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# TWENTY SIXTH NEWCASTLE SYMPOSIUM

on

# "ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

3rd to 5th APRIL, 1992

NEWCASTLE NSW AUSTRALIA

DEPARTMENT OF GEOLOGY, THE UNIVERSITY OF NEWCASTLE, NSW 2308

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C.F.K. DIESSEL
CONVENER

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## AUTHOR INDEX

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

## PREFACE

Once again, welcome to the Newcastle Symposium. The programme is as varied as ever with the main emphasis on our traditional themes: coal mining and exploration geology, coal petrology and technology, sedimentology, particularly of coal measures, and general aspects of the geology of the Sydney Basin and its hinterland, the New England Fold Belt. In all these fields interesting and stimulating papers will be presented.

Of course, the regional character of the Newcastle Symposium has never prevented us from accommodating relevant information from other fields and areas. For this reason we have always had the habit of regarding other Australian coal basins as mere extensions of the Sydney Basin, but this year we will be going further afield. Dale Leckie, a Canadian currently staying in New Zealand, and David Marchioni, an Australian and former graduate of this University living in Canada will tell us about the Cretaceous Gates Formation which appears to show distinct similarities to our Bulga Formation/Archerfield Sandstone/Bayswater Seam succession. From Canada we shall move to South-East Asia where Joan Esterle, an American now working in Australia, researched tropical peat deposits and related their structure and composition to coal lithotypes.

Participants will note that the final programme differs slightly from the preliminary notes that went out with the 2nd Circular. The reason for this is the unfortunate withdrawal of two papers due to a combination of commercial and legal considerations. While late cancellations are part of any convener's nightmares, their repeated occurrence is a positive sign that the Newcastle Symposium is a forum for today's ideas and evolving concepts, and not a depository for yesterday's information. Many papers that grace the pages of the scientific literature have been discussed first at the coal face in Newcastle, and that is the way we like it.

Claus F. K. Diessel
Convener

## FOREWORD

Welcome to the 26th Newcastle Symposium on *"Advances in the Study of the Sydney Basin"*. The recession is still with us but it appears to have had little effect on the support for the Symposium, as offers for papers have been as great as ever. The papers are as diverse as in previous symposia and will satisfy even the most catholic tastes of the participants.

The Keynote Speaker is Brian Vitnell, an ardent supporter of Newcastle Symposia and a well-known identity in the coal industry. He will speak on "The Other Side of the Coin – From Science to Local Government".

The Newcastle Geology Graduates' Society has once again organised their very popular social gathering, the Sheep Roast, on Friday evening at 6:30pm, in the University Union. As in the past, delegates will be able to prepare themselves for the avalanche of papers in the subsequent days.

An interesting Excursion has been arranged this year, tracing the footsteps of the pioneering geologists and explorers such as Leichhardt, Dana, Strzelecki, David, Clarke – visiting those localities in the Newcastle and Lake Macquarie areas which played a key role in the geological understanding and industrial development of our region.

In my foreword in the 25th Newcastle Symposium volume, I mentioned that it was unlikely that the Chair in Geology would be filled nor that any additional staff would be appointed in the near future. I am happy to say that my predictions for the future were incorrect and that the University, in its wisdom, allowed us one further staff member. We felt that the Department should take a new direction and concentrate more on the "soft rock" side of geology, an area which is not strongly emphasised in most geology departments. The successful applicant was Ron Boyd from the University of Halifax, Canada, who comes with excellent teaching and research credentials. He specialises in seismic stratigraphy, a field we feel our undergraduates should have available to them. The combination of Ron Boyd, Claus Diessel and Colin Murray-Wallace will provide the department with an extremely high profile in sedimentology.

The staff continue to attract research funding despite even greater competition for meagre funds provided by the Federal Government, with Claus Diessel topping the pole with $208,000 for 1992. Recognition of his scientific worth also came in the form of the Thiessen medal, awarded by the International Committee for Coal Petrology for his "outstanding work on the formation and utilisation of coal, especially of Australian coals". Congratulations Claus!

The profile of the Department was very high at the recent 11th Australian Geological Convention, with staff and postgraduate students offering seven papers. Phil Seccombe also convened the very popular Economic Geology section. Later this year, Bill Collins will be convening a conference at Alice Springs entitled "The application of radiogenic isotopes to field-related geological problems", and several staff will be presenting papers at international conferences in the USA, UK and Port Macquarie. The image of the Department must be enhanced as a result of this frenetic scientific activity.

It is with a great deal of pleasure that I note the achievements of two of our undergraduate students : Wendy Timms, who has just completed first year geology, has been presented with the Duke of Edinburgh Award at a ceremony in Sydney held during the royal visit, and Susan Keay has finished her outstanding undergraduate career with an armful of distinctions in geology. I trust that we will have many more students of the calibre of Wendy and Susan.

My thanks are also due to Professor Keith Morgan in performing the opening ceremony of the Symposium, this being the last time he will do so, on the eve of his retirement. I am sure that all of us wish him and his wife a long and happy retirement.

As always, the organisation of the Symposium has been superb with contributions by all staff and in particular by the formidable duo, Geraldene MacKenzie and Claus Diessel. Without them, I'm sure the Symposium would collapse.

Robin Offler
Head of Department

# PROGRAM
## 26th NEWCASTLE SYMPOSIUM
## "ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

| **FRIDAY** | **3 APRIL 1992** |
|---|---|
| **10:00 - 17:30**<br>**EXCURSION** | HISTORY OF GEOLOGY IN THE NEWCASTLE REGION<br><br>*LEADERS :* *David Branagan (University of Sydney) and Claus Diessel (University of Newcastle)*<br><br>The excursion will visit localities in the Newcastle and Lake Macquarie area which played a key role in the geological understanding and industrial development of the region, including the (former) fossil forest at Fassifern, Coal Point, Elizabeth Bay (sand mining), Frazer Park (gravel quarry), Swansea Head (fossil forest), Redhead (last coal mine east of Lake Macquarie), Merewether cliff section and other places.<br><br>Lunch will be provided.<br><br>*Because access is restricted, there will be only one bus with a maximum of 65 participants.* |
| **18:30 - 23:00** | **UNIVERSITY OF NEWCASTLE GEOLOGY GRADUATES' SOCIETY SHEEP ROAST - UNIVERSITY UNION** |

| **SATURDAY** | **4 APRIL 1992** | |
|---|---|---|
| **08:30 - 09:00** | **REGISTRATION** - Foyer of the Geology Department | |
| **09:00 - 09:05**<br>**Lecture Theatre B01** | **WELCOME** by the Head of the Geology Department, Associate Professor Robin Offler | |
| **09:05 - 09:10** | **OPENING** of the 25th NEWCASTLE SYMPOSIUM by the Vice Chancellor of the University of Newcastle, Professor Keith Morgan | |
| **TECHNICAL SESSION 1** | **LECTURE THEATRE B01**<br>**Chair** | **David Branagan, The University of Sydney** |
| **09:10 - 09:40** | *F.L. Sutherland*<br>*Australian Museum* | Late thermal events, NE New South Wales - SE Queensland : Links to Sydney Basin seismicity? |
| **09:40 - 10:10** | *Chris Jenkins*<br>*Sydney Univ.* | GLORIA imagery and geological structure of the NSW continental margin (offshore Sydney Basin). |
| **10:10 - 10:50** | **MORNING TEA** | in the FOYER OF THE GREAT HALL |
| **10:50 - 11:20** | *David Grybowski*<br>*Santos Ltd.* | Hydrocarbon exploration in Permit NSW/P10 in the offshore Sydney Basin. |
| **11:20 - 11:50** | *Peter Crozier &*<br>*John Braybrooke*<br>*D.J. Douglas & Partners* | The morphology of northern Sydney's rocky headlands, their rates and style of regression and implications for coastal development. |
| | ***** KEYNOTE ADDRESS ***** | |
| **11:50 - 12:30** | *Brian W. Vitnell, Coal Geological Services & Review Consultant*<br>The Other Side of the Coin – from Science to Local Government | |
| **12:30 - 12:35** | CHAIR | SUMMARY & VOTE OF THANKS |
| **12:40 - 13:45** | **LUNCH** | In the UNIVERSITY UNION |

| SATURDAY | 4 APRIL 1992 | |
|---|---|---|
| **TECHNICAL SESSION 2A** | **LECTURE THEATRE E01**<br>**Chair** | **John Gamble, Victoria University of Wellington** |
| 13:45 - 14:15 | *Michael Vickers & Jonathon Aitchison University of Sydney* | Lower Permian Manning Group : Tectonic implications of sedimentary architecture & provenance studies in the Nowendoc-Cooplacurripa area. |
| 14:15 - 14:45 | *Ross Jenkins University of Newcastle* | A geologic and thermal history of the Manning Group. |
| 14:45 - 15:15 | *Bill Collins University of Newcastle* | Influence of the Peel Fault System on the evolution of the Sydney Basin. |
| 15:15 - 15:45 | AFTERNOON TEA | in the Foyer of the GREAT HALL |
| 15:45 - 16:15 | *Stirling Shaw et al. Macquarie University* | Late Permian magmatism adjacent to the Mooki Thrust, Tulcumba Ridge, NSW. |
| 16:15 - 16:45 | *Albert Brakel et al. B.M.R.* | Sequence boundaries interpreted from seismic data in the Central Taroom Trough, SE Queensland. |
| 16:45 - 17:15 | *John Patterson et al. CSIRO* | The composition of carbonate minerals in coal measures of the Sydney Basin. |
| 17:15 - 17:20 | CHAIR | SUMMARY & VOTE OF THANKS |
| **19:00 FOR 19:30** | **SYMPOSIUM DINNER** | **In the UNIVERSITY HUNTER UNION (opposite the Engineering Complex)** |

| SATURDAY | 4 APRIL 1992 | |
|---|---|---|
| **TECHNICAL SESSION 2B** | **LECTURE THEATRE B01**<br>**Chair** | **Konrad Moelle, The University of Newcastle** |
| 13:45 - 14:15 | *Michael Creech FAI Mining* | Geological controls on gas distribution in the Newcastle Coalfield. |
| 14:15 - 14:45 | *M. Faiz & A. Hutton Univ. Wollongong* | Structural and stratigraphic controls on the variation of seam gas composition in the Illawarra Coal Measures, Southern Coalfield, NSW. |
| 14:45 - 15:15 | *A. Osborne & D. Branagan Sydney University* | ?Pseudokarst in the Sydney Region. |
| 15:15 - 15:45 | AFTERNOON TEA | in the Foyer of the GREAT HALL |
| 15:45 - 16:15 | *P.D. Lamb & D. Sweeney KCC & Pazground P/L* | Seismic exploration in a difficult environment. |
| 16:15 - 16:45 | *Ian Poppitt Coalex* | Wrench-faulting in the Western Coalfield. |
| 16:45 - 17:15 | *R.J. Whiteley & A. Love Coffey Partners* | Site uniformity borehole seismic (SUBS©) testing in undermined areas. |
| 17:15 - 17:45 | *David Mehan Terrence Gill & Partners* | Damage to homes following the Newcastle Earthquake -- Don't blame it all on clay soils. |
| 17:45 - 17:50 | CHAIR | SUMMARY & VOTE OF THANKS |
| **19:00 FOR 19:30** | **SYMPOSIUM DINNER** | **In the UNIVERSITY HUNTER UNION (opposite the Engineering Complex)** |

| SUNDAY | 5 APRIL 1992 | |
|---|---|---|
| **TECHNICAL SESSION 3A** | **LECTURE THEATRE E01**<br>**Chair** | **Judy Bailey, The University of Newcastle** |
| 09:00 - 09:30 | *Lloyd Hamilton*<br>*Q.U.T.* | Dykes in the northern Sydney coastline between Port Jackson and Broken Bay. |
| 09:30 - 10:00 | *Dale Leckie*<br>*Geol. Surv. Canada* | High energy shorelines and the role of shale compaction in the formation of extensive coal deposits. |
| 10:00 - 10:30 | *David Marchioni &*<br>*Wolfgang Kalkreuth*<br>*Petro-Logic Services* | Strand-plain coals of the Gates Formation, Western Canada. |
| 10:30 - 11:00 | MORNING TEA | in the Foyer of the GREAT HALL |
| 11:00 - 11:30 | *Joan Esterle et al.*<br>*CSIRO Geomechanics* | Comparison of macroscopic and microscopic size analyses of organic components in both coal and peat. |
| 11:30 - 12:00 | *Guy Holdgate*<br>*Monash University* | Variations of brown coal composition in response to relative sea level changes — LaTrobe Valley, Victoria. |
| 12:00 - 12:30 | *Claus Diessel*<br>*University of Newcastle* | The problem of syn- versus post-depositional marine influence on coal composition. |
| 12:30 - 13:00 | *Bob Creelman &*<br>*I. Taylor, CSIRO Min. Proc.* | Coal requirements for new iron-making technologies. |
| 13:00 - 13:05 | CHAIR | SUMMARY & VOTE OF THANKS |
| 13:05 - 14:15 | LUNCH | in the UNIVERSITY UNION |

| SUNDAY | 5 APRIL, 1992 | |
|---|---|---|
| **TECHNICAL SESSION 3B** | **LECTURE THEATRE B01**<br>**Chair** | **Russell Rigby, Newcastle-Wallsend Coal Co.** |
| 09:00 - 09:30 | *Dick Sanders &*<br>*Ken Preston*<br>*QCC & Pacific Coal* | Calculating reserves — a matter of some gravity. |
| 09:30 - 10.00 | *Konrad Moelle et al.*<br>*University of Newcastle* | On aspects of strata control in collieries operating in the Sydney Basin. |
| 10:00 - 10:30 | *Jeanne Young &*<br>*Scott Thomson*<br>*CSIRO & METS Pty Ltd* | Geological interpretation of radio wave tomography. |
| 10:30 - 11:00 | MORNING TEA | in the Foyer of the GREAT HALL |
| 11:00 - 11:30 | *Rod Doyle et al.*<br>*BHP/METS* | Application of the Rim technique for water infusion analyses at Appin Colliery. |
| 11:30 - 12:00 | *Ken Macleay &*<br>*Dick Sanders*<br>*Mosslake Mining/QCC Ltd* | Extraction of bulk subsurface coal samples by 'Keyhole Mining'. |
| 12:00 - 12:30 | *Kaye Hart et al.*<br>*ANSTO, Lucas Hts* | Identification of the sources of contamination of product streams in a mineral processing plant. |
| 12:30 - 12:35 | CHAIR | SUMMARY & VOTE OF THANKS |
| 13:05 - 14:15 | LUNCH | in the UNIVERSITY UNION |

# LATE THERMAL EVENTS - NE NEW SOUTH WALES - SE QUEENSLAND – LINKS TO SYDNEY BASIN SEISMICITY?

**F.L. SUTHERLAND**
**The Australian Museum, Sydney**

## INTRODUCTION

A large region of Eastern Australia, with abundant intraplate volcanism since 90Ma, shows little record of such volcanism in the last 10Ma (northern New South Wales - southern Queensland; Johnson, 1989; Sutherland, 1991). This region (between latitudes 26-36°S) includes the Sydney, Oxley and Clarence-Morton late Palaeozoic-Mesozoic basins, which lie within the older Palaeozoic Tasman fold belt sequences (Wyborn in Johnson, 1989). The part east of 150°E has no dated volcanic rocks younger than 13Ma. This is anomalous for a margin with long-lived, relatively continuous volcanism. However, the region of null volcanism (mid-Miocene) is not entirely inactive, as it includes some zones of seismic activity of uncertain or disputed origin or no ready explanation (Dalton-Gunning, Newcastle; McCue et al., 1989, 1990a, b; Gaull et al., 1990).

The east Australian-Tasman Sea volcanic belts are noted for migratory 'hot spot' chains, particularly those extending from 21°S (oldest, 33Ma) to 39°S (youngest, 6Ma), as well as other less prominent 'hot spot' centres of differing ages (Johnson, 1989; McDougall and Duncan, 1988; Sutherland, 1991). Some of these migratory chains project to present 'hot spot' positions marked by well defined concentrations of seismic activity. These show similar earthquake magnitudes to seismic zones of the Sydney Basin - Yass region (Denham, 1985; Michael-Liba and Gaull, 1989; Michael-Liba, 1989; Wellman in Johnson, 1989).

Studies of large, gemmy zircon suites, from basaltic fields in eastern Australia, include fission track (FT) and Pb/U ion probe isotopic dating of the zircons (Hollis and Sutherland, 1985; Sutherland and Kinny, 1990). In expanding these studies, a number of zircon suites showed multiple FT dates, statistically separable into distinct age groups (herein). Some of these fall within the 0-13Ma age range within the region which lacks obvious volcanic rocks of such ages. In some cases, the zircon Pb/U isotopic dating gave older ages than the FT ages, suggesting later thermal resetting of the zircons (Sutherland and Kinny, 1990). Amongst the younger subsets, the older ages (8-13Ma) lie between 28-20°S, the intermediate ages (5-8Ma) lie between

30-28°S and the youngest lie between 32-30°S. This suggests a potential migratory trend southwards, comparable in rate and directional sense expected from absolute motion of the Australian plate over Indian-Australian hot spots (6-7cm/yr; Duncan and McDougall in Johnson, 1989).

The post 13Ma FT dates lie between 150-152°E. Thus, it is tempting to ascribe this apparent migration to eruptive events linked to a discrete, subdued thermal source of 'hot spot' character, now below the Sydney basin, near the Newcastle-Blue Mountains-Illawarra seismic region. Such a juxtaposition would help explain these seismic zones and bring their origin into line with other hot spot-related seismic zones in SE Australia (Fig.1).

This account details and discusses the young FT ages in SE Queensland - NE New South Wales gem zircon suites, to develop a predictive model in relationship to seismic zones in the Sydney Basin.

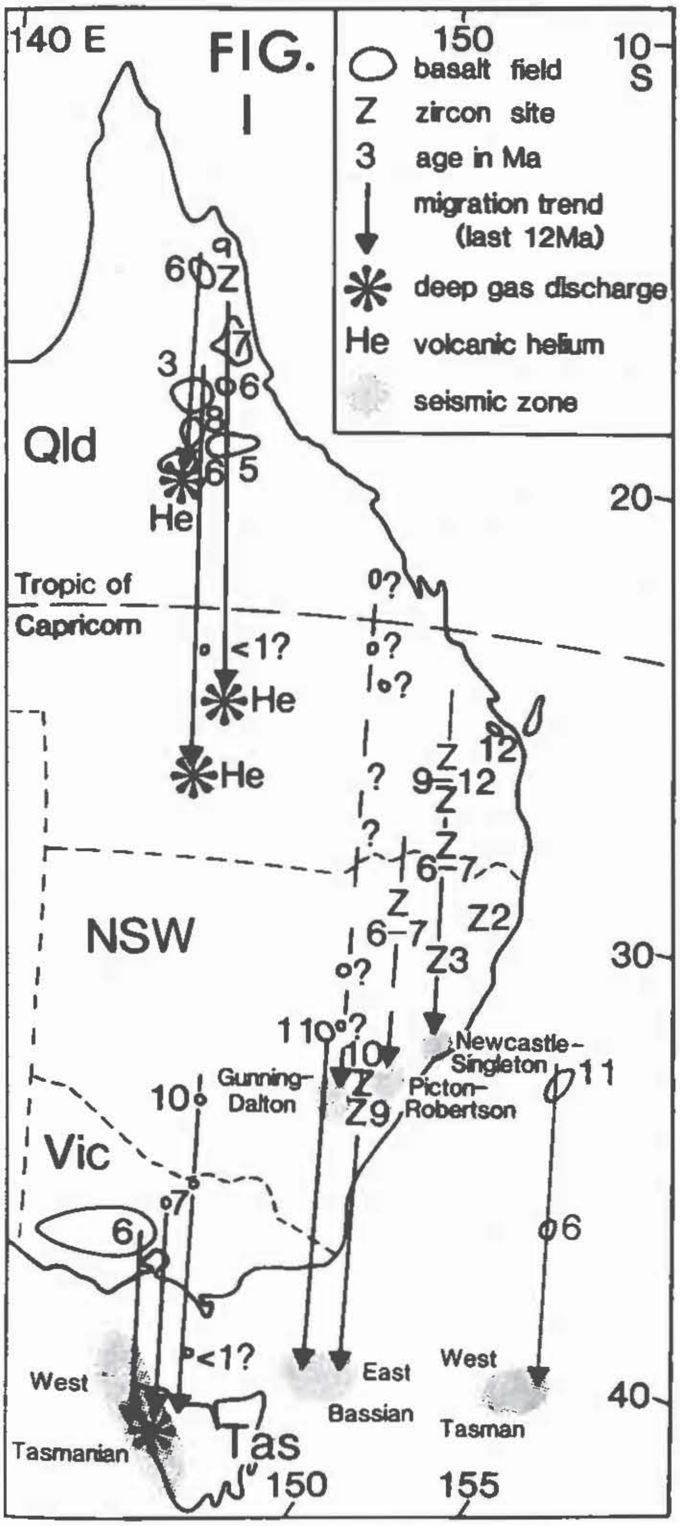
**ZIRCON DATA**

Subsets of young (post 13Ma) FT ages were found in eight alluvial zircon suites from NE New South Wales and SE Queensland localities (Table 1). Samples came from the Australian Museum Collections and from follow-up heavy mineral concentrates panned in the field. The young subset invariably accompanied an older subset or subsets within the suite. The FT dating by Geotrack International, University of Melbourne, used standard methods (Gleadow et al. 1976; Green, 1981; Hurford and Green, 1982, 1983, Green, 1985). The subset ages were established using statistical smoothing and discrimination techniques (Galbraith, 1981; Galbraith, 1988).

**TABLE 1: ZIRCON FISSION TRACK DATA, POST-13Ma AGES, SE QLD-NE NSW**

| **Locality** (Sample No. and description) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Grains** | **Ns** | **Ni** | **Na** | **Ratio** | **U(ppm)** | **RHOs** | **RHOi** | **F.T.Age(Ma)** |
| Brigooda, Qld (8722-305, alluvial grains) | | | | | | | | |
| 4 | 24 | 165 | 90 | 0.144 | 82 | 3.26SE+05 | 1.677+06 | 8.8±4.1 |
| Burrandowan, SW Kingaroy, Qld (GC323-1, alluvial grains) | | | | | | | | |
| 5 | 10 | 28 | 100 | 0.374 | 37 | 3.083E+05 | 4.418E+05 | 10.4±4.1 |
| 13 Mile Creek, Amiens, Qld. (GC344-3, alluvial grains) | | | | | | | | |
| 3 | 5 | 53 | 100 | 0.077 | 26 | 7.545E+03 | 7.628E+05 | 6.3±3.8 |
| Monte Christo Mine, Bingara, NSW (grains from washings) | | | | | | | | |
| 7 | 58 | 480 | 100 | 0.124 | 316 | 9.433E+05 | 7.632E+06 | 6.7±1.0 |
| Oban, NSW (8722-35A, alluvial grains) | | | | | | | | |
| 4 | 52 | 706 | 100 | 0.198 | 697 | 2.685E+06 | 8.257E+06 | 2.2±0.7 |
| Rocky River, Uralla, NSW (8622-129, alluvial grains) | | | | | | | | |
| 3 | 43 | 1059 | 100 | 0.043 | 427 | 5.147E+05 | 1.22E+07 | 2.9±0.4 |
| Hopes Creek, Oberon Area, NSW (GC148-3B, alluvial grains) | | | | | | | | |
| 3 | 14 | 84 | 100 | 0.184 | 63 | 2.278E+05 | 1.340E+06 | 9.4±2.5 |
| Little River, Oberon Area, NSW (8722-345, alluvial grains) | | | | | | | | |
| 6 | 19 | 64 | 100 | 0.295 | 60 | 2.240E+05 | 7.507+05 | 8.6±2.3 |

LATE THERMAL EVENTS - LINKS TO SYDNEY BASIN SEISMICITY?



Some zircon suites include sharp, large crystals (e.g. Uralla, NSW) or highly polished, corroded crystals (e.g. Hopes Creek, NSW). These show very little abrasion and indicate nearby zircon sources. They include crystals found at the margin of volcanic breccia pipes (e.g. Brigooda, Qld.). Other zircons show abrasion and rounding indicating alluvial transport. Some suites (Uralla, Oban, Burrandowan) were largely uniform, but others mix assemblages of types and colours. This suggests that some subset ages represent thermal resetting of older zircons. This was confirmed where Pb/U isotopic dating of zircons gave a formational age older than the young subset age (Sutherland and Kinny, 1990). However, some subsets are distinctive in type and colour within the suite (e.g. Hopes Creek).

## INTERPRETATION OF YOUNG SUBSETS

The thermal events in the young zircon subsets tend to be discrete features. The possibility that they represent a recent heating event (e.g. bush fire) which partly annealed an older component is unlikely, as grains of different ages from all stages of annealing rather than the narrow ages observed would be expected. A spread in ages over 9Ma with a preponderance of short tracks was observed for small euhedral zircons collected from shallow soil on a rhyolite from Bulls Nest, Mt. Belmore, NSW. Ion microprobe ages showed these zircons to be 20Ma. This is more typical of recent heating effects. Also, such heating cannot account for examples in which the younger subset shows distinct zircon characteristics, including range in U contents, from older subsets. The preferred interpretation is eruptive thermal annealing of the zircons, whether resetting material from earlier volcanics, or involving material from subvolcanic chambers related to the later eruption.

Other obvious eruptive products, such as lavas and pyroclastic deposits, related to the younger zircon subsets are scarce. Thus, if the young zircons are eruptives, then they must mostly result from minor breccia pipe activity difficult to locate within normal weathered exposures. An exception is the zircon from the Brigooda centre, where volcanics are exposed in a complex showing several eruptions within the last 13Ma (Robertson et al., 1985). Remnants of a 12Ma lava flow are known near Pialba north east of Brigooda (Robertson, 1985). A small previously unmapped basalt fill in a minor tributary near Oban represents a potential young lava tounge, but the basalt is poorly exposed and too altered for K-Ar age dating.

## SIGNIFICANCE OF YOUNG ZIRCON FT DATES

The zircon dates generally decrease in age southwards (Table 1) from SE Queensland (Brigooda-Burrandowan-Amiens) through the New England region, NSW (SW Bingara-Uralla-Oban). This migration projects towards seismic activity under the Sydney Basin between Newcastle and the Blue Mountains - Illawarra regions, implying thermal activity contributes to the instability.

To test a model involving northward migration over a small 'hot spot'

LATE THERMAL EVENTS - LINKS TO SYDNEY BASIN SEISMICITY?

source, which now produces seismic activity, requires a close match between predicted direction and migration rate of Australia (absolute motion) and zircon (eruptive) FT dates in Table 1. The motions can be estimated from established 'hot spot' traces elsewhere in eastern Australia for the last 13Ma. These include the Tasman Sea mounts to the east (McDougall and Duncan, 1988) and the leucititic (Condobolin-Cosgrove) and trachytic (Woodend) intrusives to the west (Johnson, 1989). Potential migrations suggested in the younger basaltic activity of north Queensland (Sutherland, 1991), have further age control from zircon FT dates. The migration rates along these lines (Figure 1) can be estimated by extending them to predicted hot spot positions marked by seismic zones (Wellman in Johnson, 1989), recent uplift (Bowden and Colhoun, 1984) or discharges of gasses (He, $CO_2$) with isotopic signatures indicating a likely mantle origin (Green, 1982; Torgersen, et al., 1987). The rates for migration to the southern limits of these features (Table 2) appear lowest for the Tasman Sea line (0.6-0.5$^o$/Ma) and higher for more inland lines, e.g. north Queensland (1$^o$/Ma). A rate of 0.75$^o$/Ma is selected as a likely maximum to compare predicted and actual ages of eruption north of the Newcastle-Illawarra seismic zones (Table 3). The 3Ma, 6Ma and 9Ma predictive positions, north of Newcastle, mostly lie within ± 0.3Ma and 30Kms of dated zircon sites at Uralla, Stanthorpe and Brigooda respectively. The 6.5Ma and 10.5Ma predictive positions north of Bowral-Robertson lie within ± 0.2Ma and 10Km in latitude of dated zircon sites at Bingara and Burrandowan, but longitudes lie within 10-120Kms. The Oban age is 1Ma younger than predicted, but fission tracks in this sample proved difficult to count (P.F. Green, pers. comm.) and may be underestimated. Though based on limited data, the zircon dates match a model for asthenospheric thermal sources up to 250Kms across, which intermittently triggered minor volcanic outbursts every few million years and presently activate seismicity or degassing from several mantle sources (Fig.1).

**TABLE 2: MIGRATION RATES, POST-13Ma VOLCANIC TRENDS, E.AUSTRALIA**

| **MIGRATORY LINE** | **RATE** |
|---|---|
| Tasman Sea Mounts, 33$^o$S (12.3-15.4, 10.5-11.4Ma) | **cm/yr** |
| - West Tasman Seismic Zone, 39.8$^o$S (0Ma) | 6.3-7.1 |
| Oberon, NSW, 33.7$^o$S (9.0Ma) | |
| - E. Bassian Seismic Zone, 40.8$^o$S (0Ma) | 7.6-8.3 |
| Orange, NSW, 33.3$^o$S (11-12Ma) | |
| - NE Tasmania Uplift Zone, 40.8$^o$S (0Ma) | 6.5-7.5 |
| Flagstaff Hill, NSW, 33.8$^o$S (10.3Ma) | |
| - Renison Gas Discharge, Tas., 41.8$^o$S (0Ma) | 8.4 |
| Woodend, Vic., 37.3$^o$S (5.8-6.3Ma) | |
| - Renison Gas Discharge, Tas. 41.8$^o$S (0Ma) | 7.3-8.2 |
| Mt. McLean, Qld., 15.8$^o$S (9.0Ma) | |
| - Oakwood Helium Discharge, Qld., 25.5$^o$S (0Ma) | c.11 |
| McBride, Qld., 18.5$^o$S (8-11Ma) | |
| - Juanobong Helium Discharge, Qld., 27$^o$S (0Ma) | c.8-11 |

**TABLE 3: PREDICTED MIGRATION SITES FOR ZIRCON FT DATES, NE NSW-SE QLD.**

| ACTUAL AGE | ACTUAL POSITION | MODEL AGE | PREDICTED POSITION |
|---|---|---|---|
| NEWCASTLE-BRIGOODA MIGRATION LINE (0.75°/Ma north) | | | |
| 0Ma | Newcastle area, NSW<br>33°S,151°35'E | 0Ma | Newcastle seismic zone<br>33°S,151°35'E |
| 2.9Ma | Rocky River, Uralla, NSW<br>30°40'S,151°50"E | 3Ma | 3Ma thermal zone,<br>30°45'S,151°35'E |
| 6.3Ma | Amiens, Stanthorpe, Qld.<br>28°35'S,151°50'E | 6Ma | 6Ma thermal zone,<br>28°30'S,151°35'E |
| BOWRAL-S.QUEENSLAND MIGRATION LINE (0.75°/Ma north) | | | |
| 0Ma | Bowral-Robertson, NSW<br>34°30'S,150°30'E | 0Ma | Bowral seismic zone<br>34°30'S,150°30'E |
| 6.7Ma | Monte Christo, West Bingara, NSW<br>29°50'S,150°30'E | 6.5Ma | 6.5Ma thermal zone<br>29°45'S,150°30'E |
| 10.4Ma | Burrandowan, SW Kingaroy, Qld.<br>26°35'S,151°30'E | 10.5Ma | 10.5Ma thermal zone<br>26°38'S,150°30'E. |

**DISCUSSION**

The data suggest a potential thermal input into Sydney Basin seismicity. Many earthquake solutions in east Australia are compressive in nature, including the 1989 Newcastle earthquake (Denham et al. 1981; Lambeck et al. 1984; Denham and Ellis, 1986; McCue, et al. 1990). This is compatible with stress fields modelled for the Australian Plate, although directions of principal horizontal compressive stress may differ from those modelled from the plate motions (cf Cloetingh and Wortel, 1986 and Wellman in Johnson, 1989). An expected influence from a small thermal source would be minor uplift. This would be partly accommodated by plastic flow below 45 ± 15 km in regions of high heat flow and seismic events reflect brittle failure above this (Cull, 1989). The stress is probably relieved under combined local and regional compression, providing thrust plane solutions from events deeper than 15Km and mostly strike slip mechanisms above 5Km depth (Wellman in Johnson, 1989).

Evidence for young uplift in the Sydney Basin, has been re-evaluated (Young, 1991). Earlier uplifts were associated with the larger 'hot spot' sources along east Australia (Wellman in Johnson, 1989) and off shore sources probably helped uplift the coast here around 8-3Ma, perhaps with later tectonic activity (Roy and Thom, 1991). However, the origin of features such as the Lapstone Monocline and the courses of rivers eroding through the escarpment are now given ages over 8-15Ma, although there are a few indications for minor, local recent uplift, e.g. Burralow Creek (Young, 1991). South of the postulated thermo-seismic zone, the coastal lowlands are mid-Tertiary in origin, with little evidence of later tectonic dislocations between highlands and lowlands (Nott, et al., 1991).

LATE THERMAL EVENTS - LINKS TO SYDNEY BASIN SEISMICITY?

This proposed small 'hot spot' trigger explains previously undetected minor eruptive events from SE Queensland through NE New South Wales. A broad source or smaller discrete sources may be involved. This links the model to other hot spot related seismicity in east Australia, including the SE South Australian - SW Victorian seismic zone (McCue et al., 1990a; Sutherland, 1991). It foreshadows an obvious question concerning the Dalton-Gunning seismic zone, west of Sydney Basin. Is it hot spot related? A programme for dating zircons and basalts from volcanic fields along a projected northward line, as reported for the Sydney Basin seismic zone, is needed to search for similar, unexpectedly young dates.

**Acknowledgements:**

R.E. Pogson, J.D. Hollis and B.J. Barron, Australian Museum and A.D. Robertson, Geological Survey of Queensland, assisted with sampling zircon sites. The Australian Museum Trust and the Newcastle Regional Museum, through P. Filmer-Sankey, provided funds for dating.

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# GLORIA IMAGERY AND GEOLOGICAL STRUCTURE OF THE NSW CONTINENTAL MARGIN (OFFSHORE SYDNEY BASIN)

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Long-range sidescan data from the GLORIA technology plus multibeam bathymetry are now available for the continental slope offshore of New South Wales. This imagery and associated geophysical data show that the continental margin is remarkably bare of sediment cover. Because of this, the rifted structure, basement and early post-rift sediment sequences can be more clearly imaged and more effectively sampled than in other continental margins where almost always 3-7km thickness of more recent sediments covers the basement structure.

*Methods*

GLORIA is a sidescan instrument which produces backscatter images of the seafloor, usually over a swath width of 30km at 'on the ground resolution' of about 100m and with an operating frequency of ~6.5kHz (Laughton 1981, Jenkins & Lawrence 1990). It is towed near the sea surface. A GLORIA survey over the NSW continental margin took place in September 1989 using HMAS Cook. In the allotted 49 hours 15,000km$^2$ of seafloor was imaged - the entire continental slope between Sydney and Batemans Bay plus portions of the adjacent abyssal plain. In conjunction, we acquired SeaBeam multibeam bathymetry, airgun seismic and towed-body 3.5kHz subbottom profiles. An important feature of the survey was that the track ran mostly parallel to slope and, unlike previous surveys, could very effectively define the segmentation of the continental margin which is due to cross-cutting transfer faults.

With GLORIA, as with all sidescans, a bright backscatter return is elicited from seafloor which either: (a) faces directly towards the towfish (specular reflection), or (b) is especially reflective and sufficiently rough at the right spatial scales. High backscatter will certainly result from rock exposures, but exactly how GLORIA data relate to the seafloor sediment type is currently a topic of hot debate. Current work shows that indicating high-response sedimented areas simply as sandy is incorrect and also that at 6.5kHz, layers as deep as 30m inside the seafloor may be imaged. Although several highly detailed studies have investigated the relation of backscatter return to sediment type, layering within the seafloor and bottom roughness (e.g., Gardner & others 1991), a definitive answer does not exist as to what causes backscatter contrasts.

Bearing this problem in mind, we interpreted the GLORIA imagery with the aid of the subbottom profiles, bathymetry and also all existing bottom-sampling data. Maps were constructed to show the sediment thickness and depth of rock basement, and were compared with the GLORIA results across the area. Furthermore, where structures such as sediment slides or igneous complexes were indicated in the imagery seismic data were used to verify the underlying geological structure.

*Results*

The continental slope is divided geomorphically into an upper zone characterized by smooth, relatively thickly sedimented seafloor between water depths of 200-1000m; a middle slope where submarine canyons are incised and thick sediment accumulations are held in small basins (water depth range 1000-3200m); and the lower slope which is exceptionally steep, has mostly insignificant sediment cover and is cut by large submarine canyons (depth range 3200-4850m).

The following primary geological structures were identified.
(a) Areas of exposed rock run as ridges for long distances (200km) along contour on the middle and lower slope at water depths of 2500-4000m. They represent the 'noses' of tilted-blocks in the rifted geological structure and probably consist of sandstone and shale (Sydney Basin sequence), or else granite, slate and volcanics (Palaeozoic basement). The geometry of these ridges defines the principal rifted half-graben structure in the continental margin and also its segmentation into blocks. In the GLORIA imagery they show as belts of bright backscatter running along slope.
(b) A 400-500m thick belt of sediments is perched on the shelf break and upper slope. In cross section it is sigmoidal in shape and it extends right along the continental shelf break of NSW. Seismic data and scarce direct sampling indicate that it has accumulated in the last approx. 15 million years from sediments transported to the shelf edge during low sealevel stands and from pelagic sediment supply. The seaward edge, which at present is eroded by the East Australian Current, appears in the GLORIA imagery to be marked by numerous small contour-parallel scarps each 1-2km in length.
(c) Submarine canyons up to 500m deep and 20km wide, dissect the slope and many cut right down to the basement. Several large systems offshore of Sydney-Wollongong and also Batemans Bay have a complicated shape which is apparently governed by underlying basement structure. Offshore of Jervis Bay more numerous, smaller canyons pass in straightforward manner across and down the slope. Few of the canyons have cut into the slope inshore of the 500m isobath and none reach the 160m deep shelf break. In the imagery canyons had subtle expression combining bright returns from the hard floors and facing sides, plus shadows from the facing-away walls.
(d) On the upper-middle slope at 1000-2500m water depth, enormous submarine landslides (slope gravity failures) occur. The seismic and GLORIA data indicate that some are 20km across, 30km in downslope length and 300km thick, and moved a distance of 10km at some time in the last 1 million

years. A small amount of seafloor instability probably continues to be associated with them. Wide areas consist of 'broken ground', further indicating the extreme susceptibility of the sediments on this continental slope to down-slope sliding.
(e) Raised volcanic/igneous ring complexes were detected on the middle slope at 3000m water depth. Dredgings from earlier cruises (Hubble & others, in press) showed that they are ~100Ma old and represent volcanic activity during the rifting of the Lord Howe Rise from eastern Australia. There is some evidence that similar structures occur to as far north as Newcastle.
(f) On the adjacent abyssal plain (water depth 4800m), patches of reflective sediment are observed which have a 'cirrus-like' form. No raised dune is associated, and they appear to be ribbons of silt winnowed and shaped by strong abyssal current flows. This accords with current-meter data obtained from 100m above the abyssal plain by Mulhearn & others (1988), who showed flows of up to 35cm/sec (0.7 knots) associated with the passage of mesoscale eddies in the East Australian Current.
(g) At the mouths of the larger submarine canyons, strongly backscattering sediments have spilled onto the abyssal plain. While some have spread far across the plain, others have clearly been smeared northwards by the currents referred to in (f). To judge from 3.5kHz records, these turbidite deposits are very thin (<2m).

