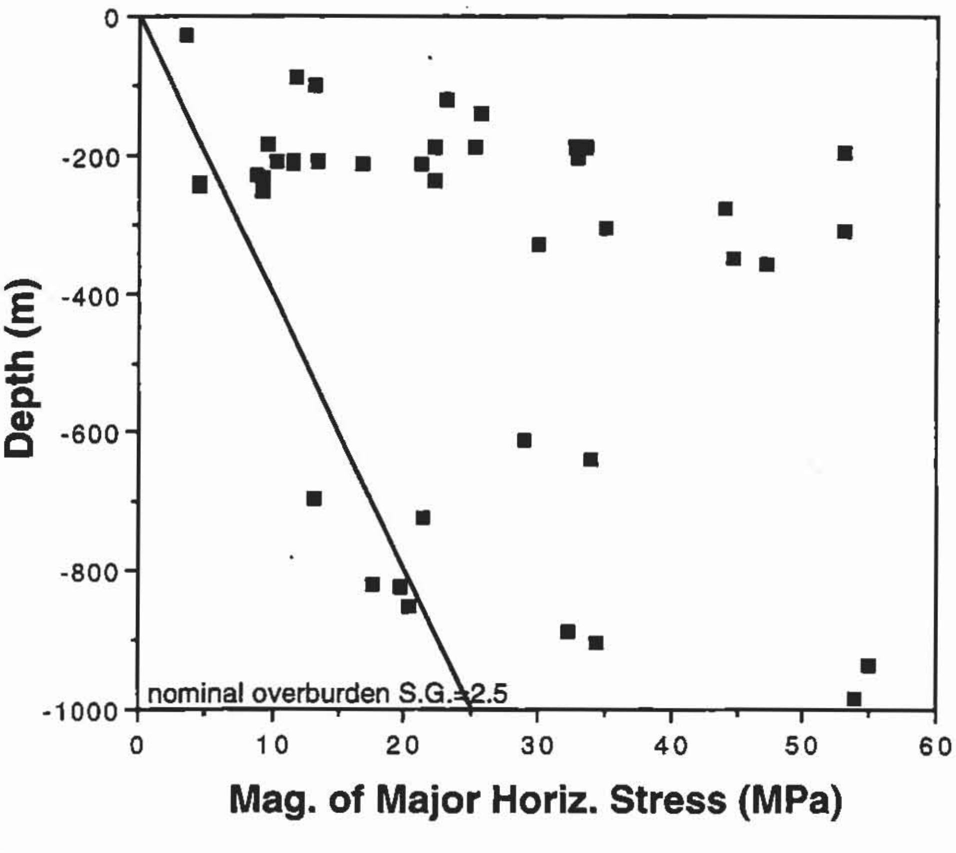

Fig. 5 Horizontal stress field magnitude versus depth for Newcastle Coal Measures

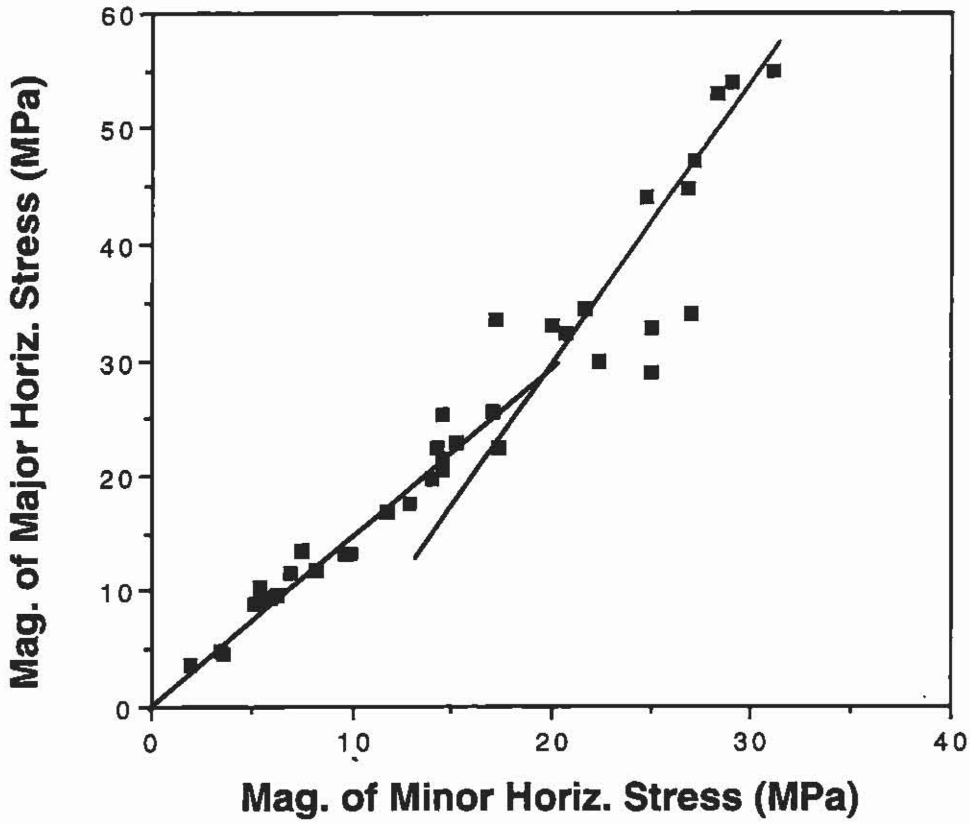

Fig. 6 Magnitude of σ_H versus σ_h for Newcastle Coal Measures

THE ENGINEERING SIGNIFICANCE OF THE CONTEMPORARY STRESS FIELD

The relatively great variability in the measured magnitude of the horizontal stress field in the Newcastle Coal Measures, both with orientation and depth, suggests that for any project where a detailed knowledge of the stress field is required, a specific program of stress measurement is going to continue to be required. The compilation of data presented here can, however, provide a framework to guide initial thinking, both with respect to orientation and magnitude. While the data available does not provide any realistic basis on which to predict stress conditions in a new area, a conservative approach would suggest assumption of a relatively high stress field magnitude as a starting point, with an orientation around NE or approximately E-W.

CONCLUSIONS

In broad terms, the Newcastle Coal Measures appear to be characterised by the following:

- a variable, but generally high, horizontal stress field magnitude, without any obvious trend with depth;
- an apparent change in the ratio of horizontal stress component magnitudes from approximately 1.5 at lower stress magnitude to approximately 2 at higher magnitude;
- a horizontal stress field aligning N-NE (approximately coincident with the trend of the Macquarie Syncline) or in an ENE direction, coinciding approximately with the system of transform faults postulated to impact the Sydney Basin at a regional scale.

ACKNOWLEDGEMENTS

The author gratefully acknowledges all those organisations that have supported the various measurement programs over an extended period.

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REDUCING THE RISK FROM HUNTER EARTHQUAKES: THE NEWCASTLE 99 PROJECT

Trevor Jones
Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT, 2601

OBJECTIVES

The primary objective of the ***Newcastle 99 Project*** is to provide the **local** Newcastle community with a broadly based description and analysis of the 1989 earthquake and a comprehensive risk assessment on which to base future risk mitigation strategies and response options. This work will commence in the 10th anniversary of this tragic event and is to be completed by March 2001. The project will draw together, in a systematic way, the wealth of data collected, and research undertaken, since the event and provide, as a minimum:

a. a comprehensive and accessible scientific record of the 1989 earthquake and its immediate and longer term consequences;

b. a comprehensive risk assessment of Newcastle and Lake Macquarie Cities on which to base all-hazard risk mitigation and emergency response plans;

c. a suite of decision support tools available to local emergency managers, planners and others to support training for, and response to, any future earthquake; and

d. material designed to maintain and enhance community awareness of the natural hazards history of the Lower Hunter Region and its significance to the Lower Hunter community.

The **national** objective is to use the 1989 Newcastle experience to test and calibrate the earthquake risk assessment techniques and models being developed under the AGSO *Cities Project*, and by collaborating agencies, for use in earthquake risk studies of other Australian urban centres.

At an **international** level, the ***Newcastle 99 Project*** will foster the recognition of earthquake risk research being undertaken in Australia through the use of Newcastle as an 'associate city' in the United Nations International Decade for Natural Disaster

Reduction (IDNDR) RADIUS Project. The RADIUS Project (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disaster) aims to produce seismic risk assessment tools for use at the local government level and is based on nine full case studies and some 50 auxiliary case studies world-wide. It is supported by the experience gained in studies already conducted in 'associate' cities.

EXPECTED OUTCOMES

If the objectives are realised, the Newcastle and Lake Macquarie communities will be demonstrably less vulnerable to the impact of future earthquakes. This improved safety will, in turn, make Newcastle and Lake Macquarie more sustainable and prosperous over the long term.

The integration of research and data sources under the ***Newcastle 99 Project*** will maximise the return on the considerable public and private investments already made, and will demonstrate the benefits of, and set standards for, a comprehensive and coordinated approach to post-event data collection and risk research.

BACKGROUND

The earthquake that struck Newcastle at 10.27 a.m. on Thursday, 28 December 1989 is the only earthquake in Australian history to have caused significant casualties and extensive damage in a major urban centre. The event and its impact has been the subject of several reports and studies. A wealth of data on the impact of the earthquake on the population, and on the buildings and other structures in the city, has been accumulated by a number of agencies. Much of the reporting was produced close to the event and tended to focus on specific aspects of the disaster, e.g., the seismic characteristics of the earthquake itself, the nature of the damage to buildings, and so on. Much of this material has been, understandably, uncoordinated. A large collection of invaluable collateral resource material has been accumulated and is being managed by the Newcastle Region Library.

Given its unique position in Australia's earthquake record and the wealth of data that has been accumulated, the Newcastle earthquake is extremely important to our understanding of the risks posed by earthquakes in major Australian urban communities such as Sydney. It has similar significance to the understanding of earthquake risk to communities in other intraplate regions of the world, as demonstrated by the considerable interest in the Newcastle event displayed by scientists in the USA and elsewhere. The promise of detailed earthquake risk information, however, has yet to be realised because of the lack of coordination in the post-event research effort and the lack of integration of the various data collections (in part because of commercial sensitivities at the time). Those research efforts and data collections represent a significant investment on the part of the various public and private sector agencies involved.

The Australian Geological Survey Organisation (AGSO - a research agency of the Commonwealth Department of Industry, Science and Resources) established the *Cities*

Project (the National Geohazards Risk of Urban Communities Project) in 1996 to undertake research aimed at reducing the risks posed to urban communities by a range of acute and chronic geohazards. The *Cities Project* has significantly widened the previous emphasis of AGSO on hazard science related to seismic monitoring and engineering seismology to embrace an emphasis on risk management as articulated in Australia/New Zealand Standard *AS/NZS 4360: 1999 Risk Management.*

To date the *Cities Project* has concentrated its efforts on a number of multi-hazard pilot projects in Queensland in which to develop and test a range of risk assessment techniques and tools such as *Risk-GIS*, a fusion of the philosophy of risk management as outlined in the standard and the application of GIS as a decision support tool. From that work has emerged the generic approach to risk assessment illustrated in the figure.

It is clear that the ***Newcastle 99 Project*** can, and should, embrace each of the elements in this process and consequently provide a strong scientific and methodological underpinning of the *Cities Project.* Conversely, with its combination of traditional expertise in earthquake hazard studies and its new emphasis on risk science, AGSO, under the *Cities Project*, is positioned to take the initiative to lead and promote the ***Newcastle 99 Project.***

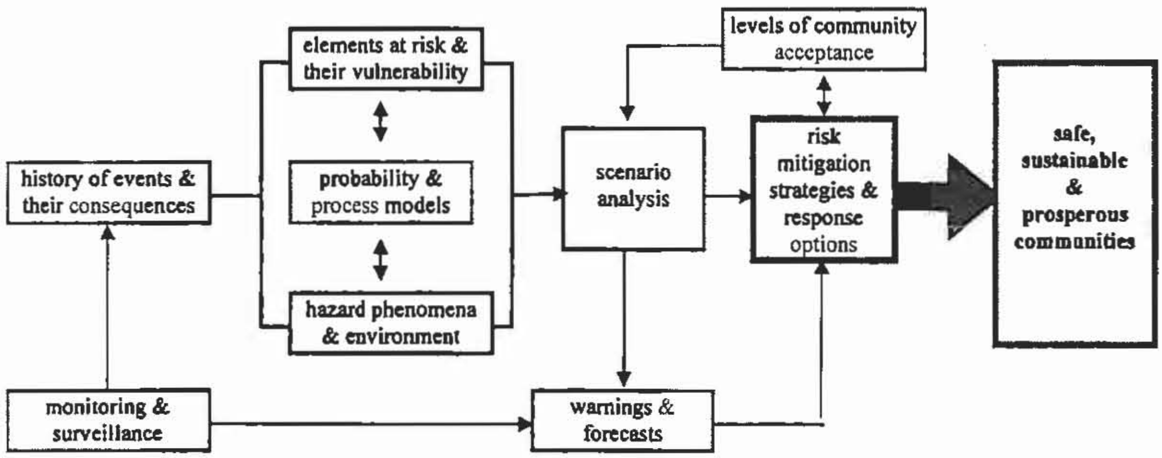

Figure: The *Cities Project* risk assessment process

SPECIFIC ACTIVITIES

Event history A major focus of the project will be the analysis of the 1989 earthquake with the view to gaining as much knowledge about the event itself, and the consequences that flowed from that experience, as possible. Attention will also be given to other historic events such as the 1868 (ML 5.3 Maitland), 1925 (ML 5.3 Boolaroo) and 1994 (ML 5.4 Ellalong) earthquakes. Evidence of paleoearthquake events and potentially active faults will also be pursued. Support for the publication of collections of historic data on CD-ROM and the Internet by the Newcastle Region Library will form part of this activity.

Hazard phenomena Detailed analysis of the geology and seismic environment of the area will be undertaken and this is where participants of the Newcastle Symposium may be able to help in particular. Analysis will be based on existing material, including extensive collections of felt intensity data from 1989, enhanced by a microtremor survey and supplemented by detailed geotechnical data from site investigations and other drilling activities. The potential also exists to undertake high resolution seismic imaging and seismic waveform modelling in key areas to estimate earthquake shaking from future events.

Elements at risk A detailed inventory of all buildings and key infrastructure facilities, such as water supply and power supply, will be developed on which to base assessments of vulnerability and risk. Many of these data are already available in local databases. However, some unique field collection will be required. Population, demographic and socio-economic data will be derived largely from the results of the 1991 and 1996 national censuses and supplemented by appropriate community data maintained locally.

Scenario analysis A range of scenario earthquake events will be run to explore the potential impact of likely future events. Those scenarios will explore issues such as the different risks that emerge with different time of impact (e.g., people at home at night rather than at work and school during the day). Impact models will be developed to investigate the effects on general building stock, special facilities (e.g., hospitals, police and fire stations), population concentrations (e.g., schools, shopping malls, sporting stadia), hazardous materials storage and lifeline utilities. Also, consequential risk models may be developed to explore issues such as the risk of fire spread after the event and the risks posed by the loss of containment of hazardous materials. The work will provide key input to emergency planning and risk mitigation strategies and provide input to event simulation models for use in computer role-play (game) products.

Risk acceptance Research is required to measure the perceptions of earthquake risk and the degree to which it is accepted by a range of key stakeholders such as the Newcastle City Council, Lake Macquarie City Council, the insurance industry, the financial services industry, Commonwealth and State government authorities, utility providers, heavy industry, the real estate industry, potential investors and the general community. An appreciation of the effects that the 1989 earthquake had on property values will also be developed.

Mitigation strategies and response options A range of mitigation strategies will be explored and tested against the results of the scenario analysis. Among these strategies may be the implementation of specific building regulations relating to the retro-fitting of older buildings; the development of construction standards for underground utilities; consideration of standards for the construction of hazardous material storage facilities; the provision of adequate redundancy for critical utility services such as power supply; and so on. Project outcomes may indicate that modifications to both local- and state-level emergency plans and urban planning schemes may be appropriate.

DELIVERABLES

The principal deliverable will be information and knowledge about the earthquake risk environment of the Lower Hunter. This deliverable will provide input to a wide range of public and private sector decision making needs. Project material will be made available in a range of forms including CD-ROM products, Internet directories and conventional hard copy products. It will also be supported by the development of decision support tools, such as risk modelling software and perhaps computer simulation 'games', principally within a *Risk-GIS* environment.

STAKEHOLDERS

In a community-based risk study such as this, there are considerable overlaps between the 'clients' and those who collaborate in the research. The following is a list of the key stakeholders identified at this stage - it will certainly expand as the project develops:

- the Newcastle community;
- Newcastle City Council (and possibly neighbouring municipalities) and its various departments;
- Lake Macquarie City Council;
- State Government agencies involved with public safety, engineering and works, community welfare and planning services;
- Commonwealth Government agencies involved in public safety and community welfare activities;
- key utility providers including Hunter Water Corporation, power, telecommunications, gas, fuel and transport services;
- emergency managers;
- the mining industry;
- major local secondary and service industries;
- the insurance industry;
- the financial services industry (banks and other lending institutions);
- welfare and other community service organisations;
- engineering and planning professionals;
- academic, educational and research institutions.

The following key stakeholders have already identified a desire to be involved and to contribute to the research effort:

- AGSO
- Newcastle City Council
- Lake Macquarie City Council
- Hunter District Emergency Management Committee
- Hunter Water Corporation
- Emergency Management Australia
- NSW Department of Public Works and Services
- Newcastle Region Library
- Natural Hazards Research Centre, Macquarie University
- Centre for Earthquake Research in Australia

- Guy Carpenter (reinsurance brokers).

Interest in the project has also been expressed by researchers in the USA including the Evansville, Indiana, Disaster Recovery Business Alliance and the University of Memphis.

COMMUNICATION STRATEGY

Effective communication in two forms is the key to the success of this project. The first form is two-way communication between the project and the community. Considerable use of the media will be made to both attract a flow of information into the project and to provide the community with the results of the work. Public access to the results of the research, unless precluded by legal constraints of privacy or confidentiality, must be guaranteed.

The second form is between the researchers involved. This will be facilitated by the maximum use of technology, especially the Internet, and by annual work-in-progress workshops to be held in Newcastle. ***Newcastle 99 Project*** researchers will be encouraged to feature the project in presentations to appropriate national and international conferences.

PERSONNEL

The allocation of personnel to the ***Newcastle 99 Project*** depends somewhat on the level of funding that can be attracted. Certainly, core resources are available from within the AGSO Geohazards Division. A full time Newcastle-based Project Leader, David Stewart, has recently been appointed by AGSO. Other key AGSO staff who would provide input include Ken Granger (*Cities Project* Director and risk science specialist), Trevor Jones (*Cities Project* Manager and earthquake risk specialist), Vic Dent (seismologist), Mr Kevin McCue (engineering seismologist), Dr Cvetan Sinadinovski (engineering seismologist) and Dr Malcolm Somerville (engineering seismologist). It is envisaged that significant use will be made of students from the University of Newcastle for field data capture.

Ms Ajita Lewis of the Newcastle Region Library is already working on the central information collection relating to the 1989 earthquake.

Professor Russell Blong (NHRC) and Mr Ben Miliauskas (Guy Carpenter/EQE) have also indicated a willingness to provide limited specialist input to the project.

EXTERNAL FACTORS FOR SUCCESS

The success of the Newcastle 99 Project will depend largely on three external factors:

- the level of community appreciation of, and support, for the project;
- funding and policy support from key public and private organisation; and
- the effective collaboration and cooperation of the various researchers and contributors involved.

ENVIRONMENTAL MANAGEMENT IN EXPLORATION

M IVES

Powercoal Mining Services, Post Office, Toronto NSW 2283

What is Environmental Management of Exploration?

Environmental Management in exploration involves minimising the impact that these activities have on the environment.

What Are The Issues?

The environmental issues involved in exploration activities relate to land management (access tracks, clearing, erosion, threatened species, aboriginal and European heritage and revegetation), water management (sourcing water and pollution from sedimentation, drilling fluids and fuels), visual amenity, noise, dust and the community.

Why Manage These Issues?

Due to changing community expectations over the last 20 years, environmental protection is now a requirement of all facets of life and the mining industry and their exploration activities are not immune.

Environmental protection is important for a number of reasons. These include:

- Our life style is affected by the state of the environment
- We owe it to our children
- It establishes good community relations
- It is good business sense, and
- It is the LAW.

What Are The Consequences of Poor Environmental Management?

As mining companies, the risks we face for not protecting the environment, include poor community reputation, prosecution (fines), operating restrictions, customer backlash and possibly limited opportunities for expansion. The most significant of these are:

a. Poor Community Relations

For most people in the community, their first and often only involvement with the mining industry is through exploration activities. Poor performance will impact on the company potentially limiting access to undertake planned work. Individual companies cannot afford to lose community support at this early stage of any project. Further, the whole mining industry is judged on the poorest performance of any one company. The good work of most of the companies can be undone by the poor performance of a single company, individual or subcontractor.

b. Legal and Economic (fines and Penalties)

Exploration activities have the potential to contravene some 14 pieces of legislation in NSW.

These include:

- Local Government Act
- Protection of the Environment Operations Act
- Water Board Act
- Mining Act
- Coal Mines Regulation Act
- Heritage Act
- Dangerous Goods Act
- Waste Disposal Act
- Prevention of Pollution to Navigable Waters Act
- Environmental Hazardous Chemicals Act
- Waste Minimisation and Management Act
- Noxious Weeds Act
- Environmental Planning and Assessment Act
- Contaminated Lands Act.
- Threatened species conservation act

Of most significance to environmental management is the Protection of the Environment Operations Act, enforced on 1 July 1999. Avenues for prosecution/fines for activities that harm, or are likely to harm the environment, include water pollution, air pollution, noise pollution and land pollution from waste, leaks and spillages.

Who is liable?

Liability in the event of any contravention of this legislation falls on:

- The Corporation or individual dealing with the waste or substance
- The directors or managers
- The person in possession of the substance
- The owner of the container in which the substance was stored, and
- The owner and occupier of the land. Need to indemnify owner.

The key points of some of this legislation is the onus of proof is reversed (alleged polluters must prove their innocence), and where an offence by an organisation is proven, the directors and managers of that organisation are also liable for the same offence, unless they can prove a defence.

What are the penalties?

Examples of penalties for infringing this legislation include:
Protection of the Environment Operations Act.

Major offence (Tier 1)	$1,000,000 for corporations,
	$ 250,000 or 7 years imprisonment for individuals
Significant offence (Tier 2)	$ 120,000 for individuals
Minor offence (Tier 3)	fines of up to $ 1,500 for individuals

× N Parks & Wildlife $5500 /day
× Threatened species c
$55000 to 220 c

What defences are available?

To defend against prosecution the accused must show:

- As an individual they had no control over the incident,
- All reasonable care was taken, and
- They acted with due diligence.

How do you demonstrate due diligence?

- Identify and establish an infringement system
- Operate and regularly evaluate its effectiveness
- Have a procedure to receive reports on compliance with the system
- Know the environmental standards of the industry
- Know the environmental laws and their requirements, and
- React immediately and personally to any failures.

In other words have an adequate Environmental Management System in place which is adequately supervised and monitored and continually updated.

Beware - inept project/task design
- clumsy implementation.
- inattention to requirements and intentions.

POEO Act - guilty until proven innocent
- failure to notify EPA -

Anvil Hill? $3-400 k
30 sites $10,000 flora, fauna & heritage studies
Flag & fence tetratheca.

PARTICULATE UFO's AND IFO's IN NEWCASTLE'S AIR

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INTRODUCTION

Many human activities produce dust, and the more varied these activities, the larger the number of sources of dust generation. Being an industry-based port city, Newcastle has got many such sources which gave the city's air a bad name in the years before stringent dust suppression measures were introduced. Today, Novocastrians breathe cleaner air than Sydney-siders do on most days, but the air is not completely free from air-borne dust. This presentation is a pictorial display of the microscopic images of a large variety of minute particles that collect as air-borne dust in various parts of Newcastle.

The main purpose of the presentation is to show that in spite of the development of many sophisticated analytical instruments, the light microscope has still a major role to play in the analysis of a complex mixture of solid particles. Indeed, the microscope is unsurpassed in its ability to allow rapid identification and inexpensive quantitative assessment of numerous organic and inorganic solids, either individually or completely mixed up in one sample. In our investigation, air-borne dust samples collected from various parts of the City were analysed with the aid of a reflected-light microscope, mostly in white light using oil-immersion antiflex objectives, although some organic particles required the application of fluorescent mode.

DUST CLASSIFICATION

Because of the wide compositional range and the many sources of air-borne particulate matter, a discussion of dust particles requires them to be grouped into suitable categories. This is not easy, because none of the terms that may be chosen for the classification are entirely unequivocal. Purely descriptive parameters, the basis for many classifications of natural materials, would be very cumbersome, and the opposite, a classification based on origin, does not work, because the sources of the dust are not always known with certainty. The outline for a classification given in Table 1 is a compromise between identification and broad-based origin. The prime distinction is between organic and inorganic particles. This yields two large groups, although even at this broad level the distinction is not always clear. One cause of ambiguity is the difficulty to identify some of the particles properly. The other cause affects some processed materials which had input from both organic and inorganic sources.

The second level of distinction made in Table 1 is between unprocessed, semi-processed and processed organic and inorganic particles. The term "unprocessed" infers that the matter is in its natural state, which does not present any analytical difficulty in the majority of particles. However, borderline cases between unprocessed and semi-processed materials exist, which require additional considerations. For example, a fragment of hair may have been sourced directly from an animal or human in which case it would be unprocessed. Alternatively, it may have broken off a brush which would put it into the semi-processed category. The fact that most brushes nowadays use synthetic materials suggests an unprocessed origin in such cases.

Heavy minerals are another example of ambiguity in classification. Some of our samples contain a small number of zircon and rutile grains. Both are common accessories in the beach sands close to the city, so that they could belong to the unprocessed category. However, in relation to the proportion in our samples of "normal" quartz-dominated beach sand, the heavy minerals appear to be over-represented, which is rather surprising in view of their high density. Since both rutile and zircon are exported from Newcastle, it is possible that the heavy minerals in our samples have been sourced from concentrates. In this case, they would belong to the semi-processed category although, in Table 1 they appear in the unprocessed group because their origin is not certain.

"Semi-processed" is a term used for materials which have not been altered in their composition but may have been changed in texture or were combined with other materials. In the organic group of particles, coal belongs to this category. Most coal particles are very clean, i.e. they have a lower ash content than their parent seams. They appear to represent washed coal, but it is possible that the clean appearance is due to the elutriation effect of the wind gusts that carried the lighter particles further than the heavier ones. On the other hand, some samples contain particularly high-ash particles which originated from washery tailings that were used in earth works. Most of such particles are weathered, which suggests that they represent old earth fill that was recently reworked.

Examples of semi-processed materials from the inorganic group are particles of crushed and sintered iron ore, and fragments of refractory bricks and linings. The latter are compound particles that consist of clean quartz grains and a bonding material. In a microscopic point-count analysis of such aggregates, the nature of the whole compound particle is recorded, not the individual quartz grain or type of mortar that might fall under the cross wire.

The term "processed" is used here for materials that have been substantially reformed in composition and texture. In some members of this category, the original materials are unrecognisable. Examples are paints and plastics, as well as some slags. However, in the majority of particles, the relationship between product and source material is less obscure. In some products of combustion, even the rank of the coal can be estimated from the degree of optical anisotropy and the shape (e.g. whether thin- or thick-walled) from its residual char. A similarly close relationship exists between the coke particles commonly found in the samples and their feed coal. Processed inorganic particles form the most complex category among which slag fragments and cenospheres appear to occur in almost infinite variety. In most cases, the variations reflect minute differences in composition, mainly iron content, and state of preservation. The latter, in the form of different degrees of rusting, is also the source of variety in metallic iron and iron-bearing metal fragments.

CONCLUSIONS

The investigations have shown that Newcastle's air is a mirror of the natural environment of the city and the activities that take place in it. The coastal setting is reflected in the large proportion of beach sand in some samples, while bushfires in the hinterland leave the charred remains of wood, leaves and grass behind. However, it is human activities, ranging from large industries to the weekend house painting and the backyard barbeque that provide the largest variety of air-borne particles. Although many of these particles are either readily identifiable or, at least, can be grouped into broad categories, there is always a small percentage of unidentified particles in every sample. Some of these are ubiquitous, while others are more common in restricted areas. Examples of these have been found in the vicinity of workshops (burned paint near panel beating shops?), or near major thoroughfares (brake linings? abraded tyre rubber?).

Table 1. Particulate matter in air-borne dust from various Newcastle localities

A Unprocessed Organic Matter:	
A1 Dispersed vegetable matter -	*A1.1 Humic matter*
	A1.2 Rootlets, rhyzomes and fibres
	A1.3 Spores and pollen
A2 Insect and animal products -	*A2.1 Parts of insect bodies*
	A2.2 Hair
B Semi-Processed Organic Matter:	
B1 Washed coal (fresh) -	*B1.1 High-volatile bituminous coal*
	B1.2 Medium-volatile bituminous coal
B2 Weathered coal -	*B2.1 Clean coal*
	B2.2 Middlings and tailings
C Processed Organic Matter:	
C2 Products of combustion -	*C2.1 Charred wood*
	C2.2 Soot
	C2.3 Char cenospheres
C3 Products of carbonisation -	*C3.1 Coke breeze*
	C3.2 Petroleum coke
	C3.3 Graphite
D Unprocessed Inorganic Matter:	
D1 Sand grains -	*D1.1 Quartz sand*
	D1.2 Shell fragments
	D1.3 Heavy minerals
E Semi-Processed Inorganic Matter:	
E1 Bricks and mortar -	*E1.1 Refractory materials*
	E1.2 Limestone
E2 Iron-bearing materials -	*E2.1 Iron ore*
	E2.2 Sinter dust
F Processed Inorganic Matter:	
F1 Synthetic materials -	*F1.1 Fragments of plastics*
	F1.2 Droplets and fragments of paint
F2 Slag -	*F2.1 Slag fragments - high Fe content*
	F2.2 Slag fragments - low Fe content
	F2.3 Slag cenospheres
	F2.4 Kish fragments
F3 Metals and derivatives -	*F3.1 Fe fragments and droplets*
	F3.2 Rust flakes
	F3.3 Non-Fe-metal fragments

STRATIGRAPHIC CORRELATIONS IN THE SOUTHERN BOWEN AND NORTHERN GUNNEDAH BASINS, NORTHERN NEW SOUTH WALES

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ABSTRACT

A stratigraphic correlation is proposed between the Permian and Early Mesozoic sediments of the northern Gunnedah Basin (Bellata and Bohena Troughs) and the southern Bowen Basin in New South Wales across the intervening Moree High. This is based on a review of borehole logs for the petroleum and selected coal exploration wells in the area, supported by some more specific lithologic and environmental indicators.

Vitrinite reflectance profiles on samples prepared from drill cores and cuttings show that coals and dispersed organic matter (DOM) in most of the Permian strata in boreholes north of the Moree High have anomalously low reflectance values relative to the coals and DOM in the overlying Triassic and Jurassic succession. This suggests a marine influence, similar to that affecting the lower Black Jack Group and most of the Maules Creek Formation in the Gunnedah Basin further to the south (Gurba and Ward, 1998), as well as the more clearly marine sediments of the Watermark and Porcupine Formations (Tadros, 1993). There is evidence of only a thin, more terrestrial coal measures unit at the top of the Permian in this area, probably equivalent to the Upper Black Jack Group, with more normal reflectance characteristics.

Geophysical log data indicate an extensive overpressured shaley interval in the lower part of the Triassic succession. This occurs at the base of the Moolayember Formation in the Bowen Basin and the base of the Napperby Formation in the Gunnedah Basin, and appears to represent a useful correlation horizon across the region.

INTRODUCTION

Although over 1300 wells have been drilled in the Queensland portion of the Bowen/Surat Basin, only 23 exploration wells and seven stratigraphic boreholes were drilled from 1963 to 1984 in the New South Wales portion (Jones, 1985). The New South Wales Department of Mineral Resources has since carried out extensive coal exploration drilling programs in the Gunnedah Basin, providing a comprehensive understanding of the area south of Narrabri (Tadros, 1993). However the area north of

Narrabri, where the Gunnedah Basin passes into the southern part of the Bowen Basin, has been subject to much more limited geological study.

The present paper represents an attempt to integrate geophysical log data from these wells with vitrinite reflectance profiles and lithologic indicators to develop a consistent stratigraphic section for the southern Bowen/Surat Basin sequence in northern New South Wales, and to correlate this with the better-known Gunnedah Basin succession. The ultimate object of the work, carried out in conjunction with the NSW Department of Mineral Resources, is to establish the stratigraphic framework and post-burial thermal history of the region, as background for future petroleum exploration.

GEOLOGICAL SETTING

The Permo-Triassic Sydney-Gunnedah-Bowen Basin and the overlying Jurassic-Cretaceous Surat Basin represent probably the most economically significant sedimentary basin system in eastern Australia. The Queensland portion of the Bowen Basin contains up to 10km of terrestrial and shallow marine sediment, including substantial coal deposits. The equivalent succession in northern New South Wales is much thinner and less complete, but it is broadly continuous with the Gunnedah Basin over the Moree High (Totterdell and Krassay, 1995). An angular unconformity separates the Bowen Basin in both areas from the overlying Surat Basin succession (Elliott, 1993).

WORK PROGRAM

Well-completion reports for a total of 27 boreholes were evaluated for this study from records of the New South Wales Department of Mineral Resources. Of the total, 19 boreholes were located in the southern Bowen Basin and 8 in the northern Gunnedah Basin. Key geophysical logs of the relevant wells were digitized and brought together with other information using *Canvas* graphics software. Cuttings and, where available, cores from these wells were sampled, with special reference to coal occurrences and to shaley rocks. Both logs and samples covered wherever possible the full Permo-Triassic Gunnedah-Bowen sequence and the lower part of the Surat Basin succession.

Re-evaluation of Stratigraphic Framework

The boreholes used in the study were drilled over a 30-year period, and different names were applied in many cases to the same stratigraphic units. Stratigraphic correlations between the wells, based mainly on geophysical logs, were drawn for an intersecting series of north-south and east-west cross-sections. The subdivisions were re-established in the light of both log characteristics (Figure 1) and organic petrology data (see below), providing a more consistent overall basis than given by the formation boundaries in the well completion reports.

Sample Collection and Treatment

Since few cores were available, material from the well cuttings in most boreholes was hand picked to select the relevant lithologies indicated by the geophysical logs, in order to minimize contamination from overlying strata due to borehole caving. Cores were sampled where available, such as in DM Bellata DDH 1, Coonarah DDH 1 and 1A. Vitrinite and other coal particles were selected from the cuttings of intervals where the well logs showed a coal seam to be present. Otherwise, priority was given to collecting shale and siltstone particles.

More than 250 polished sections were prepared from selected samples for petrographic study. These were examined in reflected light using a Zeiss *Axioskop* system with oil immersion. Mean maximum vitrinite (telocollinite) reflectance (Rv max) determinations were carried out, using on average at least 30 individual measurements for each sample.

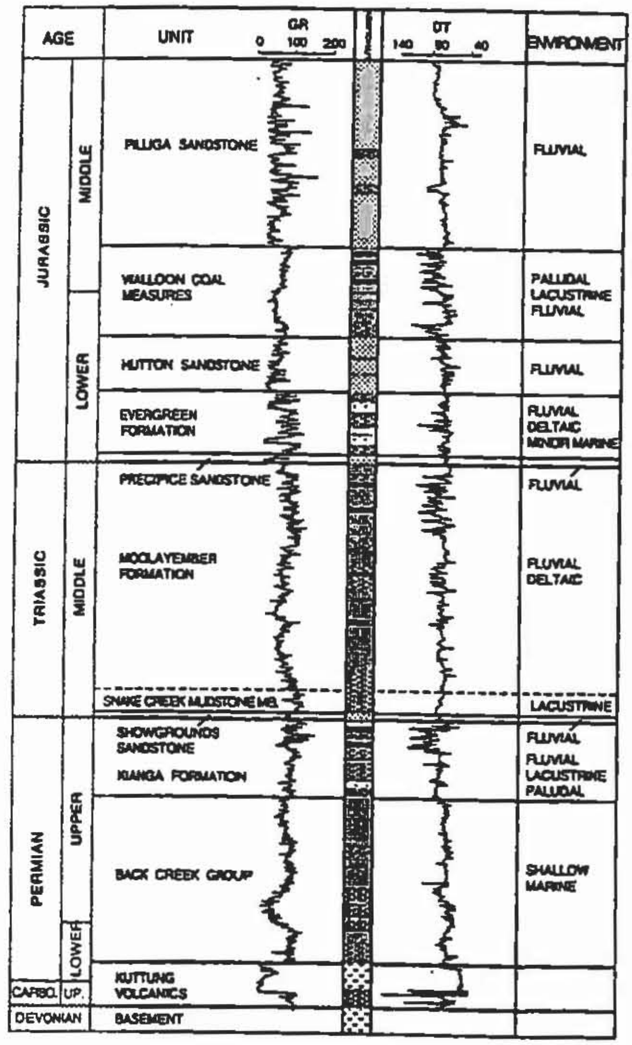


Figure 1: Preliminary representative stratigraphic section for the southern Bowen/Surat Basin sequence, northern New South Wales.

REFLECTANCE PROFILES AND REFLECTANCE ANOMALIES

Although Hilt's Law indicates that maturation in vertical sections of strata should increase steadily with depth, many workers have previously documented abnormally low (suppressed) vitrinite reflectance. As discussed by Mukhopadhyay (1994) abnormally low or suppressed vitrinite reflectance in coal or DOM may be caused by a number of factors, including marine influence on the coal-bearing sequence. Some of these are discussed more fully in relation to the study area below.

Contamination of well cuttings

In non-cored holes it is possible that cuttings from shallower intervals might become mixed with samples from deeper intervals, due to caving of the strata around the drill hole. Reflectance measurements on material embracing both the deeper samples and caved debris would therefore not represent the interval intended, and profiles involving such materials would show abnormally low reflectance values.

Hand picking the coal particles when sampling helped to eliminate some of these problems. If mixed materials were present, the contrast in reflectance also helped to separate the cavings from the intended organic matter under the microscope. Reflectance values from suspected cavings were stored separately in the data-gathering computer, and used or not used as required in the mean maximum reflectance calculation.

Effects of igneous intrusions
Contact metamorphism from igneous intrusions may increase the thermal maturity of the surrounding rocks, and hence the reflectance of any included vitrinite or other organic matter (Dow, 1977). Igneous intrusions in the southern Bowen Basin most commonly occur in boreholes close to the Moree High. The intersected thicknesses of the individual intrusions are variable, ranging up to a maximum of 192 m in the Back Creek Group of the Lantern No 1 well.

Vitrinite reflectance due to intrusions reaches 2.43% at 871.55m in Bellata DDH 1 and 5.51% at 737.62m in Wilga Park No 1 in the Gunnedah Basin, although values are lower further from the respective heat sources. The magnitude of the reflectance values associated with intrusions and the clear departure from trends associated with burial allow intruded materials to be readily differentiated in the reflectance profiles developed from the sediments alone.

Effects of marine influence
The vitrinite reflectance for the southern Bowen Basin increases steadily with depth through the Jurassic and Triassic strata, and where present into the uppermost Permian Kianga Formation. It decreases by around 0.1%, but then continues to increase at a similar to greater rate in the underlying strata of the Back Creek Group (Figure 2).

This is similar to trends reported in the coal seams in the lower Black Jack Group and in the Maules Creek Formation by Gurba and Ward (1998). As with that study, the change is believed to be an expression of marine influence on the organic matter. In intervals unaffected by igneous intrusions, the organic matter from the Watermark and Porcupine Formations in the northern Gunnedah Basin (e.g. Bohena-1, Nyora-1 and Wee Waa-1) also reflects marine influence, as do the Black Jack and Maules Creek Formations. The underlying Goonbri Formation, present in Bellata DDH 1, has even lower reflectance values, apparently due to deposition an a liptinite-rich lacustrine environment.

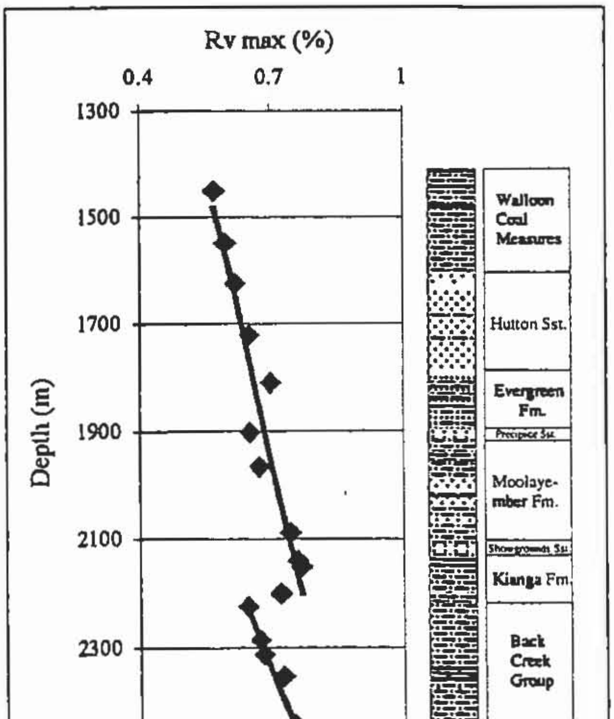


Figure 2: Rv max-depth profile in Mcintyre-1, northern New South Wales.

TRIASSIC OVERPRESSURE ZONE

The gravity load of overlying strata in a sedimentary sequence causes beds lower in the section to compact and lose porosity. Such a reduction in porosity is only possible if a commensurate portion of the (incompressible) pore fluid is allowed to escape. Layers in the section with low permeability may, however, impede the escape of the pore fluid from the beds beneath, confining it in the sediment and preventing or retarding the compaction process.

Under such conditions, previously normal hydrostatic pressures in the pore fluid increase and the sediment becomes overpressured (Chapman, 1983; Tissot and Welte, 1984). Other processes that may cause overpressuring include rapid loading, thermal expansion of pore fluids, compression by tectonic forces, and generation of oil and gas from organic matter in the rock matrix (Hunt, 1996).

In shale sequences that have been normally compacted, with associated escape of pore fluids, the porosity should decrease with increasing burial depth. In sequences that are abnormally compacted, however, the porosity-depth profile shows an increase in porosity with depth (Magara, 1978).

Such a phenomenon can be recognized from porosity logs (Figure 3) in the lower part of the Middle Triassic Moolayember and Napperby Formations in the Bowen and Gunnedah Basins respectively. The porosity-depth profile in each case shows an increase instead of a decrease in porosity with depth. This anomaly is widespread, and can be used as a marker bed to identify the base of these shaley intervals in both basins. It is also useful as a marker for correlation between boreholes in the southern Bowen and Gunnedah Basin successions.

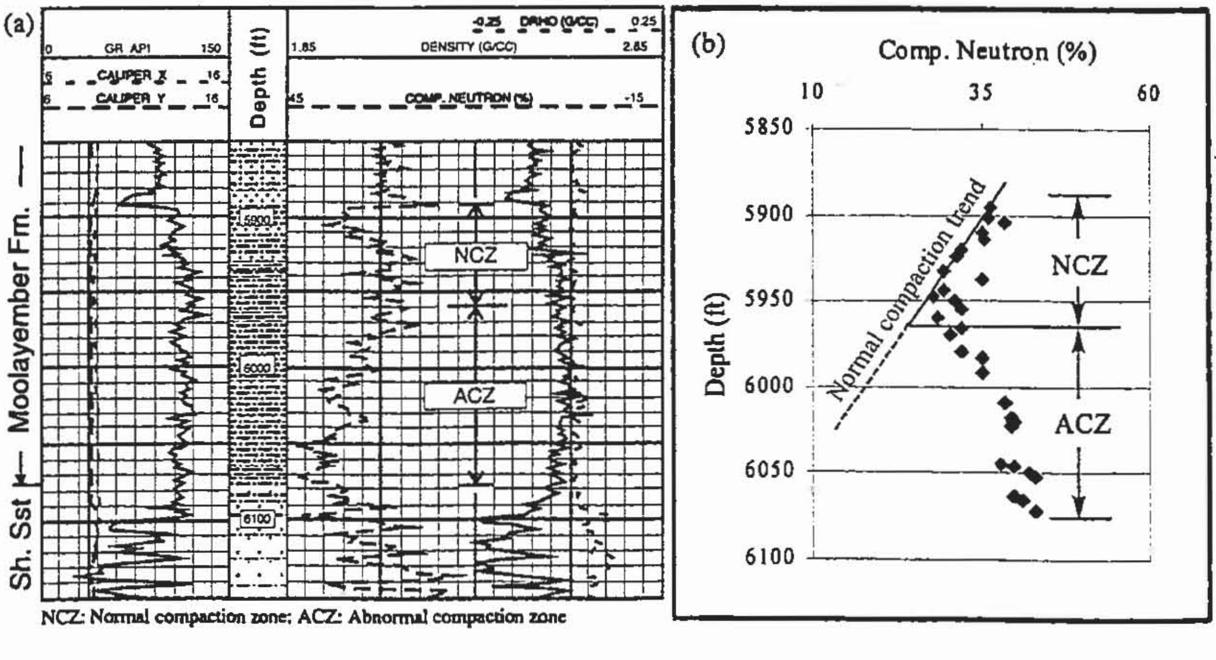


Figure 3: Normal and abnormal compaction zone in the lower part of the Moolayember Formation in Glencoe-1. (a) Porosity logs and GR response. (b) Neutron-depth profile.

STRATIGRAPHIC CORRELATIONS

The carbonaceous mudstone dominated sections at the base of Lantern-1 and Macintyre-1 represent the oldest sediments in the New South Wales portion of the Bowen Basin. These are equivalent to the lacustrine Goonbri Formation of the Gunnedah Basin further to the south (Totterdell and Krassay, 1995), which also shows anomalously low vitrinite reflectance in DM Bellata DDH 1. The Back Creek Group is well developed in the eastern part of the Bowen Basin, but thins and pinches out over the Moree High. It also pinches out towards the west. The coal seams and DOM in the Back Creek Group display lower vitrinite reflectance than the overlying Permian, Triassic and Jurassic sediments, apparently due to marine influence.

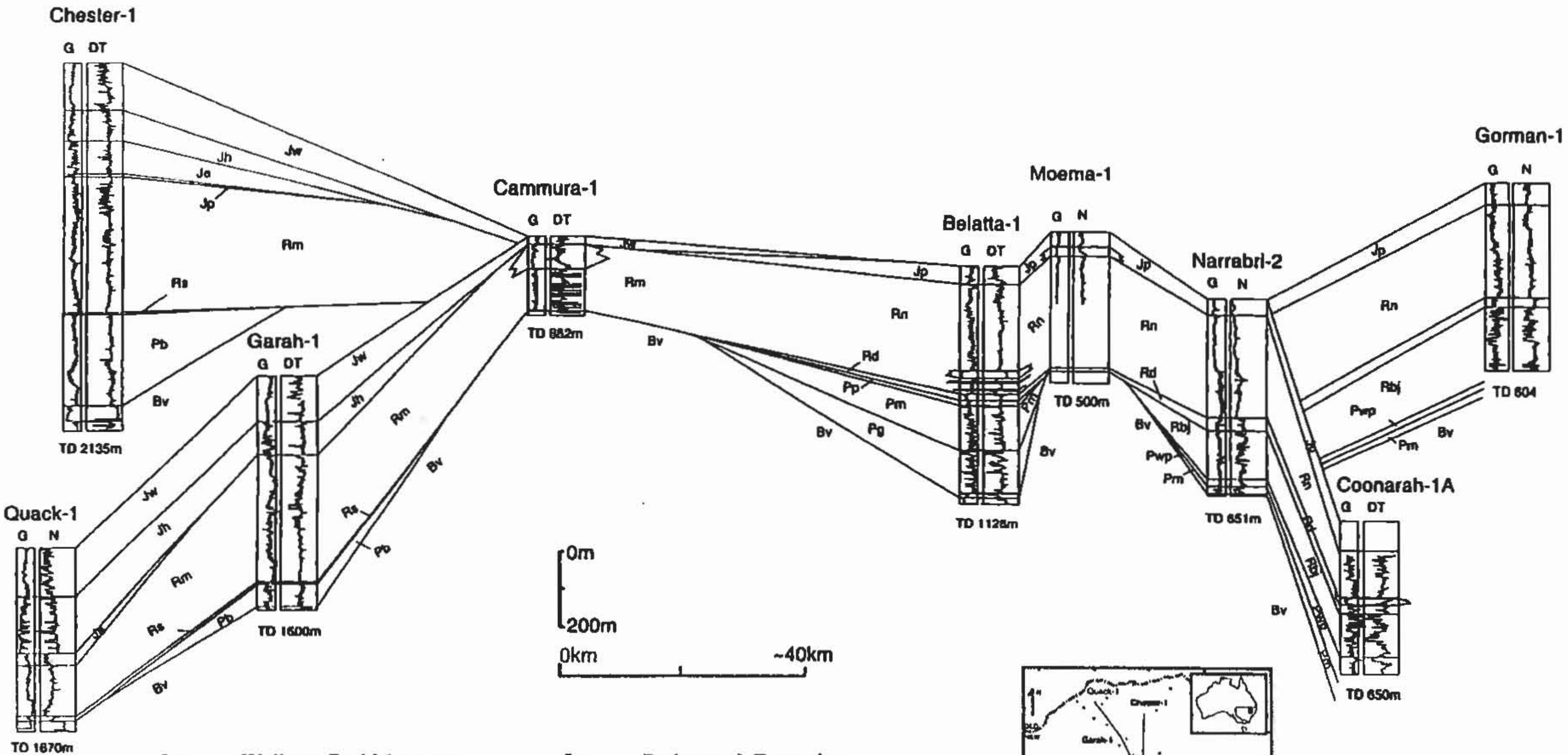
An Upper Permian coal bearing sequence, the Kianga Formation, is developed in the extreme northern and eastern parts of the Bowen Basin in New South Wales. This sequence, equivalent to the Bandanna Formation of the Blackwater Group (Shaw, 1995), shows a more normal trend of vitrinite reflectance with depth, and is therefore thought to be largely of terrestrial origin. The Black Jack Group, Watermark Formation and part of the Porcupine Formation are completely removed due to uplift and erosion in the area around Bellata and the Moree High (Figure 4). Although this makes exact correlation difficult, the Kianga Formation is probably equivalent to the upper part of the Black Jack succession, above the Arkarula Sandstone, where the coals also have more normal reflectance characteristics (Gurba and Ward, 1998).

The Lower Triassic Rewan Group unconformably overlies the Kianga Formation. This unit is present only in the extreme north of the New South Wales Bowen Basin (Shaw, 1995) and was only identified in Glencoe-1 in the present study. The Showgrounds Sandstone, distinguished from the Rewan Group by a lower gamma-ray count, is more widespread in the southern Bowen Basin, and occurs immediately beneath the abnormally compacted shale sequence in the lower part of the Moolayember Formation.

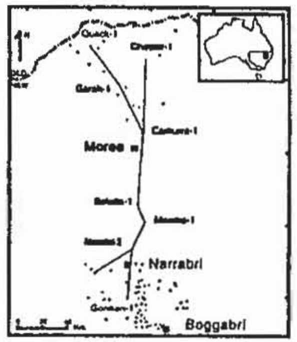
The Middle Triassic Moolayember Formation is well developed in the study area; the abnormally compacted lower part of the formation makes it a useful marker bed. Vitrinite reflectance studies also appear to show no marine influence on the Triassic sequence in the southern Bowen or northern Gunnedah Basin.

The Napperby Formation in Bellata DDH 1 above 866m, is a stratigraphic correlative of the Snake Creek Mudstone Member of the Moolayember Formation, and the overlying Triassic units are equivalent to the remainder of the Moolayember Formation (Etheridge, 1987). The abnormal compaction zones in both lower Moolayember and Napperby Formations, and the reflectance profiles, suggest that these two sequences are equivalent.

In the Surat Basin the Jurassic Walloon Coal Measures is equivalent to the upper part of the Purlawaugh Formation further to the south (McMinn, 1993); it is continuous with that unit over Moree High. Underlying units in the Surat Basin succession,



Jw	Walloon Coal Measures
Jh	Hutton Sandstone
Je	Evergreen Formation
Jp	Precipice Sandstone
Rm	Moolayember Formation
Rs	Showgrounds Sandstone
Pb	Back Creek Group
Bv	Basement and Volcanics
Jp	Purlawaugh Formation
Rn	Napperby Formation
Rd	Digby Formation
Rbj	Black Jack Group
Pwp	Watermark and Porcupine Formation
Pp	Porcupine Formation
Pg	Goonbri Formation



Datum is the base of Pilliga Sandstone.

Figure 4: Southern Bowen and northern Gunnedah Basin cross section, northern NSW.

including the Hutton Sandstone, Evergreen Formation and Precipice Sandstone , are also present further north. These generally thin and pinch out towards the Moree High (Figure 4), suggesting an angular unconformity across that feature near the Cammura No 1 well.

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BEYOND THE NORTHERN BOUNDARY: THE EARLY YEARS OF NEW ENGLAND GEOLOGY

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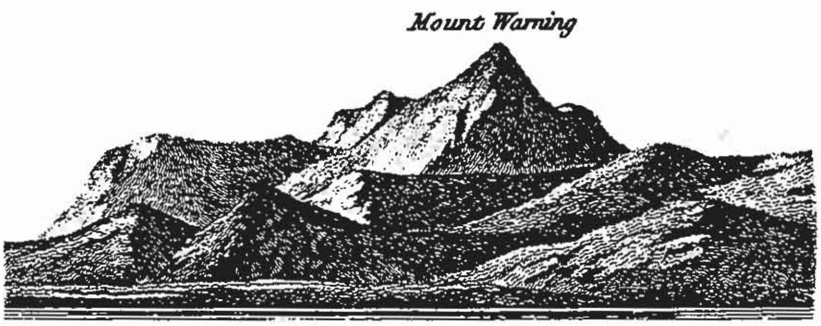
INTRODUCTION

The history of geological investigation in the New England region in its first hundred years can be divided into four parts: (a) Early observations from the sea (b) Observations of land explorers from 1817-1850s; (c) More specific mapping during the 1850s; (d) The beginning of detailed mapping and reports from the 1880s. This paper considers only European work done prior to 1856 within the present borders of New South Wales and north of the Liverpool Range, not the more extensive New England Fold Belt.

EARLY OBSERVATIONS FROM THE SEA:

Although Cook made no landings along the northern coast of New South Wales, his observations and topographic work gave some indication of the landscape of the region. In particular he noted the Brothers, the three Triassic/Jurassic shallow intrusives in the Kendall region, and aspects of the "Great Escarpment", recognising a high land behind a variable coastal region. Cape Hawke and Smoky Cape were named and obviously recognised as significant headlands, but the differences in lithology (metamorphic rocks/metabasalt and granite) escaped notice. The great mass of the Lamington volcano (Mount Warning) "this remarkable sharp peak'd mountain" and Point Danger, were particularly noted (Fig. 1). Matthew Flinders and Phillip Parker King, both extraordinary marine explorers, were also interested in the coastal geology, and the latter is specially important for the period he spent at Port Stephens. However on the coastline we find Flinders' only real geological comment was in reference to Cape Hawke "the strata in these cliffs lay forty or fifty degrees from the horizontal line."



Mount Warning by Matthew Flinders (1814)

FIRST LAND EXPLORERS: OXLEY AND CUNNINGHAM

In 1818 the first European incursion into the New England was led by John Oxley. Diverting from the flooded Macquarie River his party travelled via the Castlereagh and the Warrumbungles, south of the Nandewars and via the northern edge of the Liverpool Plains to Tamworth and the Walcha region. The ranges caused a little trouble but the upper Apsley River which Oxley reached in the last weeks of September, 1818, (at the great escarpment) forced him to divert, before reaching the headwaters of the Hastings River and thence to Port Macquarie and south to Port Stephens.

Thus Oxley crossed the Tamworth Trough, the Peel Fault, the south end of the Woolomin-Texas Block and the Hastings Block. He broadly recognised these changes coming from uniform sandstones of the Gunnedah Basin, noting in the Tamworth area "the rocks and stones which composed the bases and summits of these hills were not less various than their form, scarcely two were a like; granite, coarse porphyry, freestone and whinstone were frequently found on the same hill and the beds of the steams were of every variety of pebble." Near Walcha Road Oxley observed a marked change, the rocks "instead of being of a coarse sandstone were of a hard texture and of a blue shiny appearance when broken." Both the Apsley and Tia Falls were observed (Fig. 2), Oxley recording at Apsley "the rocks are all slate, the upper laminae of which are of a light brown colour, rotten, and easily separated. Nearer the base or surface of the water they are of a dark blue, and of a finer texture." Perhaps more significant in terms of Oxley's ideas about geology is this rather 'catastrophist' statement "at this spot the country seems cleft in twain.... the whole is indeed a grand natural spectacle, and is an indubitable mark of the vast convulsions which this country must at one period have undergone." He added "the geologist would here have a most interesting field for research, and would doubtless be enabled to account for these natural phenomena, which, from their defiance of all [?rules], perplex us so greatly." (Oxley, 1820). William Parr was named Mineralogist on this expedition, but what his contributions were it is hard to say, and Oxley clearly did not regard him as a 'geologist.'

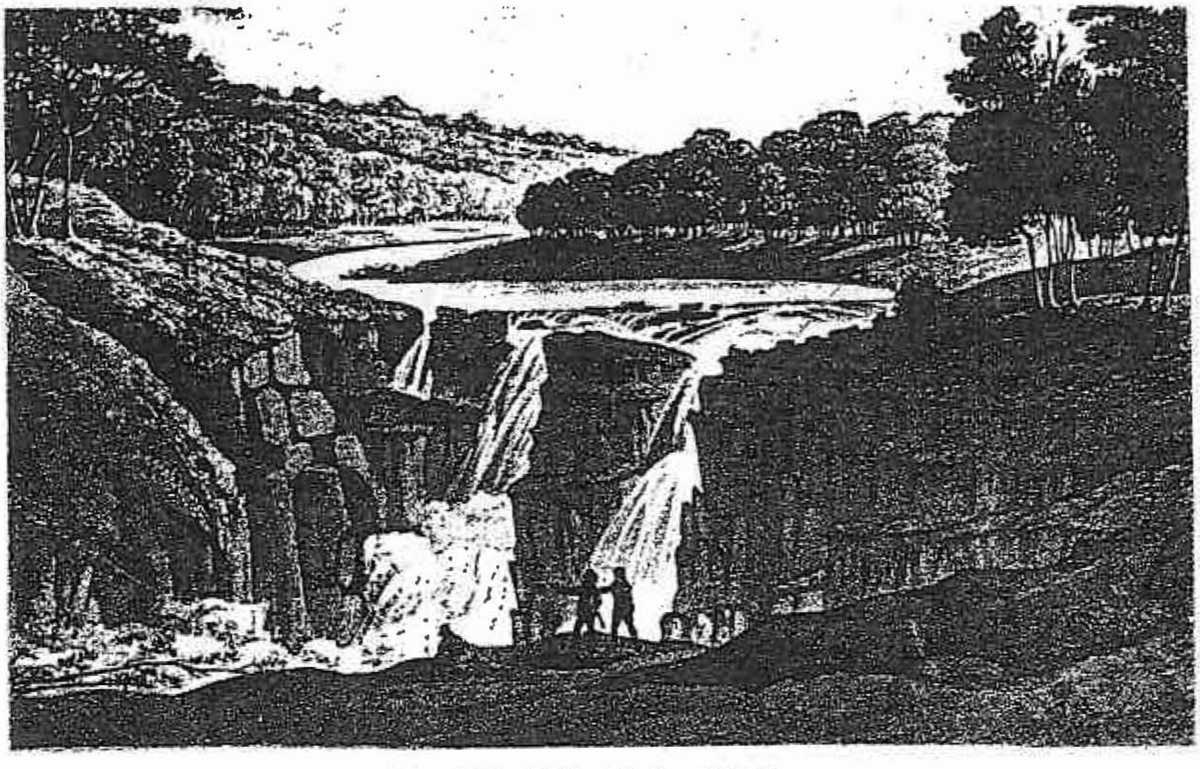


Fig. 2 Tia Falls (Oxley 1820)

EARLY NEW ENGLAND GEOLOGY

In 1827 Allan Cunningham led an expedition north beyond the Liverpool Plains, discovering the Gwydir, Dumaresq and Condamine Rivers. His route north took him close to Bingara and Warialda, and on the return trip he travelled south west from near Stanthorpe and Wallangara back to the Bingara district thence south. The journey north was largely west of, or just along the margin of the New England Fold Belt, and his reports mention sandstone, pudding-stone containing large pebbles of quartz and jasper, and, north of Masterton's Range, a rock "related to trap."

Returning from near Warwick on 18 June 1827 Cunningham recorded reaching the border of a "broken mountainous country, which exhibited a geological structure that had not been met with any part of our journey. The rock was a very hard granite, in which the quartz, greatly preponderating, was unusually large, and at this stage of our homeward-based journey our difficulties commenced." The party kept continually being pushed west by the terrain ("most wild and frightful region") until just east of the Nandewars, when they were able to travel south where "we again observed granite, but of a reddish appearance, in consequence of the quantity and colour of the felspar which might be seen disseminated through the rock, of which Hardwicke's Range [Nandewars] is evidently formed....[with] curiously formed cubical and chimney-shaped summits."

The following year Cunningham with seven companions attempted to travel to the Mount Warning district from Moreton Bay, but were diverted by heavy rain and flooding (Russell, 1888). Earlier Oxley had recognised lava from Mt. Warning forming the cliff at Pt Danger (Uniacke, 1825). Thomas Mitchell also ventured briefly to the New England in 1831-32, travelling via Burning Mountain and the Peel River but he continued quickly north-west via the Namoi, noting the trachytic nature of a southwesterly extension of the Nandewar Range.

STRZELECKI & LEICHHARDT

In the 1840s the New England was settled by squatters who pushed into the area and made the geography known, but there was little or no geology recorded until the visits of two continental Europeans, P.E. Strzelecki and L. Leichhardt.