*Conclusions*

In the context of Sydney Basin studies, the analysis of the GLORIA data and anciliary geophysical data shows that (in the area of the survey):
(i) the middle and lower slope consist of only between 1 and 3 tilted fault blocks and half-grabens, an extremely abbreviated rifted margin structure;
(ii) the tilted blocks and seaward edge of the palaeoshelf are segmented on a scale of 15-45km by slope-transverse faulting, but no evidence has been seen for large (margin-wide) transfer faults of the type predicted in tectonic models of rifting;
(iii) there is no evidence for significant rift faulting in the upper slope or indeed the continental shelf, where broad style uplift, erosion and subsidence appear to have dominated;
(iv) a palaeoshelf exists beneath the outer shelf and upper slope, where it is buried by a Neogene shelf-edge prograding sediment wedge; the palaeoshelf has up to 100m of older Cenozoic strata associated and now inclines seaward at $2^{o}$.
(v) ca. 100 Ma Mt Dromedary type volcanism of the synrift stage is extensive in the offshore southern Sydney Basin;
(vi) continued exposure of synrift igneous ring complexes and pre-rift basement attest to the extremely sediment-starved nature of this continental margin where the median sediment thickness is 500m.

Based on the GLORIA imagery and other geophysics, programs are planned which will sample the Sydney Basin where it crops out on the continental slope 50-100km east of the present coastline.

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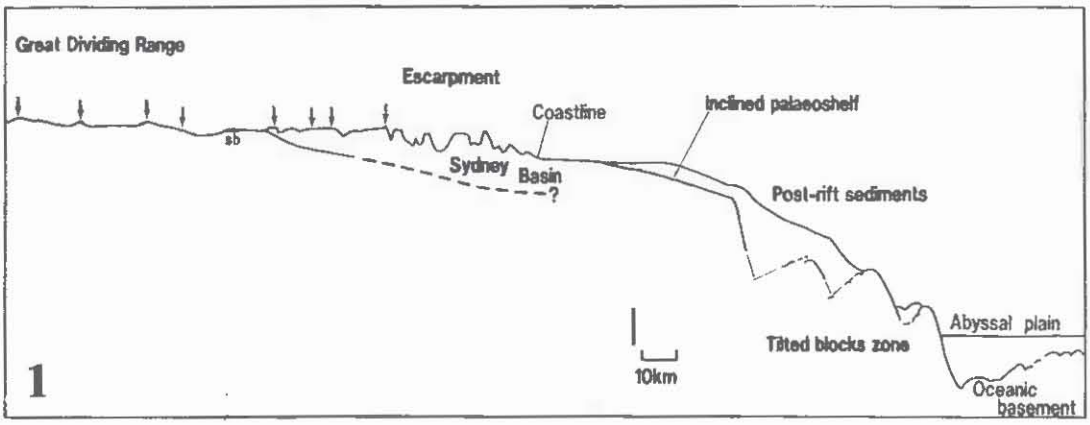
*Figures*

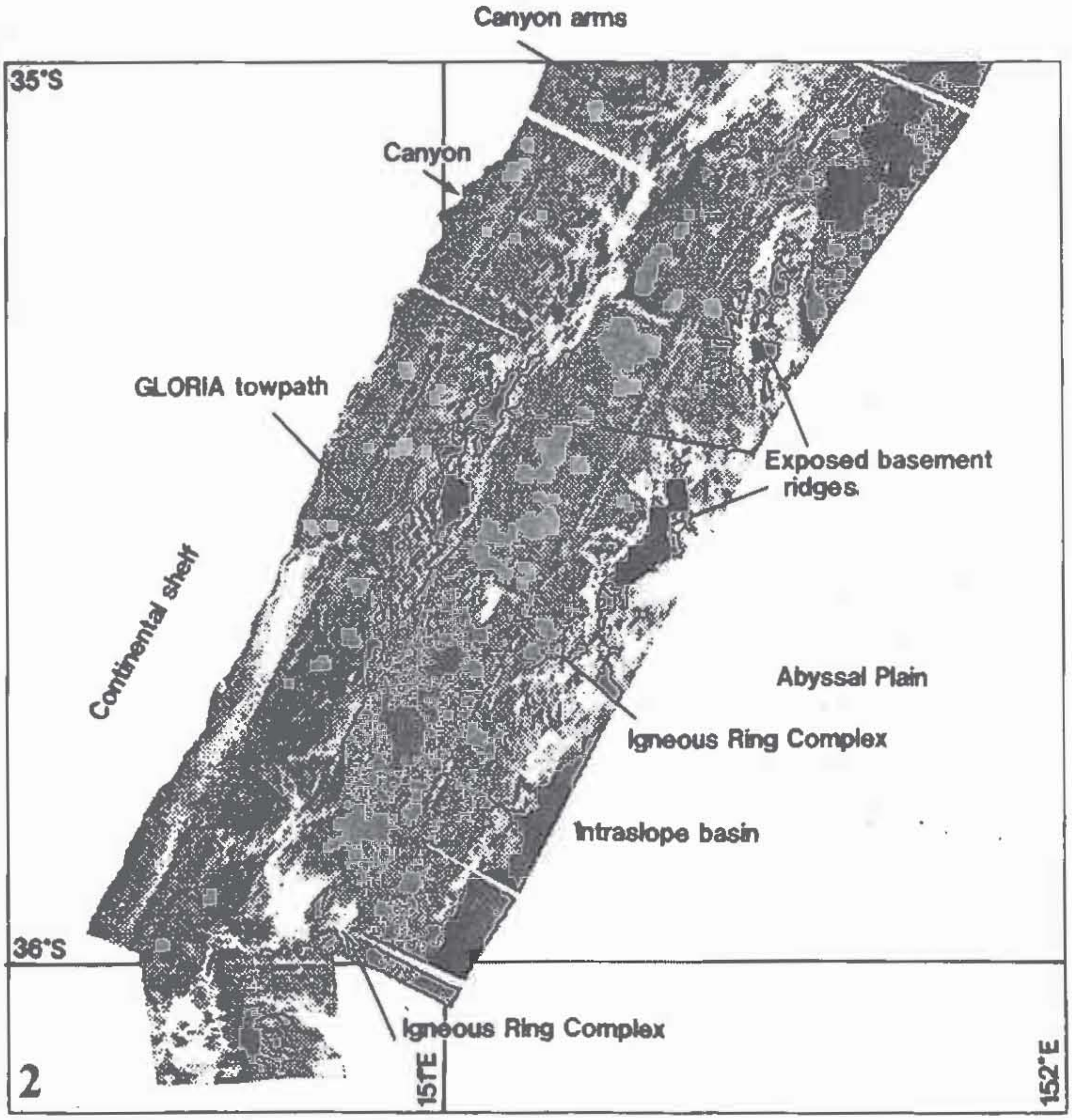
Figure 1. Cross section of the continental margin, Grabben Gullen through Kiama. Note the opportunities for sampling Sydney Basin rocks and perhaps their basement, 100km east of the present coastline. Small arrows show Cenozoic basalts in the Eastern Highlands; sb indicates Sydney Basin outlier.

Figure 2. Portion of the GLORIA image in the area offshore of Jervis Bay-Batemans Bay (coarse printing). Bright backscatter response is shown white.

Figure 3. Structure contours for the top of the rifted basement, based on seismic data. Note: (i) the gentle incline of the palaeoshelf seaward from the continental shelf; (ii) offsets in the trends of strike structures, reflecting short segments of transfer faulting; disorganized arrangement of basement highs in the middle and lower slope.

GLORIA IMAGERY ... OFFSHORE SYDNEY BASIN



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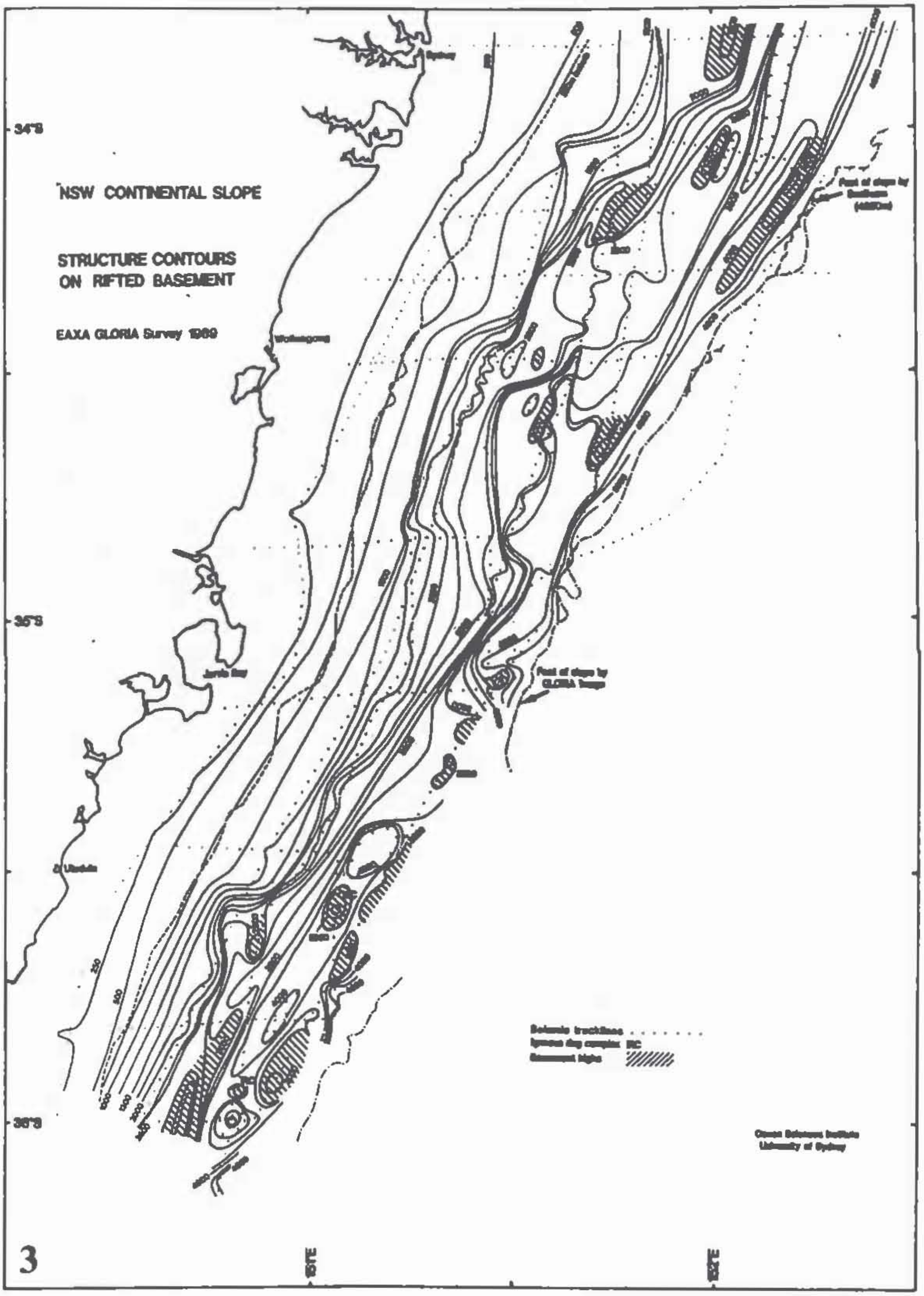

# HYDROCARBON EXPLORATION IN PERMIT NSW/P10 IN THE OFFSHORE SYDNEY BASIN

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The offshore Sydney Basin is unique frontier acreage because it is adjacent to Australia's largest gas and petroleum market on the east coast of New South Wales. Although the onshore Sydney Basin has been tested by more than 100 petroleum exploration wells, no wells have been drilled offshore.

New South Wales Permit NSW/P10 has an area of 9419 km2 and extends over the offshore northern and central Sydney Basin which is comprised of Upper Carboniferous to Middle Triassic lithiclastic and siliciclastic sedimentary rocks and volcanics. Maximum depth to magnetic basement in NSW/P10 is greater that 9 km in the southern Macquarie Syncline and south of the New England Fold Belt at the continental margin. Recent seismic reprocessing and aeromagnetic survey and interpretation have focused the exploration effort on northern NSW/P10 where thick (greater than 1600 m) Upper Permian section containing source and reservoir facies is predicted. Other areas in the permit are less prospective because of widespread intrasedimentary magnetic bodies or the absence by erosion of Upper Permian and Triassic section.

The Sydney Basin is an exhumed basin that reached its maximum depth of burial in the Early Cretaceous prior to basinwide uplift of 1.5-3.5 km during the Tasman Sea rifting. The magnitude and/or timing of the exhumation can be demonstrated with fluid inclusion, magnetisation, fission track and vitrinite reflectance data. The presence of commercial quantities of oil or gas in Upper Permian reservoirs depends on trap integrity having been maintained during the epeirogeny, or the re-migration of hydrocarbon into new traps.

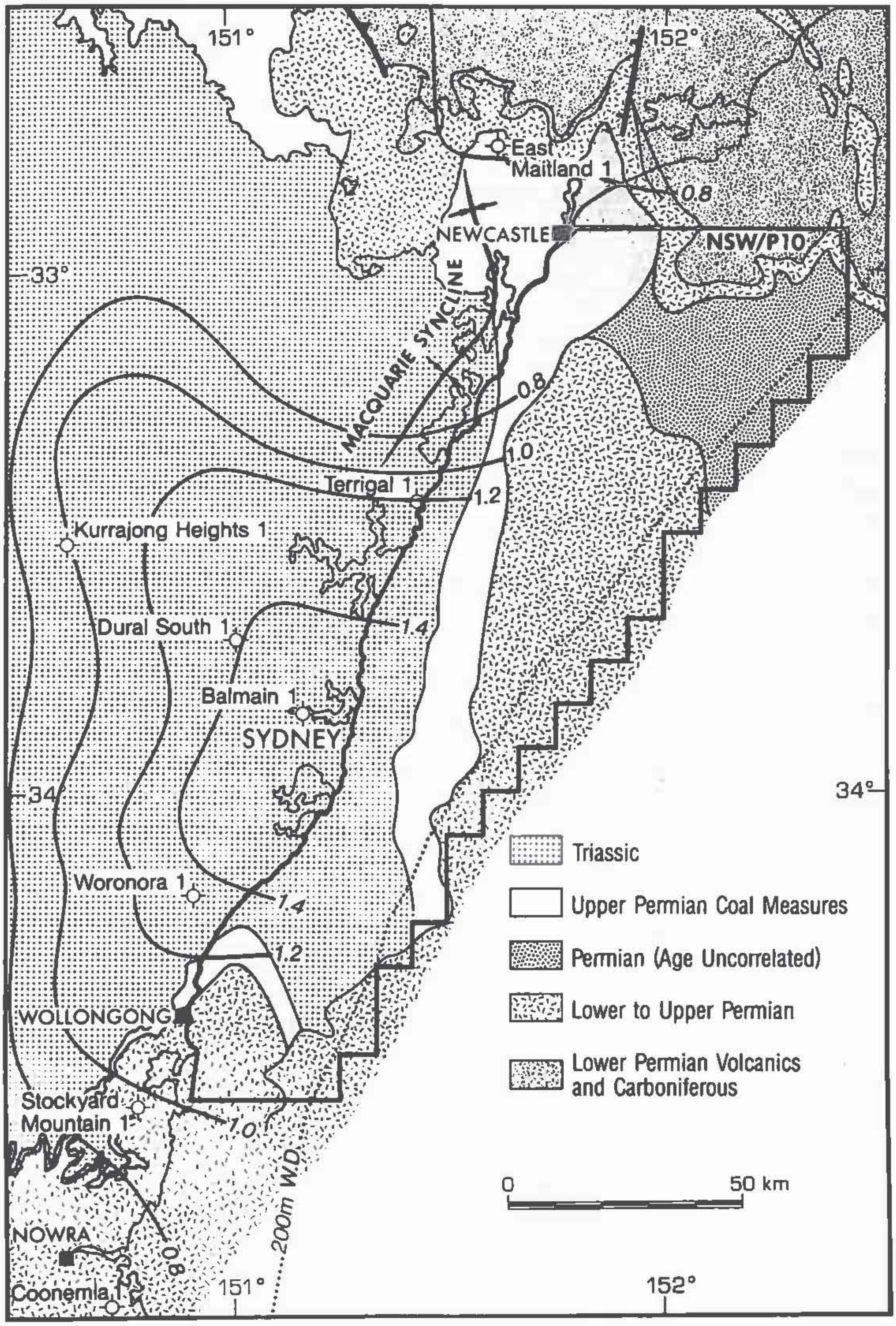


Fig. 1 Outcrop/subcrop map of the Sydney Basin. Vitrinite isoreflectance contours of the top Upper Permian coal measures from Middleton (1989).

NSW/P10, OFFSHORE SYDNEY BASIN

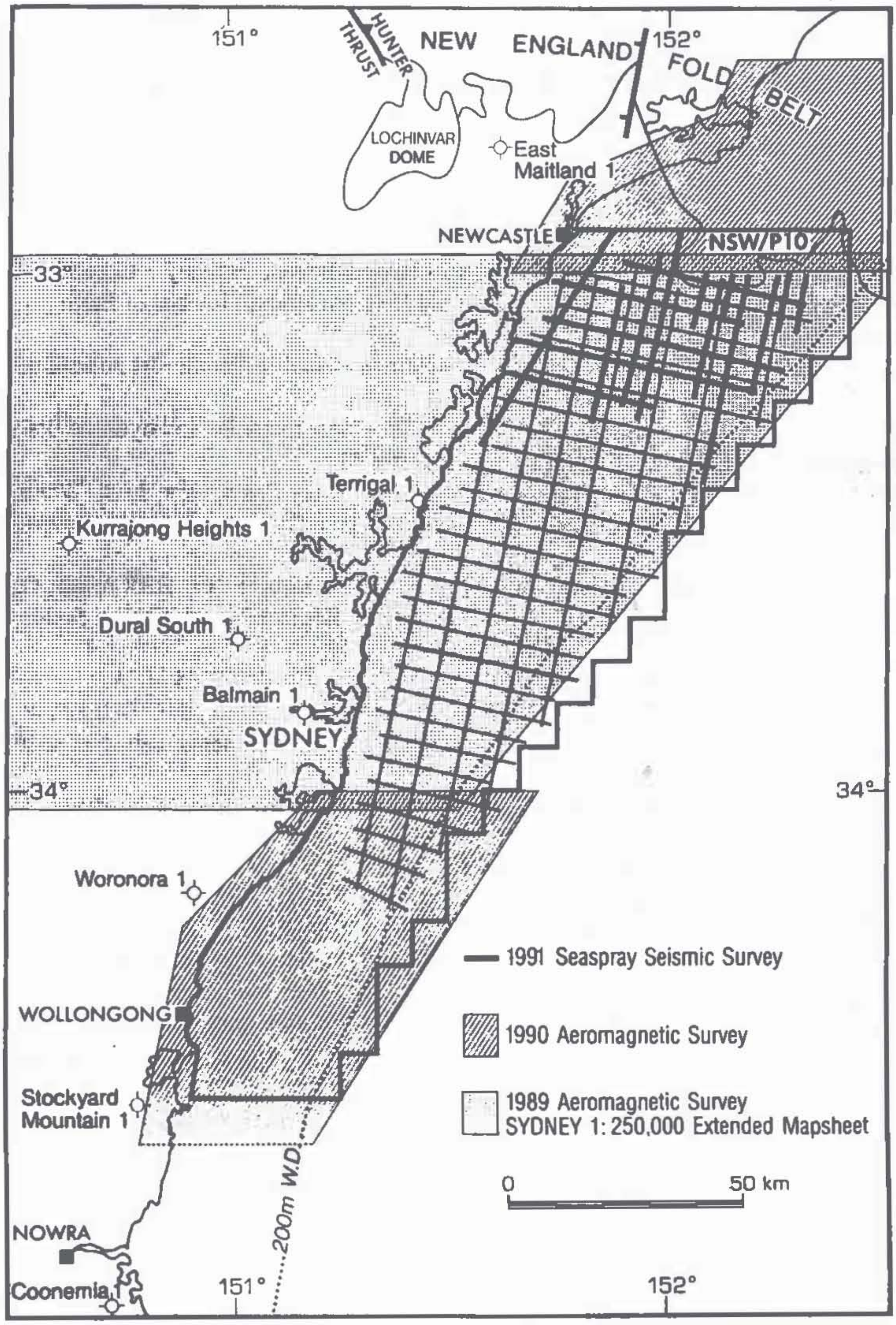


**Fig. 2** Location of 1981 seismic survey reprocessed in 1990 and the 1989 and 1990 aeromagnetic surveys.

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# THE MORPHOLOGY OF NORTHERN SYDNEY'S ROCKY HEADLANDS, THEIR RATES & STYLE OF REGRESSION AND IMPLICATIONS FOR COASTAL DEVELOPMENT

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**D.J. Douglas & Partners Pty Ltd**

## 1. INTRODUCTION

Early development of many of northern Sydney's rocky headlands appears to have been carried out without much thought being given to the headlands' rates and styles of regression. Even the back-up documents for both the Coastal Protection Act, (1979), and Warringah Shire Council's Coastal Management Strategy make little reference to the rates and styles of regression of the headlands. In fact, little is known about these aspects, despite detailed studies of coastal erosion of sandy beaches along the New South Wales coast over the last thirty years.

To start redressing this problem, this paper presents results of field studies of rocky headlands and draws tentative conclusions from them. The area studied was the 27 km of coastline between Broken Bay and Port Jackson known as the northern beach area of Sydney (Figure 1). This area comprises 19 rocky headlands which account for 51% of the coastline.

## 2. EXISTING COASTLINE

### 2.1 Seabed

A review of sea level fluctuations (Chappell, 1983) over the last 340,000 years BP suggests that the present coastline has been exposed to marine attack on three occasions, totalling 40,000 years. The most recent period started about 6000 to 6400 years BP. Therefore, the previous subaerial landscape has only been modified by marine processes in very recent times.

### 2.2 Geology & Structure

Due to low amplitude cross folding, a variety of lithologies are exposed along the coast with fine grained sandstones of the Newport Formation overlying siltstones and shales of the Garie Formation, which in turn overlie Bald Hill Claystone/mudstone (Crozier, 1990). Of the fifteen headlands studied, eight are capped by Hawkesbury Sandstone.

Variations in rock strength, structural defects and resistance to weathering has created a variety of cliff line/headland forms which can roughly be divided into two categories, shale dominant and sandstone dominant headlands. Each category has distinctive morphological features.

From detailed structural mapping of the various headlands (Crozier, 1988) there are two main joint sets as summarised in Figure 2.

Structural trends between individual headlands show a slight shift in joint pole concentration. Headlands north of Avalon show a shift in strike from 045° to 030° both progressing north and running down the stratigraphic column.

Faulting is evident throughout the stratigraphic column but normal syngenetic or growth faulting is particularly common in the lower Garie Formation and Bald Hill Claystone units. These faults are often curved, both along strike and down dip. Tectonic faulting is less common with generally more extended strike lengths which can extend from one side of the headland to the other.

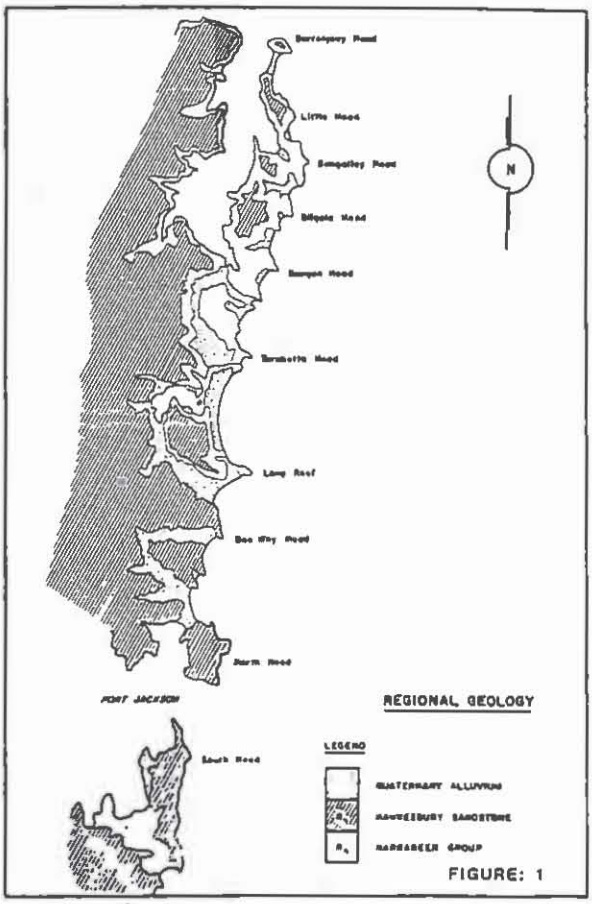
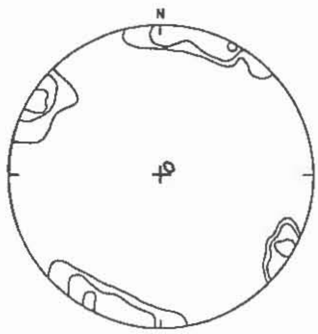



FIGURE: 1



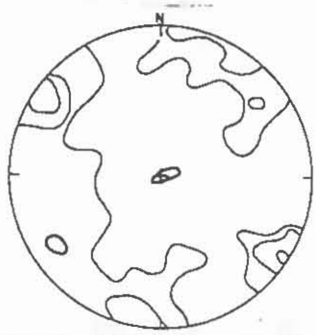

SANDSTONE HEADLAND North Head

Contour Intervals = 2, 12, 22, 24

Number of Readings = 78

Equal Area Nett

FIGURE: 2 A




SHALE HEADLAND Turimetta Head

Contour Intervals = 2, 15, 28, 30 %

Number of Readings = 254

Equal Area Nett

FIGURE: 2 B

## 3. HEADLAND MORPHOLOGY

The various subaerial and subaqueous features of the northern headlands are summarised below.

### 3.1 General Characteristics (Plan View)

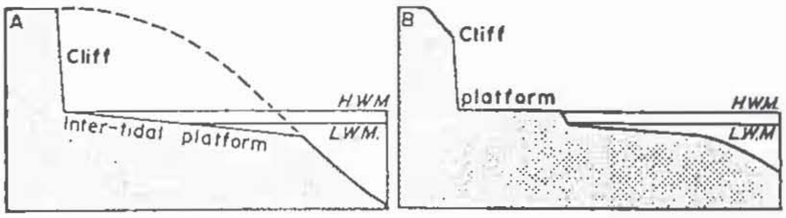
In plan view most headlands are oriented east-west and have a number of common morphological features. These features can be related to variations in aspect, particularly the northeast and southeast facing sections of headlands. These directions (quadrants) are those from which Sydney's major wave energy arrives.

Southeast Quadrant.

Platforms that face this quadrant have little stable talus debris at the base of cliffs, but often have sparse but mobile boulder populations.

Northeast Quadrant.

Cliffs are typically high and sheer, becoming more slope-over-wall type (Figure 3) towards the beaches. Rock platforms are narrow, often covered in large volumes of semi-stable, grass and shrub covered talus. Large undercuts and overhangs are common along outer northern facing sections of headlands.




A – Cliffed coast with an inter-tidal shore platform

B – Cliffed coast with a shore platform at about high tide level (Slope-over-wall)

Modified from Bird (1976)

FIGURE: 3

### 3.2 Sandstone Headlands

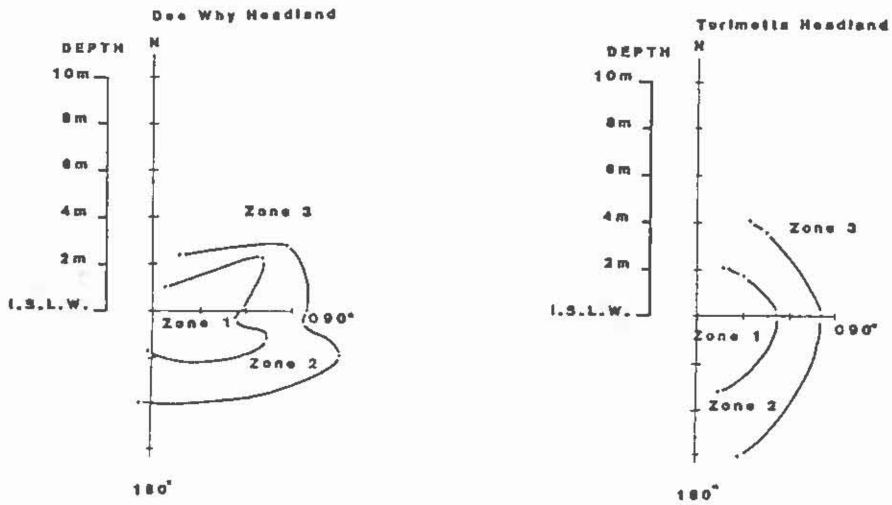
Sandstone headlands are dominated by high, irregular (saw toothed) shaped, near vertical cliffs. Thin undercuts are created by mechanical and salt weathering of shale and fine grained sandstone beds within and below the more massive, thick, coarse grained sandstone units. When these undercuts intersect near vertical joints, toppling failure occurs. This process is particularly active at the base of most cliffs extending to a height of at least 5 m above high tide level.

The resultant debris from these toppled units form equidimensional sandstone boulders and blocks (up to 64 $m^3$) that vary in thickness from 0.3 to 2.0 m and in widths from 0.5 to 4.0 m. These dimensions represent bed thickness and joint spacing.

Narrow, high tide platforms are common with only the larger, more resistant cliff debris packed at the rear of the platform. High (>3 m) outer platform cliffs are common below sea level on the more exposed sections of the platform. Platform widths, measured from the outer platform edge to the base of the cliff, vary from 0 m to 78 m, averaging 28 m.

Offshore slopes are generally steep and convex. Near shore, subaqueous cliffs and terraces have similar orientations to their subaerial counterparts. Rock debris from cliff and platform erosion is commonly packed at the base of these terraces, forming subaqueous boulder deposits. These boulders are continually abrading bedrock, forming concave depressions and abrasion pits which often contain well rounded boulders. Boulder abrasion features occur to depths of between 6-10 m below ISLW, depending on aspect as shown in Figure 4, with carbonate algae cementing boulder contacts below these depths. Pebble and carbonate sand deposits often lie further offshore, these deposits are abraded to depths of between 15 and 20 m below ISLW.

These high, near vertical outer platform cliffs cause storm waves to break and refract on the platform edge, thus reducing the wave energy available to either remove or re-arrange platform debris.




BASE BOULDER ABRASIVE DEPTH

FIGURE: 4

### 3.3 Shale Headlands

Shale headlands are dominated by low slope-over-wall clifflines that are often irregular in outline.

These headlands are less resistant to weathering than sandstone headlands, as shales slake readily in a wetting/drying environment. Interbedded siltstones are more resistant to slaking but suffer salt weathering, thus creating an alternating recessed and protruding pattern down the cliff face that relates to bed thickness. This pattern appears to be similar in both southern and northern facing cliff lines. Stability is poor, with deep weathering giving convex profiles (e.g., Narrabeen Head) and undercutting of shale beds causing both shallow circular and toppling type instability. Undercutting in weak shale beds is active at cliff bases, with undercuts up to 8 m high observed on many headlands. Cliff debris from the more resistant beds of siltstone or laminite form imbricated tablets at the back of wide rock platforms. Debris size relates to joint spacing and bedding thickness with boulders and tablets from 0.1 to 0.5 m thick and 0.3 to 2.5 m in width. Shale fragments or shale boulders are notably absent from the seaward part of these deposits.

Wide, sloping low tide platforms are common in Bald Hill Claystone, while a hybrid of low and high tide platforms are created on Garie Formation siltstones and shales. Platform widths vary from 0 m to 116 m (except at Long Reef where the maximum width is 360 m), averaging 40 m. Low (<2 m) outer platform cliffs are found at the exposed end of most shale platforms. Beyond these, slopes are generally flat and smooth with low relief terraces common, again aligned parallel to the subaerial cliffs. Rock debris from cliff and platform erosion is rare but the more resistant tablets of siltstone lie at the base of smooth rounded terraces. Abrasion features occur to much further offshore and with less influence of aspect (Figure 4) than for sandstone headlands. Smooth concave gullies with small well rounded boulders and pebbles are common, while shallow and often empty abrasion pits are scattered sporadically around the more exposed parts of the headland. As a result of these lower, outer platform cliffs storm wave action in the form of breaking and broken waves (which have higher energies) readily removes the smaller talus and boulder debris from the platform.

## 4. RATE AND STYLE OF REGRESSION

As available survey records for the northern headlands have too short a time span to be of use in determining regression rates, we have estimated average rates of regression based on the width of wave cut platforms development since the last sea level rise (Table 1). A similar approach, using a known earthquake uplift event, was used by Sunamura (1978) in Japan.

**TABLE 1**
**CLIFF REGRESSION RATES BASED ON WIDTHS OF WAVE CUT PLATFORMS**

| Rock Type at Sea Level | Regression Rates (mm/yr) av. | max. |
|---|---|---|
| Sandstone | 4.3 | 12.1 |
| Mudstone/Shale | 6.2 | 18.1 (57 at Long Reef) |

During this analysis it was noted that, contrary to our anticipation, there is no consistent variation in platform width with aspect.

The most obvious forms of regression are by both major rockfalls (see Table 2) and minor falls. The estimated volumes (from othophoto maps) of the larger falls vary from 3500 to 33500 cubic metres, generally larger than those recorded by Lewis (1975) in the Hawkesbury Sandstone sea cliffs south of South Head.

Most if not all of these falls appear to have been controlled by undercutting of weak beds.

TABLE 2.

SUMMARY OF 'RECENT' ROCKFALLS FROM THE NORTHERN HEADLANDS.

| Location | Style | Age | Volume ($m^3$) | Width of Fall - (m) |
|---|---|---|---|---|
| Little Head | Undercut | post 1974 | 33,500 | 15 |
| Careel Head | Undercut | pre 1970 | 3,600 | 12 |
| | Wedge/ Toppling failure | 1992 | 20 - 30 | 3 |
| Bilgola Head | Undercut | 1900 + | 13,200 | 15 |
| | Rockfalls | 1968 on | minor | |
| Bungan Head | Rockfalls | 1974 on | minor | |
| (Newport) | Undercut/ circular | pre 1900 | 29000? | 20? |
| Mona Vale Hd | Undercut | pre 1974 | 7,700 | 8 |
| Warriewood | Slump in soil | pre 1984 | 1,000 | |
| Turimetta Hd | Undercut | pre 1900 | 14,000 | 13 |
| Narrabeen Hd | Circular in weathered shale | pre 1973 | 7,000 | |
| | Undercut | 1974 on | minor | |

## 5. DISCUSSION

The calculated rates of cliff line regression are far greater than those noted for Nowra Sandstone (0.01 to 0.03 mm per year) in the Sassafras region of the Shoalhaven Valley (Young and McDougall, 1985). They are also greater than the few available estimates for salt weathering of Hawkesbury Sandstone sea cliffs (Roy, 1985, Pells et al., 1987 and Table 3). However, it should be noted that the rate of weathering of 'softer' sandstone (up to 5 mm per year) is similar to the average regression rate for sandstone in Table 1.

So as to get a better feel for the influence of wave regression rates, rates of differential weathering between shale and sandstone were determined from a number of road and expressway cuttings (Table 3). In most cases, the weathering products were continually being removed, thus giving a maximum rate of weathering.

It can be seen that the rates of weathering for both the weaker sandstones and for the shales are similar to the estimated cliff regression rates in Table 1. This suggests that overall the main effect that wave attack is having on the northern headland area is the removal of protective scree material, rather than actual quarrying or air pressure blasting of the sandstones or shales.

It is noted, however, that sea caves have been formed by preferential wave erosion of weathered dykes (St. Michaels Cave, Palm Beach Cave) or wide zones of very closely spaced joints or large faults, (Bilgola Cave, Warriewood Cave).

At Turimetta Head there is an undercut, 64 m long by 16 m deep and 2 m high. This undercut is partly concealed by large boulders, probably from a previous rockfall. The depth and height of this undercut may be due to factors other than normal weathering; possibly stress concentrations at the base of the cliff, the possible presence of dispersive clay minerals within a thin bed and/or airblasting by wave action. Further work is required to clarify this.

TABLE 3.

FIELD MEASURED OR ESTIMATED RATES OF WEATHERING FOR VARIOUS SEDIMENTARY ROCKS.

| Location | Lithology | Defect type Depth & Facies | Time Period (Years) | Max. Weathering Rate (mm/yr) |
|---|---|---|---|---|
| Sassafras, Shoalhaven Valley | Nowra SST | Scarp Retreat (Young and McDougall, 1985) | 30 million | 0.012 to 0.025 |
| Liverpool Cemetry | Hawkesbury Sandstone | | 106 | 0.24 |
| Bondi | Hawkesbury Sandstone | Salt weathering of sea cliff (Roy, 1983) | 100 | |
| | | limonite cemented SST | | 1 |
| | | resistant sandstone | | 1 to 2 |
| | | 'softer' sandstone | | up to 5 |
| Warringah Road Road cut, Beacon Hill | Sandstone | Differential weathering rates between retaining wall and weathered fine grained clayey sandstone | 15 | 10 to 17.4 |
| Oxford Falls Road Road cut at Oxford Falls | Sandstone | Differential weathering rates between sandstone layers within Sheet Facies | 13 | 1 to 4.6 |
| | Shale | Between sheet sandstone and mudstone | | 5 to 8.5 |
| Newcastle Expressway between Berowra and Hawkesbury River, Various road cuts | Shale | Differential weathering rates between sandstone and shale | 30 | 23 to 43 |
| | Sandstone | Sandstone | | 1 to 3.3 |
| Gosford | Narrabeen Sandstone | Salt decay in sandstone caves (Lambert, 1980) | | 0.1 to 0.2 |

## 6. CONCLUSIONS

The engineering implications of the present, preliminary study are:

- cliff face undercutting by wetting/drying and salt weathering of the weaker sandstones and shales appear to be controlling the cliff line regression rates with the importance of sea action generally being restricted to removal of rockfall material. This implies that the minimum setbacks for structures on top of cliffs should be related to the maximum depth of undercutting present within the cliff and anticipated during the life of the structure, together with a factor relating to joint/fault dip (minimum of Tan 70°) times the cliff height.

- Some of these more-at-risk areas of cliff line are indicated in Table 4, particularly the undercut areas on the northern side of Turimetta Head (the point is undercut by a 53 m long by 13 m deep and 7 m high cave which has dilated tension cracks above its inside edge).

- At the base of cliffs there is a continual risk of small rock falls, both from fretting shale beds and at lesser intervals, the toppling of larger sandstone blocks.

- Offshore structures in the zone from 3 m above Indian Spring Low Water (ISLW) to 10 m below ISLW will be subject to heavy abrasion processes.

**TABLE 4 - AREAS OF POTENTIAL INSTABILITY.**

| Location | Type |
|---|---|
| Palm Beach | Palm Beach Cave |
| Careel Head | Caves |
| Bangalley Head | Undercut on south side of headland |
| | St. Michaels Cave |
| Bilgola | Undercut cave near beach (Avalon side) |
| Mona Vale Headland | Large undercut |
| Turimetta Head | Warriewood Cave |
| | Large undercut |
| | Overhang (near point) |
| Dee Why Head | Cave |

## ROCKY HEADLANDS

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# KEYNOTE ADDRESS

# THE OTHER SIDE OF THE COIN – FROM SCIENCE TO LOCAL GOVERNMENT

**B.W. VITNELL**
**Coal Geological Services & Review**

This Keynote Address is dedicated to Kenneth George MOSHER, pioneer coal geologist, teacher and motivator to two generations of coal industry geologists in government and private enterprise.

The speaker commenced his career in the Coal Industry just over 40 years ago, joining the Joint Coal Board in October, 1951. After an initial induction period at Goulburn Street, Sydney Head Office, he was posted to Lithgow, specifically to field duties in connection with the initial regional appraisal of the geology of the Ulan-Wollar Coalfield.

In 1952 he was transferred to Cessnock and commenced an almost unbroken professional career in the Coal Industry of the Hunter Valley.

He will give a personal account, in terms of his involvement in the exploration and development of many areas and specific projects set against the policies of the times, both government and private enterprise, giving the background and implementation of many interesting projects and cameos (within the laws of libell) of people involved.

Following his early retirement in 1985, the speaker was an elected representative of Singleton Shire Council and a delegate to its various associations from 1987 to 1991, being narrowly defeated on the issue of not being able to spend money you don't have (which is poor politics!).

He will conclude with an explanation of his involvement with the political and bureaucratic process connecting Local Government and the Coal Industry.

# LOWER PERMIAN MANNING GROUP : TECTONIC IMPLICATIONS OF SEDIMENTARY ARCHITECTURE & PROVENANCE STUDIES IN THE NOWENDOC - COOPLACURRIPA AREA

**M.D. VICKERS & J.C. AITCHISON**
**The University of Sydney**

## ABSTRACT

Lower Permian Manning Group rocks outcrop within elongate basins which are bounded by regionally significant faults which separate major, and in many cases different elements of the New England Orogen. Sediments accumulated rapidly in these basins, as a result of high density mass flows and associated debris flows. Deposition probably occurred along a series of slope-aprons. Many aspects of the Manning Group indicate deposition in a strike-slip basin.

Sedimentary petrography of rocks within a small Manning Group basin in the Nowendoc-Cooplacurripa area has been examined in detail. Clast compositions vary both abruptly and systematically up-section, revealing changes in source areas, rather than the progressive erosion of a single source to deeper crustal levels. Chert clasts low in the Manning Group contain Late Devonian radiolarians, consistent with a New England source. However the schistose rocks immediately north of the basin, in the Nowendoc-Cooplacurripa area are not implicated as a sediment source.

## INTRODUCTION

The Lower Permian Manning Group (Voisey 1957, Mayer, 1972) fills a series of marine basins at the southern margin of the New England Orogen (NEO). Unconformities between Lower Permian sedimentary rocks and older basement have been recorded at two localities (Allan and Leitch, 1990), but in most places, the Manning Group is bounded by regionally significant faults. Many of these faults are parts of the Peel-Manning Fault System (PMFS) which separates major elements of the NEO. In general, rocks of the Gamilaroi terrane (Flood and Aitchison, 1988) lie to the south and west of the PMFS, and rocks of the Gwydir superterrane (Fergusson et al, 1987) lie to the north and east of the PMFS.

The Manning Group is up to 9 km thick (Mayer 1972, p. 93). In general, outcrop is poor and sedimentary structures are not visible because of deep weathering. Mayer (1972) subdivided the Manning Group into 5 units: Wards Creek Beds, Giro Diamictite, Glory Vale Conglomerate, Colraine Mudstone and Kywong Beds.

## NOWENDOC-COOPLACURRIPA AREA

The basal Wards Creek Beds and the overlying Giro Diamictite are present in the Nowendoc-Cooplacurripa area (Fig. 1). Outcrop is dominated by conglomerates, pebbly sandstones and diamictites, although poorly outcropping turbidite sandstones comprise more than half the Manning Group in this area. The rocks show an overall up-section reduction in pebble/matrix ratio, although some packages of beds are upwards coarsening. They are moderately to steeply dipping and mainly of mass flow and debris flow origin.

MICHAEL D VICKERS and JONATHAN C AITCHISON

A large zone of schist (Oxley Metamorphics [Gunthorpe 1970], Enfield Range Metamorphics [Nano, 1987]) lies to the north of the Manning Group in the Nowendoc-Cooplacurripa area. Dominant lithologies are poly-deformed quartzose schists and metabasalts (Gunthorpe 1970, Watanabe 1988). The Enfield Range Metamorphics (Nano, 1987) is dominated by quartzose schists with about 15% metachert.

In many places, the Manning Group is separated from the schists by a zone of serpentinites up to 1.5 km wide. In some areas, a very narrow (<300 m wide) metachert-dominated fault sliver separates the Manning Group from the serpentinites or the schists. These cherts are recrystallised, and they contain only poorly preserved spumellaria.

The southern margin of the Manning Group in the Nowendoc-Cooplacurripa area is in faulted contact with distinctive green and locally intensely deformed metabasalts and metadolerites. Chert is a minor component of this unit and processing for radiolarians has not yet been successful.

*Wards Creek Beds*

The basal 700 m of the Manning Group (Fig. 1) primarily consists of clast supported conglomerates (≈40%) and pebbly sandstones (≈40%). The conglomerates at the base of the unit are predominantly composed of angular to sub-angular pebble- to rare cobble-sized clasts. Boulders are very rare. Up-section, overall clast roundness increases and some clasts are well-rounded. Matrix in the conglomerates is dominated by sand-grade particles. Individual conglomerate outcrops are up to 20 m thick but are unlikely to be single beds. They probably consist of amalgamated conglomerate beds. Some pebbly sandstones in this unit have scoured bases (eg GR 824103, Cooplacurripa, 9234-1V-N).

*Giro Diamictite*

Overlying the Wards Creek Beds there is a thick (≈2100 m near Nowendoc) sequence dominated by pebbly sandstones, diamictites and sandstones. In this area, the base of the unit is marked by ≈100 m of thinly bedded very fine grained sandstone, containing infaunal trace fossils. Within the Giro Diamictite, conglomerates are subordinate and are generally thinner than in the underlying Ward's Creek Beds. Cobbles are rare in the Giro Diamictite. Outsized clasts commonly comprise <0.1% of the sandstone in any one locality, but a gradation of pebble/matrix ratios exists, from clast-supported sandy-matrix conglomerates to pebble-free sandstones. Although some groups of beds are upwards coarsening (eg GR 808114, Nowendoc 9234-1V-N), the overall up-section trend is a reduction in the pebble/matrix ratio, with sandstones becoming increasingly dominant.

Sedimentary structures are rarely visible, however one fresh road cutting on the Nowendoc-Gloucester road (GR 898930, Giro 9234-1-S) shows a considerable variety, including dish and pipe structures. These structures indicate elutriation following extremely rapid sediment deposition. High density subaqueous debris flows are suggested as the depositional mechanism. Paleocurrent data (n=5: ripples and flame structures) obtained from between 800 m and 1500 m from the base of the Giro Diamictite indicate southward transport of sediment.

Rare marine macrofossils in an assemblage containing *Trigonotreta* sp., *Aviculopecten* sp., bryozoan and crinoid fragments occurs within this unit. The age of this assemblage can be constrained as Permian (Runnegar 1969, 1970). Several Permian fauna II assemblages have been previously reported from the Manning Group (Voisey 1938, 1939; Mayer, 1969, 1972; Runnegar 1970). These fossil assemblages have been collected over a 6 km stratigraphic interval (about 3 km from the base of the Manning Group to near the top). The time range of Permian Fauna II is latest

Sakmarian to mid-Artinskian (Runnegar, 1969). The short time interval of Permian Fauna II indicates that the immense thickness of sediments in the Manning Group was deposited in a very short period of time.

## Sedimentary Petrography

The Ward's Creek Beds are dominated by chert clasts. Volcanic clasts first appear at the base of the Giro Diamictite and they become more dominant up-section. Rare granitic and quartzite clasts first appear about 1100 m from the base of the Giro Diamictite, but are not common.

Relative proportions of the various pebble types (especially chert, volcanic and granitic clasts) vary both abruptly and systematically up-section, indicating changes in source for the Manning Group. Many chert clasts contain radiolarian faunas which also differ in content up-section. Preliminary data indicate a change in provenance during the sedimentation of the Manning Group, and this has significant implications for Early Permian regional tectonics.

### *Wards Creek Beds*

The clast assemblage is dominated by chert. Clasts include black, red, green, white, as well as white and grey laminated chert. Black, red and white cherts are commonly quartz-veined and recrystallised. Polycrystalline quartz fragments, mica fragments and schist clasts are extremely rare.

### *Giro Diamictite*

The base of the Giro Diamictite is marked by a change in the clast assemblage. Chert is no longer predominant and its abundance decreases up-section. Intermediate to silicic volcanic pebbles appear at the base of the Giro Diamictite. They comprise about 10% of the total pebble content at the base of the unit, increasing to about 50% at the top. Several volcanic clast types occur: fine-grained pale green prehnite-rich devitrified tuff clasts, andesitic clasts, white rhyolitic clasts, including some with orange-coloured altered feldspars, similar to some of the volcanic rocks in the Upper Carboniferous Currabubula Formation (cf Cherry, 1987). The lighter coloured volcanic pebbles occur both as flow-banded and massive varieties.

The first occurrence of granitic clasts is approximately 1100 m from the base of the Giro Diamictite. White, biotite-bearing granitic pebbles, and pink, two-mica granite pebbles are present. Statistical analysis of clasts (≈100 clasts/sample) shows that the ratio of white to pink granitic clasts is 3:1 where they first occur, decreasing to 2:3 near the top of the Giro Diamictite.

Quartzite clasts also first occur about 1100 m from the base of the Giro Diamictite. They are relatively rare and comprise <1% of the pebbles present. They are fine-grained grey to light red coloured sandstones. Quartz is predominantly monocrystalline with abundant overgrowths. 5-8 mm scale graded bedding has been observed in some samples Polycrystalline quartz fragments, mica fragments and schist clasts are extremely rare.

## Late Devonian Radiolarians from Chert Clasts

Pebbles from weathered conglomerates and pebbly sandstones were collected for microfossil study, with a view to correlating the fossils with known assemblages and possible source terranes. In order to increase yield, the clasts were cleaned and then hand-picked, rejecting clasts that were not visibly radiolarian-bearing. They were then processed using the method of Pessagno and Newport (1972).

All radiolarian assemblages recovered are dominated by spumellaria. Samples from the Ward's Creek Beds have yielded abundant well preserved specimens of *Helenifore* *laticlavium* Nazarov and Ormiston. Samples from slightly higher in the Manning Group (basal Giro Diamictite) contain rare *Helenifore laticlavium* Nazarov and Ormiston, and abundant *Holoeciscus foremanae* Cheng.

*Helenifore* sp. has previously been recovered from the Gamilaroi terrane (Yarrimie Formation, Glenrock; Aitchison et al in press), Birpai terrane (near Yarras - Ishiga and Leitch 1988a) Djungati terrane (Pigna Barney, Barry - Aitchison et al in press), and Yugambal terrane (Willowie Creek Beds - Aitchison, in prep).

*Holoeciscus* sp. has been reported from the Gamilaroi terrane (SW of Wingham - Ishiga and Leitch, 1988b), Birpai terrane (near Yarras - Ishiga and Leitch, 1988a), and the Anaiwan terrane (Myall Creek, Yarrowitch - Aitchison 1988, 1989, 1990, Aitchison et al in press). The radiolarian assemblages clearly indicate a source terrane containing Upper Devonian rocks, however this could be one of several New England terranes.

## DISCUSSION

Coarse-grained sediments dominate the Manning Group. Individual beds are typically massive with rare elutriation (dish and pipe) structures. Massive and bedded turbidite sandstones are also important. High density mass and debris flow are the most likely mechanisms for sedimentation. Rapid deposition is indicated by the short time during which the enormous thickness of the Manning Group accumulated.

Individual fans that grew stably within a Manning Group deposystem have not as yet been identified in this study. The occurrence of similar, mixed, but commonly coarse-grained facies along strike (locally conglomerates, pebbly sandstones, massive sandstones and laminated sandstones) indicates that deposition in this area may have occurred along a slope apron, rather than on discrete individual submarine fans.

Studies of clasts in the Manning Group provide important information. Radiolarians in chert clasts have a Late Devonian source. There is a significant lack of clasts derived from basement rocks immediately adjacent to the basin margin. The change in clast assemblage up-section reveals a change in source areas rather than the progressive erosion of a single source to deeper crustal levels.

The Wards Creek Beds were derived almost entirely from a Late Devonian chert-dominated source, with an extremely minor input from schistose rocks. Both cherts and schists occur nearby, and over a wide area of southern New England. The zone of schistose rocks north of the Manning Group contains only a small proportion of metachert (Gunthorpe 1970, Nano 1987). These schistose rocks are therefore unlikely to have been the major source for the Wards Creek Beds.

The narrow fault sliver of metachert-dominated rocks occurring immediately to the north of the Manning Group may have provided some recrystallised chert clasts for the Wards Creek Beds and Giro Diamictite. However, the poorly preserved spheroidal radiolarians these rocks contain are dissimilar to the well preserved *Helenifore* sp. and *Holoeciscus* sp. recovered from chert clasts. Metabasite clasts have not been observed in either the Wards Creek Beds or the Giro Diamictite, hence the rocks immediately to the south of the Manning Group in this area are also considered to be unlikely to have been a source.

The Giro Diamictite contains volcanic clasts, the proportion of which increases up-section, indicating the erosion of either a contemporaneous or an older volcanic source. Granitic clasts occur higher in the sequence. Although the white, biotite granites could have been sourced from New England, pink, two-mica granites have not been reported from this region. The Lachlan Fold Belt could be a source for the granitic clasts as well as the quartzite clasts which first occur at the same stratigraphic level in the Giro Diamictite. Similar quartzite and granite clasts occur in the Upper Carboniferous of the Tamworth Belt (Spion Kop and Quipolly Conglomerates - see Carey [1937], White

[1968]). The quartzites were probably originally derived from a Devonian Lambie Group source (Cherry 1989).

Schist clasts were not observed in the Giro Diamictite, indicating again, that erosion of multiply deformed rocks was not important in the sediment supply to this formation.

Volcanic and volcaniclastic rocks of the Tamworth Belt are a likely source for the clasts in the Giro Diamictite. Radiolarian chert clasts have not been reported from Tamworth Belt rocks.

## CONCLUSIONS

Clasts in the lower parts of these Lower Permian rocks were derived from Late Devonian sources. Higher in the Manning Group, clasts were derived from the erosion of Upper Carboniferous rocks. Some of these clasts were derived originally from the Lachlan Fold Belt. The multiply-deformed Oxley Metamorphics, which are currently adjacent to the Manning Group in the Nowendoc-Cooplacurripa area are an unlikely source for these sedimentary rocks.

The Manning Group has several attributes, which in combination lead to an interpretation that strike-slip motion may have been an important factor in the development of the basins (Aitchison and Flood; manuscript submitted). These are:

- narrow elongate fault-bounded basins,
- enormous thickness ($\approx$9 km) of rapidly deposited sediment,
- alignment of basins along a major fault zone that separates terranes,
- development of slope apron architecture, rather than discrete fans,
- lack of an adjacent suitable sediment source.

All these factors are indications of sedimentation under an oblique-slip tectonic regime (Reading, 1980). We suggest that the basin-margin PMFS may have been acting as a strike-slip or oblique-slip system in the Early Permian.

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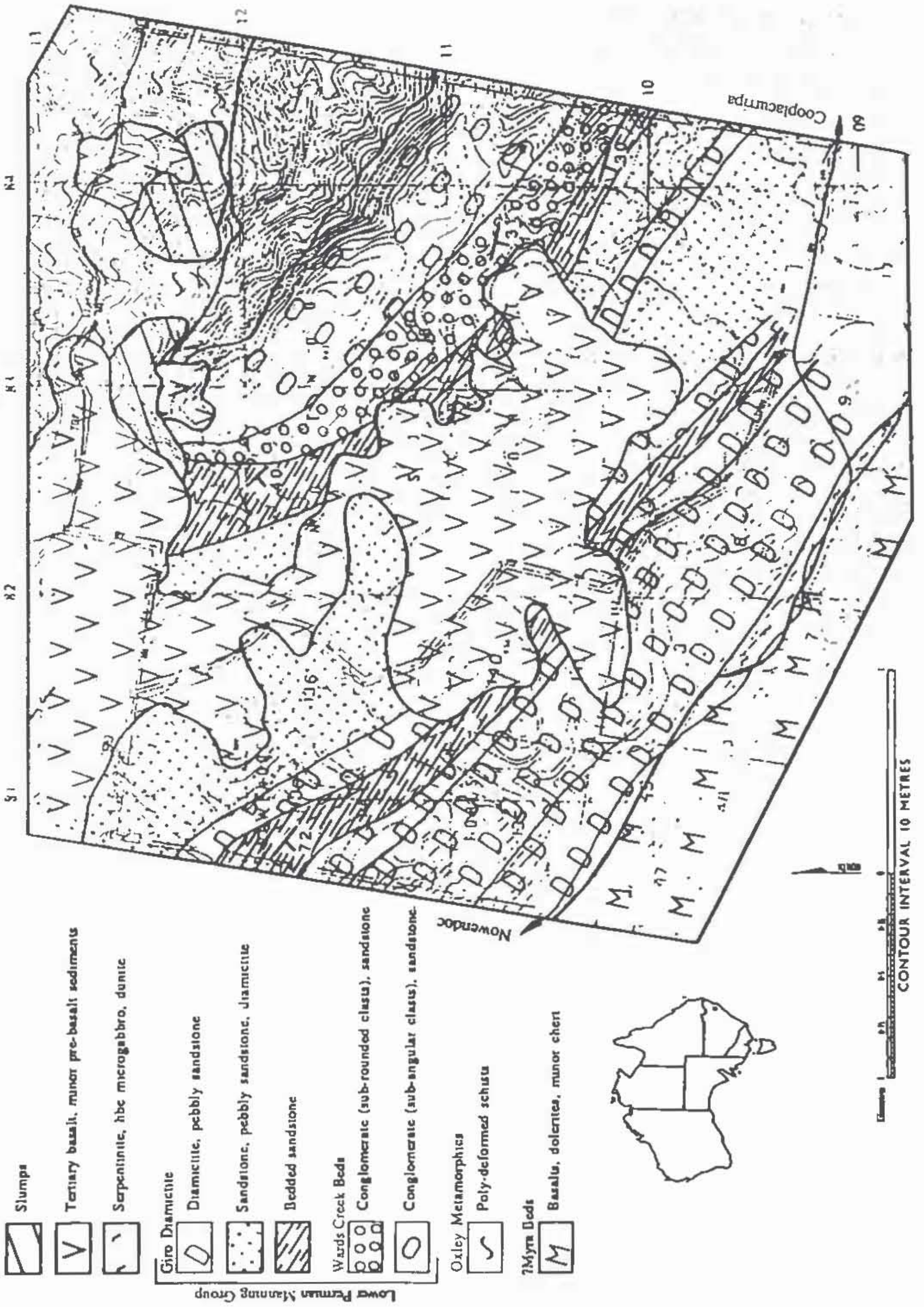


Fig. 1: Geological map of an area about 5 km SE of Nowendoc, north of the Nowendoc-Cooplacurripa Rd.

# A GEOLOGIC AND THERMAL HISTORY OF THE MANNING GROUP

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## INTRODUCTION

The Manning Group (Fig. 1) is of Early Permian (Asselian - Middle Artinskian) age, and is equivalent to the Dalwood Group in the Sydney Basin, according to palaeontological studies of different parts of the Manning Group sequence: Microflora from a silicified mudstone on the Comboyne Plateau was assigned a Late Carboniferous Stage 2 age (McMinn 1985). The presence of *Microbaculispora tentula* within this sequence, however, indicates an Upper Stage 2 age, equivalent to the Asselian (DJC Briggs *pers. comm.* 1990). The stratigraphic position of this sequence is uncertain, but is probably within the Charity Creek Beds (Table 1) and hence is towards the base of the Group. Elsewhere, fossil assemblages from diamictites in the Charity Creek Beds indicate an "Allandale", that is, Early Permian age (Brennan 1976). A brachiopod assemblage within diamictites at Curricabark is of Late Asselian age (Briggs 1987, 1991).

In the Upper Barnard area (Fig. 1) conglomerate and sandstone, which are lithologically similar to the lowest units exposed in the Manning Group, contain an "Allandale" fauna (Allan & Leitch 1990). Comparable sequences in the immediate area unconformably overlie Devonian/Carboniferous sediments (Allan & Leitch 1990), hence it is unlikely that the base of the Manning Group is much older than earliest Permian.

Fossils within the Colraine Mudstone, from the Kimbriki - Mt George area, the uppermost fossiliferous unit of the Manning Group, contain *Anidanthus springsurensis* (Laurie 1976) which is common in the Farley Formation in the Sydney Basin (McClung 1973). A more detailed study by Briggs (1987) of the same area placed these fossils within his *Echinalosia waricki* zone (mid- Artinskian), confirming that the Colraine Mudstone is of equivalent age to the Farley Formation.

## MANNING GROUP SEQUENCES

Sequences belonging to the Manning Group occur in two blocks, east and west of a meridional line passing through Mt George (Fig. 1), based on geographic separation and differences in stratigraphy (Table 1). This paper deal with the sedimentological features and thermal history of the western part of the Manning Group.

| West | East |
|---|---|
| Kywong Beds | |
| Colraine Mudstone | Colraine Mudstone |
| Glory Vale Conglomerate | Cedar Party Limestone/Kimbriki Formation |
| Giro Diamictite | Charity Creek Beds |
| Wards Creek Beds | |

**Table 1:** Correlation between the western and eastern sections of the Manning Group, after Mayer (1972) and Engel and Laurie (1978).

The Manning Group is estimated to be in excess of 9 km thick (Mayer 1972). Current palaeotemperature studies indicate that this thickness is over-estimated and a more realistic figure is in the order of 4 km (see below).

The basal sequence consists of interbedded breccia/orthoconglomerate with less common graded sandstone. The breccias vary in thickness from 5 to 25 m. They consist of angular clasts (5 - 30 mm) composed of chert, metabasalt, metapelite and sandstone. Plant fragments are abundant in some sandstones. The clast composition suggests that they were derived from the adjacent Woolomin Group sediments. The conglomerate clasts are of similar composition, commonly larger (~ 30 mm), rounded and with low to high sphericity. Intermediate degrees of rounding exist, suggesting that the transition from breccia to conglomerate is gradational. In thin section, the sand sized grains vary from angular to subrounded, both in the breccia/conglomerate and in the overlying graded sequences. Metamorphic minerals present include prehnite, chlorite, calcite and albite indicative of prehnite - pumpellyite facies metamorphism. Rare serpentinite clasts have been found in similar sequences in other areas (Allan & Leitch 1990; Cross et al. 1987) suggesting that major crustal sutures were exposed during deposition of the Manning Group.

# MANNING GROUP

The provenance, textural maturity and proximity to a chert - rich source area suggests that the Manning Group originally unconformably overlay the Woolomin Group and that this relationship has been disrupted by faulting. It should be stressed, however, that both the Manning and Woolomin Groups are regionally extensive and relatively homogeneous thus the relative positions now occupied by these groups may not reflect their original juxtaposition.

The conglomerates commonly grade upwards into pebbly sandstones and then into massive sandstone which is in turn overlain by thinly interbedded fine sandstone and siltstone. Each sequence is approximately 20 m thick and the contacts within the sequence are gradational. The interbedded sandstone and siltstone layers are approximately 50 - 100 mm thick. The sandstone is commonly graded and the siltstone, which may scour the tops of the sandstone beds, contains planar and low amplitude ripple laminations. This rhythmic sequence also contains single cycles of conglomerate - diamictite - sandstone similar to those described above. Bedding contacts within the conglomerate - sandstone sequences may be either planar or irregular. In the latter case, the contact is diffuse and injections of conglomerate into the underlying sandstone can be observed.

The presence of fining upward cycles and the absence of traction current bedforms suggests that these sequences were deposited by mass flow. It is possible to model them on the basis of the Bouma sequence (cf. Middleton & Hampton 1979; Walker 1986) with some features indicative of fluidised or debris flow. The conglomerate - diamictite - sandstone sequences represent Bouma divisions A and B and are interpretable as extremely thick, coarse grained proximal turbidites and may represent channel deposits. The interbedded, graded sandstone - laminated siltstone sequences represent Bouma divisions B and C and are interpreted as overbank deposits.

These sequences are overlain by a massive, monotonous diamictite interbedded with lesser amounts of repetitive, graded sandstone/siltstone beds. The contact is probably conformable, but no evidence has been found to substantiate this. Mayer (1972) included the conglomerate - sandstone - siltstone with the diamictite sequence, thus indicating that the units were strictly conformable, but it is felt that this is unjustified and the relationship needs to be investigated further.

The diamictite is better described as a pebbly siltstone. The clasts are generally no larger than 15 mm and grade down to silt size. Pebble sized clasts are well rounded with a high sphericity. The degree of angularity increases with increasing fineness. The clasts consist of chert, dacite, andesite, and medium to coarse grained granities and dolerites, metapelite, sandstone and vein quartz. Although massive in hand specimen, a weak fluidal texture or clast alignment is apparent in some thin sections. The presence of prehnite - laumontite or laumontite indicates that these rocks are of lower metamorphic grade than the underlying sequences. The provenance is similar to that of the underlying breccias and conglomerates, however the volcanic detritis indicates that either an active volcanic arc is providing this material or erosion has exposed older volcanic sequences. The volcanic clasts are similar to the Carboniferous ignimbrites now exposed to the south, suggesting that the extinct Carboniferous arc also supplied sediment. Larger clasts, up to 1 m diameter are also present. These clasts exhibit soft sediment deformation, have ragged margins that may grade into the country rock and are lithologically similar to the underlying sequences; they are interpreted as intraformational clasts. Less distinct features include ill-defined sandstone or conglomerate horizons that grade almost imperceptibly into the diamictite.

Interbedded sandstone and siltstone, up to 300 mm thick, are present as discrete units within the diamictite. The overall thickness of these sequences is generally less than 5 m and individual beds within them display most of the divisions of the Bouma sequence. This suggests that these sequences were deposited by turbidity currents.

The presence of turbidites and intraformational clasts within the diamictite, marine fossils within the sequence elsewhere, the lack of traction current bedforms and a textural maturity similar to the underlying sequences suggests that the diamictites were deposited by submarine mass flow, probably by the collapse of sequences similar to those now underlying the diamictite. The clay rich matrix and lack of sorting indicate that transport was by debris flow (Middleton & Hampton 1979). The absence of large exotic clasts, varvoid sequences, very fine matrix or intraformational striated pavements all argue against a glaciomarine origin. In some diamictites, large (50 - 100 mm) clasts disrupting laminated sequences are present. These have been interpreted as dropstones (Mayer 1972), indicating that ice was a transporting medium. These deposits, however, are rare.

The Glory Vale Conglomerate is described as consisting of polymict, massive and less common graded conglomerate with clasts dominated by silicic volcanics, thick bedded massive or graded sandstone, minor diamictite, minor laminated siltstone and mudstone, and rare limestone. Erosion surfaces and intraformational clasts are common within the coarser lithologies (Mayer 1972). The Glory Vale Conglomerate is not as extensive as indicated. Much of what is mapped as this unit consists of diamictite and should be assigned to the underlying sequence. Pebbly sandstones with shallow trough cross bedding suggest deposition in a high energy fluvial environment. The Glory Vale Conglomerate shows considerable variation along strike, both in thickness and lithology and probably represents deposition in response to rapid uplift of the underlying units.

## MANNING GROUP

The Colraine Mudstone consists of mudstones and siltstones, often with abundant white mica. The Kywong Beds contain cobble and pebble conglomerates, sandstones, siltstones, crystal tuffs and andesites (Mayer 1972). Plant fossils are present in the upper part of the Kywong Beds.

The presence of coarse grained, immature sediments and associated plant fossils suggests that deposition of the Manning Group began in a shallow water or terrestrial alluvial fan environment adjacent to an area of rapid uplift. Such features are typical of sedimentation in rapidly subsiding grabens (Reading 1980).

### THERMAL HISTORY

Vitrinite reflectance measurements on dispersed organic matter in sedimentary rocks can be directly correlated with peak temperature (Barker and Goldstein 1990). This technique has been applied to rocks of the Manning Groupand 53 samples have been analysed. The derived temperatures range from 356°C to 189°C. The temperatures appear to relate directly to depth of burial, with maxima attained in the basal breccia and conglomerate unit, and minima within or near the Colraine Mudstone at the top of the Manning Group. The results correlate well with the temperatures predicted from the metamorphic assemblages. It has not been possible to use this data to calculate a geothermal gradient for the Manning Group, due to the lack of well constrained stratigraphic data.

Using a range of 160°C for the Manning Group that is currently exposed and average crustal geothermal gradients from 20°C to 40°C (cf. Wilson 1989 p. 40-41) a stratigraphic thickness between 8 and 4 km can be derived for the Manning Group. The lower value is probably more realistic since a high geothermal gradient is expected in tectonically active areas such as arcs and rifts (cf. Park 1988 p.10-11). The discrepancy between the original measured thickness (9 km) and that now suggested is not surprising, however, given the paucity of bedding data due to the often massive nature of the beds and by structural data which suggests that faulting has resulted in sequence repetition.

The temperatures recorded in the basal sequences of the Manning Group are higher than those recorded in the adjacent Devonian and Carboniferous forearc sequences immediately to the south, which were also derived from vitrinite reflectance measurements (J Gibson *pers. comm.* 1992). This strongly supports the interpretation that the Manning Group was deposited in a rift setting, based on the sedimentological and stratigraphic data discussed above.

## TECTONIC INTERPRETATION

If rifting, or horizontal extension, is responsible for the basin in which the Manning Group was deposited, then extension must have had some influence on the adjacent geological features ie. those that eventuated as the Sydney Basin and the New England Fold Belt. Two end-member extensional regimes can be contemplated: a transtensional strike-slip setting (cf. Reading 1980), or an orthogonal detachment setting (cf. Lister et al. 1986). If the Manning Group was deposited in a transtensional basin, then the adjacent Peel Manning- and Nowendoc Fault Systems and associated serpentinites may represent the major crustal sutures along which the basin formed. Continued strike-slip movement in the mid- to Late Permian would result in the terrane dispersal seen in the Southern New England Fold Belt (Cawood and Leitch 1985; Offler and Williams 1987; Collins 1990). In this case, tectonism may have had little or no influence on the proto Sydney Basin. Alternatively, orthogonal extension, resulting in a series of half graben, would have provided sites for the deposition of the Manning Group and the lithologically similar sediments of the Nambucca Block, where greater amounts of extension may have taken place, resulting in alkaline or MORB type volcanism (Asthana and Leitch 1985). The detachment fault responsible for basin formation may have penetrated to the base of the crust below the northern Sydney Basin, resulting in the voluminous mafic and bimodal volcanism present at that time (cf. Leitch and Skilbeck 1991 and references therein). Both scenarios present attractive, but partial, solutions and it is tempting to combine two tectonic styles in order to solve a complex geological problem!

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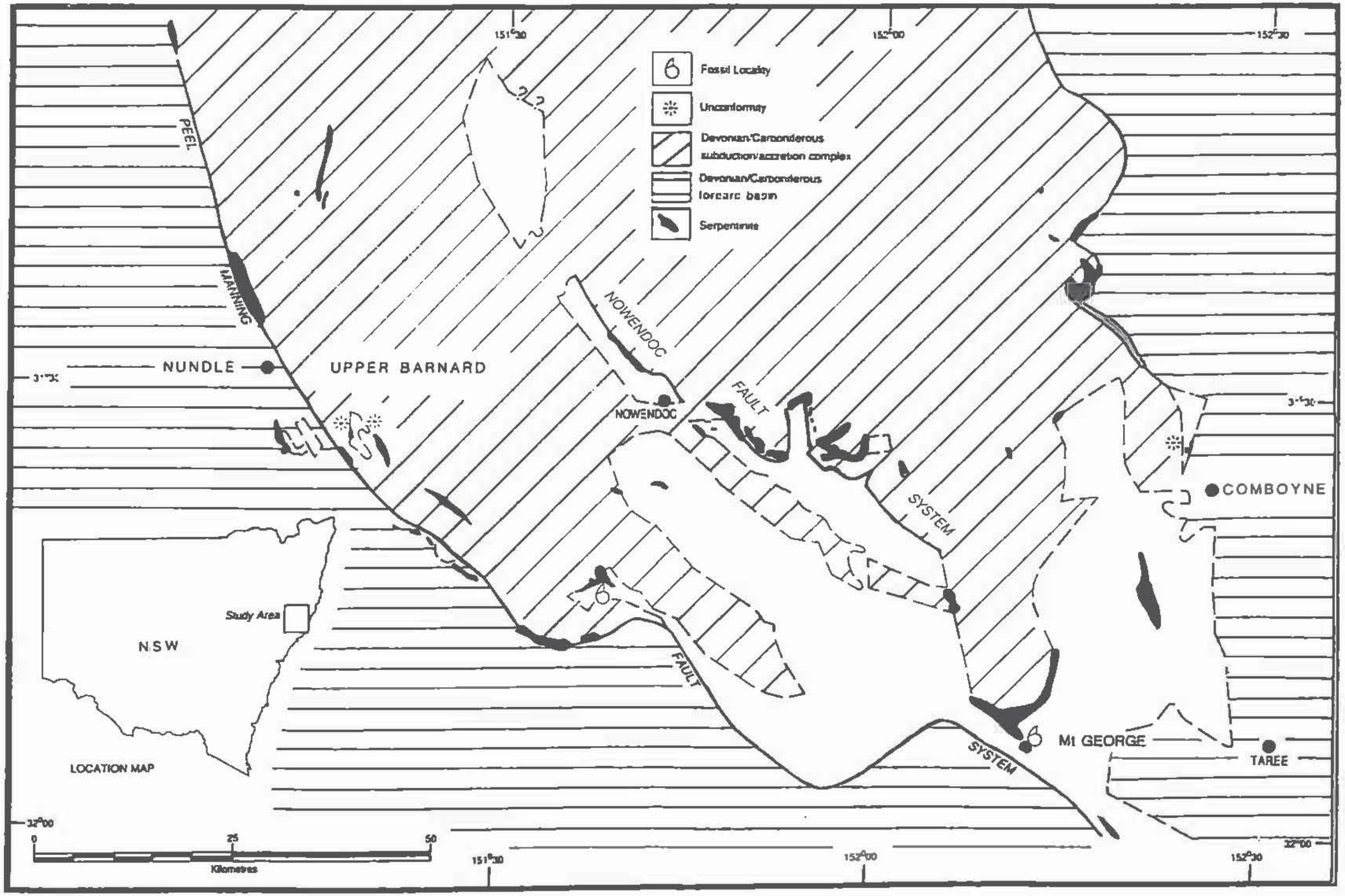


Figure 1: Location map of the Manning Group (unhatched)

# INFLUENCE OF THE PEEL FAULT SYSTEM ON THE EVOLUTION OF THE SYDNEY BASIN

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**Sedimentological influence of the Hunter Thrust?**

It has long been recognised that deposition of the Newcastle and Tomago Coal Measures, the equivalent Singleton Supergroup in the Upper Hunter Valley, and the coarse clastic rocks within coal measures farther north in the Bowen Basin, formed in response to "uplift" in the New England Fold Belt (NEFB). In the Lower Hunter region, this conclusion was largely based on the fan geometry, palaeocurrent indicators and lithological variation within the coal measures, where the increasing proportion of conglomerate and influx of pyroclastic material from the northeast during the Late Permian was taken to indicate "accelerating tectonic activity in the adjacent fold belt" (Diessel, 1980, p.104). But how was this activity manifested?

Many workers have suggested that the locus of "uplift" was the Hunter-Mooki Thrust System and its northern extension, identified seismically as the Burunga-Mooki geosuture (Finlayson et al., 1990). This may be so in the Gunnedah Basin and northward, but in the Newcastle area and southward it is unlikely, for there is no evidence that the Hunter Thrust extends southeastward from Maitland. Obvious displacement between Carboniferous and Permian rocks occurs several km north of Maitland, on the Lachnagar Fault, but any southeastward projection of the Hunter Thrust requires that it becomes strictly conformable with stratigraphy over at least tens of kilometres and therefore incapable of generating significant uplift. Indeed, preservation of Sydney Basin equivalents in the adjacent southern Tamworth Belt, the Stroud-Gloucester and Myall synclines, demonstrate that uplift in this region was limited. Yet this is the area from which the alluvial fans and braided stream deposits of the coal measures originated! Therefore, major uplift must have occurred farther eastward.