According to Paszkowski (1997) and based on Strzelecki's own "Carte Geologique" Strzelecki made a quite extensive trip in October - November 1842 from 'Tahlee', Port Stephens, which took him a considerable distance NE from Mt. Wingen (and NW of Nowendoc) thence westerly past Tamworth and possibly as far as Narrabri, returning south via Gunnedah and Pandora's Pass. However there is only a little evidence of the trip in Stzelecki's book (1845). He writes "throughout the tract of country which lies between Port Hunter, Port Stephens, and Mount Wingen, the secondary rocks of this [second] epoch are found widely separated; each detached portion having its own strike and dip. In this dislocated structure some evidences are nevertheless discovered by which their former continuity may be traced. Nearly midway between the river Karua and Raymond Terrace there is a very slight elevation or low ridge of siliceous breccia and greywacke, ranging east and west. " In the Port Stephens area Strzelecki set out the following order of occurrence (oldest to youngest): granite, porphyry, greenstone, siliceous breccia, highly inclined layers of greywacke, and argillaceous flaggy rock containing Icthyodorulite, overlain by nearly horizontal sandstone containing Conularia, and conglomerate." With the exception of the granite this is a reasonable statement of the stratigraphy of that region and the earlier notes indicate something of the character of the Hunter Thrust region.

Leichhardt's traverse, at the time (1843-44), was by far the most comprehensive made through the New England by a geologically trained observer, particularly on the return trip from near Wide Bay (where he incidentally made the first detailed description of the macadamia {beuple} nut) when he came directly south down the New England Plateau from near Tenterfield through Armidale via Apsley Falls thence to the Manning,

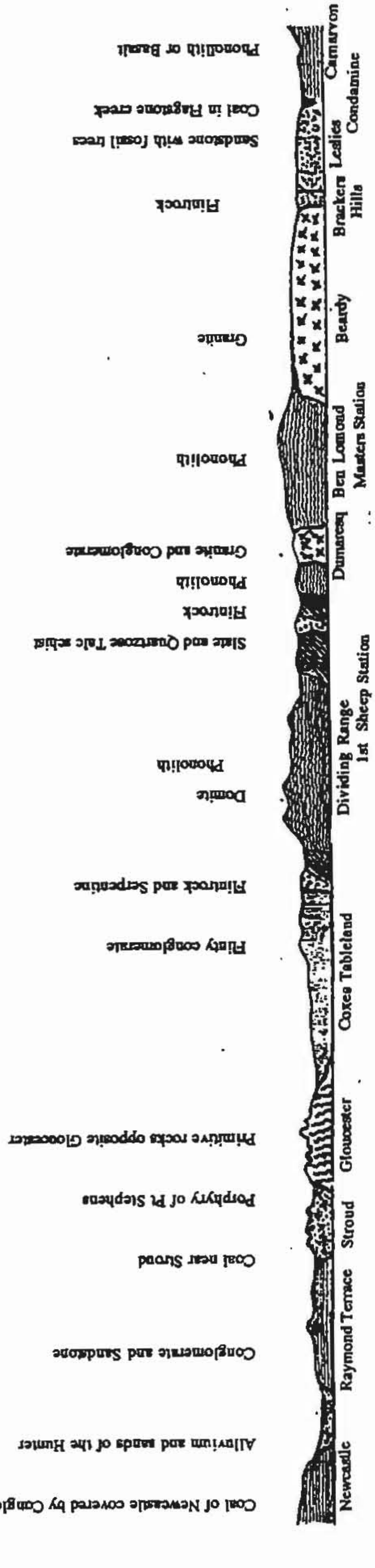


Fig. 3 Section from Darling Downs through New England to Newcastle (Leichhardt 1855)

and via Gloucester and Stroud to Newcastle. His numerous cross-sections are particularly enlightening (Fig. 3).

Covering some of the same ground as Strzelecki, Leichhardt wrote: "to the North-east of Glendon there's a complex of hills and mountains of a different nature. They're formed of a feldspathic and pyroxenic porphyry of which I don't recall having seen specimens in the Museum (the hills formed of this rock run in general from North-west to South-east or from North-east to south-west). They appear to represent sills that have risen between the pudding stone and the sandstone and a conglomerate that has been indurated in many places by the igneous contact. Towards the North, 36 English miles from Glendon, the pudding stone (and the conglomerate) appear again intruded here and there by the porphyry; and farther on is the sandstone at the base of the mountains which separate New England from the Hunter River valley."

"The Liverpool Range forms a sweeping arc of basalt around the basin of the Hunter.... The feldspathic and pyroxenic porphyries constitute a subordinate series closer to the sea. there is limestone in the mountains of the Paterson, which is said to contain trilobites, but I have not seen any, though I've found plenty of impressions of shells and of Orthoceratites at the foot of Mount Royal.....The descent to Moreton Bay is abrupt, like that from New England to Port Macquarie....Some of the streams have eaten their way into the slaty rocks of the highlands to form long gorges, for they still have more than 20 miles to flow from the highest fall to reach the true coastal lowland.

[On the Severn] "I saw for the first time granite and mica schist. The granite consists of an even mixture of quartz, feldspar and mica. This mica schist consists of very fine mica scales. I examine[d] the high lands of New England and its flanks towards Port Stephens. .... high mountains of quartz rock appear, and continue afterwards till one enters through a narrow valley into the district of Granite, which stretches for 114 miles, without interruption, southwards, where it is broken through by basalts. The granite contains many kinds of feldspar.... the granite with coarse components decomposes easily, and the blocks which sometimes lie singly strewed over the flanks, are sometimes heaped together in grotesque masses of a rounded form. The soil is formed of coarse granitic sand.

"On taking a general view of the Geology of this part of the country, we see a wide district of sandstone containing fossil trees, spead out along the western foot of mountains of quartz rock and granite. The granite forms a high tableland... At the sides and flanks of this tableland we find those hills of quartz rock and porphyry, which however also traverse the granite in broad dykes or bore through it in patches of limited extent. This granitic base for a great extent is broken through by basalt or phonolitic rocks, which on their part form a high land rising 1 000 feet above the high land of the granite. This high land is that from the Ben Lomond range, which from north to south is about 32 miles broad....[Further south] there is talcose schist....The granitic hill and mountain ranges show rounded outlines, and not those bold forms we are accustomed to see in granitic rocks of other districts. This is caused by the excess of feldspar and the great size of the components, in consequence of which the rock crumbles down easily on all sides. The forms and combinations of the blocks are often very striking; now we see mighty masses balanced upon a weak support; then appear rude imitations of tables, with a clumsy table plate and the thick legs; then, again, are heaped up five or six rounded blocks, one over the other. The Phonolite and Basalt mountains show in their outlines the same character which we have already seen, i.e., conical hills or elongated ridges, with nearly rectilinear backs and short sharp slopes. In the granitic district we can distinguish first, the coarse grained reddish granite.... then a whitish one, harder and with smaller components, quartz, feldspar, mica evenly mixed... further on a kind of Pegmatite.... and a blackish granite. Lastly, several feldspar porphyries....The conglomerates and pudding stone seem....to be only local formations."

"The talcose schist and talcose slate, which form the fall of the Apsley, belong to the Eastern Coast system, which extends from the Gloucester to the Bunya Bunya chain, and even to Wide Bay.....[Concerning] the Waterfalls of the Apsley, one source stream of the Macleay: from the appearance of the moderate hilly country we could scarcely suspect that we are in the neighbourhood of a cleft nearly 300 feet deep. We come unexpectedly to such an abyss; the opposing walls being formed of vertical slate cliffs, whilst at the right side, covered with ledges and some vegetation, allows a descent to the creek bed. The rocks stand nearly forward, like columns, and the quartz which traverses them in veins appears to have permeated and hardened the rock itseld. One quartz vein, three inches thick, runs from north to south along the rocky banks of the actual waterfall. The fall is distant twenty miles from the commencement of the coast land. The mountains extend thus far without a break and dip then quickly and steeply. It is probable that the floods have gradually hollowed out the long and deep channel, and that the fall itself is at the present day slowly travelling onward, till it shall have broken through the whole slaty area, and remain stationary at the (if not harder, at least) less cleaved basalt and phonolite.

"[In the vicinity of Mt. George] crops out an orbicular serpentine which is banded by quartz rock...I entered a new formation which accompanied me nearly uninterruptedly far down the Gloucester. The same is a conglomerate or pudding stone...between Gloucester and the Williams crops out a dark, nearly crystalline, limestone, with many stems of a Crinoid.

"The geologist of the Southern Hemisphere has to follow the general principles, which for geological observation are set down in the Northern Hemisphere [based on observations] he will gradually build up an independent geology for the southern hemisphere which he may then compare in large outlines with that of the northern one.

To intrude, however, constantly with the talisman of European nomenclature, will be a sore hindrance to a free and satisfactory development; instead of the tree in its own home soil developing itself freely and beautifully, we shall only rear a miserable plant in the hothouse of European geological cabinets."

GOVERNMENT INTEREST

The 1850s saw the beginning of gold mining in New South Wales, and a rapid spread of searching for the yellow metal from the central west of the colony to the New England. Involved in this was Samuel Stutchbury who tried to combine his perceived role as Geologist for the colony undertaking a regional survey, with acting as a skilled prospector reporting on both "reported" finds and potential sources, as the Colonial Secretary Deas Thomson requested. After mapping as far northwest as Yeoval Stutchbury turned north to the Warrumbungles then to the Nandewars, continuing northerly ultimately into Queensland and Moreton Bay. He first entered true New England territory in May or June, 1853, and remained essentially in the Tamworth Belt. However he made some important observations at Bingara where he hit the Peel Fault. He reported that "near Bingera serpentine as a main rock comes in. The whole of the country in which mining for gold is now carried on is of serpentine as the principal rock, appearing in all its varieties of constitution and colour, from the common schistose to the compact noble serpentine. Its colours are as varied as the whole of those of the British isles, from the dark chocolate brown with red veins to the various shades of green with light green veins; some are veined with silky amianthus and coarse asbestos; it contains diallage, bronzite, actynolite, quartz crystallised and in veins; semi-opal occurs from the adhesive absorbent cachalong (in reniform masses) to wax opal. In addition to the above-mentioned minerals, the serpentine is penetrated by a close grained syenite standing in irregular tors; on the western side of the syenite is a dark green compact felsparite with distinct crystals of albite (cleavelandite), the green colour resulting from hornblende, the weathered surface exhibits the cleavelandite in large well defined crystals, a considerable quantity of iron ore (chromite?) occurs in isolated masses.

"I was most disappointed in not finding or hearing of the existence of any native, or ores of copper, almost universally associated with such rocks in othere parts of the world, and it would be singular if this should be the exception. I did not trace the eastern extent of the field nor enter into the detail of its gold produce, knowing that it had been examined especially with the latter view by the Reverend W.B. Clarke. Gold appears to be very generally dispersed through the soil, and much of it on the surface of the flat lands. At present there does not appear to me (so far as I could observe) to have been any well conducted trial below the surface, probably from the want of sufficient water; on this account it will so long prove precarious until some well organized system is adopted for establishing reservoirs and aiding the collection of water by mechanical means. At Collett's Valley the serpentine ceases and gives place to porphyritic rocks, which cross the Gwydir at this point and prevail as far north as Molroy."

West of Bingara, near the Horton River and some thirty six miles away near Gravesend Stutchbury recorded two occurrences of limestone, both trending N20^{0}W, containing corals (?favosites fibrosa) and crinoid remains, and Stutchbury felt "there is no intervening dislocation or fault." At the more northerly site "one quarter of a mile further east there is another band of hard greenish grey limestone, the intermediate space being covered by conglomerate; this is succeeded by very large blocks of vitrified sandstone varying both in colour and texture." On the McIntyre he recorded "a range of hard, flinty slate abuts upon the river. This range trends to the NE, forming a crescent and is flanked on the west and south-west by sandstone ridges of considerable extent. In washing the earth in the bed of the river....I found very small gold, and minute rubies, sapphire, garnet and chrysotile etc." Stutchbury's contributions to the New England Fold Belt story were mainly in Queensland and must be left to another time.

Rev. W.B. Clarke was also in New England in 1852-53. Clarke and Stutchbury overlapped on the Darling Downs. However Clarke's reconnaissances took him through much of the New England Fold Belt and east into the Clarence Basin. In late October 1852 Clarke set out to "examine the headwaters of rivers rising in the highlands north of the Hunter Valley, i.e. Manning, Macleay, Hastings, Clarence and Tweed flowing east, and the Peel, Namoi, Gwydir, Macintyre and Condamine flowing west." Clarke went first to Tahlee, the A. A. Co's Port Stephens headquarters, home of P.P. King, which had been the haven for Strzelecki, Leichhardt and J.B. Jukes and discussed geology with P.P. King and his son P.G. King. He moved thence across to Wingen, via the Mt Royal Range and Barrington Tops.

By 6 November Clarke was camped on Cann's Plains on the Peel River, where he found the country "had the classic features of the gold country west of the Blue Mountains and in Victoria, with thick beds of quartz. E.W. Rudder the Commissioner was being tactful with the disputes among the more than 150 miners already on the field. Clarke continued to the Hanging Rock diggings, reporting that the gold occurred capriciously as lumps near the surface or as fine dust in granite (?) not quartz. The relation of gold to granite was observed at Bingara, Rocky River (Uralla) and Hanging Rock, but values were low. Gems (sapphires, emeralds and rubies) were widespread and tin occurred from the Peel north to the Condamine.

From Armidale Clarke wrote "....huge granite masses assume a modular, concretionary structure, decomposing into rounded, smooth, and domelike masses, or into separate tors reposing upon each other in picturesque forms..." The ranges north of Armidale were described as composed largely of various types of granite, through which trappean basalts and greenstones had been forced. From NE of Armidale to Grafton, a road section that he described in detail, he recognised grey granite, basalt with chrysotile at Guy Fawkes, greenstone (at Hernani), felspathic rock ("this is evidently an altered slate"), schist, trap, granite, felspathic grits derived from granite or from slates that have been altered, similar green felspathic grits, and, at Grafton, sandstone with fossil wood and coal.

By June 1853 Clarke had traversed much of the Clarence Basin and had made several ascents of the 'great escarpment'. He recognised the synclinal character of the Clarence Basin and equated the 'carboniferous' formations exposed with the Wianamatta of the Sydney Basin, and was particularly interested in the unconformity between the basin rocks and the older formations (including slate, schist, serpentine, granite and limestone), which further south he had nominated as being, in part at least, Silurian, as the term was then understood. He believed the basin rocks covered much of the slaty sequence exposed to the south. Clarke believed that the escarpment west of the Clarence was the direct result of faulting, and he thought it was the continuation of faulting along the escarpment in the Apsely-Macleay Rivers region. From Grafton to Tabulam he recognised 16 units, particularly "siliceous slate and serpentine, in stony ridges, striking E.S.E. on black soil, and just a little further north, at Yulgilbah, "granite with serpentine, and compact feldspar, in ridges with black flats; on the hills grey cornean." Continuing west from Tabulam to Tenterfield he went from sandstone with quartz pebbles to granite, ophite and green schist pebbles (?derived from conglomerate), flinty slate, granite, ophite and siliceo-felspathic schist to pegmatite (decomposing into sand) on the tableland, and finally granite. This brings us back essentially to the point where Cunningham first noted New England granite back in 1828.

ODERNHEIMER

While the surveys by Stutchbury and Clarke were by their nature broad reconnaissances, Clarke's particularly so, because of his episodic ventures into the region, Ferdinand Odernheimer's mapping of the Cordillera Gold company's leases at Nundle in 1855 was one of the most detailed mapping exercises undertaken in the New England region (Branagan, 1984). But we must leave him, the tin and silver mining stories of the 1860s and '70s and the mapping by C.S. Wilkinson and T.W.E. David in the 1880s till another time.

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THE COALFIELD GEOLOGY COUNCIL OF NSW KENNETH GEORGE MOSHER INAUGURAL MEMORIAL LECTURE

B VITNELL
Coal Geologist (Retired)

THE COALFIELD GEOLOGY COUNCIL OF NSW

The Coalfield Geology Council of NSW was established as the Standing Committee on Coalfield Geology of NSW on 6 October 1961 under the aegis of the Department of Mines NSW. The inaugural Chairman was Joe W. Whiting and the Secretary Clifford T. McElroy. Ken Mosher was its second Chairman from the 8th March 1963 and Ken G Wood was the second Secretary.

The original aim of 'The Committee' was encapsulated in the statement "exchange of ideas on geological techniques and terminology employed in Coalfield Geology with a view to standardisation". The Committee, now Council has continued to meet quarterly. Contributing many important references for the industry, it has also instituted an Annual Award for Excellence in 1993. Today, 'The Council' continues the work of its founders.

In 1998 it was decided by 'The Council' to institute an Annual Lecture in memory of Kenneth George Mosher, an inaugural member, past Chairman and highly esteemed past Chief Geologist of the Joint Coal Board. This inaugural lecture will outline the life and career of Ken Mosher as a prelude to the institution of an annual lecture by a person selected by the Executive of the Council on a topic of the science or technology of Coalfield Geology.

KEN MOSHER

Ken Mosher was born in Sydney on 30th October 1913. He was one of a family of 3 children and was educated at Maroubra Primary and Sydney High School obtaining his leaving certificate in 1930. He attended Sydney University from 1931 to 1934, graduating with a Bachelor of Science, majoring in Geology and Mathematics. He then commenced his professional career as a geologist with the Geological Survey of NSW. His career extended for 41 years in employment, excluding Military Service. Beyond 1975 he was the Principal of Mosher and Associates, a consultancy which was to continue for a further 15 years until his death in 1990.

BRIAN WILLIAM VITNELL

Before proceeding to an examination of his geological career, mention must be made of his two other great loves – ***Scouting and the Army***.

He joined the Cubs at the minimum age of 8, commencing an association which was to span nearly 50 years. His love of Scouting saw him serve in various levels attaining the position of Area Commissioner, Northern Metropolitan Area, Sydney. This service was interrupted only during World War II and his absence interstate post-war from 1940-1950. During his service in Scouting, Ken was awarded a number of significant decorations for services to the Movement up until 1978 when he retired from Scouting.

As if this was not enough to fill his time, he enlisted in the Sydney University Regiment, in his first year. During the period 1931-1940 he rose through the ranks serving as Private to Lieutenant. Following his marriage to Imelda Agnes Henderson, whom he had known since 1934, he enlisted for overseas service in the 2/18 Australian Infantry Battalion. During his service he was taken Prisoner-of-War at the fall of Singapore in 1942 and incarcerated at Singapore, Sandakan and Kuching in Borneo.

He was repatriated to Australia in September 1945. Three years later he resumed service in the Citizen Military Forces helping to reform the Sydney University Regiment. He was to serve the Regiment for a further 13 years as Captain, Major and Lieutenant Colonel-in-Command. He received the Efficiency Decoration (E.D.) in 1954 and was accorded the honour of the award of the Order of the British Empire (Military Division) for his contribution as Second-in Command of the Unit, invested while Commander in 1959.

On his retirement from the Regiment in 1961 he spent a further two years at the Eastern Command Staff Training Unit before retiring as full Colonel in 1963. He maintained contact at Regimental functions almost up to his death.

I personally well remember the high esteem in which Ken was held by all ranks past and present at this time. Between 1955 and 1957, I was assistant to him as Chief Geologist of the Joint Coal Board in the Goulburn Street office of the Board. He had, of course, access to the Adjutant of the Regiment, but I may say that a degree of my time was spent as a "runner" and Goulburn Street "Honorary Adjutant" between there and the Regimental Headquarters at the University.

I have introduced the Scouting and Army aspects of Ken's life at the outset, which although in most part being parallel, they were nevertheless subordinate to his professional career. Despite his Scouting and Army activities, geology and especially Coal Geology was Ken's passion. I believe these aspects contributed materially to the character of the man. The character that many of us, although diminishing in number, knew and remember with affection.

COAL GEOLOGY

However, it is his career as geologist, administrator, confidant and friend which is the basis of this, the inaugural Kenneth George Mosher Memorial Lecture. He never undertook any aspect of this career without enthusiasm and zeal and could not understand why others were slow or unwilling to embrace his concepts.

Ken's initial interest at Sydney University was maths and physics. But after doing a geology subject to fill in a gap in his timetable, he moved the emphasis of his degree into geology. On Graduation in 1934 he joined the Geological Survey of NSW where his initial appointment was as Mineralogist at the "old" Mining Museum at George St, North. His subsequent activities at the Survey (pre-war) were directed towards Energy Resources. At this time he held the position of Secretary, State Fuel Research Committee for 3 years in addition to his field activities.

He worked as assistant to H.G. Raggatt, firstly in a field assessment of hydro and thermal power sources as part of a statewide evaluation of hydropower potential. As the war years approached, he assisted Raggatt in assessing likely sources of iron ore in NSW.

He was granted leave from the Survey between 1940-46 in respect of his war service and resumed duty on his return from those harrowing days. Then ensued a period when under the benign rule of the public service, returned staff, especially P.O.W.'s were able to return to normal service. Here relates one of life's strange twists. Back in 1934 Jack Harrison, Joe Whiting, Fred Hanlon and Ken joined the survey on the same day. Under public service rules seniority was determined by date of birth and in the order given, Ken was the youngest. All save Whiting (who was rejected on medical grounds) enlisted during World War II and all resumed with the Survey afterwards, with the same seniority ranking. During this time Ken was engaged on field activities which took him away from home for lengthy periods.

Meanwhile with a developing coal crisis in the then totally fragmented electricity industry, Ken with the encouragement of Leo Jones began to develop an interest in coal again. He undertook a detailed survey of the Burragorang Valley coal deposits, before their inundation by Warragamba Dam.

Ken was able to see that he had no future for significant promotion and in late 1948 he applied for the position of Senior Geologist with the South Australian Department of Mines, taking up the position in June 1949. His duties were "to supervise and control the functioning of the Coal Section of the Department.....and to be directly responsible to the Director of Mines for the above matters". Ken was also involved in evaluation of uranium deposits in South Australia at this time.

His early philosophy on the seemingly perennial differences of approach between Geologists and Mining Engineers appears on his personnel file as part of an appeal against classification circa early 1950 in his own hand and ends as follows. "I suggest that engineers and geologists must share equally the fruits of the success or failure of any project upon which they work jointly, and to classify one as more important than the other is unacceptable". Prothetic words of nearly 50 years ago.

Ken spent what was to be a relatively short time with the South Australian Department of Leigh Creek in the north of the state, site of an extensive deposit of thermal coal. In July 1950 Ken resigned from the South Australia Department of Mines and took up the position of the first geologist with the Joint Coal Board. Before leaving South Australia, Ken in true Mosher style and with the sense of responsibility which always characterised his activities throughout life, prepared a lengthy and comprehensive review of the Coal Section, its personnel and activities.

The Joint Coal Board was set up by the NSW and Commonwealth Governments after the disastrous 1949 NSW coal strikes to bring order and control to the coal mining industry in NSW. A direct result of the coal strikes was the loss to the NSW coal industry of the interstate thermal coal trade to Victoria and South Australia and the set up of the Latrobe Valley brown coal mines and power stations and the Leigh Creek mine in South Australia.

Ken commenced duties with the Joint Coal Board in July 1950. There he remained, for what in retrospect and in terms of what was achieved seems a short time. Firstly as Geologist, then Supervising Geologist and (from 6/3/62) Chief Geologist until his resignation to accept appointment as Coal Geologist, Rio Tinto/Zinc Corporation (Aust) Ltd, effective July 1962. Despite the foibles of the Joint Coal Boards seemingly belittling classifications, Ken was known to all throughout his service as the Chief Geologist of the Board. He was succeeded in this position by J.B. Robinson.

In December 1950 at a high level meeting held between senior Federal and State politicians and bureaucrats, confusion, muddled thinking and complete lack of knowledge as to what geology had to offer the coal industry are evidenced in the minutes. It was time for Mosher action! After being with the Board for six months Ken joined in with discussions and sought ways to improve the parlous state of the coal and electricity industries. By seeking ways of discovering new coal deposits in order to boost production quickly, he sought to prevent the prevailing blackouts which were occurring at the time.

One of Ken's many achievements at the Joint Coal Board include the promotion of the concept of coalfield site power stations such as the subsequent Munmorah, Vales Point and Liddell power stations, instead of the mostly Sydney sited power stations. Ken also initiated small opencuts in the Lithgow area for a short-term coal supply in the early 1950,s. They were required to bolster an inadequate supply from the Lithgow area underground mines.

Due to post war building material shortage Ken and Imelda and their young family actually spent some months living in a Joint Coal Board house at Bellambi. The house had the interesting feature of two electrical wiring systems. One supply from South Bulli Colliery, ran half the house and the oven of the stove. The other supply from the unreliable domestic power grid ran the other half of the house and the hotplate of the stove. It made for some interesting living and cooking arrangements."

There can be no doubt that during his years with the Joint Coal Board, Ken's career reached its zenith. Having regard to the state of affairs when he first joined and the disinclination to accept his advice through much of his employment, it is only due to his supreme organisational skills that any headway was made at all.

At a very early stage, recruitment was made to fill District Geologist positions at Cessnock, Newcastle and Lithgow, while Ken himself attended to Wollongong matters as part of his overall responsibilities. It is interesting to note that these positions were originally titled Senior Prospecting Supervisors and Prospecting Supervisors, due to objections from the Commonwealth Bureau of Mineral Resources and the State Department of Mines, but were later retitled.

Having obtained a staff, Ken set out to win over his reluctant employer, departmental colleagues, universities and industry to his cause. He was a man before his time placed in a conservative coal industry. An industry managed at all levels by men who developed management practices and work experience well before the War, men who found it difficult to grasp the intangibles of the science which presented new opportunities.

His career with the Board was indeed epoch making and he introduced techniques and methods which in updated forms are the basis of successful geological exploration and mine development of the present day. There are very few coal geologists who do not in some way work in similar or derived methodology, advanced by the explosion in technology from the 70's onward.

Initially he devoted his position to standardising the methodology of Coalfield Geology and Coal Mining Geology and Technology. His first internal document was a volume of Geological Standards and Practices, supplied to all staff and all new starters at the Board. The document itself was a major undertaking and was in loose bound form so that additions/amendments could be made as time and circumstance dictated. I still have mine!

Early policy of the Board was to seek to improve the productivity of the industry, generally by the delineation of areas that could be prospected for potential open cut coal. Of course we are speaking of potential mining on a vastly lesser scale than today's operations. The favoured method of exploration was by percussion drilling leading to chip samples, which by the standards of the time were much-contaminated stratum by stratum.

A major priority of Ken's was to introduce rotary cored drilling as used in the metalliferous industry. It was quickly determined that the accepted (A size) slim core drilling of that industry was unsatisfactory in softer sediments and friable coal, leading to the need for larger diameter (N size) cores. In addition, single tube barrels which circulated the drilling fluid against the core being cut, before ejecting it from the face of the drilling bit under pressure, did not assist maximum core recovery.

I well remember undertaking a major drilling programme at Ulan, north of Mudgee in 1951/2 using screw-feed drilling rigs hired from the Snowy Mountains Authority and the type of equipment described above. Core recovery in coal varied between 30-40% by volume in a seam which was not particularly bright and friable!

So Ken determined that he and his prospecting supervisors would become responsible for improving the technology of diamond drilling! What followed, with the assistance of a major drilling equipment manufacturer, is history. The development of the double (then triple) tube core barrel with bottom (face discharge) drill bits in various configurations, using vastly improved drilling mud as the circulating fluid.

The initial, primitive but successful combination was described in a paper in the bulletin of the AUSIMM in 1957 under the joint authorship of Ken, myself and M.G. (Pat) Lees of Triefus Industries (Aust) Pty. Ltd. Subsequently Ken was presented on his retirement with a handsome nickelled model of the split tube core barrel by Triefus Industries inscribed "To Ken Mosher – a Split Inner Tube Core Barrel".

At these times the gradual introduction of hydraulic feed drilling rigs further improved core recovery and presentation. With experience, geologists monitored the drilling of coal seams until drillers could be properly trained.

Ken was responsible for consolidating all colliery working surveys, in the lower Hunter Valley, on the same height datum. This was so it was possible to relate adjacent workings to each other. This allowed the use of structure contours to outline configuration of the coal seams, which could be drawn and seam trends plotted to show zones of splitting and deterioration.

This uniformity lead to the first major study of a working coalfield using early exploration bores and information from colliery workings. K.J. Kemezys, a geologist at the Cessnock Board office was employed for the purpose of producing a report on the Greta Coal Measures. This work produced as an internal Board report was widely circulated but not published. It was revised twenty years later as an internal Coal & Allied Industries report by K.J. Bartlett, also unpublished and now presumably lost. The funds obtained by Ken's efforts were those remaining from a levy on production which had earlier produced the "Stowage Fund", an aborted attempt to control the workings of the thick Greta Seam at depth by filling the workings with slurry.

By 1954 as the result of a political decision, the Board ceased all open-cut prospecting activity. But by a lucky overlap not long before, the then Electricity Commission of NSW had approached the Board regarding delineation of coal reserves for power generation. The focus of which was initially in the Central Coast and Illawarra areas and later in the Upper Hunter.

This gave Ken the opportunity to broaden the scope of exploration activity during the second half of the 50's and the early 60's. As a result a close and rewarding relationship between Board and Commission technical staff resulted. The delineation of large resources of open cut and underground coal resulted in the establishment of Power Stations, Vales Point, Liddell, Munmorah and Bayswater Generating Stations in the north, Tallawarra in the south and Wallerawang and Pipers Flat in the west. This exploration also formed the basis for the major development of the export trade in the late 60's.

These brief glimpses of major activities during his time with the Board understate considerable his ever increasing influence in the area of practical coal geology. He began to form closer links with Professional Institutes and learned societies almost from his first days. He fostered relations with the Universities and research organisations such as CSIRO. He instituted vacation employment of geology students and subsequently the introduction of women to the office and the field. As well attending Congresses and Conferences at which he spread his message. To attempt to list them would occupy too much space, but his close involvement with the Geological Society of Australia, Australasian Institute of Mining and Metallurgy and the Australian Institute of Geoscientists are worthy of mention. He was a member of the Standing Committee on Coalfield Geology of NSW (forerunner to the Coalfield Geological Council of NSW) from 1961 up until shortly before his death. He was The Committee's second Chairman. He attended the Second and subsequent Symposia "Advances in the Studies of the Sydney Basin" in 1967 (there is no reference to the first in his records).

In July 1962 Ken resigned from the Joint Coal Board to accept employment as Coal Geologist with Rio Tinto Management Services (Aust) Pty Ltd. Thus, halfway through his post-war career as a coal geologist Ken joined an organisation which was itself almost immediately to go through further change. As from mid July it was announced that Rio Tinto and Consolidated Zinc would merge and with effect from 1 January 1963 all staff from both organisations were to be employed by the new company Conzinc Rio Tinto of Australia Limited (CRA).

Ken was to spend 13 years with the CRA group and the records show that his high hopes for the future were not realised. Due to changes in corporate policy following the merger, coal did not assume the wider spectrum that had been intended when he was employed and his talents were not utilised to the full.

However, this disappointment was obvious only to his closest friends and all was not doom. He was able to carry on his influence from many of his curricular activities in coal geology and associated events, as well as his extra curricular activities detailed at the beginning of this narrative.

Some of his achievements with CRA included; the expansion of Kembla Coal and Cokes, Wollongong leases to allow the development of Darkes Forest mine and Westcliff Mines, very early use of surface seismic and magnetic onshore and offshore surveys for coal exploration and the introduction of geological staff attached to the Coal Cliff Colliery for conduct of the coal exploration and underground mine geology work. By now he had become a if not the pre-eminent figure in operational coal geology and technology and had the satisfaction of seeing many of his proteges and junior colleagues advance into the industry. His opinions were sought publicly and privately on a wide scale and were given freely and without restraint, save loyalty to his employers.

These activities involved the full spectrum of corporate and individual entities and following his embarking beyond 1975 as a consultant, he gave more free advice than ever he was paid for. He did have the satisfaction of some meaningful consultancies and directorships in the 10 years that followed, before time and the ravages of his war service took their toll. . One of Kens consultancies was with the German coal industry Saarberg Coal who were looking into importing Australian coal from various mines, this however was scuppered by port disruptions in the late seventies.

Much of Ken's output in his professional employment is not preserved: he had very strict standards of confidentially, and although there is evidence that he kept personal copies of much of his work, the vast majority of it was destroyed, or handed back to his several employers. He regarded himself very much as a hands on leader, and almost nothing of his endeavours was published in journals. However, there are memories of his time in abundance. Despite the passing of time and the erasure of some of these memories, the legacies remain.

The last thing that he would want mentioned – in addition to his honours in other fields, he was awarded Membership of the Order of Australia for service to Science and the Community in January 1984. His Honorary Life Membership of the Australasian Institute of Mining and Metallurgy in August 1986 was given "for his dedicated involvement with the affairs of the Institute over a long period of time .... his unswerving dedication to the advancement of knowledge of Australia's Black Coal deposits and for his pioneer work on the standardisation of recording of coal geology information and its application to industry while inter alia Chief Geologist of the Joint Coal Board". Those of you who knew Ken only in his later years have been denied one of life's rewarding experiences. Toward the end of his life, Ken said, 'that he was privileged to have had a paid hobby all his life'.

CONCLUSION

I can do no better than quote from the late Ken Glasson's eulogy at his funeral in February 1990. "He was the professional perfectionist, the epitome of integrity the embodiment of sincerity and trust. An enthusiast in all he undertook, his unfailing source of encouragement to others who needed it, his thoughtfulness and kindness, his keen sense of humour and fun – all these qualities were his. When Ken was serious in discussing a problem he concentrated, but when he enjoyed a joke his whole face laughed, his blue eyes danced with merriment and finally his whole body would shake with enjoyment." He was a human dynamo.

It is to be hoped that successive coal oriented generations will perpetuate the memory of this fine man by each year adding to the state of our science by a presentation in his name. He was a great friend and colleague to me and I consider it an honour to have been selected to give the first of them.

ACKNOWLEDGEMENTS

For her kind and helpful review of the text, grateful thanks are extended to Mrs Imelda. Mosher. The text was retyped and edited, in the absence of the author, for inclusion in the Newcastle Symposium Volume. This was done under a very tight deadline and it is hoped that it meets with the author's and Mrs Mosher's approval.

LAVA TUBES, LOBES AND SHEETS: EMPLACEMENT OF THE LATE PERMIAN MARGINAL BASIN BLOW HOLE FLOW, SOUTHERN SYDNEY BASIN

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INTRODUCTION

The southern Sydney Basin comprises the shallow marine Permian Shoalhaven Group and predominantly freshwater sequences of the Late Permian Illawarra Coal Measures and overlying Triassic rocks. The Shoalhaven Group consists of marine clastic sedimentary rocks together with several mafic lavas near the top. The uppermost unit of the Shoalhaven Group is the Broughton Formation which has a shallow regional dip of 1-2° towards the northwest but local dips of up to 12° have been recorded (Bull & Cas 1989). The lower units of this formation are best exposed along the coast near Kiama where near continuous outcrops along low cliffs provide both vertical and lateral sections through the sequence. Exposures away from the coast are very poor and are restricted to sporadic road cuttings and cliff sections.

In the Kiama area the Broughton Formation can be subdivided into the Westley Park Sandstone Member (lowest unit), the Blow Hole Latite Member and the overlying Kiama Sandstone Member. In this scheme the term latite, which forms the lithological part of the formal stratigraphic name, follows historical usage that, in the widest sense, denotes a fine-grained mafic to intermediate rock with equal or nearly equal amounts of plagioclase and K-feldspar. On the basis of modern chemical nomenclature the Blow Hole flow is a shoshonitic basalt (Carr 1998).

WESTLEY PARK SANDSTONE MEMBER

The Westley Park Sandstone Member consists of a cold-water marine inner shelf succession of volcaniclastic strata with facies ranging from strongly bioturbated massive silty sandstone to better sorted cross-stratified tractional deposits formed under shallower water conditions. The sequence immediately below the Blow Hole flow in the Kiama area consists of 3-4 m of high-energy, flat and cross-stratified sandstone probably deposited above fairweather wavebase in water depths of ~20 m, erosionally overlying ~15 m of poorly-bedded bioturbated sandstone deposited slowly in water depths close to storm wave base.

BLOW HOLE FLOW

Raam (1964) proposed that the Blow Hole flow resulted from two separate outpourings of lava separated by a lens of volcaniclastic sandstone known as the Rifle Range Sandstone Member. Both lavas were interpreted as submarine flows that locally intruded into and incorporated masses of unconsolidated, water-saturated sandy substrate. More recently Bull and Cas (1989) have described the unit as being tripartite with the middle unit being at least partly intrusive. In the present study the Blow Hole stratigraphic unit is also subdivided into three facies.

Sheet and lobe facies

The lower unit of the Blow Hole flow consists of a series of lobes typically several tens of metres wide and up to ~8 m thick. The contact between this lava and the underlying Westley Park Sandstone Member is typically sharp, planar and conformable while the upper contact is undulatory on the scale of an outcrop and curvi-planar over several tens of metres to define a flow lobe.

Tube and breccia facies

The middle unit of the Blow Hole Latite Member is typically ~10 m thick and consists of digitate lava masses, surrounded mainly by volcanic breccia and minor volcaniclastic sandstone. The unit overlies the lobes of the lower unit and infills the areas between adjacent lobes. In this middle unit, digitate lava masses range between tens of centimetres and tens of metres in width and commonly are circular to ellipsoidal in cross-section but may be irregular. Bulbous apophyses occur on some masses. Contacts between the lava masses and surrounding breccia are generally sharp and planar, but some contacts, particularly with sandstone, are ragged or delicately sutured and fluidal. Some of the circular to ellipsoidal masses can be traced laterally a few tens of metres to define well-developed, undrained lava tubes.

Columnar jointed facies

A complete section through the upper unit of the Blow Hole flow is not exposed at any single outcrop. The unit has a maximum thickness of ~50 m and consists mainly of thin (~2 m thick) layers of massive basalt at the base and top of the flow separated by a thick columnar-jointed basalt. Most columns are ~40 cm in diameter and their long axes are subvertical. The top of the flow is uneven with localized relief of up to ~5 m. In addition, small areas of the flow top consist of highly oxidized scoria which, in some cases, has undergone minor sedimentary reworking. Devitrified glassy material and sedimentary inclusions comprising masses of red-brown volcaniclastic sandstone showing contorted bedding are common, particularly near the base of the unit. These sedimentary inclusions are petrographically very similar to the Rifle Range Sandstone Member.

KIAMA SANDSTONE MEMBER

At Kiama the vesicular upper part of the Blow Hole Latite Member has been partly reworked to form a thin breccia to conglomerate layer with clast roundness increasing upwards through the deposit. This unit resulted from wave reworking of the scoriaceous flow top probably during the initial stages of a transgression. The overlying basal portion of the Kiama Sandstone Member consists of storm-redeposited sandstone beds with occasional siltstone laminae. In contrast, the stratigraphically equivalent sequence overlying the Blow Hole flow in road cuttings south of Kiama represents a fluvial sequence overlain by a permafrost palaeosol (Retallack 1999).

DISCUSSION

Close similarities in petrography and geochemistry between the basalt lavas from the three facies indicate similar viscosities at similar temperatures. At the time of emplacement of the lobe and sheet facies the environment was shallow marine, ranging from lower to middle shoreface. Water depths were probably ~20 m, being shallower to the south than at Kiama. Lava may have transgressed from subaerial to subaequeous and was emplaced relatively passively with lava flux sufficiently high to form lobes and sheets rather than pillows. The presence of seasonal, or at least not permanent, sea ice in the Late Permian may have inhibited wave action during some eruptions and contributed to the formation of submarine extensions of subaerial lavas.

The middle unit of the Blow Hole flow probably originated from a subaerial vent and then flowed into a shallow submarine environment, with initial water depths of 10-15 m, in much the same way as many current lavas from Kilauea volcano, Hawaii, and several other active basaltic volcanoes flow into the sea. In all of these cases transition from subaerial to subaequeous produces an abundant supply of detritus and provides a possible modern analogue for development of the tube and breccia facies. The Late Permian lava flux was sufficiently high to produce well developed lava tubes which, in some areas, "burrowed" into the unconsolidated, water-saturated lava delta and sand pile to produce intrusive contacts.

Eruptive conditions for the columnar jointed facies in the upper Blow Hole flow were different to those that prevailed for both the lower and middle units. Water depths at the time of emplacement were probably less than 5 m and the top of the flow would have been subaerial. Although no single outcrop provides a complete vertical section through the unit, no evidence for a break has been encountered and the columns appear to be continuous. The occurrence of well-developed, subvertical columnar joints in a reasonably thick (~50 m) lava indicates that this unit cooled as a single entity from a static body of magma with a horizontal cooling surface. Erosion has removed much of this unit but the columns occur over an area of at least 4 km^2 which suggests that the unit represents a ponded facies.

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COMPOSITION AND ORIGIN OF THE EARLY PERMIAN BOGGABRI VOLCANICS, GUNNEDAH BASIN, NSW

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INTRODUCTION

The Early Permian Boggabri Volcanics (BV) crop out over an area of about 350 km^2 immediately north of Boggabri, in the north-eastern corner of the Gunnedah Basin (Hanlon, 1950). They are part of the extensive volcanic pile that forms the basal units of the Sydney-Bowen (depositional) Basin (SBB) sequence beneath a thick Permo-Triassic sedimentary cover.

Mapping has shown that the BV comprise mainly lavas and lesser ignimbrites as well as rare scoria, tuff, minor intrusives and sparse sedimentary rocks deposited in a continental setting (Brownlow, 1997). These rocks range from basalt to pyroxene and biotite rhyolite. Mugearite and benmoreite lavas? of uncertain affinity in the north-eastern corner of the outcrop area, may represent the top of the volcanic pile.

The composition and origin of the BV are important regionally as keys to Early Permian magmatism and the origin of the Sydney-Bowen Basin.

COMPOSITION

Petrology

Basalts exhibit a phenocryst assemblage of (Cr-spinel)-olivine-plagioclase (troctolite) ± rare augite ± rare Ti-amphibole? occurring as isolated crystals or as glomeroporphyritic aggregates in a groundmass of plagioclase, pyroxene (augite ± enstatite ± pigeonite) and fine- to very fine-grained opaque oxides (< 150 μm). Abundance of olivine relative to plagioclase distinguishes olivine basalt from olivine-poor basalt.

Andesites comprise two pyroxenes (± groundmass pigeonite), coarse Fe-Ti oxides (> 150 μm) and apatite accompanying calcic plagioclase in groundmasses that are varied and range from very fine-grained hyalopilitic with reddish brown glass to fine-grained intersertal or trachytic. Most andesites are olivine-free apart from rare xenocrysts, but olivine andesite contains essential olivine and is probably a basalt-dacite hybrid.

Dacites characteristically comprise enstatite ± augite (hence enstatite and augite dacite respectively), relatively coarse oxide granules (> 250 μm) and apatite (> 25 μm in diameter and up to 750 μm in length) as well as ubiquitous plagioclase, but lack olivine and quartz. Zircon is generally absent, but one altered leucocratic dacite contains abundant and relatively coarse grains.

Pyroxene rhyolites characteristically comprise enstatite plus plagioclase and opaques, and lack biotite and quartz phenocrysts. Augite? or biotite? occur sporadically as rare tiny groundmass phases. The relative abundance of enstatite compared to plagioclase distinguishes rare melanocratic pyroxene rhyolite from abundant leucocratic pyroxene? rhyolite. The latter identification is tentative and texturally based, because the pyroxene? is invariably altered to limonite + silica ± ferroan carbonate.

Biotite rhyolites are generally leucocratic and characteristically comprise a trace of biotite (<1%) and zircon in addition to sodic plagioclase, opaque oxides and apatite. Minor anorthoclase may be present but pyroxene and K-feldspar are apparently absent. Phenocrystic quartz is rarely present. Biotite rhyolites strongly resemble leucocratic pyroxene rhyolites in lithofacies, field occurrence and alteration styles (e.g., white devitrified rhyolite and hackly, green pitchstone) but differ in ferromagnesians.

Mugearite and benmoreite are characterised by plagioclase, apparently only a single pyroxene (augite), and Fe-Ti oxides, accompanied by olivine in one mugearite.

Most BV are altered. Basalts and andesites commonly have altered groundmasses, with slight to complete phenocryst destruction. Felsic lavas and ignimbrites are commonly devitrified and locally hydrated to form dark green, hackly pitchstones with perlitic fabric. However, fresh glass survives, for example in the groundmass of some andesite and dacite lavas, an augite dacite vitrophyre dyke (UNER68624 of Brownlow, 1997), and in the vitrified zones of certain dacitic and rhyolitic ignimbrites.

Mineralogy

The principal phenocrysts in the BV are plagioclase accompanied by olivine, one or two pyroxenes (up to three, including groundmass phases), rare amphibole, anorthoclase or quartz. Accessories include chrome-spinel, Fe-Ti oxides, apatite, and zircon.

Olivine occurs in all basalts and in olivine andesite. It ranges overall in basalts from Fo_{84} to Fo_{72}, but exhibits much narrower ranges in individual rocks.

Plagioclase is ubiquitous and displays an extended compositional range from calcic bytownite (maximum An86) to albite (minimum An8). The compositional range is very wide in some rocks, especially dacites and andesites, but is narrow in rhyolites. Maximum An content decreases progressively from basalt to andesite to dacite to rhyolite. Potassium content is characteristically low, especially among the intermediate to calcic plagioclase, but rises to about 6% orthoclase in albite and oligoclase in rhyolite. Anorthoclase is also recognised in some biotite rhyolites. Plagioclase in mugearite and benmoreite is slightly more sodic than in BV of similar SiO_2.

Pyroxenes dominantly display two remarkably restricted compositional ranges: enstatite in the range En_{61-77} (average En_{70}) and Wo_{0-4} (average Wo_2), and augite in the range to En_{40-49} (average En_{44}) and Wo_{36-44} (average Wo_{40}). The former are abundant in the andesite-melanocratic pyroxene rhyolite range and occur as groundmass phases in basalts and leucocratic rhyolite (tentatively identified altered relicts). The latter are abundant in the andesite-augite dacite range, mainly present as common groundmass phases in basalt and rare as groundmass phases in enstatite dacite and pyroxene rhyolite. Augite from hybrid olivine andesite is notable because it is the only augite to show even modest Fe-enrichment (En_{40-44}). Pigeonite has also been tentatively identified in the groundmass of olivine basalt and andesite. MnO is significantly enriched in enstatite from more felsic rocks (up to about 2%). Al is consistently low to zero, and charge-balance calculations indicate minor Fe^{3+} in Z (four-fold) sites of some pyroxenes.

Amphibole is rare and generally altered, but small, fresh Ti-amphibole? phenocrysts occurs in an olivine-poor basalt.

Notable features of BV opaque oxides include the common co-existence of ilmenite and titanomagnetite, the wide range of their compositions and inferred temperatures and oxygen fugacities, the limited development of chromian titanomagnetite and Mg-Al-chromite in olivine basalt, and the high MnO content (10%) of ilmenite in biotite rhyolite in contrast to <1% in most other rocks. Inferred oxygen fugacities in analyses samples are generally above the Nickel-Nickel Oxide buffer (Lindsley, 1976), but range slightly below in an augite dacite vitrophyre dyke (UNER68624).

Geochemistry

Select (least-altered) BV range from basalt (~ 50% SiO_2) to rhyolite (up to ~ 79 to 80% SiO_2 - figure 1a). Most select rhyolites contain high H_2O (6-8%), and are therefore pitchstones (Brownlow, 1997). Alkali contents in select andesites and dacites plot along the border between the sub-alkali and alkali fields on TAS (figure 1a). Immobile element plots confirm these TAS-based identifications (figure 1b). Select basalts, andesites and dacites are medium-K and metaluminous, but select rhyolites (mainly pitchstones) mostly plot as high-K and peraluminous (figure 1c, d). Sub-alkaline rocks are mainly calc-alkaline, but some are marginally tholeiitic (figure 1e, f). Altered BV follow these broad trends, but tend to have lower alkalis, and more obvious tholeiitic tendencies (high FeO_t/MgO due to loss of Mg). The lavas of uncertain affinity are more altered but are tentatively classified as mugearite and benmoreite based on TAS, their one-pyroxene and sodic plagioclase petrography and trace element characteristics (see below), but do not show clear alkaline tendencies on immobile element plots.

Trace element abundances vary significantly, particularly in the andesite-dacite range. Low trace element contents characterise leucocratic pyroxene rhyolite, a select augite dacite vitrophyre dyke (UNER68624), as well as a select olivine basalt (UNER68612 – Brownlow and Arculus, 1999). Moderate abundances characterise biotite rhyolites, most select dacites and andesites, and a select basalt with minor groundmass Ti-amphibole? High LREEs characterise mugearite and benmoreite.

DISCUSSION

Composition

The BV comprise mainly sub-alkaline to marginally alkaline basalts, andesites, dacites, pyroxene rhyolites and biotite rhyolites. The high SiO_2 content of rhyolite pitchstones is inconsistent with the rarity of phenocrystic quartz. These rocks originally were probably slightly peraluminous or even metaluminous and contained 74-75% SiO_2 but

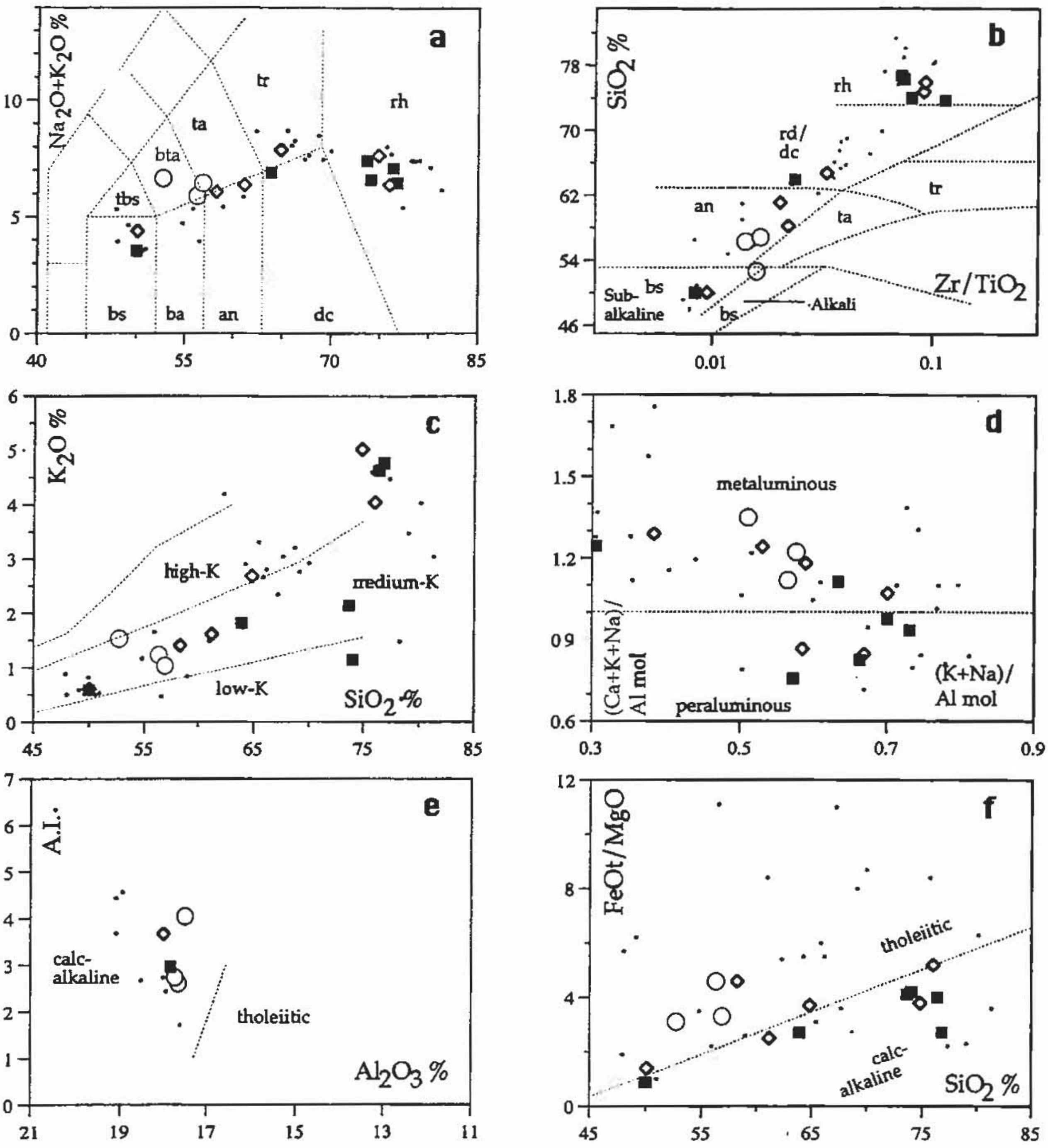

Figure 1. Classification of the Boggabri Volcanics. a: Total Alkali Silica (TAS) diagram (LeMaitre et al., 1989). b: SiO_2 v Zr/TiO_2 (Winchester and Floyd, 1977). SiO_2 v K_2O (see LeMaitre et al., 1989). d: Alkalinity v alumina saturation, see LeMaitre et al., 1989). e. Alkali Index v Al_2O_3 (Middlemost, 1975). f: SiO_2 v FeO_t/MgO (Miyashiro, 1974). Squares and diamonds designate select (least altered) samples with low and moderate incompatible element abundances respectively. Small dots indicate altered samples. Circles indicate mugearite-benmoreite of uncertain affinity.

gained SiO_2, CaO and H_2O and lost alkalis while transforming to pitchstone (Brownlow, 1997).

Affinity

Coexistence of two or three pyroxenes in andesites, most dacites and the groundmasses of some basalts indicates a sub-alkaline affinity (BVSP, 1981; Wilson, 1989). Ti-amphibole? in the groundmass of one basalt indicates a tendency to mild alkalinity. A tholeiitic tendency among altered rocks is due to MgO loss, reflected in show FeO_t/MgO ratios.

Troctolitic phenocryst assemblage and aggregates in basalts are typical of Mid Ocean Ridge Basalt (MORB), and atypical of arcs or Ocean Island Tholeiites (OITs) where early clinopyroxene (i.e., preceding or accompanying plagioclase respectively) would be expected (BVSP, 1981; Wilson, 1989). Similarly, the lack of enstatite phenocrysts in basalt indicates a MORB rather than arc or OIT affinity. The lack of olivine in most andesites, dacites and rhyolites, or of Fe-enrichment in most pyroxenes, distinguishes BV from some evolved MORB and Continental Flood Basalt (CFB) suites (BVSP, 1981; Wilson, 1989). BV olivine basalts are more primitive than in most continental suites. The apparent rarity of amphibole and restricted occurrence of quartz and biotite is atypical of arc volcanic rocks. The lack of pigeonite as a pyroxene phase among more felsic rocks is compatible with MORB affinity (Wilson, 1989). The apparent absence of K-spar is typical of arc tholeiites or low-K calc-alkaline volcanic rocks (BVSP, 1981; Wilson, 1989).

Mineral chemistry indicates that olivine in basalts have typical MORB compositions, and overlap the OIT range and the more primitive range of CFBs (BVSP, 1981; Wilson, 1989). Plagioclase resembles MORB both in its An range and especially in its low Or content, which distinguishes it from OIT, continental and arc suites (BVSP, 1981). Chromite and titanomagnetite are arc-like or like some Hawaiian types due to low Mg which also distinguishes them from MORB analyses. Augite is N-MORB or arc-like, but lacks the Fe-enrichment of evolved tholeiites (E-MORB, OIT, CFB), and is not as primitive as Hawaiian or MORB megacrysts (BVSP, 1981). Enstatite and olivine also lack significant Fe-enrichment that is common in evolved tholeiites. In contrast, MnO is enriched in ilmenite and enstatite in some leucocratic rhyolites. Oxygen fugacities range broadly from slightly below the Ni-NiO buffer to significantly above it, and is apparently independent of bulk composition; this might be due to environmental factors rather than being an intrinsic property of the rocks.

The MORB-normalised element abundance pattern of the freshest and most primitive olivine basalt analysed (UNER68612) is unusual (Brownlow and Arculus, 1999). It clearly show an arc signature with high Ba_N (MORB-normalised Ba), Pb_N and Sr_N, low Nb_N, and high $(Al/Y)_N$ but has only intermediate K_N, Rb_N and Th_N (leading to unusually high Ba/Rb). HREE and $(Nb/Zr)_N$ are close to MORB values, but depletion of the former (atypical of arc or MORB basalts) contrasts with enrichment of the latter and suggests re-enrichment of a once depleted source. A Zr-Hf-Sm anomaly in olivine basalt and high Mg/Cr and high Ni/Cr are unusual and not reported in any standard geochemical reservoirs. A mixed source is indicated, possibly involving an arc signature (high Ba, less elevated Rb and K) superimposed on primitive MORB with a minor nephelinite or carbonatite component (Brownlow, 1997; Brownlow and Arculus, 1999).

Petrogenesis

Modelling (after Pearce and Parkinson, 1993) suggests derivation of the BV from Fertile MORB Mantle that had been enriched by subduction zone fluids (imposing an arc signature), then depleted during arc volcanism (depleting both the MORB and arc signatures) and then re-enriched by addition of a minor nephelinite or carbonatite component to produce features such as the contrast between depleted heavy rare earths (HREE) and enriched Nb (Brownlow, 1997; Brownlow and Arculus, 1999). The source was therefore effectively doubly enriched, and doubly depleted, and produced depleted MORB-like melts that were oxidised and overprinted with an atypical (residual) arc signature and nephelinite/ carbonatite characteristics.

Initial arc enrichment and subsequent depletion probably accompanied Late Carboniferous Andean-style arc volcanism. The residual sub-arc mantle was re-enriched before or during Early Permian crustal extension. This may have occurred at relatively low temperature under spinel-lherzolite conditions and produced oxidised melts with high Mg/Cr, low Sc and V (Brownlow, 1997). Varying degrees of enrichment and depletion of the melt zone would have produced a range of melt compositions from which diverse rock types developed through fractionation, lesser magma mixing, and a variety of eruptive and alteration processes.

Regional comparisons

Among regional comparisons, the more mafic BV most closely resemble the Werrie Volcanics in the Wingen area of the Hunter Valley (Vickers, 1993, Brownlow, 1997). Mugearite and benmoreite atop the BV pile enhance comparison with the Werrie Volcanics and the more mafic rocks of the Mount Terrible Volcanic Complex (Teale et al., 1999) in the Werrie Syncline of the Tamworth Belt. The few available data from other basal Early Permian volcanics of the SBB also suggest broad similarities, including with the Gunnedah Basin (e.g., Caprarelli and Leitch, 1998), lower Alum Mountain Volcanics (Roberts, Engel and Chapman, 1991), the Camboon and Lizzie Creek Volcanics (Hutton, 1999). Scarcity of phenocrystic quartz in dacites of the Camboon Volcanics (L.J. Hutton, pers. comm., 1999) further supports this comparison.

The BV differ in detail Late Carboniferous volcanic rocks of the Tamworth Belt (Flood et al., 1988; Vickers, 1993) even though Early Permian and Late Carboniferous systems substantially overlap along the length of the Sydney-Bowen Basin and into North Queensland (Brownlow, 1997).

The BV also contrast in detail with Permo-Carboniferous igneous rocks of the central and eastern New England Orogen (NEO) including the Halls Peak volcanics, the Hillgrove and Bundarra Plutonic Suites, the Petroi Metabasalt, and the Early Permian NEO mafic complexes (Brownlow, 1997). These igneous rocks apparently constitute a separate igneous province, and may have developed through subduction several hundred kilometres eastward of that controlling the Late Carboniferous arc (Brownlow, 1999).

CONCLUSION

The BV comprise basalt-rhyolite spectrum of mainly subalkaline to mildly alkaline affinity, possibly associated with minor mugearite and benmoreite atop the pile. Modelling suggests that the BV source was Fertile MORB Mantle (i.e. mantle that is capable of melting to yield MORB) that had been enriched by subduction zone fluids, then depleted during arc volcanism (i.e., leaving both depleted MORB mantle and residual arc signatures) and then re-enriched by addition of minor nephelinite or carbonatite (i.e., doubly-enriched, doubly-depleted). Melt was then probably extracted at relatively low temperatures under spinel-lherzolite conditions. This would explain the combination of mainly MORB-like petrology, arc-like oxide mineral chemistry, the lack of Fe-enrichment, and lesser nephelinitic/ carbonatitic features as well as other unusual features including an atypical (residual) arc-signature. It would also explain the difficulty of classifying these rocks by conventional discriminants and ratios.

A plausible geological model (Brownlow, 1999) is that the Australian plate moved SSE then S then SSW during the Permo-Carboniferous and caused transpressional and then transtensional stress along the site of Late Carboniferous Andean volcanisn. This reactivated the sub-arc mantle during or after re-enrichment of that zone by nephelinitic or carbonatitic melts. This model encompasses 'embryonic sea-floor spreading' (extension terminated before new oceanic crust began to form - Brownlow, 1981), and widespread asthenospheric intrusion (Caprarelli and Leitch, 1998). Breakage (Vickers, 1993; Caprarelli and Leitch, 1998) or rollback of the relict Late Carboniferous slab could also have been involved. Contemporary subduction was not directly involved, but may have occurred several hundred kilometres to the east where an apparently separate igneous province developed.

ACKNOWLEDGEMENTS

This study arises out of post-graduate investigations at U.N.E. by J.W.B. supervised by R.J.A. and Peter Flood. Thanks to Laurie Hutton (GSQ) for valuable discussion concerning the Camboon Andesite. Thanks to Dave Suppel and Rob Barnes for their constructive reviews. Published with the permission of the Director-General, N.S.W. Department of Mineral Resources.

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SOME TRENDS NOTED IN THE NERONG VOLCANICS NORTH OF KARUAH

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1. INTRODUCTION

The Nerong Volcanics, north of Newcastle, has long been considered a promising source of hard rock resources, for applications such as bitumen and concrete aggregate, road base, and bulk rock applications such as armourstone.

Coffey Partners International Pty Ltd (Coffey) recently undertook a reserves assessment for a proposed hard rock quarry north of Karuah, NSW (Figure 1). The study involved geological investigation into the nature and extent of hard rock resources at the subject site. The work revealed some geological trends within the profile, which were comparable to regional type sections for Nerong Volcanics (Engel et al 1962).

The cores revealed macroscopic and microscopic evidence of the environment of emplacement, indicating accumulated volcanic flows with extreme heat induced welding, subsequent devitrification hydrothermal activity, and later, intrusion by dyke rocks.

2. BACKGROUND INFORMATION

The site is located on the south western flank of a prominent hillform, typical of those formed by high strength rock of the Nerong Volcanics in the Port Stephens area. Geologically, it is situated on the outer western limb of the Girvan Anticline, and as such the thickly bedded volcanic sequence dips to the south west at about 40°.

Major structural trends in the area consist of a series of northeasterly and north-northeasterly trending faults (Figure 1), and the orientation of these faults is reflected in fracture trends visible in the limited amount of in-situ surface exposure.

The Nerong Volcanics were said by Engel (1962) to be up to 820m thick, consisting of rhyodacite, with a 60m thick unit of hornblende andesitic ignimbrite approximately 320m from the base of the formation (p.138). The rhyodacites of the area consist of kaolinitized quartz and biotite fragments set in a devitrified quartzo feldspathic groundmass which still contains welded glass shards.

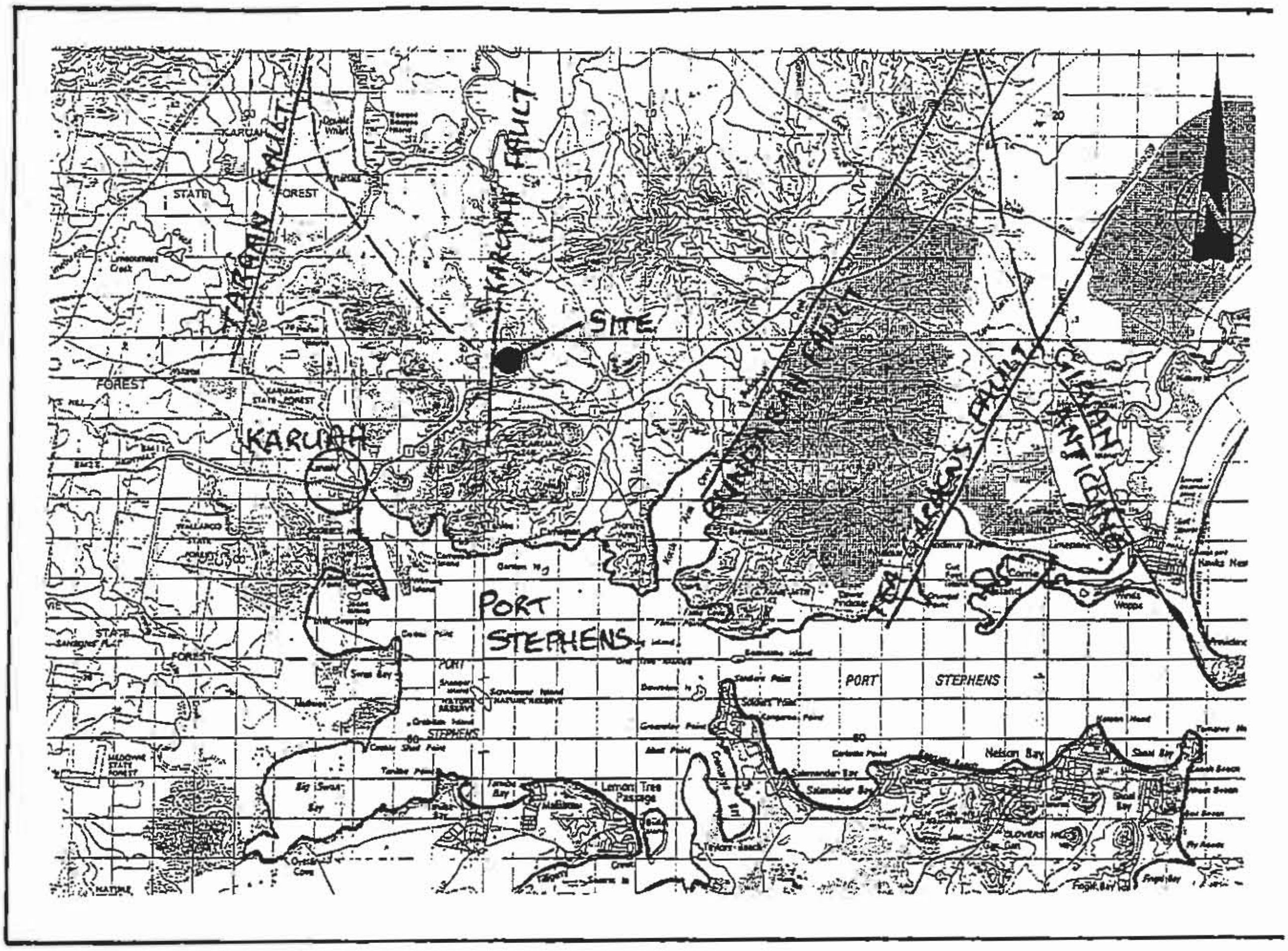

FIGURE 1 – SITE LOCATION AND MAIN GEOLOGICAL STRUCTURAL FEATURES

According to the mapping of Buck (1995), the site would be located within the Port Stephens Ignimbite, a predominantly rhyolitic unit, in which lithoidal ignimbrite is dominant, but which contains a glassy component towards the base which has resulted from extreme welding.

3. SURFACE ROCK OBSERVATIONS

Unweathered, the rock is of very high to extremely high strength with unconfined compressive strength typically ranging from 100 MPa to >200MPa. Weathering is controlled by fracturing, and, where the rock has not been highly fractured by faulting, weathering is typically confined to a rind a few millimeters thick along fracture surfaces. Despite the resistance to weathering, in-situ surface outcrop consists predomiantly of corestones and boulders, which have gathered on the steeper slopes to form scree-like deposits. Observation of in-situ rock and reliable indications of bedding and fracture orientations are therefore confined to exposures in access tracks.
The rock types exposed at the surface have been variably described as hornblende andesite (Offler) andesitic ignimbrite (Australian Petrographic Services 1998) and latile tuff (Geochempet 1996).

Besides the vastly dominant volcanics, other rock types exposed at the surface include sandstone, conglomerate, and an altered dyke rock. The sandstone and conglomerate were exposed in a track to the south of the main ridge, adjacent to the existing Karuah Red Quarry. The conglomerate consisted of large cobble sized clasts of igneous origin, in a matrix of sandstone. Such conglomerates are typical of discontinuous beds which occur in the Nerong Volcanics, representing stream beds which formed on the volcanic deposits between subsequent phases of activity.

4. MINERALOGY

4.1 Principal Rocktypes

Petrographic examinations were undertaken on selected samples from the bore cores by Dr Hans Dieter Hensel. Classifications provided have been plotted onto borehole section in Figure 2. The dominant rock type encountered was classified as a hornblende dacite. The hornblende dacite was described as a mildly altered, felsic, volcanic rock, consisting of abundant plagioclase feldpsar in a heterogeneous, devitrified quartzofeldspathic groundmass. The groundmass supported an original mineralogy of sparse crystals of quartz and orthopyroxene with scattered amphibole and minor biotite. The orthopyroxene and biotite have almost totally been replaced by secondary minerals, although some orthopyroxene cores remain.

The dominant secondary mineral is chlorite, which predominantly occurs as crystals and flakes. Chlorite also fills the internal surfaces of intensely microfractured plagioclase crystals. Other secondary minerals include smectite and kaolinite, and traces of sericite.

The groundmasses are heterogeneous with the prevailent variety being a dark, slightly chloritic variety with negligible recognisable quartzo-feldspathic crystals and a lighter coloured variety, also heterogeneous, containing less chlorite. The groundmass was shown by staining tests (Geochempet 1996) and alkali aggregate reactivitiy tests (Coffey 1998) to be predominantly feldpathic with a minor quartz component.

The rock has been classified as dacite due to the presence of 1% to 4% quartz phenocrysts and some quartz in the groundmass indicating a silica over saturated magma.

4.2 Lateral Variations in Mineralogy

As previously discussed, the rocks exposed at the surface have been described variably. The findings of this study indicate mineralogy to be more variable towards the southern end of the ridge, in the area where the previously described rocks were sampled. A borehole (BH1) drilled at this end of the site revealed a hornblende quartz andesite, similar in mineralogy to the abovementioned hornblende dacite.

4.3 Trends with depth – zone of hydrothermal alteration

Figures 2 to 5 present some mineralogical trends noted with depth. As shown by the figures, variations in mineralogy occur which indicate a zone of intense hydrothermal activity, resulting in hydrothermal modification of the original rock type.

The resultant hydrothermally modified hornblende dacite is similar to the original, in terms of mineralogy however, the rock has undergone extensive replacement by hydrothermally generated and mobilised minerals, the most abundant being adularia and prehnite. These minerals appear to have been introduced by many microscopic veinlets, and it is worth noting that this zone of apparent hydrothermal activity contains extensive, visible fracturing and veining with veins typically varying from 1mm to 20mm in thickness.

The adularia replaces predomiantly the groundmass but also some of the feldspar. The rock also contains minor submicroscopic haematite and goethite.

4.4 Groundmass Variations

The following observations were made by Dr Hans Dieter Hensel regarding groundmass variations and evidence of fluid activity.

As many as four types of groundmass were observed. The main variation is the degree of quartzofeldspathic crystallisation, and the degree of devitrification, with a lighter groundmass displaying less chlorite and a greater degree of devitrification than the darker material. The heterogeneity reflects variations in the fluid activity, with a blotchy, coarse texture indicating places where the fluids collected. A third greenish variety also related to fluid activity, is dominated by fine grained concentrations of chlorite. A further variation on this greenish groundmass contains a distinctive texture consisting of graphically intergrown, relatively large dirty quartz crystals amidst a well crystalised chlorite. The rock from the hydrothermally altered zone in borehole BH 2 (42m) contains a groundmass with numerous remnant small shard-like structures.

5.0 MODE OF FORMATION AND HYDROTHERMAL ACTIVITY

Engel (1962) suggests the Nerong Volcanics were derived from two major volcanic centres, one to the south of the present Hunter Fault System and one located southeast of the current Port Stephens region. The lateral variation in chemical composition, discontinuous flow banding, and lateral discontinuity of some units encountered in this study lends support to the scenario of multiple volcanic sources.

Hensel (1998) reports no unambiguous indicators of the style of eruption, ie, lava flow or ash flow but postulates that when the flows or clouds came to rest the resultant heat below several superimposed flows may have been high enough to weld any ash, and fluid activity may have caused any vitric groundmass to rapidly de-vitrify.

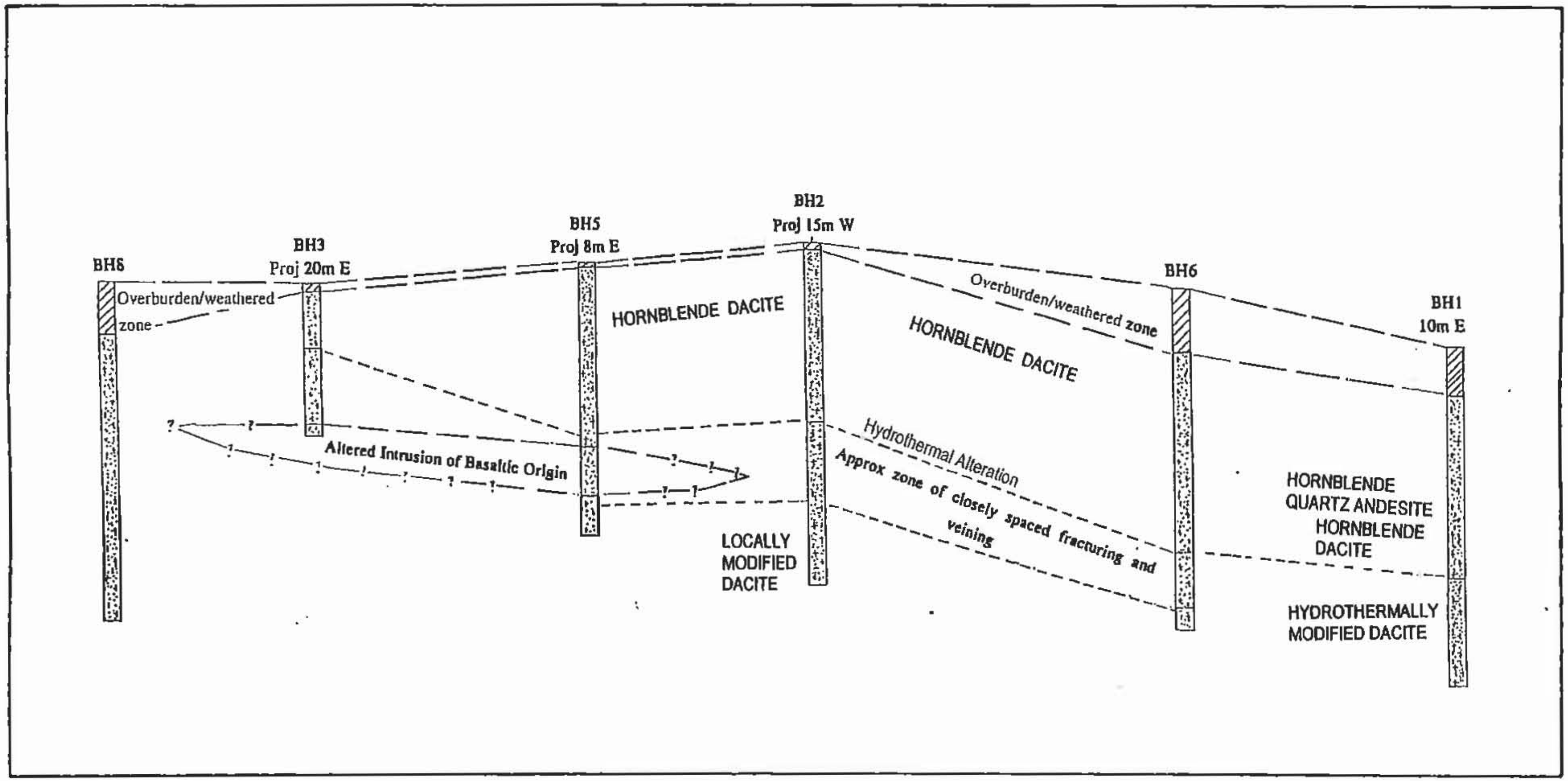

FIGURE 2 – INTERPRETIVE CROSS SECTION THROUGH STUDY AREA, SHOWING MAIN FEATURES AND APPROXIMATE EXTENT OF HYDROTHERMAL ACTIVITY (SCALE 1:1000)

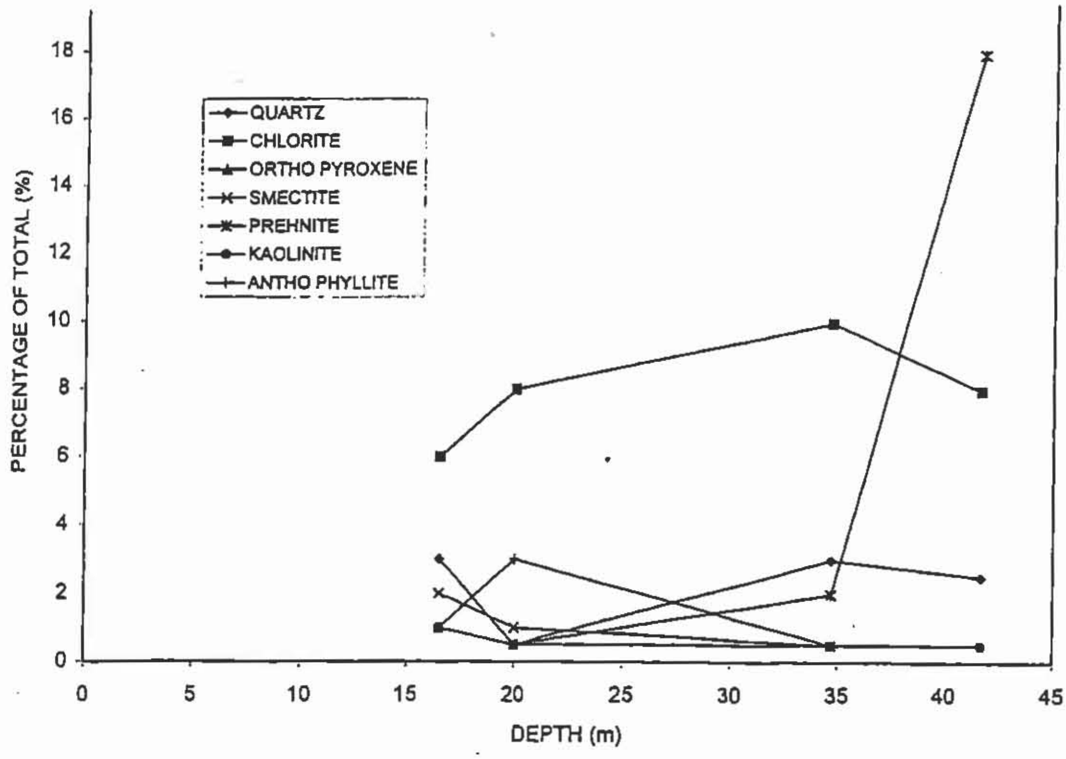

FIGURE 3 – MINERALOGICAL TRENDS WITH DEPTH IN BH 1 – MINOR COMPONENTS, ZONE OF HYDROTHERMAL ALTERATION BELOW 32M.

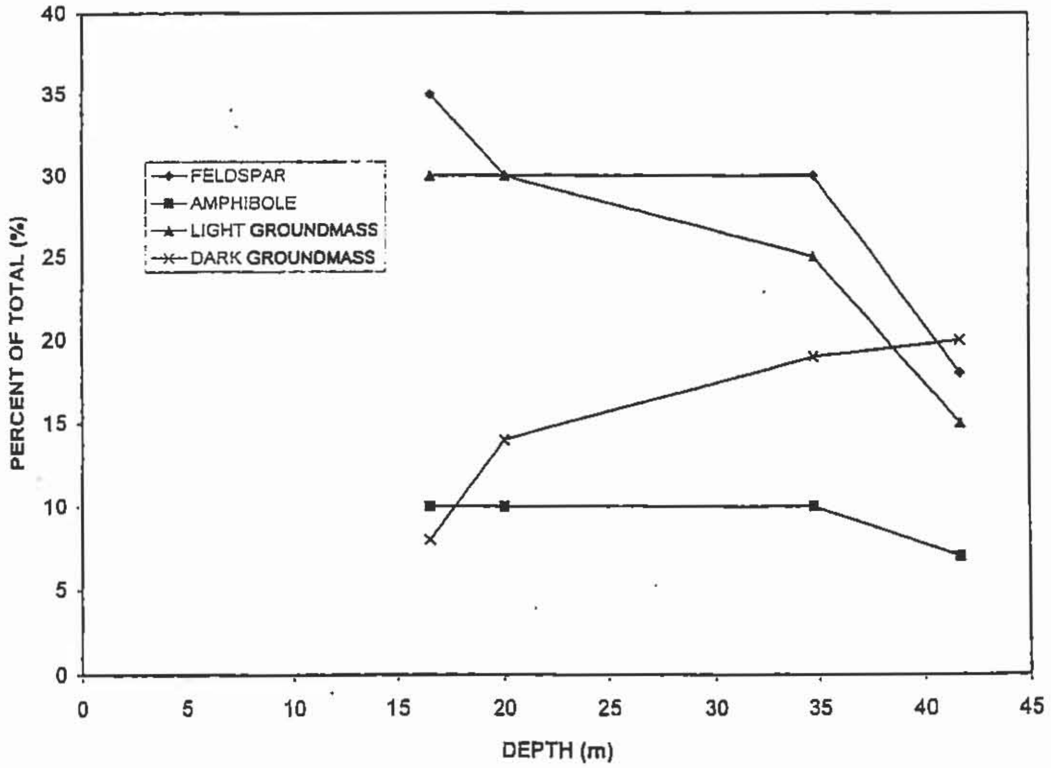

FIGURE 4 – MINERALOGICAL TRENDS WITH DEPTH IN BOREHOLE BH 1 – MAJOR COMPONENTS, ZONE OF HYDROTHERMAL ALTERATION BELOW 32m.

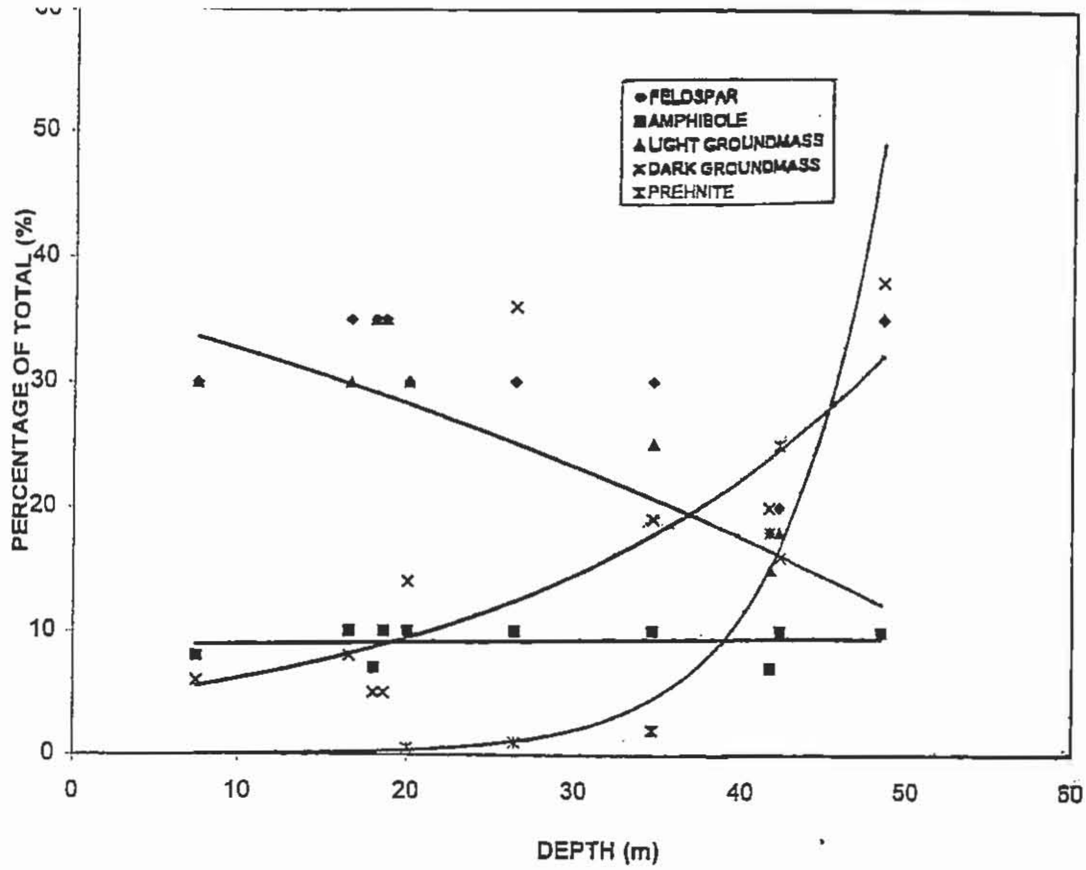

FIGURE 5 – OVERALL MINERALOGICAL TRENDS IN MAJOR COMPONENTS FROM ALL BOREHOLES. ZONE OF HYDROTHERMAL ALTERATION TYPICALLY OCCUR BELOW 32m – 35m.

The degree of fracturing within the zone of hydrothermal replacement in lower levels of the studied section is indicative of a buildup of fluid pressures within and between successive flows sufficient to cause intensive hydraulic fracturing, with up to 8 microfractures and veins observed within 0.5mm in some samples from this zone of fluid activity.

The presence of flow structures and macroscopic flow banding, paucity of shards and negligible recrystalisation of groundmass indicates cooling after extrusion was rapid.

6.0 SUBSEQUENT INTRUSIVE ACTIVITY

One interesting feature revealed by the study was the presence, in the northern part of the study area, of weathered, altered dyke rock at the surface, and altered basalt encountered at depth in boreholes BH 3 and BH 5 (Figure 2).

The altered basalt obtained in the core was described by Hensel (1998) as a sparsely porphyritic volcanic rock made up of abundant plagioclase feldspar, lesser amounts of calcic pyroxene, and secondary minerals opaque oxides, and pyrite. Secondary minerals are predominantly a smectite clay and some chlorite, forming pseudomorphs after olivine. Subtly different zones indicate several stages of replacement.

The altered dyke rocks exposed at the surface, are weathered to a degree which makes original mineralogy difficult to determine. The rocks appear brecciated. Fractures traverse the rock irregularly and there are a number of elongate voids. The texture of these rocks, consisting of feldspar laths. Close, intergranular crystals suggest it is not a weathered version of the dominant dacitic rocks nor a weathered version of the previously discussed altered basalt. The feldspars are predominantly plagioclase, with sodic rims possibly indicative of hydrothermal alteration or, more likely in this case, residual fluids during late stage crystallisation. This indicates that the rock was probably a dyke rock with a composition and mineralogy somewhere around that to be expected in a dolerite. The presence of abundant smectite pseudomorphs after olivene and orthopyroxene is consistent with this mineralogy.

7.0 CONCLUDING REMARKS

The investigation revealed several interesting geological features. The testing undertaken indicated the rock would meet the requirements for use in a broad range of construction applications, and development of the quarry is currently underway. Exposures which are to be revealed during quarrying will shed further light on some features discussed herein.

ACKNOWLEDGEMENT:

The author wishes to thank Mr Col Greene of Mountain Industries Pty Ltd, for input to the project, and for permission to use the information in preparing this paper.

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THE INFLUENCE OF COAL MEASURE GAS ON SEISMIC EXPLORATION DATA IN THE SOUTHERN SYDNEY BASIN

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ABSTRACT

Geophysical evidence from seismic reflection surveys over mined and unmined areas, VSP surveying and full waveform sonic logging all point to the existence of zones of anomalous seismic attenuation within parts of the sedimentary sequence overlying the Bulli Seam in the Appin area. It is proposed that the presence of free gas within pores, fractures and partings provides a mechanism for this attenuation. The effect is particularly strong over mined areas and in the vicinity of the river gorges in the area. In both cases, increased fracturing/bedding plane separation is proposed. A LOTEM survey conducted over mined out areas of Appin Colliery adds support to this assessment. While the existence of zones of poor seismic data is a hindrance to coal mine exploration, their seismic manifestation may be of use in the exploration for coal seam gas.

INTRODUCTION

Given the depth of the mining, geological conditions and ground surface constraints in the southern Sydney Basin, exploration drilling is costly and an ineffective means of exploration for structures. Seismic reflection methods, both 2D and 3D have been developed to perform this function (Riley et al, 1997; Poole et al, 1998). In the last five years BHP have shot three 3D surveys at Appin and Tower Collieries and probably in excess of 400 line km of high resolution 2D surveys. These surveys are routinely undertaken ahead of longwall developments and in new mining areas. Their success can be judged by the fact many structures have been mapped and that in recent years there have been no production delays caused by mining into significant structures. Figure 1 shows an example of such a structure mapped by a seismic reflection survey.

An intriguing aspect of the seismic results from the Appin area is an abrupt loss of reflection signal which occurs in some areas. As shown in Figures 2 and 3 these losses can be traced right back to the strength of the reflectors on the shot records. The losses in seismic signals must be due to changes in the seismic wave propagation through the earth.

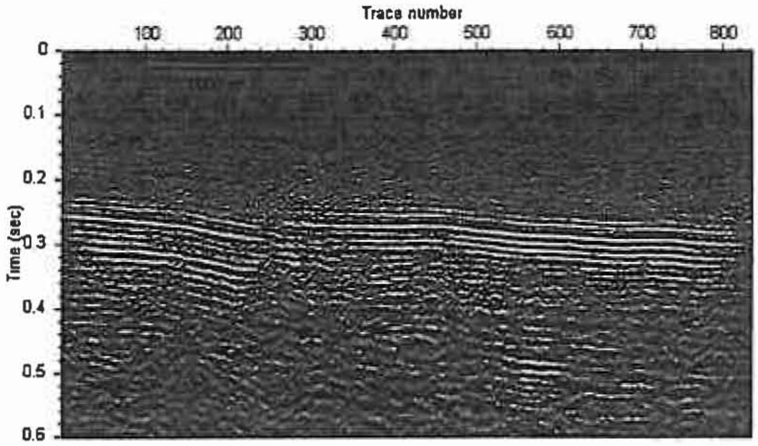

Figure 1. A 2D seismic reflection section from Elouera Colliery showing a fault intersecting coal seams at 250 ms two-way reflection time.

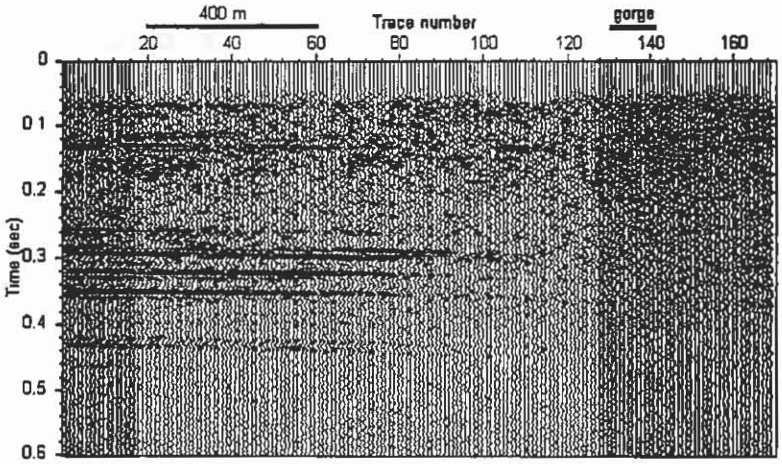

Figure 2. Part of a 2D line crossing the gorge of the Nepean River at Douglas Park. The gorge is about 120 m wide and is located between traces130 and 142.

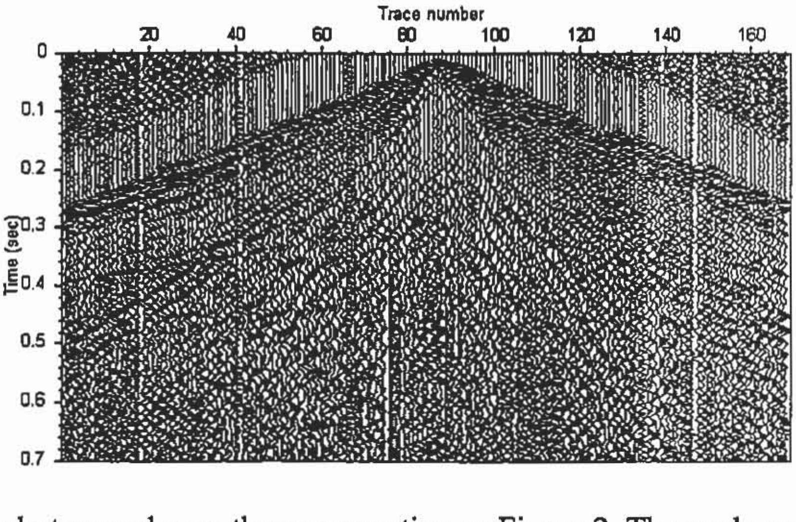

Figure 3. A shot record over the same section as Figure 2. The coal seam reflections begin at 0.4 seconds to the left and as in Figure 2, they are lost to the right.

One explanation for this is that it might be due to there being free gas within partially saturated pores, fractures and partings in the rock mass. In such situations there is high seismic wave attenuation (Mavko and Nur, 1979) and if this suggestion is correct then it appears that little if any of the seismic energy propagates through the gassy layers.

Evidence for gas effects on seismic exploration data have been collected over a number of years and through a number of different geophysical methods. That seismic energy is lost in gassy zones is an annoyance when undertaking coal mine exploration but this behaviour could be exploited when it is gas that is the target of the exploration.

FIRST SUGGESTIONS

For many years it has been recognised that often around the river gorges in the Appin area, there are regions where seismic data are always poor. An explanation often given was that the shot and geophone coupling was poorer when the Hawkesbury Sandstone cropped out as in the vicinity of the gorges. The Wianamatta Shale was thought to provide much more effective source and detector coupling. However there were too many exceptions for this to be an adequate explanation.

A new insight was gained in 1991 when a VSP survey was shot (Hatherly et al, 1993) into a geophone string which had been cemented by BHP into a borehole located well away from the gorges. Unlike surface seismic reflection surveys VSP surveys make it possible to track the propagation of seismic waves down through the earth. Wave behaviour and processing parameters for seismic reflection surveys can thus be determined.

As part of the analysis of this VSP survey, measurements were made on the rate of the broadening of the seismic signals as they propagate past the geophones. In normal circumstances the rate of broadening decreases with depth in response to the increasing confinement. In this survey the opposite effect was observed. In the Bulgo Sandstone below the Bald Hill Claystone it was found that the rate of broadening increased. A very high attenuation rate of 1 dB/wavelength was indicated. To account for this, attenuation based on the movement of pore fluids within pores containing both gas and fluid was proposed. Subsequent VSP surveys have also demonstrated this behaviour.

OTHER DOWN-HOLE DATA – FULL WAVEFORM SONIC LOGGING

BHP have also run full waveform sonic logs in exploration and coal quality bores. Unlike conventional sonic logging which captures just the transit time for the P-wave propagating between source and receivers, full waveform sonic logs capture the full seismic waveform. The behaviour of P-waves, S-waves and a coupled borehole fluid/interface wave known as the Stoneley wave can all be observed.

Figure 4 shows an example from one of these logs. Below 420 m the behaviour is normal. Above this depth first the P-wave and then the S and Stoneley waves are significantly attenuated. The velocities of the waves are not severely affected but the attenuation losses are significant. Higher up the hole all energy was lost.[1]

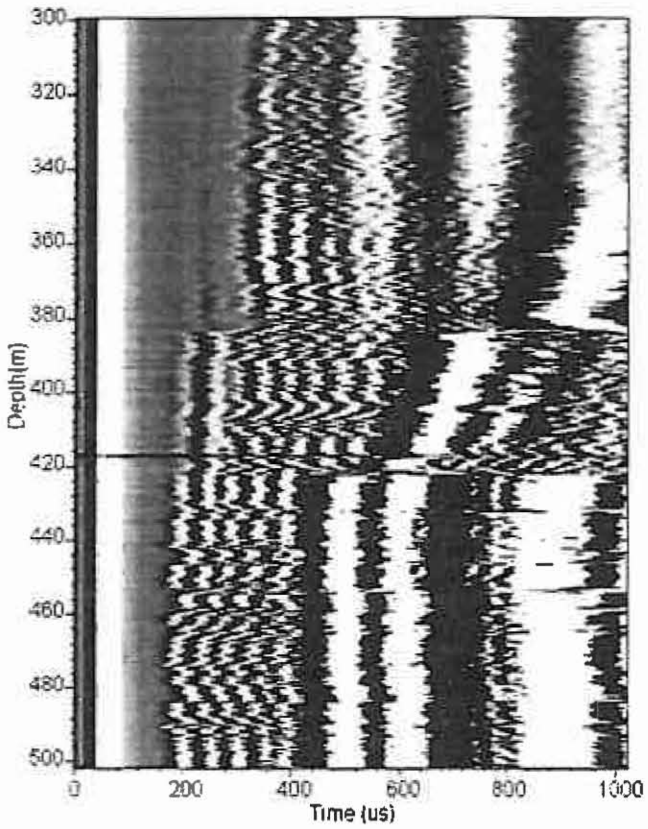

Figure 4. Full waveform sonic log for Appin 64 showing high absorption above 420 m and particularly above 380 m. The P-wave is the first event; the S-wave is mainly visible above 380 m and the Stoneley wave is the low frequency event after 0.4 seconds.

SURVEYS OVER A CAVED ZONE

Vozoff et al (1997) report on seismic and LOTEM surveys undertaken through ACARP and German/Australian bilateral funding. An intention was to determine whether electromagnetic surveying using the LOTEM technique could be useful for delineating areas of gas drained coal. Experience with RIM surveying had showed that coal seam resistivity varied significantly with water content (Vozoff et al, 1993) and it was hoped that LOTEM surveys could also exploit these differences to evaluate the effectiveness of gas drainage programs.

As part of this project a seismic reflection survey was shot along the LOTEM profile line which extended over the Appin mine workings from virgin coal through gas

[1] As an aside it is mentioned that this behaviour would have also occurred during normal sonic logging. However the practice with these tools is to set and signal strength such that a P-wave onset is observed. A geologist would be oblivious to this situation unless the operator reports that high gains were required.

drained coal and mined coal. With the LOTEM survey it was found that the results were totally dominated by a very thick (250 m) resistive layer overlying the Bulli Seam in the mined area. Normally the resistivity is about 100 Ωm and its change to about 2000 Ωm after mining suggests a significant loss of pore water and/or increase in the amount of free gas present. Changes in the Bulli Seam resistivity could not be determined given the size of the changes that occurred in the layers above.

The seismic section across this same profile is shown in Figure 5. Within the mined area there is a total loss of reflection data. It is not sufficient to say that this loss is due to the fracturing and caving. Seismic reflection sections over longwall panels from England (Fairbairn, personal communication) and Poland (Pietsch and Slusarczyk, 1992) show strata disturbance but clear signal propagation through the goaf to underlying reflectors. We suggest that free gas has formed within the sediments overlying the Bulli Seam and has contributed to both the major resistivity anomaly and the loss of seismic signal. In the European work gas must not have been present in any significant quantities.

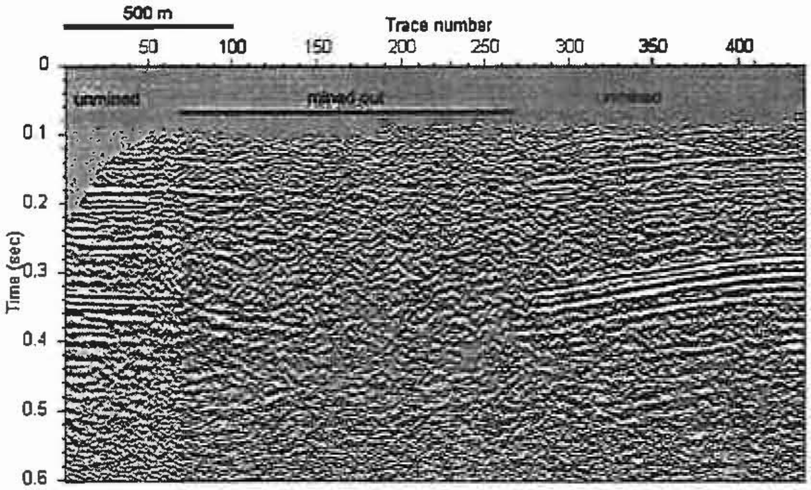

Figure 5. Seismic reflection line from Appin Colliery showing the effect of longwall mining of the Bulli Seam which is at 350 ms two-way travel time.

GAS AND SURFACE SEISMIC REFLECTION SURVEYING

The results of the surveys described in this paper all point to the potential for free gas within rock pores to significantly affect the quality of seismic reflection data in the Appin area. Areas where the seismic reflection data are poor may contain strata with elevated gas concentrations.

Our suggestion is that beneath the gorges there is a concentration of horizontal stress. This causes bedding plane separation and fracturing, and reduces the resistance to erosion. On-going deepening of the gorges is a consequence. From the seismic point of view, it is possible that the fractures and partings create pathways for gas migration and accumulation and that it is this gas which causes the losses of seismic energy in the vicinity of the gorges illustrated in Figures 2 and 3. On the basis of the width of the deterioration in the seismic sections shown in such sections we estimate that the zones of fracture and parting may extend more than 400 m beyond the gorges.

CONCLUSION

Through seismic reflection surveys, VSP surveys, full waveform sonic logging and LOTEM surveys undertaken over a number of years, we have arrived at the conclusion that zones of anomalous seismic attenuation in the Appin area may be due to the presence of free gas within pores, fractures and partings somewhere between the ground surface and the coal seams. At this stage we cannot state how much gas is required to produce this effect and a laboratory study into this would make an ideal research project. While this attenuation causes difficulties with seismic exploration for coal seam structures, it could be that the mapping of seismically opaque zones could be of interest in coal bed methane exploration and also for studies into the sources of gas make into coal mine workings.

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EFFECT OF COMMINUTION ENERGY ON ROSIN RAMMLER DISTRIBUTIONS FOR COAL

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INTRODUCTION

Sizing data in the coal industry is frequently analysed and presented as a Rosin-Rammler plot. The Rosin-Rammler distribution assumes random breakage in a homogeneous material. This plot of log(log(100/R)) against log X on special co-ordinates produces in an ideal case a straight line with slope or distribution modulus "n", and a factor "k" the size modulus which is often called the characteristic size of the material. This "k" is the screen aperture size on which 36.8% of the material is retained.

The equation to the function is $R = 100e^{-(x/k)^{\wedge}n}$ where

R is the cumulative percentage retained on screen size x

e is the base of the natural logarithm

k is the size modulus

n is the distribution modulus.

The distribution modulus "n", the slope of the line, is a measure of the closeness of grading. It parameterises the distribution of particle size and is therefore called the "distribution modulus". The larger the distribution modulus, the steeper the slope and the more closely sized is the material. When "n" is infinite the product is perfectly uniform; that is all the particles have exactly the same size. When "n" is small the sizes are spread out over a wide range, and the material contains a high percentage of fines.

The slope of the Rosin Rammler distribution "n" is said to be a property unique to a particular coal (Sanders 1994) and to remain essentially constant with increasing comminution, producing a family of parallel lines with a progressively finer size modulus "k". The absolute size modulus "k" measures the actual size of the material so that large values of "k" represent coarse material (Bennett 1936). The size modulus "k" is a function of the amount of breakage and size reduction that the coal has undergone.

On a minesite, size reduction is a function of the energy input on a given coal during mining, handling and processing. For utilisation as coke oven or power plant feed, size reduction is achieved by milling. The prediction of size reduction in any of these processes has been the subject of copious research over the past 50 years (Broadbent and Callcott 1956, Bull et al 1975). LePage (LePage and Proudfoot, 1974; LePage and Sedgeman, 1979) developed a method of predicting plant feed sizing on a minesite for a given coal based on the relationship between the Rosin Rammler distribution coefficient "n" and Hardgrove Grindability Index (HGI): $HGI=35.5n^{-1.54}$. Callcott (1976) proposed an alternative relationship n= 1.3333-HG1/120.

The HGI test involves grinding a 50g sample of 1.18x0.6mm coal in a special ball mill for 50 revolutions. The mass % passing 75 microns after grinding is the HGI index. A hard coal, therefore has a lower HGI than a soft coal. If "n" can be obtained from the HGI of a given coal, and the particle size "k" from *a priori* knowledge of a given coal or a desired top size, then these two parameters can be used to produce a projected plant feed size. However, the success of this method is variable because of 1) the geological variability of coal and 2) the variability in energy imparted to coal during the mining operation (Swanson et al, 1993).

One problem lies in the validity of typing a coal with these parameters without knowledge of their response to energy. Bennett (1936) found that the values of the distribution modulus for all the coals produced by shattering are higher than the values for run of mine coal. A drop shatter test of a sized coal would be expected to give the nearest approximation to the ideal distribution with "n" =1. Most plant feeds have distributions around "n" =0.6, suggesting far more fine material than that produced by the drop shatter process. Hence, methods for adjusting a given size distribution to the desired size distribution include screening and successive selective breakage of coarse oversize material, and subsequent tumbling.

Rosin and Rammler(1933) stated that "*The exponential equation* $R=100e^{-bx^n}$ *is a universal law of size distribution valid for all powders, irrespective of the nature of the material and the method of grinding.*" However, they also found that the law is only applicable after a certain stage of pulverization and that the exponent "n" lies, for the most part, between 1 and 1.35. The range of values hitherto observed in the case of coal is 0.8 and 1.5. Given this, can HGI, an index obtained at high energies of grinding (~30kWh/t) be used to estimate breakage and size reduction in a heterogeneous material at low comminution energies (<0.25kWh/t) of mining, handling and processing?

The aim of this paper is to present a physical examination of the variability of Rosin-Rammler distributions as a function of coal type and comminution energy. Mathematical treatments of the Rosin-Rammler distribution can be found elsewhere (Rosin and Rammler, 1933; Brown and Wohletz, 1995). A large quantity of sizing data has been collected by CSIRO during the course of projects investigating the comminution behavior of coals (Esterle et al, 1994). This paper presents the sizing data for one coal seam from a Bowen Basin mine obtained for a range of comminution energies from 0.005 kWh/t to greater than 50 kWh/t.

METHODS

A large amount of sizing data was generated from test work conducted to investigate the comminution behavior of coal (Esterle et al, 1994; Bailey et al, 1994). Results from two types of tests were available: single particle breakage (SPB) and coal grinding. Variables tested for SPB included coal type, impact orientation and block size, but all results presented here are from a starting block size of 50mm, and the results are an average of perpendicular and parallel impact. The range of energies applied during these tests ranged from 0.005-0.2 kilowatt hours per tonne (kWh/t). For comparison a 2m drop is approximately 0.005 kWh/t.

Variables for the grinding tests also included coal type and energy (as a function of grinding time) from 1.6 to 53 kWh/t using a small ball mill (Bailey et al, 1994). Samples were prepared to pass 4mm before grinding tests were conducted; this energy was accounted for in the result. From these two data sets, the comminution response throughout the whole energy range from drop weight (0.001kWh/t) to grinding (53kWh/t) was available for one seam at a the Bowen Basin coal mine (Table 1).

The analysis of the data was made using a Microsoft Excel workbook written by Darren Edward of Chris Clarkson and Associates. The workbook contains macros for calculating Rosin-Rammler parameters "n" and "k" and produces plots from input size distributions.

Table 1: Coal types and data sets from a Bowen Basin mine used in this study.

SECTION	BRIGHTNESS	BREAKAGE-SPB	GRINDING
Top	Interbanded	X	X
Middle	Dull banded	X	X
Bottom	Bright banded	X	X

RESULTS

Examples of Rosin-Rammler size distributions for a range of comminution energies are presented for dull banded (Figure 1), interbanded (Figure 2) and bright banded (Figure 3) coal from the seam.

As expected, for each coal type the daughter particles became finer as a result of increased comminution energy from low impact drop weight tests up to high impact grinding. The Rosin-Rammler slope or "n" however is not constant across the energy range and it increases with energy for each coal type.

Plots of "n" against energy for these distributions from the three coal types are shown in Figure 4. For these data sets there is a strong trend of increasing slope with increasing comminution energy. This same trend is seen regardless of coal rank or type (Figure 5) and among the lower energy single particle breakage tests "n" stabalises after 0.075 kWh/t (exception the $R_{v,max}$=0.7 dull banded coal).

Slopes for the grinding tests initially decrease at low energies and become steeper again at the higher grinding energies. The first grinding sample (grinding feed) was prepared to a 4mm topsize by crushing the oversize in a jaw crusher, thereby producing an artificially coarse size distribution (large "n"). Mine product, produced to a constrained topsize (screen and crush oversize) also has a larger "n" than mine feed (see Table 2). The distribution modulus for subsequent grinding tests did not exceed that of the grinding feed until a grinding energy of 10 kWh/t was applied. Other coals that had been similarly prepared and ground in this ball mill displayed the same trend (Bailey and Esterle, 1994).

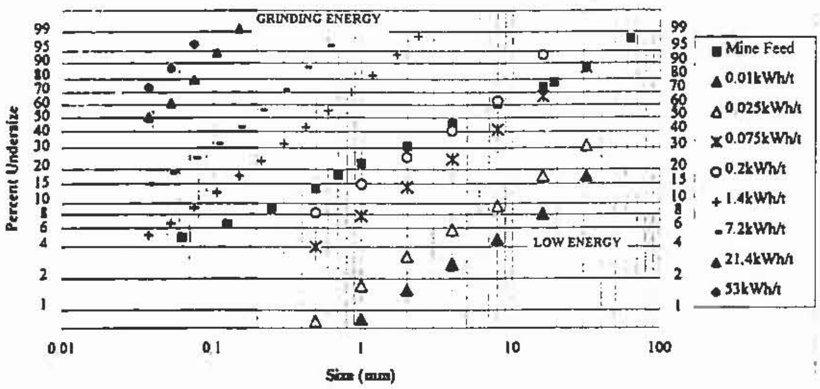

Figure 1. Rosin Rammler plot of daughter particles derived from various comminution tests from low energy (0.025-0.2kWh/t) breakage tests and high energy (1.4 to 53kWh/t) grinding tests for dull banded coal. Mine plant feed data included for comparison.

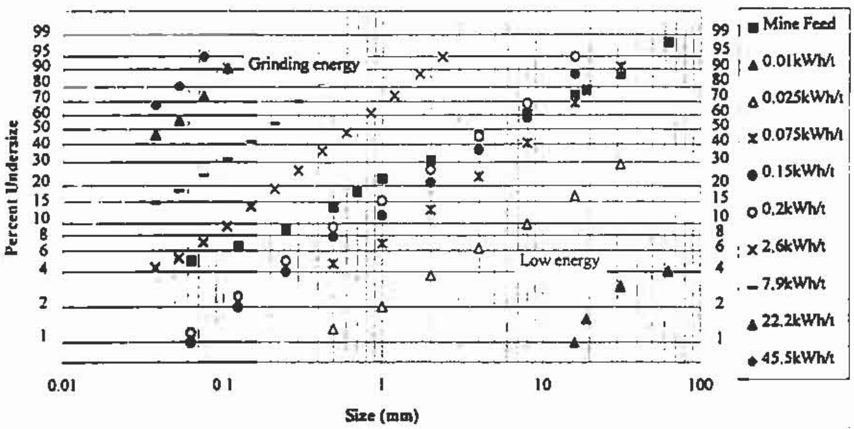

Figure 2. Rosin Rammler plot of daughter particles derived from various comminution tests from low energy (0.01-0.2kWh/t) breakage tests and high energy (2.6 to 45.5kWh/t) grinding tests for interbanded coal. Mine plant feed data included for comparison.

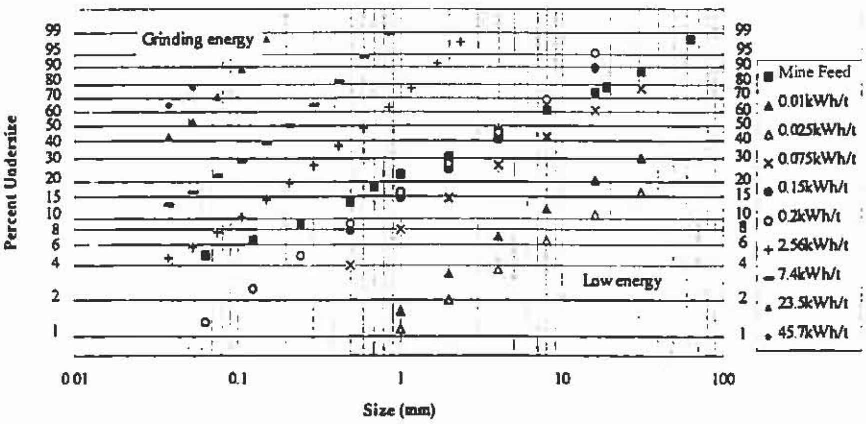

Figure 3. Rosin Rammler plot of daughter particles derived from various comminution tests from low energy (0.01-0.2kWh/t) breakage tests and high energy (2.56 to 45.7kWh/t) grinding tests for bright banded coal. Mine plant feed data included for comparison.

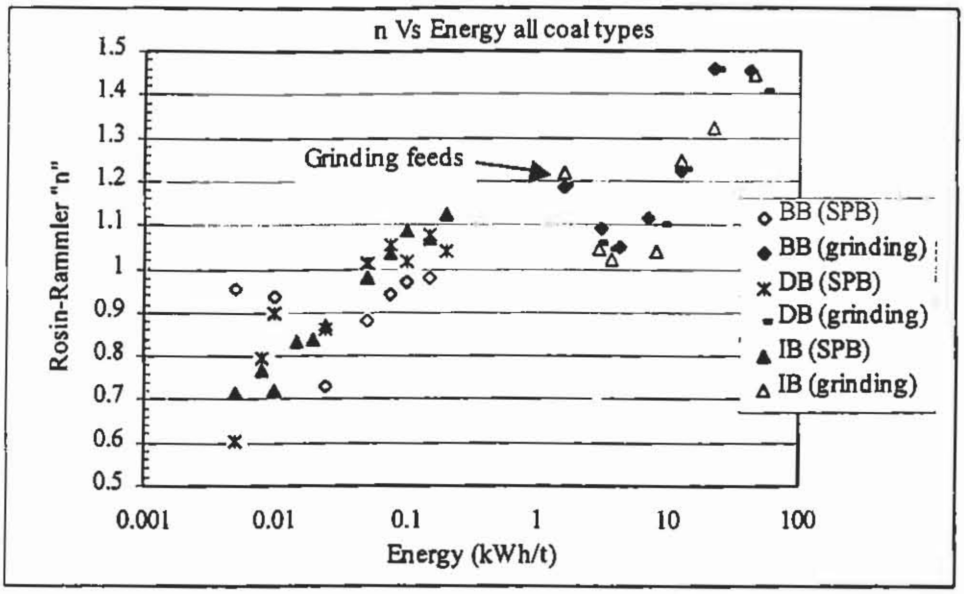

Figure 4. Plot of changing size distribution modulus "n" of daughter particles from tests with increasing comminution energy for Seam 1. SPB is single particle breakage tests.

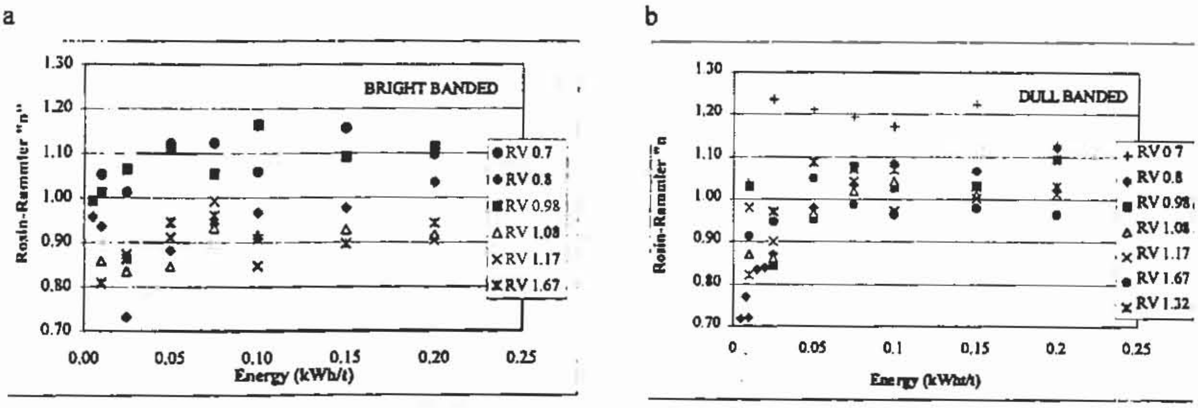

Figure 5. Plot of changing size distribution modulus "n" of daughter particles from single particle breakage tests of a) bright banded and b) dull banded coals from seams of different ranks.

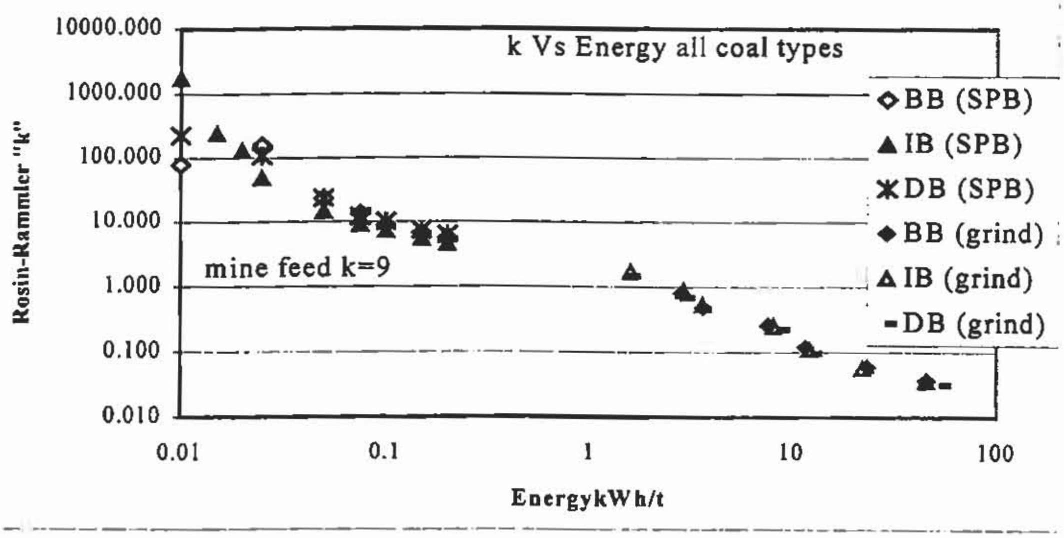

Figure 6. Plot of changing size modulus "k" with increasing energy.

a

b

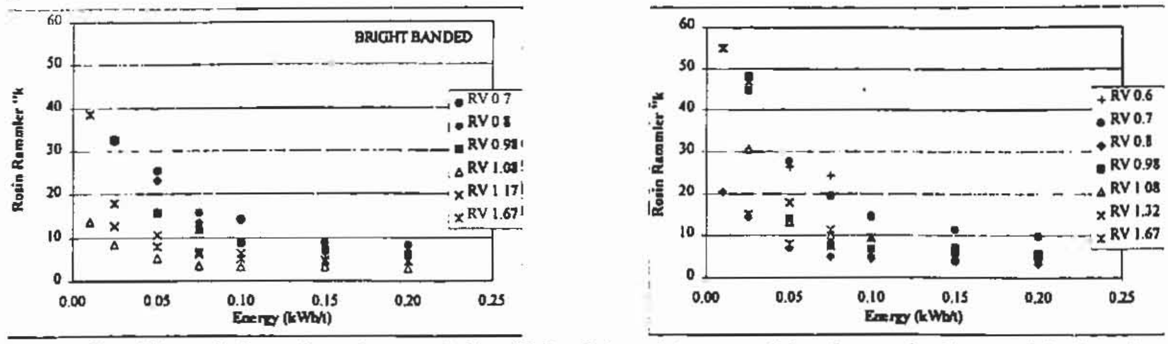

Figure 7. Plot of changing size modulus "k" of daughter particles from single particle breakage tests of a)bright banded and b)dull banded coals from seams of different ranks.

"K" decreases with increasing energy for all coal types (Figure 6), regardless of rank (Figure 7). The dull banded coals are consistently coarser than the bright banded coals at low energies, but at after grinding the type differences are reduced in these samples.

HGI values for the coal ply samples are similar to the literature values (Queensland Coal Board, 1995) for mine product (coking and thermal) of Seam 1 (Table 2). The dull banded coal has the lowest HGI (52) and the interbanded coal the highest (57) for this sample set. The HGI values for the type samples and mine product were used to calculate "n" by the Le Page and Callcott methods. The value of "n" ranges from 0.74 (dull banded) to 0.78 (interbanded) for the Le Page method and from 0.86 (dull banded) to 0.90 (interbanded) for the Callcott method. However, both methods underestimate the amount of fine coal produced from the seam as mined.

Table 2. HGI values used to predict the size distribution modulus "n" are compared with the measured "n" values for mine feed and product (coking and thermal). Calculations given in text.

Coal type	HGI	Size modulus "k" measured (mm) (0.1kWh/t)	size distribution constant "n" measured (0.1kWh/t)	calculated Le Page	Callcott
bright banded	54	8.8	0.96	0.76	0.88
inter banded	57	7.3	1.02	0.74	0.86
dull banded	52	10.2	1.09	0.78	0.90
mine feed		9.1	0.63		
coking coal	55		0.72	0.75	0.87
thermal coal	53		0.68	0.77	0.89

In order to determine the dependency of "n" and "k" on rank, these parameters were plotted for dull banded and bright banded coal types broken with 0.075 kWh/t (Figures 8 and 9). Over the entire rank range (0.5 to 1.7 Rv,max) investigated, the bright banded coals have lower "n" and "k" values than the dull banded coals, as a function of their inherent friability. Both parameters decrease with rank, but the trend is more evident in the bright banded coal types. Similar to HGI, the trend of increasing breakage with increasing rank reverses after the low volatile bituminous range (~Rv,max=1.6%). However, the reversal of trend occurs at a much lower rank (~Rv,max 1.3%) for single particle tests (0.075kWh/t) than it does for grinding tests (~30kWh/t), as seen in Figure 10.

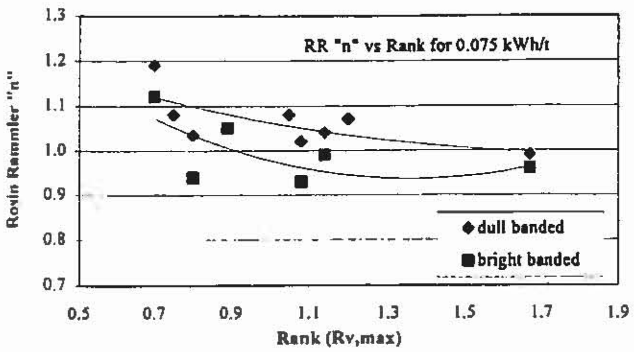

Figure 8. Rosin-Rammler "n" obtained from SPB tests at 0.075 kWh/t for a rank type suite.

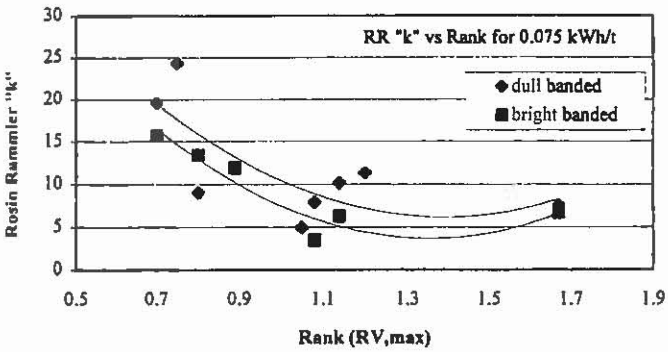

Figure 9. Rosin-Rammler "k" obtained from SPB tests at 0.075 kWh/t for a rank type suite.

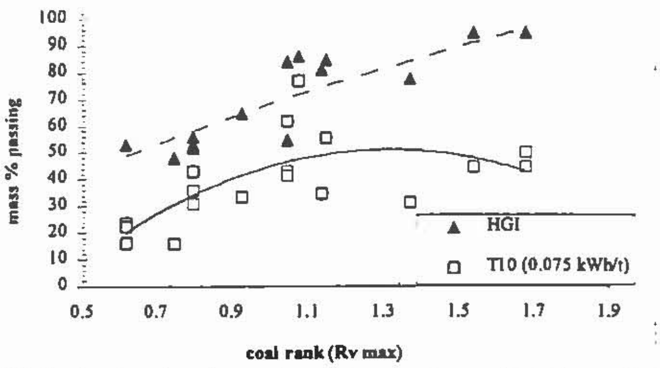

Figure 10. Comparison of mass percent passing T10 (5mm) for SPB tests at 0.075kWh/t and HGI (75um) at ~30kWh/t for coal samples of increasing rank.

DISCUSSION

The distribution modulus produced by single particle breakage at energies up to 0.2 kWh/t confirm the findings of Bennett that shattered coal produces "n" values that are greater (steeper) than run of mine coal and that they approach a slope of 1. The data obtained for both the breakage and grinding tests for these coals suggest that the slope of the Rosin Rammler distribution "n" is not unique to a coal but increases with comminution energy. Rather than producing a family of parallel lines with a progressively finer size modulus "k" they fan out as "n" increases with energy.