Limited analysis of clast material in conglomerates from the upper Newcastle Coal Measures (Ziolkowski, 1978) indicate that, of the "ultradurable" material (Patrick & Peterson, 1978), 20% to 90% is radiolarian chert from the accretionary prism of the southern NEFB. The remainder are fine-grained silicic tuffs that may be Carboniferous, or Early Permian volcanics of the Tamworth belt. Even so, the absence of crystal tuffs, which dominate the volcanic sequences of the southern Tamworth Belt, is intriguing. Two important implications are:

(i) Early Permian and Late Carboniferous sequences of the Tamworth Belt were being eroded in the Late Permian, but uplift was not related to the Hunter Thrust because palaeocurrent directions indicate provenance from the northeast and east, where the Hunter Thrust did not exist;
(ii) major uplift must have occurred in the accretionary prism farther eastward for material to be transported *across* the rising arc and fore-arc region of the Tamworth Belt. What mechanism generated the uplift? The answer requires knowledge of the dynamics and timing of structural events in the Sydney-Bowen Basin *and* the NEFB.

**Age of the Hunter-Bowen Orogeny in the New England Fold Belt.**
The NEFB, extending some 2000 km from Townsville to Newcastle, is a typical arc-forearc basin-subduction/accretion system that formed in the Devonian and Carboniferous, but was further deformed and exhumed (uplifted) during west-directed thrusting associated with the Hunter-Bowen Orogeny. During the uplift, the Sydney-Bowen Basin evolved in response to thrusting, from an incipient back-arc, or "retro-arc" in the Early Permian, to a foreland basin in the Late Permian, and detritus from the fold belt flooded generally westward into this meridional depository. As the thrust belt evolved, the *frontal* zone became the Sydney-Bowen Basin, reflected by the thin-skinned tectonism in the region (eg. Glen & Beckett, 1989; Collins, 1991) and the *internal* zone was the subduction/accretion complex of the NEFB.

In the southern part of the NEFB, uplift during thrusting is recorded in the Sydney Basin by the increasingly high-energy depositional realm of the Newcastle Coal Measures, the Permo-Triassic sedimentary megacycle of Conaghan et al. (1982). During this cycle, the 256 4 Ma old Awaba Tuff (Gulson et al., 1990) of the upper Newcastle Coal Measures was deposited, which provides an approximate age of uplift associated with the Hunter-Bowen Orogeny. The Thornton Claystone in the Tomago Coal Measures, dated at 266 1 Ma (Gulson et al., 1990), provides an upper age limit for deformation. The age of the Hunter-Bowen Orogeny in the Newcastle region, part of which involved the Hunter Thrust, is therefore constrained between 250-265 Ma. Minor thrusting continued into the Triassic (Moelle & Sutherland, 1977) as part of the cratonward migration of deformation that is typical of thrust belts (eg. Glen & Beckett, 1989).

In the northern part of the NEFB, thrusting was typically thin-skinned, west-directed, and associated with a strongly developed cleavage (Henderson et al., 1992). Rb-Sr dating of foliation-forming biotite, which grew under amphibolite to greenschist facies conditions, yielded ages of ~255 Ma, which dates the Hunter-Bowen Orogeny in the area (Leitch et al., 1992). The locus of orogeny also migrated progressively westward as indicated by Late Triassic folding in the Bowen Basin (eg. Henderson et al., 1992). Clearly, the Hunter-Bowen Orogeny was a major structural event that extended more than 1000 km along the eastern margin of the Sydney-Bowen Basin and outboard in the NEFB.

**Late Permian dispersal in the Southern New England Fold Belt**
The NEFB doubles in width from ~200 km at its northern extension in Queensland, to ~400 km in the southern region, the SNEFB. The doubling coincides with enormous structural complexity and juxtaposition of crustal blocks of differing structural and sedimentological histories. For example, penetrative cleavage development in the Permian Nambucca Block (Fig. 1), possibly a rift basin (Leitch, 1988), is generally orientated E-W (Offler, unpubl.) and developed in the Late Permian (Lennox and Roberts, 1988; Fukui et al., 1990), but the bounding accretionary prism remnants of the Coffs Harbour Block to the north and Armidale Block to the west contain variably-orientated subduction/accretion fabrics that formed in the Mid- to Late Carboniferous (Graham & Korsch, 1985; Dirks et al., 1992).

Cawood and Leitch (1985) described the rotation and translation of the structural blocks of the SNEFB as the "Permian dispersal event" and use tectono-stratigraphic relations and overlap assemblages to reconstruct the SNEFB as an elongate, N-S trending belt similar to that in the northern NEFB. Can the "dispersal event" be dated isotopically, and the mechanism of dispersal be understood within the tectonic framework of the region?

The bounding "dispersal" faults of some of the structural blocks have been recently dated (Landenberger et al., unpubl.). Where the metamorphic grade is sufficiently high, S/C mylonites developed, and biotite grew in the C (shear)-plane during deformation. One major fault, the Wongwibinda-Yarrowitch Fault (WYF) (Fig. 1), which is at least 200 km long, is the western boundary of the Nambucca-Hastings Block. Rb-Sr ages from biotites that formed on the shear-planes of the fault range in age from 256-265 Ma (Landenberger et al., unpubl.), which is the identical age for the Hunter Bowen Orogeny. The WYF is one of a series of splay faults off the Peel Manning Fault System (PMFS), which cut Permian strata of the Stroud-Gloucester Syncline and the highly disrupted Permian sediments of the so-called Barnard Basin (Leitch, 1988). Therefore, the isotopic ages on the WYF are consistent with regional-scale field relations and indicate that *the Permian dispersal event is the same age as the Hunter Bowen Orogeny*. The E-W foliations of the Nambucca Block are truncated by the WYF along an 80 km interval, requiring crustal-scale rotation of at least 90° of the block in the Late Permian to restore the foliation to the typical N-S orientation associated with the Hunter Bowen Orogeny! How did the dispersal originate?

**Oroclinal Bending**

Despite the doubts over the existence of the Texas-Coffs Harbour double orocline, it provides the best mechanism to drive the "Permian dispersal" event, thereby doubling the width of the NEFB in the southern region. Field mapping as far back as the 1960s suggested the presence of an orocline (Lucas, 1960, and it has been substantiated by further mapping (Olgers et al., 1974; Korsch, 1981; Flood & Fergusson, 1982), and by aeromagnetic surveys (Wellman & Korsch, 1988). The age of the orocline has been inferred to be Late Carboniferous (eg. Murray et al., 1987), but could be any age between the Carboniferous subduction/accretion event and the Early Triassic post-tectonic granitoid intrusive event (245-250 Ma: Shaw et al., 1991).

It is significant that Early to Mid(?) Permian sediments are intensely deformed in the axis of the orocline in the Bonshaw Block (Fig. 1) and the cleavage is rotated into concordance with the regional structure (Olgers et al., 1974) indicating complex Mid- or Late Permian deformation. Furthermore, none of the major Late Permian "dispersal" faults of the SNEFB appear to cut the orocline, yet some must have displacements in the order of hundreds of km to explain rotation of the Nambucca-Hastings Block, implying that oroclinal bending was *after* the "Permian dispersal". However, the broad curved axial traces of major fold structures in the Nambucca-Hastings Block (Fig. 1) are of similar scale to those of the orocline, suggesting that oroclinal bending began *before* "dispersal" faulting. Similarly, open warping of subduction/accretion fabrics in the "Wollomombi Zone" of the Armidale Block (Landenberger et al., unpubl.), which is bounded by the WYF (Fig. 1), suggest pre-dispersal oroclinal bending. The apparent paradox can be explained if *oroclinal bending and dispersal were contemporaneous*, which requires that some of the faults were merely accommodation structures for the orocline.

Kinematic indicators of the "dispersal faults" in the SNEFB generally indicate E-W to NE-SW directed compression, with a large dip-slip reverse component. The WYF is an irregularly trending, but invariably W-dipping reverse fault that forms the eastern boundary of the Wollomombi Zone, and it was responsible for juxtaposing the Tia and Wongwibinda migmatite complexes against lower grade rocks to the east. On the western side of the Wollomombi Zone, faults are east-dipping but also show reverse movement, indicating that the zone is a large-scale "pop-out" structure that formed in response to E-W compression, probably during oroclinal bending. Southwestward, beyond the Tia Complex, kinematic indicators reflect NE-directed thrusting and presumably, regional NE-SW compression (Dirks et al., 1992).

Notably, the large rotation required to emplace the Nambucca and Hastings blocks into their present position should be recorded as strike-slip movement, which is the case on the Yarras Suture (Lennox et al., 1991), which separates the Hastings from the Yarrowitch block (Fig. 1), but kinematic evidence for

strike-slip movement on the WYF, the western bounding fault of the Nambucca Block, is lacking. Either the original bounding fault is completely reactivated, such that all evidence of prior movement is lost, or it has been overthrust during the later, but still 260-250 Ma old, compressional event that produced the WYF. The latter alternative appears to be the most likely as evidence of major rotation (strike-slip movement) should be recorded as overprinted S/C mylonitic fabrics within the WYF. However, the kinematic history of the WYF is regionally consistent and simple.
The deepest crustal zones (~6 kbar=22 km, Dirks et al., 1992), exposed in the southern Tia Complex and beyond, coincide with the merging of the major "dispersal faults" such as the Yarras, Wongwibinda-Yarrowitch and Nowendoc faults. Kinematic studies on the Nowendoc and Yarras faults show evidence of sinistral motion on both (Hand, 1988; Lennox et al., 1991) and all have been described as subsidiary splay faults from the Peel-Manning Fault System (PMFS), which was regarded as the master fault system for Permian dispersal (Collins, 1991, p.421).

Major movement on the PMFS is also strike-slip sinistral, although the kinematic indicator patterns are complex (Offler and Williams, 1987; Offler et al., 1989). However, Permian movement on the PMFS south of Tamworth appears to be restricted by the presence of small Early Permian basins that appear to overlap the Peel Fault (Allan & Leitch, 1990). The contrast with inferred 100 km-scale displacement on the WYF, and probably others such as the Yarras Suture, suggests that major movement was taken up farther eastward during the later stages of Permian dispersal, implying an eastward migration of deformation. Nonetheless, the PMFS truncates the N-S trending folds of the southern Tamworth Belt, including the Stroud-Gloucester Syncline, indicating that large scale sinistral movement in this region occurred *after* the fold-and-thrust structures associated with the Hunter-Bowen Orogeny ($D_1$-$D_3$) had formed (Collins, 1991).

**"Uplift" of the New England Fold Belt**
The PMFS and splay faults are therefore "out of sequence" relative to the earlier ($D_1$-$D_3$) stages of the west-propagating Hunter-Bowen Orogeny (eg. Glen & Beckett, 1989), which suggests that a different stress regime affected the SNEFB in the later stages of deformation. This regime is considered to have been induced by oroclinal bending, which rotated and translated crustal blocks deformed by the Hunter Bowen Orogeny, thereby generating the "Permian dispersal" event of the SNEFB. The regional eastward migration of deformation and change from strike-slip dominated to dip-slip reverse is considered to coincide with tightening in the axis of the orocline, producing a crustal-scale "pop-out' structure, which is the Wollomombi Zone.

Generation of the pop-out structure, closure and thickening of the deep-water, ocean-floored trough represented by the Nambucca Block, rotation and translation of the block, were all part of an extensive, complex, progressive deformation event within the *internal zones* of the Hunter-Bowen Orogen.

Deformation began in the mid-Permian (~265 Ma) as a west-propagating fold-thrust system, but evolved into a double orocline in the latter stages, terminating before intrusion of ~250 Ma old "post-tectonic" granitoids of the SNEFB. The most significant uplift of the SNEFB was in the cental axis of the Late Permian (260-250 Ma) orocline, where the major faults were subsidiary to the PMFS, which in turn was the bounding fault system to the orocline. Thus, evolution of the Peel Manning Fault System in the Mid-to Late Permian was a major factor that controlled "uplift" in the NEFB and was therefore responsible for generation of the high-energy fluvial systems that flooded the Sydney Basin as foreland molasse deposits.

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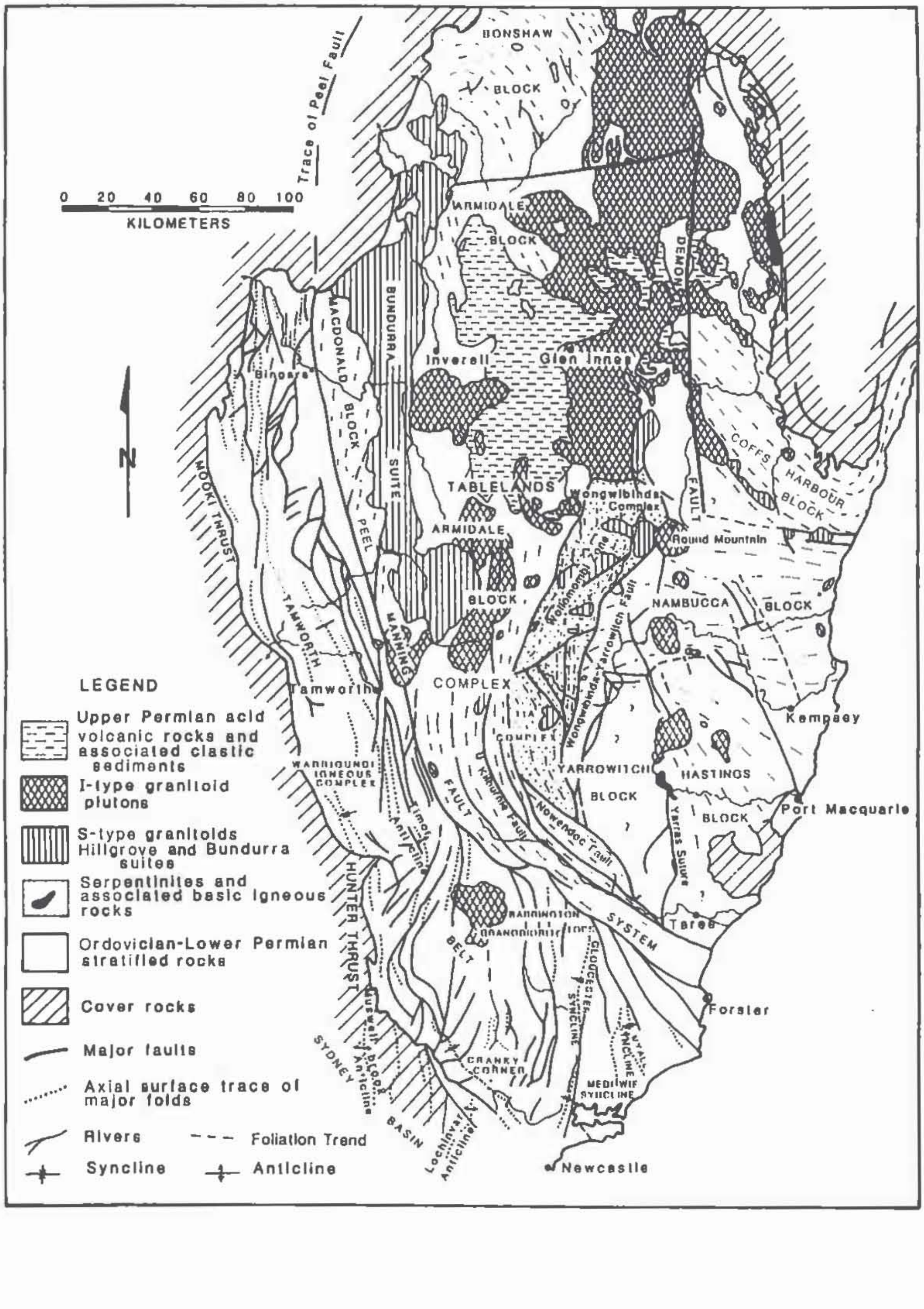
FIG.1 Map of southern New England Fold Belt



# LATE PERMIAN MAGMATISM ADJACENT TO THE MOOKI THRUST TULCUMBA RIDGE, NSW

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## INTRODUCTION

Although the New England Fold Belt was commonly the site of volcanic activity from Devonian to the Late Triassic, the composition, abundance and locus of this magmatic activity changed with time. Throughout the Devonian and much of the Carboniferous, volcanism was largely restricted to the western side of the Fold Belt. The earliest volcanism occurred just west of the Peel Fault to produce the Early Devonian andesites of the Bog Hole and Drik Drik Formations, followed in turn by the Late Devonian basaltic to andesitic volcanic rocks of the Baldwin and Mostyn Vale Formations (Brown, 1987) that were erupted from near the western edge of the Fold Belt. This was followed in the Early Carboniferous by andesitic lavas, ignimbrites and ?shallow intrusive rocks of the Merlewood Formation probably from vents within the western part of the Belt. In the Late Carboniferous the voluminous dacitic to rhyolitic volcanism of the Currabubula Formation (McPhie 1984) was erupted from centres west of the Mooki Thrust although the work of Buck (1988) in the the Hunter Valley indicates that some centres are in the area only just west of the Hunter Thrust. By the Early Permian, volcanism was rhyolitic, andesitic and basaltic as recorded in the Temi Formation, Boggabri Volcanics and Werrie Basalt including the Warrigundi "intrusives" (Flood et al., 1988; Leitch and Skilbeck, 1991; Vickers, 1991).

To the east of the Peel fault, some basaltic rocks of Devonian and Carboniferous age were incorporated into the subduction complex and in the Late Carboniferous and Early Permian, S-type plutons of the Hillgrove and Bundarra Plutonic Suites were emplaced (Flood and Shaw, 1977). In the Early Permian some areas of eastern and southern New England underwent rifting that produced local thick accumulations of MORB-like pillow basalt (Leitch, 1988). During the Late Permian, vast volumes of granite and associated volcanics were emplaced in a belt that extends from Tamworth in the south to Stanthorpe in

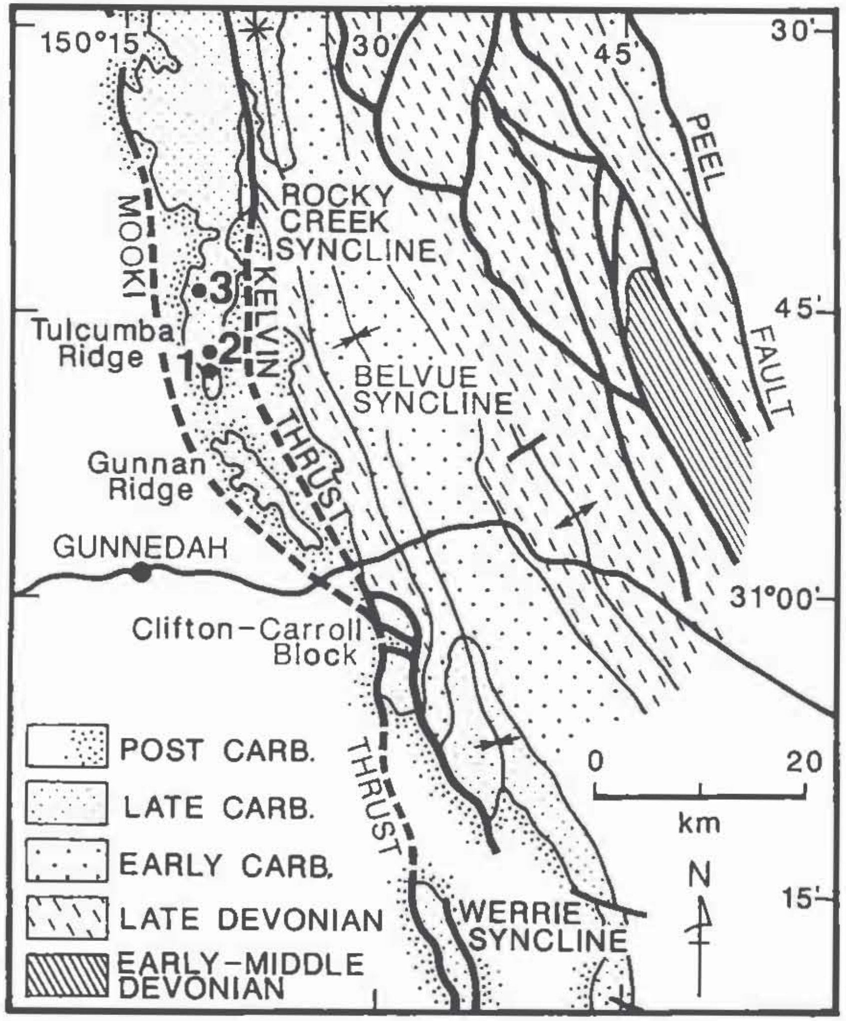


Fig. 1 Simplified geology of the New England Fold Belt west of the Peel Fault (after Liang, 1991). Numbers 1-3 refer to the analyses in Table 1.

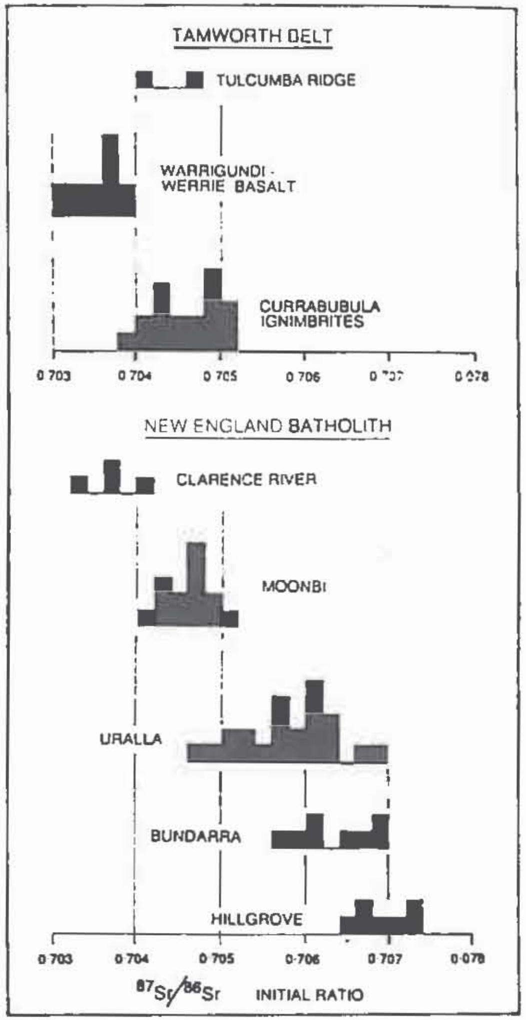


Fig. 2 Histogram of $^{87}Sr/^{86}Sr$ initial ratios of lamprophyres from Tulcumba Ridge compared with other igneous rocks of the New England Fold Belt.

the north (Shaw and Flood, 1981), although a few granitoids such as the Barrington Tops and Balala plutons (275-265 Ma, Shaw et al., 1991) predate this event. It has generally been considered that in the Late Permian, magmatism became restricted to the eastern side of the Fold Belt.

This paper reports the presence of Late Permian lamprophyre dykes from the Tulcumba Ridge, 20 km NNE of Gunnedah. New isotopic data for these rocks show that Late Permian magmatism extended at least as far west as the Mooki Thrust and that the possible relationship between igneous activity east of the Peel Fault and contemporaneous tephra deposits in the adjacent Gunnedah Basin must be reconsidered.

## IGNEOUS DYKES, TULCUMBA RIDGE

The Tulcumba Ridge (Fig. 1) lies within the western part of New England Fold Belt and is separated from the Gunnedah Basin immediately to the west by the Mooki Thrust system. To the east, the Kelvin Thrust separates the Tulcumba Ridge from the Rocky Creek and Belvue Synclines. The Tulcumba Ridge sequence consists of Late Carboniferous volcanogenic sandstones, conglomerates, ignimbrites and lavas of the Currabubula Formation. Liang (1991) has shown that these rocks are preserved as an overturned fault-propagation angular fold produced by Late Permian thrusting. The youngest lavas that outcrop along the western side of the ridge include dacitic and andesitic rocks that may be Early Permian in age (Liang, 1989) although the rhyolitic lavas interbedded in the Currabubula Formation indicate that this area was near-vent during the Late Carboniferous.
Within the Currabubula Formation, Liang (1989) mapped several types of near-vertical igneous dykes trending either north-south or east-west. A rhyolite dyke (grid ref. 430966) with chemical affinities to the lava flows of the Currabubula Formation is interpreted to be a feeder for the lavas, and a trachydacite dyke (grid ref. 427013) that has chemical characteristics similar to the Early Permian Warrigundi Igneous Complex (Flood et al., 1988) could be a feeder for the youngest lavas. The three lamprophyre dykes that have been mapped range up to 1.5m in width, are marked by chilled margins and multiple injection zones and have fresh biotite phenocrysts useful for Rb/Sr isotopic dating.

## LAMPROPHYRE DYKES

The lamprophyres are pale grey to greenish porphyritic rocks with phenocrysts of biotite, clinopyroxene, plagioclase and opaques in a sub-ophitic groundmass of plagioclase, clinopyroxene, opaques and needles of apatite. Biotite

Table 1. Major and minor element data: lamprophyres, Tulcumba Ridge

| Analysis no. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| | **MU48025** | **MU48033** | **MU47980** | **CAL*** |
| **Grid ref.** | 435900 | 441892 | 424975 | |
| **$SiO_2$** | 45.84 | 43.38 | 54.47 | 51.00 |
| **$TiO_2$** | 1.05 | 1.42 | 1.09 | 1.10 |
| **$Al_2O_3$** | 16.14 | 12.35 | 15.74 | 14.00 |
| **$Fe_2O_3$** | 5.10 | 4.26 | 6.42 | tot. 8.20 |
| **FeO** | 4.01 | 2.69 | 1.48 | - |
| **MnO** | 0.35 | 0.36 | 0.12 | 0.13 |
| **MgO** | 3.55 | 4.59 | 3.11 | 7.00 |
| **CaO** | 7.33 | 11.87 | 4.86 | 7.00 |
| **$Na_2O$** | 3.96 | 1.72 | 4.82 | 2.70 |
| **$K_2O$** | 3.87 | 5.99 | 4.20 | 3.10 |
| **$P_2O_5$** | 0.83 | 1.19 | 0.62 | 0.60 |
| **$H_2O^+$** | 2.91 | 1.96 | 1.72 | tot. 2.40 |
| **$H_2O^-$** | 0.62 | 0.53 | 0.47 | - |
| **$CO_2$** | 3.99 | 7.30 | 0.30 | 2.00 |
| **Total** | 99.55 | 99.61 | 99.42 | 99.40 |
| **Ba** | 3246 | 6074 | 2710 | 1050 |
| **Cr** | 77 | 202 | 35 | 370 |
| **Cu** | 59 | 63 | 58 | 43 |
| **Ga** | 19 | 18 | 17 | 18 |
| **Nb** | 12 | 14 | 10 | 13 |
| **Ni** | 29 | 62 | 19 | 150 |
| **Pb** | 54 | 98 | 85 | 13 |
| **Rb** | 89 | 216 | 136 | 70 |
| **Sr** | 489 | 1159 | 191 | 715 |
| **Th** | 39 | 25 | 30 | 9 |
| **U** | 8 | 5 | 9 | 3 |
| **V** | 204 | 180 | 228 | 170 |
| **Y** | 23 | 24 | 26 | 23 |
| **Zn** | 82 | 80 | 85 | 88 |
| **Zr** | 466 | 724 | 436 | 190 |

CAL* = Av. 1590 calc-alkali lamprophyres (Rock, 1991 p78)
Grid ref. = Australian metric map grid 1:25,000 Kelvin and Willuri

phenocrysts commonly exceed 2 mm across. Subhedral to euhdral grains of clinopyroxene are partly to completely pseudomorphed by calcite. Modally the rocks are classified as kersantite.

# LAMPROPHYRES, TULCUMBA RIDGE

## CHEMISTRY

The three lamprophyre dykes are mafic in composition (Analyses 1-3, Table 1) with $SiO_2$ ranging from 43-54%, and are distinctly high in $K_2O$, $P_2O_5$, and in two lamprophyres, $CO_2$. Although the carbonate-rich lamprophyres plot as tephrites on a total alkali-silica diagram (TAS), the $CO_2$-poor lamprophyre plots as trachyandesite. All three lamprophyres have high abundances of Rb, Sr, Ba, Zr, V, U and Th. These elements are present in much higher abundances than would be expected from orogenic basalts (Gill, 1981) but are characteristic of lamprophyres associated with calc-alkaline rocks (Rock 1991) (Analysis 4 Table 1). Using the simple CaO vs MgO discriminatory diagram of Rock (1991) the lamprophyres fall within the field of overlap of those associated with calc-alkaline rocks.

Table 2. Rb and Sr isotopic data: lamprophyres, Tulcumba Ridge

| | Rb | Sr | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ | Age Ma +/- | Ri +/- |
|---|---|---|---|---|---|---|
| **MU48025** | | | | | | |
| **Biotite** | 395.3 | 272.1 | 4.2120 | 0.719128 | 249.6 | 0.704172 |
| **Whole-rock** | 89.0 | 489.0 | 0.5270 | 0.706043 | 4.3 | 0.000117 |
| **MU48033** | | | | | | |
| **Biotite** | 511.2 | 134.1 | 11.0784 | 0.743928 | 248.5 | 0.704766 |
| **Whole-rock** | 216.0 | 1159.0 | 0.5397 | 0.706674 | 2.3 | 0.000102 |

## AGE

The age and initial $^{87}Sr/^{86}Sr$ ratio of two biotite-bearing lamprophyre dykes were determined using separated biotite-whole rock pairs (Table 2). Isotope analyses of whole rocks and separated biotite were determined at the Centre of Isotope Studies, a joint Universities-CSIRO facility at North Ryde, using a single collector VG 54E mass-spectrometer. Standard values used are; $\lambda\ ^{87}Rb=1.42*10^{-11}\ a^{-1}$; $^{86}Sr/^{88}Sr=0.1194$; E&A $SrCO_3=0.708039 \pm 0.000065$ (2 $\sigma$ external precision, population of 48); Variance of $^{87}Rb/^{86}Sr=0.5\%$; Biotite age uncertainty (2 $\sigma$) = 1.5%. Whole rock Rb and Sr were determined by XRF at Macquarie University, variance of $^{87}Rb/^{86}Sr=1\%$.

The two biotite - whole-rock isochrons give ages of 249.6 and 248.5 Ma and initial $^{87}Sr/^{86}Sr$ ratios of 0.70417 and 0.70477 respectively (Table 2). The Sr values of the biotites are exceptionally high and the Rb values low compared with biotites from most granitoids of the New England Batholith but appear typical of biotites from K-rich rocks of basaltic or intermediate composition (eg Wass & Shaw, 1984; Flood et al., 1988). As such, $^{87}Rb/^{86}Sr$ ratios of the biotites are low (Table 2) and therefore calculated ages critically dependent on their whole-rock Rb/Sr and $^{87}Sr/^{86}Sr$ ratios. Although the whole-rocks have high calcite (and therefore high Sr) contents, the similarity of the calculated ages between the two dykes would suggest that the calcite is genetically related to the magma.and not a result of secondary alteration. Initial $^{87}Sr/^{86}Sr$ ratios of the lamprophyre dykes are somewhat higher than those of the Warrigundi Igneous Complex (Fig. 2) which has been interpreted as having formed in an extensional environment with minimal crustal involvement (Flood et al., 1988). The lamprophyre initial ratios fall within the range of the Currabubula ignimbrites, the Clarence River and Moonbi Plutonic Suites of the New England Batholith (Fig. 2) but slightly lower than the average for lamprophyres associated with calc-alkaline igneous rocks (Rock 1991, p98; 0.7068 for an average of 99).

## CONCLUSIONS

The Tulcumba Ridge lamprophyres extend the distribution of Late Permian igneous rocks significantly west of the Peel Fault. Although volumetrically insignificant they are located between a major igneous belt of Late Permian granitoids (Group 1 of Shaw et al., 1991) to the east and contemporaneous tephra deposits in the Gunnedah Basin to the west. Whereas previously, tephra in the Gunnedah Basin was considered to be distal and sourced from Group 1 granitoids of the Batholith (Shaw et al., 1991), a much closer source could better explain the grain size and thickness of some of these tephras. The position of a volcanic centre near the Tulcumba Ridge at a considerable distance from the main belt of silicic volcanism in the Late Permian may be similar to the present Mt Taranaki (Egmont) relative to the more silicic volcanoes of the Taupo Volcanic zone, New Zealand.

The lamprophyres are geochemically similar to lamprophyres associated with calc-alkaline rocks (Rock, 1991). They are high in the lithophile elements K, Rb, Sr, Ba, U, Th and possess moderate to low initial $^{87}Sr/^{86}Sr$ ratios that overlap the I-type granitoids of the New England Batholith.

Within the Central Complex of the New England Fold Belt, a number of lamprophyre dykes have been observed (Henley, 1991) but only one (and of Tertiary or post-Tertiary age) has been found more than several kilometers west of the Peel Fault. As observed by Henley (1991) the distribution of lamprophyres in the Fold Belt may be biased as a result of greater attention being paid to mineralised areas and/or the problem of poor outcrop. Not mentioned by Henley (1991) is a large biotite-bearing lamprophyre dyke that occurs at Bungendore Spur between Bendemeer and Manilla (grid ref.031977). The biotite has been dated at 248.4 Ma (Average of 2; unpublished data) similar in age to the Tulcumba Ridge lamprophyres. Extensive dyke swarms of calc-alkali rhyolite to basalt within the Gwydir River and Balala plutons in New South Wales, and within the Herries pluton south-west of Warwick in Queensland are also of similar age and form part of the Group 1 granitoids that were emplaced between 253 and 244 Ma ago (Shaw et al., 1991).

More detailed mapping and isotopic data are required to determine if the western extension of Late Permian magmatism outcrops only in the Tulcumba Ridge block, or is present in other blocks of the Tamworth Belt.

## ACKNOWLEDGEMENTS

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# SEQUENCE BOUNDARIES INTERPRETED FROM SEISMIC DATA IN THE CENTRAL TAROOM TROUGH, SE QUEENSLAND

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## INTRODUCTION

As part of the BMR-GSQ-NSWMRD Sedimentary Basins of Eastern Australia Project, a network of 88 industry seismic lines in the Taroom region, SE Queensland, an area bounded by latitudes 25° and 26°S and longitudes 149° and 150° 30'E, was selected and interpreted . Geologically, this area lies near the northeastern margin of the Jurassic - Cretaceous Surat Basin, and extends across the greater part of the underlying Taroom Trough of the Permo-Triassic Bowen Basin (Fig. 1). The stratigraphy here of interest (Fig. 2) begins with the Early Permian Camboon Andesite, followed by marine formations and the Late Permian Baralaba Coal Measures. The succeeding Triassic units are all fluvial. A major unconformity separates the Bowen Basin succession from that of the Surat Basin; the latter in this region is also fluvial, except for the acritarch-bearing Westgrove Ironstone Member. The Glenhaughton 1 well, in the northwest corner of the region here discussed, penetrated a succession that is similar to that in the Denison Trough to the west. Unfortunately, there is a gap in the seismic coverage between the eastern and western areas, and recent publications still differ in some of the details of the correlations of the Permian marine units. Among the aims of the study are the re-interpretation of the seismic sections using a sequence stratigraphic framework, and the production of a series of synthesised structure contour and chrono-isopach maps of selected horizons and intervals.

## SEISMIC INTERPRETATION METHODOLOGY

Seismic sequence analysis was carried out by identifying discontinuities on the basis of reflector terminations according to the method of Vail (1988). The seismic sections were first examined for places where two reflectors converge, and these reflector terminations were marked with arrows. Where a number of such terminations occur along a reflector (or locally, a non-reflecting horizon), the discontinuity surface between truncating and toplapping reflectors below and onlapping and downlapping reflectors above was marked with a colored pencil. Each reflector was given its own color and a provisional code number; we anticipate that permanent designations will be given to significant reflectors later.

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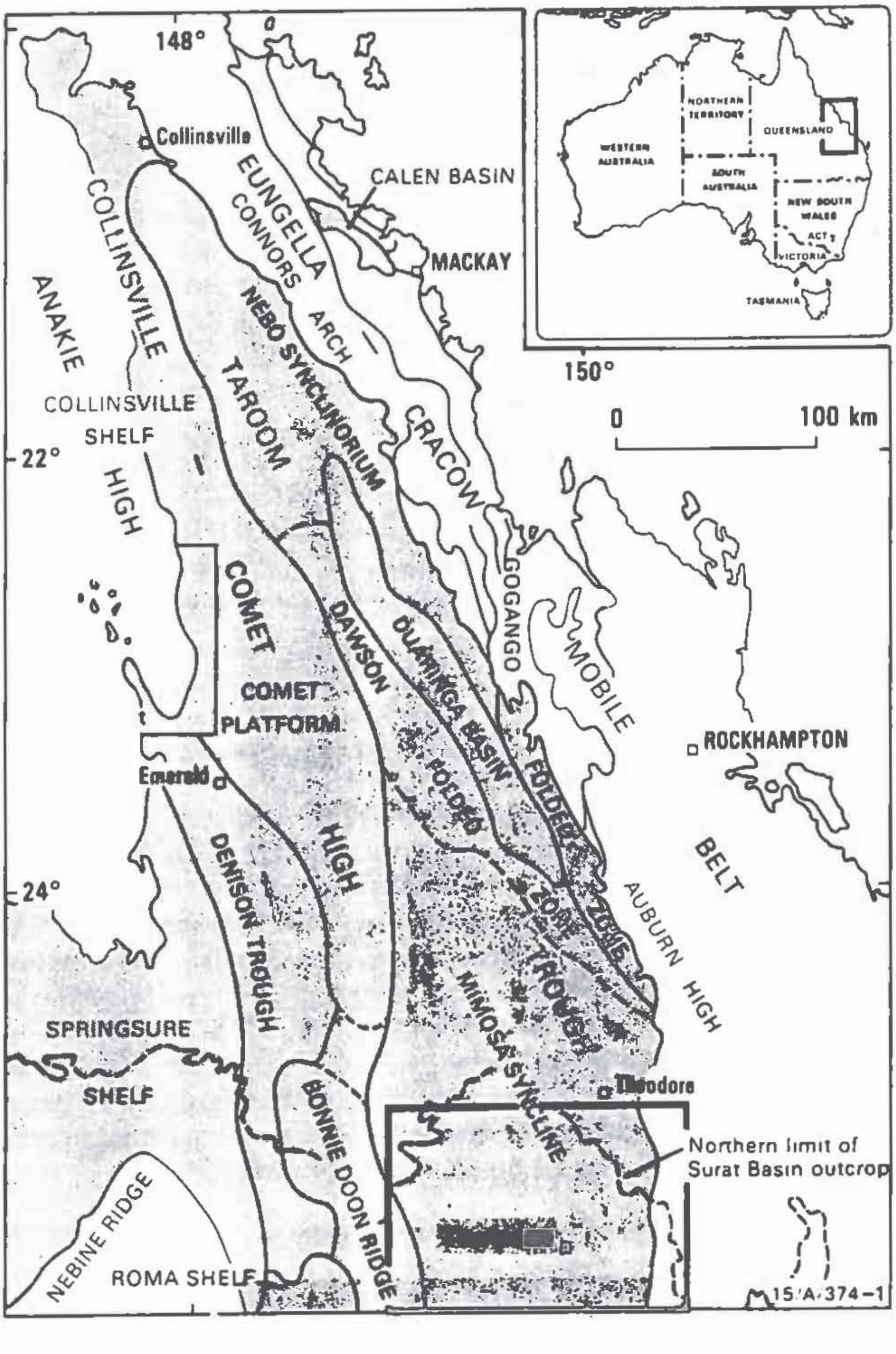


**Figure 1. Location and geological setting of the Taroom region.**

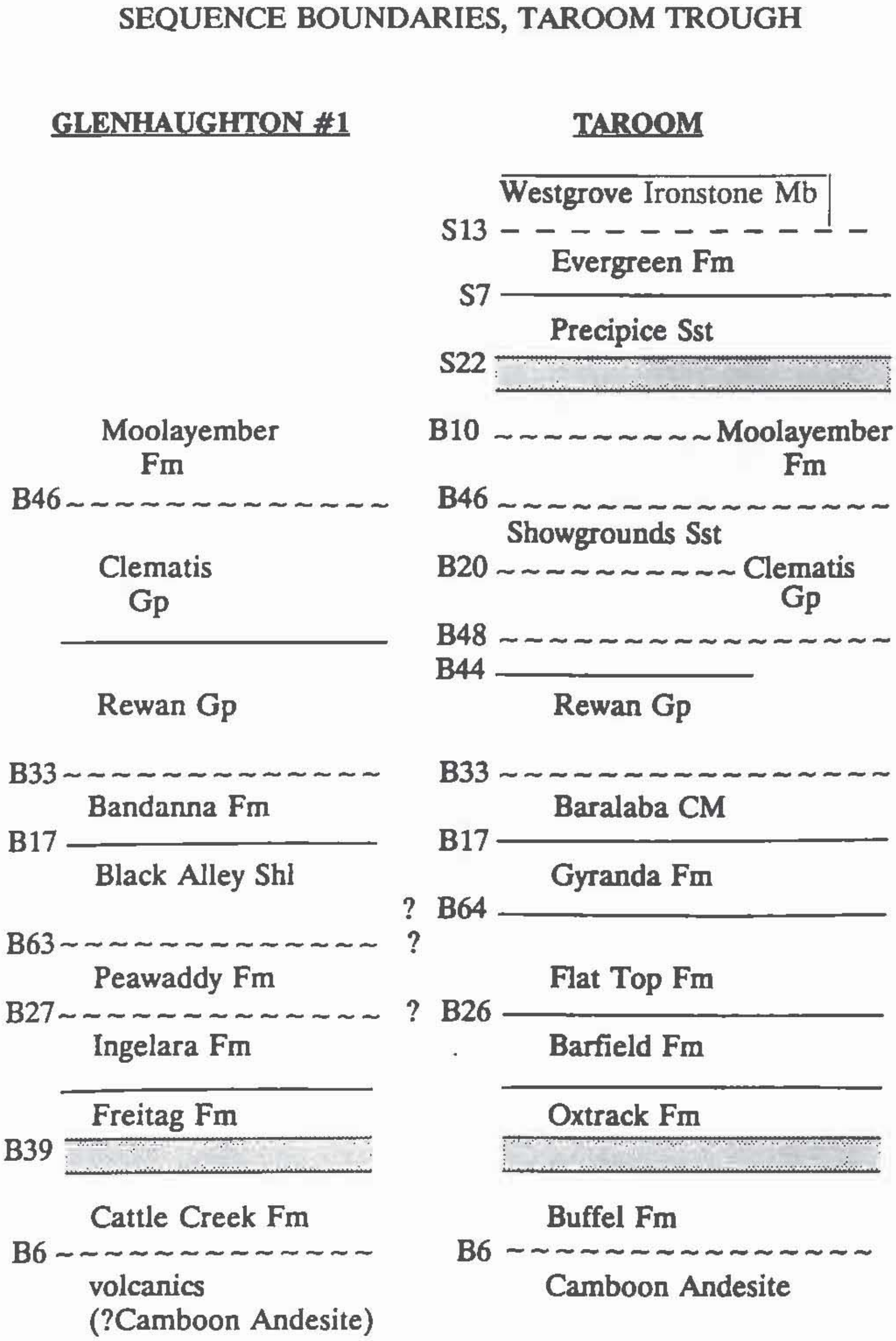


Fig. 2: Stratigraphy of the region, showing the positions of sequence boundaries, unconformities, and other reflectors (indicated by code numbers).

Sequence boundaries:
Major unconformities:
Maximum flooding surface:
Other boundaries:

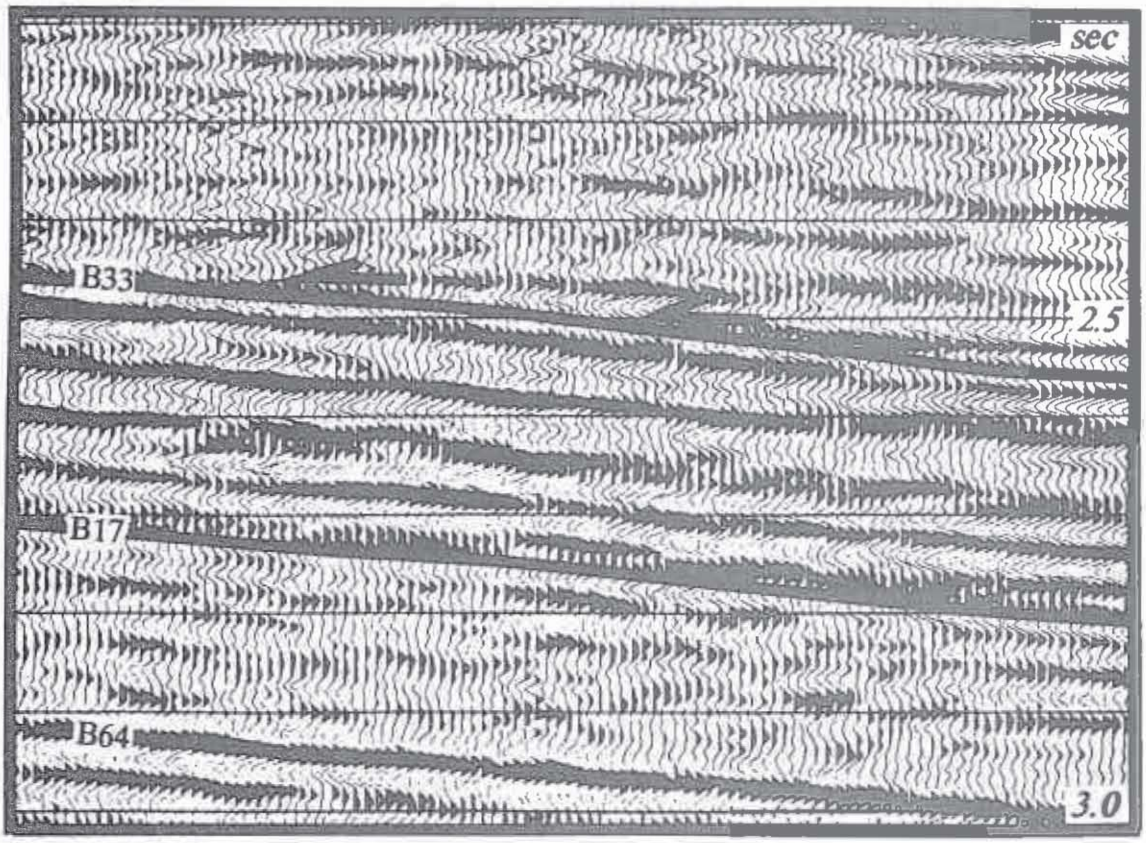


Fig. 3: Seismic expression of the Late Permian coal measures (Baralaba Coal Measures) between reflectors B33 and B17 in seismic section C83-GL-02. Note onlap of the basal beds of the Rewan Group onto B33. Vertical scale in seconds of seismic two-way travel time.

Discontinuities which become conformable were traced across the section by reflection correlation. Some reflectors which were not apparent discontinuity surfaces were also selected at this stage on the basis of the strength of their reflections. Correlation was continued onto intersecting lines, and all closed loops were checked by tracing the loop ties for each reflector. Formation depths in any wells drilled on a seismic line were converted to seismic two-way travel time using the supplied time-velocity table, and tied to the seismic section. Different published lithostratigraphic well-picks and time-depth tables inevitably gave disparate results for the same well, and emphasise the need for caution with well ties. In future, generating synthetic seismograms for wells may enable well ties to be made with greater confidence. The interpreted seismic line was then digitized using Petroseis software and checked for mis-ties.

At this stage, no attempt has been made to identify transgressive and highstand systems tracts. This is because most of the succession preserved in the two basins in the area is non-marine, and the marine portion, mostly Early Permian, is relatively thin. Discriminating between systems tracts in non-marine sediments is not only difficult, but the sequences themselves may be related more to sediment supply and tectonics than to sea-level changes. The importance of sediment supply in generating sequence stratigraphy has been explained by Galloway (1989), and is highlighted by the situation in the present-day Gulf of Mexico, where the Mississippi Delta region is in a highstand phase while the adjacent Texas coast is still in a transgressive phase.

## REFLECTORS AND SEQUENCE BOUNDARIES

Thirteen reflectors were chosen as the framework for seismic interpretation in the main part of the Taroom region (Fig. 2). Two lie within the lower Surat Basin, one is the major unconformity separating the two basins, and the remainder are within the Bowen Basin. Around the Glenhaughton 1 well, seven reflectors were used, all within the Bowen Basin, including one not found in the main study area.

The contact between the Camboon Andesite and the overlying Early Permian marine rocks is a regional sequence boundary usually marked by a high acoustic impedance contrast (provisionally designated B6 in Fig. 2). The only ties of B6 to wells in the Taroom region are poor ones to the base of the marine interval in Cockatoo Creek 1 and Glenhaughton 1.

The next highest sequence boundary (B39) has been recognized only in the northwest corner of the region, at the base of the Freitag Formation, here only a short distance above the base of the marine sediments. This level was identified from well logs as an unconformity by Cundill & Meyers (1964). It is interpreted as corresponding to the major unconformity in the eastern Taroom Trough where the whole of the Fauna III assemblage is missing, but it cannot be identified on the seismic sections there because the Buffel Formation is so thin as to be below the limit of seismic resolution.

Two reflectors (B26 and B64) were originally chosen soley on the strengths of their reflections, and they correspond approximately to the bases of the Flat Top and Gyranda Formations respectively in Cockatoo Creek 1. Locally there are suggestions of truncated beds below them, but evidence of their being sequence boundaries is not strong enough to be convincing. In the Glenhaughton 1 area, the base of the Peawaddy Formation (B27) is difficult to detect seismically, however Dickins (1983) has interpreted this level as representing a major tectono-sedimentary change, involving marine transgression, local unconformity, the introduction of volcanic detritus, and a change in marine fauna. The base of the Black Alley Shale (B63) truncates beds in a number of seismic lines, and represents a paleontological hiatus (Dickins, 1983); our field studies of a section near Carnarvon Gorge has shown that this surface is an erosional sequence boundary. If the correlations of B27 with B26 and B63 with B64 could be made with greater certainty than at present, they would imply that B26 and B64 are also probable sequence boundaries.

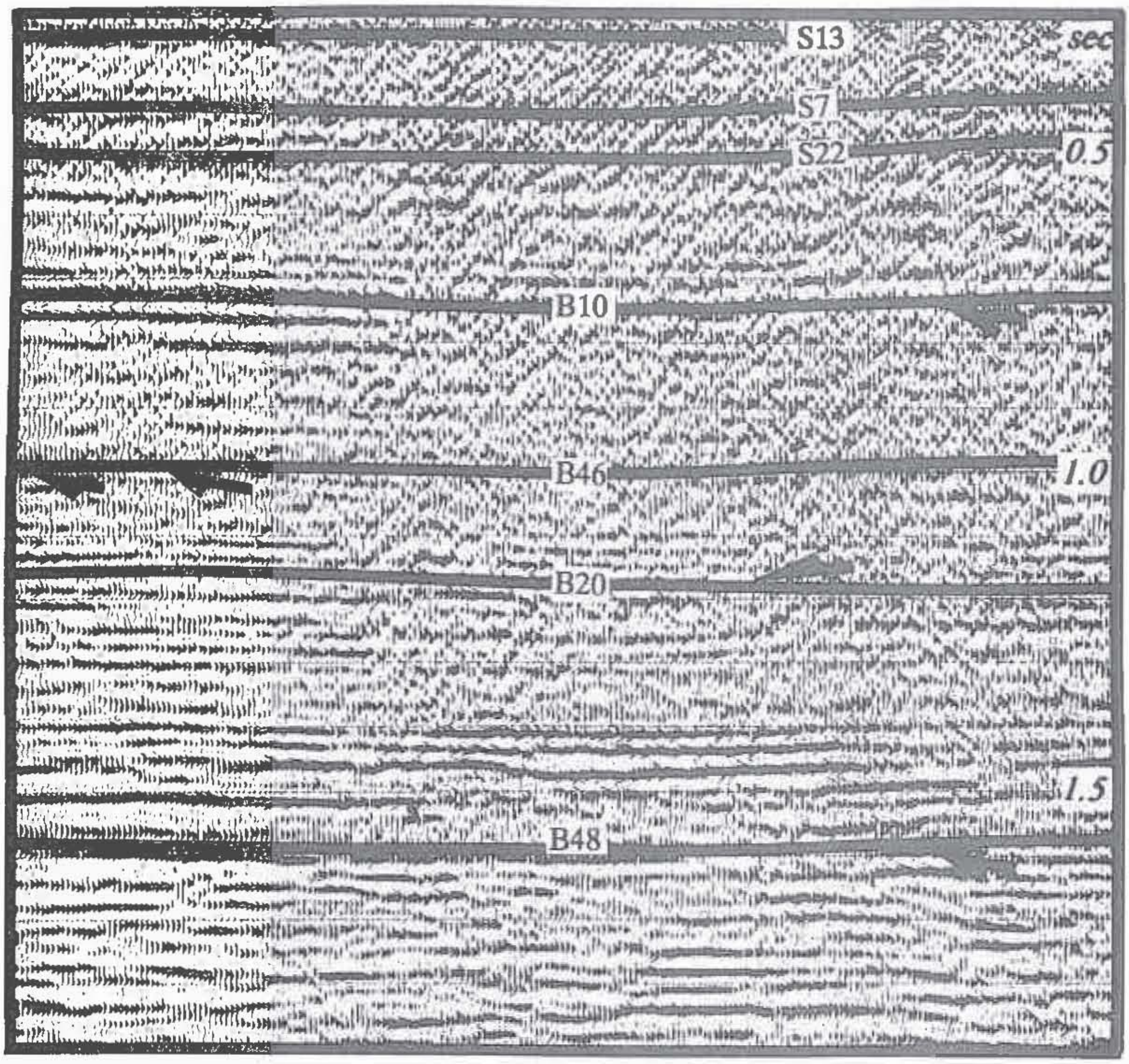


Fig. 4: Interpretations of reflectors B48, B20, B46, B10, S22 S7, and S13 in the Triassic and Jurassic strata of line T82-L-105. Vertical scale in seconds.

The base of the Late Permian coal measures is usually expressed as a well-marked reflector (B17) at the base of a zone of strong reflections (Fig. 3). As it truncates underlying beds in only two (possibly four) seismic sections, it is doubtful that it is a sequence boundary, but it may be a parasequence boundary.

The top of the coal measures (B33) is one of the most obvious sequence boundaries, confirming numerous references in the literature to a regional scour surface at this level. Underlying strata are truncated in many sections, erosional relief on it is sometimes visible, and locally there are onlaps and downlaps onto it. It is generally a strong reflector at the top of the zone of strong reflections caused by coal seams (Fig. 3).

## SEQUENCE BOUNDARIES, TAROOM TROUGH

Of the five reflectors picked in the Triassic succession, all except the lowest one (B44) have been identified as sequence boundaries. B44 is locally absent, due to its truncation by the sequence boundary above it (B48). It shows up as a strong trough flanked by strong peaks in some sections, but on many other lines is poorly defined. Although its nature is usually obscure, it can be seen possibly truncating strata below it in two lines. Its position in the seismic sections locates it in the upper Rewan Group.

Reflector B48 truncates not only B44, but also many other beds. Though locally a strong reflector, it is only intermittently well developed (Fig. 4). In the Tiggrigie Creek 1 well it ties to the base of the Clematis Group, where it can be seen to separate two distinctly different packages of reflectors. The Clematis base has been described previously as locally disconformable (Dickins and Malone, 1973) or erosional (Elliott and Brown, 1988). Reflector B20 within the Clematis Group shows high impedance contrast in some places, but is not evident as a sequence boundary. However, it ties approximately with the base of the Showgrounds Sandstone in Tiggrigie Creek 1, and elsewhere there is a hiatus below it (Elliott and Brown, 1988), signifying that it is an erosion surface.

The next sequence boundary (B46) truncates underlying beds, including B20, in some seismic lines, but usually does not show this trait, and on the poorer quality sections can be difficult to identify. In the Glenhaughton 1 area it is the only non-Permian sequence boundary that can be recognized. It appears to correlate with the base of the Moolayember Formation in Tiggrigie Creek 1. A better-developed truncation surface (B10) is present higher up, within the Moolayember Formation (Fig. 4).

The base of the Surat Basin succession (S22) is the strongest unconformity in the region. It represents the peneplanation surface formed during the Late Triassic, following the mid-Triassic folding episode. Erosion of these folds is particularly conspicuous near the eastern margin of the Bowen Basin. In the axial portion of the Taroom Trough the angular discordance is not as great, and at times the reflectors are parallel.

Two reflectors have been picked in the overlying sediments, corresponding to the Precipice/Evergreen boundary (S7) and the oolitic Westgrove Ironstone Member of the Evergreen Formation (S13) in the GSQ DRD 6 bore. In the Taroom region these horizons occur at shallow depths, where recording quality is often poor, and the reflectors can be difficult to identify. No seismic evidence has so far been found that either is a sequence boundary, however Elliott and Brown (1988) report a reflector at the S13 level as a "basin-wide sequence boundary". The Westgrove Ironstone Member records widespread chemical sedimentation denoting a dearth of clastic input, at the time of a marine incursion. Such "sediment starvation" is indicative of a maximum flooding surface.

CONCLUSIONS

Ten sequence boundaries (including two major unconformities) have been identified in the Taroom region from the interpretation of industry seismic sections. All but the sub-Surat unconformity occur within the Permo-Triassic succession of the Bowen Basin. Sequence boundaries can be recognized in fluvial deposits, and two associated with the Triassic Moolayember Formation (B46, B10) have not been reported before as erosion surfaces. Some surfaces suspected to be sequence boundaries from outcrop or drilling evidence (B27, B20) are not apparent as such on the seismic sections. It is likely that there are other sequence boundaries not seen seismically. In the marine Permian sequences, no maximum flooding surfaces have been found so far, probably also because the resolution of the seismic data available is inadequate, however one flooding surface has been recognized in the Surat Basin.

This paper is a contribution to the National Geoscience Mapping Accord project: Sedimentary Basins of Eastern Australia. It is published with the permission of the Executive Director, BMR Geology & Geophysics, Canberra.

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# THE COMPOSITION OF CARBONATE MINERALS IN COAL MEASURES OF THE SYDNEY BASIN

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## ABSTRACT

Scanning electron microscopy and microprobe analyses are presented for the carbonate minerals found in selected coal seams from the Sydney-Gunnedah Basin. The compositional ranges have been established for the three main types of carbonate minerals observed: calcite-ferroan calcite in cleats, dolomite-ankerite in cleats or veins and siderite-magnesian siderite nodules in coal or claystone bands.

## INTRODUCTION

Environmental concerns with greenhouse and acid gas emissions from conventional coal fired power stations have led to interest in integrated gasification-combined cycle processes (IGCC) which offer improved cycle efficiencies, with a consequent reduction in greenhouse gas emissions of at least 20%. It has therefore become important to assess the suitability of Australian coals for use in such processes both overseas and locally. Many of the IGCC systems include slagging gasifiers and this appears the most appropriate technology for the bituminous coals of the Sydney Basin. Australian bituminous coals have advantages of high volatile yields, low sulphur content and high reactivity but many of these coals have high ash fusion temperatures (>1500°C), which can lead to problems in slag discharge and may require the addition of fluxing agents in order to lower slag viscosity and ensure reliable operation of the slagging gasifier. Accordingly, there is renewed interest in the carbonate minerals which are the precursors of the natural fluxing components CaO, MgO and FeO, in the coal ash slags.

The general mineralogy of Australian and Sydney Basin coals is well understood and has been reviewed by Corcoran (1979) and Ward (1986 and 1989). Petrographic studies have established the broad type and distribution of the carbonate minerals in many coal seams (Kemezys and Taylor, 1964). Three main types are recognised: siderite as nodules, calcite as cleat and vein infilling and ankerite, also as cleat and vein infilling. Later studies using X-ray diffraction (Taylor, 1968 and Ward, 1978) suggested that much of the ankerite was in fact dolomite. However, both petrographic and X-ray diffraction procedures are often unable to unequivocally establish the chemical compositions of carbonate minerals because of the wide ranging substitutions which occur between calcium, magnesium, manganese and iron in the various minerals. The objective of the present work has been to directly determine the compositions of the three carbonate types in coal seams of the Sydney Basin. This paper reports the results of on-going scanning electron microscopy and microprobe investigations.

## EXPERIMENTAL PROCEDURES

Polished grain samples were available from earlier CSIRO characterisation studies of Australian coal seams and were simply repolished to ensure unoxidised mineral surfaces for analysis. The samples were selected on the basis of the petrographic analyses and profile descriptions for the various core sections, as reported in CSIRO Location Reports. This enabled an effective coverage of the main carbonate minerals present, and of variability with stratigraphic depth in each seam. Information on the seams examined is given in Table 1. The emphasis has been placed on seams of the Greta and Wittingham Coal Measures in the upper Hunter Coalfield. However, some seams have also been included from the Newcastle, Southern and Gunnedah Coalfields. Each seam was examined at only one locality, but generally four individual sub-sections were examined for each seam.

Scanning electron microscopy (SEM) was carried out using a CAMBRIDGE S240 microscope and semi-quantitative chemical analyses obtained using a NORAN X-ray energy dispersive spectrometry (EDS) facility. Selected samples were then quantitatively analysed using a Cameca, CAMEBAX electron microprobe and wavelength dispersive spectrometry (EMPA). When appropriate the average composition and formula were determined from a number of individual point analyses (usually 5-20) on each carbonate type.

## RESULTS AND DISCUSSION

Results of the present work are fully consistent with those of the earlier petrographic examinations and, for many samples, allowed the identification of the specific types of carbonate minerals present for the first time. However, the present protocol did not allow quantitative evaluation of the proportions of each type present or the examination of the same seam in different areas. As it is known that the relative amounts of carbonates and especially cleat infilling carbonates, can vary markedly in samples from the same seam (Brown, Durie and Schafer, 1960), the present results are only representative of each coal seam at one particular location and it would be unwise to assume that they are necessarily representative of the seam more widely. Thus the current results should be combined into one data set which can then be reliably used to provide information on the range in compositions observed for the three main types of carbonate minerals, i.e. calcite, siderite and ankerite. While some differences were observed in the relative amounts of the main types, between seams and with stratigraphic depth, it is not possible to assess their significance at this time.

A total of 76 samples from 20 coal seams have been semi-quantitatively examined and 30 samples from 13 seams have been analysed by microprobe. The compositional ranges observed for the three main carbonate types are plotted in Figure 1. Typical energy dispersive spectra for the various carbonate types are shown in Figure 2. The chemical compositions are in accord with those of carbonates in the Northumberland coalfield, northern England (Smythe and Dunham, 1947). From Figure 1, it is evident that calcites are all of similar chemical composition, that siderite grains are variable in magnesium content in the range siderite to magnesian siderite and that ankerites are variable in composition between dolomite [$CaMg(CO_3)_2$] and ankerite [$Ca(Mg,Fe)(CO_3)_2$]. It is felt that ongoing accumulation of data for other Sydney Basin coal seams is unlikely to reveal new carbonate mineral types. However, the compositional ranges observed might well be extended somewhat, if the number of sample locations and samples were increased. More detailed discussion of results for these carbonate mineral types is given below.

## COMPOSITION OF CARBONATE MINERALS IN SYDNEY BASIN COALS

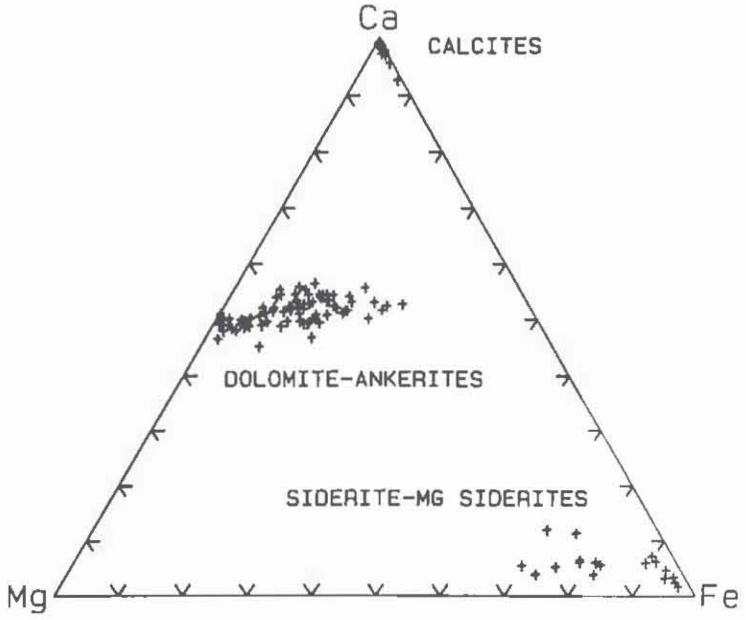


**Figure 1. Composition of carbonates in Sydney Basin coals**

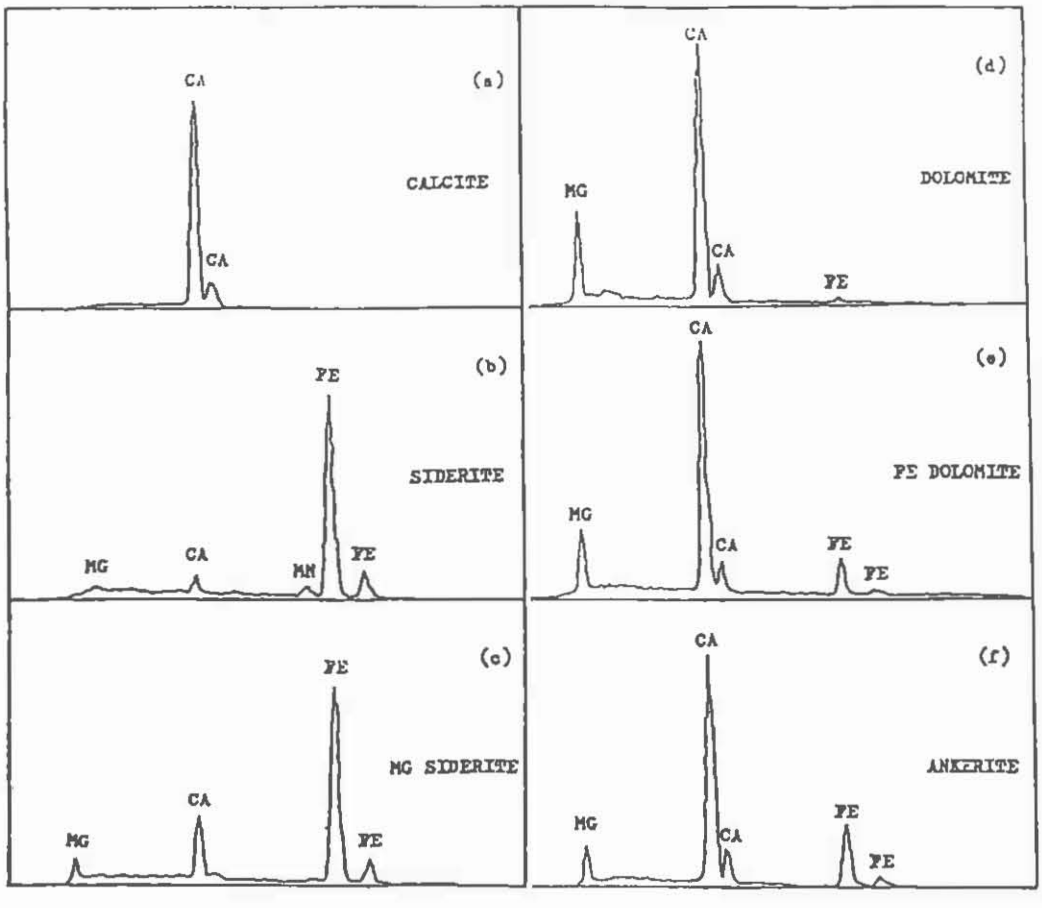


**Figure 2. Energy dispersive spectra of various carbonate types**

Table 1 Coalfields and Seams Examined

| Coalfield | District | Coal Measures | Seam | CSIRO Location Report No. |
|---|---|---|---|---|
| Gunnedah | Upper North-West | Black Jack | Hoskisson | 392 |
| Hunter | Singleton-Muswellbrook | Wittingham | Wambo | 389 |
| | | | Ravensworth | 350 |
| | | " | Bayswater | 358 |
| | | " | Liddell | 277 |
| | | " | Edinglassie | RI549R |
| | | " | Ramrod Creek | RI549R |
| | | " | Barrett | 347 |
| Hunter | Singleton-Muswellbrook | Greta | Brougham | 349 |
| | | " | Grasstrees | 352 |
| | | " | Puxtrees | 351 |
| | | " | Thiess | 351 |
| | | " | Balmoral | 316 |
| Newcastle | Newcastle | Newcastle | Great Northern | 363 |
| | " | " | Fassifern | 368 |
| | Maitland-Cessnock-Greta | Greta | Homeville | 228 |
| Southern | Wollongong | Illawarra | Bulli | 344 |
| | " | " | Balgownie | 344,268 |
| | " | " | Wongawilli | 264 |
| | " | " | Tongarra | 344 |

Table 2 Structural Formulae for Siderites and Mg-siderites

| CSIRO Laboratory Nos. | Coal Seam | Structural Formula | | | | |
|---|---|---|---|---|---|---|
| **Siderites** | | | | | | |
| 51708, 51709, 51711 | Hoskisson | $Fe_{0.94}$ | $Mg_{0.02}$ | $Ca_{0.02}$ | $Mn_{0.02}$ | $CO_3$ |
| 32085 | Edinglassie | $Fe_{0.93}$ | $Mg_{0.02}$ | $Ca_{0.03}$ | $Mn_{0.02}$ | $CO_3$ |
| 10117 | Balgownie | $Fe_{0.92}$ | $Mg_{0.02}$ | $Ca_{0.04}$ | $Mn_{0.02}$ | $CO_3$ |
| 32102 | Ramrod Creek | $Fe_{0.92}$ | $Mg_{0.03}$ | $Ca_{0.03}$ | $Mn_{0.02}$ | $CO_3$ |
| 23845,23846,23852,23853 | Fassifern | $Fe_{0.91}$ | $Mg_{0.02}$ | $Ca_{0.03}$ | $Mn_{0.04}$ | $CO_3$ |
| 22263, 22275 | Bayswater | $Fe_{0.89}$ | $Mg_{0.03}$ | $Ca_{0.06}$ | $Mn_{0.02}$ | $CO_3$ |
| 21845 | Grasstrees | $Fe_{0.88}$ | $Mg_{0.05}$ | $Ca_{0.06}$ | $Mn_{0.01}$ | $CO_3$ |
| 10547 | Liddell | $Fe_{0.87}$ | $Mg_{0.05}$ | $Ca_{0.06}$ | $Mn_{0.01}$ | $CO_3$ |
| **Mg-siderites** | | | | | | |
| 21663, 21677 | Brougham | $Fe_{0.81}$ | $Mg_{0.12}$ | $Ca_{0.06}$ | $Mn_{0.01}$ | $CO_3$ |
| 21752, 21753, 21758 | Thiess | $Fe_{0.80}$ | $Mg_{0.13}$ | $Ca_{0.06}$ | $Mn_{0.01}$ | $CO_3$ |
| 22275 | Bayswater | $Fe_{0.80}$ | $Mg_{0.14}$ | $Ca_{0.04}$ | $Mn_{0.02}$ | $CO_3$ |
| 21774 | Puxtrees | $Fe_{0.78}$ | $Mg_{0.15}$ | $Ca_{0.06}$ | $Mn_{0.01}$ | $CO_3$ |
| 23844-23846,23851,23853 | Fassifern | $Fe_{0.78}$ | $Mg_{0.15}$ | $Ca_{0.06}$ | $Mn_{0.01}$ | $CO_3$ |
| 51709, 51711 | Hoskisson | $Fe_{0.75}$ | $Mg_{0.20}$ | $Ca_{0.04}$ | $Mn_{0.01}$ | $CO_3$ |
| 21844, 21845 | Grasstrees | $Fe_{0.75}$ | $Mg_{0.13}$ | $Ca_{0.11}$ | $Mn_{0.01}$ | $CO_3$ |
| 21663, 21677 | Brougham | $Fe_{0.70}$ | $Mg_{0.17}$ | $Ca_{0.12}$ | $Mn_{0.01}$ | $CO_3$ |
| 51713, 51721 | Hoskisson | $Fe_{0.75}$ | $Mg_{0.23}$ | $Ca_{0.04}$ | | $CO_3$ |
| 38671 | Wambo | $Fe_{0.70}$ | $Mg_{0.24}$ | $Ca_{0.06}$ | | $CO_3$ |

# COMPOSITION OF CARBONATE MINERALS IN SYDNEY BASIN COALS

Calcites Calcium carbonates, presumably calcite, were observed in a number of individual samples from the Hoskisson, Liddell, Barrett, Puxtrees, Thiess, Great Northern, Fassifern, and Tongarra seams. Generally both sideritic and ankeritic type carbonates were also present. The calcite observed was predominantly cleat material and had mostly been liberated from the coal during crushing (Figure 3a). Occasional infillings were observed within inertinite. In all cases the chemical composition was both essentially pure $CaCO_3$ and remarkably constant throughout the Sydney Basin coal measures. The composition for several selected individual calcite grains is shown in Figure 1. Some variation towards ferroan calcite was detected especially in the Fassifern seam while minor amounts of ferroan dolomite were observed in rare instances as phases crystallising within the calcite cleats (Figure 3a).

Siderite/Mg-siderites Iron carbonate minerals were observed in many of the samples and in all of the seams examined. This is consistent with the findings of Taylor (1968) and Ward (1978). Thus it would seem that siderites are ubiquitous to the Sydney Basin coal seams but can vary in amount from location to location. The siderite type minerals were almost always observed as nodular or massive siderite grains in either coal or claystone bands (Figures 3b and 3c). They very rarely occurred in cleats or veins in the coal. Again, this is consistent with results of earlier studies (Kemezys and Taylor, 1964).

Findings of the present work were that nodules often contain two distinct phases, siderite and Mg-siderite (Figure 3d) and that the composition of the iron carbonate minerals is variable between these two phases (Table 2). The proportions of the two phases is probably quite variable as well, but in our observations nodules were typically siderite with minor Mg-siderite or vice versa. Minor amounts of calcite and ankerite were also observed within or on the edges of some sideritic nodules. Microprobe analyses of the mixed nodules confirmed the presence of two distinct phases rather than a continuum of magnesium contents. Thus it was possible to average the individual analyses for each sample and determine the formula for the siderite and/or Mg-siderite observed. The composition of the Mg-siderite varied in the different samples and average formulae so determined are given in Table 2. Compositions ranged up to 25% $MgCO_3$. Energy dispersive spectra which illustrate the range in compositions observed are shown in Figure 2. The present analyses appear to be in agreement with the few previously published analyses for predominantly siderite samples from the Bulli, Great Northern and Tongarra seams (Brown, Durie and Schafer, 1960).

Siderite appeared to be the only or predominant iron carbonate phase observed in the Liddell, Great Northern, Edinglassie, Ramrod Creek, Bulli, Wongawilli and Balgownie seam samples. However, Mg-siderites were predominant in the Grasstrees, Puxtrees, Thiess, Brougham and Barrett seams. Samples from the Hoskisson, Fassifern, Bayswater, Ravensworth and Tongarra seams contained both siderite types, but it is not possible to estimate the relative amounts. In several instances the Mg-siderites were associated with claystone bands but again the significance of this is hard to assess at this time (Figure 3c). The different siderite compositions observed presumably reflect the composition of the pore waters at the time of crystallisation. Current results are insufficient to establish whether the different compositions are in some way related to depositional conditions or to different stages during diagenesis and maturation.

Dolomite-Ankerites Petrographic studies reported these phases as ankerites which apparently formed in cleats and veins later in diagenesis, after the coal had been compacted and undergone most of its maturation (Kemezys and Taylor, 1964). X-ray diffraction studies indicate that these phases have the characteristic structure of dolomite (Taylor, 1968 and Ward, 1978).