The absolute size modulus "k", a function of the amount of breakage and size reduction that the coal has undergone, decreases with increasing energy. Both coal types displayed similar trends, although there were subtle differences between them. For similar applications of low breakage energies the bright banded and interbanded coal had a smaller "k" than the dull coal. At high grinding energies the different coal types had similar "k" values.

Across the rank range investigated there was a type effect for breakage. Dull banded coals are harder to break than interbanded and bright banded coals at a given energy, resulting in larger "n" and "k" values. Similar to trends observed between HGI and rank, "n" and "k" both decrease as rank increases up to a point where the trend reverses and coals become less friable as they approach the low volatile bituminous rank. However, the reversal of trend occurs at a lower rank, around Rv,max 1.3% for low breakage energies than it does for energies (~30kWh/t) attained in grinding. This has implications for estimating breakage behaviour of different coals at the low energies of mining from such a high energy grinding test. By using a high energy test, the slope will always be steeper and underestimate the fine material that is generated during multiple, but lower energy breakage events.

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EVIDENCE OF RIFTING IN THE NORTHERN SYDNEY BASIN. THE MAITLAND-CESSNOCK-GRETA COALFIELD & CRANKY CORNER BASIN

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INTRODUCTION

The Maitland-Cessnock-Greta Coalfield is located on the periphery of the Lochinvar Anticline. The Cranky Corner Basin is an outlier situated to the north. The study area contains early Permian Greta Coal Measure sedimentation and is currently classified as part of the Newcastle Coalfield (Figure 1).

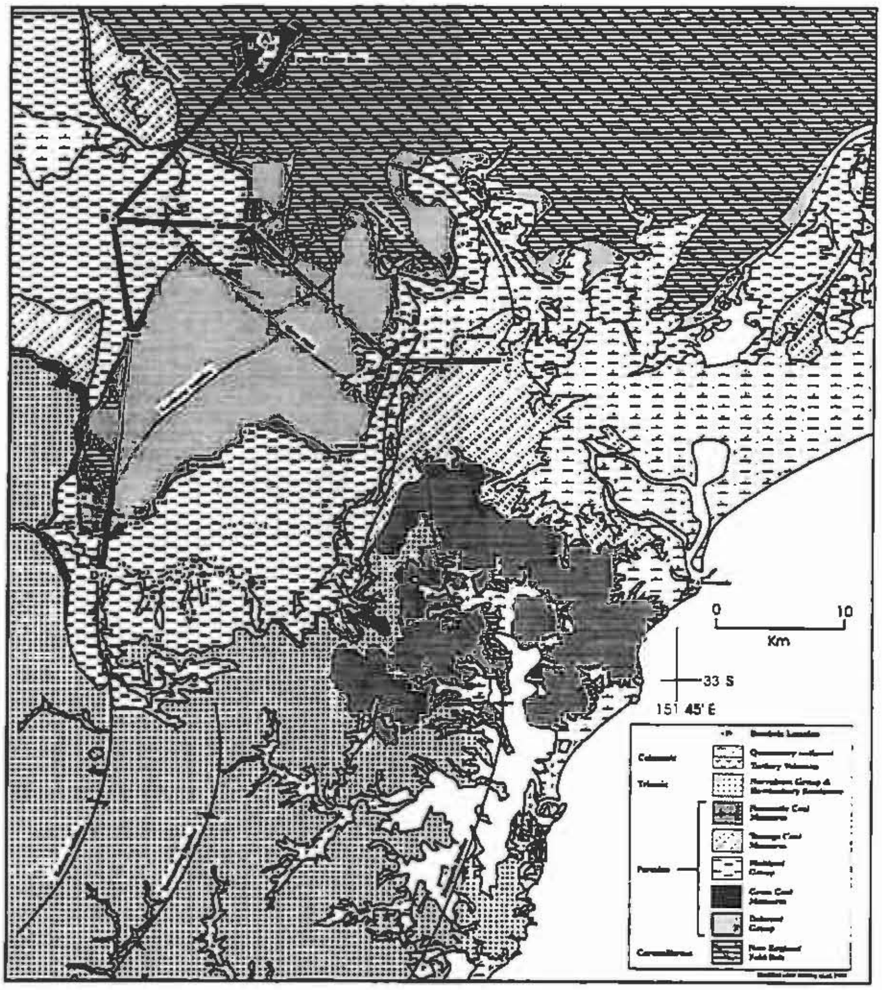
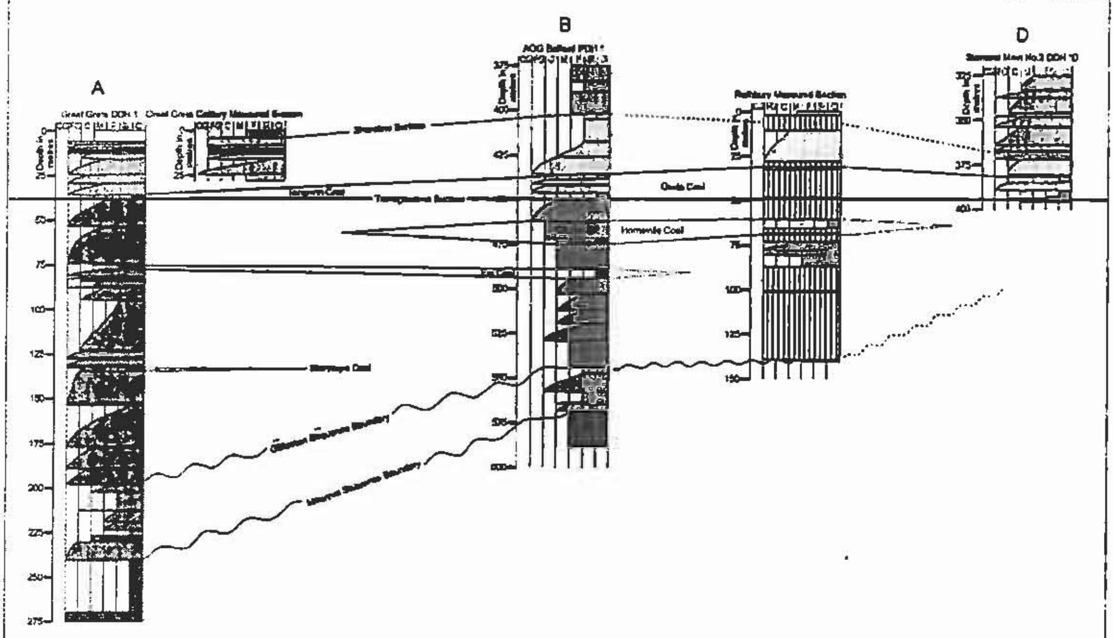


Figure 1. Location of the Maitland-Cessnock-Greta Coalfield and Cranky Corner Basin

The regressional Greta Coal Measures are a coarse clastic event bounded by marine sediments of the Dalwood Group and Maitland Group. The basal Dalwood Group contains the basic volcanic facies of the Lochinvar and Allandale Formations overlain by the fine grained, nearshore to shoreface sandy facies of the Rutherford and Farley Formations. The Maitland Group commences with the sandy to silty shoreface to shelf facies of the Branxton Formation overlain by the well sorted, upper shoreface facies of the Muree Sandstone and ceases with the offshore facies of Mulbring Siltstone.

NEW INTERPRETATION

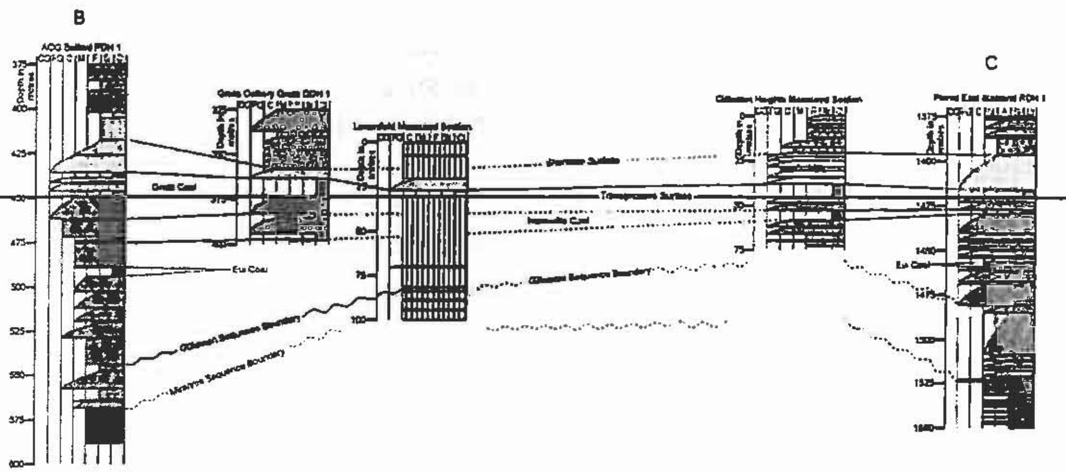
Two fluvial to marine sequences are recognised in the study area, the Mirannie Sequence and the Gillieston Sequence. The Mirannie Sequence (Section A-D) represents a regressive facies developed after a relative fall in sea level. It can be divided into a lowstand systems tract (lst) and a transgressive systems tract (tst). The Mirannie lst is characterised by pebble to cobble polymictic orthoconglomerates and coarse grained bartop sand sheets in the Cranky Corner Basin to upward fining lithic sandstones in the Maitland-Cessnock Greta Coalfield. It has a correlative conformity with the upper Farley Formation south of Greta. A transgressive surface is denoted by the development of a mire. A sandy, braided channel facies develops in the Mirannie tst. Thin, pyritic, carbonaceous beds developed on floodplains between inter-distributary channels.



Section A-D. Maitland-Cessnock-Greta Coalfield and Cranky Corner Basin

There is no evidence for the Mirannie tst on the Maitland-Cessnock-Greta Coalfield. It and the highstand systems tract (hst) have been eroded after a subsequent relative fall in base level. The Mirannie Sequence appears to onlap a high region towards to axis of the present Lochinvar Anticline (Section B-C).

The Gillieston Sequence (Section A-D) commences in the distal part of the study area with a sandy braided channel facies called the Neath Sandstone. This is a well sorted, quartz-lithic sandstone with pebble bands. The remainder of the Gillieston lowstand systems tract is represented by a pebble conglomerate braided channel facies with sandy bartops. Thin mires develop on abandoned channels of the fluvial system. Peat swamp development became more persuasive as the accommodation decreased towards the end of lowstand tract sedimentation. The Homeville Coal seam is a reflection of this development (Section B-C).



Section B-C. Maitland-Cessnock-Greta Coalfield and Cranky Corner Basin

The Paxton transgressive system tract (tst) commences at base of the Greta Coal seam. This represents a transgressive surface. An increase in the rate of base level rise produced a sediment bypass surface. A reduction in sediment load and a peat growth rate commensurate with change in accommodation produced a high vitrinite, low ash coal seam. As the rate of base level rise increased a marine transgressive signature of increasing pyrite content occurs in the coal seam. Above the Greta Coal seam the Paxton tst shows a well developed facies variability. In areas of high sediment supply a coarse braided channel facies developed. In areas of reduced sediment load a sandy braided channel facies developed. Thin peat swamps of limited extent developed on floodplains between the sandy channels. The high pyritic content of these coals suggests a similar tidal influence found in the top portion of the Greta Coal seam. As the fluvial gravel facies retrograded a transgressive barrier sand, called the Cessnock Sandstone, initiates the shoreline surface. This sandstone commonly has a pebble lag deposit at its base. Elsewhere a quartz-lithic muddy sandstone with a basal shell lag deposit represents a distributary channel facies. As water depth increased the barrier sand is replaced by a deltaic or nearshore slope sandy facies. The remainder of the Paxton tst is represented by shallow marine shelf sands and siltstones.

CONCLUSION

The Greta Coal Measures in the study area reflect uplift of a proto-oceanic rift flank in the Tamworth Belt. Line source alluvial fans, representing the Greta Coal Measures, emanated from this uplift (Figure 2). The Mirannie and Gillieston Sequences developed in a setting where basin fill equalled tectonic subsidence. A high accommodation rate was equalled by a high sediment load from the rift flank. This explains the predominantly aggradational stacking pattern of the parasequence sets seen in the lowstand systems tract. Isostatic unloading of the rift flank caused rebound of the rift basin. This fall in relative base level produced the erosional unconformity between the Mirannie and Gillieston Sequences. The rift flank had a reduced topography during Gillieston Sequence deposition. This is evidenced by greater coal seam development on a lower gradient fan slope. Post rifting thermal subsidence produced a marine transgression. The rift trough was the depocentre for the Maitland Group sediments.

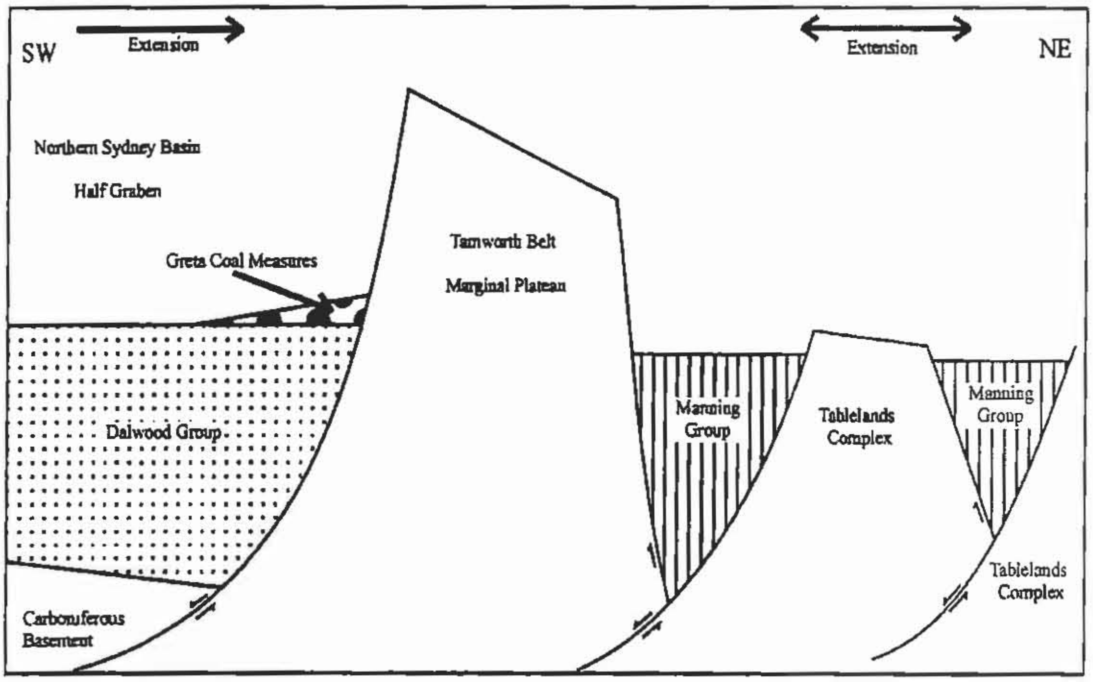


Figure 2. Diagrammatic representation of the tectonic geology of the Northern Sydney Basin and Manning Group in the Early Permian between 305-270 Ma

NEW INSIGHTS INTO THE DEFORMATION HISTORY OF THE HUNTER COALFIELD

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INTRODUCTION

Deposition of the Greta and Wittingham Coal Measures in the northern Sydney Basin, occurred from 277 to 252 Ma, a period of ~25Ma (Roberts *et al.* 1996). During and subsequent to deposition, both coal measures experienced a number of deformation events, which are manifested as folding, faulting and a series of joint sets and vein arrays. Many models have attempted to explain the structure and timing of deformation events recorded in the rocks of the northern Sydney Basin. However, substantial disagreement exists amongst authors as to the number and timing of deformation events (Figure 1A). Thus, there is need for a refinement of the structural history of the northern Sydney Basin.

Recent structural studies of the early to mid Permian Greta and Wittingham Coal Measures (GCM & WCM) exposed at Bayswater Colliery Company (BCC) has led to a reinterpretation of the number and timing of deformation events in the Hunter Coalfield. The relative ages of the later deformation events have been determined from dating of the Savoy sill, combined with a tectonic analysis of the joints contained within the intrusion. This paper summarises the outcomes of these studies and presents a revised version of the timing of the deformation events in the Hunter Coalfield.

STRUCTURAL FEATURES OF BAYSWATER COLLIERY AREA

Prior to deformation, the Greta and Wittingham Coal Measures were deposited in a rift basin setting, and subsequently underwent burial and diagenesis. During deposition, an orthogonal joint set formed which subsequently has been reactivated, reoriented or displaced by later deformation events. The joints strike 140-160° and 050-070°, and are sub-vertical. They are characterised by plumose structures, and normally show no displacement. Spacing ranges from 10cm to 10m, depending on bed thickness and rock type. According to the joint classification of Bahat (1991), these features suggest a 'burial/compaction' origin. The early formation proposed for these structures also supports this view.

Structural analysis of the Greta and Wittingham Coal Measures indicates that ten regional or local scale phases of deformation have affected the Hunter Coalfield:

Deformation One (D_1) produced macroscopic, asymmetric, meridionally trending, shallow south plunging folds (F_1) with axial planes dipping steeply to the east. During the formation of the Muswellbrook Anticline, and other subsidiary F_1 flexures (the Western Anticline and Calool Syncline), steepening and rotation of the earlier-formed compactional joints took place. The folds are believed to postdate deposition of the GCM, because of the absence of stratigraphic thinning of these measures in the hinge of either anticline. However, the presence of stratigraphic thinning in the hinge of the Muswellbrook Anticline in the WCM and seam splitting in the hinge of the Calool Syncline, indicate both structures were present prior, and active during, deposition of the WCM. D_1 is interpreted to be the result of E-W directed σ_1 (Figure 2).

Deformation Two (D_2) is characterised by meridional trending jointing (J_2), which possibly formed as a result of east-west extension (or stress relief) imposed on the F_1 folds. D_2 structures are relatively few in number and have been displaced by shear joints formed during D_3. The J_2 fractures generally occur in shales and mudstones, and as coal cleats. The second deformation event is absent from the WCM (Figure 2).

Deformation Three (D_3) is characterised by the formation of oblique slip, N-NNW striking normal faults showing varying displacement (1 - 12m in the GCM and <10cm in the WCM), and reactivation of the NW striking compactional joints. Slickenlines/fibres record movement of 68-87° to the S, and indicate that the principal stress directions σ_1, σ_2 and σ_3 are 87°→254°, 00°→351° and 06°→082° respectively, using the program of Sperner *et al* (1993). The presence of D_3 structures in the WCM indicates a post 252 Ma age for this phase of deformation.

Deformation Four (D_4) produced small scale (<1m displacement) ESE to SE trending thrust faults and associated low-angle joints. The timing of this deformation event could not be constrained in the GCM. However, in the WCM, thrusts and joints of this orientation are overprinted by D_5 structures. It is tentatively concluded that these structures are related to the compressive deformation event that formed thrust faults of similar orientation, some 20km to the N (Lohe *et al.* 1992)

Deformation Five (D_5) reworked the 060° compaction joints, and is manifested by steeply dipping, ENE trending, dominantly, sinistral faults. Slickenlines on the sub-vertical 060 compaction joints plunge 16-40° to the SE and indicate that the principal stress directions σ_1, σ_2 and σ_3 are 06°→210°, 60°→110° and 31°→305° respectively. ENE trending calcite veins appear to have also formed during this event. Small D_5 thrust faults have been found to displace the earlier formed D_4 NW trending joints. The presence of D_5 structures in the Savoy sill constrains the age of this deformation event to be post 225Ma (see section on intrusions).

Deformation Six (D_6) is characterised by the formation of meridionally trending joints and faults in the GCM. Reactivation of the NNW striking normal faults occurred at this time, producing a second, more clearly defined set of slickenlines on fault surfaces. The slickenlines record dominantly dip-slip movement (78-84° to the N or S) and indicate that the principal stress directions σ_1, σ_2 and σ_3 are 82°→266°, 00°→175° and 08°→085° respectively. The event responsible for this normal faulting was associated with a substantial fluid flow, resulting in the formation of many meridional striking calcite and pyrite veins. These veins average 3mm in width, but some exceed 150mm.

The sixth deformation event is also thought to be associated with the intrusion of a dyke which has been emplaced along pre-existing S-SE trending D_4 planes of weakness. This conclusion however is tentative, as the timing of this intrusion is based on the presence of D_7 joints recorded in the intrusion.

Deformation Seven (D_7) is associated with the formation of the NE to ENE striking normal faults and joints, and reactivation of the earlier formed NE compaction joints. These faults show a variation in displacement (>10m in the GCM and <1m in the WCM), and show two sets of slickenlines, the earlier D_5 set, and the dip-slip lineations associated with this event. The lineations from this event indicate that the principal stress directions σ_1, σ_2 and σ_3 are 73°→330°, 07°→218° and 15°→127° respectively.

The D_7 deformation was also associated with the intrusion of the Puxtrees sill (located in the Puxtrees seam in the GCM) and NE trending dykes in both coal measures. The Puxtrees sill abuts against and crosses the D_7 normal fault planes, and has used the brecciated zones of D_6 faults to migrate between displaced coal members. The NE trending dykes in the WCM form a 'dyke swarm', and have closely spaced joints which increase in spacing with distance from the dyke host contact. This indicates that emplacement was not into open pre-existing discontinuities but along fractures created by tensile stresses associated with the wedging action of the magma. The NE trend of dykes at Bayswater is consistent with the regional trend of dykes in the Hunter Coalfield.

This extensional deformation event has been widely recognised throughout the Sydney Basin (Gray, 1975; Gale, 1980; Lohe *et* al. 1992), but to the authors' knowledge dating of any NE trending dykes in the Hunter Coalfield has not been carried out. However, radiometric dates of rocks throughout the Sydney Basin (Carr & Facer, 1980) indicate a peak between 210 and 150 Ma, which is thought to be related to this magmatic event.

Deformation Eight (D_8) is characterised by low angle NNW trending joints in the thin (<5m) D_7 dykes, and sub-vertical joints in the thick (>50m) Savoy sill. The change in dip of the joints is thought to reflect the different mechanical properties of the rocks. From the orientation of these joints and assuming they are thrusts, σ_1 is ENE - WSW.

Deformation Nine (D_9) is characterised by ENE to E trending normal faults and joints. The faults have displacements of 15-60m in the WCM (Bayswater No. 3 mine), and are prominent features further north at Mount Arthur North, with displacements up to 110m (also in the WCM). Slickenlines record dominantly dip-slip and minor dextral movement, with lineations plunging 80° to the W, indicating that the principal stress directions σ_1, σ_2 and σ_3 are 84°→182°, 01°→081° and 10°→351° respectively. Magnetic surveys indicate that these E-W trending faults displace the meridional $D_{6/7}$ dykes in the WCM. Evidence for this deformation event is rare in the GCM.

Deformation Ten (D_{10}) is the only post-intrusion deformation event recorded in the GCM. This deformation is characterised by ENE striking thrusts, which generally dips 45° to the N. One such fault in the GCM clearly truncates the Puxtrees sill. Lineations on fault/joint planes of similar geometry and orientation indicate that the principal stress directions σ_1, σ_2 and σ_3 are 42°→113°, 35°→241° and 27°→351° respectively. It should be noted however, that this interpretation is based on a minimal amount of data.

INTRUSIONS IN THE COAL MEASURES AND K-AR DATING

Intrusions in the Greta and Wittingham Coal Measures occur both as sills and dykes. The sills are laterally extensive, especially in the WCM and have affected most seams.

Owing to the highly weathered nature of dykes and sills found in the pits, K-Ar radiogenic dating has been carried out on a drill core sample from a teschenite sill (18.7m thick), and from fresh exposures in the Savoy sill (>50m thick). The teschenite 'Bayswater' sill (drill hole UGP4; 1416957.97 281446.97) gave a K-Ar age of 162.8 ± 4.8 Ma (Middle Jurassic), and is significantly different from the Middle Triassic age (232-235 ± 4 Ma) of teschenite sills recorded <10km to the south (Gamble *et al* 1988). The dolerite unit of the Savoy sill gave a K-Ar age of 225.1 ± 4.9 Ma (late Triassic).

It should be noted that the age and composition of the teschenite 'Bayswater' sill (in WCM) cannot be assumed to be exactly the same as either the meridional (D_6) and NE (D_7) striking dykes. Both dykes differ texturally and mineralogically from the teschenite sill and are compositionally similar to the teschenite sill examined by Gamble *et al.* (1988). However, the age obtained from the 'Bayswater' sill is consistent for a significant magmatic event in the late Triassic/Jurassic. The 'Bayswater' sill may therefore give an approximate age for the NE trending dykes.

A structural analysis of the Savoy sill has revealed a minimum of five phases of deformation affecting the late Triassic intrusion. The first event that can be correlated with the adjacent rocks in the Savoy sill is the D_5 deformation event. Thus, all subsequent deformation events postdate this time post 225 Ma in age (Figure 1B).

MAITLAND GROUP SEDIMENTS

The Maitland Group lies conformably between the GCM and WCM. A small outcrop of Maitland Group sediments were also examined in this study, and further confirmed the structural history proposed for the GCM and WCM. It should be noted only deformation events D_4, D_5, D_6 and D_9 were observed, however the chronology conformed with the regional structural interpretation (Figure 2).

LOCALISED OR REGIONAL DEFORMATION EVENTS?

Observations made in this study, suggest that some of the structures in the Bayswater open cuts are the result of local deformation events. To confirm this, the deformation events proposed in previous studies in surrounding areas were compared with those proposed for the Bayswater area. On the basis of the comparison, seven deformation events are considered regional, the remainder local, and were rarely seen outside the Bayswater Lease. This comparison with previous work also helped to constrain the timing of deformation events.

DISCUSSION AND CONCLUSIONS

The conclusion that the D_5 event postdates the Savoy sill has significant implications. It was initially proposed, from the orientation of σ_1 in the GCM and WCM that D_5 may be a continuation of D_4. However, if it assumed that the Savoy sill was emplaced post D_4 and pre D_5 compressional events, an extensional event (occurring between D_4 and D_5) must be proposed to explain the emplacement of the sill. The age of the Savoy sill (and that of Gamble *et al.* 1988) indicates a possible mid Triassic age for this event (Figure 1B). From the orientation of early formed, monzodiorite dykes within the dolerite in the Savoy sill (NW), a NE-SW extensional stress regime is thought to have existed at the time of the intrusion of the Savoy sill.

In summary, prior to deformation, the GCM and WCM underwent burial and diagenesis resulting in the development of an orthogonal NE and NW trending 'compaction/burial' joint set. Subsequently, they record eleven phases of deformation (six extensional and five compressional) from the late Permian to the Tertiary (Figure 1B). The principal stress directions derived for each of these deformation events, their chronology and proposed ages, are as follows:

D_1	E - W σ_1 (Muswellbrook Anticline)*	late Permian (~260-270 Ma)
D_2	E -W σ_3	late Permian
D_3	NE - SW σ_3 *	late Permian (<252 Ma)
D_4	NE - SW σ_1 (Hunter Thrust)*	late Permian / early Triassic
$D_{4/5}$	? NE - SW σ_3 (intrusion of thick sills)	mid Triassic (225 - 235 Ma)
D_5	NE - SW σ_1	mid/late Triassic (<225 Ma)
D_6	E - W σ_3 *	late Triassic/early Jurassic
D_7	NW - SE σ_3 (NE dykes)*	Jurassic (210 - 150 Ma)
D_8	E - W σ_1 *	Cretaceous
D_9	N - S σ_3	Cretaceous/Tertiary
D_{10}	N - S σ_1 *	Tertiary

* Indicates the deformation event is regional (far field) as opposed to local (near field) in nature.

Structural models proposed by various authors for the Hunter Coalfield are therefore inconsistent (both in terms of the number and timing of deformation events), and do not account for all the structures recorded in the Greta and Wittingham Coal Measures. The reason for this is that previous interpretations have been based on either regional or localised structures/studies (rarely both), and few interpretations have been based on structures that have been dated in their synthesis.

OUTCOMES - HOW THE NEW INSIGHTS DIFFER FROM OTHER PREVIOUS STRUCTURAL INTERPRETATIONS/MODELS

- Gray (1975) concluded that all the joints in the Permian rocks (near Ravensworth) are postorogenic, Tertiary in age, developed independent of faulting and folding, and are the result of lateral expansion. He also concluded that the final phase of deformation is associated with the emplacement of igneous dykes, sills and plugs. The current analysis suggests that joints and faults formed simultaneously, as a result of the several deformation events, and that 3 deformations occurred post the Jurassic intrusions.
- The structural interpretation of Gale (1980) is broadly similar to that proposed in this study, however the results of this analysis reinterpret the chronology of his D_4 and D_5 deformation events. He presented no definitive evidence to indicate that the meridional

normal faults pre-dated the Hunter Thrust. The chronological order of these two events has been further constrained in the current study.

- Collins (1991) assumed all late Permian deformations were compressional, and as a result, suggested the early formed normal faults (equivalent to D3 in the current study) proposed by Gale (1980) were the result of an E-W extensional event (D6 in the current study). The current study refutes this view and proposes a NE-SW extensional event (D3) during the late Permian.
- The N-S compressive D_6 event (equivalent to D_{10} in current study) proposed by Roberts *et al.* (1991) is interpreted as Tertiary in age rather than Triassic. They constrained the timing of the deformation event on folding of early Triassic sediments in the Lorne Basin.
- Lohe *et al.* (1992) suggests three late-stage compressional events occurred post the NE-SW regional extension, however the chronology of these events was not determined. The current study suggests this view and provides chronological evidence for two of the three previously unconstrained compressional events. The latest event described in their study (E-W compression) was not recorded in the rocks of Bayswater Colliery. Further, the regional NW-SE extension deformation event and related magmatism proposed by Lohe *et al.*(1992), is interpreted as Jurassic, rather than Cretaceous/Tertiary in age.
- The structural model of Glenn & Beckett (1997) for the Hunter Coalfield incorporated five compressional events, relating them to a foreland fold-thrust belt setting. In their model, regional compression continued from the late Permian to the early Triassic, which is in accord with the current model.
- The present study dates the Bayswater and Savoy sills and proposes the possibility of a mid-Triassic extension event. To the authors' knowledge this event has not been recognised in the past.

ACKNOWLEDGMENTS

The work presented in this paper comprises part of the first author's B.Sc (Hons) thesis submitted in November 1998 to the Geology Department, University of Newcastle. A Billiton Study Bursary, provided by Mr John van der Riet of Ingwe Coal Corporation funded the project. The assistance and guidance of Mr Gary Salter of Bayswater Colliery is gratefully acknowledged. We thank Dr. Eric Lohe for reading an earlier draft of this manuscript.

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	Greta Coal Measures (277-269 Ma)	Maitland Group (269-262 Ma)	Wittingham Coal Measures (262-252 Ma)	Savoy sill (225 Ma)
pre D_1	σ_3 σ_3 Burial joints	σ_3 σ_3 Burial joints	σ_3 σ_3 Burial joints	Not present
D_1	σ_1 F1 folds	σ_1 F1 folds	σ_1 F1 folds	Not present
D_2	σ_3 Release joints	Not present	Not present	Not present
D_3	σ_3 Normal faults/joints	Not observed	σ_3 Normal faults/joints	? Correlation σ_3 Dykes and rare joints
D_4	σ_1 Low-angle joints/faults	σ_1 Low-angle joints/faults	σ_1 Low-angle joints/faults	σ_1 ? Correlation Low-angle joints
D_5	σ_1 Oblique slip - dom. sinistral	σ_1 ? Steeply dipping thrusts	σ_1 Oblique slip - dom. sinistral	σ_1 Oblique slip - dom. sinis
D_6	σ_3 Sub-vertical joints/faults	σ_3 Sub-vertical joints/faults	σ_3 Sub-vertical joints, dyke ?	? Timing σ_3 Veins, conjugate joint se
D_7	σ_3 Intrusions, joints & faults	Not observed/present	σ_3 Dykes, joints & faults	
D_8	Not observed/present	Not observed/present	σ_1 Low-angle joints	? Sub-vertical joints
D_9	σ_3 Normal faults/joints	Not observed/present	σ_3 Normal faults/joints	σ_3 Normal faults/joints
D_{10}	σ_1 Low-angle joints/faults	σ_1 Low-angle joints/faults	Not observed/present	Not observed/present

Figure 2: Phases of deformation recorded in rocks of different ages in the Hunter Coalfiel. Arrows indicate stress directions. Each phase of deformation is represented by an arrow, and is accompanied by the type of structural element recorded.

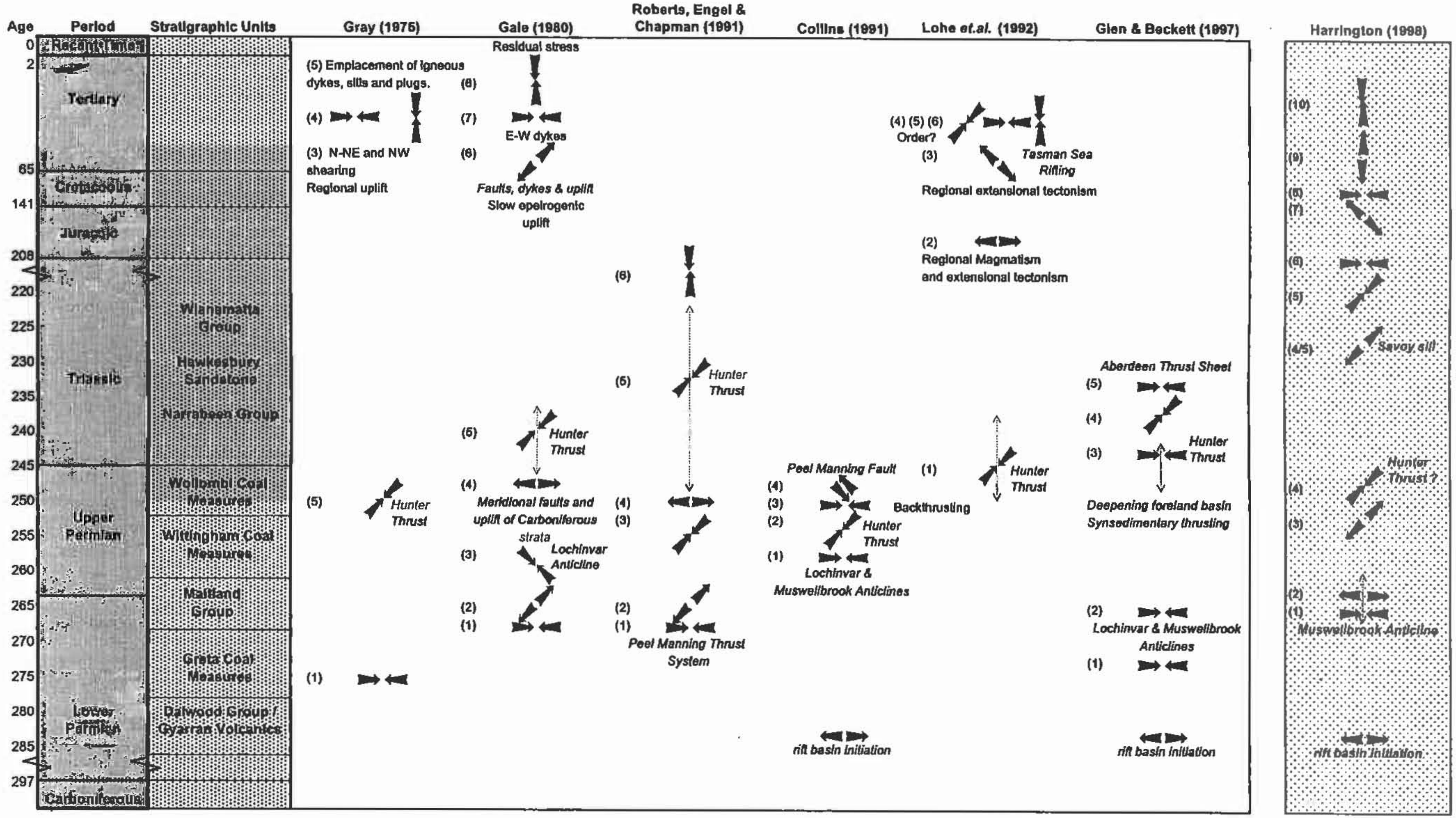

Figure 1: Summary of deformation events and stress fields proposed by various authors for the northern Sydney Basin and New England Fold Belt. 1A: Previous structural interpretations/models. 1B: Current Interpretation.

ROCK MASS DEFORMATION MONITORING

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INTRODUCTION

Modern mining activities require optimisation of the mine plan for production within well understood stability and safety criteria. Performance of these structural designs needs to be monitored so that the safety margins of the overall mine plan can be assured while the reserve losses implicit in pillars are minimised. This is particularly critical when mining is closely associated with other cultural developments or population centres, where the long term performance of the total underground structure needs to be continuously and non invasively monitored for elastic failure, creep and plastic failure events.

Commercially available strain gauges are routinely used to measure deformation associated with mining activities, for example in monitoring pillar stability or roof caving. However there is an increasing need to monitor rock mass deformations over a long term (for example associated with pit slope stability), or remote from mining operations (for example, surface infrastructure or nearby buildings, roads, etc). Previously this has not been possible because the sensitivity and long term stability of the commercial strain gauges is not adequate. A new precision borehole strain monitoring system (**BTSM**) currently deployed by CSIRO Exploration and Mining has the potential to solve these new issues in rock mass deformation monitoring. This technology was originally developed for use in hard rock mines (Gladwin 1977) and refined considerably for earthquake research (Gladwin et al. 1994, Gwyther et al., 1992). This paper describes a case study of the use of the BTSM in monitoring longwall coal mining over the period 1993-1998.

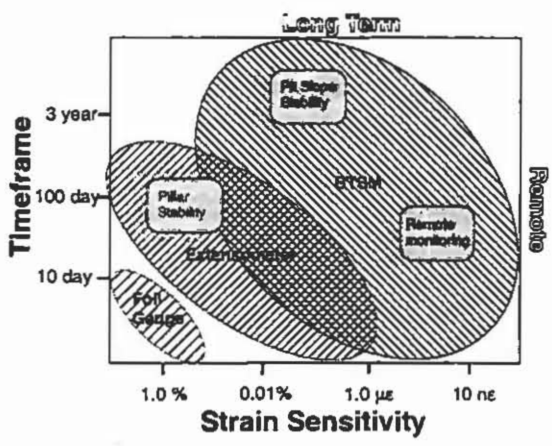

Figure 1. Domains of application in monitoring deformation associated with mining - commercial strain gauges (eg. Foil gauges or extensometers) and the borehole tensor strainmeter (BTSM).

CASE STUDY

BTSM instruments were deployed at Cataract Reservoir, south of Sydney, in 1993 to provide long term monitoring of longwall mining induced strain variations beneath the reservoir. The instruments used have a wide dynamic range allowing continuous monitoring tensor plane strain within the range of 10^{-3} to 10^{-9}. A mine plan of the extraction sequence monitored is shown in Figure 2. The coal seam is at 450 m depth, and instrument installation was at approximately 100 m depth, 50 m below the reservoir bottom to evaluate strains at this critical depth. Sites were chosen to provide an early estimate of maximum mining induced strains (CCT), a forward analogue of the final approach to the dam wall (CAT), and direct measurement of any effects related to the dam abutment itself. Target depths were core drilled to ensure adequate coupling conditions for the transducer elements

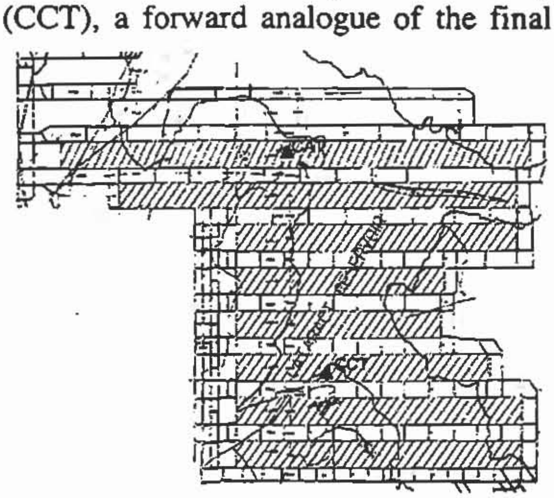

Figure 2. Mine extraction plan, with instrument sites shown as CAT (above panel 508) and CCT (above panel 503). The dam wall site is 3 km to the north.

BTSM instruments provide nanostrain sensitivity by measurement of three components of the horizontal plane strain induced by tectonic or engineering processes. Earth tilt measurement at nanoradian sensitivity was also included in the instrument modules. Data is available at the measurement site in real time, and can also be used to monitor elastic failure or rock creep processes over extended periods of time. Instruments are installed from the surface in vertical boreholes, and there is no interference in the mining operation. Sites must be carefully chosen to provide representative strains in the monitoring environment, and the target depths are core drilled to ensure adequate coupling conditions for the transducer elements, with the core samples used to determine the elastic moduli of the rocks at the measurement sites. Operational integrity of the instrument is verified in real time by direct continuous measurement of the solid earth tides. These have a peak to peak strain amplitude of approximately 0.05 to 0.1 microstrain (see Figure 3) and are also used to provide in situ calibration for the measurement system

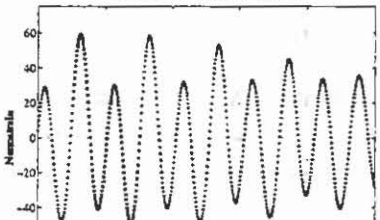

Figure 3 Solid Earth tide observed on strainmeter.

Instrumental deformation, u, is monitored in three directions perpendicular to the axis of the borehole. These deformations are related to surrounding rock deformation via shear and areal strain hole coupling factors c and d, and quantities t_{ij} which describe the influence of topography and geology in mapping a regional strain field to strains at the instrument site.

These parameters are all determined after instrument installation.

Raw transducer readings are processed to provide estimates of the measured engineering areal strain in the plane perpendicular to the borehole, $\varepsilon_a = e_{xx} + e_{yy}$. The engineering shear strains, γ_1 and γ_2 are calculated in an axis system with the x axis to the east, and the y axis to the north. The γ_1 is standard engineering shear, $(e_{xx} - e_{yy})$, and γ_2 is $2e_{xy}$. These measures are then used to calculate any other strain parameters, for example in mining applications the maximum and minimum compression axes for the strain ellipse can be measured at a site for each point in time. Strains are analysed from an arbitrary zero, taken as the undisturbed state of strain at the site.

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2}\cos 2\theta_1 & \frac{1}{2}\sin 2\theta_1 \\ \frac{1}{2} & \frac{1}{2}\cos 2\theta_2 & \frac{1}{2}\sin 2\theta_2 \\ \frac{1}{2} & \frac{1}{2}\cos 2\theta_3 & \frac{1}{2}\sin 2\theta_3 \end{bmatrix} \begin{bmatrix} c & 0 & 0 \\ 0 & d & 0 \\ 0 & 0 & d \end{bmatrix} \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_a \\ \gamma_1 \\ \gamma_2 \end{bmatrix}$$

In terms of vectors and matrices this can be written as

$$\tilde{U} = G.H.T.\tilde{s}$$

RESULTS:

The measurement program was begun in 1993 immediately prior to the beginning off the extraction sequence of the first panel in the series (501). Measurements at all three sites were taken at 30 minute intervals, recorded locally at the site, and every three hours transmitted via a VHF link to a central recording facility at the operations centre at the Cataract dam. This site provided a redundant recording system and direct access to the data via a dial in modem interface. The control software at the site included remote intervention for maintenance of the data, for storage and general processing of the data. At regular intervals the data was extracted from the unmanned base station, network performance and timing was verified, and the data archived and processed at CSIRO.

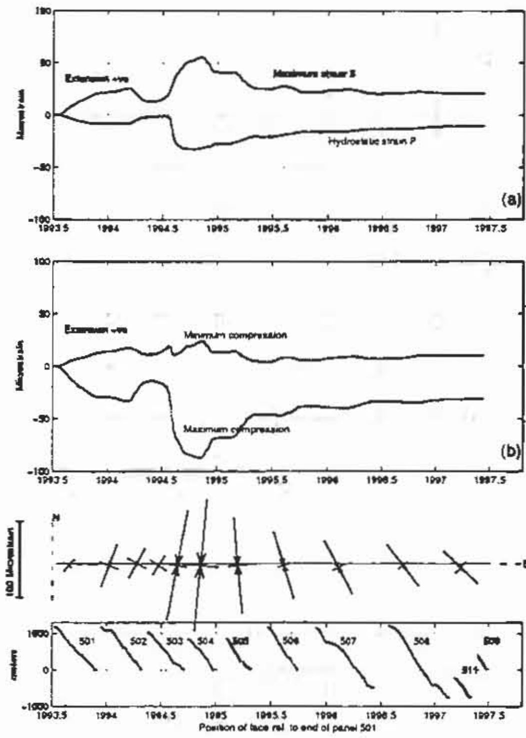

Figure 4. a: Maximum Shear and hydrostatic strains observed at site CCT (panel 503).b: Maximum and minimum compressional strains. c: Principal axes of observed strain. d: Progression of mining

Figure 4 shows a time sequence of principal axis strain data measured at site CCT (above panel 503), with the upper plot (a) showing the maximum shear (S) and hydrostatic strain (P) , and plot (b) the maximum and minimum compression axes of the strain ellipse relative to the undisturbed state. Initially the longwall was about 1200m to the south of the instrument. The lower plot panel indicates the principal axes interpretation of the strain sequences measured at 503, at each point in time marked with a principal axis plot. Arrowheads on the principal strain axes give the direction of strain, and the azimuth of the axis plot gives its normal geographic azimuthal orientation (east to the right, north up). The bottom plot shows the position of the advancing longwalls measured from the western end of each panel. The longwall passed under the 503 site about 30 July, 1994 (1994.6), at which time the site went into approximate cross panel uniaxial compression. Mining operations in panel 509 have an influence at the 503 site (1400m distant) at a level of less than 10 microstrain. The maximum horizontal compressive strain reached approximately 80 microstrain as the 504 panel was mined, shear strains reached 50 microstrain, and the mean hydrostatic strain was approximately 20 microstrain. Strain changes were evident at the CCT site in the 503 panel immediately the extraction of 501 panel was begun.

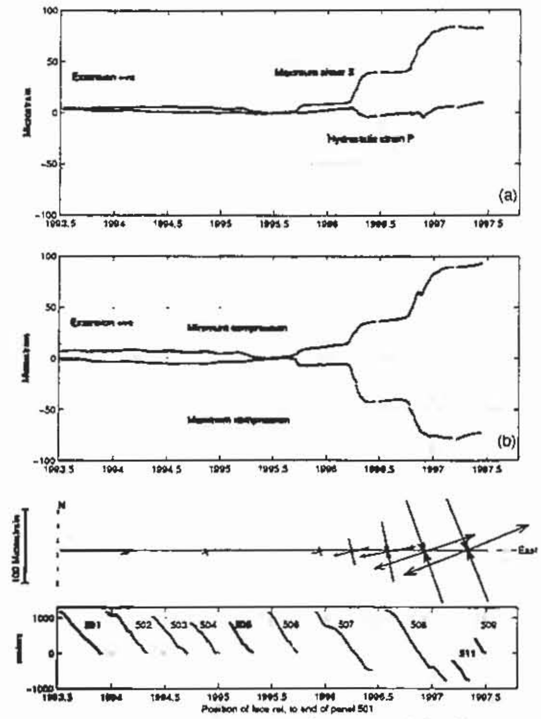

Figure 5. *a: Maximum Shear and hydrostatic strains observed at site CAT (panel 508).b: Maximum and minimum compressional strains. c: Principal axes of observed strain. d: Progression of mining.*

Strains over the same interval measured at the site CAT (above panel 508) are shown in ***Figure 5***. Borehole recovery effects (associated with the local strain relief surrounding the borehole during drilling) are superimposed on observed strains in borehole instrumentation. These effects have been removed to facilitate analysis of the mining induced strains (this procedure was not possible for 503 because mining of 501 began immediately after installation). Longwall operations passed beneath site 508 in November 1996, and the **magnitudes** of strain offsets observed were similar to those observed at CCT site (panel 503) when operations were in close proximity to CCT site (panel 503).

The **detail** of strain response at this site **was markedly different** to that observed at panel 503. In particular the relaxation of north/south strain (ε_{yy}) observed at 503 during mining in the preceding panel was not observed at 508 site during mining of the preceding panel. The strains at CAT resulting from the mining operations are almost fully shear strain. The changes in azimuth of principal axes indicate that the maximum shear strain (S) is orientated at a angles of approximately 10° and 100° East of North.

Note that the hydrostatic strain term (P) indicates net dilation (ie. positive hydrostatic strain) at CAT site after mining of panel 508 was complete, with a current overall increase in dilation of 10 to 20 microstrain since commencement of mining panel 506. This result contrasts with an overall net compression of approximately 10 microstrain as was observed at site 503.

There is also clear evidence of a rate increase in dilation or tensional strain (ie decrease of compressional strain) beginning approximately at the commencement of mining panel 506. This rate of decrease of compressional strain continues to the present time.

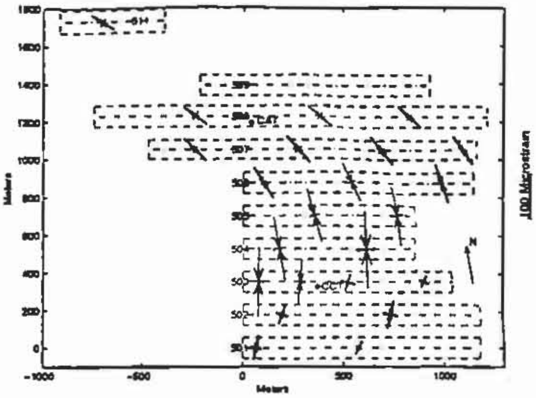

Figure 6. Map view of principal axes of strain observed at site CCT during longwall operations. Each set of strain axes shown at a position in a panel represents the strains observed at CCT when the longwall face was being mined at that position.

A map view of the principal axis strains **measured at site 503** due to the progression of the longwall is shown in ***Figure 6***. The figure shows the position of longwall panels 501 to 511 in map coordinates. The mining proceeded from east to west in panels 501 to 508, followed by panels 511 and 509. A series of principal axes plots have been superimposed to indicate the state of strain (relative to the undisturbed state) **observed at the 503 measurement site** when the long wall sequence had reached the particular position. The sites of the strain meters above 503 (CCT) and 508 (CAT) are indicated by the stars. The maximum strains above the panel (at the instrument depth) can be estimated directly from the figure. Azimuth is relative to the north point shown. The result clearly indicates a significant rotation of the principal strains with progression of the longwall.

Detail of strain meter response to longwall operations over a 12 day period when the face operations were directly below the instrument (a depth of approximately 400 m) are shown in ***Figure 7***. The periods of mining activity are shaded. Note that they reflect the fact that face cutting occurs in two shifts separated by a maintenance shift interval which can clearly be identified. The major strain changes induced by the mining are restricted essentially to the periods of mining activity. The figure indicates the direct causal relationship of the observed loads to mining operations. Detailed examination indicates that the immediate elastic response followed by a short term plastic response consistent with expectations from subsidence data.

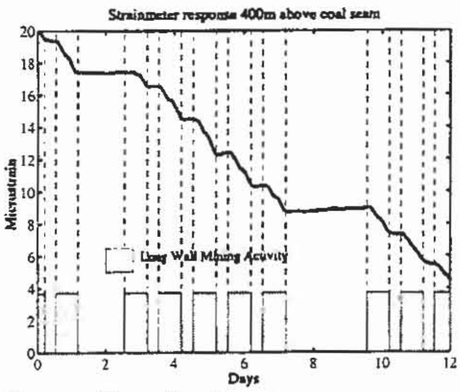

Figure 7. Strainmeter response to longwall mining directly beneath the instrument.

Tiltmeters installed in the instrument provide a measure of earth tilt with a resolution of better than 1 nanoradian. Figure 8 shows North and East tilt records from two observation sites, with the convention is that +ve is a tilt upwards. The data indicate that tilts of order 200 microradians occurred at site 503 during the closest approach of the longwall mining to the instrument site, with a total tilt amplitude change of 400 microradians due to the mining activity, predominantly downwards to the east (along panel). The tilt records are well correlated with the mining process. Tilt changes at site 508 during close longwall operations show remarkably similar behaviour to those observed at site 503. Following completion of panel 508, mining of the relatively distant panel 511 was carried out prior to mining of the adjacent panel 509. Consequently the overall tilt amplitude observed at CAT is higher (of order 600 microradians), again predominantly downwards in an easterly direction. The dam wall site tilt records are constant at these scales.

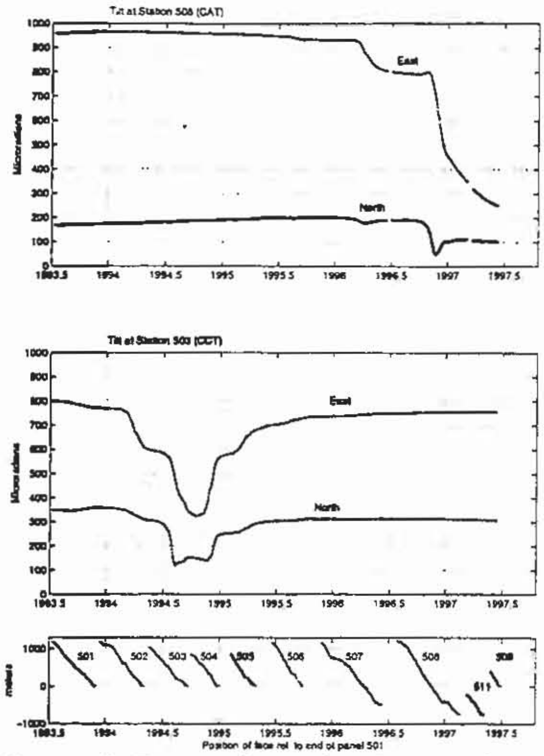

Figure 8:.East and North tilt records at observation sites above panels 503 and 508

The complete tilt data set from panel 503 indicates that significant subsidence induced tilts occurred by longwall activity at least two panels from the measurement site. Large tilts (>400 microradian) occurred during the mining, but returned approximately to initial conditions after two further panels were mined. These plots show that tilt is predominantly influenced by longwall mining of 5 adjacent panels. Detailed investigation of tilt changes as each panel is mined indicates that significant tilt changes occurred 15 days before panel 502 face passed site CCT, and 20 days before panel 503 face passed by CCT. These times indicate that significant tilt changes were initiated when the face position was approximately 180 m ahead of the observation site. Reversal in the azimuth of the maximum tilt direction, with a temporary tilt northwards, are evident each time a panel face passes the observation site, with the exception of panel 502 face

DISCUSSION:

Data from both 503 and 508 sites indicate that, at the measurement depths, horizontal strains of order 100 microstrain are locally associated with the progression of the longwall. These strain estimates are the change of strain state relative to the initial (undisturbed) environment at the beginning of the measurements. The 508 site, mined in November 1996, indicates strains of similar amplitude but different character to those observed at site 503 (mined in mid 1993).

Changes in the strain components (ε_{xx}, ε_{yy} and ε_{xy})as mining is carried out in the preceding panel have differed significantly between the two sites.

- At site CCT (panel 503) there was a significant relaxation of cross-panel strain (ε_{yy}) as the face in panel 502 passed by CCT, and the strain due to the mining of panels 502/503 was essentially cross-panel uniaxial strain (see Figure 4) as expected.
- At site CAT (panel 508), the cross-panel strain (ε_{yy}) decreased (ie added tensional strain) as the face in panel 507 passed by CAT site, and along-panel strain (ε_{xx}) increased (extensional strain). These changes indicate that the strain field associated with the mining of panels 507/508 was essentially shear strain at the observation depth of 90 m (see Figure 9), with directions of maximum shear of approximately 10° and 100° east of North.

Site CAT (508) showed an unexpected decrease in compressional strain as adjacent panels were mined, resulting in an overall decrease of 10 to 20 microstrain, compared to an overall increase of 10 microstrain in compressional strain at CCT (503). It should be noted that these strain changes occur in the presence of a significant lithostatic stress load. At 100 m, this produces compressive strains of order 100 microstrain in the horizontal plane, which increase linearly with depth. Strains from these gravitationally induced horizontal compressive stresses are added to the strain changes observed to determine the total strain field. If the current rate of decrease of compressional strain continues, the site would go into net tension in 10 years.

Tilt signals at the two sites showed similar behaviour at each observation site during the progression of longwalls. Behaviour of changes in the maximum tilt direction varied significantly at the two sites, however both indicate approximately east-west tilting, consistent with the geometry of the panel layout. The tilt changes recorded at site CCT (503) indicate that subsidence close to the surface is predominantly influenced by longwall activity in 5 adjacent panels, with significant tilt occurring at a site directly above a panel when mining operations are approximately 180m from the site.

Strains observed at site 508 during mining of 503 were less than 10 microstrain, and strains observed at 503 during mining of 508 were similarly less than 10 microstrain and indicate the expected strain at a distance of 1 km from the mining operations. Strains observed at the Dam Wall site show mining induced strain effects are of magnitude less than 1 microstrain at this time.

CONCLUSIONS:

Observations of this type allow planning engineers to modify initial mine plan towards higher recovery ratios with the benefit of data on the actual performance of the *in situ* rock. In the case reported here, panel widths were increased by 5% for panels following 507, after the observations from mining of panels 503-506 indicated that strain amplitudes were well below rock failure stress conditions at the observation depth. Information on potential failure of the structure to perform as expected is available in real time through loads imposed on intact remote rock of the creep and plastic deformation of the material very close to the mine workings. Thus optimal stability performance of the mine plan can be achieved.

The results from this case study indicate that the BTSM instruments may have a useful contribution to monitoring rock mass deformation in situations such as the following:

- Long term monitoring of ground deformation in the vicinity of surface mine infrastructure, buildings, pumping stations etc. which are are at a distance of 100's of meters to some kilometers from the mining operation
- Long term monitoring of viability of underground infrastructure, eg. Hoisting and ventilation shafts, declines, large voids such as workshops, crushing excavations, etc.
- Monitoring of deformation of the rock mass separating multiple coal seams during coal extraction, providing engineering data for use in planning extraction of overlying or underlying seams.
- Measurement of slope stability in deep pit mines, for example incircumstances where the pit wall surface is decoupled, and monitoring of changes in deformation at distance from the operation
- Optimisation of pit slope by measurement of actual performance with slope modification.

In summary, the extremely high sensitivity of the BTSM instrument enables remote monitoring of deformation, with no disturbance to mining operations. The high stability of the BTSM measurements provides reliable data over a long timescale in cases where mining operations extend over a number of years.

ACKNOWLEDGEMENTS

The authors acknowledge funding support for this research from Bellambi Collieries Pty. Ltd. We thank Terry Cheeseman of Sydney Water for his ready assistance in field maintenance, and Mark Kochanek and Zak Jecny of CSIRO Exploration and Mining for assistance during installation and field repairs.

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DIRECT OBSERVATION OF LONGWALL CAVING WITHIN THE OVERBURDEN

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Coffey has for several years been involved in longwall mining above old mine workings at a Hunter coal mine. The current mining horizon is only 35m to 40m above the old workings consisting of pillar extractions as well as longwall panels. It is believed that this mining configuration, as illustrated in Figure 1, is presently the only case in Australian underground coal mines, and it provides an excellent opportunity to characterise directly and systematically mining-induced deformations and fractures within the overburden.

The underground mapping of mining-induced fractures and strata deformations caused by mining at the lower level is part of the strata management plan at the current mining horizon. Figure 1 illustrates a bending zone associated with the goaf edges or remnant pillars in the underlying mine layout. The underground mapping of roadways at the current level has found that the bending zones differ from other sections of the roadways by showing the development of bending strata and *open* defects, including bed separations, tensile and shear fractures and re-activated joints. Water inflow was also observed resulting in weakening of strata. Importantly, the mapping has been carried out to calibrate the numerical values of angles α and β (Figure 1), against the variations in rock strengths and other geological factors, as well as the geometric configurations of the underlying mine layout. This is one of the key issues for the success and efficiency of the strata management plan implemented by the mine.

Bending zones were clearly observed underground, and roadways located in the bending zone showed bedding planes coated with carbonaceous materials and newly formed fractures and re-activated open vertical joints forming unstable blocks in the roof, requiring specifically designed roof support.

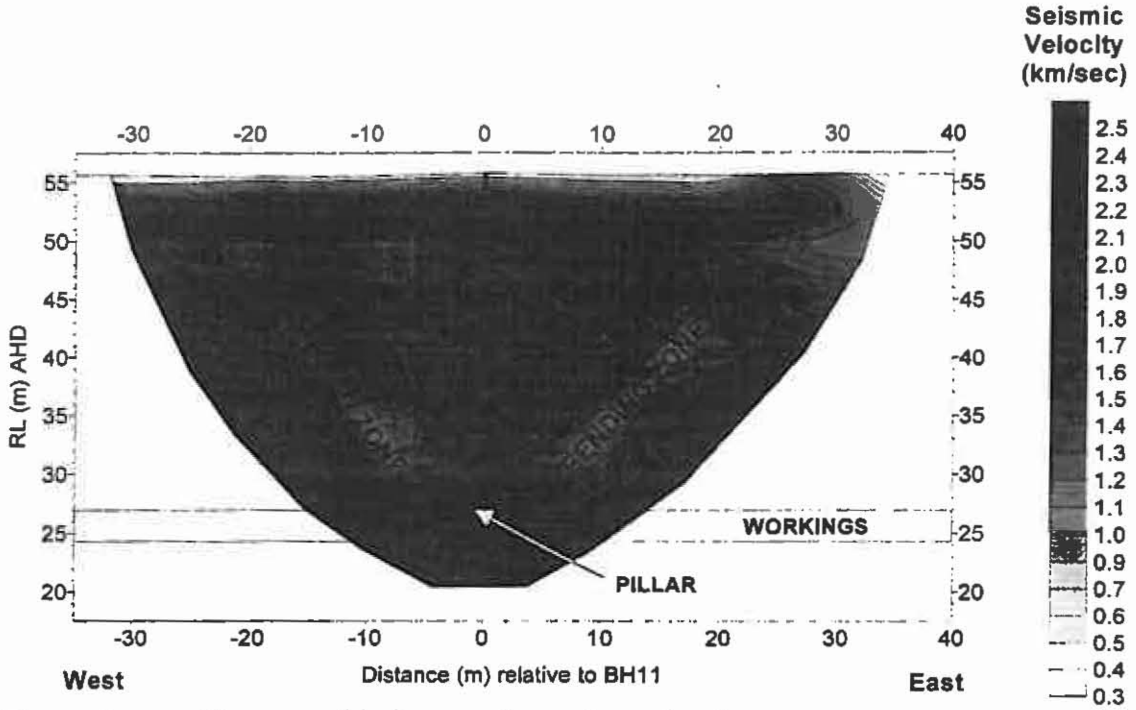
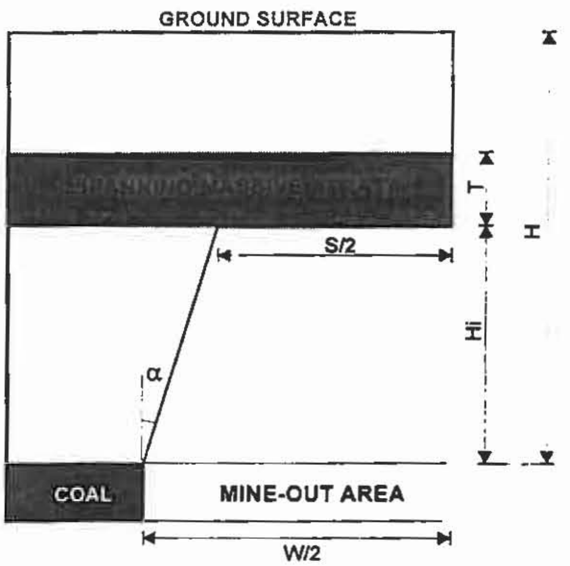


Figure 2 Tomographic image of caved overburden



W = Extraction Width
S = Spanning Distance
H = Depth of Cover
T = Thickness of Massive Unit
Hi = Interburden Thickness between Massive Unit and Seam

Figure 3 Geotechnical model for spanning distance

Coffey's subsequent work on other sites has also indicated the existence of the bending zone, as illustrated by the Tomographic Image in Figure 2.