In the present study we have quantitatively analysed dolomite-ankerites in 15 individual samples and 10 coal seams. Semi-quantitatively we have recorded energy dispersive spectra from a further 17 individual samples and 3 seams. The indications are that all results will plot along the dolomite to ankerite line shown in Figure 1. Thus the chemical compositions range between those for pure dolomite, to ferroan dolomite and to ankerite with about 60% substitution of Mg by Fe and Ca. This is not really surprising as the secondary phases formed by crystallisation in cleats would be dependant upon the composition of liquors moving through the cleats. As selective crystallisation of say dolomite occurs, the composition of liquors is also changed and other carbonate phases can then crystallise to yield zoned mixtures of carbonate phases. The present results are similar to those of Smythe and Dunham (1947) for ankerites in the Northumberland coalfield, although they did not find dolomite.

The present work indicates the complex nature of crystallisation within ankeritic cleats. In many instances the cleat material was zoned either parallel to or across the cleat. Figure 3e shows one such zoned dolomite/ankerite cleat. Distinct areas of different composition are clearly evident based on differences in the intensity of electron back-scattering and confirmed by EDS spectra and microprobe analyses. Fibrous ferroan dolomite (Fe-dolomite) was also observed in coals from the Thiess and Hoskisson seams as shown in Figure 3f.

Changes observed in the chemical composition of these mixed Ca, Mg, Fe-carbonates result from varying degrees of substitution of magnesium in the dolomite structure by mainly iron and to a small extent calcium. This is consistent with well established carbonate geochemistry (Smythe and Dunham, 1947 and Deer, Howie and Zussman, 1962). For the present purposes we have defined the boundary between dolomite and Fe-dolomite as 5% substitution of Mg by Fe and accepted the boundary between Fe-dolomite and ankerite as 20% substitution of Mg by Fe (from Deer, Howie and Zussman, 1962). From our results (Figure 1) it is evident that relatively few analyses correspond to dolomite (say 10%), considerably more phases would be Fe-dolomite (say 20%) and the rest would be ankerites. Thus the validity of the petrographic results is confirmed for most samples.

Several samples from the same sections as examined by both Taylor (1968) and Ward (1978) for the Homeville, Balgownie and Liddell seams, were also examined here. Dolomite was found in the Homeville and Balgownie samples, although Fe- dolomites and ankerites were also found, often zoned with dolomite in the cleats. For the Liddell samples we found only Fe-dolomite and ankerite, but this may reflect the limited sampling. Thus the XRD results are partially confirmed, especially as Fe- dolomites would probably show very similar patterns to that for dolomite. The reason why some ankerites apparently do not show the XRD pattern for ankerite remains to be explained.

## CONCLUSIONS

1. The carbonate minerals in twenty coal seams from the Sydney Basin have been examined using scanning electron microscopy and electron microprobe analysis. Compositional ranges have been established for the three main carbonate types observed: calcites, siderites and dolomite-ankerites. Calcites and dolomite-ankerites occurred mainly as cleat or vein infillings in the coal, whereas siderites occurred mainly as nodules in coal or claystone bands.

2. The calcites were essentially pure $CaCO_3$ with minor amounts of iron substitution for calcium (ferroan calcite). Siderites varied in composition from siderite,

$Fe_{0.94}Mg_{0.02}Ca_{0.02}Mn_{0.02}CO_3$ to magnesian siderite $Fe_{0.7}Mg_{0.25}Ca_{0.05}CO_3$. Dolomite-ankerites varied in composition from dolomite, $CaMg(CO_3)_2$ to ankerite, $Ca(Mg_{0.4}Fe_{0.54}Ca_{0.06})(CO_3)_2$. These compositional ranges are not unusual for carbonate minerals in sedimentary deposits.

3. Sideritic nodules were of uniform composition within each individual section but sometimes varied between sections of a seam. Some siderite nodules contained minor areas of magnesian siderite or vice versa.

4. Cleat infillings by calcite were typically uniform in composition, whereas cleat infillings by dolomite-ankerite were generally variable in composition. Zones of dolomite/ferroan dolomite/ankerite were observed parallel to the cleat, in many samples.

5. The present results are insufficient to establish differences between seams or to account for the variability in siderite and dolomite-ankerite compositions which were observed.

## ACKNOWLEDGEMENTS

We thank Mr P. Marvig for the preparation of polished blocks, Mr D. Condie for use of the CSIRO Interactive Coal Properties Information System, Dr D.H. French for his data plotting program and Dr M. Smyth for helpful discussions in relation to earlier CSIRO petrographic studies.

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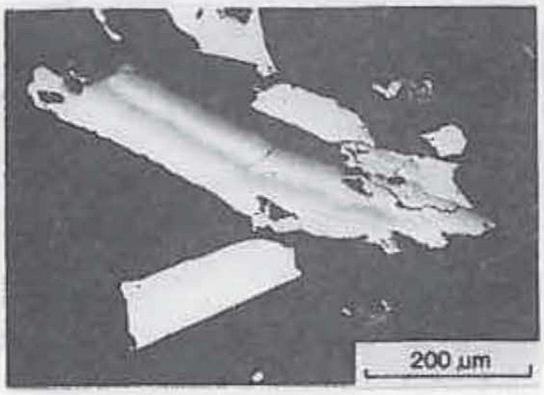
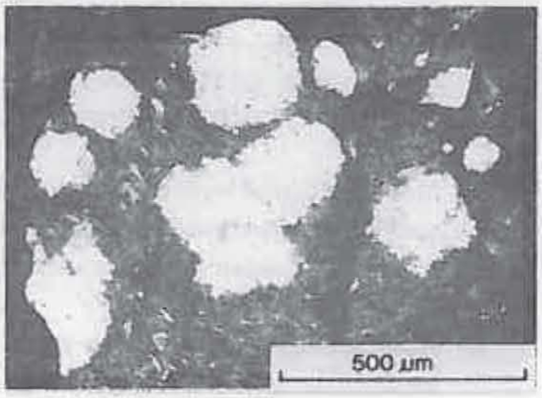
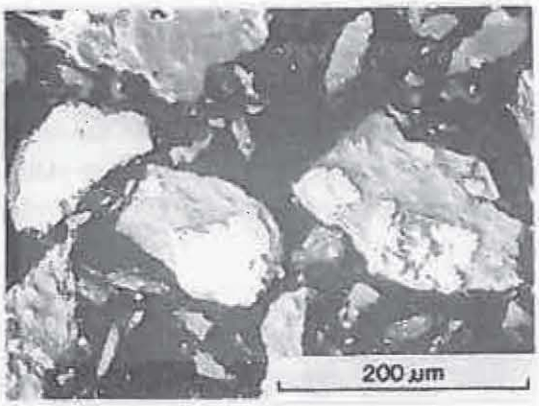


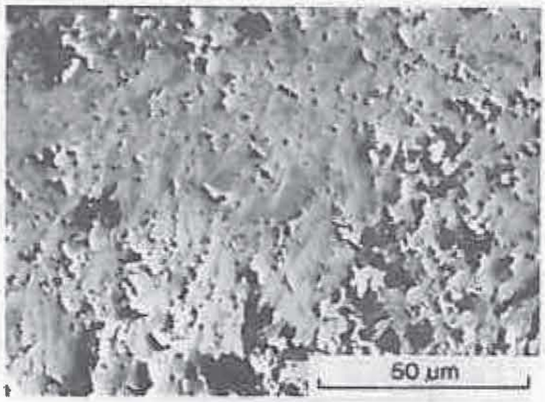

(a) Calcite in cleats with
Fe-dolomite zones (grey)



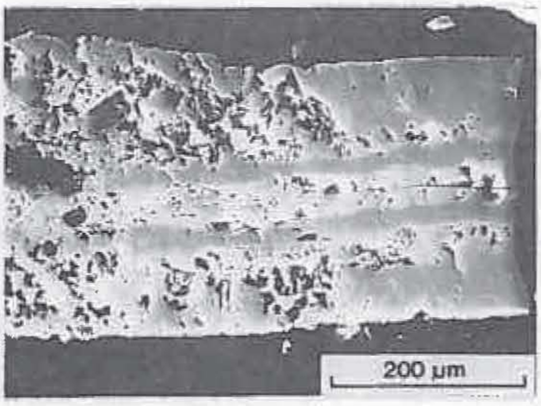

(b) Siderite nodules in coal



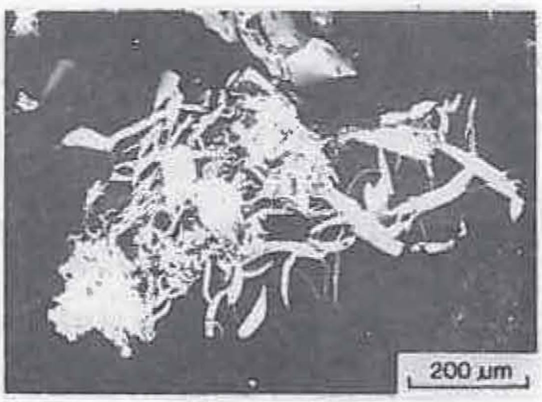

(c) Siderite grains in claystone (grey)




(d) Siderite (grey) with minor
Mg-siderite (dark grey)




(e) Dolomite (dark grey) and
ankerite (grey) in a cleat




(f) Mg-siderite aggregates (white)
and fibrous Fe-dolomite (grey) in coal

Figure 3. Scanning Electron Microscope Photographs of Carbonates

# GEOLOGICAL CONTROLS ON GAS DISTRIBUTION IN THE NEWCASTLE COALFIELD

**M. CREECH**
**FAI Mining Ltd., Teralba**

ABSTRACT

The collation of in-situ gas data from Teralba, West Wallsend and Newstan Collieries has indicated that gas distribution is influenced by seam level (not necessarily depth of cover), seam dip direction, impervious layers and geological barriers. Thinner, less persistent seams generally contain higher in-situ gas than the economic seams at a given locality and level.

This work has contributed to mine planning by enabling scientifically based predictions of in-situ gas contents to be made for seams in areas where they have not been tested.

## INTRODUCTION

A considerable volume of in-situ gas data (127 samples) is available from Teralba and West Wallsend Collieries (FAI owned), from Newstan (Elcom) and from a future pit near Wakefield known as Lachlan (FAI owned). These pits comprehensively cover an area of 100 sq. km located between the north western shores of Lake Macquarie to the east and the Sugarloaf Range to the west (Fig. 1). This data is comprised largely from samples taken from surface drilling but also includes measurements taken underground from the worked seam and upholes.

These data were collated onto a map and entered onto computer for graphic presentation. This work identified significant in-situ gas variations both across the area, and vertically through strata which could not be explained by changes in depth of cover alone. Further studies revealed additional factors which appear to control gas distribution in this region.

## GEOLOGICAL FACTORS CONTROLLING GAS DISTRIBUTION

### Seam Relative Level

Three domains of gas distribution became evident, these being Teralba/Stockton Borehole (high gas), Wakefield/Newstan (low gas) and West Wallsend (confusing).

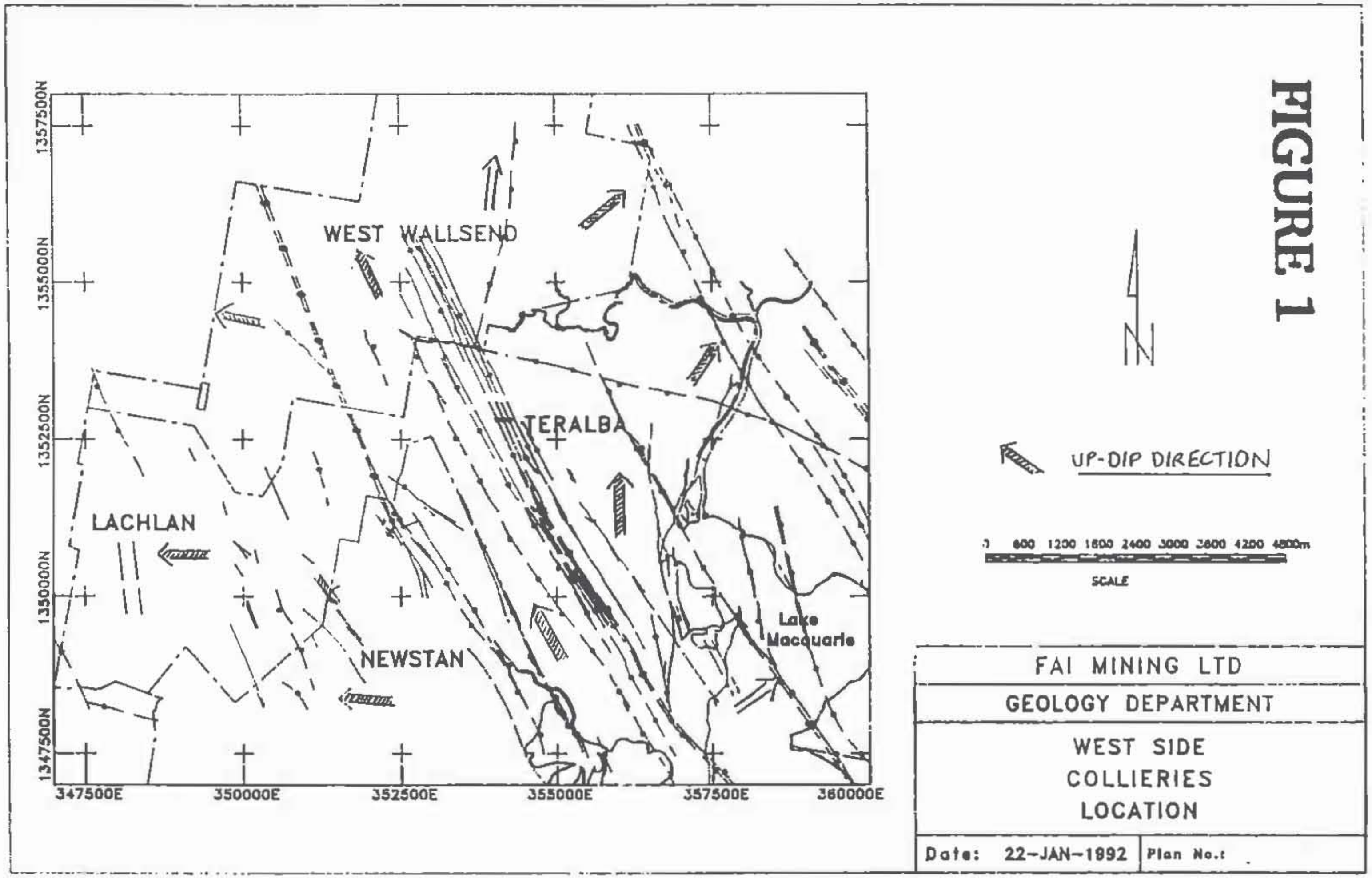

1357500N
1355000N
1352500N
1350000N
1347500N
347500E
350000E
352500E
355000E
357500E
360000E
WEST WALLSEND
TERALBA
LACHLAN
NEWSTAN
Lake Macquarie
N
UP-DIP DIRECTION
0 600 1200 1800 2400 3000 3600 4200 4800m
SCALE
FAI MINING LTD
GEOLOGY DEPARTMENT
WEST SIDE
COLLIERIES
LOCATION
Date: 22-JAN-1992
Plan No.:

FIGURE 1

## GAS DISTRIBUTION - NEWCASTLE COALFIELD

Gas contents were graphed against both depth of cover and relative levels and the seam from which each sample had been taken was identified. At Teralba Colliery, seam R.L. and depth of cover vary significantly as the pit extends under Lake Macquarie and also below significant topographic highs. As a result the graph of gas content against depth of cover is significantly different from that employing relative level. Indeed on inspection, depth of cover appears to be irrelevant, in relation to Young Wallsend and Borehole samples (Fig. 2). A more consistent relationship is discernible plotting gas content against seam level.

### Impervious Geological Barriers

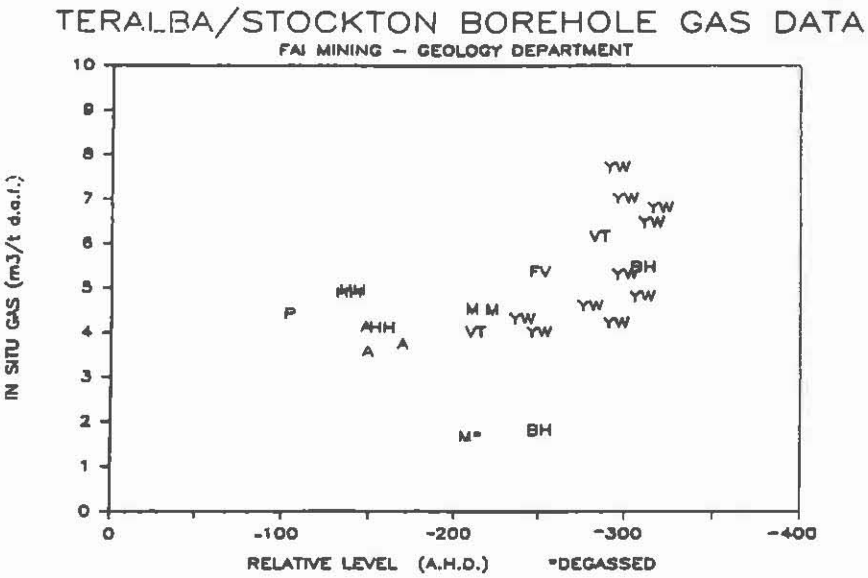
Assuming seam gas migrates upwards, its movement through strata will be impeded by impervious dykes, and impervious sedimentary layers. Common in the strata at this locality are dykes (east-west and north-south striking, but predominantly NW-SE striking) and numerous tuff layers. The former would impede horizontal movement within stratigraphic horizons, and the latter vertical movement through strata. Tuffaceous beds are common within and above coal seams in the Newcastle Coalfield and these layers would restrict migration of gas to movement within coal seams themselves. This observation may explain the more consistent relationship between seam level and gas content, rather than depth of cover.

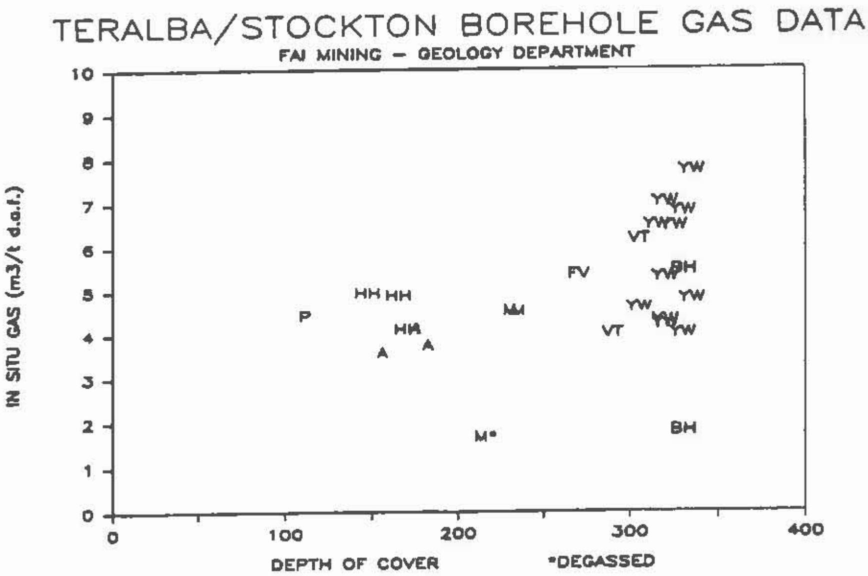
A paper published by Creedy (1988) detailed geological controls on in-seam gas distribution he identified in British coalfields. Creedy concluded that the vast majority of gas movement occurs during coalification and any folding or structures appearing at this time would be reflected in seam gas distribution. Later structural features displayed only minimal influence on seam gas contents. This may well be the case in the Newcastle Coalfield as the Macquarie Syncline (early Triassic - late Permian) and the majority of dykes (Jurassic-Cretaceous)may have been active/emplaced during coalification (Warbrook 1981). The idea that the present gas distribution is a relict feature also would suggest that seam RL (if folding was comtemperaneous with coalification) will control gas distribution not the far less permanent, depth of cover which changes considerably over geological time.

### Seam Continuity

The graph of the gas data for Wakefield/Newstan (Fig. 3) illustrates well another trend of gas distribution, common across the whole area of this study. For a given relative level, the thinner seams contain more gas than the thicker (including economic) seams. This would be expected if gas migration is restricted to movement within seams (due to impervious sedimentary layers) and thinner seams more commonly suffer full seam faulting or discontinue or thin laterally.

# FIGURE 2


TERALBA/STOCKTON BOREHOLE GAS DATA
FAI MINING – GEOLOGY DEPARTMENT
IN SITU GAS (m3/t d.a.f.)
RELATIVE LEVEL (A.H.D.)
*DEGASSED


TERALBA/STOCKTON BOREHOLE GAS DATA
FAI MINING – GEOLOGY DEPARTMENT
IN SITU GAS (m3/t d.a.f.)
DEPTH OF COVER
*DEGASSED

GAS DISTRIBUTION - NEWCASTLE COALFIELD

## Seam Dip Direction

Assuming gas migration is restricted to movement within coal seams, the up-dip direction of the seam in relation to other barriers (such as dykes) will influence in-situ gas content. This appears to explain the high gas domain at Teralba (up-dip direction is generally 45° to the dominant NW-SE dyke/fault system) and the low gas Wakefield/Newstan domain where seam up-dip directions generally parallel these structures, or there appears to be no significant subvertical barriers to impede gas movement (Fig. 1). The current area of longwall mining at West Wallsend is similar to Teralba in regards to gas contents, although relative levels are shallower at West Wallsend and therefore absolute gas contents are much lower (Fig. 4). However the situation is unclear as up-dip direction varies from 45°-90° to the dominant NW-SE dyke structures.

## Conclusions

The following geological factors appear to control seam gas contents in the Newcastle Coalfield:

1. The gas distribution appears to represent a relict feature reflecting gas migration during coalification (Creedy, 1988) and structures existing at that time.

2. Gas migration is restricted to movement within seams due to the numerous impervious tuff layers in the strata.

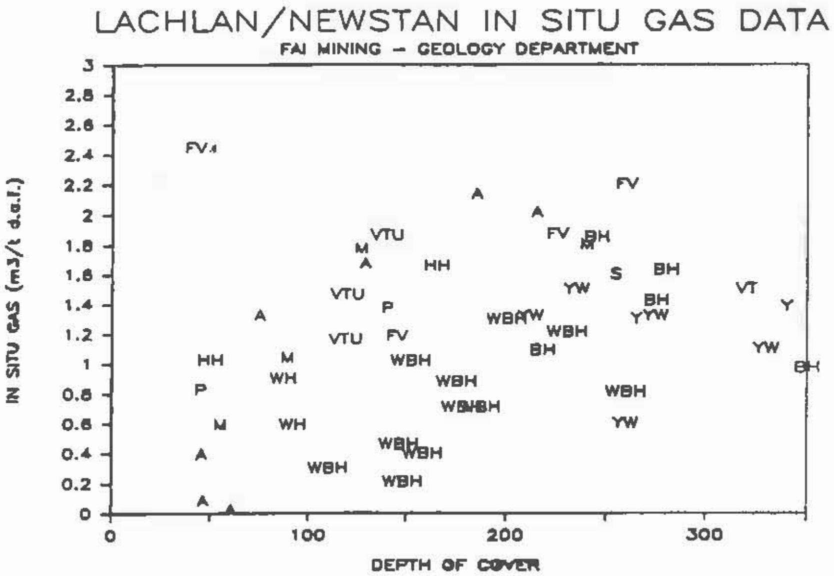
3. Seam relative level controls seam gas more strongly than depth of cover as a result of 1 and 2 above, and the assumption that the Macquarie Syncline existed during coalification.

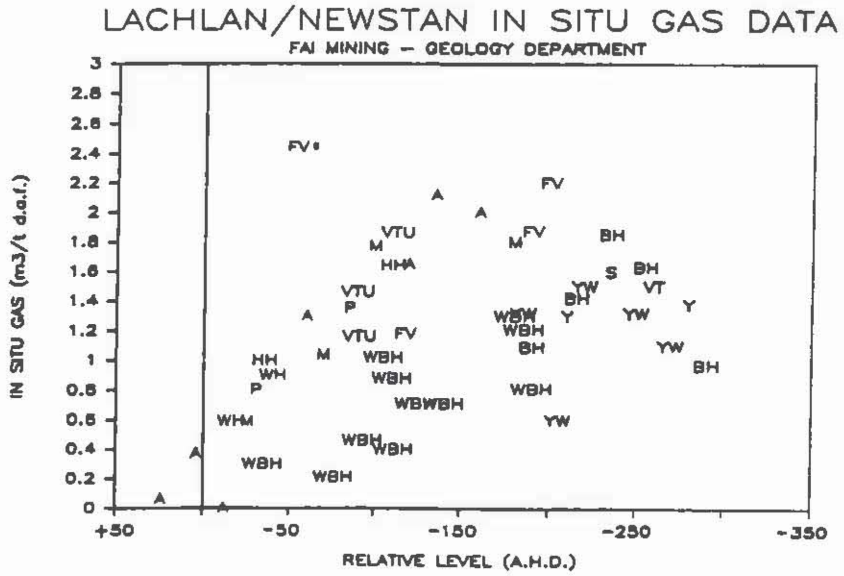
4. Dykes sedimentary closures and full seam faulting will therefore impede gas migration within a seam, if present at the time of coalification.

5. The up-dip direction of the seam in relation to other barriers such as dykes affects gas contents.

6. Thinner, less persistent seams contain higher gas at a given locality and level than thicker seams as they more commonly suffer full seam faulting and sedimentary closures (washouts, pinching out, etc.).

# FIGURE 3


LACHLAN/NEWSTAN IN SITU GAS DATA
FAI MINING – GEOLOGY DEPARTMENT
IN SITU GAS (m3/t d.a.f.)
DEPTH OF COVER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FAI MINING – GEOLOGY DEPARTMENT
IN SITU GAS (m3/t d.a.f.)
RELATIVE LEVEL (A.H.D.)

# GAS DISTRIBUTION - NEWCASTLE COALFIELD

MICHAEL CREECH


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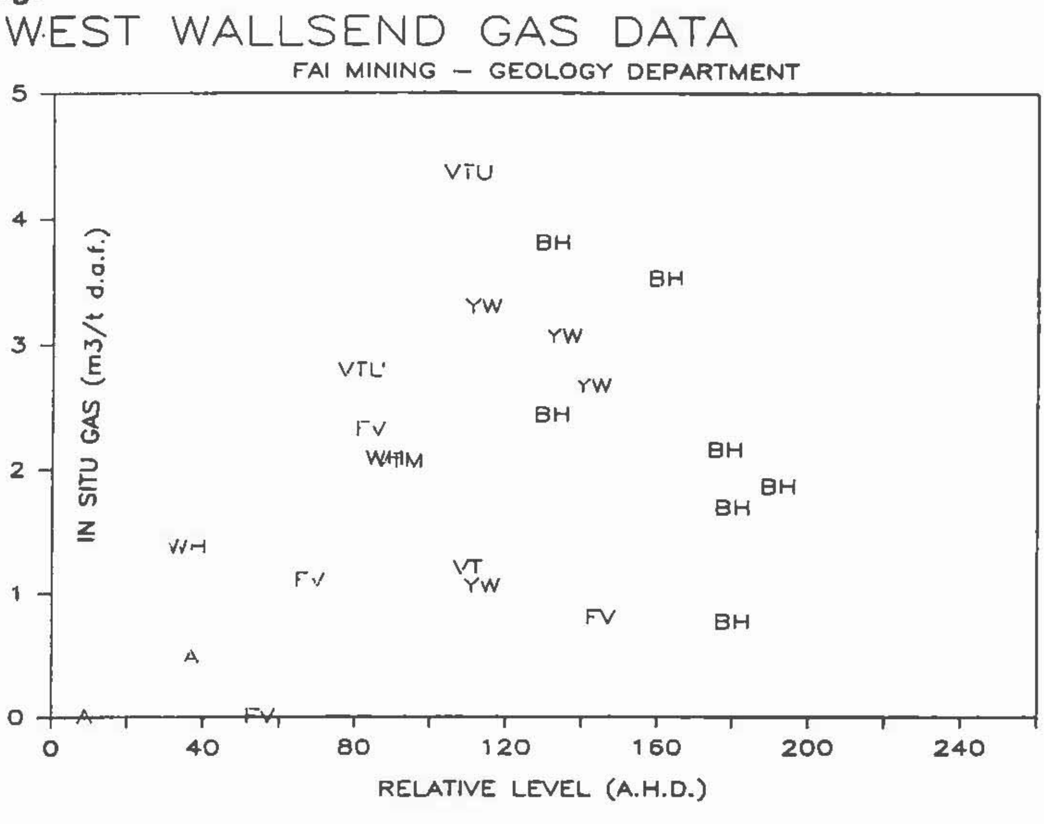
**Figure 4.**



# STRUCTURAL & STRATIGRAPHIC CONTROLS ON THE VARIATIONS IN COAL SEAM GAS COMPOSITION OF THE ILLAWARRA COAL MEASURES, SOUTHERN COALFIELD

**M.M. FAIZ & A.C. HUTTON**
**University of Wollongong**

## INTRODUCTION

The major coal bearing unit of the Southern Coalfield, the **Illawarra Coal Measures**, was deposited in a fluvio-deltaic environment in the Late Permian (Fig. 1). Coal seams in this sequence vary in rank from high volatile bituminous, in the southern and western parts, to medium-low volatile bituminous, in the northern and eastern parts of the coalfield. The seams contain variable amounts of gas, with compositions ranging from almost pure methane to almost pure carbon dioxide.

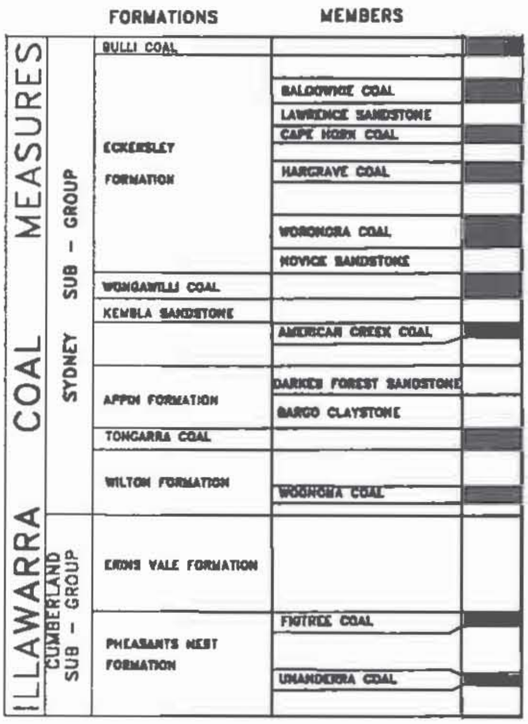



**Fig. 1 Stratigraphy of the Illawarra Coal Measures (Standing Committee on Coalfield Geology in New South Wales, 1971).**

Worldwide experience shows that $CH_4$ is the major component of coal seam gases and $CO_2$ accounts for less than 5 per cent. The occurrence of large amounts of $CO_2$ in the Illawarra Coal Measures is believed to be the result of the introduction of this gas from pneumatolysis (Hargraves, 1963). However, in many areas where large proportions of $CO_2$ are found, a major igneous source is not evident.

The occurrence of a mixed gas environment causes numerous problems in the coal mining industry, e.g., ventilation and gas drainage. Coal seams containing large amounts of $CO_2$ are more prone to gas outbursts. In order to control these problems, a clear understanding of the variations in gas composition is required. Data on the gas composition of coal seams of the Illawarra Coal Measures are now available. These include measurements from surface bore holes and underground mine samples collected by various coal and petroleum companies. This paper presents current research on the variations in seam gas composition, and in particular its relationship to the stratigraphy and geological structure of the Illawarra Coal Measures.

## GEOLOGICAL STRUCTURE

Figure 2 shows the principal structural elements in the study area. The main structural feature is a broad N-S trending syncline with its axis running south from Camden. The eastern flank of this structure is dominated by a series of minor anticlinal-synclinal folds, with axes trending NW-SE. Conversely, the western flank comprises a series of monoclinal folds with small easterly dips. Three main fault directions are recognized:- NW-SE, N-S to NNE-SSW and WSW-ENE (Shepherd, 1990). NW-SE is the most dominant direction of faulting.

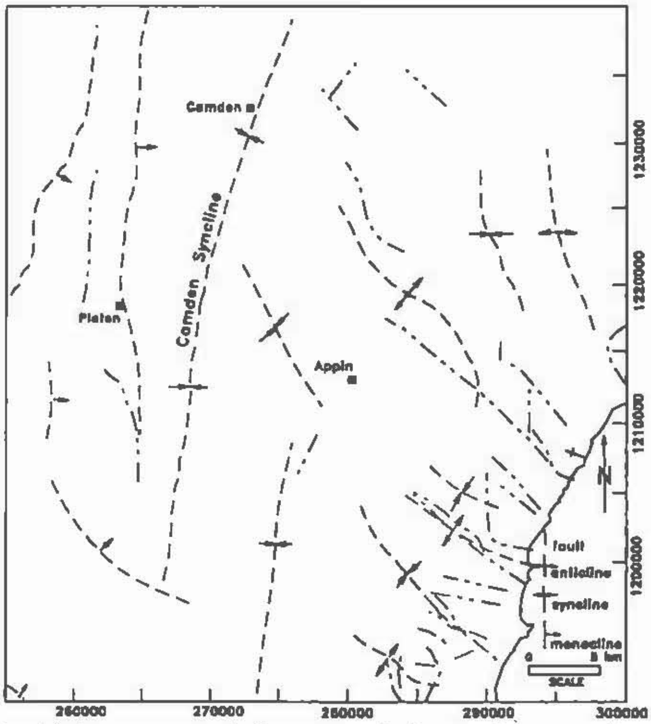



Fig. 2 Major structural features of the study area (based on Sherwin and Holmes, 1986).

Aeromagnetic investigations have indicated that many of the major structural features recognized in the Southern Coalfield (including anticlinal and synclinal structures) are related to block faulting of the basement (Clark, 1990).

## COAL SEAM GAS COMPOSITION

The principal constituents of coal seam gas are hydrocarbons (mainly $CH_4$), $CO_2$ and $N_2$. Over 95 per cent of this gas is retained in coal as sorbed molecules on pore surfaces. The remainder occurs as free gas held within the matrix porosity or as gas dissolved in groundwater. The sorption capacity of bituminous coals is in the order of 20 $m^3/t$ $CH_4$, 10 $m^3/t$ $N_2$ or 30 $m^3/t$ $CO_2$ (Creedy, 1988).

Large amounts of $CO_2$, $CH_4$ and $N_2$ are formed during coalification. Pyrolysis experiments have shown that approximately 104 $m^3/t$ $CH_4$, 55 $m^3/t$ $CO_2$ and

$10m^3/t$ $N_2$ are produced, in addition to a large amount of water, when a coal reaches the medium volatile bituminous rank stage (Rightmire, 1984). In the early stages, coalification is dominated by dehydration and decarboxylation reactions, and as a result higher amounts of $CO_2$ and $H_2O$ are formed relative to $CH_4$. At later stages, dealkylation becomes dominant and consequently increasing amounts of $CH_4$ are formed. Although large amounts of $CO_2$ are produced, most of this gas is removed in solution because of its high solubility in water. Therefore, gas from a bituminous coal typically comprises more than 90% $CH_4$ with the remainder being $CO_2$ and $N_2$. When exceptionally higher concentrations of $CO_2$ are found in coals indications are that it was introduced from external sources, eg. intrusive igneous bodies or deep-seated faults.

Surface bore hole and underground measurements indicate that seam gases from the Illawarra Coal Measures show a wide range of composition, varying from pure methane to almost pure carbon dioxide. Other gaseous components e.g., ethane, propane, butane, nitrogen, hydrogen sulphide, helium, neon, argon and krypton, occur in minor or trace amounts.

Variations in the gas composition may be controlled by many geological factors, e.g., thermal history, stratigraphy and structure. Faiz and Cook (1991) showed that these variations are not related to changes in coal type and rank.

Bulli Coal gas composition, i.e., the ratio $CH_4/(CH_4+CO_2)$ in percent, is shown in Figures 3. Methane is dominant seam gas component in a belt, running N-S along the central part of the study area. On either side of this belt greater amounts of $CO_2$ occur and the variations show a more complicated pattern.

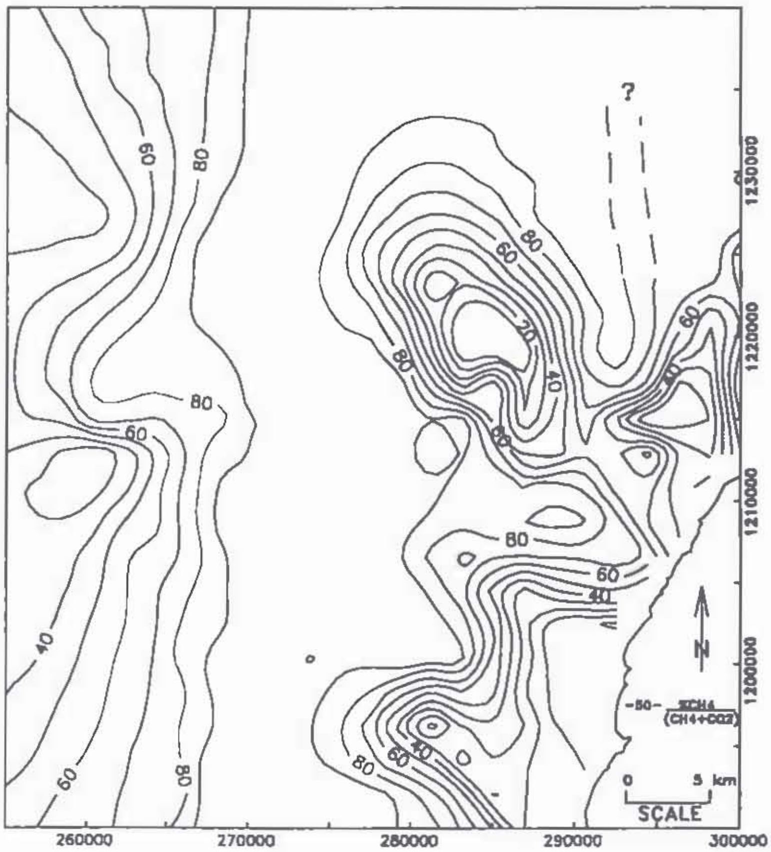



**Fig. 3 Gas composition of the Bulli seam**

## ROLE OF STRUCTURE AND STRATIGRAPHY ON SEAM GAS COMPOSITION

Figure 4 shows a central N-S belt of $CH_4$-rich gas which parallels the main controlling syncline (Camden Syncline). On the eastern side of this syncline, a majority of the $CO_2$-rich areas occurs on structural highs which include anticlinal and horst structures, and increased amounts of $CH_4$ are seen towards synclinal structures. On the western side, the $CO_2$ content gradually increases along the up-dip direction of the monoclinal structures that form the western flank of the Camden Syncline (west of the Nepean Fault zone).