The angle α (Figure 1) provides important information for the occurrences of longwall caving, and it can also be used for the characterisation of zones with concentrated open fractures, which may act as a conduit for water inflow. Figure 3 demonstrates another application of angle α with regard to the impact of massive strata on surface subsidence occurrences. If the massive strata, such as the conglomerate found in the Newcastle Coalfield or the basalt flows in Bowen Basin, are sufficiently strong and thick, they may span across the extracted panels, resulting in much reduced surface subsidence. However, due to the inevitable variations in rock strengths, strata thickness and defect characteristics, the development of spanning strata can be highly variable, leading to irregular surface deformations such as localised high strain concentrations, which are difficult to predict. Consequently, the spanning strata are often considered as a risk to the management of subsidence. The spanning distance, a key input parameter for spanning analysis, of a massive unit can be calculated based on the geotechnical model presented in Figure 3. The establishment of the spanning distance then leads to the assessment of areal distribution of spanning strata over the extracted longwall area, based on the well established Voissoir Beam Method.

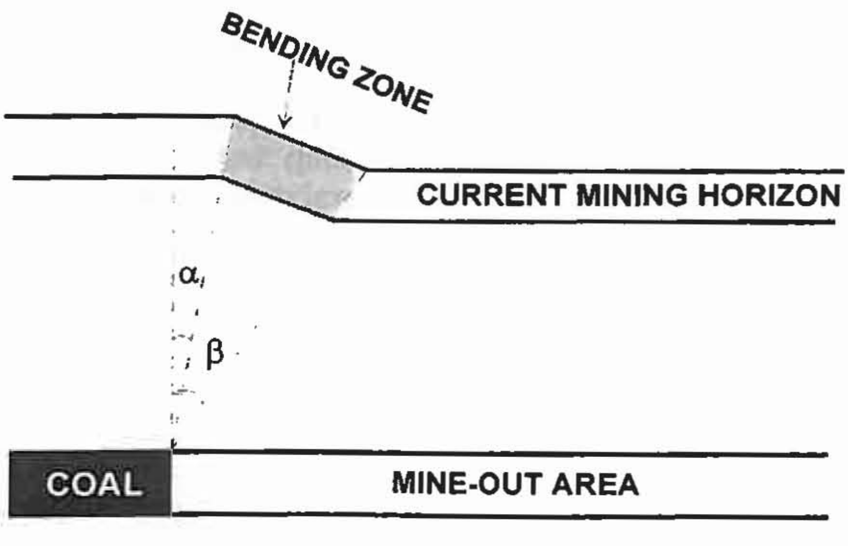


Figure 1 Strata bending associated with goaf edges or remnant pillars in underlying workings (not to scale)

ROOF ROLLS, CLAY DYKES AND RELATED FEATURES IN THE BULLI SEAM, BURRAGORANG VALLEY MINES, NSW

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INTRODUCTION

While up to 8 coal mines were operating in the Burragorang Valley area during the early- and mid-70's (15), there are now only 2 mines left, the Oakdale and the Brimstone Mines, both operating in the Bulli Seam.

Apart from quality control problems to keep up with the ever-changing requirements of the market place, both mines have also some localised gas drainage and strata control problems, and thickness variations over short distances may cause budgeting problems. Strata control, however, is -in general- less of a problem than it is in most South Coast mines, at least in recent and current workings.

The author has been involved in geological mapping and quality control at the Oakdale Mine only, but archives inherited from the "Clutha period" suggest that both mines, and also the now-closed Nattai Bulli and Nattai North Collieries, share a common geology, hence they must also share (or must have shared) often common problems or, at least, similar sets of actual and potential problems.

In Oakdale Colliery, current geological and operational problems are linked to the presence of a small number of sandstone channels in the roof (often accurately predictable), minor faulting (both normal and reverse), igneous dykes and sill/cinder areas, monoclines, swillies, a very variable top coal ply causing abrupt thickness variations and, finally, a number of injection features occurring in the top part of the seam: pillow structures, clay dykes, intermediate features globally described as *roof rolls* or *clay rolls*, and clay layers or masses (clay sills) injected into bedding planes. Such injection features occur seldom randomly; they are usually in the form of swarms confined to areas of variable dimensions and shapes, starting and ending abruptly.

This paper summarises the results of a 2-year effort in observing and plotting various injection features occurring in recent and current workings of the Oakdale Colliery. Additional observations were also carried out in still accessible parts of old workings (main access and transport roads and some returns), but data thus obtained are only partly useful, mainly for limited statistical purposes. It must be stressed that all injection features at Oakdale Colliery originate in roof strata. This contrasts sharply with our previous observations in some South Coast mines where such features almost always originated in the floor strata (1-3).

Though various injection features occur in all *'Valley Collieries'*, according to verbal communications, and occasionally cause major strata control- and dilution problems, we could find no mention of these features in Colliery reports[1] and mine plans, or in publications dealing with the geology of any of the Burragorang Valley mines, and this is one of the main reasons leading to the presentation of this paper.

The paper does not deal with the topic of the formation process and age of injection features, about which a number of publications **(7-11)** could provide a number of likely scenarios. Our emphasis is going to be on their distribution pattern, directional and dimensional characteristics, and their effect on mining.

SETTING

The study area is located 21km W-NW of Camden. The general geology of the area, as described and interpreted by McLean and Wright **(15)** is still valid. The area where we proceeded to underground mapping is broadly located between 1228000 -1233000 N, and 252000-256000 E.

No general map of main geological features (dykes, faults, monoclines, etc) is appended, as only the structures affecting our main study area are considered as relevant (Fig.2).

Only one minor fault is known in the area, striking 335°[2]; two directions of igneous intrusions follow 065° and 100° directions. The main monocline directions in the general area vary between 330° and 345°; the same applies to major swilley axes.

Gradient

The average gradient is 1 in 20, i.e. less than 3°. The apparent direction of dip is 087° in the general area.

Joints in immediate roof

Most roof joints are vertical or sub-vertical, except in the vicinity of major structures, and often occur in swarms. Dominant strikes are 005°-015° in the eastern workings, and 335 ° -350° in western workings. Locally the N-NW trending joints may delineate small-scale grabens (often ≤ 0.2m), over short distances. The general range of variations for the Colliery Holding appears to be 327°-028°.

Stress régime

The latest measurement of stress orientation in Oakdale Colliery by Schmidt **(22)** suggests an average 120° (WNW-ESE) direction for σ_1, without providing any indication on the magnitude of the horizontal stresses. CSIRO **(12, 14)** and ACIRL reports **(18)** indicate a great variability of the bearing of σ_1, emphasizing that the virgin stress geometry was affected by geological structures in the workings, a remark that is supported by Schmidt's measurements along the two sides of a likely fault/monocline axis at Oakdale.

Magnitudes for σ_1 values determined by CSIRO for Nattai North and Nattai Bulli areas vary between 18.0MPa and 22.6MPa. Lower values reported in the same reports

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[1] Except in one hand-written report by P. Temby, dated 3.7.95 where there is a mention of *stone dykes* between C15 and C16 of 500 panel, and also of thrust (?) planes and associated slickensides elsewhere in the same panel

[2] All mentioned directions are magnetic

relate to particular topographies. It is fair to assume a maximum horizontal stress (ζ_1) value of 20.5 MPa ± 2MPa for the general area around the Oakdale No.3 Shaft, with local variations for geological structures, roof lithology, and surface topography.

BULLI SEAM

Seam thickness in recent and current workings of the Oakdale Colliery varies between 1.5m and 2.6m, but main variations occur between 1.9m and 2.4m. McLean and Wright (*op.cit.*) believe that such fluctuations are caused by the lensoid configuration of dull coal components, but massive washouts by Triassic sandstone channels are also present, and we believe that the nature of the coal/roof contact in shale/mudstone roof areas is also significant in explaining disparate thicknesses measured in some contiguous boreholes. This contact may be planar, undular, flammate or botryoid. As a result, the uppermost 0.15 to 0.25m of the average seam section may be coal or stone or a mixture of both.

Roof

Sandstone roof is an exception in recent and current workings and, currently, occurs in the form of a 80 to 130m wide channel. Over the rest of the area the immediate roof is formed by a variable thickness (0 to 5m) of mudstone/claystone/shale/siltstone sequence underlying the sandstone, according to bore logs. Logs describe the roof as *'shale grading up to siltstone'* in one borehole, *'carbonaceous shale and claystone'* in another hole, and *'siltstone grading up to siltstone'* in a third hole, all holes being situated within and around the current southwestern development district. Our own observations suggest that a mudstone (hard, sandy, carbonaceous at base, grading up to a siltstone) is the most common roof type in the area. This mudstone usually displays a block- or conchoidal fracturing, when not affected by swarms of joints.

Roof conditions are generally very good, except along axes of major swilleys, in fault zones, over major sill/cinder areas, and along axes of major clay dykes, usually described as roof rolls, as these dykes never extend below mid-seam.

Floor

Coaly/carbonaceous shale, occasionally containing coal laminae or coaly shale phases forms the immediate floor for a thickness seldom exceeding 0.5m. More usually, this coaly/carbonaceous sequence is about 0.15m thick and included in the working section by some geologists, while excluded by some others. It is underlain by a variable thickness of siltstone grading down to a sandstone.

Minor floor heave has been observed, sporadically and along short stretches, in both headings and cut/throughs, and at intersections. Whereas the phenomenon is more readily explainable in sandstone roof areas (extra load on pillars transferred to floor), it may be that mining practices are sometimes directly responsible for the initiation of the process, especially where floor is excessively mined in thin seam areas. It should also be noted that roof rocks at Oakdale are much stronger than floor rocks: UCS 36-124MPa for roof rocks; 27-81MPa for floor rocks. Coal strength varies between 13.4MPa and 31.5MPa (**20**).

Cleats

The average cleat pattern is formed by the conjugate sets 312° and 043°. The first set represents the *'face cleat'*, and the second, the main *'butt cleat'*. There are numerous other, minor cleats (**4**).

The strike of the face cleat varies between 282° and 340° in the panels situated around and to the east of No.3 Shaft, the higher values occurring at the eastern edge of workings.

ROOF IRREGULARITIES / INJECTION FEATURES

Description

There are no sedimentary or tectonic floor rolls or drainage channels at Oakdale Colliery. Clay dykes and sills, roof rolls (massive clay sills confined to the immediate roof area), clay wedges, pillow structures (usually flat- or convex-bottomed incursions of the immediate roof in top coal, circular or elliptic in shape), and various transition forms between coal and roof are very common, though not all together.

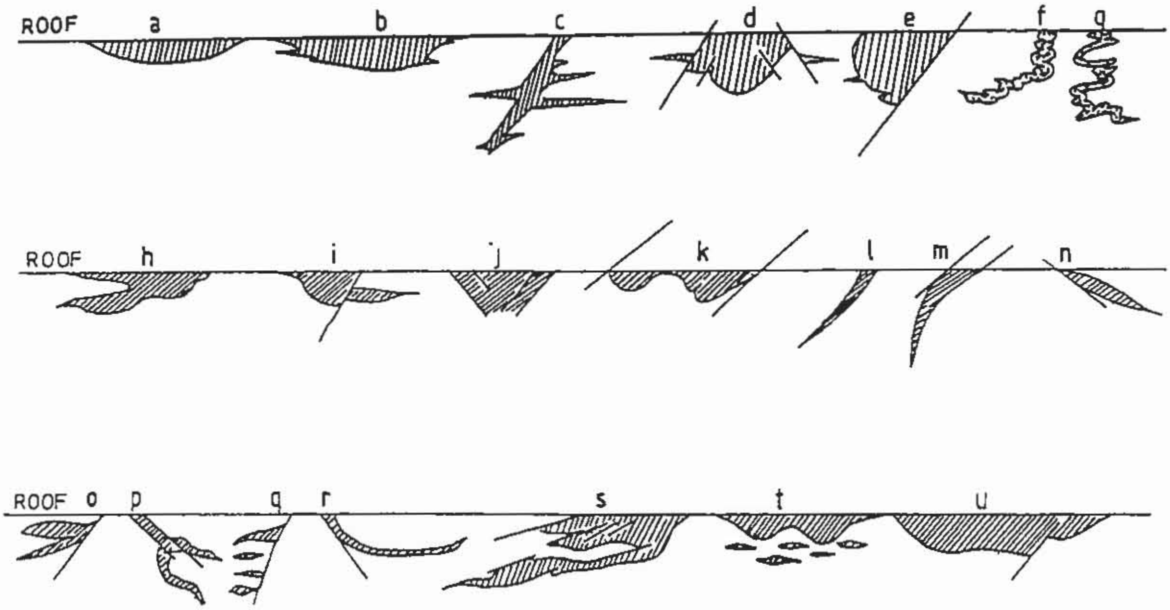

Fig. 1 - Current types of clay injection features and pillow structures (a-g idealised types; h-u examples from Oakdale Colliery - Bulli Seam)

a-b pillows; **c** clay dyke and sills; **d-e** roof rolls; **f-g** contorted dykes; **h** 500 panel, 40m i/b B4, E rib; **i** 500 panel, 30m i/b B4, E rib; **j** 500 panel, 12m i/b B1, E rib; **k** 500 panel, D18, opp.C/T; **l** 500 panel, ½ way C16 to B16, N rib; **m** 600 panel, D2 to E2, W rib; **n** 600 panel, D7 to E7, E rib; **o** 500 panel, 8m i/b A22, W rib; **p** 500 panel, 45m i/b A21, W rib; **q** 500 panel, A21 toB21, 3m on S rib; **r** 25m i/b A19, W rib; **s** 20m i/b B4, E rib; **t** 350 panel, Track Rd, 10m i/b C/T 3; **u** 300 panel, 50m i/b AA15, E rib (Scale appr. 1:100)

Apart from what we called 'pillows' or 'cushions', all rolls, clastic dykes, sills and wedges are injection features originating in roof strata. A capital observation about injection features at Oakdale Colliery is that not a single one reaches the floor, whereas clay dykes originating in floor rocks, at South Coast collieries, often reach the roof and form a massive roof rolls between coal and the *in situ* roof strata (**1, 2**).

We had much difficulty in attributing names to various injection features, as original descriptions for types do not always fit what is actually observed, be it dimension-wise or lithology-wise. Thus the term *'pillow structure'*, as described by Diessel (**10-11**) should belong to *"bodies of sand in a matrix of clay or silt... rang[ing] in size from a few centimetres to several decimetres"*. We use the same term on a morphologic basis only; no sandstone is involved; the matrix is coal, and there is [often] no separation of the protrusion from the layer above. The pillow structures we showed on our plans all have apparent diameters exceeding 1m, often varying between 2 and 5m.

Terminology is a real problem (6-8, 23), as even the terms *clay dyke / stone dyke / clastic dyke* do not seem to have a general acceptance. As for the term *roof roll*, this may describe totally unrelated features for various authors (2, 13, 22).

The term *stone intrusion* used by Ward (21) might be a good all-round word, provided it be qualified by some additive specifying its mode of formation: gravity, injection, etc. Thus pillows would be gravity formations, originating in the immediate roof layer, whereas [other] injection features have their origin in layers higher up in the strata succession, at least at Oakdale.

Fig.2 illustrates a selection of roof irregularities (features) observed at Oakdale, as they appear on ribs, after the passage of the continuous miner, or at the face, during extraction. This selection represents only a fraction of the actual variability observed. On the mining roof, the only reminder of the mass that has been mined is an inverted V (i.e. Λ), often asymmetric in section, with slickensided surfaces, and filled by coal, followed by a rough zone corresponding to the trace of the actual intrusion line. This trace may be a few centimetres in width for small rolls, but may exceed a metre for large ones, in which case it is delineated by inverted V's on both sides, indicating that the roll has -in section- a conical part in the immediate roof strata. Long or short slickensided marks in roof overhead are the proofs of clay dykes and roof rolls that have been mined, even when such features are not directly observable on ribs due to repeated stonedusting. The coal filling of the inverted V's falls during, or shortly after mining.

The difference between pillows (mainly gravity features) on the one hand, and clay dykes and roof rolls (injection features) on the other hand, can be readily made depending on whether or not a slickensided trace is present in the roof.

Most clay dykes are low-angle features ($\simeq 30^{\circ}$) and extend rarely to half-seam level from the roof, that is about 1m. Most do not exceed 0.5m in depth. The width of clay dykes varies between a few centimetres and a few decimetres, whereas what we call roof rolls may be a few metres long and up to a metre in depth. Intrusions into bedding planes almost always have a visible connection with a dyke or roll; even without this connection they are readily recognisable by their light colouring and relative softness.

Clay dykes in some areas are almost exclusively of the 'contorted' type, simulating worm borings or squeezed tooth paste. Considering that, in some other areas, clay dykes may have a contorted aspect on one rib, and a planar shape on the other rib, it all comes to the relative thickness of the clay material reacting to compaction.

Areal Distribution and Frequency

All accessible roadways between the No.1-2 and the No.3 Shafts (distance $\simeq$ 4.5km, in a NW-SE direction), and between north and southern boundaries of the Oakdale Colliery Holding (distance $\simeq$ 4.2km) have been inspected. Eastward development workings in 300- and 600 panels, each extending $\simeq$ 1.2km, have also been mapped. Nearly 2000 intersections of clay dykes and roof rolls have been plotted on district plans, together with over 150 pillow structures. 890 injection features and 112 pillows were within a 2km radius from the No.3 Shaft; these were re-inspected for size measurements and to ascertain their nature, trend and continuity. Fig.2 shows the features observed in panels around No.3 Shaft.

A very high concentration of injection features was found in some panels or parts thereof (e.g. 200- and 500 panels), gradually or abruptly passing to areas devoid of such features (e.g. parts of 600-, 300-, LW5 panels). In some other areas all we could observe were pillow structures. The current gradient (and direction of dip) of strata, and depth of cover can provide no clue to the reason of this sporadic occurrence, though we assume that "*these structures are parallel to the tension joints of the affected area, which means that such joints have been formed early, when the injected material was soft and had a high water content*" (**11**, p.296).

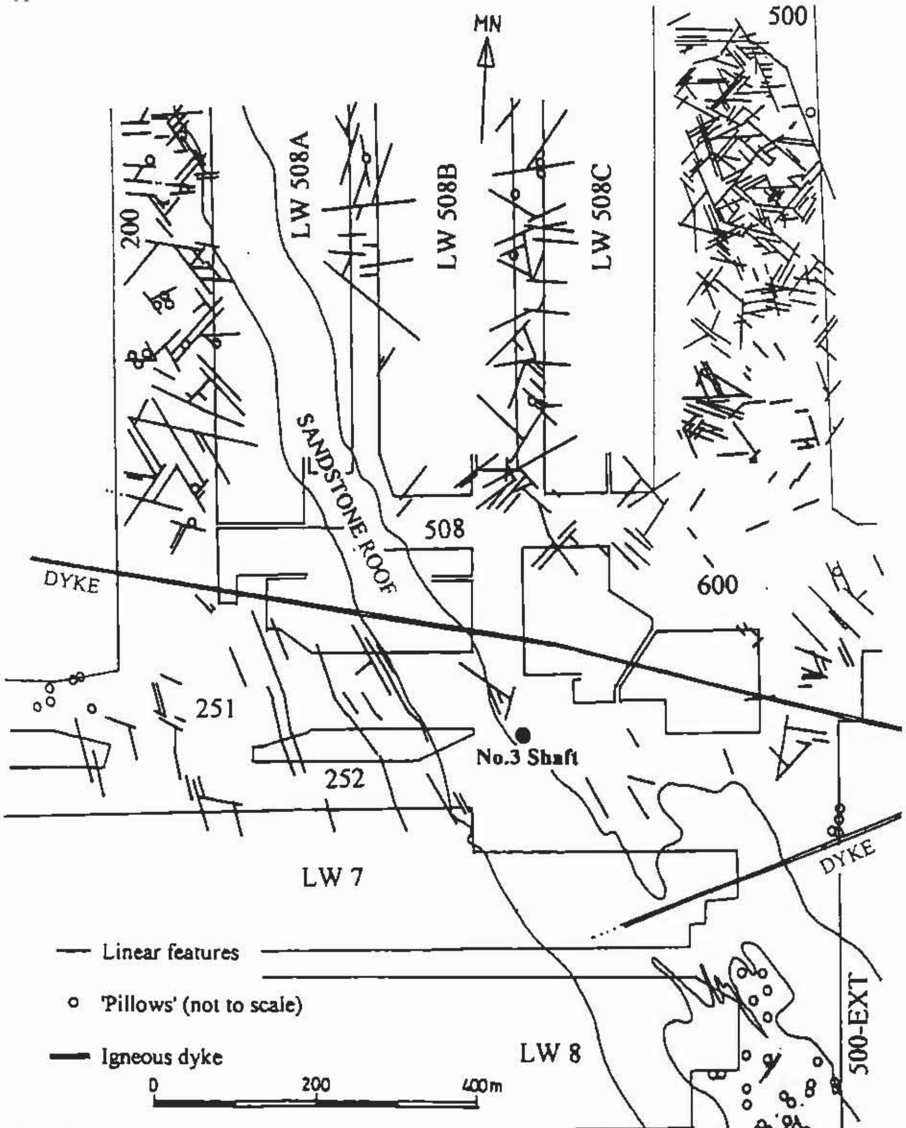

Fig. 2 - Linear injection features (Clay dykes and roof rolls) and gravity structures (pillows) in panels around No.3 Shaft - Oakdale Colliery

. To give some examples, the average frequency of injection features is 14/100m (i.e. one feature every 7m) in a 290m section of the track road in 500 panel; this section is bordered to the north by a zone totally free of similar features, and to the south by a zone where the frequency is 2/100m (i.e. one feature every 50m).

Dimensions

A diagram has been prepared to illustrate the length of linear features (clay dykes and roof rolls), suggesting that, at Oakdale Colliery, an average dyke or roll has a length of 36m, the measured extremes being 5m and 315m (Fig.3). The ratio of injection features longer than 100m is only 2.5%, while about 70% of all rolls and dykes have lengths varying between 10 and 50m. No valid results could be obtained as to the width and depth of injection features, as these were found to be very variable over short distances.

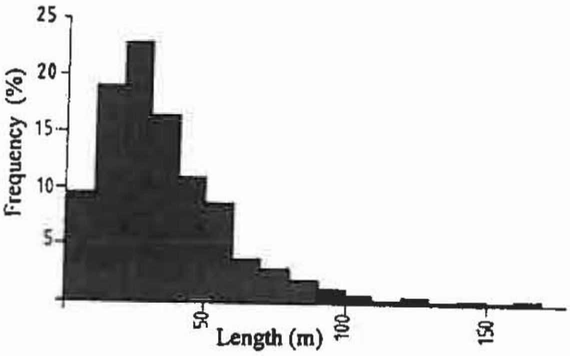

Fig. 3 - Length variations of injection features

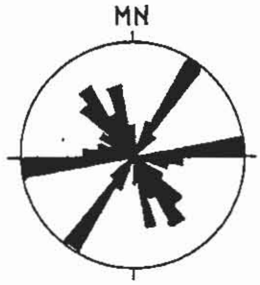

Fig. 4 - Bearings of injection features (10° intervals; full circle 15 %)

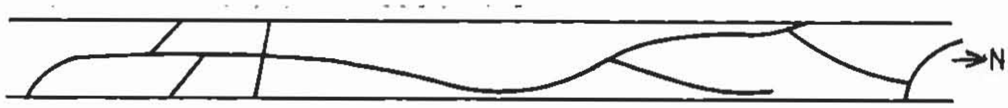

Fig. 5 - Example of the undulating nature of slickensides on the roof marking the presence of clay dykes and roof rolls: a 60m portion of the first N-S heading situated to the east of No.2 Shaft. Projections of slickensides on the floor are shown. Intersections between slickensides and rib lines represent the locations of injection features (Scale 1 : 500).

Directional trends

Fig.4 summarises the directional trends measured. The straightness of a so-called linear feature is only a matter of scale, and Fig.5 illustrates the real shape of traces of clay dykes and roof rolls (slickensides) as they appear in the roof strata. For statistical purposes, the angle of an imaginary straight line joining the same feature observed on the two ribs or, the position in one rib and the terminal point of the corresponding roof mark were used to measure the bearing. Dominant trends appear to be 035°, 091°, 137° and 165°. The last two directions are roughly the same as those of dominant roof joints, whereas the first two directions correspond, maybe fortuitously, to the trend of the main igneous intrusions. No specific study has yet been carried out to determine whether all injection features observed are of a same age.

Effects on mining

Only a small percentage of roof rolls and clay dykes are of a size to have a noticeable effect on mining operations. There were instances, however, when very large rolls appeared as 'faults' at the face, causing very difficult roof conditions through tens of metres of drivage. Otherwise their only practical effect is to reduce plant yields by 1 to 3% over a short period of time as areas with swarms of large features are of relatively small size. Rolls may be hard, but easy to mine as they have a tendency to detach from the roof, and dykes are easy to mine because of their softness. Their appearance, softness and colour are so similar to those of weathered igneous dykes that, in some instances, they were mistaken for igneous dykes and plotted as such on district plans.

CONCLUSIONS

This study is only meant to be a 'starter' for further studies with the aim of explaining the areal distribution of clay intrusions, and their localisation in the top part of the seam. The relative age of their formation may be another interesting topic. One possibly useful clue for this last topic is that no sandstone intrusions occur in sandstone roof areas. A very small number of 'relics' of roof rolls shown on Fig.2 are all clay structures, not entirely eroded by the Triassic channel.

ACKNOWLEDGEMENTS

The author is indebted to Oakdale Collieries Pty Limited for the permission to publish this paper, and to Mr. Phillip Wakeford, Mine Manager, for his support .

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THE WOLLOMBI COAL MEASURES

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INTRODUCTION

The Wollombi Coal Measures crop out in the northern part of the Sydney Basin (Figure 1). They conformably overlie the Wittingham Coal Measures and underlie the Triassic Narrabeen Group (Table 1), and comprise conglomerate, sandstone, siltstone, shale, tuff, claystone, and coal. The Wollombi Coal Measures has a thickness of 274.17 m in its type section in DM Doyles Creek DDH 11 and reaches a maximum recorded thickness of approximately 335 m.

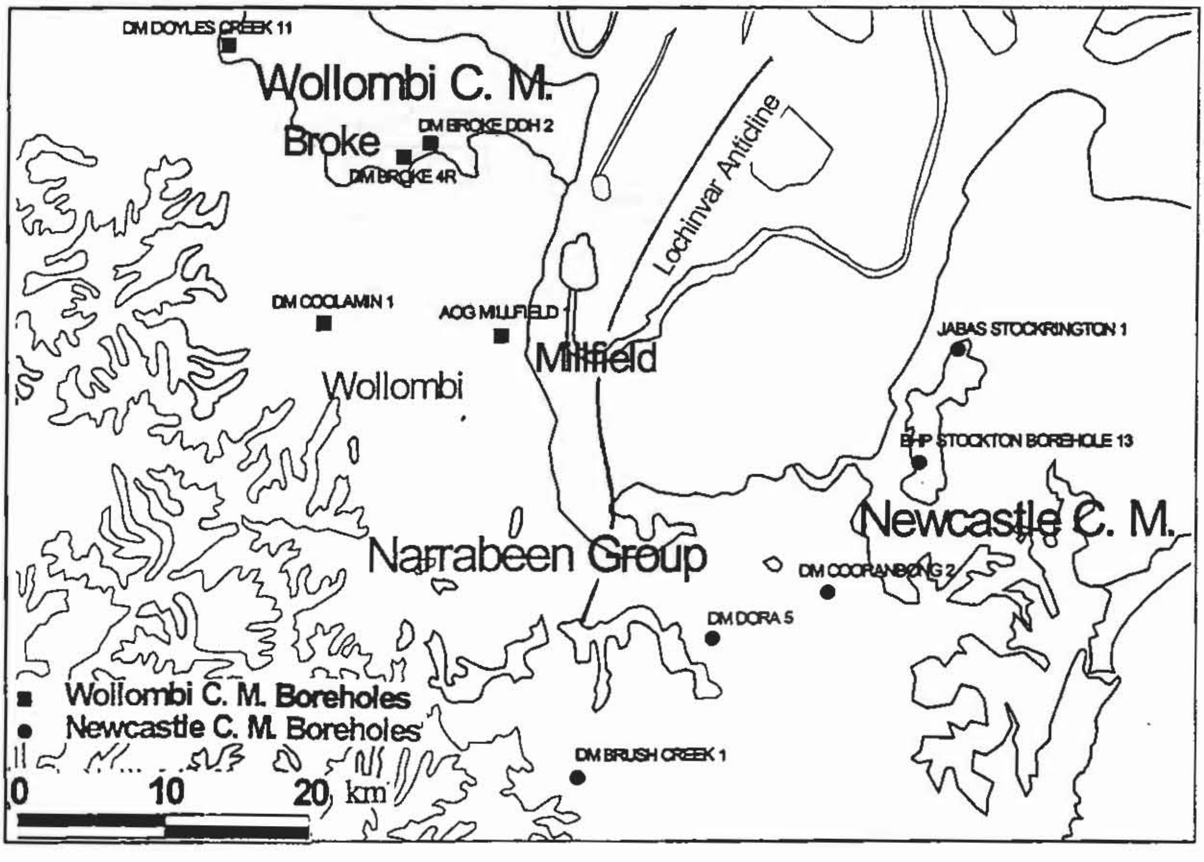

Figure 1. Northern Sydney Basin

The stratigraphy of the Wollombi Coal Measures was formalised by the Standing Committee on Coalfield Geology of New South Wales (1975). The coal measures were subdivided into five major units: the Watts Sandstone, and the Apple Tree Flat, Horseshoe Creek, Doyles Creek, and Glen Gallic Subgroups. The subgroups were further subdivided into formations, which in turn were subdivided into rock units with member status.

Drilling by the NSW Geological Survey in the Broke area during 1996 / 97 has provided further information on coal seam development within the Wollombi Coal Measures.

This paper proposes that consideration be given to either redefining the stratigraphy of the Wollombi Coal Measures by elevating several tuffaceous horizons to formation status, or entirely replacing Wollombi Coal Measures nomenclature with Newcastle Coal Measures nomenclature.

Narrabeen Group			
Wollombi Coal Measures	Glen Gallic Subgroup	Greigs Creek Coal	
		Redmanvale Creek Formation	
		Dights Creek Coal	Hillsdale Coal Member
			Nalleen Tuff Member
			Hobden Gully Coal Member
	Doyles Creek Subgroup	Waterfall Gully Formation	
		Pinegrove Formation	Hambledon Hill Sandstone Member
			Wylies Flat Coal Member
			Glengowan Shale Member
	Horseshoe Creek Subgroup	Lucernia Coal	Eyriebower Coal Member
			Longford Creek Siltstone Member
			Rombo Coal Member
			Hillside Claystone Member
			Carramere Coal Member
		Strathmore Formation	
		Alcheringa Coal	
		Clifford Formation	
	Apple Tree Flat Subgroup	Charlton Formation	Stafford Coal Member
			Monkey Place Creek Tuff Member
		Abbey Green Coal	
	Watts Sandstone		
Wittingham Coal Measures		Denman Formation	

Table 1. Stratigraphy of the Wollombi Coal Measures

PREVIOUS STUDIES

Since early this century exploration drilling has intersected parts of the Wollombi Coal Measures, although most boreholes have targeted the Wittingham Coal Measures.

In 1981 the NSW Department of Mineral Resources conducted the Wollombi Coal Drilling Programme in an area encompassing the towns of Broke, Wollombi and

Millfield specifically targeting the Wollombi Coal Measures. The programme comprised the drilling of three boreholes, of which only DM Coolamin DDH 1 obtained a full intersection of the Wollombi Coal Measures. The Wollombi Coal Drilling Programme identified an inferred coal resource in what was thought to be the Greigs Creek Coal in the Broke-Wollombi-Millfield area.

Baker (1987) proposed the drilling of three boreholes in the vicinity of Broke around the periphery of the Triassic escarpment to obtain further intersections of the Wollombi Coal Measures.

No interest was shown in the Wollombi Coal Measures until the 1996 / 97 Broke Drilling Programme. The general consensus of most workers was that apart from the area between Broke and Millfield the Wollombi Coal Measures were an uneconomical interval that was intersected in drillcore prior to reaching the proven coal resources of the underlying Wittingham Coal Measures.

THE 1996 / 97 BROKE DRILLING PROGRAMME

Following a review of the Wollombi Coal Measures in the Broke / Wollombi / Millfield area the NSW Geological Survey decided to conduct further exploration around the edge of the Triassic escarpment in the vicinity of Broke. Drilling commenced in August 1996 and was completed in January 1997.

The primary aim of the Broke Drilling Programme was to obtain further intersections of what was thought to be the Greigs Creek Coal near Broke. Four boreholes were subsequently drilled of which DM Broke DDH's 2 and 4R obtained complete intersections of the Wollombi Coal Measures.

After the completion of the first borehole it was realised by the author that the uppermost seam intersected was the Hillsdale Coal Member, not the Greigs Creek Coal as was previously thought. A tuffaceous unit underlying the Hillsdale Coal Member was identified as the Nalleen Tuff Member and seam number two identified as an upper split of the Hobden Gully Coal Member. The similarity of this interval with the upper parts of the Newcastle Coal Measures was also observed.

The Hillsdale Coal Member, Nalleen Tuff Member, and Hobden Gully Coal Member are now considered by the author to be respectively equivalent to the Wallarah / Great Northern seam, Awaba Tuff, and Fassifern seam found in the Newcastle Coalfield. The overlying Greigs Creek Coal is therefore probably equivalent to the Vales Point seam.

STRATIGRAPHY

The stratigraphy of the Wollombi Coal Measures was formalised by the Standing Committee on Coalfield Geology of New South Wales (1975). The stratigraphy of the Wollombi Coal Measures is also discussed in several publications including, Beckett (1988), Sniffin and Beckett (1995), Stevenson et al. (1998) and Stevenson (1999).

Watts Sandstone
The Watts Sandstone is the basal unit of the Wollombi Coal Measures. It comprises fine to coarse grained sandstone which is typically massive and moderately well sorted in parts. It is conformable with the underlying Denman Formation and the overlying Abbey Green Coal. The Watts Sandstone has a thickness of 25.6 m in its type section and reaches a maximum thickness of approximately 36 m.

Apple Tree Flat Subgroup
The Apple Tree Flat Subgroup is subdivided into the Abbey Green Coal and the Charlton Formation.

The Abbey Green Coal, is conformable between the Watts Sandstone and the Monkey Place Creek Tuff Member. The unit generally comprises two coal seams separated by interlaminated sandstone and siltstone. Both seams are mostly dull to dull and bright, grade to carbonaceous siltstone in parts, and have tuffaceous bands. The Abbey Green Coal has a thickness of 7.44 m in its type section and reaches a maximum recorded thickness of 21.49 m in AOG Millfield DDH 1. The Abbey Green Coal lenses out to the southwest of Broke as basal horizons progressively disappear from the unit. In DM Coolamin DDH 1 the entire unit is not developed.

The Charlton Formation comprises the Monkey Place Creek Tuff Member overlain by several metres of interlaminated to interbedded sandstone, siltstone, and claystone, which in turn is overlain by the Stafford Coal Member. The Monkey Place Creek Tuff Member is a buff coloured, silt size to medium grained, biotite rich tuffaceous unit. In the vicinity of Broke the unit ranges in recorded thickness from 1.41 to 1.89 m and reaches a maximum thickness of 6.55 m in its type section. The progressive loss of basal units within the Wollombi Coal Measures towards the southwest, indicates that the Monkey Place Creek Tuff is likely to directly overlie the Watts Sandstone at some point between Broke and DM Coolamin DDH 1. The Stafford Coal Member comprises interbanded inferior coal, carbonaceous shale and tuffs, and has a thickness of 2.58 m in its type section. In the vicinity of Broke a seam split develops and thickens to the south. The maximum thickness of the Stafford Coal Member is in the order of about 10 m near Millfield.

Horseshoe Creek Subgroup
The Horseshoe Creek Subgroup is subdivided into the Clifford Formation, Alcheringa Coal, Strathmore Formation, and the Lucernia Coal. The Lucernia Coal is further subdivided into the Eyriebower Coal Member, Longford Creek Siltstone Member, Rombo Coal Member, Hillside Claystone Member, and Carramere Coal Member.

The Clifford Formation comprises interlaminated to interbedded sandstone, siltstone, tuff and coal, and reaches a maximum recorded thickness of 56.38 m in its type section.

The Alcheringa Coal comprises coal and interbedded sediments and has a thickness of 14.36 m in its type section. The Alcheringa Coal is the lowermost of two easily recognisable thick coal bearing intervals in the Wollombi Coal Measures.

The Strathmore Formation comprises interbedded to interlaminated sandstone, siltstone, and conglomerate, with minor tuff and coal. It has a thickness of 20.71 m in its type section and ranges in thickness from about 22 to 31 m in the Broke area.

The Lucernia Coal is the uppermost of two easily recognisable coal bearing horizons within the Wollombi Coal Measures and comprises several interbedded coal and tuffaceous phases separated by intervals comprising interbedded to interlaminated sandstone and siltstone. It has a thickness of 18.02 m in its type section.

Doyles Creek Subgroup

The Doyles Creek Subgroup is subdivided into the Pinegrove and Waterfall Gully Formations.

The Pinegrove Formation comprises tuff, sandstone, shale, and minor coal, and attains a maximum recorded thickness of 44.55 m in its type section. The formation is divided into the Glengowan Shale Member, Wylies Flat Coal Member, and the Hambledon Hill Sandstone Member. The Glengowan Shale Member, which has a thickness of 16.21 m in its type section comprises interbedded to interlaminated sandstone and siltstone with minor conglomerate. The Wylies Flat Coal Member comprises inferior coal with tuffaceous bands and has a thickness of 5.32 m in its type section. In the Broke area the Wylies Flat Coal Member generally comprises two coal beds, both less than 0.5 m in thickness, separated by a tuff and an interbedded to interlaminated sandstone and siltstone phase. The lower seam comprises the brightest lithotypes. The Hambledon Hill Sandstone Member comprises interbedded to interlaminated conglomerate, sandstone, siltstone, and minor tuff, and has a thickness of 22.71 m in its type section.

The Waterfall Gully Formation comprises shale, carbonaceous shale, and tuffaceous claystone. It has a maximum recorded thickness of 13.72 m in its type section.

Glen Gallic Subgroup

The Glen Gallic Subgroup is subdivided into the Dights Creek Coal, the Redmanvale Creek Formation, and the Greigs Creek Coal. The Dights Creek Coal has been subdivided into the Hobden Gully Coal Member, the Nalleen Tuff Member, and the Hillsdale Coal Member.

The Hobden Gully Coal Member comprises two or more coal seams separated by generally interbedded to interlaminated sandstone and siltstone. The coal member reaches a maximum recorded thickness of 22.8 m in its type section. The upper coal split, called the Hobden Gully seam (Stevenson et al., 1998), reaches an economically mineable underground working thickness between about Denman and just south of Broke, where a thickness of 3.43 m is recorded. The Hobden Gully seam has a very distinctive profile, with a general trend of an upward reduction in brightness and coal quality and the presence of three tuffaceous units to about 0.15 m in thickness in the upper parts of the seam.

The Nalleen Tuff Member comprises tuff and tuffaceous sandstone, siltstone, or claystone and has a thickness of 5.68 m in its type section. In the Broke / Millfield area the member ranges in thickness from 2.15 to 6.98 m, and comprises a buff coloured silt size to medium grained tuffaceous unit that tends to be carbonaceous towards the top.

The Hillsdale Coal Member comprises coal and minor bands. It ranges in recorded thickness from 0.79 m in DM Broke DDH 2 to 7.09 m in DM Coolamin DDH 1, and has a thickness of 2.94 m in its type section. The member comprises mainly banded lithotypes and has an overall dulling-upwards appearance. The thickness of the member is largely dependent on the amount of erosion that has taken place during deposition of the overlying coarse clastic sediments of the Redmanvale Creek Formation.

The Redmanvale Creek Formation comprises interbedded conglomerate, sandstone, and minor siltstone. Throughout the coalfield it overlies the Dights Creek Coal and underlies the Greigs Creek seam, with the exception of the Broke area where the Narrabeen Group has eroded into the upper parts of the Wollombi Coal Measures and sits directly on the Redmanvale Creek Formation. Consequently in the Broke area the boundary between the Wollombi Coal Measures and the overlying Narrabeen Group is uncertain. The formation has a thickness of 21.47 m in its type section.

The Greigs Creek Coal is the uppermost unit of the Wollombi Coal Measures. It comprises mainly dull banded coal with minor shale and claystone bands. The Greigs Creek Coal has a thickness of 0.61 m in its type section and reaches a maximum thickness of 1.83 m. The Greigs Creek Coal is not present in the Broke area due to its removal by the coarse clastic sediments of the overlying Triassic Narrabeen Group.

CORRELATION WITH NEWCASTLE COAL MEASURES

Prior observations

Since early this century the uppermost Permian coal measures, the Wollombi and Newcastle Coal Measures, have been thought to be equivalent, however, no detailed attempt to correlate individual units appears to have been attempted.

The major impediment to accurate correlation has been the paucity of drilling data that intersected the Wollombi Coal Measures in the southeastern parts of the Hunter Coalfield and the Newcastle Coal Measures in the western parts of the Newcastle Coalfield.

There were no complete intersections of the Wollombi Coal Measures between Broke and the Lochinvar Anticline area until AOG Millfield DDH 1 was drilled in 1966. Since 1966 several boreholes have obtained complete intersections of the Wollombi Coal Measures to the south of Broke and also within the Newcastle Coal Measures in the western parts of the Newcastle Coalfield. However, drillhole spacing between Newcastle and Wollombi Coal Measures intersections is still about 25 km.

Prior to current attempts to correlate individual units within the two coal measures a number of observations had already been noted. These include the following:

1. The Narrabeen Group overlies the Wollombi and Newcastle Coal Measures and can be mapped continuously from Broke around the Lochinvar Anticline and into the Newcastle Coalfield.

2. The base of the Wollombi and Newcastle Coal Measures is respectively the Watts Sandstone and Waratah Sandstone, which are known to represent the same stratigraphic unit and underlie almost the entire northern Sydney Basin.

3. The Standing Committee on Coalfield Geology of New South Wales (1975) noted that the Greigs Creek Coal comprised similar coal to the Wallarah seam in the Newcastle Coalfield.

4. The similarity between the Wallarah, Great Northern and Fassifern seams from the Newcastle Coalfield and coal seams intersected in the Millfield area was recognised by geologists working in the Millfield area, however, the uppermost seam was variously identified as the Wallarah / Great Northern, Fassifern, or Greigs Creek seam.

Current Studies

The results of the Broke Drilling Programme have enabled a more detailed correlation of the Wollombi Coal Measures with the Newcastle Coal Measures. A number of coal seams and tuffaceous units, including the Hillsdale Coal Member, Nalleen Tuff Member, Hobden Gully Coal Member, Monkey Place Creek Tuff Member, and Abbey Green Coal, have been respectively correlated with the Wallarah / Great Northern seam, Awaba Tuff, Fassifern seam, Nobbys Tuff, and Lambton Formation (Table 2). Other un-named tuffaceous units within the Wollombi Coal Measures have been correlated with named tuffaceous units within the Newcastle Coal Measures, including the Mount Hutton, Warners Bay, Stockrington and Edgeworth Tuffs.

The identification of the Hillsdale and Hobden Gully Coal Members as being equivalent to the Wallarah / Great Northern and Fassifern seams has led to increased exploration of the Wollombi Coal Measures. To date one company has recently been granted an exploration licence to explore for opencut and underground resources within the Wollombi Coal Measures. If the Wollombi Coal Measures show the same lateral trends as the Newcastle Coal Measures there may also be some resource potential within the Abbey Green Coal, which is the correlative of the Borehole, Yard, Dudley, and Nobbys seam interval.

The author in conjunction with staff from the University of Newcastle and Powercoal Pty Ltd has sampled a number of tuffaceous units from the Wollombi and Newcastle Coal Measures. The samples are currently undergoing elemental analysis and magnetic intensity studies in order to determine if a chemical or magnetic signature can be assigned to the various tuffaceous horizons. The results of these studies as well as the ongoing interest in revisiting the Wollombi Coal Measures stratigraphy is likely to further increase the accuracy of the correlations presented in this paper.

Due to the results of the Broke Drilling Programme and subsequent studies the author is proposing that consideration be given to either redefining the stratigraphy of the Wollombi Coal Measures along the lines of the recent modifications to the Newcastle Coal Measures, where laterally extensive tuffaceous marker horizons are elevated from member to formation status and divide coal bearing formations containing coal seams with informal names; or that Newcastle Coal Measures nomenclature entirely replaces the current Wollombi Coal Measures nomenclature.

Narrabeen Group				
Glenn Gallic Subgroup	Greigs Creek Coal		Vales Point seam	Moon Island Beach Formation
	Redmanvale Creek Formation			
	Dights Creek Coal	Hillsdale Coal Member	Wallarah seam; Great Northern seam	
		Nalleen Tuff Member		Awaba Tuff
		Hobden Gully Coal .M.	Fassifern seam; Upper Pilot seam	Boolaroo Formation
Doyles Creek Subgroup	Waterfall Gully Formation			
	Pinegrove Formation	Hambledon Hill Sand. M.; Wylies Flat Coal M.; Glengowan Shale M.	Mount Hutton Tuff	
Horseshoe Creek Subgroup	Lucernia Coal	Eyriebower Coal M.; Longford Creek Silt. M.; Rombo Coal Member; Hillside Claystone Member; Carramere Coal M.	Lower Pilot seam	
	Strathmore Formation		Hartley Hill seam	
	Alcheringa Coal	un-named Tuff		Warners Bay Tuff
			Australasian seam	Adamstown Formation
		un-named Tuff	Stockrington Tuff	
			Montrose seam; Wave Hill seam	
	Clifford Formation	un-named Tuff	Edgeworth Tuff	
Apple Tree Flat Subgroup	Charlton Formation	Stafford Coal M.	Fern Valley seam; Victoria Tunnel seam	
		Monkey Place Creek Tuff M.		Nobbys Tuff
	Abbey Green Coal		Nobbys seam; Dudley seam; Yard seam; Borehole seam	Lambton Formation
	Watts Sandstone			Waratah Sandstone

Table 2. Lithostratigraphic correlation of Wollombi and Newcastle Coal Measures.

CONCLUSIONS

The Wollombi Coal Measures crop out in the northern part of the Sydney Basin. They conformably overlie the Wittingham Coal Measures and underlie the Narrabeen Group.

The Wollombi Coal Drilling Programme, which was the first programme specifically designed to investigate the Wollombi Coal Measures identified an inferred coal resource within the uppermost seam of the Wollombi Coal Measures in the Broke / Wollombi / Millfield area, which at that time was thought to be the Greigs Creek Coal.

The results of the Broke Drilling Programme and subsequent studies include; the correct identification of the Wollombi Coal Measures stratigraphic interval in the southern part of the Hunter Coalfield, and a postulated correlation of several units within the Wollombi and Newcastle Coal Measures.

The Hillsdale Coal Member, Nalleen Tuff Member, Hobden Gully Coal Member, Monkey Place Creek Tuff Member, and Abbey Green Coal, have been respectively correlated with the Wallarah / Great Northern seam, Awaba Tuff, Fassifern seam, Nobbys Tuff, and Lambton Formation (Table 2). Several tuffaceous units including the Mount Hutton, Warners Bay, Stockrington and Edgeworth Tuffs have also been identified within the Wollombi Coal Measures.

The author is proposing that consideration be given to either redefining the stratigraphy of the Wollombi Coal Measures by elevating tuffaceous marker horizons to formation status; or entirely replacing the current Wollombi Coal Measures nomenclature with Newcastle Coal Measures nomenclature.

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CORRELATION OF TUFFS IN THE NEWCASTLE AND WOLLOMBI COAL MEASURES BASED ON GEOCHEMICAL FINGERPRINTING

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ABSTRACT

The Permian Newcastle and Wollombi Coal Measures contain many tuffaceous horizons. Major and trace element X-ray fluorescence analysis of four stratigraphically well defined interseam tuffs, Awaba, Mount Hutton, Warners Bay and Nobbys (Monkey Place Creek) combined with step-wise discriminant analysis revealed that Y, La, V, Cl and Cu have different concentrations between the four tuffs and were the most powerful group of discriminating elements for the NCM and WCM combined. Y, La, Ba, Rb and Co were the five best discriminators between Awaba, Mount Hutton and Nobbys tuffs of the NCM, and Ga, La, Zr, Cs and Ba between Mount Hutton, Warners Bay and Monkey Place Creek tuffs of the WCM. These results indicate that each of the tuffs have a unique signature which can be used to correlate the Newcastle and Hunter coalfields; also for correlation across a regional area.

INTRODUCTION

The Newcastle and Wollombi Coal Measures of the Sydney Basin contain numerous tuffaceous units within a succession of siliciclastic deltaic and alluvial sediments (Herbert 1994). These units vary in thickness from 1mm to 25 metres (Diessel 1980) and record accumulation of volcanic ash in brackish lakes and lagoons (Herbert 1994). Two possible sources of the ash are an offshore high in the east and the New England Orogen in the NE (Harrington 1989). Several modes of deposition have been suggested, including pyroclastic fall, flow and surge.

Tuffs are ideal chronostratigraphic markers as they are widespread, distinctive, and geologically instantaneous (Prothero & Schwab 1996). The potential for a regional time surface has been known since the early 1920's however, geochemical fingerprinting has only been developed in the past fifteen years (Huff & Kolata 1989). The use of geochemical data and multivariate discrimination to identify a unique fingerprint of individual volcanic beds is a more precise method of correlation (Mitchell *et al.* 1994), allowing correlations to be carried out where previous attempts using sequence stratigraphy, lithostratigraphy and biostratigraphy have been unsuccessful.

PREVIOUS WORK

Successful correlation based on geochemical fingerprinting of K-bentonite beds of the Decorah subgroup, Mississippi Valley, has been detailed in many papers (Huff 1983; Cullen-Lollis & Huff 1986; Kolata *et al.* 1986; Kolata *et al.* 1987; Huff & Kolata 1989; Huff & Kolata 1990). This regional correlation has been carried out over 900km and has enabled reconstruction of paleoenvironments and paleogeography of the middle Ordovician Decorah subgroup. A much larger scale correlation was achieved using the same techniques to correlate a single tuff horizon on two separate continents, the Millbrig K-bentonite in eastern North America was correlated with the 'Big-Bentonite' in northeastern Europe (Huff *et al.* 1992). This correlation has facilitated the reconstruction of Ordovician plate boundaries.

Previous attempts to correlate Newcastle and Wollombi Coal Measures have lacked the precision provided by geochemical fingerprinting. Exploration of the Hunter coalfield has been less extensive as a result. In this study an attempt to overcome this problem has been made by determining the chemical composition of particular tuffs. The aim is to ascertain whether they have distinctive geochemical signatures useful for correlation. Once a regional correlation is achieved standardisation of the nomenclature of the Newcastle and Hunter coalfields can be carried out. This paper summarises the results obtained from a preliminary investigation of the tuffs in the two Coal Measures (Figure 1). It shows that each of the four tuffs have a unique geochemical signature and that the Newcastle and Hunter coalfields can be geochemically correlated.

METHODS

Four stratigraphically well defined tuffs, Nobbys (MPC), Mount Hutton, Warners Bay and Awaba, were sampled from four cores (ETD7, STOWE, DMB2 & DMB4R; Figure1). The least weathered samples were selected at several intervals throughout the four tuffs. Whole-rock samples were ground using a Tema ring mill and mortar and pestle. 0.8 to 1.6 grams of sample (depending on silica content) was combined with 8 grams of lithium tetraborate/metaborate mix and oxidant (NH_4NO_3). Glass discs were prepared and analysed for major and trace elements using X-ray fluorescence spectroscopy.

The data were subjected to step-wise, multivariate discriminant analysis using the statistical program SPSS version 8.0. This analysis was used to determine the ability of different elements to distinguish between the four tuff horizons. The best combination of elements achieve discrimination superiority and therefore a geochemical fingerprint (Kolata et al. 1986).

RESULTS

The results of discriminant function analysis of chemical data obtained from the Newcastle and Wollombi Coal Measures, is summarised in Table 1. The number of discriminant functions calculated is equivalent to the number of variables entered, or to Table 1 summarises the results and lists the three functions, their eigenvalues and corresponding canonical correlation coefficients, for the Newcastle and Wollombi data. The canonical correlation coefficient is a measure of the functions ability to distinguish between the groups (Huff, 1983). The eigenvalues represent a measure of the amount of variance among the group of elements, accounted for by each function. The first two account for 91.5% of the variance accounted for by the model.

Table 1: Properties of the discriminant functions of the four tuffaceous layers

Function	Eigenvalue	Percent of Variance	Canonical Variation
1	1.425	58.0	.767
2	.821	33.4	.672
3	.209	8.5	.416
		100.0	

Group	Function 1	Function 2	Function 3
1 (Awaba)	-1.641	8.270	2.392
2 (Mt Hutton)	.853	1.014	-.617
3 (Warners Bay)	.962	.657	.794
4 (Nobbys/MPC)	.700	-1.333	-9.411

The canonical correlation coefficients associated with the functions indicate that the first two discriminant functions are each highly correlated, whilst the third is somewhat less correlated. The correlations of the combined data sets show that the functions, especially those in the first two groups, effectively separate the four units. Within each of the three functions given, different elements are important to each of those functions (Huff, 1983). The order of importance of the elements to the discriminant model for the combined data is Y, La, V, Cl and Cu. The value of the functions are calculated as the means of the groups. These may be thought of as the defined point coordinates within a three-dimensional grid. less than one of the groups, which ever of the two is smaller. The data plots (Figures 2 & 3), show a definite correlation between the tuffs within the separate coalfields, showing that the individual members carry a distinctive geochemical fingerprint. When the strongly altered or carbonate veined tuffs are removed from the data set, the differentiation between the tuffs becomes more apparent.

When the data from both Coal Measures are combined (Figure 4), distinctive grouping for each of the tuff units is revealed. The power of the discriminant function analysis shows that the tuffaceous layers are able to be correlated with certainty across the separate study areas, and across larger areas for regional correlation.

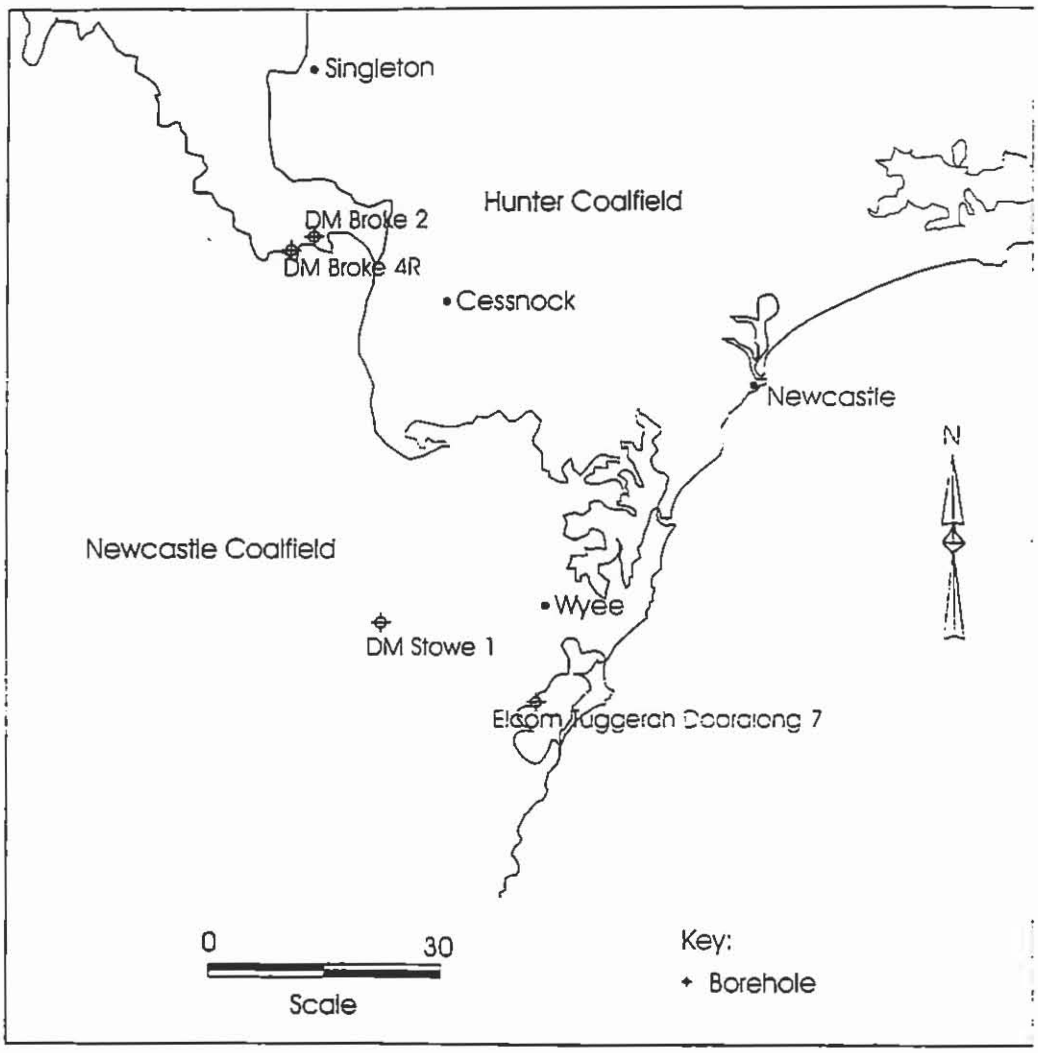

Figure 1: Location of the Newcastle and Hunter Coalfields in the Sydney Basin and cores used in this study.

The territorial map for the tuffs from the Newcastle Coal Measures is shown in Figure 2. It shows that the individual tuffs define and have distinctive geochemical signatures which allow them to be separated using discriminant function analysis. Separation is greater in the tuffs from the Wollombi Coal Measures (Figure 3), and a more distinctive geochemical pattern is observed. From this figure, it can delineated that the tuffs fall into distinctive groups; or show individual geochemical signatures for each of the different tuffs in the data set, even where this is some overlapping as in the Newcastle data set.

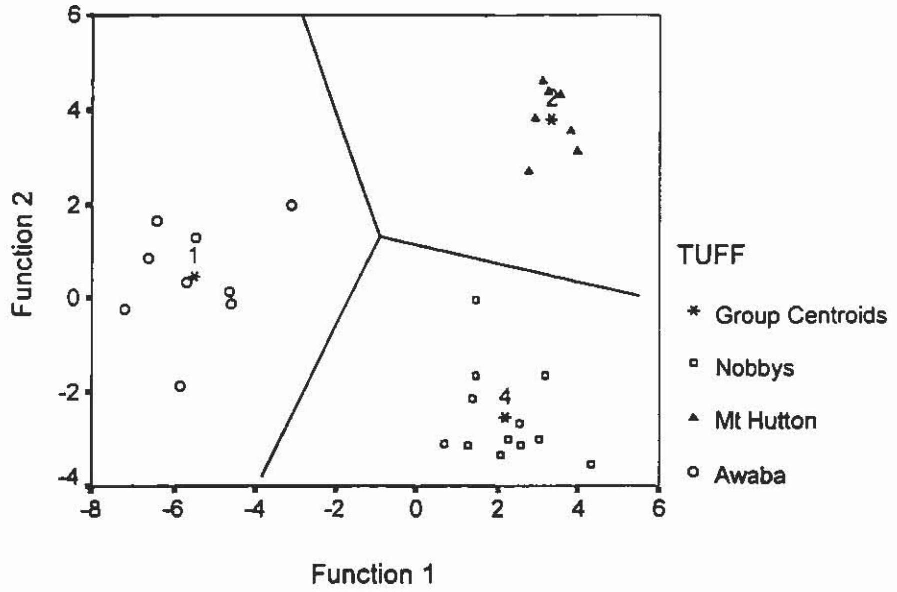

Figure 2: Territorial map constructed from the two canonical function calculated for the Newcastle Coal Measures data. Asterisks mark the group centroids.

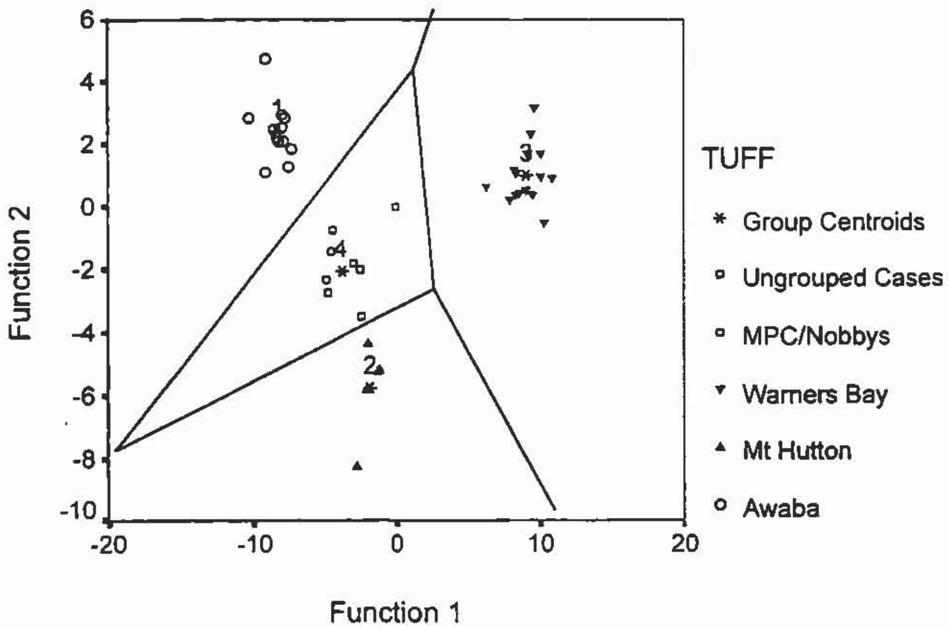

Figure 3: Territorial map constructed from the two canonical functions calculated from data for the Wollombi Coal Measures data. Asterisks mark the group centroids.

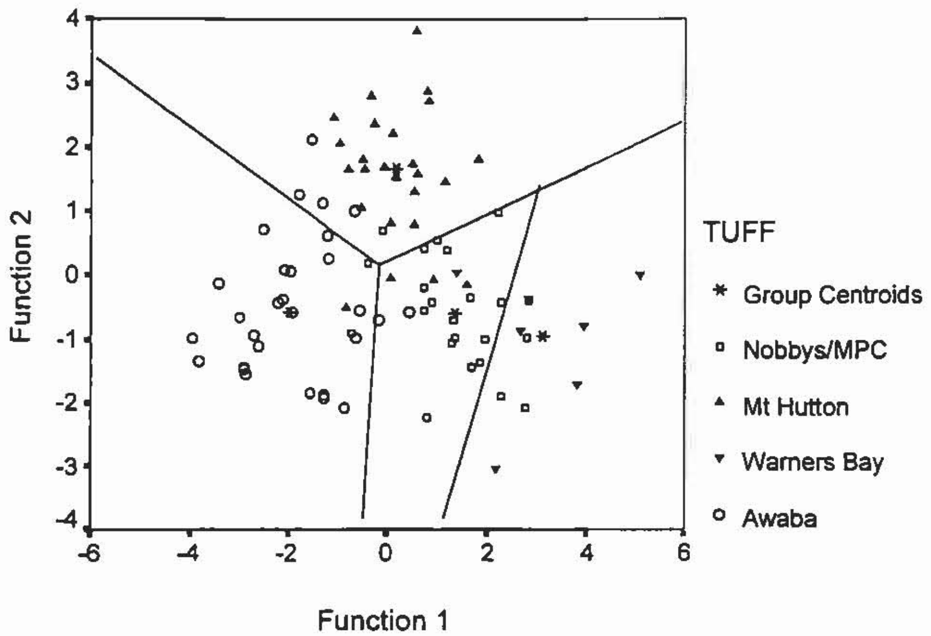

Figure 4: Territorial map for the data obtained from the Newcastle and Wollombi Coal measures. Asterisks mark the group centroids.

DISCUSSION

The preliminary results obtained in this study, indicate that the individual tuffs in the Newcastle and Wollombi Coal Measures are geochemically distinctive and unique, and thus are geologically significant. The geochemical fingerprint shown by the individual tuffs is probably a reflection of the difference in the composition of the original parent ash composition (Huff, 1989). The unique signatures allows the tuffs to be correlated across the separated coalfields (Newcastle and Wollombi), and may lead to correlation being carried out on a regional scale. This approach to correlation, married with the already documented lithostratigraphic field evidence for both the Newcastle and Wollombi Coal Measures, will allow the confident identification of suspect layers within seams.

The ability of discriminant analysis to identify distinctive geochemical signatures in tuffs and to separate them on the basis of these signatures, will allow correlation between coal measures to be made more readily and will remove the uncertainty that has existed in the past. It is also useful for the identification of unknown beds on the basis of this geochemical fingerprint and when combined with lithostratigraphic and biostratigraphic data, the discriminant analysis becomes even more powerful. The strength of the discriminant analysis lies in the enhanced interpretation of the evidence which it provides (Huff *et al.*, 1989), and is only limited by the number of samples and sample distribution within the data sets.

ACKNOWLEDGEMENTS

This study was supported by funding from the NSW Department of Mineral Resources and Powercoal. We thank Darryl Stevenson, Michael Creech, Jenny Bailey for assistance with XRF analysis, Tim Rolph, Segun Osunkoya, and Carol Simpson for their support and input to this project.

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K/Ar DATING OF AUTHIGENIC CLAYS RELATED TO IGNEOUS INTRUSIONS IN HUNTER VALLEY COALS

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INTRODUCTION

The Sydney Basin is composed mainly of Permian and Triassic marine and non-marine clastic sedimentary strata together with economically significant coal deposits and volumetrically minor igneous rocks. Many of these igneous rocks are also economically significant not only for their use in the construction industry but also for their deleterious effects on coal mining, particularly in underground mines utilising longwall extraction systems. Igneous activity in the Sydney Basin ranges from Early Permian to Tertiary in age and although episodic in nature, activity was unlikely to have ceased for periods of more than approximately 10 million years (Carr & Facer 1980; Embleton *et al.* 1982). Dating of the time of emplacement of igneous rocks using the K-Ar isotopic system is a relatively straightforward procedure if suitable analytical facilities and samples of appropriate, fresh, primary minerals are available. In the case of intrusions in coal seams, however, the occurrence of fresh, primary minerals is very rare due to widespread alteration produced by interaction between the igneous rock and fluids in the coal seam. This interaction produces a variety of secondary minerals with most primary minerals and glass being altered to clays (mainly kaolinite) and carbonates. Consequently, relatively few isotopic dates for intrusions into coal seams have been determined. A detailed study of several hundred samples of igneous rocks from the Sydney Basin found only six samples of intrusions into coal seams which were suitable for conventional K-Ar dating (Carr & Facer 1980). Techniques for K-Ar dating of authigenic illite, developed in response to the need by the petroleum industry to understand the timing of diagenesis in petroleum source-rocks and reservoirs, are now well established (Clauer & Chaudhuri 1995). As part of a larger project on the impact of igneous intrusions on coal mining and the alienation of coal reserves, a preliminary investigation of the timing of formation of authigenic illite by alteration of intrusions in Dartbrook Mine has been undertaken.

GEOLOGICAL SETTING

Dartbrook Mine is a modern underground coal mine located in the Upper Hunter Valley of New South Wales. Geologically, the mine is situated immediately west of the Aberdeen and Hunter thrust faults that form the structural boundary between the northern Sydney Basin and the New England Fold Belt to the east. The mine currently extracts coal from the Late Permian Upper Wynn A (WUA) seam, the uppermost member of the Vane Subgroup which is the lower of the two subgroups of the Wittingham Coal Measures. Despite being located near the margin of the Sydney Basin, the Wynn seam dips to the northwest at approximately 6° in Dartbrook Mine and the relatively simple geological structure in the region allows high productivity by Australian standards. In the mining lease the Wynn seam coalesces with the overlying Bayswater and Broonie seams to produce a "mega-seam" which allows considerable flexibility in mining operations in areas where faulting intersects the underground workings. Coal is extracted from longwall panels using machinery suitable for thick seam mining and during 1998 the mine produced in excess of 3.2 Mt of export quality thermal black coal.

Minor faulting has been encountered in mine workings and in boreholes. Surface seismic techniques have been trialed but have not resolved structure to an encouraging degree. In contrast, data from both surface and airborne magnetic surveys have been used extensively with some excellent results. These surveys identified several major intrusions (Moloney & Doyle 1996) the presence of which was later confirmed by their intersection in mine workings and drill cores. These intrusions mainly comprise altered, mafic dykeswhich are essentially vertical and normally strike between 045° and 065° but one has an orientation of 330° (Figure 1).

ANALYTICAL METHODS

Samples consisting of approximately 500 g of material were collected from dykes encountered in underground mine workings and from core recovered as part of an in seam drilling program. These samples were crushed into chips with maximum dimension <10 mm and then gently disaggregated by using a repetitive freezing and thawing technique to avoid artificial reduction of rock components and contamination with K-bearing minerals such as K-feldspar (Liewig *et al.* 1987). Grain size fractions (<1, <2 and 2-6 μm) were separated in distilled water according to Stoke's law and the efficiency of this separation was controlled by a laser granulometer. The mineralogy of the size fractions was determined by X-ray diffraction (XRD) on air dried samples, after exposure to ethylene glycol and after heating to 400°C. Potassium content was determined by atomic absorption using Cs ion suppression. Argon was extracted from the separated mineral fractions by fusing samples within a vacuum line serviced by an on-line ^{38}Ar spike pipette and the isotopic composition of the spiked Ar was measured with an on-line VG3600 mass spectrometer. The ^{38}Ar spike was calibrated against international standard biotite GA1550 (McDougall & Roksandic 1974) with the average of six analyses of the standard giving 1.3349E-09 mol/g. Blanks for the extraction line and mass spectrometer were periodically determined and the $^{40}Ar/^{36}Ar$ value for airshots averaged 294.44±1.16 (2σ, n=10). The K-Ar ages were calculated using ^{40}K abundance and decay constants recommended by Steiger and Jäger (1977).

CLAY MINERALOGY

XRD analyses of samples indicate that kaolinite and illite/smectite are the major clay mineral components of the separated grain size fractions (Table 1). Glycolation produces a shift of the 10 Å illite peak indicating the presence of mixed layer smectite components. Progressive size reduction increases the proportion of illite in the clay component and the <1 μm fractions also minimize contamination by other mineral components. Illite crystallinity measurements confirm the authigenic origin of the illite/smectite. Scanning electron microscopy (SEM) images of whole-rock chips indicate crystallisation of authigenic clay minerals in altered host dykes and support the contention that the clay mineral assemblage consists mainly of kaolinite with only minor platy illite phases (Figure 2). Transmission electron microscopy (TEM) investigations are in progress and are being used to identify and distinguish

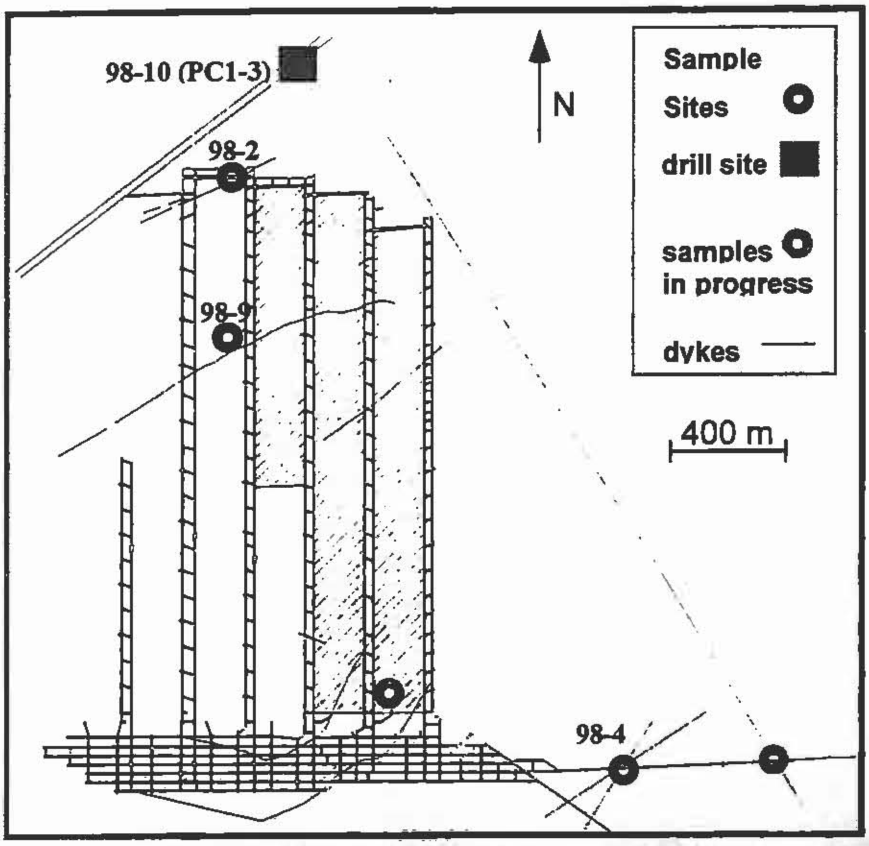

Figure 1 Sample locations in Dartbrook Mine

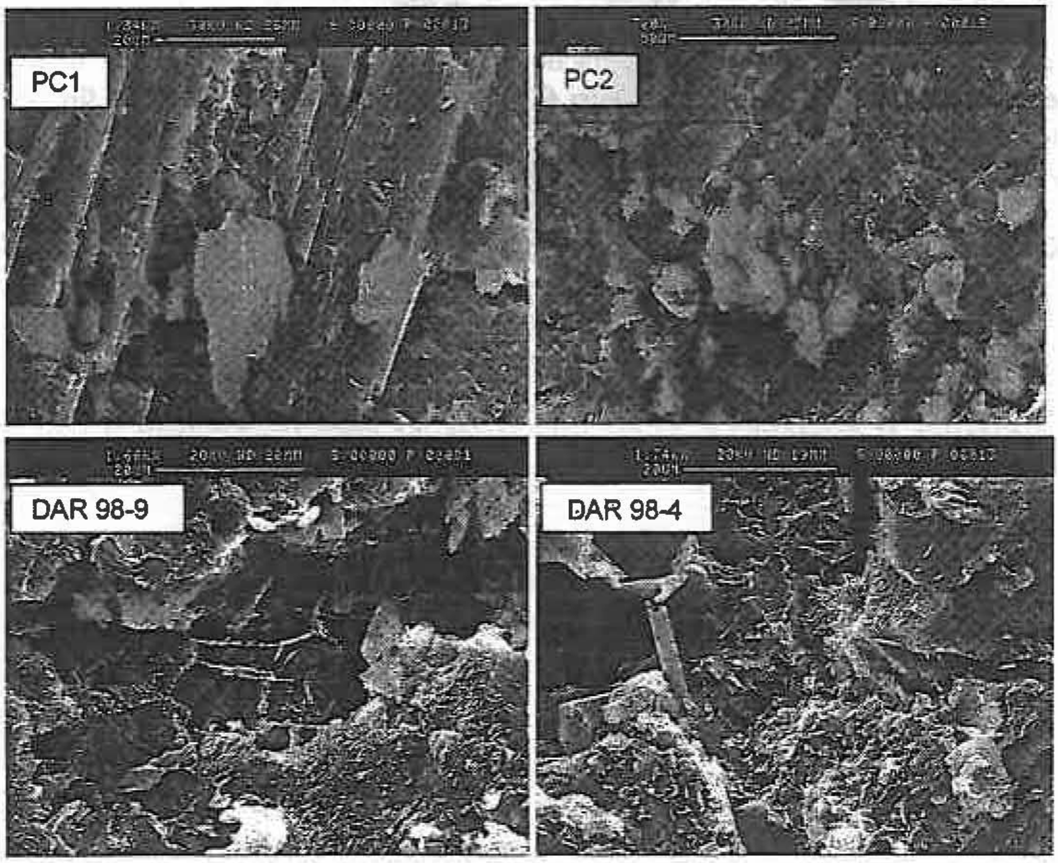

Figure 2 SEM images of sample chips. Flaky illite dominates PC1, PC2 and DAR98-4. DAR98-9 contains authigenic illite on relict K-feldspar.

authigenic clays from contaminents by individual grain analysis for a purity control as proposed by Hamilton *et al.* (1992).

K-Ar DATA

A total of 21 K-Ar dates were determined and these range from 109.6 to 69.2 Ma (Table 2; Figure 3) with a mean of 90.4±10.2 Ma. Radiogenic ^{40}Ar ranges from 21.4 to 96.6% indicating negligible atmospheric Ar contamination and reliable analytical conditions for most analyses with the exception of sample DAR98-9 which contains only ~20% radiogenic Ar. The reliability of the ages is also confirmed by the agreement within 2σ analytical uncertainty for the duplicate analyses of the <2 µm and 2-6 µm fractions for samples DAR98-4 and DAR98-9 and the <2 µm fraction for sample DAR98-2 (Figure 4). Duplicates of the coarse fraction for sample DAR98-2 were also measured but the ages differ by almost four times the 2σ analytical uncertainty. This discrepancy probably reflects heterogeneity in the contamination of this coarse fraction. The relatively low contents of K for illite are consistent with an authigenic origin.

Samples PC1, PC2 and PC3 all come from the same dyke intersected in a horizontal drill core (Figure 5). This dyke was intersected over a 14 m zone consisting of altered igneous rock (~60%) and cindered coal (~40%) with the intensity of alteration decreasing away from the margins of the intrusion. The three ages for the different size fractions in samples PC1 and PC3 are identical within 2σ analytical uncertainty (Figure 3), suggesting that all size fractions for these samples are of similar high purity and are isotopically homogeneous. In sample PC2 and samples of other dykes different size fractions produce different K-Ar ages with the coarsest fraction invariably older than finer fractions (Figure 3). This relationship of increasing K-Ar age with increasing grain size is consistent with increased contamination in the coarse fractions (2-6 µm) relative to the finer fractions and suggests that the most reliable isotopic ages for authigenic illite are obtained for the finest size fractions (<1 µm). The higher purity of the finest size fractions is also supported by the XRD, SEM and TEM data.

DISCUSSION

The validity and importance of the assumptions involved in K-Ar dating of authigenic illite (e.g. contamination, closed system behaviour, excess Ar) are discussed in several recent publications including Hamilton *et al.* (1992) and Clauer and Chaudhuri (1995). The relationship of decreasing K-Ar age with decreasing grain size fractions is typical of the pattern shown by illite ages for sedimentary rocks from diagenetic and low-grade metamorphic environments in which decreasing K-Ar ages are interpreted to reflect a decreasing proportion of older detrital components in progressively finer grained size fractions (Clauer & Chaudhuri 1995). In the altered dykes contamination of the coarser size fractions by K-poor phases such as kaolinite rather than by older detrital components results in older K-Ar ages. Irrespective of occurrence in sedimentary rocks or altered intrusions, however, the most reliable isotopic ages for authigenic illite are obtained for the finest size fractions. The finest illite fractions from altered intrusions in the Dartbrook area produce K-Ar ages in the 70-100 Ma range. One of the major effects of the interaction of coal and magma is the alteration of the cooling intrusion by addition of water and carbon dioxide from the devolatilization of coal (Hamilton 1968). Smaller intrusions are commonly completely altered whereas larger intrusions are altered at the margins only and become progressively less altered towards the core. Growth of authigenic illite in altered dykes is presumed to commence during this early episode of alteration so that the oldest

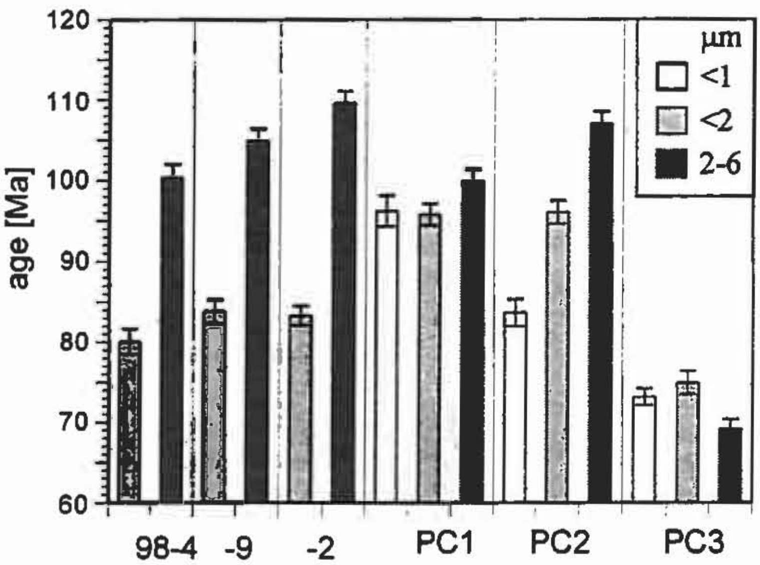

Figure 3 K-Ar ages for different samples and size fractions (µm). Bars indicate 1σ analytical uncertainty.

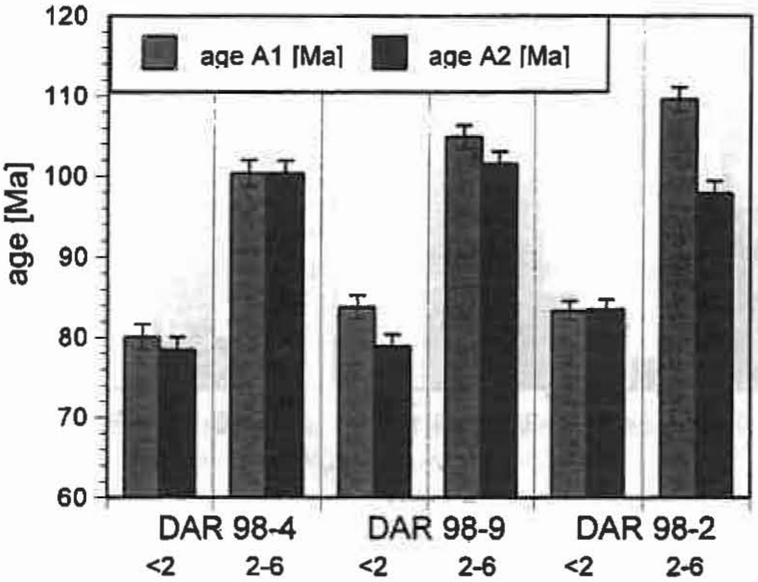

Figure 4 K-Ar ages for duplicate samples. Size fraction in µm. Bars indicate 1σ analytical uncertainty.

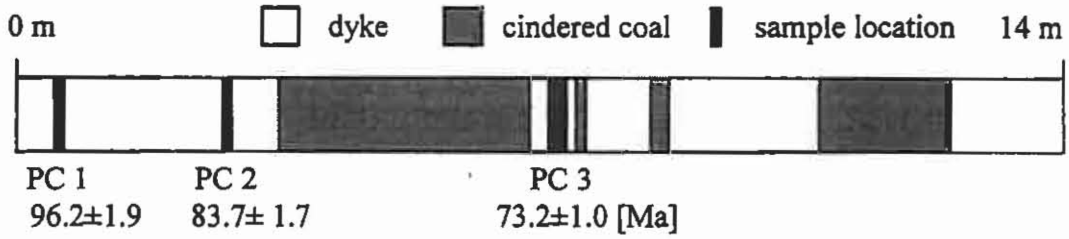

Figure 5 Sketch of horizontal drill core showing sample locations, K-Ar ages [Ma] for <1 µm fractions and analytical uncertainties (±1σ).

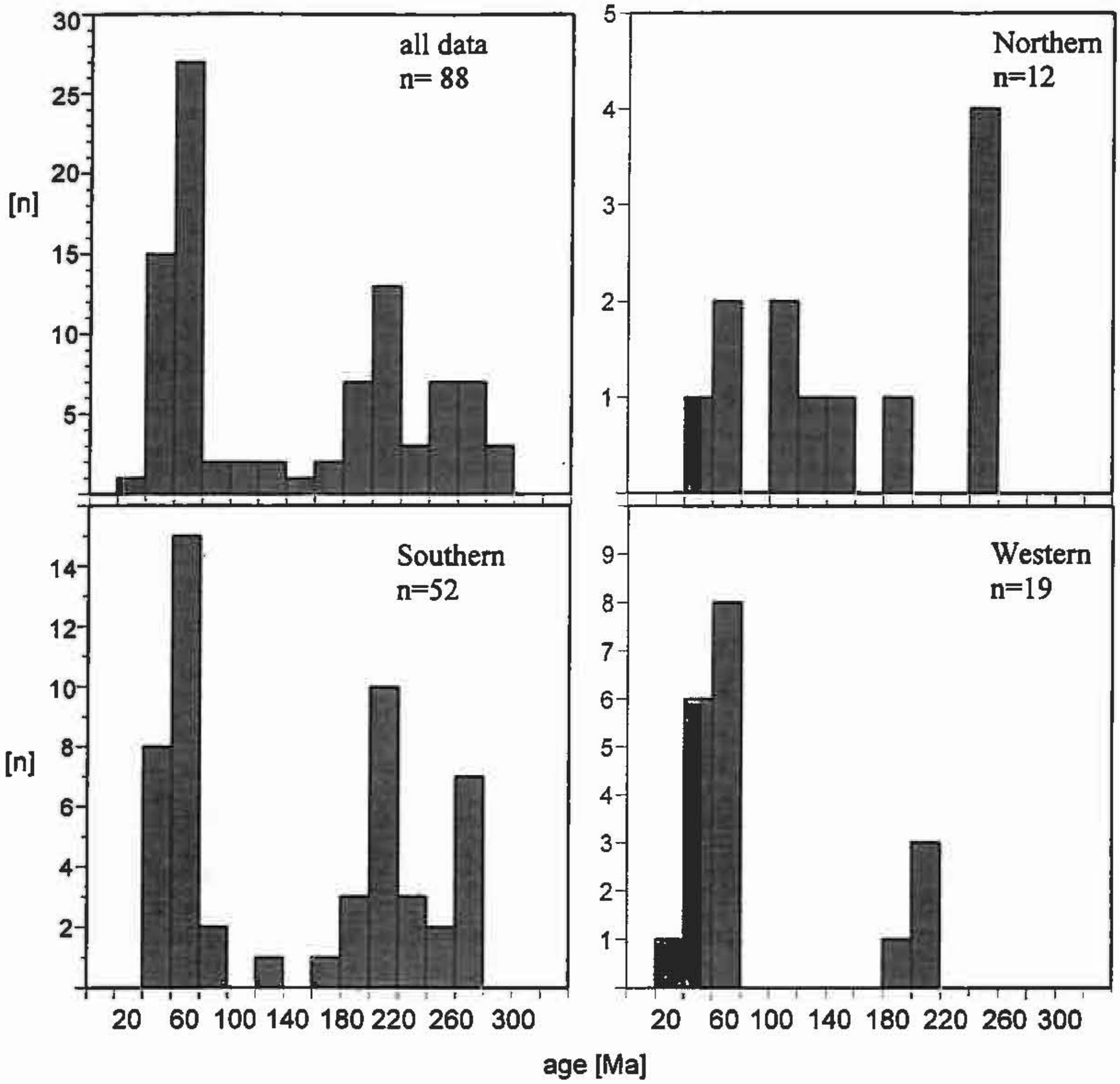

Figure 6 Histogram of K-Ar ages for igneous rocks in the Sydney Basin and subdivided by Coalfield

reliable K-Ar age for authigenic illite approximates the time of emplacement of the intrusion. On this basis the consistent 80-84 Ma ages recorded by the finest fraction (<2µm) recovered for samples DAR98-2, DAR98-4 and DAR98-9 are taken to approximate the time of emplacement of these dykes.

The finest fractions (<1µm) for each of the three samples from the largest dyke sampled during the present investigation (samples PC1, PC2 and PC3) provide three different ages (98, 84 and 72 Ma) which decrease with increasing distance from the margin of the dyke. The reliability of the oldest and youngest of these ages is confirmed by their internal consistency in that they are indistinguishable from the ages recorded by both coarser size fractions for each sample. These three ages may record the timing of different alteration events with the outer part of the intrusion being altered at the time of emplacement at ~98 Ma, and the progressively younger ages recording the timing as alteration pervaded farther and farther into the intrusion.

A compilation of published K-Ar ages for igneous rocks in the Sydney Basin (Figure 6) shows the episodic nature of igneous activity in the region with peaks at approximately 260, 210 and 70 Ma. This pattern of ages for the entire basin is highly influenced by data from the Southern Coalfield which constitutes almost 60% of the data set. The data set for the Northern Coalfield is relatively small but it appears to have representatives of the oldest and youngest episodes as well as an episode at ~90 Ma recorded by basalt dykes with ages of 90.1 and 92.7 Ma (Embleton *et al.* 1982). The average K-Ar age of 90.4 Ma for illite formation in Dartbrook Mine is indistinguishable from the K-Ar ages for these dykes.

The only major tectonic activity that affected the whole Sydney Basin was doming and initial rifting of the Tasman Sea which caused rapid uplift and erosion 100-70 Ma (Falvey 1974), together with attendant intrusive igneous activity responsible for the elevated coal rank in the basin (Middleton 1993). The coincidence between this 70-100 Ma interval and the range of K-Ar illite ages recorded from Dartbrook intrusions provides additional evidence for the timing of this major event and implies that K-Ar dating ofauthigenic illite from altered dykes provides a viable mechanism for dating these altered intrusions.

ACKNOWLEDGEMENTS

The paper presents preliminary results from a project funded by the University of Wollongong, Dartbrook Coal, CSIRO-DPR and the ARC under the Strategic Partnerships with Industry Research and Training Scheme. Professor Ian McDougall, Research School of Earth Sciences, ANU, is thanked for his very helpful advice during the set-up of the CSIRO-DPR K-Ar laboratory.

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Table 1: semiquantitative XRD data for separated size fractions from altered dykes.

sample ID fraction [µm]	illite/smectite [%]	kaolinite [%]	Additional phases [traces]	LPS D[v,0.5] µm
DAR98-2 <2	80	20		1.93
DAR98-2 2-6	60	40	(qz)	3.96
DAR98-4 <2	70	30		2.35
DAR98-4 2-6	60	40	(qz)	5.05
DAR98-9 <2	80	20		2.29
DAR98-9 2-6	60	40	Albite, qz	4.78
DAR98-10				
PC1 <1	50	50		0.75
PC1 <2	30	70	Albite, qz	1.15
PC1 2-6	20	80	Albite, qz	3.45
PC2 <1	20	80		0.85
PC2 <2	20	80	Albite, qz	1.11
PC2 2-6	10	90	Albite, qz	2.89
PC3 <1	20	80		0.69
PC3 <2	10	90	Albite, qz	0.90
PC3 2-6	10	90	Albite, qz	2.33

qz = quartz, LPS = laser particle sizer, D[v,0.5] = volume median diameter [in µm]

Table 2: K-Ar data for authigenic illite from altered dykes, Dartbrook Mine.

sample ID fraction [µm]	K [%]	rad 40Ar [10-10mol/g]	rad 40Ar [%]	age [Ma]	±σ [Ma]
DAR98-2 <2	1.92	2.846	46.5	83.5	1.4
DAR98-2D <2	1.92	2.840	48.8	83.3	1.2
DAR98-2 2-6	2.26	3.940	64.6	97.8	1.4
DAR98-2D 2-6	2.26	4.428	68.1	109.6	1.5
DAR98-4 <2	1.35	1.878	66.4	78.5	1.1
DAR98-4D <2	1.35	1.917	40.3	80.1	1.6
DAR98-4 2-6	1.35	2.416	67.5	100.3	1.6
DAR98-4D 2-6	1.35	2.415	86.0	100.3	1.6
DAR98-9 <2	1.47	2.056	21.4	78.9	1.2
DAR98-9D <2	1.47	2.187	22.8	83.8	1.5
DAR98-9 2-6	2.01 / 2.04	3.669	68.0	101.6	1.4
DAR98-9D 2-6	2.01 / 2.04	3.792	77.9	104.9	1.5
DAR98-10					
PC1 <1	2.61	4.474	80.3	96.2	1.9
PC1 <2	2.30	3.923	91.2	95.8	1.4
PC1 2-6	1.54	2.743	96.0	99.9	1.4
PC2 <1	2.51	3.727	82.8	83.7	1.7
PC2 <2	2.02	3.456	91.2	96.1	1.4
PC2 2-6	1.74 / 1.79	3.372	93.3	106.9	1.5
PC3 <1	1.48	1.917	81.1	73.2	1.0
PC3 <2	0.95	1.260	87.8	74.9	1.4
PC3 2-6	0.94	1.149	69.2	69.2	1.2

D = duplicate analysis

INFLUENCE OF IGNEOUS INTRUSIONS ON COALBED METHANE POTENTIAL, GUNNEDAH BASIN, NSW

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INTRODUCTION

The Gunnedah Basin, New South Wales, has for many years been the subject of petroleum and (more recently) coalbed methane exploration. Australian Coalbed Methane Pty Ltd and Pacific Power are jointly exploring more than 12,000 km^2 of the Gunnedah Basin for coalbed methane resources. The coal is of high-volatile-bituminous rank, with a mean maximum vitrinite (telocollinite) reflectance of between 0.56 and 1.1%. Coals affected by igneous intrusions occur at many localities in the Gunnedah Basin. Numerous sills, dykes and plugs of alkali-olivine basalt and teschenite have intruded the Permian and Triassic strata, particularly in the central and southern regions (Figure 1). Coals of these successions, heat-affected by the magma, have been varyingly altered, and thermal aureoles have been developed around individual intrusions (Gurba, 1998).

Igneous intrusions are commonly regarded as unwelcome phenomena in CBM exploration tending either to totally dispel seam gases, or to selectively replace CH_4 with CO_2. Contrary to this view, Bunny and Weber (1996) suggested that dolerite sills intersected in ACM Yannergee DDH 1 (Figure 1) might have beneficial effect on coal bed methane potential acting as impermeable seals.

As a part of an ongoing research project, a detailed study has been undertaken to investigate the relationships between the distribution and extent of the thermal aureoles created by igneous intrusions in the Gunnedah Basin and its implications for coalbed methane exploration. This paper discusses the extent of thermal aureoles related to sill-form igneous intrusions encountered in drill cores and the nature and extent of petrographic and chemical changes, as they relate to coal seam gas content and gas composition.

THERMAL AUREOLES IN ACM YANNERGEE DDH 1

ACM Yannergee DDH 1 (YE 1) was the second coalbed methane exploration hole drilled in the Gunnedah Basin by Australian Coalbed Methane Pty Ltd and Pacific Power. It was sited in the Bando Trough (Figure 1). An aggregate of nearly

36 metres of coal was intersected in YE 1. Two massive doleritic sills intruded the Permian sequence:

- an upper sill 39.3 m thick at 763.3-802.6 m;
- a lower sill 20.8 m thick at 857.6- 878.4 m.

The lower dolerite intruded a coal seam (Figure 1).

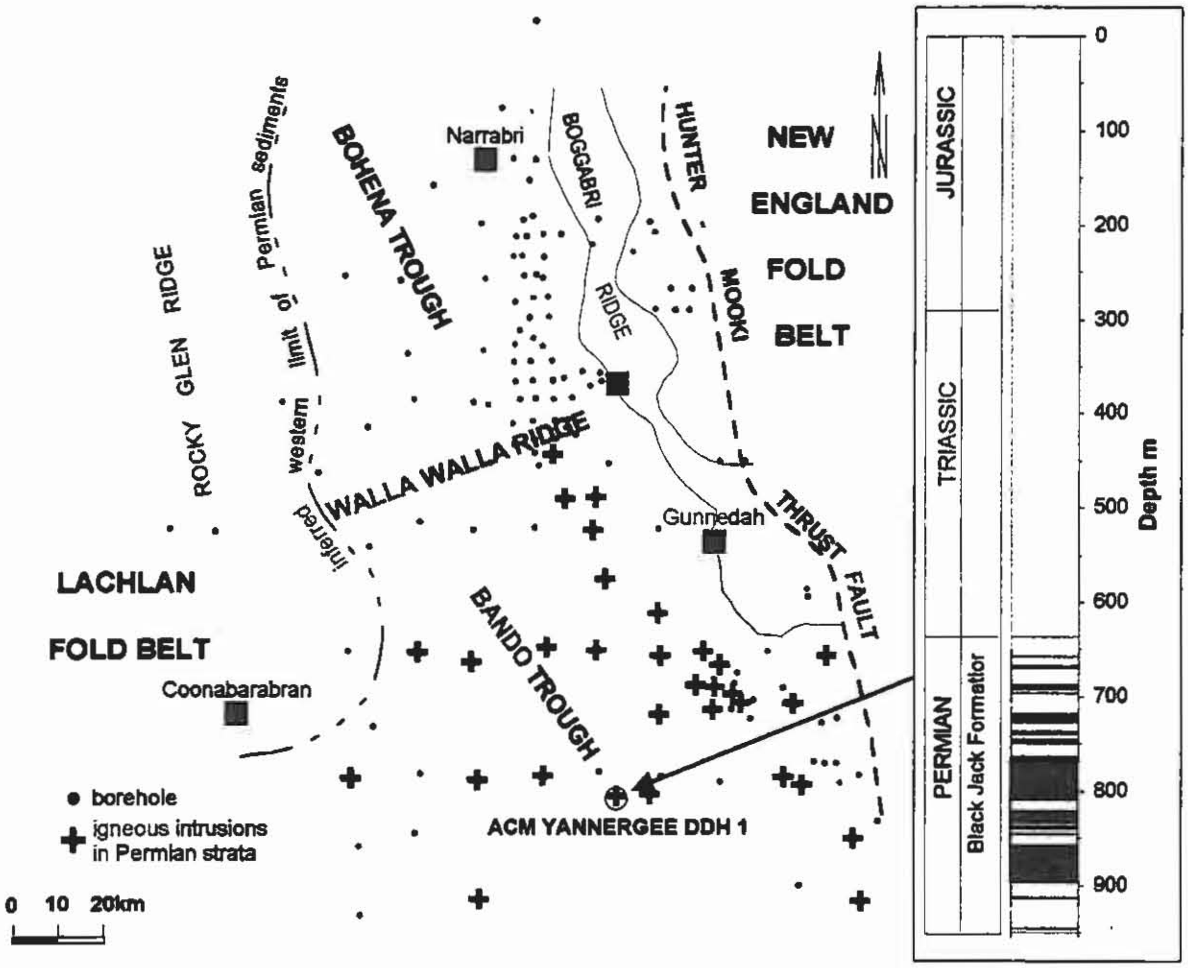

Figure 1. Distribution of igneous intrusions in Permian strata of the Gunnedah Basin and stratigraphic profile of ACM Yannergee DDH 1.

Vitrinite Reflectance

Optical properties of coals have been used to estimate the extent of the thermal aureoles developed around the two dolerite sills in YE 1. Apart from the routine reflectance measurements (maximum and minimum vitrinite reflectance), additional microscopic studies on coal samples have been particularly directed to describe the development of mosaic structures, reflectance anisotropy, and the development of slits and pores, and mineralisation.

The mean maximum vitrinite reflectance in YE 1 ranges from 0.67-0.80% for unaltered coal to above 6% in heat-affected coal (Figure 2). The vitrinite in a sample taken 0.68 m from the sill/sediment contact (856.96 m) contains small spheres, which resemble those known to be an intermediate stage in the formation of coke mosaic structures (Chandra and Taylor, 1982). Since mosaic structures can only form from bituminous coal, the coals in YE 1 have attained most, if not all of their high-volatile bituminous rank prior to the intrusion.

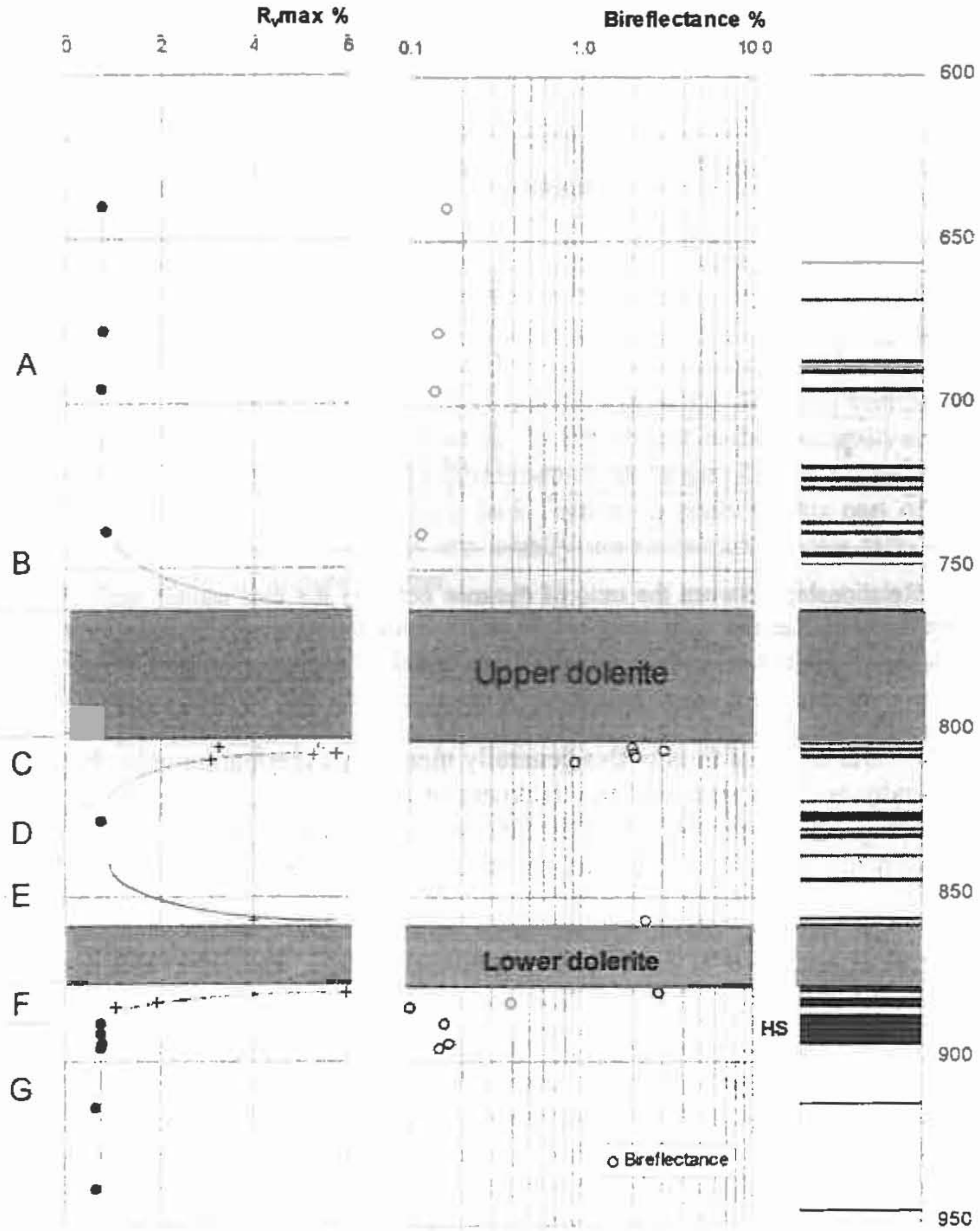

Figure 2. Mean maximum vitrinite reflectance and bireflectance against depth and alteration zones (A-G) due to dolerite sills in ACM Yannergee DDH 1. Crosses in reflectance profile indicate heat-affected coals.

Two coalification curves can be identified in vertical sequences where igneous material has intruded the strata. A linear regression line can be fitted to the data to represent coalification due to normal depth of burial, and a superimposed pair of exponential (or power) curves to the coals in the heat-affected zones (Figure 2).

The maximum vitrinite reflectance in the zones of thermal aureoles in YE 1 is related to intrusion thickness of and the distance from the coal seam. This relationship, which is shown graphically in Figure 3, follows the trend established for other boreholes in the Gunnedah Basin (Gurba, 1998 p. 262), and enables predictions to be made of the extent of the thermal effects below igneous intrusions.

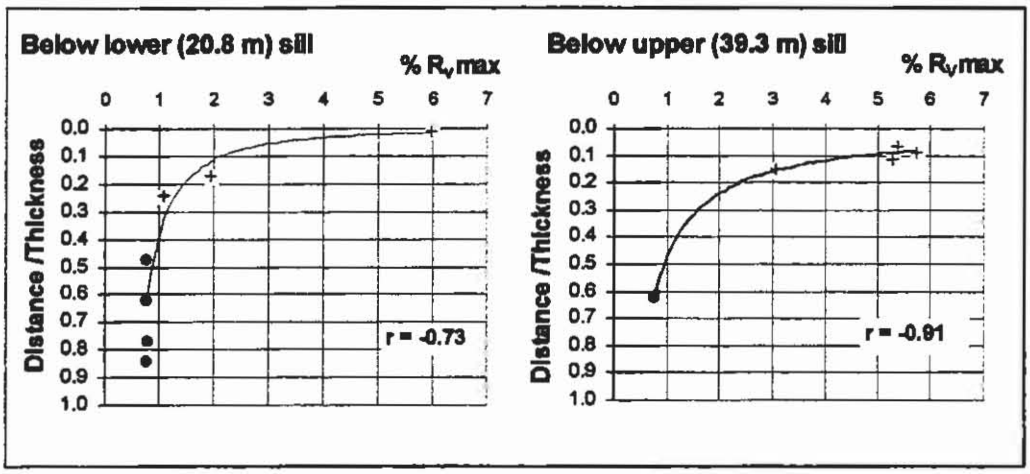

Figure 3. Relationship between the ratio of distance between the coal sample and the sill to thickness of the sill and mean maximum vitrinite reflectance (% $R_v$max) in ACM Yannergee DDH 1. (+) indicates heat-affected coal.

As a rule of thumb, this generally means that thermal aureoles below the sills are usually no more than half the thickness of the intrusion. However, above the sills the thermal effects extend over a distance equal to their thickness. For example, the lower intrusion is 20.8 m thick and has an underlying thermal aureole that is 9 m thick.

Reflectance Anisotropy

Reflectance anisotropy of vitrinite (= bireflectance = maximum minus minimum vitrinite reflectance) increase with temperature of alteration. By the study of the bireflectance behaviour in vertical sequences, the heat-altered zones can be delineated. In YE 1, in response to heat from the intrusion, initially the bireflectance drops towards the sill from 0.15-0.16 (typical for non-heat affected coal in this borehole) to below 0.1%, and then rises to above 3% (Figure 2). The same situation is observed below and above the sill in the transition from unaltered to heat-affected coals.

Chemical Characteristics of the Coal

The volatile matter yield below the upper sill has decreased in analysed coal samples (805-808 m) to below 15% (daf). The observed increase in volatile matter yield (30-40% daf) in the samples from the sill/sediment contact in conjunction with increasing ash, suggest that an abundance of carbonate minerals has masked the trends in the volatile matter of the organic fraction. Microscopic observations confirmed high carbonate contents in these samples. The increases in volatile matter content in the direction of igneous intrusions may also suggest that during natural coking the volatiles were either never released or were later reabsorbed by the seam.

Extent of the Thermal Aureoles

Based on the changes in optical and chemical properties of coal in ACM Yannergee DDH 1 discussed above the following zones can be delineated in the Permian section intruded by two dolerite sills: unaltered zones (A, D, and G in Figure 2); and thermal aureoles developed around the dolerite sills (B and C around the upper sill, and E and F around the lower sill). Boundaries between the zones are gradational.

A. Unaltered zone above the upper sill (from the top of the Permian section to about 740 m). This zone includes coals that do not appear to be thermally affected by intrusions and are in high-volatile bituminous rank range ($R_v$max in the range 0.75-0.78%), typical for the upper Black Jack Formation coals in this part of the basin (Gurba and Ward, 1995). Coals are usually inertinite-rich (above 60% inertinite) with high content of mineral matter.

B. Thermal aureole about 20 metres thick above the upper dolerite sill. No samples have been studied yet close to the sill/sediment contact above the upper dolerite sill and the thickness of the altered zone is estimated only approximately. However, slightly altered sample, from a depth of 739.1 m, indicates that the alteration zone above the sill is less than 24 m thick.

C. Thermal aureole developed below the upper sill is more than 6 m thick but less than 24 m thick). Coals are heat-affected ($R_v$max=3.07-5.39%) with high degree of anisotropy. They contain many pores. These pores are usually empty, but at the sill/sediment contact they are filled with mineral matter or carbonaceous matter formed from volatiles. It is interesting to note that a coal sample from a depth of 827.1 m (between the two dolerites) has a $R_v$max of 0.77% and shows no evidence of heating (Figure 2). This indicates that the thermal aureoles between two sills do not merge and non-affected zone (D) occurs between dolerites.

D. Unaltered zone between two-dolerite sills. Mean maximum vitrinite reflectance drops to 0.77% at the depth of 827.1 m (Figure 2). This sample is vitrinite-rich with high amount of liptinite. Strong fluorescence has been observed from liptinite and also from vitrinite

E. Thermal aureole (around 14 metres thick) developed above the lower dolerite sill. Coal sample taken 0.68 m from the sill/sediment contact is strongly heat-affected, contains spheres, pyrolytic carbon and much carbonates.

F. Thermal aureole (less than 9 metres thick) developed below the lower sill. Coals are altered to medium-volatile-anthracite range ($R_V$max=1.09-5.97) and are strongly anisotropic. Liptinites are no longer recognised. Similar to the samples underlying the upper dolerite in zone C they developed abundance of devolatilisation pores.

G. Unaltered coal ($R_V$max = 0.76-0.80%) representing the Hoskissons seam has been identified about 8.4 m below the bottom contact of the lower dolerite sill.

EFFECT OF DOLERITE SILLS ON COALBED METHANE IN YE 1

Gas Content

The lower dolerite sill, which intruded a coal seam, developed the thermal aureole (zone F in Figure 2) that extends for 9 m below the dolerite (Figure 4). Samples analysed from the seam 3 metres below the dolerite are separated from the intruded seam by carbonaceous mudstone and claystone, and are altered to medium-low volatile bituminous range. The maximum vitrinite reflectance is about 2%. Optically these coals are characteristic by development of small slits and devolatilisation pores. These sample show gas contents in the range 10-12 m^3/t (daf) (Figure 4) and rapid desorption rates.

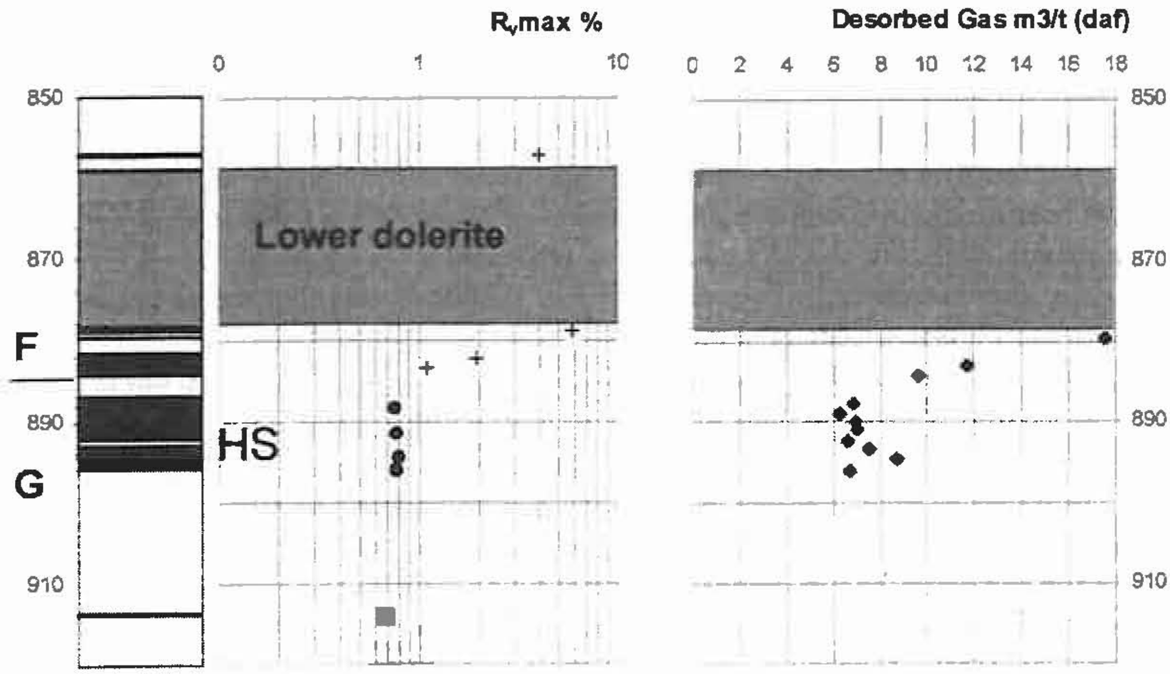

Figure 4. Mean maximum vitrinite (telocollinite) reflectance and total desorbed gas (m^3/t daf) against depth below the lower dolerite sill in ACM Yannergee DDH 1. Crosses in reflectance profile indicate heat-affected coals. HS - Hoskissons seam.

Unaltered coal samples, from the Hoskissons seam, 8.4 m below the bottom contact of the dolerite sill, show gas contents in the range 6-9 m^3/t (daf). The mean maximum vitrinite reflectance is 0.76-0.80% and no slits or pores are present.

The samples within the thermal aureole above the unaltered Hoskissons seam show higher gas volumes. A similar situation has taken place below the upper intrusion gas (content 10-15 m^3/t daf). This increase in gas volume in thermal aureoles below both dolerite sills may be due in part to additional methane generation during coalification from high-volatile bituminous coal to medium-low volatile and anthracite.

Gas Composition

Gas analyses on coals in YE 1 generally indicate methane contents above 90% (air-free basis) with the remainder being principally carbon dioxide. Nitrogen levels are usually below 1%. Where analysed, higher hydrocarbons comprise a very minor component up to 0.05%. Methane levels for intruded coals within thermal aureoles are very high (95%+), contrary to the CBM experience and expectation. Unaltered coal samples representing the Hoskissons seam (zone G) also contain high level of methane (90-99%) with a mean of 94%. The lowest methane contents (78%-88%) were returned by samples higher in the hole (unaltered zone A).

CONCLUSIONS

The coal petrology of samples from borehole ACM Yannergee DDH 1, collected from above, between, and below two dolerite sills, indicates that thermal aureoles extended:

- below the sills for a distance of approximately half the thickness of the sill, and
- above the sills for a distance approximately equivalent to the sill thickness.

It is speculated that the upper aureoles are thicker as the result of the upward movement of volatiles following intrusion.

The thermal aureoles can be clearly identified from profiles of mean maximum vitrinite reflectance and in particular from bireflectance profiles. In addition, heat-affected coals under the microscope display characteristic features (e.g. slits and devolatilisations pores), that are not otherwise present.

The gas content of some heat-affected coals was found to range from 10-12 m^3/t (daf). Unintruded coals some 5 m below these heat-affected coals were found to contain gas in the range 6-9 m^3/t (daf). All the samples were found to contain > 90% methane.

More work needs to be done. Nevertheless, these results confirm that locally increased rank due to igneous intrusions can be potentially significant for coal bed methane. The igneous intrusions in YE 1, by providing an additional heat source have elevated coal rank from high-volatile bituminous through medium-low volatile to anthracite. The progress in coalification, although over a short stratigraphic distances, was probably accompanied by the generation of thermogenic gas. The two sills in each case may have acted as seals immediately overhead. The thermal methamorphism of the coals appears to have produced additional surfaces (pores and slits) for methane adsorption.

ACKNOWLEDGMENTS

The Authors wish to acknowledge the permission of Australian Coalbed Methane Pty Ltd and Pacific Power to include data from exploration programs in the Gunnedah Basin in this presentation and provision of samples for petrographic study.

This work was undertaken as part of Australian Research Council Collaborative Research Grant No. ARC C39917621.

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Is it that intrusions create oil to occlude gas.

COALIFICATION PATTERN OF THE GUNNEDAH BASIN, NSW

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INTRODUCTION

The overall objective of this study is to evaluate the degree of coalification (coal rank) of the Gunnedah Basin coals using different indices, and delineate the 3-dimensional coal rank pattern in the basin. Extensive data sets comprising 400 measurements of vitrinite reflectance, together with further proximate and ultimate analyses and electron microprobe data, have been used to study regional and local coal rank trends (Gurba, 1998). The Gunnedah Basin provides an excellent prototype from which many of the factors affecting the coalification pattern of high-volatile bituminous coals can be demonstrated.

Coalification and the Concept of Coal Rank

The development from peat through the stages of the different brown coals (lignites), sub-bituminous and bituminous coals to anthracites and meta-anthracites is termed ***coalification.*** The relative level of coalification determines ***coal rank,*** that is the position of a coal in the peat-anthracite series. Being a concept rather than a property (Diessel, 1992), rank cannot be measured, but it can be assessed by means of those physical and chemical coal properties which change most during coalification. Different methods have been applied to monitor these changes.

The coal rank in the Gunnedah Basin has been investigated using both petrographic (vitrinite reflectance and fluorescence) and chemical methods (proximate and ultimate analyses, and electron microprobe techniques). The intention of this study was to investigate the efficacy of particular rank parameters over the high-volatile bituminous range, such as encountered in the Gunnedah Basin, in order to highlight the complexity of the coal rank concept and draw attention to the inherent limitations of coal rank studies involving a single rank parameter. An attempt has been made to evaluate a number of different coal rank indicators together, and compare one to other, rather than investigate one single factor as an indicator in isolation. Of particular importance to this study was the validity of vitrinite reflectance, air-dried moisture content and elemental carbon of vitrinite (telocollinite) as rank parameters through the high-volatile bituminous range.

Geological Setting

The area for the present study is located in the Mullaley Sub-basin, which makes up the central part of the Gunnedah Basin (Figure 1). The Gunnedah Basin is part of the Sydney-Bowen foreland basin system of Eastern Australia. It contains up to 1200 m of marine and non-marine Permian and Triassic sediments. The Permian sedimentary sequence was formed by three major terrestrial depositional episodes separated by two marine transgressive/regressive events. Coals occur in two separate stratigraphic intervals, the Leard and Maules Creek Formations near the base and the Black Jack Group at the top of the Permian sequence, with a thick marine succession, the Porcupine and Watermark Formations, in between. In the western and northern parts of the basin the Permo-Triassic strata are overlain by rocks of the Jurassic and Cretaceous Surat Basin sequence. The detailed stratigraphy, depositional and structural subdivisions of the Gunnedah Basin are given by Tadros (1993, 1995).

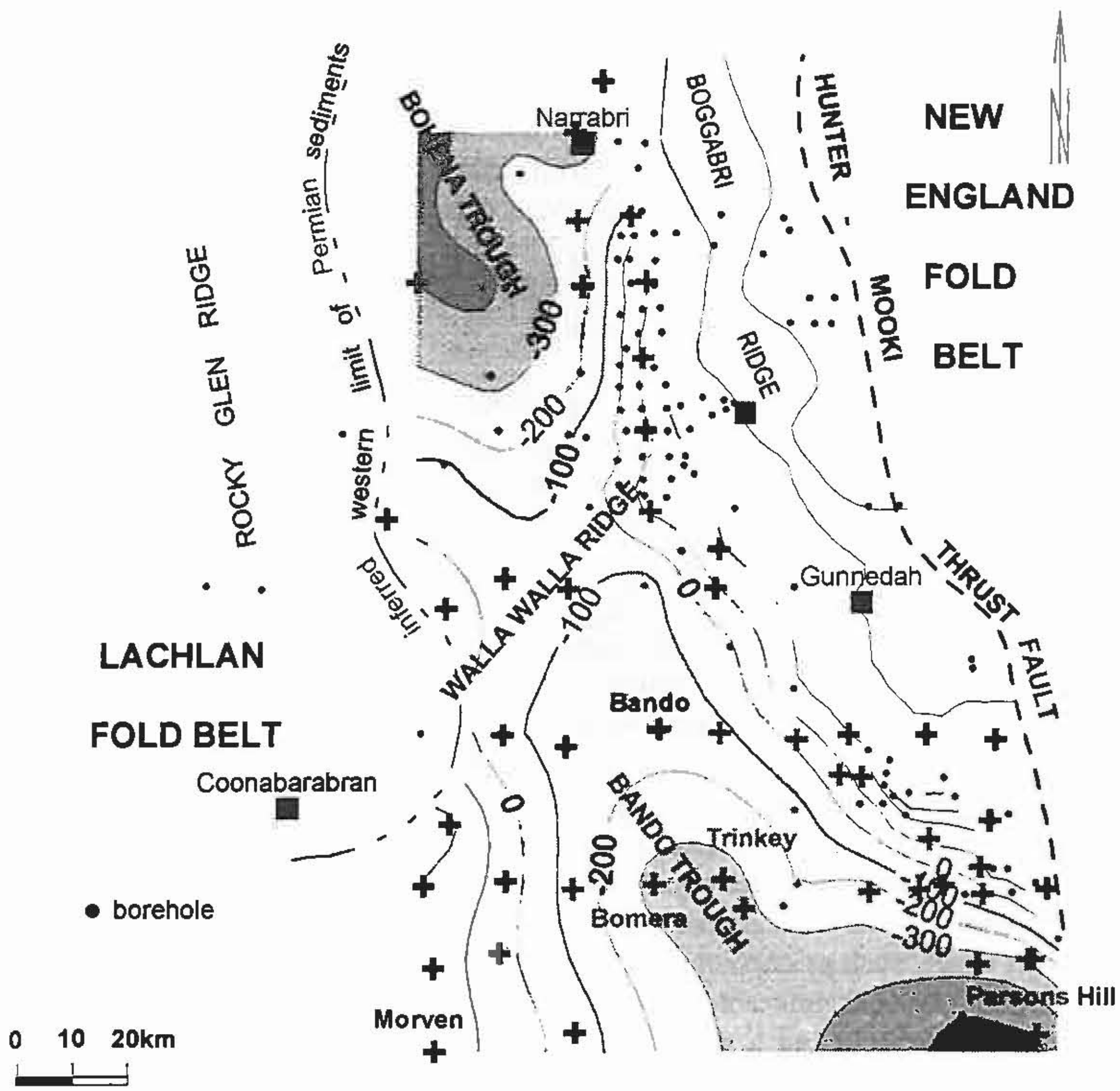

Figure 1. Location of the study area in the Gunnedah Basin and structure contour map (m asl) on the base of the Hoskissons Seam (Upper Black Jack Group, Late Permian). (+) indicates borehole sampled for vitrinite reflectance.

THREE-DIMENSIONAL PATTERN OF COAL RANK VARIATION

Coal Rank

The coal in the Gunnedah Basin is of high-volatile bituminous rank, with a mean maximum vitrinite (telocollinite) reflectance of between 0.56 and 1.1 % and air-dried moisture that varies from more than 8% to less than 2%. Over this range the elemental carbon of telocollinite determined by electron microprobe ranges from 77% to 87 % (wt); whole-coal carbon content (dry, ash-free) as determined by ultimate analysis increases from about 79% (daf) to about 86% (daf), and the whole-coal oxygen decreases from about 14% (daf) to less than 6% (daf). The volatile matter content ranges from 25% (daf) to 45% (daf). Increases in volatile matter and hydrogen contents commonly occur in marine-influenced coals. Maximum vitrinite reflectance above 1.5%, carbon content above 87% (daf), oxygen below 5% (daf) and volatile matter below 20% (daf) usually indicate coals that are heat-affected due to igneous intrusions.