A cross-section through the study area further shows these relationships (Fig. 5). Stratigraphic variations in gas composition show well defined trends (Fig. 6). At a particular geographical location, a gradual decrease in the $CO_2$ content from the upper units to the lower units, including the non-coaly intervals, is commonly seen. At a particular location, the gas of the Bulli and Balgownie Coals comprises greater amounts of $CO_2$ than the underlying Wongawilli or Tongarra Coals. This trend is most pronounced in areas where high amounts of $CO_2$ are present.

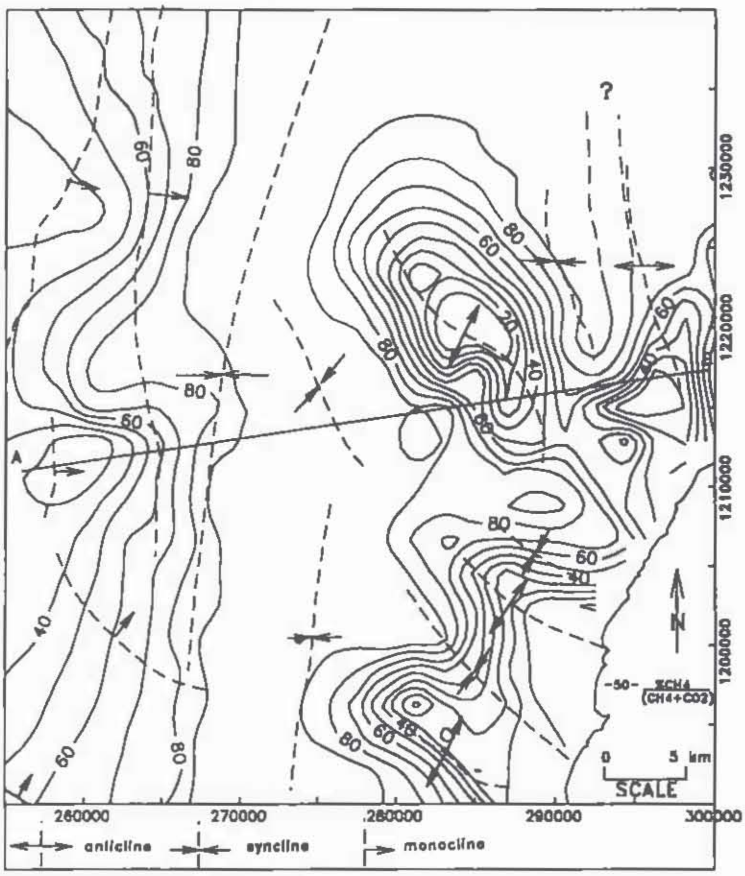



**Fig. 4 Geological structure in the study area and gas composition of Bulli seam.**

## DISCUSSION

It is evident that the regional variations in seam gas composition, show a clearly defined relationship with structure. In general, low concentrations of $CO_2$ occur in structural lows, e.g., Camden, Douglas Park and Novice Synclines (Fig. 5). A gradual increase in the $CO_2$ content is seen along the up-dip direction of anticlines and monoclines and in horst structures. Furthermore, there is a

GAS COMPOSITION - SOUTHERN COALFIELD

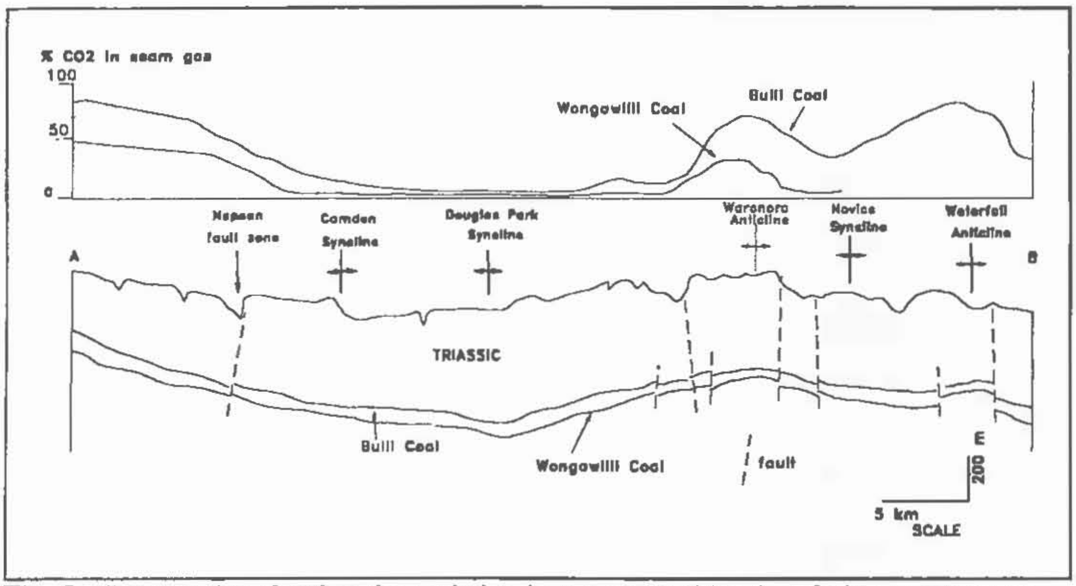



**Fig. 5** Cross-section showing the variation in gas composition in relation to structure.

preferred concentration of $CO_2$ at stratigraphically higher levels, analogous to structural control of gas distribution. These two similar observations indicate that $CO_2$ has preferentially migrated in an upwards direction. However, there are also localized regions where anomalously high $CO_2$ contents occur, which are probably associated with faulting or igneous bodies or both (e.g., Cordeaux and South Bulli Collieries).

Hargraves (1963) suggested that the occurrence of $CO_2$ is related to igneous activity. This view was mainly based on the relationship between isolines of $CO_2$ percentage in seam gas and the igneous sill intruding the Bulli seam at Bulli Colliery. It was also pointed out that in the northern part of the Metropolitan Colliery, the $CO_2$ isolines are sub-parallel to the direction of major faults. Hargraves and Lunarzewski (1985) showed that in the vicinity of a 70 m fault at the Metropolitan Colliery, the gas composition changes from largely $CO_2$, on the upthrown side, to largely $CH_4$ on the downthrown side. The igneous origin of $CO_2$ in $CO_2$-rich seam gases has been indicated by carbon isotope studies (Smith *et al.*, 1985).

Although on many occasions it has been documented that $CO_2$-rich gases are related to igneous intrusions and faulting, there are also many areas in which seam gas is composed of $CO_2$ with no proximity to such features. Furthermore, there are numerous areas where coal is in contact with igneous intrusions and has been thermally affected, but the seam gas comprises almost pure $CH_4$. Reasons for the latter could be that either the intrusion occurred before the main episode of coalification (i.e., before the main phase of $CH_4$ generation) or that insignificant amounts of $CO_2$ were released from the intrusions causing no change in the original gas composition.

Contrary to this hypothesis, it is possible that large amounts of $CO_2$ were also

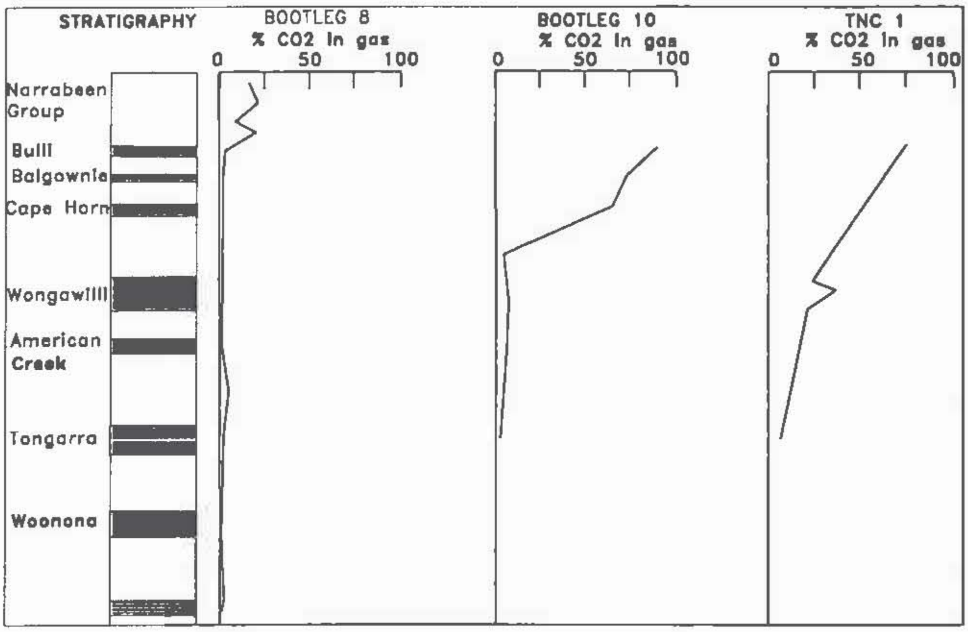



**Fig. 6 Stratigraphic variations in gas composition from selected bore holes.**

introduced into the Permian and Triassic sedimentary sequences of the basin *via* deep-seated faults from the underlying basement or mantle. Based on gravity and magnetic data, Leaman (1990) suggested the existence of a deep-seated mafic layer beneath the Sydney Basin.

It is believed that many of the NW and NNW trending faults in the Southern Coalfield are very deep structures that probably represent reactivation of basement structures due to extensional tectonism associated with the Tasman sea floor spreading in the Early Tertiary period (Lohe and McLennan, 1991). Some dykes parallels this NW to NNW system of faults and these are considered to be contemporaneous with faulting in the Early Tertiary (Facer and Carr, 1979). Therefore, significant igneous activity occurred during the Early Tertiary, together with the emplacement of large amounts of $CO_2$ into the sedimentary succession of the Southern Coalfield from igneous intrusions and *via* deep-seated faults.

The correlation between gas composition isolines and structures would suggest an up-dip migration of $CO_2$ (down a pressure gradient) along permeable strata and coal seams, or along seam boundaries. Stuffken (1957; cited in Creedy, 1988), who studied $CH_4$ content variations in Dutch coal mines, indicated that gas movement in coal seams is an in-seam process. Gas migration usually takes place *via* two pathways:- diffusion and in solution. Diffusion of gas in coal, however, is a very slow process and the long distance migration of $CO_2$ towards structural highs, by diffusion along coal seams, is arguable.

The Sydney Basin experienced a major episode of rapid uplift in the Late Tertiary which resulted in the loss of up to 1 km or more of sedimentary cover (Branagan, 1983; Middleton and Schmidt, 1982). During uplift, an opportunity for gas migration may have occurred due to significant reductions in the confining stresses and pressures which resulted in the formation of an open cleat network within the seam (subsequently closed by mineralization). Due to its higher solubility and desorption properties, $CO_2$ could have migrated more readily than $CH_4$ towards structural highs down the pressure gradient. Another possibility is the migration of $CO_2$ along the permeable strata (e.g., sandstone) towards structural highs and then the subsequent vertical diffusion into the adjacent coal seams.

## SUMMARY

Coal seam gases of the Illawarra Coal Measures show a wide range of composition, ranging from almost pure methane to almost pure carbon dioxide. Regional variations in the composition show a good correlation with the geological structure. High levels of $CH_4$ are usually associated with structural lows with increasing amounts of $CO_2$ occurring towards structurally higher levels. Furthermore, the inter-seam variations indicate that at a particular geographical location, the highest concentration of $CO_2$ is found in the top-most seam (i.e., Bulli Coal) with a gradual decrease in the $CO_2$ percentage with increasing seam depth.

It is believed that most of the $CO_2$ presently occurring in coals is of volcanic origin and was probably introduced from igneous intrusions and *via* deep-seated faults during Tertiary or Jurassic volcanic events.

It is suggested that further detailed work be carried out in other parts of the world where $CO_2$-rich gases are encountered in coals to identify any similar structurally-related $CO_2$ occurrences.

## ACKNOWLEDGEMENTS

The authors wish to thank The Australian Gas and Light Company., BHP Steel International, Collieries Division (Illawarra), Kembla Coal and Coke Pty. Ltd., Metropolitan and South Bulli Collieries for providing most of the data used in this study. Special thanks are due to Prof. A.C. Cook, Drs. B. Agrali, R.D. Lama, I. Stone and D. Titheridge, MESSRS J. Anderson, B. Clark, J. Goodall, J. Hanes, P. Lamb, P. Maddocks, and J. Wood, and staff of the Geology Department, University of Wollongong for their support throughout this research project. The valuable assistance of MESSRS M. Perkins and A. Depers with computing work and editing is greatly appreciated.

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# ?PSEUDOKARST IN THE SYDNEY REGION

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**The University of Sydney**

## INTRODUCTION

The Sydney region consists essentially of Triassic rocks containing a high proportion of silica. Naturally occurring soluble materials are quite rare.

It is therefore surprising that a number of karst-like surface and subsurface features occur in the region. The features are widely scattered and occur at several stratigraphic levels and in different topographic situations ( Fig. 1 ). This is a very preliminary outline of these interesting topographic features, some of which have been referred to briefly by Jennings ( 1983 ).

## COASTAL FEATURES

Two coastal features occur in the Newport Formation, at North Avalon, north of Sydney. These are St. Michael's Cave, and The Ovens. The former is well-known, but its origin is still debated, the latter is a less-easily accessible but quite extensive narrow cave, about .5km to the north.

St. Michaels Cave has an entrance well above present sea-level, but the cave floor descends from the entrance to a level not much above sea-level, and the rock platform immediately in front of the cave is cut into by an indentation. The sides of this channel are marked by strongly sheared rock, in the nature of close spaced jointing. The eroded channel is usually interpreted as formed by the removal of dyke rock, and that the cave owes its formation to the undercutting of the dyke with consequent widening and deepening by collapse of walls and roof. The present shape ( plan ) is shown in figure 2, while an approximate long section is shown in Figure 3. Large rock falls from the roof about five years ago caused the access to the cave to be restricted by the local council, largely on the basis of its possible responsibility for any injuries sustained. There are some iron- rich speleothems in this cave.

St. Michaels Cave has always been something of an enigma because of the nature of the material which fills the vertical "dyke". It is quite unlike the usual compact weathered basalt found in dykes in the region, and present in dykes just a few hundred metres to the north. It has been variously described as soil which has filled an eroded dyke from above, or as breccia derived from an explosive eruption similar to the material found in diatremes such as Hornsby

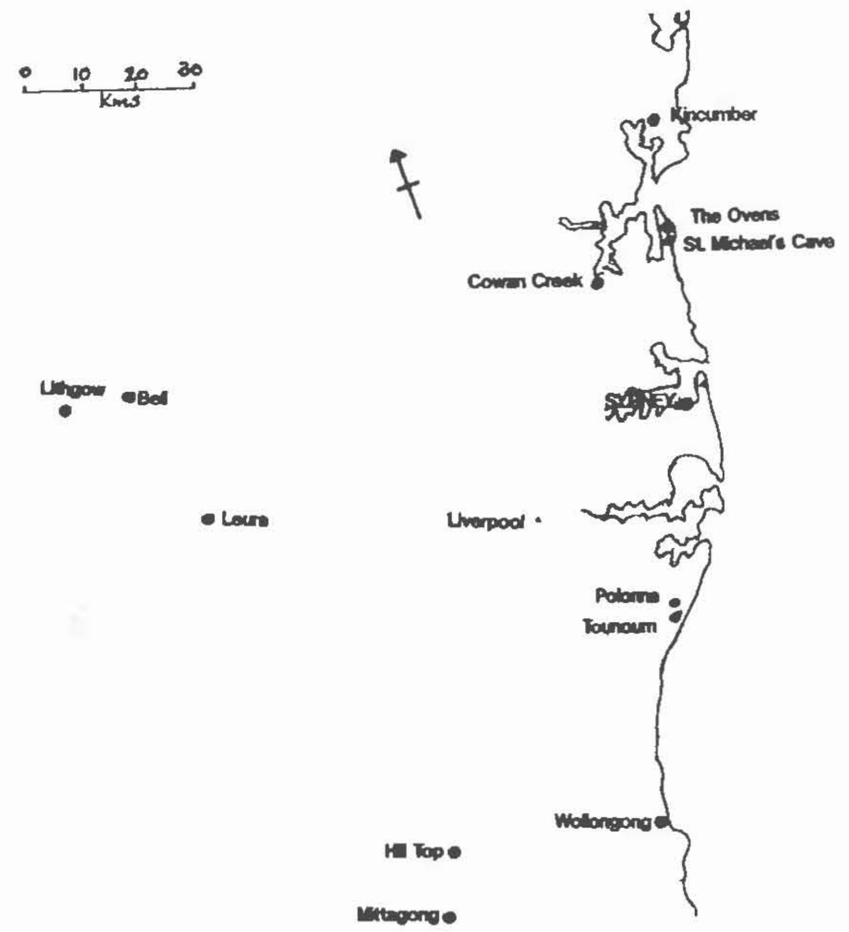



Fig.1 LOCALITY MAP SYDNEY REGION ? PSEUDOKARST

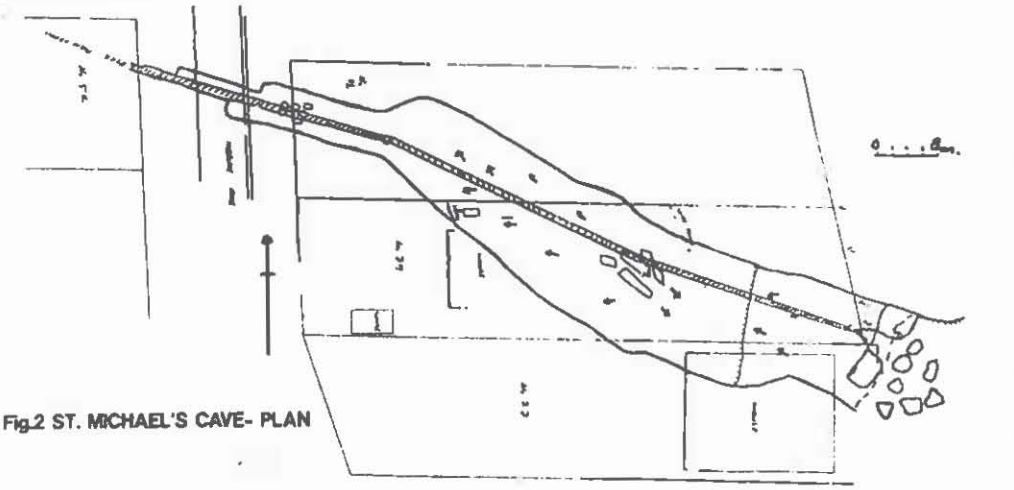


Fig.2 ST. MICHAEL'S CAVE- PLAN

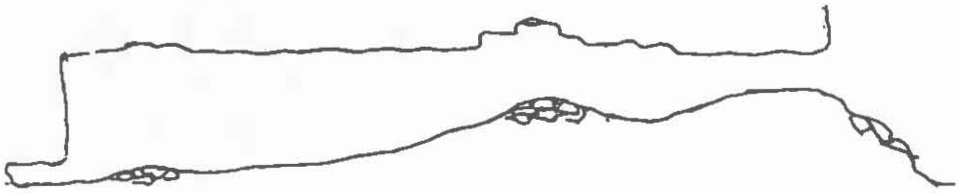


Fig.3 DIAGRAMMATIC LONG SECTION - ST. MICHAEL'S CAVE

and Minchinbury. L.Hamilton ( pers. comm. ) leans to the latter opinion, as does our examination of thin sections. While erosion has clearly played a major role in the formation of this cave, we believe that solution has been involved to some extent.

The Ovens ( Figs. 4 & 4a ) is a more typical "sea-cave" with its base at sea-level at the entrance, but further into the cave cross-sections indicate that it has been cut well below present sea-level. However the cave also contains evidence ( such as the wide notch above the present sea-level on the cross-sections, and attached marine organisms ) of higher sea-level.

The plan of this cave is quite similar to that of St Michaels Cave, suggesting a similar origin, erosion of soft material, but there is no dyke material present. Carbonate speleothems are present and calcite is common in vertical fractures associated with dykes in the adjacent rocks.

There are other sea caves along the Sydney coast ( e.g. at The Gap ) and within Sydney Harbour ( e.g. Clontarf ), many of which seem to be associated with prominent zones of shearing as described by Branagan et al ( 1988 ).

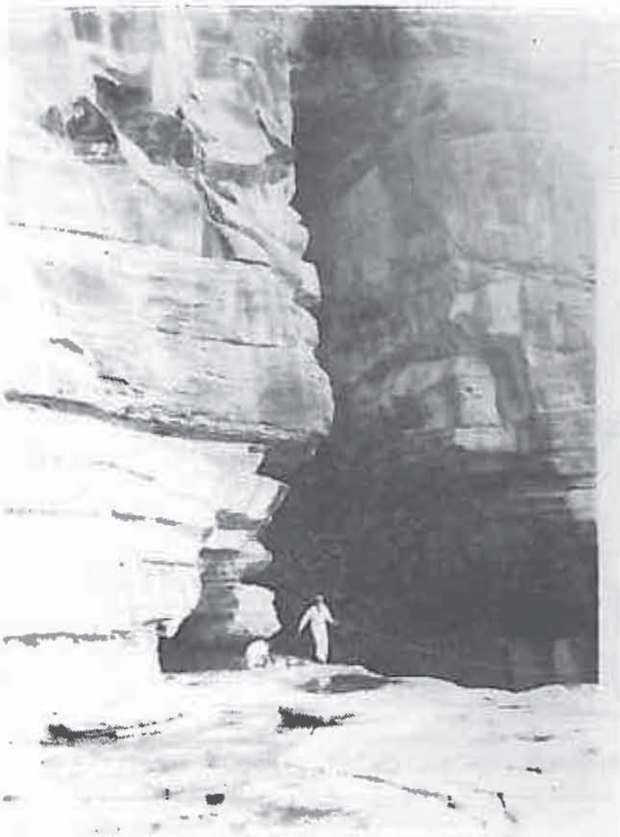


Fig.4a ENTRANCE to THE OVENS

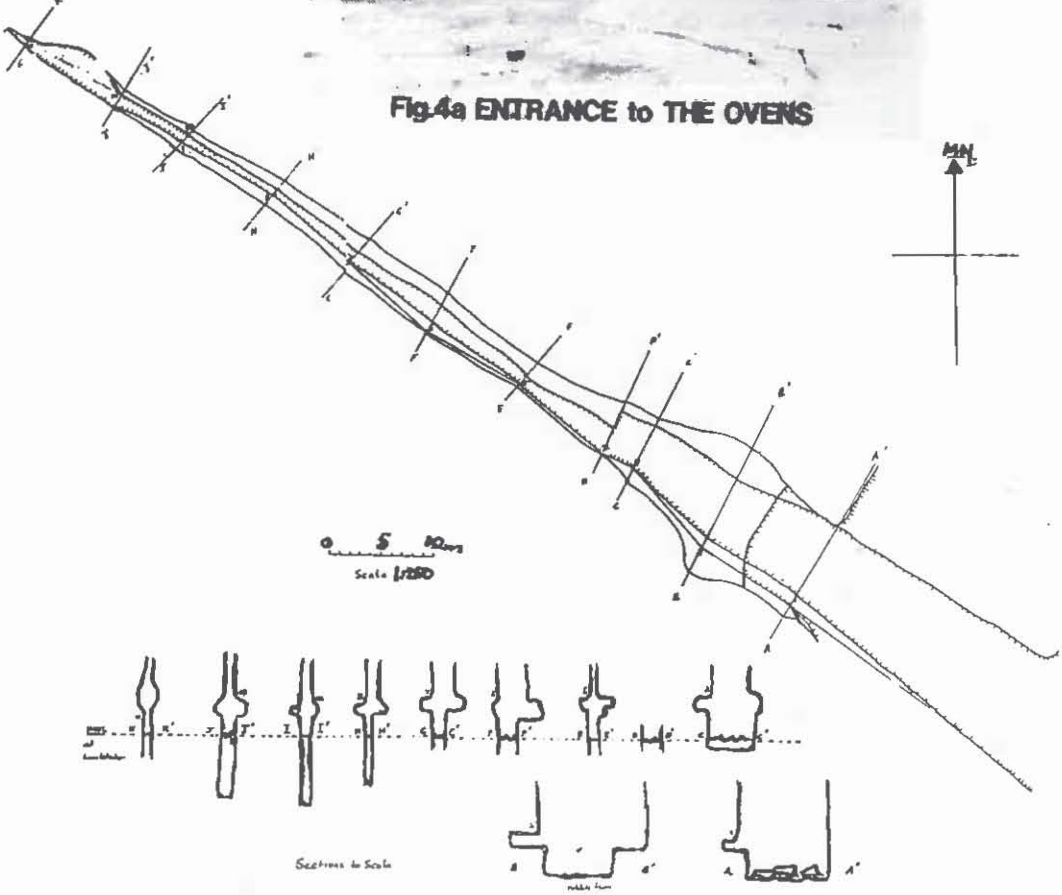


Fig.4 THE OVENS - PLAN and CROSS-SECTIONS

## ROYAL NATIONAL PARK

Two occurrences in the Royal National Park, south of Sydney, occur at about the same stratigraphic level as those at Avalon. Like St. Michael's Cave they occasionally attract attention in the popular tourist literature. Polonna Cave is better known, because of the easier access. It has been briefly descibed by Lovering ( 1951 ). It is an overhang with numerous phototrophic speleothems The surrounding rocks contain evident carbonates (?mostly siderite). Tounoum Cave is a small cavern also containing speleothems.

"Caves" showing some resemblance to Polonna Cave are known from Roseville Chase, North Sydney, and Ku-ring-gai Chase, but these occur within the Hawkesbury Sandstone.

## TUNNELS

Tunnel Walk at Hill Top, near Mittagong, is an active relatively long ( 85m ) through cave in Hawkesbury Sandstone, just below the overlying the Mittagong Formation ( Figure 5 ). This lithic sandstone unit may contain carbonates in places.

A similar tunnel, 60m long, near Cowan Creek is mentioned by Jennings ( op cit ) based on a report by Pavey ( 1975 ). Endless Cave, Kincumber, is a 35m long and intermittently active outflow cave fed from small solution tubes ( Jennings op cit ). Although Jennings states these are all in Hawkesbury Sandstone, the last two named may be in Narrabeen rocks.

Overall there are many reports, widely scattered, and mostly in popular literature, of caves and tunnels in the sandstones of the Sydney region, and there has ,to date, been no systematic study of these interesting natural features and their mode of formation.

## BLUE MOUNTAINS

Perhaps most interesting are the large tubes which occur in siliceous Narrabeen Group sandstones in valleys of the Blue Mountains. Networks of tubes at least several hundred metres in extent, lined with hard iron oxides, have been examined at Leura ( Figure 6 ). Newspaper reports of these caves and their

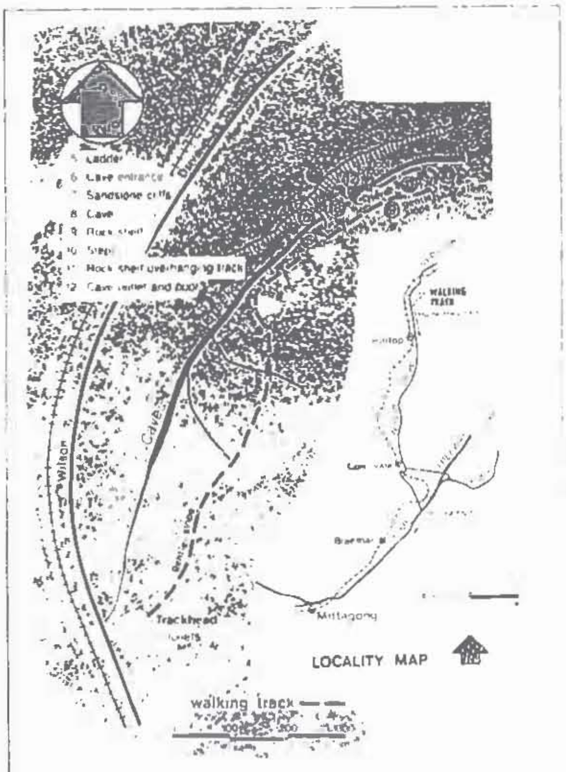
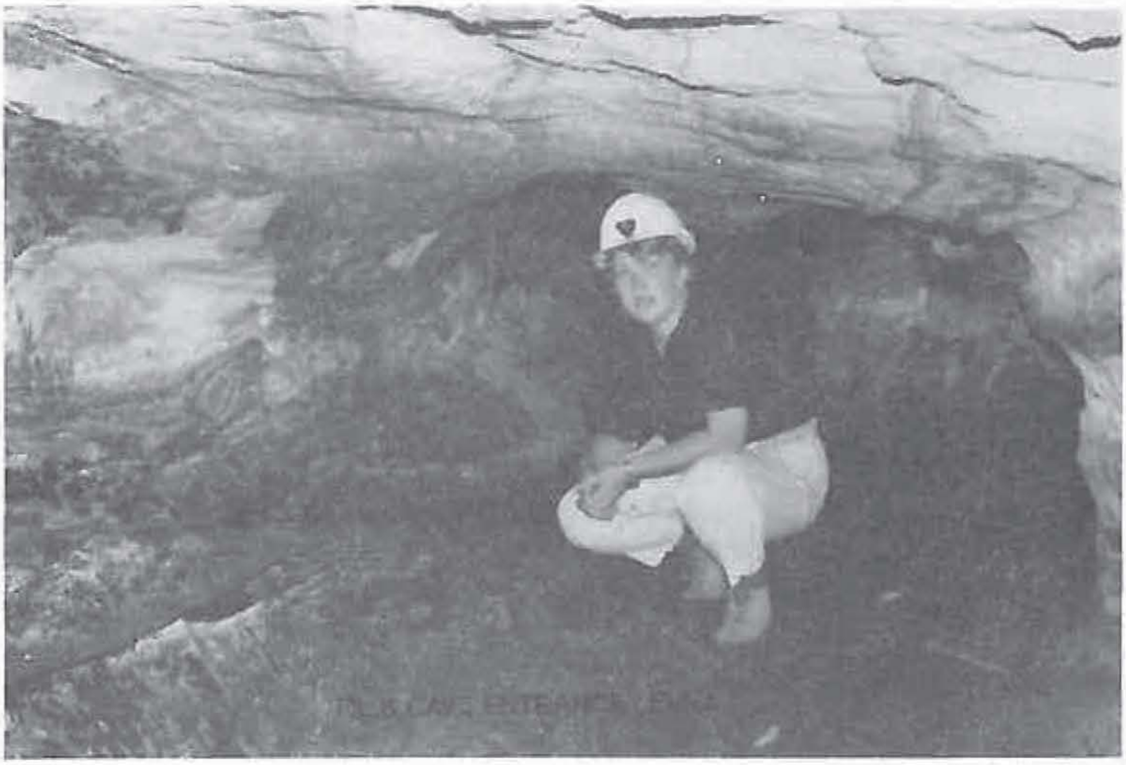



Fig.5 TUNNEL CAVE, HILL TOP (after Dept of Lands)



examination ( 1904, 1926 ) give some details of their nature, together with highly coloured material on their likely use by convicts, bushrangers, and sundry conmen. These caves appear to be the result of solutioning, although they are not presently active.

Other sites, possibly at the same stratigraphic level, occur, as indicated on some topographic maps of the region, and in tourist photos, but they have not yet been examined by us. These probable solution structures may be related to the extensive iron concretions which occur in the western Blue Mountains. The concretions, which are the result of iron migration, ( "Liesegang" patterns), often take the form of pipe-like bodies up to 1m in diameter. A combination of solutioning and direct erosion of poorly cemented sand grains from within such concretions seems to have occurred. Jennings ( op cit ) suggested that under certain conditions silica solubility could cause cavitation. This is supported by other workers, although James ( pers. comm. ) believes that many processes may have operated concurrently in the Sydney region and elsewhere, and that the dominant process cannot be readily determined. She suggests that some answers may be given by a detailed study of the Canyon country in the northern Blue Mountains.

There are several "blind valleys" in the Blue Mountains: these and the interesting "Pagoda" region north of Bell ( Figure 1 ) may be the result of karst-producing processes. The "Pagoda" region shows some similarities to Ruined City, Arnhem land descibed by Jennings ( op. cit.).

## CONCLUSION

There are many and variable cave-like features throughout the dominantly siliceous rocks of the Sydney Basin, including the coal measures and marine Permian rocks, which are not discussed in this paper. The age of the karstification is possibly Tertiary, but it may vary for different features and different localities. Much more research is called for on these interesting and quite widespread features.

## ACKNOWLEDGEMENTS

Discussion with colleagues at a karst conference held at Buchan, Victoria in February 1992, organised by Dr. John Webb of Latrobe University, was helpful in clarifying some of our ideas on this subject. Professor E. Hamilton-Smith provided some interesting historical photographs.

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# SEISMIC EXPLORATION IN A DIFFICULT ENVIRONMENT

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## 1. INTRODUCTION

Kembla Coal and Coke Pty Limited produces a high quality coking coal from underground mines in the Bulli Seam near Wollongong. The coal seam is overlain by about 500 metres of Permian and Triassic sediments and is known to be intersected by several fault systems.

The company commenced longwall mining at West Cliff Mine in 1982. In 1984, mining operations were severely disrupted due to the unexpected intersection of a 10 metre fault in a longwall gate-road.

This event, and its expensive consequences, has provided KCC with a strong impetus for trying to obtain accurate long term structural data for mine planning purposes. Surface reflection seismic is the only currently available technique capable of providing the required detail.

However, access to the surface in the lease area is often difficult. The majority of the area occurs in rugged bushland, partly water catchment and partly included in the Register of the National Estate. The more or less accessible plateau area is dominated by stunted eucalypts with an understorey of sparse to very dense small trees, shrubs and grasses. The plateau area also includes heathlands that are often permanently waterlogged.

The area is dissected by several major creeks that have incised up to 100 metres below the plateau level to form inaccessible steep-sided gorges typically 200-500 metres wide. They generally comprise a series of sandstone bluffs ranging from less than 5 metres to over 30 metres, which descend from the plateau down to creek level. Vegetation within the gorge is dominated by tall Eucalyptus and Angophora species. Vehicle access is limited to the dry plateau areas (see Fig. 1).

Obtaining high resolution seismic data in this environment required innovative approaches and substantial modifications to previously used methods.

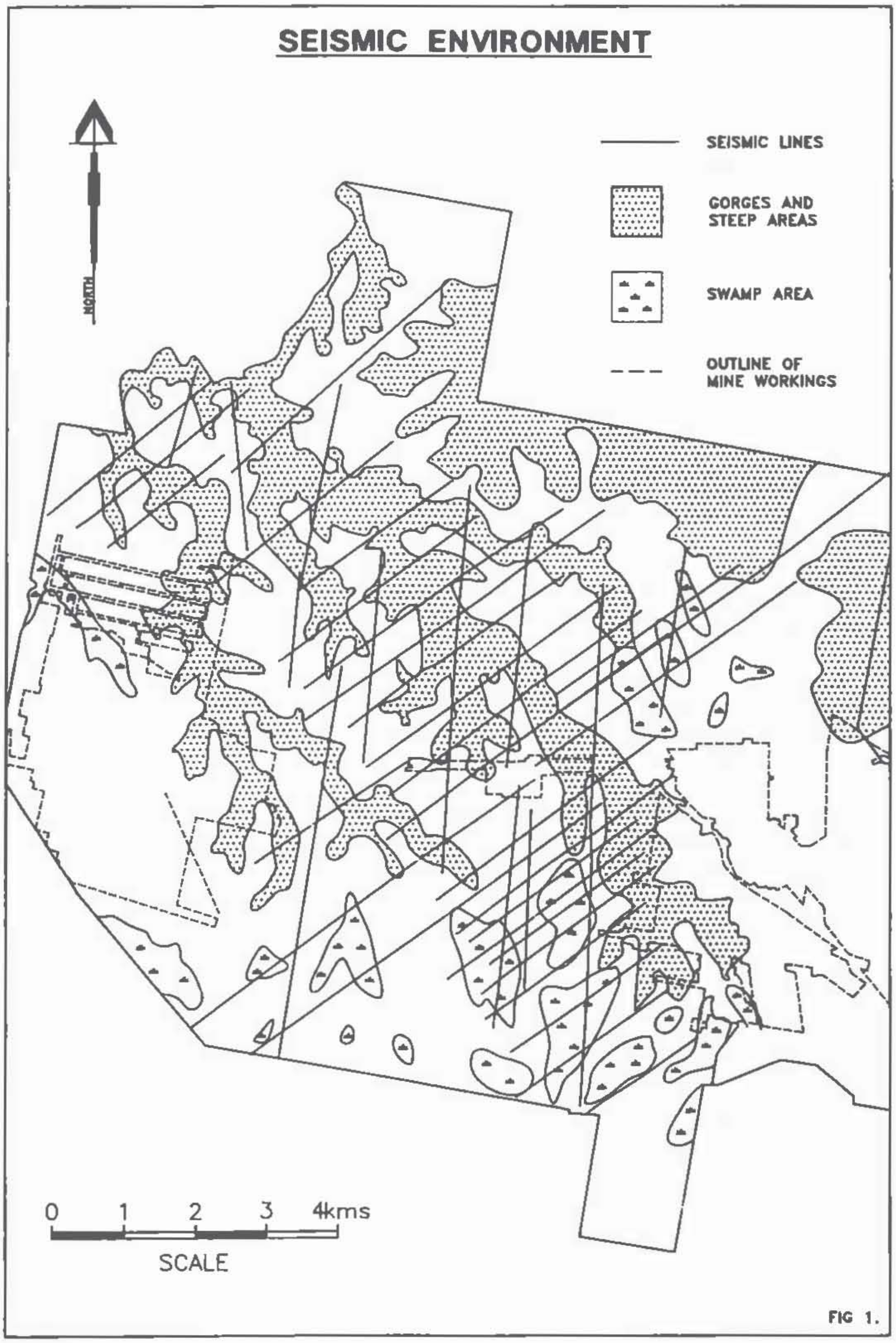
SEISMIC ENVIRONMENT
NORTH
SEISMIC LINES
GORGES AND STEEP AREAS
SWAMP AREA
OUTLINE OF MINE WORKINGS
0 1 2 3 4kms
SCALE

FIG 1.