A relatively good correlation has been established between vitrinite (telocollinite) reflectance and moisture for the coals (excluding marine-influenced) in the Gunnedah Basin (Gurba and Ward, 1995). A moisture content below 2% almost invariably indicates mean maximum vitrinite (telocollinite) reflectance very close to or above 0.8%. The air-dried moisture content of Gunnedah Basin coals is controlled chiefly by coal rank, and unlike vitrinite reflectance is not affected by depositional environment or maceral composition. Elemental carbon of telocollinite determined by electron microprobe also seems not to be significantly affected by the changes in depositional environment that cause lower reflectance in marine-influenced coals.

Coalification Profiles

Detailed coalification profiles have been constructed for several boreholes based on mean maximum vitrinite reflectance, air-dried moisture content and carbon content (dry, ash-free). The stratigraphic intervals covered in this study range from 70 to 900 m. In addition to rank-induced trends, anomalies in vitrinite (telocollinite) reflectance have been identified and mapped due to depositional environment, igneous intrusions and 'pseudovitrinite' (discussed by Gurba and Ward, 1998). If allowance is made for these anomalies, linear (first-order) regression lines generally fit the profile best and coalification increases more or less with stratigraphic depth..

The increase of rank with depth is generally expressed as coalification gradient (% $R_V$max/100m). Coalification gradient determined for the Permian sediments based on mean maximum vitrinite (telocollinite) reflectance ranges from 0.025% $R_V$max/100m to 0.2% $R_V$max/100m. Values obtained from the south-eastern part of the Gunnedah Basin range from 0.025 to 0.035 $R_V$max/100m, whereas in the western part values are slightly higher and average about 0.06% $R_V$max/100 m. The lowest coalification gradient 0.025%$R_V$max /100m determined in DM Parsons Hill DDH 1 (south-eastern part of the Gunnedah Basin) may be the result of low paleogeothermal gradient reflecting a low paleo-heat flow, or it may be the result of very rapid sedimentation and uplift.

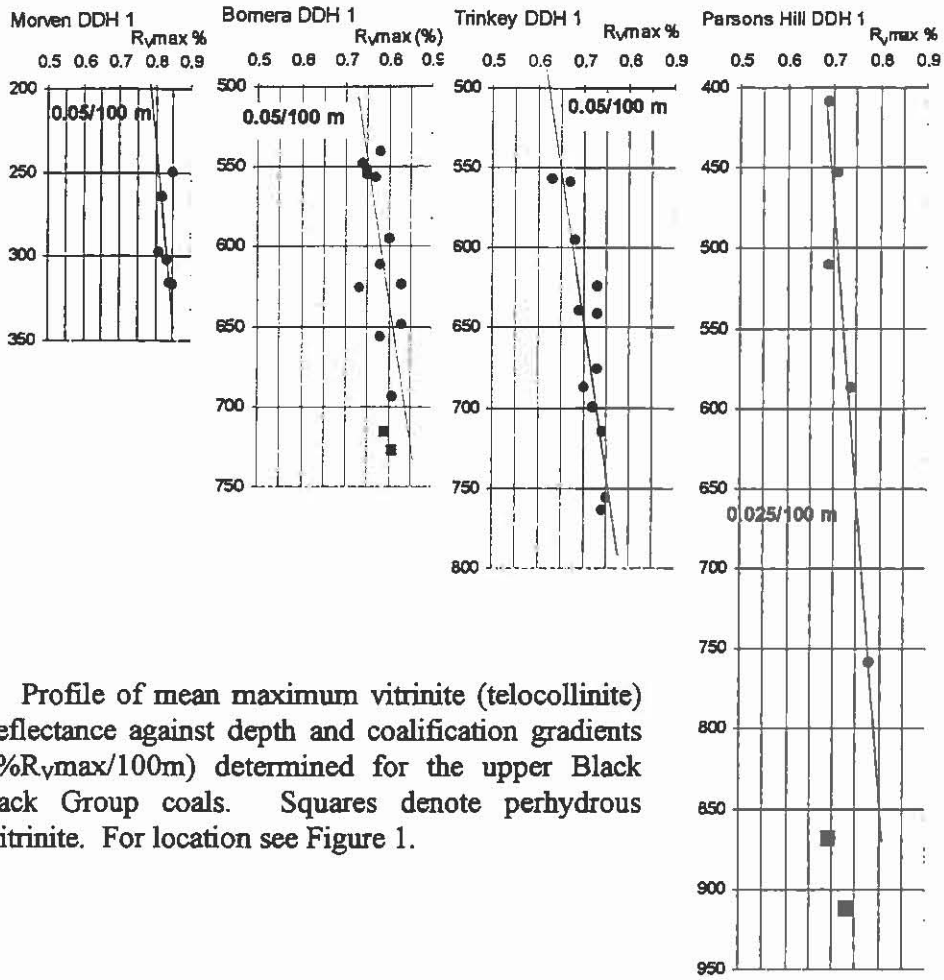

Figure 2. Profile of mean maximum vitrinite (telocollinite) reflectance against depth and coalification gradients (%$R_V$max/100m) determined for the upper Black Jack Group coals. Squares denote perhydrous vitrinite. For location see Figure 1.

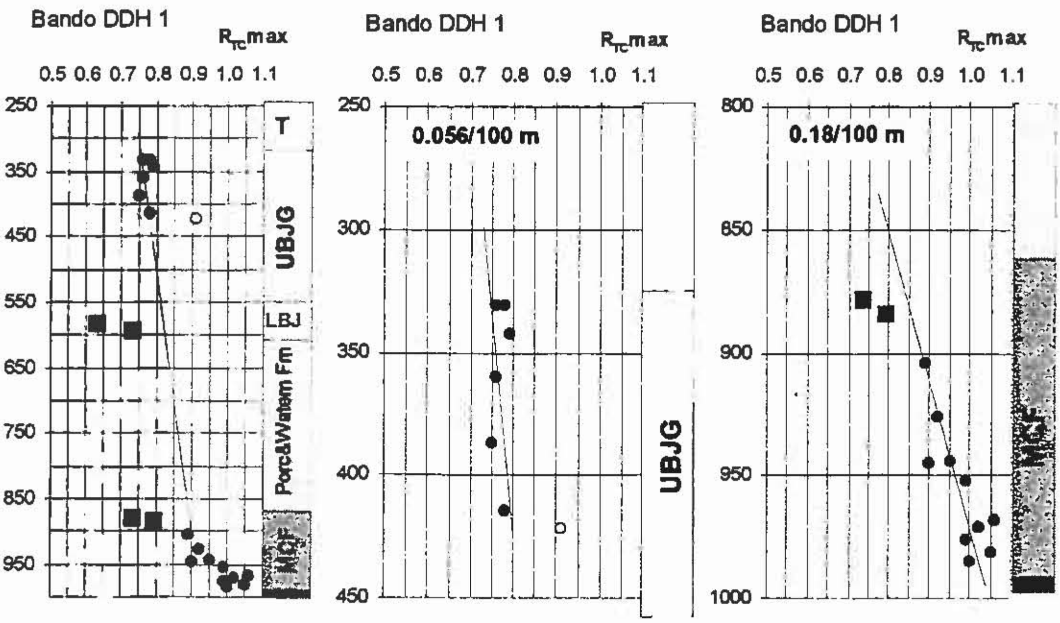

Figure 3. Profile of mean maximum vitrinite (telocollinite) reflectance against depth for DM Bando DDH 1. Paleogradients have been calculated individually for the upper Black Jack coals (middle) and for the Maules Creek Formation (right). Squares indicate perhydrous vitrinite. For location see Figure 1.

Coalification gradients estimated separately for the Early Permian sediments are in the range 0.10-0.20 R_Vmax/100m, and are higher than for Late Permian Upper Black Jack Group (Figures 2 and 3). The change in gradient in DM Bando DDH 1, as shown in Figure 3 may be due to a curvilinear pattern in the reflectance/depth relationship (Suggate, 1998) or due to different rates of heat flow in the Early Permian sediments. The higher paleogradients in the lower part of the succession are consistent with a rift setting for the basin in the Early Permian (Scheibner, 1993), with a relatively high rate of heat flow. The upward change to a lower gradient is probably associated with the change from rift to foreland tectonics during the basin's depositional history. The limited data on coalification gradient in the Early Permian sediments in this part of the Gunnedah Basin do not allow further elaboration of this discussion.

Based on extrapolation of mean maximum vitrinite reflectance data to an initial reference value (R_Vmax=0.2%), the estimated eroded section in the Gunnedah Basin varies from about 1000-1500 m along the eastern side to below 500 m in the central part and about 800-900m along the western side, next to the Rocky Glen Ridge. The estimation of paleogeothermal gradients and the thicknesses of section eroded are subject to errors due to the short stratigraphic intervals covered (especially in the western part) and depositional factors influencing the evolution of vitrinite reflectance. Despite these factors, the estimation of eroded section in the Gunnedah Basin seems to support fluid inclusion data presented by McDonald and Skilbeck (1996).

Lateral Rank Variation

Coal rank in the Gunnedah Basin increases from the north-east to the west and south-west (Gurba and Ward, 1995). This is indicated by the lateral distribution of air-dried moisture, carbon (dry, ash-free) and mean maximum vitrinite (telocollinite) reflectance in the laterally continuous Hoskissons seam (Late Permian, Upper Black Jack Group). With allowance for coal type and anomalies in vitrinite reflectance, it is also shown for the Permian sequence generally.

The pattern of coal rank variation for the underlying Melvilles seam appears to reflect similar lateral changes in coal rank across the basin, although the vitrinite reflectance values are lower than those of the Hoskissons seam, due to marine influence on this part of the succession. If these environmental factors were not taken into account, the coal rank as expressed by vitrinite reflectance would appear to decrease for the lower Back Jack Group coals, relative to those of the upper Black Jack Group interval.

Up to a distance of about 20 metres below the top of the Early Permian Bellata Group measured vitrinite reflectance data deviate towards low values from the "normal" regression line, due to the effects of marine influence associated with the Porcupine Formation. The values can be up to 0.2% lower than these for unaffected coals. The rank trend for the lower Bellata Group, however, after removal of effects due to marine influence, corresponds closely in form to the lateral trend in maximum vitrinite (telocollinite) reflectance exhibited by the Hoskissons seam, but with higher overall values involved.

TIMING OF COALIFICATION

The relationships between the relative timing of coalification and tectonic deformation may be divided into three types: (1) pre-deformational coalification; (2) syn-deformational (or pre- + post-deformational coalification; and (3) post-deformational coalification. The Gunnedah Basin has had a complex subsidence history that involved several phases of subsidence interrupted by episodes of uplift and erosion (Tadros, 1993).

The geometry of the geological structure of the Gunnedah Basin and the three-dimensional pattern of coal rank variation have both been expressed as a series of surfaces using computer-based modelling techniques. From the regression lines the elevation of 0.75% and 0.80% mean maximum vitrinite (telocollinite) reflectance and the elevation to 2% moisture content (air-dried) were determined for each individual borehole. A comparison of the isorank lines (Figure 4) with the structure contours of the basin (Figure 1) provides evidence that coalification in the Gunnedah Basin could not have been exclusively pretectonic or entirely post-tectonic. Individual compartments of the Gunnedah Basin achieved their current degree of coalification in different times.

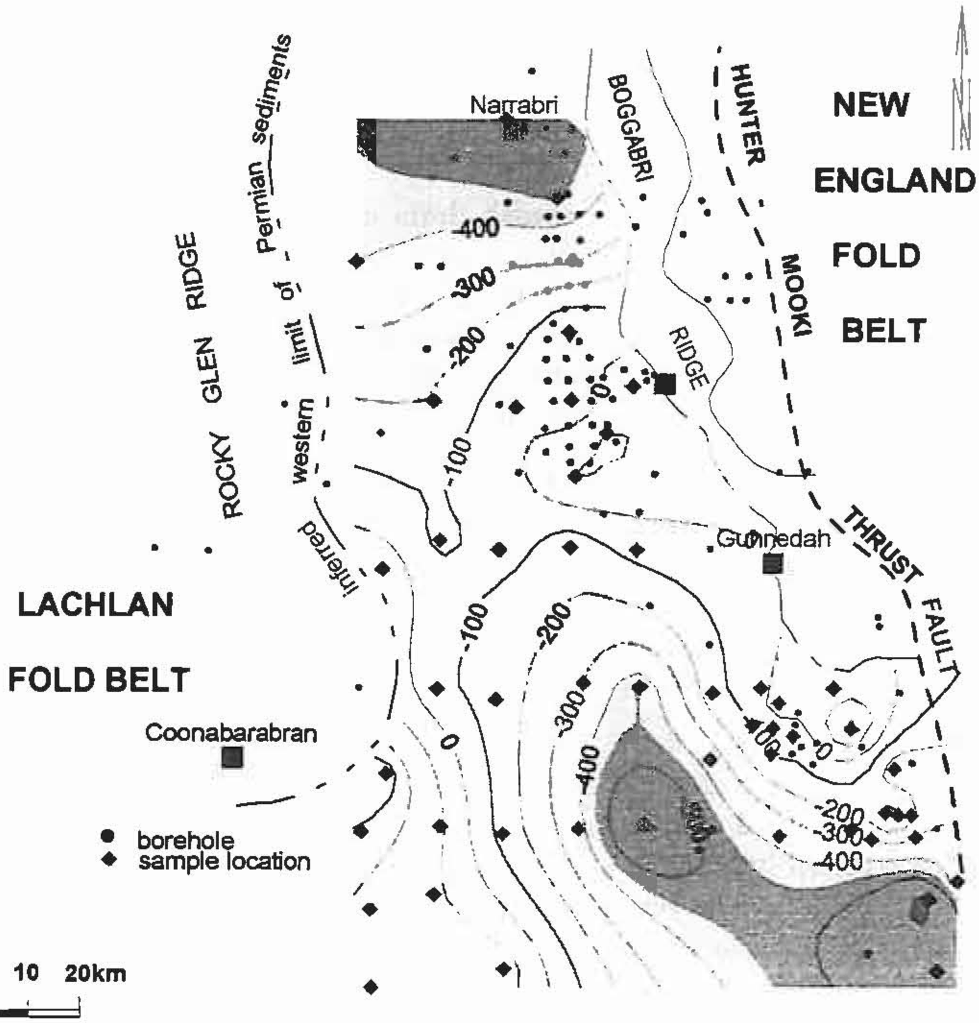

Figure 4. Structure contours (m asl) of the 2% moisture content (air-dried).

In general, the iso-rank surface marked by the 2% moisture value (Figure 4) follows the structure on the base of the Hoskissons seam in the central part of the basin fairly closely, although the relevant surfaces dip at slightly different angles. A different pattern exists north of the Walla Walla Ridge, where the northerly-dipping iso-rank surface cuts across the synclinal geological structure of the Bohena Trough. The spatial configuration shown by structure contours of the 2% air-dried moisture is confirmed by the iso-rank surface representing 0.80% mean maximum vitrinite reflectance as well that representing 0.75% $R_v$max.

On the basis of this coalification pattern, it is suggested that coal rank was established largely before deformation, although some syn- and/or postdeformational coalification has occurred. Two phases of coalification probably took place: the first before the Middle Triassic uplift and erosion, and the second phase (or continuation of the first) during burial under the Jurassic of the Surat Basin. The relationship of the coal rank spatial system to geological structure along the eastern side of the Gunnedah Basin seems to support the uplift suggested for the northern part of the Gunnedah Basin between the Permian and Triassic by Korsch et al. (1993) and Tadros (1993). The southwestward coal rank increase observed in the Gunnedah Basin was probably an expression of an increase in paleogeothermal gradient in that direction combined with burial by the overlying Surat Basin succession. Such a variation in paleogeothermal gradient may be associated with basement discontinuities.

INFLUENCE OF IGNEOUS INTRUSIONS ON COAL RANK

Overprinted on the general rank pattern are high rank anomalies due to igneous intrusions. The thermal aureoles associated with the intrusions are generally very narrow, and contact metamorphism is not an explanation for the regional increase in rank from east to west in the Gunnedah Basin. The lateral variation in rank (highest in the west) in relation to the distribution of igneous intrusions (mainly in the south-east) suggests that the presence of dykes and sills was not a major factor in producing the regional coalification pattern.

IMPLICATIONS FOR PETROLEUM EXPLORATION

Microscope observation shows evidence of oil expulsion from coal in many boreholes studied for this project. Carbon content and vitrinite reflectance data show that the coals of the Gunnedah Basin lie within the main oil generation zone. For Australian sedimentary basins Brooks (1970) regarded carbon contents of 80% and 85% as limiting values for the boundary between the oil generation zone and gas-condensate generation zone. The areas most promising for oil fields in Australia are those where little erosion of sediment has taken place subsequent to deposition and diagenesis. This may place the Bando and Bohena Troughs, with the small amount of erosion that has apparently occurred, as the most prospective areas in the Gunnedah Basin. However, in estimation of hydrocarbon potential of the Gunnedah Basin the regional distribution of thermal aureoles due to igneous intrusions also has to be taken into account.

ACKNOWLEDGMENTS

This study was carried out at the University of New South Wales, School of Geology as part of the research requirements leading to a PhD degree. Special thanks are expressed to New South Wales Department of Mineral Resources and to Pacific Power for assistance in the provision of samples and access to analytical data. The personal assistance of Carl Weber, Jeff Beckett and Julie Moloney, among others is gratefully acknowledged. Malcolm Bunny and Ian Milligan, of Earth Resources Pty Limited, are thanked for provision of geological data and assistance with sampling. Thanks are also expressed to Harold Read for help with sample preparation. The study was funded by an Australian Postgraduate Research Award, and in part under the Small Grants Scheme of the Australian Research Council. Scholarship and other support was also provided by Pacific Power.

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CARBONATE SPECIATION IN WYNN SEAM COAL

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INTRODUCTION

Carbonate minerals commonly occur in coal either as primary or secondary minerals. According to Stach *et al.* (1982) and Taylor *et al.* (1998) siderite/calcite are commonly-occurring carbonates primary minerals and calcite/siderite/dolomite are commonly-occurring secondary minerals.

This study was initiated to determine the location and properties of carbonate species in the Wynn seam which is the top seam of the Foybrook Formation (Fig. 1) of the Wittingham Coal Measures. The Wittingham Coal Measures has been divided into the Jerry's Plains Subgroup and the older Vane Subgroup. The latter contains two Formations - the Archerfield/Bulga Formation and the Foybrook Formation (older formation).

Diessel (1992) considered stated the Wynn seam and the Bayswater seam constitute the upper and lower portions of the same seam, a seam that has been split by a marine clastic wedge. The Wynn seam formed in front of an advancing sea whereas the Baystwater seam was formed behind a prograding shoreline. In some areas of the Hunter Coalfield, the Wynn seam, Baystwater seam and the Broonie seam coalesce to form a seam in excess of 20 m thick (Doyle and Lohe, 1996). In other parts of the coalfield, the Wynn seam splits into the upper Wynn seam and the lower Wynn seam.

A preliminary microscopic study of two randomly-selected samples from the Wynn seam showed siderite (small, <1 mm random, oolite-like bodies) and calcite (fracture infillings/veins). It appeared that the siderite was generally found in inertinite-rich microlithotypes and the calcite was associated with vitrinite layers. Given the importance of carbonates in the combustion of coal, it was decided to further investigate the occurrence of the carbonates minerals.

Five samples were selected from run-of-mine product with the aim of establishing:

i. the type and distribution of the carbonate species;

ii. the degree of liberation of the carbonates when the coal was crushed; and

iii. the distribution of the carbonates after float-sink tests.

CARBONATE MORPHOLOGY

Preliminary microprobe analysis of the carbonate veins showed dolomite and ankerite present as well as calcite. The three carbonates are reported as calcite in the remainder of this study because all point counts used reflected light microscopy and it was not possible to distinguish between dolomite, ankerite and calcite using this technique.

Based on morphology, the carbonates could be divided into several types.

Calcite

Simple Vein: a vein, normally perpendicular, sub-perpendicular or rarely intersecting bedding at an angle of 45° or more, that is filled or partially filled with calcite; some veins that are infilled with calcite show no crystal boundaries whereas other veins are filled with dogtooth spar (calcite) perpendicular to the long axis of the fracture.

Composite Vein: a vein, normally perpendicular, sub-perpendicular or rarely intersecting bedding at an angle of 45° or more, that is filled or partially filled with two or more phases of calcite.

Dendritic Vein: a set of veins comprising one or more large fractures with several dendritic fractures diverging from near one or both ends of the main fracture; all fractures are filled with calcite.

Feather Vein: a set of veins comprising one large vein that is relatively long, normally perpendicular, sub-perpendicular or rarely intersecting bedding at an angle of 45° or more, with several smaller, shorter veins, commonly paired on either side of the main vein; each vein in the set is filled or partially filled with calcite.

En Echelon Veins: a set of veins comprising several relatively short fractures, oriented oblique to bedding, which occur as a set that abut a simple vein near the mid section of the latter.

Ladder Vein: a set of veins comprising two large fractures, relatively long, normally perpendicular, sub-perpendicular or rarely intersecting bedding at an angle of 45° with several smaller, shorter veins between the larger fractures; all veins are filled with calcite.

Parallel Vein: a vein, normally parallel, sub-parallel or rarely intersecting bedding at an angle of 20° or less, that is filled or partially filled with calcite.

Breccia: macerals, usually vitrinite, so strongly intersected with calcite veins, generally perpendicular to sub-perpendicular to bedding, that the zone has a brecciated texture.

Cell Infillings: cell lumen in fusinite and semifusinite filled with calcite.

Siderite
Simple Nodule: a single spherical to ovoid siderite 'pod' composed of numerous radiating crystals; the lengths of the diameters of simple nodules are variable.

Composite Nodule: normally a group of two or more spherical to ovoid siderite 'pods', each composed of numerous radiating crystals; composite nodules have a variety of shapes but generally are somewhat flattened parallel to bedding.

DISTRIBUTION OF CARBONATES

The first exercise was to determine the distribution of the siderite and calcite. To do this, representative subsamples from each of the five samples were selected and 200 randomly selected fields examined. The average diameter of siderite nodules in each field was estimated using a graticule in the ocular of the microscope (Table 1).

Microscopic observation confirmed the observations made for hand specimen. Calcite is predominantly found in vitrite and vitrinertite layers; siderite is predominantly found in inertite layers but also, less commonly, in vitrite and vitrinertite layers. Of the fields counted, 77% of the field containing siderite nodules were in inertite, with only 11% and 12% of the fields in vitrite and vitrinertite, respectively. On a microlithotype basis, 40% of the inertinite fields counted contained one or more siderite nodules whereas only 7% and 12% of the vitrite and vitrinertite, respectively, contained siderite.

Most inertinite fields contained several siderite nodules whereas most vitrite and vitrinertite fields contained only a single nodule. However, the average diameter of the siderite nodules was larger in vitrite than in inertite. In inertite, the average diameters of siderite were clearly biased towards the low size end of <0.1 mm (44% of the total fields containing nodules and 57% of the inertite fields containing nodules). In vitrinite and vitrinertite most siderite nodules were in the size range of 0.5-1.0 mm (4.7% of the total fields counted and 38% of the fields in vitrite) and 0.1 to 0.5 mm (6.0% of the total fields counted and 50 % of the fields in vitrinertite).

FLOAT-SINK TESTS

To determine the effect of density separation on the carbonate distribution, polished grain mounts were prepared from each *float-sink* fraction and examined in reflected light mode. A point count was carried out to determine the occurrence and distribution of the carbonates in each fraction (Table 2). A second point count to determine if there was a correlation between the carbonate type and the maceral type was also undertaken, using the same polished blocks (Table 3).

The samples for float-sink tests were ground to -11.2 with the -0.5 mm fraction removed as per the Australian Standard AS 2646.6 (HARD COAL - PREPARATION OF SAMPLES). One half of the crushed sample was set aside for sizing according to Australian Standard AS 1038.17(D) (SIZE ANALYSIS OF COAL AND COKE [using 'square hole' sieves]) (Table 4.) and the second set was set aside for *float-sink* analysis as per the Australian Standard, AS 1661 (FLOAT AND SINK TESTING OF HARD COAL) (Table 5).

Of the crushed coal, 64% of the crushed coal was in the S1.6 fraction. Whereas the sample used in this study was relatively small and biased towards coal containing abundant carbonate, these data suggest that washing the coal at a density of 1.6 removes a significant amount of the carbonate, but not all.

Occurrence and Distribution of Carbonates

The data clearly (Table 2) show that the abundance of both calcite and siderite increases as the density fraction increases. The S1.6 fraction contains 24.8% and 12.7% calcite and siderite respectively whereas the F1.4 fraction contains only 0.9% and 0.8% calcite and siderite respectively. The carbonates generally are within coal grains rather than occurring as free carbonate. The *float-sink* samples were originally crushed to -11.2/+0.5 mm and then crushed to -2 mm in the laboratory prior to setting in Astic resin. Under these conditions, the majority of grains were greater than 0.1 mm diameter, and as is shown in the following section little carbonate is liberated as free carbonate grains until the grain size is approximately -0.125 mm.

It was also noted that the samples contained only minor mineral matter other than carbonate, mostly clay minerals.

Coincident with the trend for increased carbonate in the denser fractions, there is a decrease in the telocollinite and desmocollinite contents in the denser fraction. The inertodetrinite content appears to increase with increasing density of the fraction. Semifusinite in the F1.4 fraction has large open cell lumen whereas in the F1.6 and S1.6 fractions, the cell lumen are mostly filled with calcite. The F1.4 fraction contains essentially mineral-free coal.

Carbonate-Maceral Associations

Maceral-maceral and maceral-carbonate associations were counted. Each grain was allocated to a category depending on its composition. Where grains contained more than 90% (visually estimated) of one maceral or one carbonate, the grain was allocated a single-maceral or single-carbonate category. Where a grain contained more than 10%, combined, of two or more macerals and/or carbonate, the grain was allocated to a bimaceral-carbonate or trimaceral-carbonate category.

These data show that as the density of the fractions increases, the calcite and siderite content increases. For example, in the S1.6 fraction, 55.5% of the grains contain vitrinite and calcite, 5.8% of the grains contain vitrinite and siderite and 25.8% of the grains contain vitrinite-inertinite and calcite and/or siderite. Thus 87.1% of the grains contain carbonate in one association or another. A small number of grains consist only of calcite or siderite. For the F1.4 fraction, less than 1% of the grains contain carbonate.

SIZE ANALYSIS

The size analysis subsample was sieved with mesh diameters of 1.4 mm, 0.5 mm, 0.125 mm and 0.075 mm. The weight of each sized fraction was taken and representative subsamples were made into polished grain mounts. A point count on each block was made (Table 2) to determine if there was relationship between grain size and the occurrence and abundance of carbonate after crushing.

The significant findings from the data are that neither calcite nor siderite are liberated until the grain size is in the size fraction of -0.5 mm to +0.125 and the finer the grain size the greater the liberation of carbonates. At a grain size of -0.5 to +0.125 mm, 0.9% and 1.2% of the calcite and siderite are liberated, respectively. At a grain size of -0.075 mm, 9.9% and 2.1% calcite and siderite, respectively, are liberated. Whereas there is a significant increase in the proportion of calcite liberated with decreasing grain size, the proportion of siderite liberated with decreasing grain size does not appear to change significantly below a grain size of -0.125 to +0.075 mm.

It is also significant that mineral matter other than carbonates was not liberated as the grain size decreased. This may be a function of the small amount of non-carbonate mineral matter in the sample initially or because the clay minerals, the dominant mineral matter other than carbonate, is confined to cell lumen which have a size range that is smaller than 0.075 mm.

With respect to macerals, there is a decrease in the percentage of telocollinite and semifusinite as the grain size decreases as might be expected. Both macerals are large and are progressively broken into smaller pieces. As a consequence, the crushing produces many fragments of coal that are within the inertodetrinite size range and that were counted as inertodetrinite (derived from semifusinite) or desmocollinite (derived from telocollinite).

Given the width of the veins, it is predicted that most of the liberated calcite was derived from the larger *composite* and *simple* calcite veins rather than smaller *dendritic, feather, en echelon, ladder and parallel veins*, the *breccia* zones and the *cell infillings*.

The reserve sample indicates that siderite and calcite were approximately equal constituents of the coals initially (7.6% and 8.5% respectively). However, as stated above, the percentage of siderite in the finer fractions is approximately 2%. On the other hand, the percentage of siderite in fractions greater than the -1 to +0.5 mm size range is similar to that in the reserve samples. This indicates that although crushing to increasing smaller grain sizes increases the proportion of calcite liberated, this is not the case for siderite. The data suggest that the siderite is a harder, more competent mineral that is difficult to crush to a small grain size. The siderite would only be effectively liberated where all grains were crushed to a small size. To do this would produce a very fine-grained product that has inherent difficulties in relation to handling and storage. It may also require froth flotation to separate the density fractions rather than the conventional float-sink methods.

SUMMARY

Siderite, calcite, dolomite and ankerite were identified in run of mine samples from the Wynn seam, Wittingham Coal Measures.

1. The carbonates in the Wynn seam are siderite, occurring as single and composite

nodules, and calcium carbonates including calcite, dolomite and ankerite. Siderite is found mostly in inertinite-rich microlithotypes, such as inertite, whereas the calcium carbonates infill veins which have a variety of morphologies. Calcium carbonates are concentrated in the vitrinite-rich microlithotypes such as vitrite.

2. When crushed, neither calcite nor siderite are liberated until the grain size is in the size of the grains is as small as 0.5 mm to +0.125 mm; the finer the grain size the greater the liberation of carbonates.

3. The *float-sink* data show that a combination of crushing to a grain size of less than 2 mm and then washing at a density of 1.5 to 1.6 would effectively separate carbonate from the coal. However, this would be accompanied by a decrease in yield of coal product unless the grain size was less than 0.5 mm. The float fraction would be enriched in vitrinite and reduced in inertinite compared to original sample.

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Table 1. Occurrence of Siderite Nodules in Various Microlithotypes.

		SUBSAMPLE													
		DB 1	DB 4	DB 7	DB 9	DB12	DB13	DB14	DB15	DB18	DB20	Total		% of Total Nodules	
	Siderite Diameter														
Inertite	<0.1 mm	6	13	14	32	57	1	15	1			95		44.2	
	0.1-0.5 mm	5	2		2	3	6	13	21			53		24.7	
	0.5-1.0 mm								3	11	3	18		2.8	
	1.0-1.5 mm												*166*	0.5	*77.2*
	>1.5 mm														
	Zero Nodules*	16	17	16	21	2	38	4	24	7	5	246			
Vitrinite	<0.1 mm														
	0.1-0.5 mm				1				1	11	3	6		2.8	
	0.5-1.0 mm		1	1					3	1	2	10		4.7	
	1.0-1.5 mm			1					1		1	6		2.8	
	>1.5 mm									1		1	*23*	0.5	*10.7*
	Zero Nodules*	29	33	54	25	37	35	46	26	3	16	304			
Vitrinertite	<0.1 mm	3	3	1	1						1	11		5.1	
	0.1-0.5 mm			1	1		1	5			1	13		6.0	
	0.5-1.0 mm		1					2	5		1	2		0.9	
	1.0-1.5 mm								1						
	>1.5 mm														
	Subtotal												*26*		*12.1*
	Zero Nodules*	40	31	12	17	1	19	14	13		38	185			
Total Number of Nodules		*14*	*20*	*18*	*37*	*60*	*8*	*35*	*36*	*24*	*13*		*215*		

* - nodules were not observed in the fields

Table 2. Point Count Data for Carbonate Liberation.

	PERCENTAGE OF GRAINS													
Size Fractions	Telo	Desmo	Fusinite	Semi	Inerto	Macrinite	Sclerot	Liptinite	Minerals#	Voids	Free Calcite	Free Siderite	Calcite-Coal	Siderite-Coal
Fines	28.8	17.6	0.3	19.3	12.6	1.0			2.1	2.0	4.2	1.0	9.1	1.0
Reserve	11.7	18.7	0.9	26.4	14.9	2.8	0.6	0.9	1.2	5.0			7.6	8.5
-2.0 to +1.0	10.0	17.4	0.3	26.4	12.5	2.2		0.6	1.6	4.8			11.6	12.2
-1.0 to +0.5	13.9	18.5	1.2	31.1	12.5	1.6		0.3	0.9	4.5			11.6	7.7
-0.5 to +0.125	18.5	20.5	1.3	21.4	15.6	2.2		0.9	0.3	1.8	0.9	1.2	10.4	6.5
-0.125 to +0.075	23.7	18.5	1.6	20.6	10.7	2.5			0.3		4.4	2.2	11.0	1.8
-0.075	27.6	15.6		15.6	23.4	2.1			0.3		9.9	2.1	9.9	1.4
Density Fractions														
F1.4	27.0	31.6	1.6	24.1	7.4	0.9		0.9	2.2				0.9	0.3
F1.5	22.8	26.2	1.5	30.4	4.8	1.8			0.9	5.1			3.6	1.8
F1.6	12.2	24.8	1.2	30.9	10.6	1.6		0.3	3.2	3.2			7.7	3.8
S1.6	2.1	20.0	1.8	24.7	10.5	0.3	0.3		2.1	2.5			21.8	12.7

Telo – Telocollinite; Desmo – Desmocollinite Semi – Semifusinite; Inerto – Inertodetrinite; Sclerot – Sclerotinite # - minerals excluding carbonates

Table 3. Point Count Data, Carbonate Associations.

Fraction	Association									
	V	V>I	V=I	I>V	I	Cal in V+I	Cal Free	Sid in V+I	Sid Free	Cal &/or Sid in V+I
F1.4	11.6	7.7	69.4	5.3	3.8			0.4	0.4	
F1.5	16.4	6.5	38.9	1.4	4.2	27.2	0.4	3.2	0.9	0.4
F1.6	8.0	2.5	32.8	8.5	6.0	34.3		6.0	0.5	1.0
S1.6	2.9	0.4	8.3			55.3		5.8	1.4	25.8

V - vitrinite; I - inertinite; Cal - calcite; Sid - siderite

Table 4. Size Distribution

Size (mm)	Fractional %	Cumulative %
-2.0 to +1.4	34.8	34.8
-1.4 to +0.5	37.4	72.2
-0.5 to +0.125	19.6	91.8
-0.125 to +0.075	3.3	95.1
-0.075	4.9	100.0

Table 5. Float-Sink Data

Fraction	Mass (g)	Fractional Mass%	Cumulative Mass%
F1.40	348.0	15.3	15.3
F1.50	196.0	8.6	23.9
F1.60	268.0	11.8	35.6
S1.60	1466.0	64.4	100.0

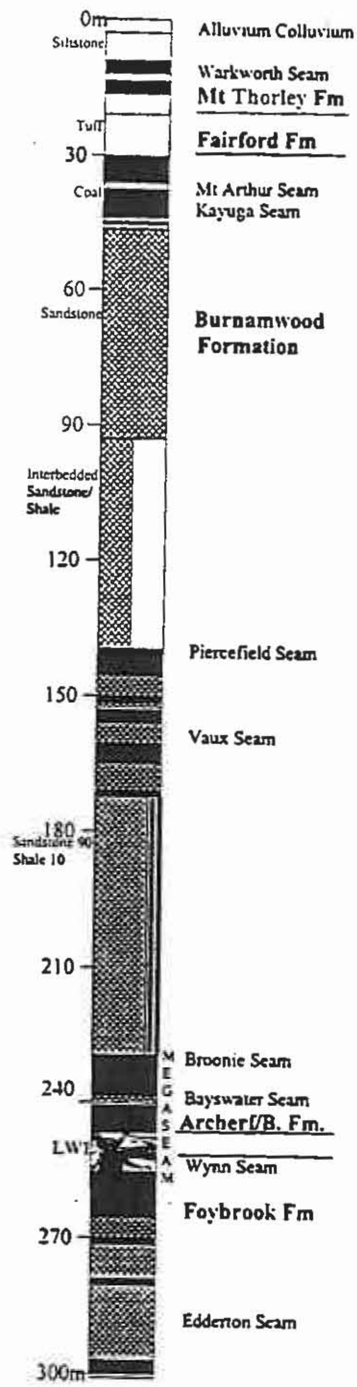

Figure 1. Stratigraphy of the Wittingham Coal Measures

AIRBORNE vs GROUND MAGNETICS FOR INTRUSION DELINEATION IN THE HUNTER

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Introduction
Aeromagnetic surveys (both fixed wing and helicopter) have been used very successfully in recent years by coal companies for mapping the larger igneous intrusions prior to, and during coal mining operations. Location of such hazards in a timely manner, especially for underground operations is critical to a mines success.

The more recent widespread use of high resolution ground magnetometers has also been very successful in mapping both large and smaller scale igneous intrusions and faults in some cases. This paper will show, by way of mosaic and comparative colour images, the additional hazards that can be mapped by ground magnetics. Due to limitations in colour plate reproduction here, the images presented are available at **www.ultramag.com\symp99.htm**.

As the coal industry moves towards more challenging geological environments, the author believes that ground magnetics has an indispensable role to play for many existing and new underground mine exploration programs.

A Coal Geologists Nightmare
There are at least two examples in the lower Hunter where 1m thick dykes thicken to over 10m at seam level at 200m depth. Such dykes, if unforseen, can pose major problems (seven digit price tags) to underground mines. Such hazards rarely outcrop and are almost impossible/uneconomic to drill. Furthermore, such hazards will not be detected by current aeromagnetic technologies, contrary to some industry beliefs.

Theory vs. Reality
Most dykes in the Hunter are best modelled as near vertical, thin sheets with infinite strike length. They are usually normally magnetised with small remanence and often have a "bulk" susceptibility of 0.01SI - typical of an "average" basalt. Dyke magnetic response at the surface (and in the air) is essentially a monopole. This means the magnetic intensity falls off with the inverse distance squared. Ground and instrument

noise aside, this fact is central to the difference in airborne and ground mapping capability. Table 1. Illustrates these facts.

Table 1. Dyke Magnetic Response

Theory (Modelling with Potent)				Reality of Detection in 1999		
Dyke Thickness [m]	**Groun d [nT]**	**Heli [nT]**	**Fixed Wing [nT]**	**Ground**	**Heli**	**Fixed Wing**
0.5	2.17	0.60	0.40	Sometimes	No	No
1.0	4.24	1.20	0.81	Usually	No	No
2.0	8.70	2.43	2.39	Yes	Sometimes	No
3.5	14.94	3.87	2.52	Yes	Yes	Sometimes
5.0	21.36	4.83	4.13	Yes	Yes	Yes

Notes :-

1. Terrain clearance/sensor height :-
    - 2m Ground
    - 50m Helicopter
    - 80m Fixed Wing
2. Depth from surface to top of unweathered dyke 20m.
3. Vertical dyke, normally magnetised
4. Responses are peak to peak and based on a "typical Hunter Valley dyke" :-
    - F = 57,200nT (Earths inducing field). I = -65° (inclination from horizontal). Az = 12° (Azimuth from North)
    - θ = -45° (NW strike). Survey lines perpendicular to strike.
    - k = 0.01 SI (magnetic susceptibility, including allowance for minor magnetic remanence in the direction of the earths field)

With typical aeromagnetic survey specifications of 0.01nT resolution, and ground specification of 0.1nT, a non geophysicist could be forgiven for assuming, that a fixed wing survey flown at 100m can easily detect a 0.5m thick dyke. The reality of detection is clearly far from this theoretical ideal. The reality of detection is based on interpretation of images using state-of-the-art ER Mapper, generated from several real overlapping data sets graciously provided by a number of coal companies in the Hunter Valley.

Assuming anomalies are no smaller than 5 times the resolution specification, the disparity between theoretical and actual detection capability is presented in Table 2.

Table 2. Practical Signal : Noise Ratio for a 2m Thick Dyke

	Theoretical Response [nT]	Actual Resolution [nT]	Signal : Noise Ratio
Ground	8.7	2.2	3.95 : 1 (ie. detected)
Helicopter	2.43	2.4	1.01 : 1 (ie. in noise envelope - marginal)

Fixed wing	2.39	2.5	0.96 : 1 (ie not detected)

Whilst claims of superior signal to noise ratio for airborne methods made by aeromagnetic contractors and associated consultants may be true at a theoretical level, the **real signal to noise ratio is close to 4 times better for ground surveys.** Put simply on a commercial footing, this means ground magnetics gives the best opportunity to detect and mitigate hazards from magnetic intrusions. This leads to :-

- Safer working conditions around intrusions (better management of potential gas build up etc.)
- Better mine design.
- Better mine management.
- More reliable production and continuity of supply and cashflow.
- More profitable mines.
- Follow on benefits to the general community.

The difference between theoretical instrument specifications and reality solutions is due to a number of factors including :-

- Spurious instrument noise.
- Unspecified instrument drift (ie alkalai vapour - airborne instruments).
- Heading/compensation errors.
- Poor diurnal correction (mainly airborne).
- Processing artefacts.
- Griding.
- Irregular terrain clearance (airborne).
- Geological noise ie paleo channels (all surveys).

Other noise sources effecting all surveys can include poorly understood regional scale induction currents in the upper crust (exacerbated in the air as base stations are on the ground) and localised cultural noise from railways, high tension power lines, mine infrastructure etc.

Whilst Table 1 is representative of a number of areas in the Hunter, it is not intended as a catch all approach. Magnetic properties of intrusions can be complex. Magnetic properties can vary considerably between intrusions in close proximity, both laterally and with depth for a given intrusion. There can also be a range of surface noise sources impacting differently on different types of surveys.

Depth Limitations

Magnetic modelling by the author (unpublished) indicates that, for sub 5m thick dykes in the Hunter Region, the bulk of the magnetic response can be attributed to the top 50m for a ground survey. It is thus difficult to reliably interpret incremental thickening/thinning of mafic dykes and plugs below this depth. A thin intrusion at 60m depth or greater can thus not be detected by any current surface or airborne survey.

Overcoming Depth Detection Limitations

Future technological developments facilitating deep intrusion detection could be three fold. Firstly, more sensitive vector magnetometers are in the sidelines. These may be suited to both ground and airborne use. However, they would require extremely accurate orientation systems (currently available, but expensive), better compensation systems coupled with better diurnal correction and better data processing systems.

Secondly, sensitive down hole magnetometers "looking" sideways could be deployed along with the conventional suite of well logs.

Thirdly, high sensitivity magnetometers could be incorporated into in seam drilling equipment and exploited in a proactive manner.

Conclusions

Of all the magnetic survey options available to the coal exploration geologist at the time of writing, only ground magnetic surveys can reliably detect typical basaltic Hunter Valley intrusions that are as thin as 1m in width and weathered in the top 20m.

The magnetic technique will evolve in the not too distant future to enable even better depth detection capability of all magnetic intrusions.

Given the ubiquity of sub 3m dykes in the Sydney Basin, unlikely to be detected from the air, the potentially high cost of dealing with such unexpected dykes in an underground mine and the relatively low cost (typically $ 4,000 to $ 7,000 / km^2) of ground magnetic surveys, not to mention safety issues, prudent mine managers could do worse than exploit the inexpensive insurance policy offered by high resolution ground magnetics.

NEW SIGNIFICANT SURFACES IN ONSHORE SEQUENCE STRATIGRAPHY

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INTRODUCTION

The development of sequence stratigraphy has drawn attention to the important part significant surfaces play in stratigraphic analysis. The term "significant" is used here primarily in a chronostratigraphic sense, i.e. sequence-stratigraphically significant surfaces are planes, mostly in the form of depositional discontinuities, that separate in time all overlying rocks from all underlying rocks. Unconformities, for example, have no physical or temporal relationship to their underlying rock types but form a time frame within which an ordered sequence of conformable strata was formed (van Wagoner et al., 1990). These strata can be hierarchically arranged into sequences, systems tracts, parasequence sets, parasequences, bedsets, beds, laminasets and laminae. Naturally, their bounding surfaces, which are the subject of this paper, also form a hierarchy measured by magnitude, frequency and significance.

THE SURFACES USED IN SEQUENCE STRATIGRAPHY

Stratal units are constrained by bounding surfaces five of which are commonly distinguished in sequence stratigraphy.

1. *Sequence Boundary (SB):* Surfaces of this kind rank highest in the hierarchical arrangement. They consist of unconformities and their correlative conformities that transcend litho-stratigraphic boundaries over large areas. Depositional breaks, erosion and onlap are common features of sequence boundaries. In Figure 1, a sequence boundary has been placed at the top of HST Parasequence 4 in the left portion of the diagram. The sequence boundary also constitutes the base of the PEATY SOIL which was formed during a eustatic lowstand from the exposed and degraded peat, although the latter was originally deposited by HST Parasequence 4, i.e. as part of the highstand systems tract. A similar situation was described by Diessel et al. (1995) and Diessel (1998) from the Hunter Valley where the sequence boundary occurs at the contact between the Wynn and the Bayswater seams.

2. *Transgressive Surface (TS):* The systems tracts that occur within a sequence are also separated by significant surfaces. The basal lowstand systems tract (LST) is underlain by the sequence boundary but is separated from the overlying transgressive systems tract (TST) by the transgressive surface. This surface is an expression of the first flooding that occurs in response to a relative sea-level rise, for example, at the beginning of a new eustatic oscillation. In Figure 1, the transgressive surface has been drawn as a wavy ravinement surface in order to infer partial erosion of the LST-derived PEATY SOIL.

3. *Maximum Flooding Surface (MFS):* The upper bounding surface of the transgressive systems tract is the maximum flooding surface which in marine environments occurs within the so-called condensed section due to the low rate of clastic deposition. The maximum flooding surface marks the highpoint in the eustatic oscillation and forms the demarcation between the onlapping transgressive systems tract below and the downlapping highstand systems tract above. Its upper bounding surface (not shown in Figure 1) is the sequence boundary that is eroded into the highstand systems tract after the sea level has dropped again to a low position. This sequence boundary also forms the base of the next overlying lowstand systems tract with which another sequence begins.

4. *Flooding Surface (FS):* Each systems tract is characterised by a specific set of parasequences formed in response to repeated advances of the sea. In the transgressive systems tract, parasequence sets show a retrogradational (landward stepping) arrangement, whereas in the highstand systems tract they are progradational, i.e. have a seaward stepping geometry. Parasequences are bounded by marine flooding surfaces which correspond to minor oscillations within the eustatic cycle. In Figure 1, three examples of parasequence-bounding marine flooding surfaces are illustrated as FS 1 to FS 3. Their wavy nature infers minor basal erosion. In coal seams that have been split by marine parasequences, the flooding surfaces may extend for some distance into the amalgamated portion of the seam as lagoonal or lacustrine shale bands. Detailed examples of these flooding surfaces and their extensions into coal seams have been described from the Gippsland Basin in Australia (Holdgate, 1997) and Lower Lusatia (Schneider, 1990, 1992; Standke et al., 1992, 1993; Suhr et al., 1992; Diessel, 1998).

5. *Bedding Surfaces (BS):* Parasequences are composed of stratal units with low magnitude and high frequency, represented by bedsets, beds, laminasets and single laminae. These stratal units are separated (and bounded) by stratification planes or bedding surfaces of various origins. Many are characterised by truncation, abrupt changes in composition and texture with or without slight erosion, or show signs of non-deposition in the form of intense bioturbation (burrows and/or roots). Because these bedding surfaces do not extend beyond the limits of the rock units they envelope, they have no specifically sequence-stratigraphic significance. In coal seams, beds correspond to lithotypes and their composing laminae.

SIGNIFICANT SURFACES IN COAL MEASURES

Although the above-mentioned stratal units and surfaces were originally defined in reference to marine sediments, they have been recognised in paralic coal measures as well (Beaumont et al., 1971; Ryer, 1984; Van Wagoner et al., 1987, 1990; Cross, 1988; McCabe, 1993; McCabe and Shanley, 1994; Aitken, 1994, Beaubouef et al., 1995; Bohacs and Suter, 1995, 1997; Boyd and Diessel, 1995; Diessel et al., 1995; Tyler and Hamilton, 1995; Petersen and Andsbjerg, 1996; Holdgate, 1997; Petersen et al., 1998; Diessel, 1998). The recent application of high-resolution sequence-stratigraphic analysis to coal seams by Diessel et al. (1998) has made it desirable to define five additional significant surfaces. Their identification is based on a detailed investigation of the vertical changes in coal seams and their interseam sediments, as well as detailed regional well correlation of the coal units (Wadsworth et al., 1998; Diessel et al., in press). Coal composition was investigated by means of photometric and maceral analyses on closely spaced lithotype-based strip samples and solid blocks over the full thickness of several coal seams from Australia and Canada. A discussion of the new surfaces is given below.

1. *Accommodation Reversal Surface (ARS):* Cyclic shifts between balanced and unbalanced accommodation / peat-accumulation ratios leading to reversals in accommodation trends appear to be widespread. Ideally, they follow the vertical pattern A→B→C→B→A, whereby the reversal surface coincides with the symmetry plane located in C. In coal seams, such a cyclic pattern may be shown by a lithotype succession beginning with predominantly bright coal at the base, and moving through various stages of interbedded bright and dull lithotypes to dull coal and possibly coaly shale, after which the trend reverses back to predominantly bright coal at the top of the cycle.

Under the microscope, trend reversals in lithotype composition are identified as systematic changes in the proportions of components indicating dispersal. These components are either transported by surface water into the mire, such as most allochthonous detrital minerals, or are generated and redistributed within the mire, such as dispersed sporinite and inertodetrinite. Both conditions require a high groundwater table and partial submergence of the mire, i.e. a high accommodation / peat-accumulation ratio. Additional information can be obtained from derived maceral and/or mineral ratios, supplemented by isometamorphic variations of telovitrinite reflectance and fluorescence (Diessel and Gammidge, 1998).

In Figure 1, a position which indicates a reversal from decreasing to increasing accommodation is indicated to the right of position "A", which corresponds to the middle portion of the B Seam from Bullmoose Mountain in British Columbia, illustrated in Figure 2. The reverse trend, i.e. a change from increasing to decreasing accommodation is shown in Figure 1 to the left of position "B". This situation corresponds to the central portion of the C Seam from Bullmoose Mountain, illustrated in Figure 3. In these two examples, the accommodation reversals occur within amalgamated coal seams, in "A" at the peak of the raised-mire development, and in "B" within the flooded to limnotelmatic portion of the mire.

The accommodation reversals are not confined to coal but extend into the interseam sediments as the amalgamated coal splits into daughter seams. In both "A" and "B", the accommodation reversals coincide with the respective maximum flooding surfaces although genetically, the two situations are quite different. The inundated, limnotelmatic portion of the mire to the left of position "B", which may be punctuated by a clastic band, is the natural extension of the maximum flooding surface to the right of position "B". In position "A", the relationship between the accommodation reversal within and outside the coal is more complex, because the accommodation reversal surface to the right of "A" is the product of the amalgamation of the upper and lower bounding surfaces (both also accommodation reversal surfaces) of the clastic seam split to the left of "A". The third accommodation reversal surface within the seam split corresponds to the waxing and waning of the accommodation rate during clastic deposition, thus coinciding with the maximum flooding surface. Theoretically, this extends from the marine (position "C" in Figure 1) to the onshore (lacustrine) realm where it terminates against the raised mire to the right of "A", although a thin clastic band may extend into the seam as an indication of a brief inundation.

In the hierarchy of significant surfaces, the accommodation reversal surface covers a wide range of magnitudes and frequencies. The fact that it may coincide with but is not restricted to other high ranking surfaces shows that it is not constrained by stratal units but transcends rock types and depositional environments. In position "C" of Figure 1, it separates the transgressive systems tract from the overlying highstand systems tract, but accommodation reversals have also been observed at the sub-parasequence level (Diessel et al., 1998).

2. *Non-marine Flooding Surface (NFS):* Although the flooding surface (FS) has been defined as 'a surface separating younger from older strata across which there is evidence of an abrupt increase in water depth' (van Wagoner et al., 1987, 1990), it is conventionally regarded as a marine boundary. Typically, this surface sharply overlies a shallowing-upward succession, and may show evidence of a depositional hiatus associated with the abrupt reversal from decreasing to increasing accommodation. In view of the hydrological connection between sea level and groundwater table in paralic coal measures, a marine flooding surface is predicted to correlate landwards to a non-marine flooding surface. The replacement of marine by non-marine flooding signifies a landward decline in the magnitude (to a lesser extent also rate) of the accommodation increase, so that the abrupt rise in relative sea level near the coast translates landward into a weaker rise of the connected groundwater table. Nonetheless, similar criteria of recognition should still apply to the non-marine flooding surface: it should correlate with an accommodation reversal surface overlying a shallowing-upwards succession, and it should be associated with a depositional hiatus. The main criterion of the non-marine flooding surface is its sharp contact against the underlying coal characterised by drying-upward cycles. A non-marine flooding surface is identified by "D" in Figure 1. It

correlates with the marine flooding surface (transgressive surface = TS) to the left of the diagram.

3. *Give-up Transgressive Surface (GUTS):* Apart from experiencing termination of peat formation because of sudden flooding of a mire, peat accumulation can also be terminated by a gradual or stepwise increase in accommodation. We refer to this surface marking the stage at which peat formation gives way to subaqueous, usually clastic sedimentation as a give-up transgressive surface, analogous to the reef abandonment processes described in carbonates by James and Bourque (1992). In contrast to the drying-upward coal cycles found underneath the non-marine flooding surface, the increasingly limnotelmatic coal below the give-up surface is characterised by wetting-upward cycles, as shown by the rising detrital-mineral content and other indicators of the allochthonous dispersal of peat components. In Figure 1, two examples of give-up transgressive surfaces are illustrated, one to the left of position "E" in the upper right portion of the diagram, and between "B" and "E" further below. Because give-up transgressive surfaces do not transcend other lithological units but are restricted to the roofs of coal seams, they do not rank as highly in the hierarchy of sequence-stratigraphically significant surfaces as the accommodation reversal and non-marine flooding surfaces.

4. *Terrestrialisation Surface (TeS):* Where included in published sequence stratigraphic examples, coal is mostly regarded as the final stage of the terrestrialisation of shallowing-upward, paralic parasequences, which respond to decreasing accommodation (van Wagoner et al., 1987, 1990). Such coals, also referred to as 'regressive coals' (Diessel, 1992), are separated from their underlying subaqueous floor sediments by a terrestrialisation surface, examples of which are illustrated in Figure 1 in position "F" and within the HST parasequences 2 to 4. These surfaces are commonly non-hiatal, i.e. as water depth and accommodation rates gradually decrease, there is no break in sedimentation but rather a shift in the deposited material from predominantly allochthonous clastic sedimentation to autochthonous peat accumulation. The subsequent coal thus represents a continuation of the shoaling-upward parasequence. Further upward, this trend is often terminated by a sudden increase in accommodation. The rate of this accommodation increase will determine whether peat formation is replaced by clastic sedimentation, whereas the magnitude of the accommodation increase will determine whether this is in the form of marine or non-marine sediments, i.e. whether the base of the coal roof is a marine or non-marine flooding surface. Because the terrestrialisation surface is restricted to the floor of a coal seam, its sequence-stratigraphic rank is similar to that of the give-up surface.

5. *Paludification Surface (PaS):* Peat may also accumulate under a regime of gradually increasing accommodation by the processes of paludification (Frenzel, 1983; Boron et al., 1987), leading to the formation of 'transgressive coals' (Diessel, 1992; Petersen and Andsbjerg, 1996). In this case, the base of the coal is referred to as a paludification surface. This surface may be the up-dip extension of a non-marine flooding surface, which itself may correlate seaward with a marine flooding surface. As

indicated in the two positions marked "G", PaS also doubles as an accommodation reversal surface, and is commonly hiatal in nature. If peat accumulation was initiated by paludification and accommodation continues to increase gradually beyond the maximum rate of peat production, peat formation will be replaced by clastic accumulation (lacustrine or floodbasin deposits if still in the non-marine realm, otherwise by marine deposits). The termination of peat accumulation is likely to be marked by a give-up transgressive surface (GUTS).

SUMMARY AND CONCLUSIONS

The investigations have identified five additional surfaces of varying significance in the sequence-stratigraphic analysis of non-marine sediments. Two of these, called paludification and terrestrialisation surfaces, occur at the bases of coal seams, while two other surfaces, referred to as non-marine flooding and give-up transgressive surfaces form their tops. The last two differ in the relative abruptness of the flooding event that generates these surfaces. Like the marine flooding surface, its non-marine equivalent is the product of abrupt flooding, although an assessment of this kind depends on the scale of the observation. It could be argued that only tsunamis cause truly abrupt flooding, whereas flooding events generated by a combination of eustasy and basin subsidence commonly build up to a maximum and then wane again. Because of the addition of the rates of basin subsidence and eustatic sea-level rise, the lead time between the onset of flooding and its maximum is often short, so that the flooding appears to be abrupt. This perception may be accentuated in near-shore sediments by non-deposition or erosion of sediments accumulating early during the transgression. In this case, the maximum flooding surface and the basal erosion surface coincide, as has been inferred in FS 1 to 3 in the left portion of Figure 1. Further landward, the lead time is extended and basal erosion is weaker, so that the non-marine flooding surface at "D" may become separated from the maximum flooding surface to the left of "A". A similar landward separation of the surfaces marking the beginning of flooding and its peak governs the relationship between the paludification surface at "G" to "E" (initiation), the give up transgressive surface at "B" to "E" (increasing intensity) and the maximum flooding surface (mfs) to the right of B. As mentioned above, in offshore sequence stratigraphy the term "maximum flooding surface (MFS)" marks the boundary between the transgressive and highstand systems tracts within a sequence. The use of a (lower case) "mfs" in Figure 1 identifies the occurrence of a maximum flooding at a lower level of magnitude, for example, at the scale of a parasequence.

A fifth surface, called the accommodation-reversal surface, may either coincide with some of the other surfaces or occur separately in coal or interseam sediments. We consider the identification of reversal surfaces between increasing and decreasing accommodation as an important step in the development of onshore sequence stratigraphy. It is quite possible that in completely limnic basins laterally correlatable accommodation reversal, may provide the only meaningful surfaces available to sequence-stratigraphic enquiry.

ACKNOWLEDGEMENT

We appreciate the anatomical contribution of Roger G. Walker who originally identified the connection between the give-up transgressive surface (GUTS) and the accommodation reversal surface (ARS).

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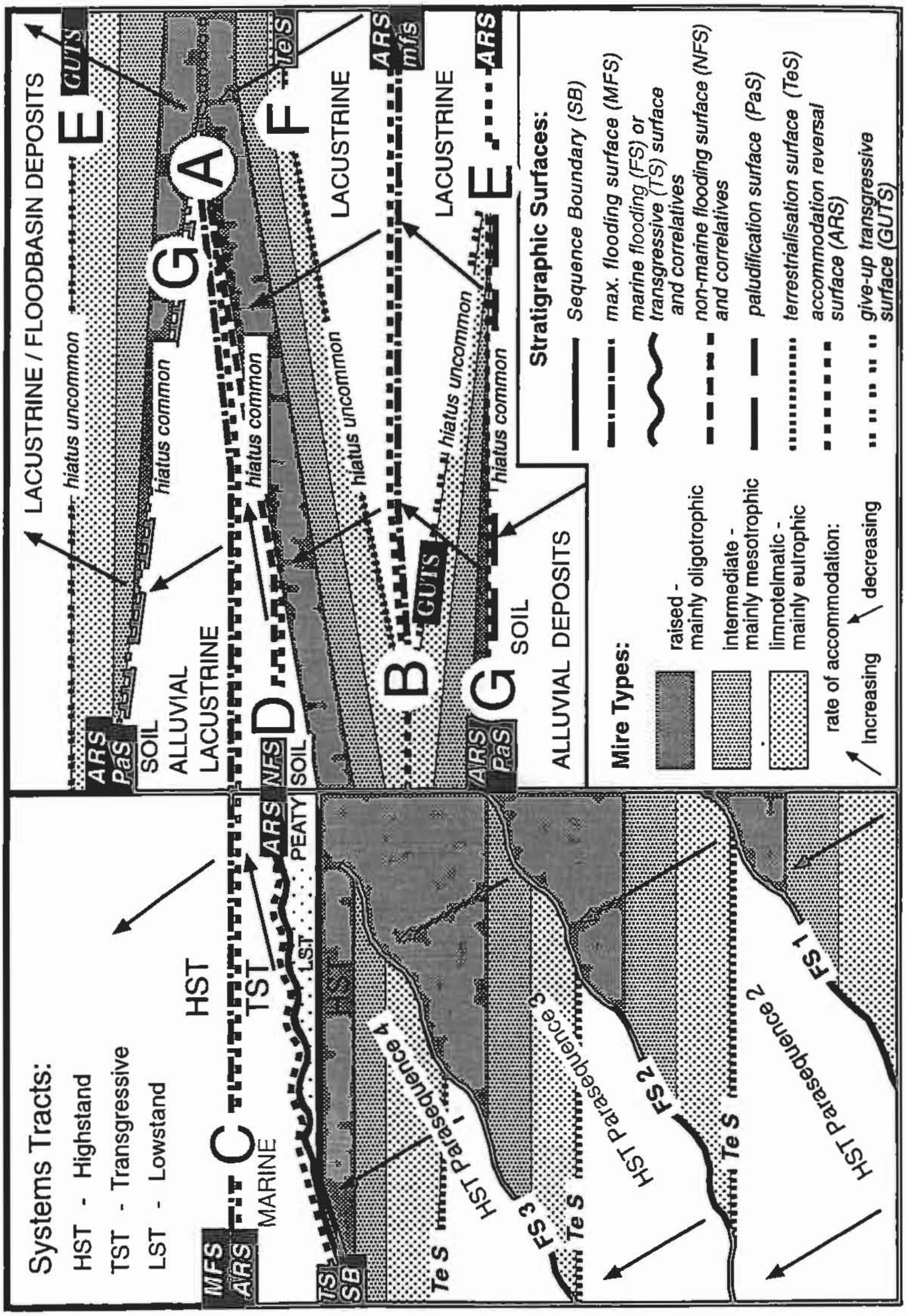

Figure 1. Sequence-stratigraphically significant surfaces in coal-bearing sediments.

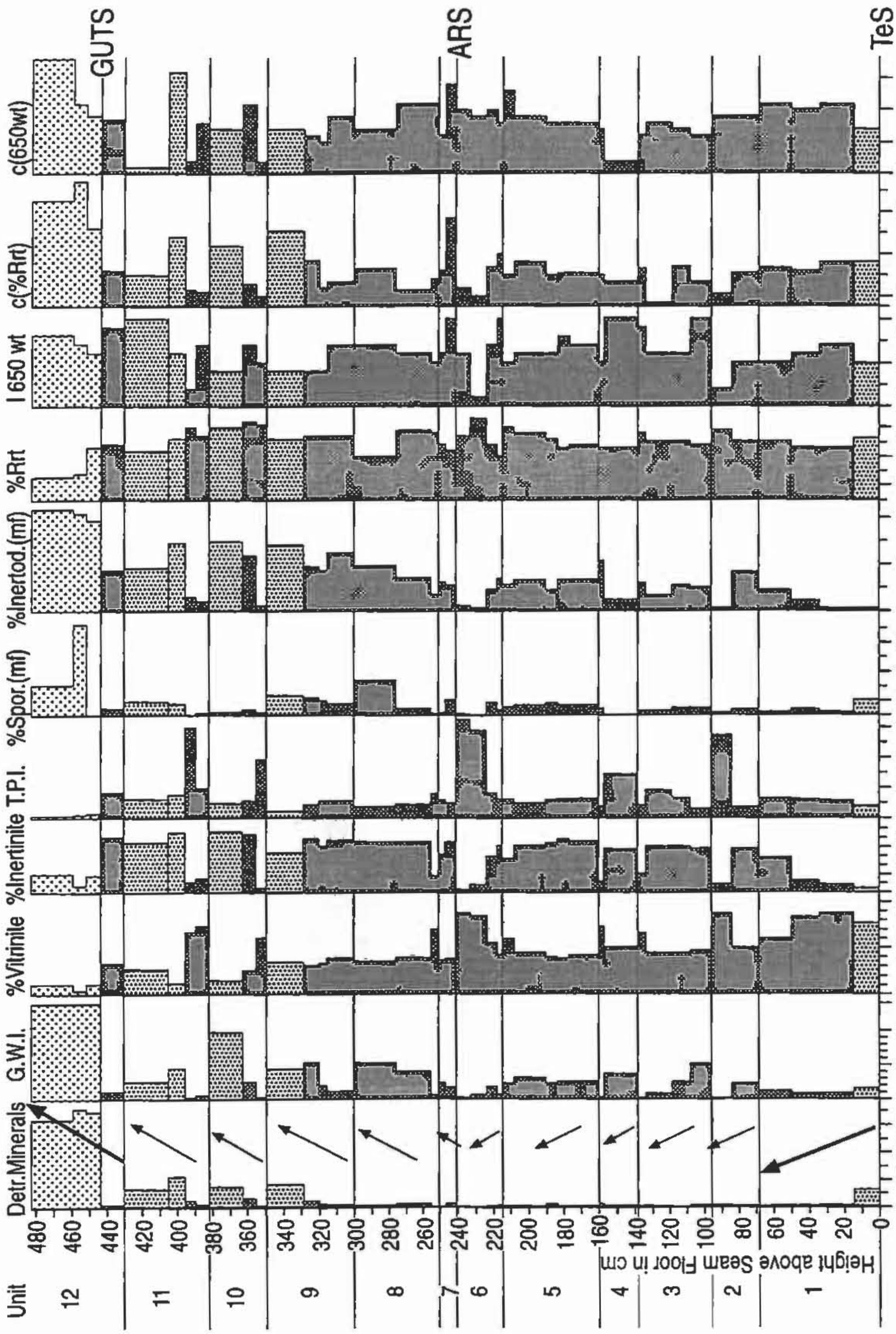

Figure 2. Petrographic parameters of the B Seam. Dark stippled signature: coal with less than 10% detrital minerals; intermediate signature: coal with 10 - 30% detrital minerals; light stippled signature: more than 30% detrital minerals. Left pointing arrows = decreasing, right pointing arrows = increasing accommodation.

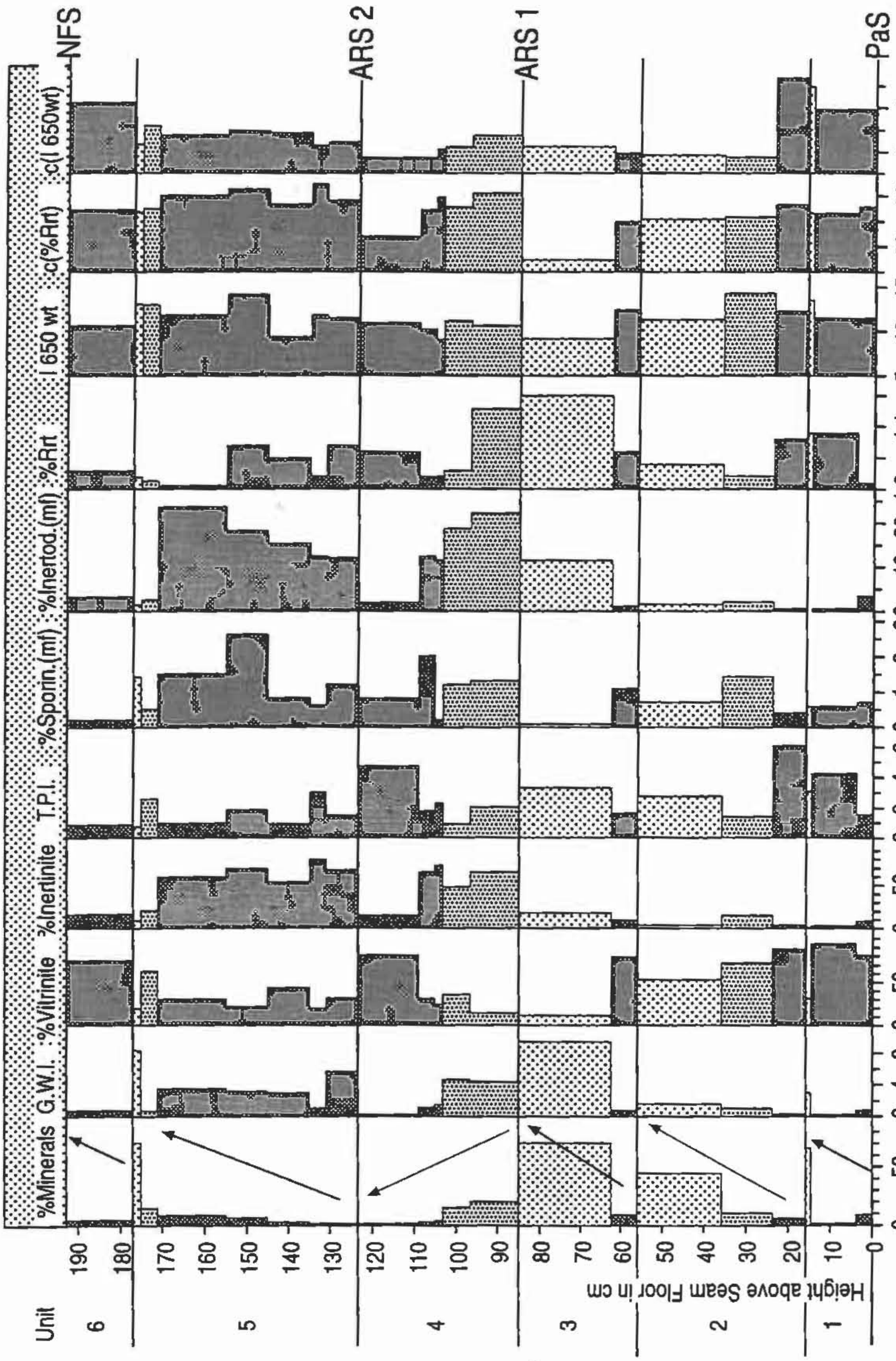

Figure 3. Petrographic parameters of the C Seam. Dark stippled signature: coal with less than 10% detrital minerals; intermediate signature: coal with 10 - 30% detrital minerals; light stippled signature: more than 30% detrital minerals. Left pointing arrows = decreasing, right pointing arrows = increasing accommodation.

A REVIEW OF COAL QUALITY PREDICTION FROM GEOPHYSICAL LOGS

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1. INTRODUCTION

The oil industry has extensively and successfully been using geophysical logs to quantitatively characterise reservoir geometries and lithologies. In coal bearing reservoirs, geophysics are also used to determine coal quality parameters such as ash, yield and volatile matter (Mullen, 1988). Although geophysical logging is an essential exploration tool for the coal industry, the data are generally only used for the coal seam correlation and identification of lithologies within the interburden. Is there a scope for utilising geophysics as a predictive tool in which coal quality variation can be predicted?

A recent in-house literature survey (Kahraman, 1998) indicated that much of the work on coal quality determination using geophysical tools was done in the late seventies and early eighties. A second peak occurred in the late eighties and early nineties (Figure 1). The earlier activity in the seventies could be related to the high oil prices whilst the second peak in the nineties could be related to tax credits associated with alternative fuel sources such as coal bed methane.

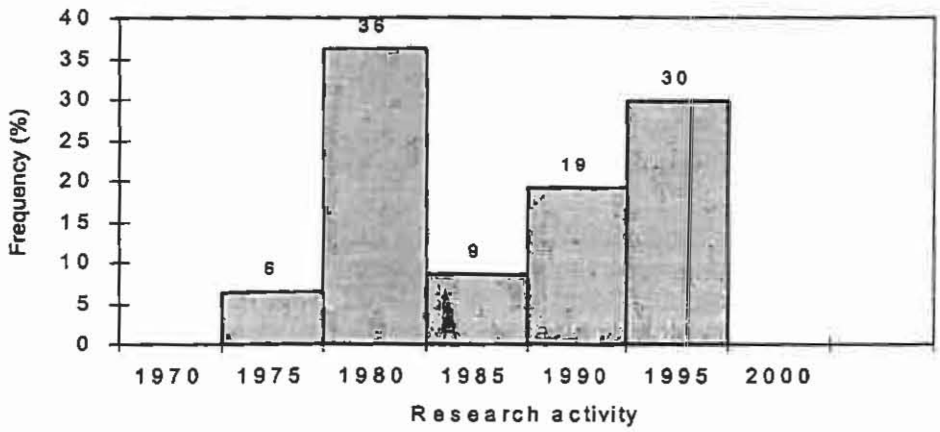

Figure 1. Research activity on coal quality determination from geophysical logs between 1970 and 1998

The level of activity in coal-bed methane resulted in research focused on the link between the coal quality and coal-bed methane formation, particularly in North America.

For the coal industry, coal coring and assay has been the traditional primary source for determination of moisture, ash, and carbon content. Borehole coring is an expensive and time consuming exercise but the value of the laboratory test data from the bore cores is invaluable. However, in areas where little or no core data is available or quality of data is not reliable, extrapolation of coal quality is also poor, geophysical wireline log data offers a viable and cheap method of determining coal quality and improving the statistics of bore core extrapolation .

In the following sections, a condensed summary of available and accessible literature from our survey is given. The other literature that was not available at the time of this paper written or thought to be less related to the subject is given elsewhere (Kahraman, 1998).

2. PREDICTION OF COAL QUALITY FROM GEOPYHSICAL LOGS

It appears from the literature that a series of simple cross-plots are the only way of determining the coal quality from the geophysical logs. Core to log relationship is not always represented by simple equations (straight lines). Once the cross-plot is prepared and the regression equation is established, it is easy to predict the expected values for each additional drill hole. These relationships will remain the same within a coalfield as long as the geological conditions of the deposition remain the same. Hence it is important to understand the geological variability and group the data into domains for analysis.

Although the prediction of ash content from the density logs is simple, the accuracy of ash determinations from the geophysical logs are affected by a number of factors such as inaccurate measurement of the borehole cavity, effective resolution of the density tools, coal's inherent moisture and maceral composition. Two samples with identical ash content may have different density log responses, suggesting that the macerals in the coal may account for part of the difference. Other problems in quality predictions are inaccurate determination of the core sample depth, a core sample that is not representative of the effective interval measured by the logging probe and variations in borehole conditions that cannot be corrected by density compensation equations.

Similarly, gamma ray can be used to predict the coal quality although a small variation in clay content and the reducing geochemical environment adjacent to a coal seam might give a high gamma ray response. Problems associated with variations in ash composition are also present in the resistivity log response and there is little correlation between the resistivity and ash and other coal quality parameters.

There were many attempts around the world to predict the coal quality from geophysical logs. In the following sections a summary of the research activity in several countries will be given.

2.1 Australia

The research activity in Australia concentrated between the early and mid eighties. A coal borehole core analyser, which was based on measurements of the Compton linear attenuation coefficient and the photoelectric mass-absorption coefficient of the material, was developed by McCracken & Mathew (1980). The laboratory tests and measurements on 23 coal samples collected from a single colliery near Wollongong showed an accuracy of 1% ash and 0.01 g/cm^3 density for coal whilst the accuracy of ash determinations decreased to 2.7% ash for 41 coal samples from nine different seams and locations in New South Wales.

Renwick (1980) suggested that at least three log calibration core holes be drilled, specifically for the purpose of determining mathematically the possible relationship between log response and laboratory core measurements. The resultant analytical data, particularly ash content could be plotted against depth to produce a core ash log which is then correlated with the long spacing density at the same scale. Once the basic correlations are made, the information is entered into a statistical package and by cross plotting the data the trends in data set could be established. It is also possible to extract information on lithology and depositional environment and to relate the ash content to specific energy (Renwick, 1980).

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In a regression analysis, the third order polynomial relationship was suggested to produce optimum correlation coefficients (Groves and Bowen, 1980). The researchers calculated an ash content from the density log with an absolute accuracy of ±4% for the Boggabri area New South Wales whilst they calculated an absolute accuracy of ±8% for an area near Toowoomba, Queensland. They also mentioned the use of neutron to estimate the volatile matter content of raw coal ±5% for any one coal-bed. They concluded that no accurate log calibrations could be achieved for the inherent moisture content of raw coal because of the relatively high neutron moderation of the current neutron-neutron logging method in water rich seam intervals. The factors that could influence the ash determination as a function of the density were also outlined. These are the degree of coalification or rank of the coal, the type of mineral matter associated with the coal (whether it is clay, quartz, pyrite, carbonate), the maceral composition of coal and the moisture content associated with either mineral matter or the coal substance.

The qualitative similarity between density, sonic and resistivity logs related to complementary coal properties was investigated (Till, 1985, 1987). The resistivity of coal samples in the laboratory showed no simple relationship between the ash percent and porosity, however anisotropy and the physical state of the coal such as fracturing affected the data (Till 1985). The sonic response of coal did not show a consistent relationship to ash percentage. However, the sonic velocity appeared to relate to either the porosity or rank of coal with the sonic velocity decreasing as the porosity increased or increasing as the rank increased. Till also concluded that density response of coal can only be related to coal quality over a limited area because several factors such as maceral composition and the minerals content affect the density. The author used to evaluate the Negoita's M-N method and found that the method showed little promise to predict the coal quality from the geophysical log as it was highly operator dependent. The density and gamma logs were found to be the most useful contributors in first order multivariate regression analysis involving the density, gamma, neutron, sonic and focussed electric logs. Single log prediction of coal quality using the gamma or long spaced density log was accurate but the error decreased if a second or third polynomial regression equation was used.

Borsaru *et al.* (1985) achieved accuracy of 2.2% ash for ash contents between 7 and 28% ash in dry boreholes by using spectrometric gamma-gamma methods. Later Borsaru *et al.* (1988) used the neutron capture technique at Curragh mine in Queensland and at Drayton mine in Hunter Valley of New South Wales.

The neutron-gamma and gamma-gamma techniques for ash prediction were compared at the Callide Mine by Borsaru *et al.* (1992). It was concluded that both gamma-gamma and neutron-gamma measurements could predict the ash content in coals seams and delineate the seams and inter-seam sediments. The other advantage of the neutron-gamma tool was that it could be calibrated against the iron content in order to predict the iron percentage in coal. Biggs (1991) and Borsaru *et al.* (1993) estimated the iron content in coal and its implications for estimating the ash fusion characteristics using the neutron-gamma technique (SIROLOG tool) at Callide Coalfields. Later, Borsaru and Ceravolo (1994) used a low activity spectrometric gamma-gamma borehole logging tool in Callide Coalfields which does not require any special shielding for the radioactivity because the activities of the gamma-ray sources used with the tool was very low.

2.2 Canada

Cross plotting techniques for three different wells from Canada, England and Europe were also used by the Canadian researchers (Kowalski & Holter, 1976; Kowalski & Fertl, 1977). In the interpretation, the densilog is plotted on the y-axis and second device is plotted on x-axis of a graph. The locations of the carbon, ash and moisture points are determined form this plot and the amount and quality of the coal was determined. The method calculates carbon, ash and moisture by solution of three simultaneous linear equations of the form:

$$\rho_{log} = (\%Carbon)(\rho_{carbon}) + (\%Ash)(\rho_{ash}) + (\%Moisture)(\rho_{moisture})$$

$$\Delta t_{log} = (\%Carbon)(\Delta_{carbon}) + (\%Ash)(\Delta_{ash}) + (\%Moisture)(\Delta_{moisture})$$

$$1 = (\%Carbon) + (\%Ash) + (\%Moisture)$$

in which ρ is the bulk density and Δt is the interval transit time. Second equation could be applied to conductivity and neutron porosity as well.

The other tools such as gamma ray log were used to evaluate the thermal coal deposit at Coal Valley, Alberta by Smith *et al.* (1977) whilst the prompt gamma-ray analysis technique (Metalog) was applied to coal seam determination and sulphur content of the seams (Nargolwalla & Seigel, 1977). A correlation coefficient of 0.95 and an average relative error of <8 percent of the actual grade over the sulphur concentration range examined was obtained from this study.

Edward (1978) and Edwards and Banks (1978) concluded that the proper evaluation of a coal property requires accurate information on the in-situ water and ash content of the coal. The researchers divided the coal seam into three components; coal, water, and wet ash. Coal was defined as fixed carbon and coal volatiles (dry mineral matter free coal), whilst the wet ash was defined as the dry ash residue after burning, plus the water and volatiles associated with the ash when in-situ. A series of formulas was developed to find the coal, water and wet ash content.

$$1 = Pc + Pw + Pa \qquad \rho_b = Pc\rho_c + Pw\rho_w + Pa\rho_a \qquad R = Req / \theta^M$$

where

Pc = the volume portion of coal, Pw = the volume portion of water, Pa = the volume portion of wet ash, ρc = density of pure coal, ρw = density of water, ρa = density of wet ash, R = bulk resistivity, Req = the equivalent resistivity of the combined conductors, θ = Pw + Pa (the sum of volume proportions of all conductors for the system), M = exponent for the system

Using the geophysical logs to determine the coal parameters leads to site-specific relationships and if a high degree of accuracy is required, the constants for the equations must be carefully determined using the local data (Hoffman & Wilson, 1989). Difficulties include data handling problems, identifications of bad data, the fundamental differences between in-situ geophysical measurements and laboratory analyses and the quality and calibration of the geophysical logs.

2.3. United Kingdom

A universal chart was employed to investigate total of four boreholes from Yorkshire and Nottinghamshire areas (Reeves, 1971). This chart used the mud weight density, hole diameter, count rate and calculated ash percentage. However, Reeves indicated that controlled borehole conditions do not exist and there is a difficulty in using a single chart for all conditions. He proposed several alternative steps to construct a chart for each borehole. He also proposed an alternative method that determines the total aluminium silicate content by running, at least theoretically, a spectral type of log, which is adjusted so as to read only radiations caused in the aluminium silicate region as a result of neutron bombardment. He commented that the techniques developed by the oil industry to determine the moisture content is directly applicable to coal seams. However the conventional gamma-ray/neutron logs are much more sensitive to small moisture contents in calcareous and arenaceous rocks, and where there is relatively high moisture content or neutron moderation media the response is less pronounced. He also suggested a method to determine the type of coal. The simplest way to proceed would be to plot the gamma-ray deflection against the density measurement for a type coal and depending where the points fall, the variety of coal could be identified by a graph. Later Reeves (1979) outlined the latest developments in coal wireline logging techniques and he gave an example to show differences between two different rank coals by using a sonic tool.

MacCallum (1992) reported that within the confines of a single site, over distances of up to about 1000 m, many seams maintain their gamma and density signatures and could be readily correlated in terms of seam fingerprint and quality. However, the differences in geophysical responses from the same coal seam could occur in distances as little as 3 m apart as well.

2.4 United States of America

Bond *et al.* (1971) used the sonic log vs density frequency cross plot values for carbon and ash in their equations for the Illinios Basin. The development of a log analysis procedure for coal quality required a certain amount of empirical study by comparing log responses to proximate analysis. The results showed excellent comparison on a coal quality data set containing a moisture and ash content ranging from 5% to 20%.

The density logs were used to determine the ash and moisture contents, and the calorific value (Norris & Thomas, 1980). The averages for the log intervals corresponding to the core report intervals were calculated and used with the core information in linear regression analysis to generate a set of three slopes and intercepts which allowed estimation of in-situ quality parameters. Some of the main problems encountered by using this technique were the log and core interval matching since the driller's depths usually differ somewhat from the log depths, some depth shifting of the core interval obtained from the driller's depths may be necessary to fit the core interval to the log interval. Another problem occurred when partings were removed and not noted on the core report. In this case the in-situ analysis showed a higher ash value than the core.

Daniels *et al.* (1983) also used three simultaneous equations to predict the coal quality from the geophysical logs. They reduced the equations two by solving the percentage of ash, water and coal from another procedure which utilised the density-ash cross plot or from the linear regression equation derived from the cross plot. Their main criticism in prediction of coal quality method was that the accurate and consistent means of determining moisture content was difficult to obtain. The other problems, which could affect the accuracy of results, are inaccurate determination of the core sample depth, a core sample that is not representative of the effective interval measured by logging probe, variations in borehole conditions that cannot be corrected by density compensation equations and variations in the density of the ash component of the sample. The wet bulk density of ash was obtained either from core measurements or from the density log measurements in the non-coal regions of the well whilst the dry bulk density was calculated from ash-density cross plot by extrapolating the linear regression line on the cross plot to 100%. This led to calculation of the porosity for the ash and ash percentage. The solution proposed by Edwards and Banks (1978) to calculate the moisture content was criticised by the authors on the basis that the solution involves a number of approximations and assumptions that produce at least as much uncertainty in the final results. They also indicated that there is some correlation between the total sulphur content in coal and the induced polarisation response, which is a measure of the electrical polarisability of the mineral components in a rock.

Fishel and Mayer (1979) made correlations between the extremely high-resolution (EHD) density tool curves and ash content. Hallenburg (1979) showed an example how a computerised on-line analysis by using conductivity and density values would be a useful tool to identify the ash content and calorific value. An interdisciplinary approach to model a Texas lignite deposit was used by Alcock et al. (1986).

Mullen (1988) employed the geophysical log analysis algorithms to calculate the main coal quality parameters in the San Juan Basin of Colorado and modelled these algorithms using a basin-wide data after Fasset and Hinds (1971). Later, Mullen (1989) established some localised algorithms using one borehole which was completely cored to determine the resource potential Fruitland coal-beds. These algorithms were applied to the other wells in the area and the log-calculated values were very close to results measured from the cores. The minimum gas content was calculated and the calculated results were quite comparable to the core measured values.

Mayor *et al.* (1990, 1994) used coal quality parameters to calculate the gas content from coal seams and concluded that log analyses could be performed much more rapidly and inexpensively than the core analyses. The major difficulty was found to be depth control when comparing coal seam reservoir open hole data to core data. To overcome this problem, computerised axial tomography (CAT) scan was used. To determine the use of wireline-log and core data, the depth-shifted proximate, ultimate and gas content core data and the log data were investigated statistically. The most significant correlation was obtained between the log density and the coal ash content and gamma ray log was found to be of limited utility for quantitative evaluation of ash content.

Herron *et al.* (1988) and Herron (1991) briefly reviewed the logging properties of organic matter and presented a variety of wireline approaches that have been taken to evaluate the potential source rocks. Later, Herron *et al.* (1992) examined the impact of statistical uncertainties of elemental concentrations on geochemical log interpretation by using a fixed interpretation model and a synthetic data set.

Colson (1991) used a computer package of Schlumberger (ELAN) to predict the gas content of Black Warrior Basin. The rank and the maceral content of the seams were also determined from the geochemical tool response. Schlumberger's geochemical logging tool was also used by Johnston (1990) and Johnston and Scholes (1991) to determine the cleats, cleat porosity, the mineral and maceral contents and the rank of the seams in a coal-bed methane gas study in San Juan Basin.

Usman *et al.* (1991) presented a methodology that integrates the existing technology with new measurements and techniques. Coal formation specifically for identification, resource definition (thickness), gas content (reserves), recoverable reserves (permeability, porosity and reservoir pressure) and reservoir performance could be evaluated by using such procedure. The methodology provides evaluation alternatives depending on the coal seam thickness and the type and concentration of the fracture system. For example thin seams found in basins like the Black Warrior and the Appalachian require a different evaluation suite of logs compared to those required for the relatively thick (greater than 60 cm) coal seams found in the San Juan and Picaenca Basin.

2.5 Elsewhere

Simultaneous equations were also used by Weltz (1976) for Pecket Zone in Brunswick Peninsula in Chile. He successfully calculated the moisture content and heating value of the coals studied. In his calculations, the volatile matter and fixed carbon was calculated as total carbon.

Lavers and Smits (1976) noted that it was possible to establish a relationship between the bulk density (as the logs measure) and ash content in a geological province in South Africa. Although coal rank, coal and ash type did not cause any calibration problems in South Africa and Australia for the researchers, these parameters showed difficulty in the interpretation of Indonesian coals. However, some relations were still obtained between calorific value and neutron log, volatile matter and single-electrode resistivity log.

Brom & Driedonks (1981) gave the correlation of ash content to the HRD response in two different coalfields without any reference to their geographical location. It was noted that establishing a separate relationship for each seam could improve the accuracy of prediction. Also, the use of short spaced neutron-neutron tool showed the changes in H-content over the IH range and depicted variations were found to be caused by differences in the maceral content. The hydrogen rich intervals were thought to be vitrinite rich, whilst low-hydrogen parts represented inertinite rich horizons. The a devolatilisation phenomenon as well as maceral content was also thought to cause volatile matter differences in neutron reading cross plots. The calorific value was also obtained from the available logs. In addition, the washability was determined from density log. The bed resolution density was calibrated against the HRD to obtain reference BRD count rate levels corresponding to specific gravities of 1.45 and 1.6. The cumulative float at specific gravity 1.45 was then determined by summation of all intervals with log deflections indicating specific gravity lower than 1.45. To calculate the weight yield, the figure obtained divided by the total interval thickness and multiplied by a weighting factor corresponding to the ratio of average float density to average coal density (1.4/1.5) and a similar procedure was followed for the sinks. The results showed a reasonable comparison with the actual washability data (within about 5% absolute). The sulphur content was also successfully predicted from the neutron-capture gamma-ray spectra with an accuracy of about 1% absolute.

3. A CASE STUDY

Figure 2 shows preliminary results for a regression analysis that was applied to predict quality parameters for a coal seam that had only quality values from composite samples from four boreholes in Queensland. The regression coefficient is not the best but it is substantially high (r^2=0.72-0.76) considering only the use of average values from the plies. It is believed that this could be further improved if controlled sampling of the plies is employed in the analysis. Selecting a shorter sampling interval for the proximate analysis in the next drilling program could give a better correlation coefficient in the regression analysis and better accuracy in predicting the quality parameters.

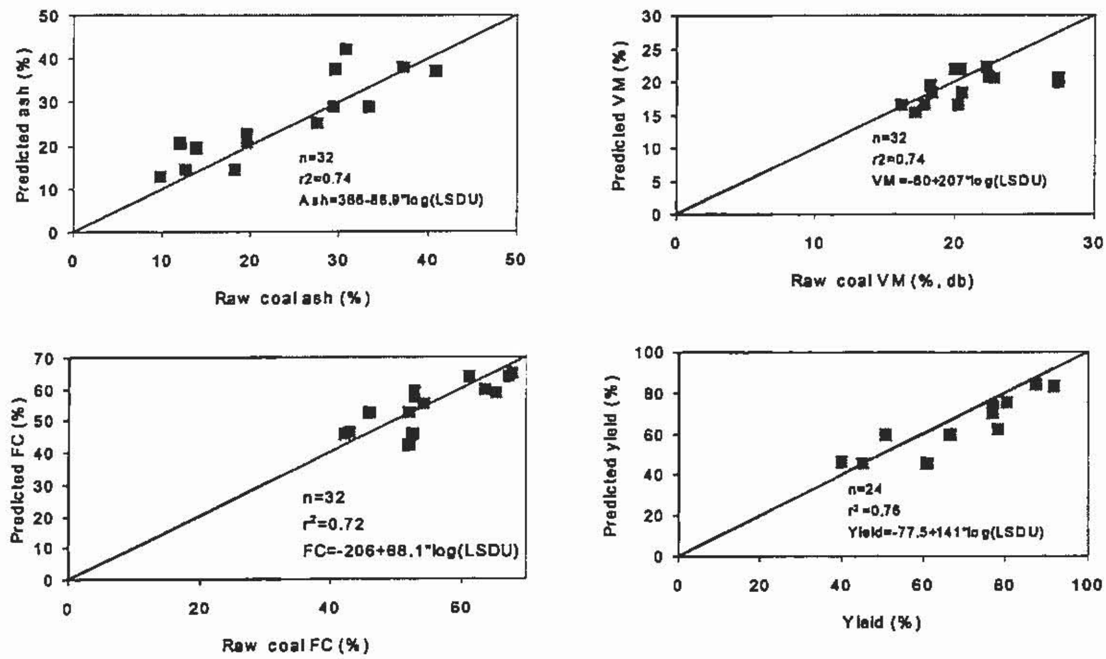

Figure 2. Regression analysis applied to predict basic quality parameters from geophysical logs for a Queensland coal.

4. CONCLUSION

The oil industry has been extensively and successfully using the coal quality prediction methods from the geophysical logs to determine the lithologies and their thickness and the reservoir characteristics quantitatively for many years. For the coal industry, coring has been the traditional primary source to determine the coal quality such as moisture, ash, and carbon content. Borehole coring is an expensive and time consuming exercise although the value of the laboratory test data from the bore cores is not debatable. However, in areas where little or no core data is available or quality of data is not good, or a rapid quality determination is required, geophysical wireline log data could offer a viable and cheap alternative to determine the coal quality.

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CONTROLS ON PHOSPHORUS VARIABILITY AT THE MINESCALE

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INTRODUCTION

The level and variability of phosphorus content in coal is an important issue for coking coal producers. Market specifications often require phosphorus levels to be below 0.04% in product coal. Where product coal exceeds this level, financial penalties may be incurred by the producer. Hence it is important to determine and understand the controls on variability in phosphorus levels within a mineable seam so that mining can pro-actively schedule blending or preparation procedures to ensure that phosporous levels are kept to within specifications.

Previous studies by Ward et al (1996) examined a series of coal seams in the Bowen and Sydney basins of eastern Australia. Ply-by-ply studies of these seams suggested that high phosphorus contents could be linked to individual plies or to partings within the seam that might be removed by selective mining or processing. Commonly the phosphorus occurred within the mineral apatite or bound within aluminophosphate minerals as infillings of the pore spaces and cavities within the microstructure of inertinite macerals. Less commonly they occurred within veins. Hence, there was a suggestion that high phosporous contents could be linked to the inertinite-rich or dull to dull banded coal types within a seam.

There is a general consensus that precipitation of phosphorus minerals occurs early during peatification and diagenesis. The concentration of phosphorus is often high in living plants and is released during plant decay and remobilised for nutrient uptake by the living. Hence, phosporous levels are often higher near the surface of peat bogs (Figure 1). High phosphorus contents have been found in tuffs as well as other partings within coal seams. Hence, phosphorus distributions within or between seams should be related to the depositional configuration of the peat deposit or to properties of the sediments that formed the immediate roof of the seam. In some cases increases in phosphorus occur where the coal seam has been subsequently intruded by dykes, therefore the complete geological history of a given seam may be required to understand the controls on phosphorus occurrence in coal (for a good summary of phosphorus occurrence in coals see Corcoran et al, 1994).

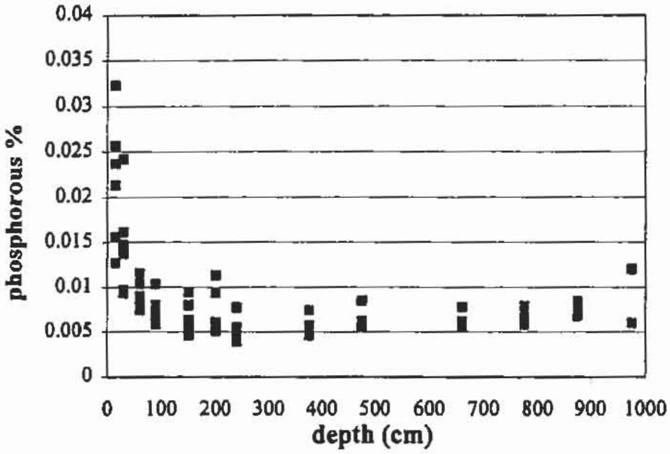

Figure 1. Plot showing decreasing phosphorus levels with depth in a modern low ash peat deposit. Unpublished data from Esterle.

Partridge and others (1993) examined the distribution of phosphorus by size and density fractions of plant feed for Australian coals with a view to its removal during coal preparation. Alternatively, if phosphorus was concentrated to a specific fraction, that fraction might be isolated and chemically treated by citric acid leaching. They found that, where trends were apparent the phosphorus concentrations were generally linked to the denser, high ash coal and stone fractions in both coarse (+4mm) and fine (-1mm) fractions. However, this relationship was variable and mine dependent with one mine exhibiting a reversal of trend—the phosphorus was tied to the coarse, low ash fraction. The distributions of phosphorus by size and density described above were determined on run-of-mine samples crushed to pass 50mm top size. During preparation it is possible that high phosphorus coal and/or rock might be distributed into the smaller size fractions, thus masking any associations with natural size distributions.

This study was undertaken at a mine in the Bowen Basin where phosphorus levels are highly variable within and between pits that mine the Main Seam. In one particular pit, the phosphorus levels varied laterally on the order of 50m spacings and the high phosphorus zone within the Main seam was associated with the departure of a rider seam in the roof. The objectives of this study were to determine:

1. whether high phosphorus levels could be linked to a particular ply or stone parting and thus be managed through selective mining and/or density separation during processing;
2. whether phosphorus could be linked to a specific size fraction in the ROM as a function of coal/rock type and thus be removed by simple screening and possible chemical treatment of specific size fractions; and
3. the origins of the high phosphorus zone within the main seam

GEOLOGICAL SETTING

A map showing the distribution of phosphorus within the Main seam in the study area is presented in Figure 2. In this pit, total seam phosphorus levels are consistently high (>0.04%) in the Main seam across the pit, but extremely high (0.1 to 0.25) in a narrow

(~200 m) NS striking zone in the pit centre. Geologically, this high phosphorus zone parallels the departure of the rider from the Main seam. Within the split, the interburden contains a sandstone wedge that thickens to the south. Two small dykes also occur in the high phosphorus zone. Hence, the precipitation of phosphorus minerals could have two origins, epi- and diagenetic during peat accumulation and subsequent burial or post coalification.

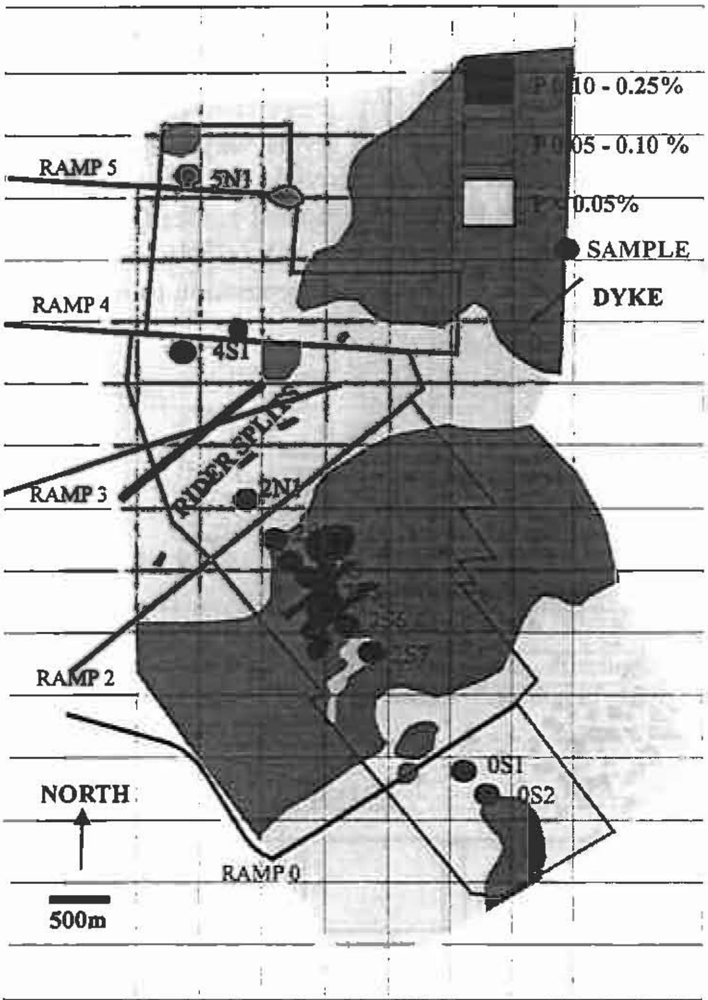

Figure 2. Map of study area showing the location of samples, high phosphorus areas and dykes. Section through profiles shown in Figure 4.

METHODS

To determine variability within the Main seam, a series of seam brightness profiles were made and channel samples were collected from mineable plies across the study pit (Figure 2). Plies were determined by stone partings, hence these ply samples contain a mix of lithotypes; as such the correlation between lithotype and phosphorus was not attempted. Profile spacing was tightened in Pit 2 to encapsulate the variability across the high phosphorus zone. Samples were dispatched for proximate analysis and determination of phosphorus and total sulphur content.

Also available to the study were three bulk samples of ROM coal size fractions from two other pits (Pit 4 and 8) across the mine site. These samples were not crushed, but sized using a mobile screening plant into +200, 200x100, 100x50, 50x0.5 and 0.5x0.075mm fractions. The +200mm fraction was hand sorted into coal and rock, and the other size fractions density separated at 2.0 g/cc. Both the coal and rock fractions from all sizes were analysed for phosphorus content.

RESULTS

Vertically within the Main seam phosphorus levels vary from 0.01 to 0.2% or greater. A simple cross plot of phosphorus against ash yield for ply sample across the minesite suggests that phosphorus does not follow the mineral matter (Figure 3). Although some stone partings are high phosphorus, the low raw ash (<20%) coal plies can also contain high phosphorus content. Hence, simple density separation to remove phosphorus is not applicable across the minesite.

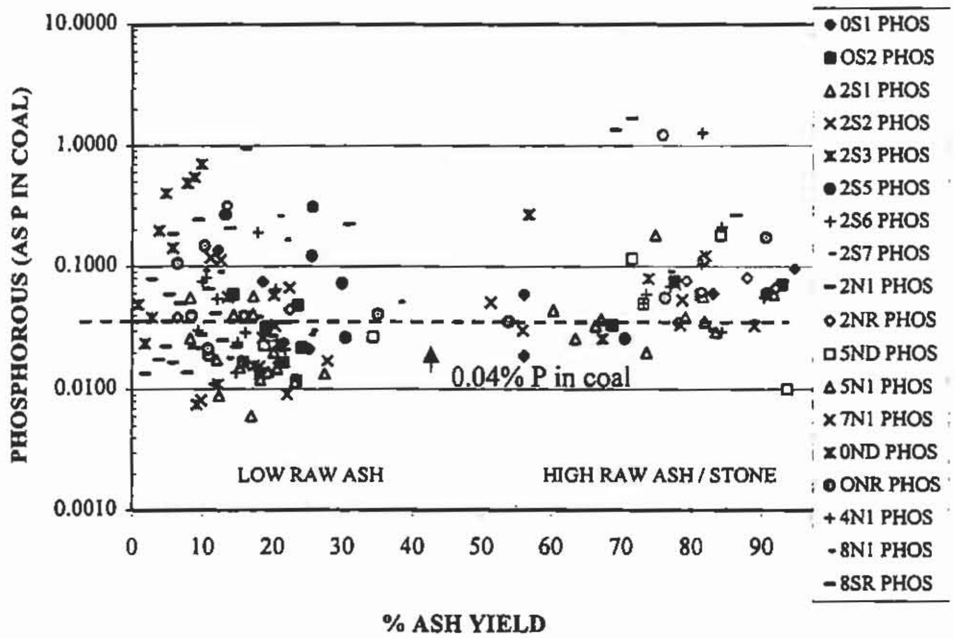

Figure 3. Phosphorus contents against raw ash yield for ply channel samples from various locations around the mine.

Within the Main seam, the highest phosphorus contents (>0.1%) shift stratigraphically across the seam, but are mainly associated with the middle of the seam in the dull banded to interbanded coal plies (Figure 4). The rider seam where merged is generally high in phosphorus content. The rider seam splits and thins southward as the Main seam increases in phosphorus content, but samples could not be collected from the rider in this area. Due to their occurrence in the mid-section of the seam, the high phosphorus coal zones in this pit are not easily avoided by selective mining.

The two dykes cross cutting the seam within the pit have variable, but consistently high phosphorus content, 0.49% and 0.20%. Within 2m either side of the former dyke, the phosphorus level in the middle ply of the Main seam is 0.70% and 0.55%.

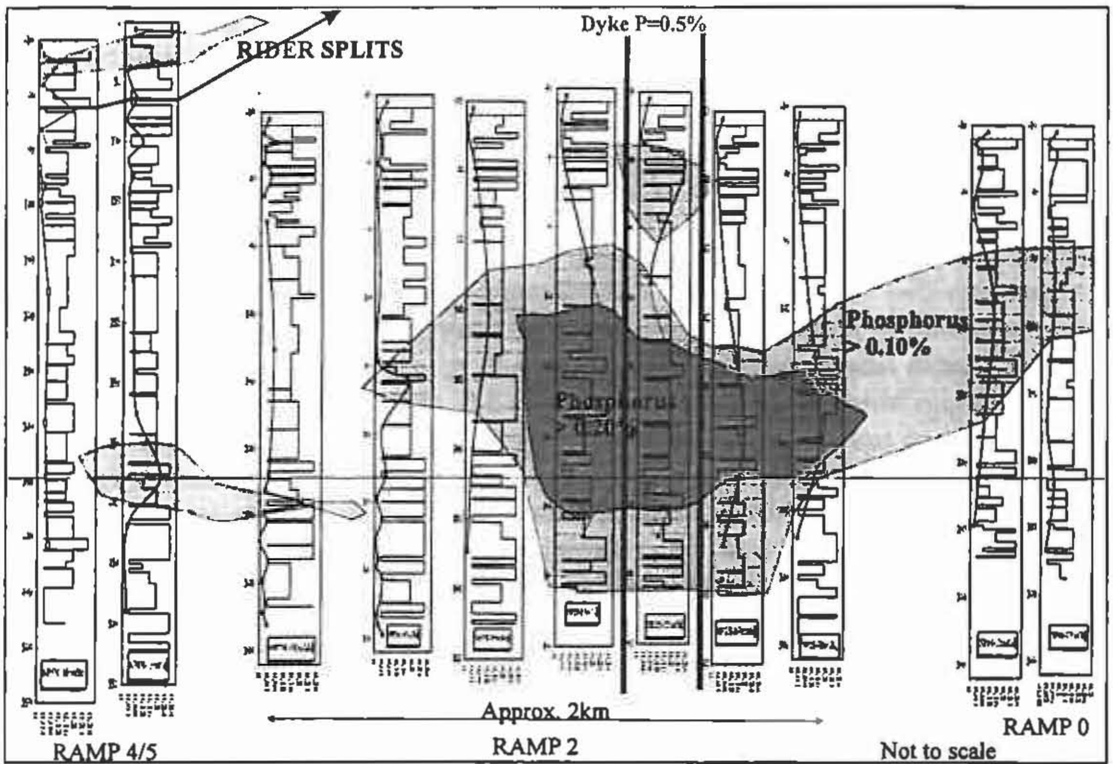

Figure 4. Cross section through brightness profiles showing distribution of high phosphorus (>0.1%) zones relative to rider split and dyke occurrences. Location of section shown in Figure 2.

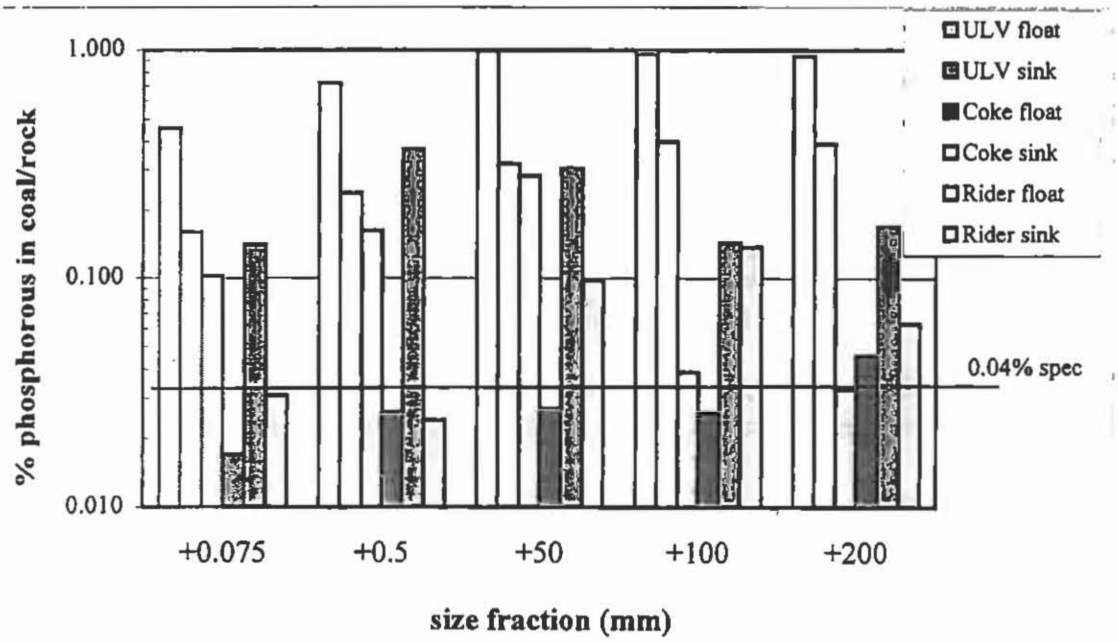

Figure 5. Phosphorus contents for float and sink fractions in different size fractions from the ROM samples at three locations.

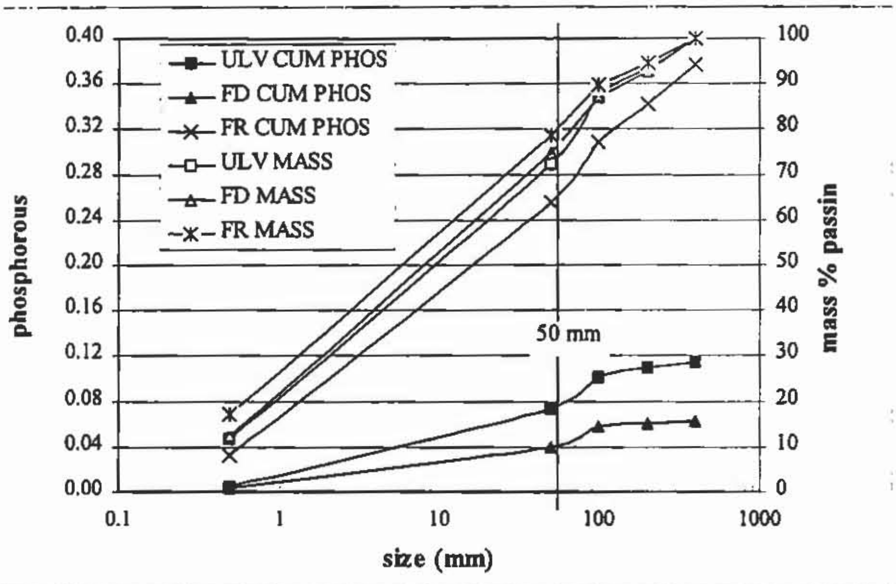

Figure 6. Size distributions and distribution of phosphorus content in the different size fractions of the ROM samples.

The distribution of phosphorus in the float and sink fractions of the ROM samples are presented in Figure 5. The Rider seam is consistently above specification in both the float and sink fractions for all size fractions, but phosphorus content is higher in both densities and the size fractions that are greater than 50mm. For the coking coal, the rock is higher in phosphorus than the within specification clean coal in all size fractions except +200mm. For the ULV, the rock is also consistently higher in phosphorus than the clean coal, but the clean coal is also above specification in the coarse fractions greater than 50mm.

When plotted as a cumulative percent for for each size fraction (Figure 6) it can be suggested that the highest phosphorus contents are associated with the coarser fractions for all ROM samples. From the ROM sizing, 65 to 80% of the ROM is less than 50mm before it enters the crushing station. Except for the Rider seam, which is consistently out of specification, the –50mm fraction of the feed might be density separated to remove the high phosphorus rock. Were chemical leaching an option for phosphorus removal, a smaller proportion (20-35%) of the ROM could be treated if only the +50mm material were scalped off. Were this material crushed, the higher phosphorus coal and rock would be redistributed to the smaller size fractions.

DISCUSSION

Similar to the results found by Partridge et al (1993), phosphorus reduction in either the Main or rider seams at this mine cannot be achieved across the minesite by simple density separation in the preparation plant. An exception to this is the coking coal. In contrast to that earlier study, the analysis was conducted on uncrushed samples and the results show a relationship between size and phosphorus content for these coals. The highest phosphorus contents for all samples occur in the coarser size fractions. As the coarser +50mm material contributes only 20-35% of the ROM, an option might be to scalp this material for stockpiling or subsequent processing to remove phosphorus. This does not apply to the rider seam for which both coal and rock at all size fractions except the –0.5mm are very high phosphorus.

From observation, the coarser fractions from the Main seam ROM samples are composed generally of dull to dull banded coal lithotypes suggesting that their origin is from the high phosphorus mid-section of the seam. The rider seam also contained dull banded coal but its ROM was not examined. The origin of the high phosphorus mid-section in the Main seam and its association with the departure of the rider seam is more difficult to determine.

Its geographic association down dip from the rider split suggests that emplacement occurred in association with peat accumulation. The rider seam where merged is consistently high in phosphorus, but its composition where split is unknown. The occurrence of high phosphorus in the mid-section of the seam dissuades direct association with sediments within the roof from which phosphorus might percolate downward into the peat. The lateral migration of the high phosphorus zone towards the split suggests that emplacement might have been contemporaneous with subsidence and subsequent burial. Based on the assumption that the phosphorus here occurs in the mineral apatite, then the requisite conditions may have resulted from the time transgressive encroachment of neutral to alkaline waters into the acidic peat mire.

However, the occurrence of two small dykes (phosphorus content = 0.49%) traversing the high phosphorus zone and the increase in levels within the coals suggest that emplacement was post coalification. The phosphorus values presented from the modern peats suggest that levels rarely exceed 0.04%. Hence, in order to exceed this level secondary enrichment is required.

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IONIC AND SULPHUR ISOTOPE COMPOSITION OF ILLAWARRA RAINFALL

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INTRODUCTION

The majority of global atmospheric sulphur deposition is from anthropogenic sources (Berner & Berner 1987). The presence of excessive amounts of non-seasalt sulphur in the atmosphere can cause serious illnesses in humans and environmental acidification (Anderson 1978). This project studies the ionic and sulphur isotope composition of rainfall from the Illawarra. Many studies have been conducted in heavily populated regions of the Northern Hemisphere but the current study represents the first such measurements for the Illawarra. Data collected over a period of 153 days are used to identify and quantify the contribution of the major sources of non-seasalt sulphate (and other ions) in the Illawarra. Natural and anthropogenic processes emit aerosols of the 12 major ions analysed in this study (Cl^-, SO_4^{2-}, Na^+, Mg^{2+}, K^+, NH_4^+, F^-, NO_2^-, Br^-, NO_3^-, Ca^{2+} and PO_4^{3-}) into the atmosphere. Dry and wet (bulk) deposition processes remove these aerosols from the atmosphere.

The two most abundant natural isotopes of sulphur are ^{32}S and ^{34}S which have a relatively constant ratio in nature and deviations are due to fractionation. Many natural and anthropogenic sulphur sources contribute to the global sulphur cycle (Brimblecombe *et al.* 1989). Some sulphur sources directly contribute sulphur to the atmosphere, while others involve transport mechanisms which cause different amounts of isotope fractionation and hence small deviations from the natural isotopic abundances (Nielsen 1974; Krouse 1980). The $^{34}S/^{32}S$ ratios are normalised with reference to the Canon Diablo triolite standard ($\delta^{34}S = 0$) and reported as a $\delta^{34}S$ value in parts per thousand (‰) by international convention. The different sulphur sources have defined $\delta^{34}S$ values (Fontes 1980; Krouse 1980; Wadleigh *et al.* 1994) which allow the determination of the contribution of different sources.

Sulphur Sources

Seasalt aerosols are introduced into the atmosphere by seaspray (Wagenbach *et al.* 1998). These aerosols travel inland from coastal regions and are major contributors to the sulphur content of bulk deposition, though it decreases with distance from the coast (Wakshal & Nielsen 1982). The $\delta^{34}S$ value of seasalt sulphate is constant at +21‰ (Halas 1987).

Sulphur is a basic requirement of life, it is added to the atmosphere during an organisms life and after death (Schidlowski 1989; Davis *et al.* 1998). The largest source of biological sulphur is DMS (dimethyl sulphide), which is released into the atmosphere by marine micro-organisms. DMS has a $\delta^{34}S$ value of $\sim +15.6$‰ (Calhoun *et al.* 1991; Wadleigh *et al.* 1994).

Fossil-fuels contain sulphur as an impurity in the form of organic compounds, metal sulphides and sulphate. During combustion the sulphur escapes into the atmosphere as SO_2, SO_3, char, soot, fly ash or sulphuric acid droplets (Flagan & Friedlander 1978; Brimblecombe *et al.* 1989). Fossil-fuel combustion is the largest anthropogenic source of sulphur to the atmosphere and bulk deposition (Cortecci & Longinelli 1970; Barrie *et al.* 1984). The sulphur content of different fuels varies widely, natural gas has the lowest (0.05%) and some types of coal have the highest sulphur content (7%) (Brimblecombe *et al.* 1989). The isotopic signature of sulphur released by automobiles lies between +12 and +16‰ (Nielsen 1974).

The sulphur content of mineral ores can exceed the amount of extractable metal. The sulphide content of the ore is released as SO_2 during the refining process and as much as 30-40% of the total emissions are converted to sulphuric acid for commercial gain (Brimblecombe *et al.* 1989). The $\delta^{34}S$ values for mineral sulphide lie between -6 and +9.5‰ (de Caritat *et al.* 1997).

Identification of Sulphur Sources

Ionic and isotopic identification may be used to determine the sources of rainwater sulphate. The main source of chloride ions is the ocean, and it has a constant marine ratio with sulphate (Wadleigh *et al.* 1994). This ratio therefore gives an estimate of the marine content of rain and any sulphate in excess of the seasalt ratio is called excess (or non-seasalt) sulphate. The contribution from each source depends on the distance from the sulphur source and its productivity. $\delta^{34}S$ values with nss sulphate content may be used to estimate the relative contribution of each source (Krouse 1980).

Ion Sources

Five of the 12 ions analysed during this study (Cl^-, Na^+, Mg^{2+}, K^+ and NH_4^+), have seasalt as the main source. Chloride has a few industrial sources, including aluminium refining and fertiliser manufacture (Graedel 1978) but the contribution from these sources is very small (Manahan 1994). Potassium is released during fertiliser and cement manufacturing (Lee *et al.* 1998) and magnesium is released during cement and steel manufacturing (Graedel 1978).

Studies from the Northern Hemisphere, have identified automobile emissions as a significant source of four ions (F^-, NO_2^-, Br^- and NO_3^-) (Wadleigh *et al.* 1994). Fluoride is also emitted during the manufacture of aluminium and steel (Graedel 1978). Nitrite and nitrate ions form from NO_x gases emitted during the combustion and refining of fossil-fuels and mineral refining. Nitrate ions are also emitted during fertiliser manufacturing. Phosphate and calcium ions are produced during the steel-making process (Robinson 1971).

METHODS

Twelve bulk deposition collectors were placed in the Illawarra. The collectors were arranged into two transects - an East-West transect to gauge the change in marine content of the rainwater with distance from the ocean and a North-South transect to gauge the effect that Sydney pollution has on the Illawarra with distance from the city. A cluster of collectors was also placed around the major industrial complex at Port Kembla (near the BHP steelworks). This was to allow the measurement of the $\delta^{34}S$ values of industrial sulphur sources and hence gauge the influence that industry has on rainwater content with distance from the complex.

Collection

The collectors consist of a stainless steel bin, elevated one and a half metres above the ground on four star pickets. A square pyramidal stainless steel funnel sat on top of the bin and extended into a six-litre borosilicate glass bottle. The bottles were retrieved and replaced once every two weeks, depending on the rain frequency. Each sample was filtered through a 0.45μm membrane into a High Density Poly-Ethylene bottle to remove suspended solids and stored in a cold, dark storage room at 4°C.

Analysis

A small volume was taken from each sample for ionic determinations. The anions and cations were analysed separately on a Waters Alliance 2690 Ion Chromatograph. The anion and cation concentrations were analysed twice to allow an averaging of the results.

The remaining solutions were pre-concentrated in anion exchange columns with a BIORAD® AG1-X8 Cl^- form resin. The samples were poured through the columns at 5 mL/min then the anions were eluted off the resin using 0.5 mol/L HCl at 5 mL/min. The concentrated sample was collected from the columns and 100 mg of solid $BaCl_2$ was added, this reacted with the sulphate to form $BaSO_4$ crystals. The $BaSO_4$ was combusted to form SO_2, which was analysed by a Micromass Prism III mass spectrometer. Two international standards, NBS127 and Soufre de Lacq, with known $\delta^{34}S$ values were used to determine the $\delta^{34}S$ values for the samples.

RESULTS

Over a period of 153 days through autumn and winter, 73 bulk deposition samples were collected. Ionic results were obtained for all 73 samples. The sources of each ion were determined using correlations, factor analysis, spatial variations and non-seasalt determinations.

Ionic Results

All 12 ions were correlated to one another, using *Statview* to determine the relationships between the ions. Six of the ions (Cl^-, SO_4^{2-}, Na^+, Mg^{2+}, K^+ and NH_4^+) showed a strong correlation to one another. Three of the other ions (F^-, NO_2^- and Br^-) correlated strongly to one another and calcium and sulphate correlated very strongly to each other. These correlation results were used to support the factor analysis that was also performed.

Factor analysis was performed on all of the ions and three dominant factors were identified. The first accounted for 45% of the variance and showed the best correlation with Cl^-, SO_4^{2-}, Na^+, Mg^{2+}, K^+ and NH_4^+. This factor was interpreted as seasalt. The second factor accounted for 27% of the variance and showed the best correlation with F^-, NO_2^-, NO_3^- and Br^-. This factor was interpreted as automobile emissions. The third factor accounted for 13% of the total variance and showed the best correlation with Ca^{2+} and PO_4^{3-}. This factor was interpreted as the steel-making process.

Factor analysis was also performed by site and two dominant factors were identified. The first factor accounted for 75% of the variance and correlated best with the sites closest to the coast. This is because of the high seasalt deposition, fossil-fuel combustion, population concentration and proximity to industry, such as mineral refining. As a result the seasalt and non-seasalt content of rainwater was measured as highest at coastal sites. The second factor accounted for 25% of the variance and correlated best with the four sites that are farthest from the coast. These sites received less seasalt and non-seasalt ions than the coastal sites.

The ions interpreted as being mostly marine derived showed definite spatial trends with the highest concentrations found at sites closest to the ocean and a decrease with distance from the coast. An example of this trend is that the chloride ion concentration was 5.37 ppm at 1.7 km from the coast and 1.17 ppm when 46.1 km from the coast. The ions interpreted as being mostly derived from automobile emissions showed the highest concentrations at those sites near heavily used roads. For example, the nitrite ion concentration was 0.95 ppm adjacent to a busy freeway and 0.17 ppm at the southernmost collector, which is the farthest from a major road. The highest non-seasalt sulphate concentration (1.61 ppm) was at the collector in Wollongong city, near heavy industry and population. The lowest levels were at the westernmost collector (0.00 ppm), farthest from industry and population. The non-seasalt sulphate sources in the Illawarra were identified as industrial, fossil-fuel combustion, mineral refining and dimethyl sulphide.

Isotopic Results

Sulphur isotope results were obtained for 14 of the 73 samples. The $\delta^{34}S$ values ranged from +11.8 to +19.4‰. The $\delta^{34}S$ values of natural sulphur sources are +21‰ for seasalt and +15.6‰ for DMS, while the anthropogenic sulphur sources have lower $\delta^{34}S$ values, +12 to +16‰ for automobiles, +9.5 to -6‰ for mineral refining. The $\delta^{34}S$ values of 5 coal samples used in the Illawarra were measured with an average of +2.7‰. Therefore, the higher the $\delta^{34}S$ value of the sample, the higher the natural sulphur content. Those sites with high $\delta^{34}S$ values had low non-seasalt sulphate levels and were closest to the ocean. Those sites with the high non-seasalt sulphate concentration had low $\delta^{34}S$ values and were closest to industry.

The isotope results measured in this study had high values, close to that of seasalt and much higher than measured in studies in the polluted Northern Hemisphere, for example +4‰ from North Bohemia (Novák *et al.* 1995). The non-seasalt sulphate levels were low compared to values from the Northern Hemisphere, for example 3.9 ppm from Canada (Wadleigh *et al.* 1994). These results indicate that the Illawarra is a relatively clean area with very little pollution.

CONCLUSIONS

The results of this study show that the Illawarra is relatively unpolluted compared to the Northern Hemisphere. Ionic and isotopic results indicated that the majority of atmospheric deposition in the Illawarra is from seasalt. The seasalt contribution was found to decrease with distance from the ocean. Three major ionic sources were identified: seasalt (45%), automobile emissions (27%) and steel-making (13%). The atmospheric deposition exhibited distinct spatial patterns, the majority of anthropogenic ions were deposited near Wollongong city and the Port Kembla industrial complex. This study was performed after the closure of Southern Copper, a large copper refining plant. This study may be repeated in the future once the smelter is reopened to determine if it has an impact on atmospheric deposition in the Illawarra.

ACKNOWLEDGMENTS

This research was conducted as part of an honours degree at the University of Wollongong. I would like to thank my supervisor, Professor Allan Chivas, the other staff in the School of Geosciences and Daniel Palamara for their help during this research.

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