SEISMIC EXPLORATION IN A DIFFICULT ENVIRONMENT

## 2. NATURE OF CHALLENGE

Prior to 1989, seismic exploration had been confined to the areas of the plateau accessible to vehicles. This had failed to sufficiently define seam structure in potential longwall areas. It became necessary to obtain high quality and high resolution seismic data from the sensitive gorge and heathland, as well as from the more accessible areas.
Certain field requirements were necessary to carry out high resolution seismic work.

- Seismic lines had to be essentially straight, with accurately surveyed locations for each geophone station along the line.

- Access was required for drilling rigs to drill shotholes every 24 metres along the line. Previous tests had determined that best results were obtained by drilling below the interpreted base of weathering defined by a separate refraction survey. Shothole depths ranged between about 8 and 30 metres and required a hammer drill with compressor to efficiently and economically drill the hard, damp and sometimes clayey sandstone.

- Light vegetation along the lines had to be cut to avoid excessive noise caused by rustling of grass and small bushes, which would interfere with the seismic recording. At the same time it was necessary to retain cover and root systems to avoid localised erosion problems which would be difficult and expensive to repair.

- Refraction and reflection recording required hand portability or modification of equipment to enable access to difficult areas.

***A prime prerequisite for the seismic programmes was a works plan which prevented permanent damage to the fragile and sensitive environment.***

## 3. APPROACH TO THE CHALLENGE

Before any detailed planning could be undertaken it was necessary to locate suitable equipment to access the sensitive areas.

Canterra CT 300 heliportable drills with downhole hammers capable of drilling the hard sandstones were located in New Zealand. A helicopter of suitable capacity with a pilot experienced in sling work, was needed to lift the rigs from site to site in the inaccessible areas. In the most recent programme a helicopter was mobilised from Canada.

In the more accessible plateau areas, Air-trac drills, mounted on tracks and having compressors equipped with low pressure balloon tyres, were used to drill the shotholes.

For clearing lines, where machine access was feasible, a traxcavator was used to prepare access for the air-trac drills and recording crews.

Hand portable refraction equipment was obtained for recording refraction data.

For reflection recording, substantial extension cables were required to connect the recording truck, located on the plateau, to the geophones and shots in the gorge. (In 1991, a telemetry recording system was used. This equipment enabled the recording truck to be located up to 1.5 km from the 'live' geophones).

For general access and provision of materials and equipment to the seismic lines, John Deere or Yamaha Quad lightweight, balloon tyred, all terrain vehicles were used.

Prior to the commencement of field work, expert external advice to minimise the environmental impact was obtained from forest and land conservators, on appropriate methods for line clearing and restoration to be adopted.

## 4. THE FIELD OPERATIONS

On-site planning involved an examination of aerial photographs to try and reduce access to the more sensitive and rugged sections of the line.

A preliminary traverse was then made by the survey crew along the proposed route of the seismic line. The flagged route was followed by the botanist and archaeologist who identified rare species or sensitive plant groups and potential or actual archaeological sites. The sites and areas of sensitive vegetation were cordoned off to ensure that they were not disturbed during the course of the seismic survey.

A sketch plan produced by the surveyors during the initial traverse was then used to determine the type of equipment to be used in clearing the various sections of the line.

On plateau areas with relatively gentle topography, lines were generally cleared using a traxcavator. The clearing was carried out under the supervision of the surveyor and care was taken to remove only the vegetation necessary to obtain the required access and to conduct the seismic survey. Larger trees were generally avoided and every possible attempt was made to avoid unnecessary disturbance of soil and to retain the existing root systems.

Where tree cover was thin and conditions allowed, a mower/slasher was successfully used to mow grass and small shrubs, instead of using the traxcavator.

In sensitive areas unsuitable for machine clearing, only hand clearing was carried out.

To reduce weight pin flags were used in surveying instead of pegs. Accurately surveyed pin flags were placed at regular, close intervals along the seismic lines to allow accurate location of shotholes and geophones. In the survey just completed (1992) it was necessary to place and survey 17,000 pin flags.

SEISMIC EXPLORATION IN A DIFFICULT ENVIRONMENT

Portable refraction equipment was used to record refraction data for determination of shothole depths. The equipment was backpacked in and out of the gorge and other inaccessible areas.

Prior to drilling shotholes in the gorge areas it was first necessary to selectively lop branches from the tall trees near each of the drill sites to ensure safety in lowering and lifting out drilling equipment by helicopter.

Throughout the latest survey, access along seismic lines (other than by drills) was restricted to the John Deere and Quad all terrain vehicles which provided support for the various facets of the operation.

In order to ensure that erosion did not occur during the course of the seismic survey, rows of sandbags were placed across the lines at strategic locations shortly after clearing. These diverted drainage away from the seismic lines and into surrounding bush.

Immediately after all work was completed final restoration work was carried out. First, all pegs, detonator wire and other survey debris were removed. Then, further drainage control measures were introduced in the form of small earth banks or rows of sandbags. The earth banks were constructed by a mini-excavator on rubber tracks with very low ground pressure. This excavator was able to easily access virtually all plateau areas with negligible impact.

Finally, brush and seed heads were hand cut from the adjacent bush and placed across the seismic lines. This provided seed, shade and moisture retention for seedlings, and leaf mulch. It had the additional benefit of discouraging further access to the seismic line.

## 5. REGENERATION

In the smaller seismic programmes confined to plateau areas conducted in 1987-88 some small localised problems had been experienced as a result of over-clearing. These have required remedial work comprising further drainage control followed by seeding with local species and annual grasses. Additionally, these areas were covered with straw mulch to prevent erosion and encourage the re-establishment of vegetation cover.

Elsewhere lines completed in this period are now regenerating satisfactorily.

The clearing and restoration methods developed during the 100km survey carried out over 1989-90 represented a substantial step forward. Many of the gorge and swamp lines are now barely distinguishable due to their almost complete regeneration. Regeneration in the plateau areas has been slower, partly due to very dry conditions throughout most of 1991. However, regeneration is now proceeding well following recent wet weather.

Further improvements introduced into the seismic survey in 1991 have resulted in substantially less damage on seismic lines due to a reduction in traffic using the lines. It is expected that regeneration of recently completed lines will be more rapid than previous lines.

## SUMMARY AND CONCLUSIONS

KCC has now carried out over 200kms of seismic line over the past 5 years. Of this, nearly 150km has included the rugged gorges and sensitive swamps.

The clearing and restoration methods described in this paper have evolved over the course of several separate seismic programmes during the past 5 years.

Evidence to date indicates rapid regeneration of the sensitive gorge and swamp environments, such that many sections are barely distinguishable less than 2 years after completion. Plateau areas are now showing good signs of regeneration. These will continue to be monitored but complete regeneration is expected within a few years.

It is believed by the authors that the methods developed over the past 5 years, in response to the challenge, should enable future seismic surveys to be used in this most sensitive environment without permanent damage resulting.

## ACKNOWLEDGEMENTS

The authors wish to thank Kembla Coal and Coke Pty Limited for permission to publish this paper. The substantial technical contribution of Peter Stuckey is gratefully acknowledged. Thanks also to David Olsen and David Titheridge for their constructive reviews.

# WRENCH-FAULTING IN THE WESTERN COALFIELDS

IAN POPPITT
Coalex Pty Ltd

ABSTRACT NOT AVAILABLE AT TIME OF PRINTING

# SITE UNIFORMITY BOREHOLE SEISMIC (SUBS©) TESTING IN UNDERMINED AREAS

**R.J. WHITELEY & A. LOVE**
**Coffey Partners International Pty Ltd**

## INTRODUCTION

Conventional geotechnical studies of undermined areas normally involved grid drilling or closely spaced drilling to locate collapsed or cavernous zones. This approach is rarely cost-effective and it is usual for such drilling to achieve only a 10 to 20% probability of detecting an opening.

Recently Coffey Partners International Pty Ltd developed a downhole-to-surface seismic method to assist geotechnical studies in undermined areas. This test called Site Uniformity Borehole Testing (SUBS©), is designed to increase the effective radius of investigation of a single borehole and to detect any laterally changing conditions around a borehole. SUBS© testing uses seismic energy to assess variations in ground conditions radially around the hole to distances approximately equal to the borehole depth.

A principal advantage of SUBS© testing is that it is a non-destructive test and can be easily and rapidly performed once the hole has been completed. It is desirable that the drill holes be completed through the geological horizons of internal.

### Operational Procedure

A 12-channel seismic detector array with hydrophones at 2m intervals (Figure 1) is lowered in an uncased PVC cased or PVC cased hole (if collapse is expected) with a minimum internal diameter of 500m. Seismic coupling to the surrounding earth is achieved by filling the hole with water or drilling fluid.

The in-hole detector array remains fixed throughout the test and an interval of up to 22m of the borehole can be tested at one time to depths in excess of 100m. Seismic energy is generated at the surface, usually with an impact source such as a hammer. (Figure 1). If this is close to the collar of the hole then a vertical seismic profile is obtained which can be correlated with the

the hole. The seismic source is then successively placed at closely spaced locations around the borehole at increasing distances up to at least the depth to the deepest detector. This provides a radius of investigation (really an effective cone of investigation) for the SUBS © test which is approximately equal to the hole depth.

## Theory of SUBS © Testing

Seismic waves which travel from each surface source point at varying angles to the in-hole detector array are recorded on a digital seismograph and stored on computer disk for later processing and interpretation using computer seismic ray tracing. Figure 2 shows a schematic diagram of the propagation of the seismic energy for two equidistant source locations $S_1$ and $S_2$. The travel-times of the first arrival P-waves from a surface source to a down-hole detector are controlled by the elastic properties of the earth materials and the distribution of subsurface interfaces. In Figure 2 the travel times to a detector at point R from the sources at points $S_1$ and $S_2$ are $T_{S1R}$ and $T_{S2R}$ respectively.

Should the subsurface conditions or elastic properties vary laterally around the borehole within the effective cone of investigation, for example as a result of prior excavation or mining, then the travel-times to each subsurface detector will be different for the seismic source at the same distance on either side of the hole. Any condition which weakens the rock will normally lead to a scattering of the seismic wave and a delay in its travel-time. For example, for the mine workings shown in Figure 2, $T_{S1R}$ will be less than $T_{S2R}$. Surface seismic refraction testing centred on the borehole accounts for lateral soil or rock variations.

## Example of SUBS © Testing

SUBS © testing was completed to assist the assessment of the likelihood of old bored and pillar coal mine workings and shallow depth, less than 30m, below an area in East Maitland proposed for residential development.

A borehole, BH4, was specifically drilled to "calibrate" SUBS © testing in this environment over known old workings. Figure 3 shows an interpreted vertical seismic profile at BH4 together with the seismic velocities and lithologies obtained from the geotechnical log. Coal was intersected near the bottom of this hole. It can be observed that the seismic velocities in the sandstone and siltstone roof works are quite low in the range 900-1450 m/s suggesting that they are goafed.

SUBS © testing and surface seismic refraction profiles were completed along two orthogonal lines centred in BH4.

Figures 4 and 5 show the travel-time plots obtained from the SUBS © testing along the NS and EW profiles. For convenience, these have been plotted in a manner which combines the first arrival seismic data from the individual sources to single downhole receiver at different depths from 1.5 to 15.5m.

It can be observed from these data that the travel-times are different in two directions. This indicates that the earth is laterally inhomogenous around BH4. In particular, the travel-time is obtained along the NS profile beyond offsets of about 8m from BH4 are considerably delayed on both sides of the hole. This suggests a major low velocity zone striking approximately in this direction.

Computer ray-trace modelling (Whiteley, 1990) was undertaken on the date shown in Figures 4 and 5 and using a near-surface model obtained from hammer refraction across BH4.

Figure 6 shows the results obtained for the receiver at 15.5m depth. The synthetic travel-time data fits the EW field times using a uniform subsurface with a velocity of 1450m/s. In Figure 7, a lateral variation within the deepest layer and a reduction in velocity to 900 m/s is required to obtain a reasonable fit of the synthetic to the field travel-time date.

This indicates that the earth near at BH4 has been severely affected by undermining and that major cavernous zones occur in the general EW direction. The location at BH4 would not be considered suitable for normal residential construction.

## CONCLUSIONS

The SUBS© test the radius of investigation of geotechnical boreholes and assists in the assessment of subsurface conditions and of the detection of ground affected by shallow underground mining.

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## Figures

Figure 1

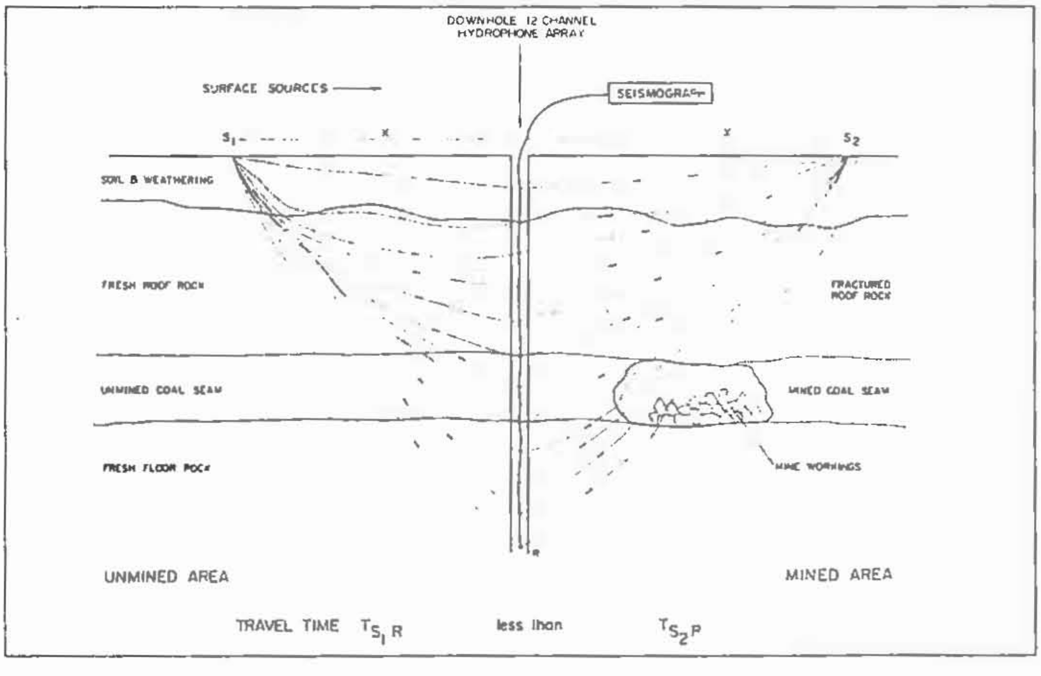



Figure 2

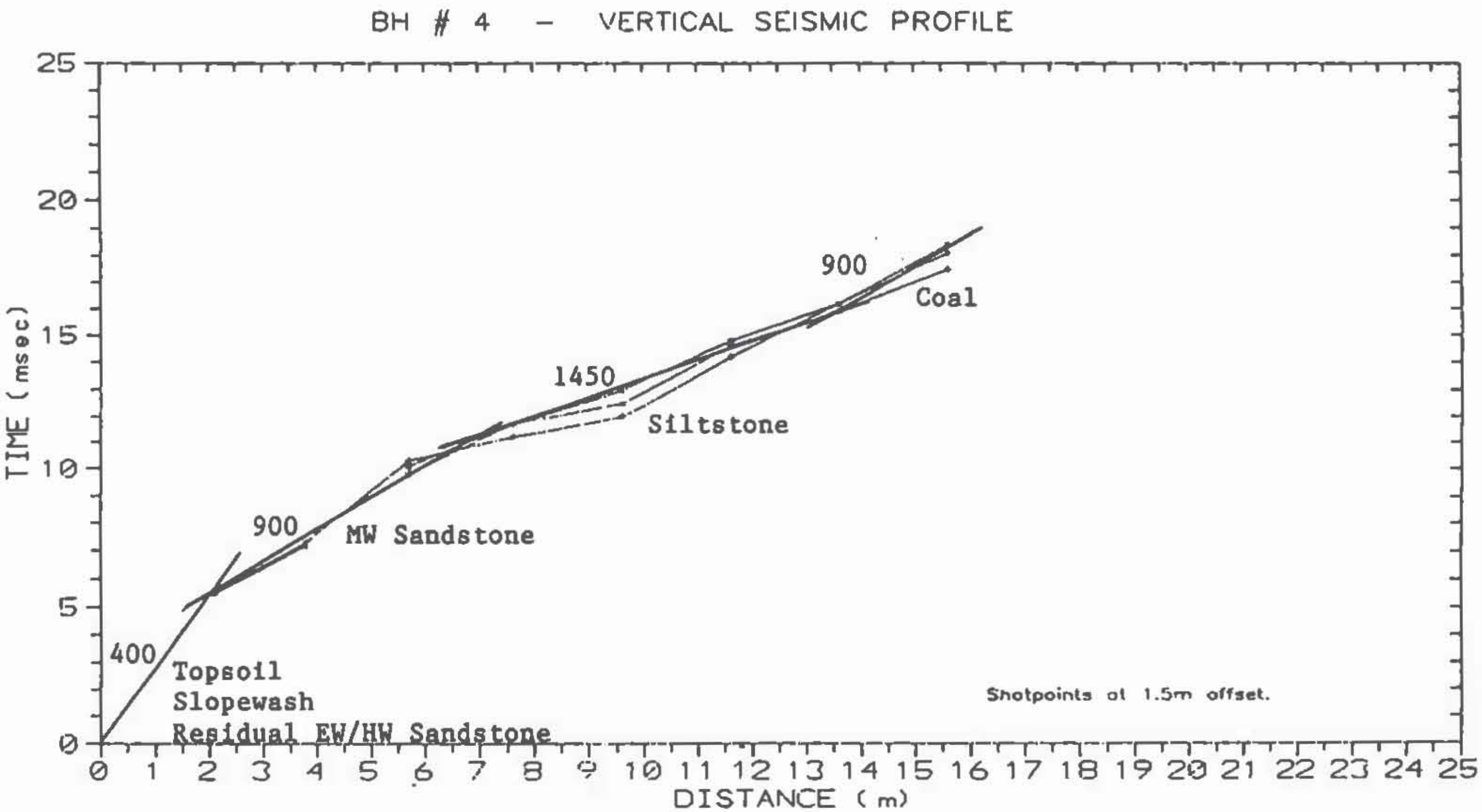

BH # 4 - VERTICAL SEISMIC PROFILE
TIME ( msec)
DISTANCE ( m)
400
Topsoil
Slopewash
Residual EW/HW Sandstone
900
MW Sandstone
1450
Siltstone
900
Coal
Shotpoints at 1.5m offset.

Figure 3

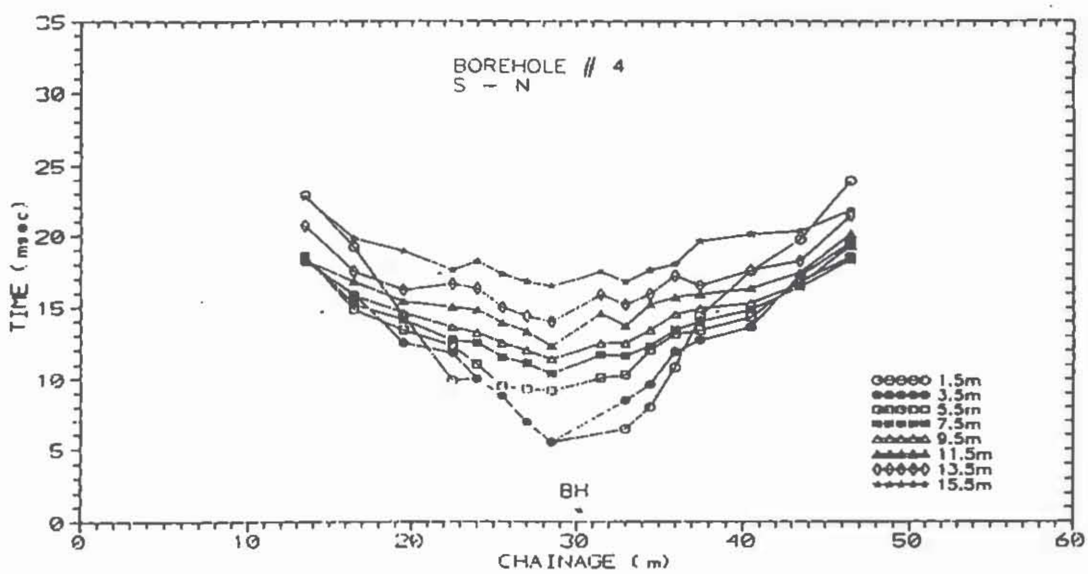



Figure 4

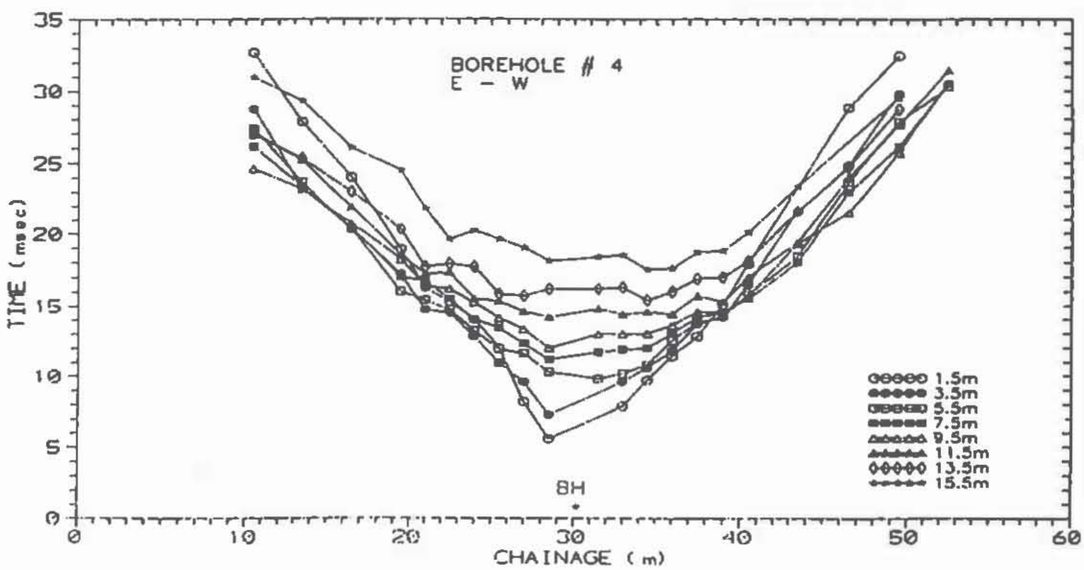
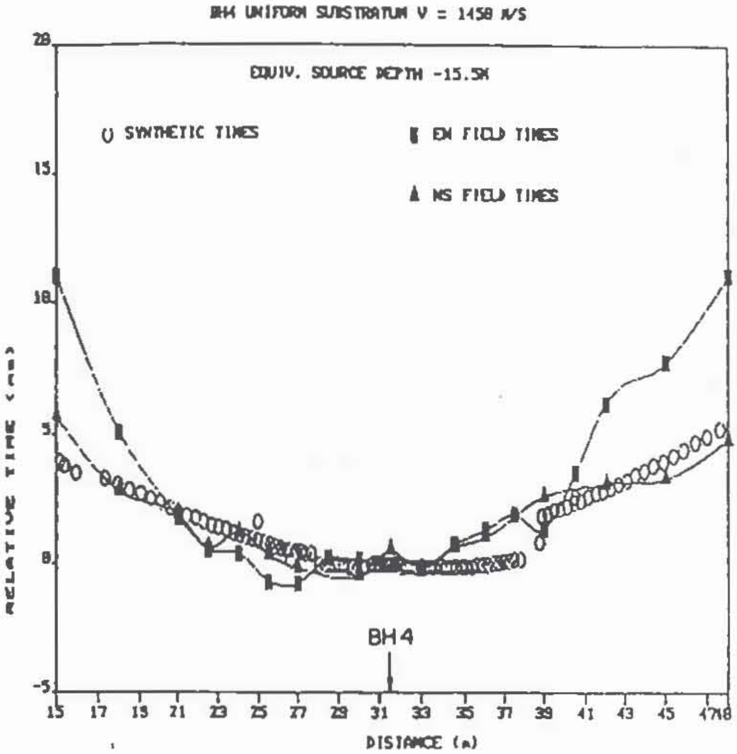



Figure 5




NORTH-SOUTH PROFILE

COMPUTER MODEL DERIVED FROM DOWNHOLE SEISMIC TESTING

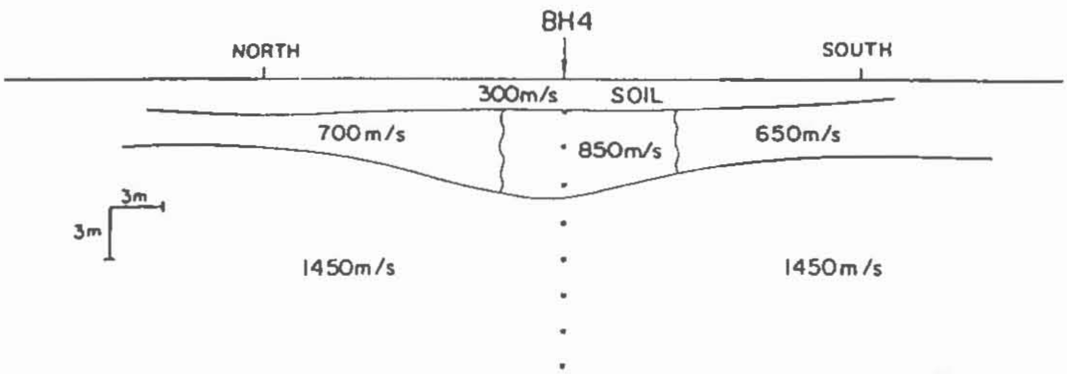
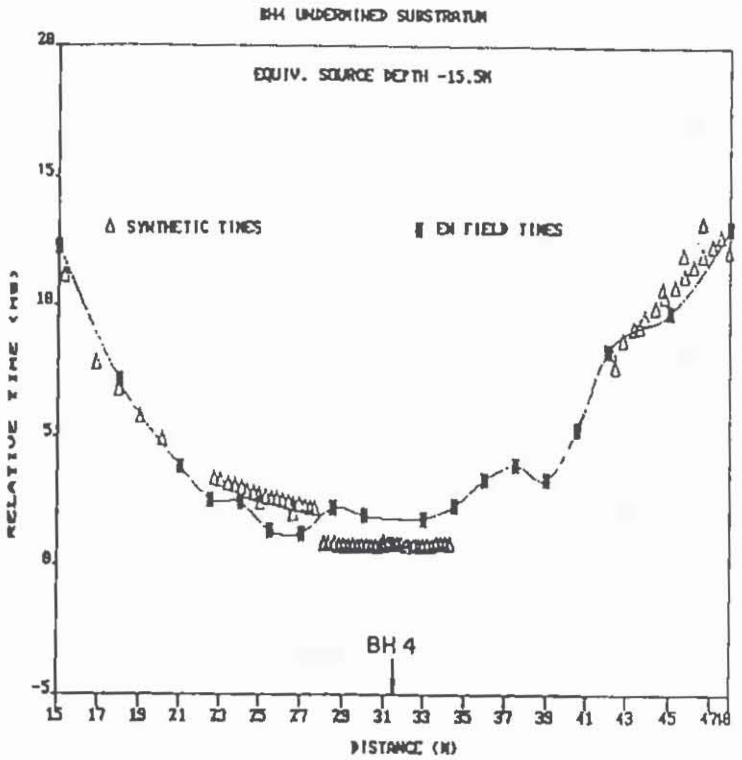



Figure 6




<u>EAST-WEST PROFILE</u>

<u>COMPUTER MODEL DERIVED FROM DOWNHOLE SEISMIC TESTING</u>

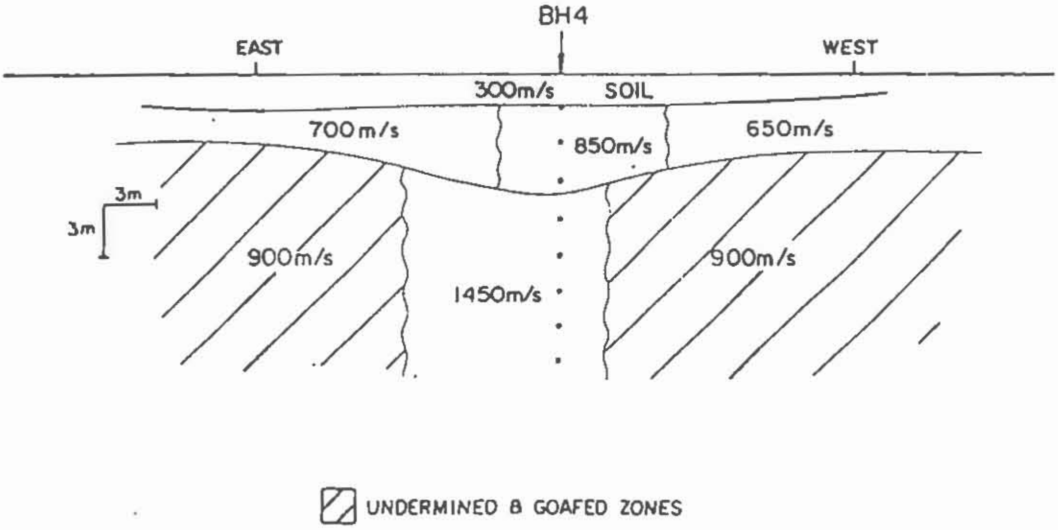



Figure 7

# DAMAGE TO HOMES FOLLOWING THE NEWCASTLE EARTHQUAKE – DON'T BLAME IT ALL ON CLAY SOILS

**D. MEHAN**
**Terrence Gill & Partners**

ABSTRACT

There is a widely held belief that most of the damage which has occurred to homes in the Newcastle Region following the earthquake is in no way related to the earthquake.

This study presents the results of a number of investigations into claims for earthquake damage from the files of a small engineering consultancy, Terrence Gill & Partners Pty Ltd (TGP).

The results of the study show that there is sufficient evidence to suggest that inadequate repairs to earthquake damage and earthquake induced weaknesses to homes are major factors in the cause of post earthquake damage.

BACKGROUND

The Newcastle earthquake of December 1989 had a major impact on the Newcastle region. It caused the death of 13 people and, even now, earthquake damage claims are being received by insurance companies.

On page one of the Tuesday June 18, 1991 edition of the Newcastle Morning Herald, the headline read "One in a million chance of quake-related cracks appearing". The article went on to describe a report prepared by D J Douglas & Partners Pty Ltd (Ref. 1) which stated that:

> *"extremes in climatic conditions have caused considerable changes in soil moisture contents, with resulting effects on building foundations .... this movement is being interpreted as a latent of recurrent defect resulting from the earthquake, whereas in fact it may have had little or nothing to do with it".*

Subsequently, the Insurance Council of Australia and the GIO commissioned Irwin Johnston Partners (IJP) and D J Douglas Partners (DJD) to report on the "factors influencing the structural behaviour of residential buildings in Newcastle following the December 1989 earthquake" (Ref. 2). This report concluded in part that:

> *"the earthquake itself is not considered to have been the cause of further building distress observed after the early months of 1990"* and that *"movement of reactive clay soils is considered to be the most influential of the factors that have contributed to new cracking"*.

These studies have been quite influential, and there is now a tendancy to blame the weather and clay soils for any occurring damage and to mitigate losses accordingly. The writer has viewed a number of reports which contribute damage in a wholesale fashion to clay shrinkage and settlement.

## EARTHQUAKE DAMAGE TO HOUSES

The ground motion produced by earthquake waves occurs as a vibration both backwards along the line of the wave and up and down perpendicular to the line. The most destructive force is caused by the horizontal component of the ground motion. When the ground beneath a structure moves suddenly to one side the building tends to remain in its original position because of inertia. As a result the building suffers distortions.

Earthquake distortions induce craking to masonry walls. The cracking breaks masonry wall panels into segments and, in effect, articulates the building.

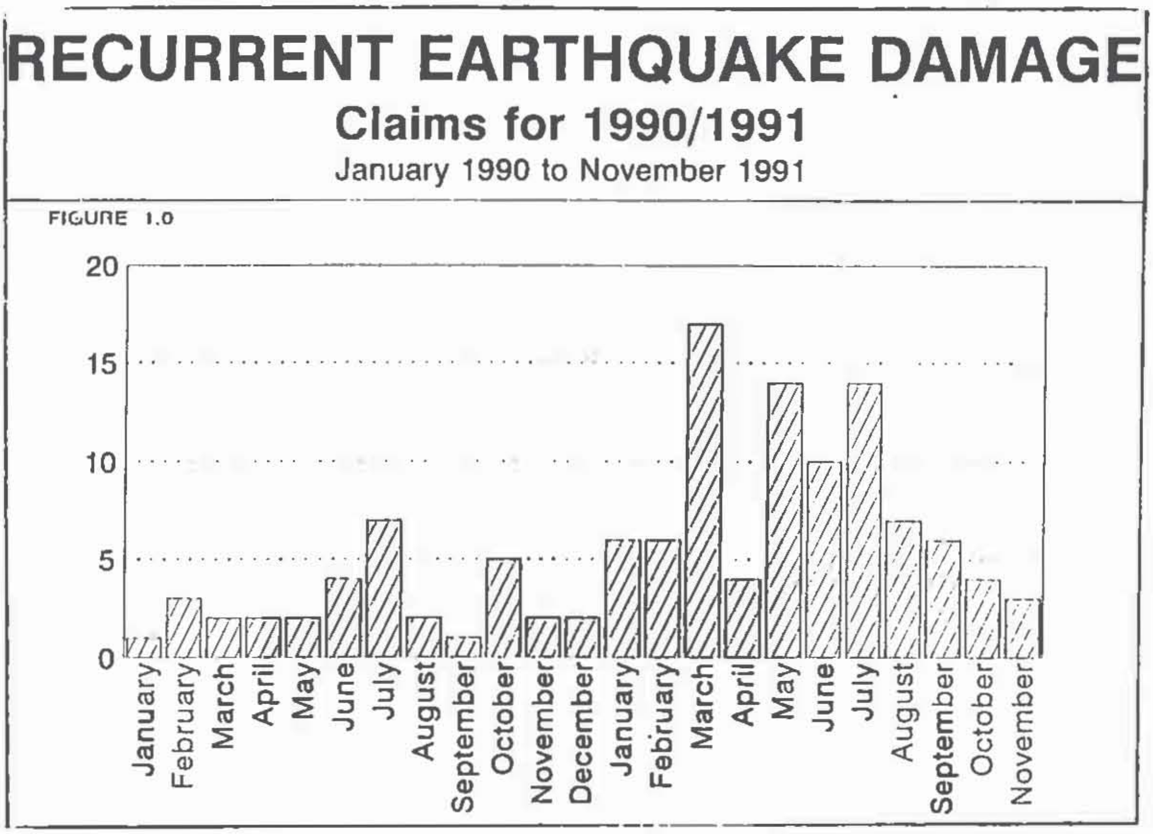
## RESULTS OF STUDY

TGP has investigated over 1,000 earthquake related claims for and on behalf of the insurance industry.

The graph in Figure 1.0 shows the gross number of earthquake damage claims investigated by TGP where damage has occurred to houses which had already had earthquake repairs undertaken. Figure 2.0 shows the proportion of different causes which were attributed to the claims.

RECURRENT EARTHQUAKE DAMAGE

Figure 1.0 shows that claims for recurrent earthquake damage began to be received soon after the earthquake, and that a large number of claims were received before the very dry "drought" period.



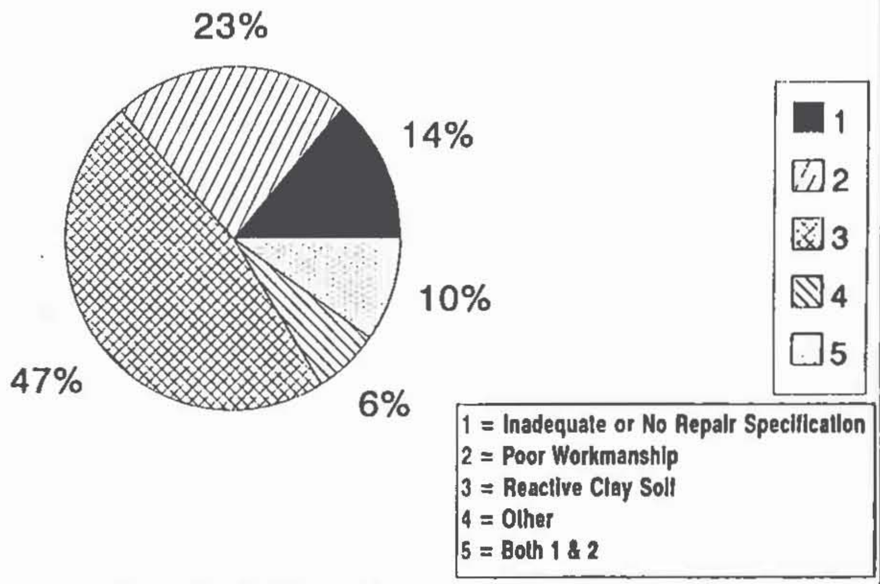

The general procedure adopted in the earthquake repair works has been firstly to prepare a damage report. The majority of investigations for these reports were carried out by professional engineers, however, a number were performed by architects and builders. There were also a large number of claims where no report was prepared. This damage report listed items of visible damage noted during the inspection. Next, a detailed specification and scope of works for repairs was usually prepared, however, the damage report was often used as the basis for obtaining quotes from builders and no specification was prepared.

Repairs were then undertaken. Sometimes these repairs were performed under engineering supervision, other times they were not supervised, or were supervised by a loss assessor.

Figure 2.0 indicates that whilst a large proportion of recurrent damage is the direct result of ground movement caused by reactive clay soils, a slightly greater amount has been caused by inadequate repairs due to poor workmanship, inappropriate specification, or even no specification at all. Other causes include landslip, mine subsidence, etc.

CAUSE OF RECURRENT DAMAGE
January 1990 to November 1991

FIGURE 2.0




Unclear or lack of specification meant that certain items of earthquake damage were overlooked or simply not repaired when they became apparent during repair work. In addition inappropriate methods of repair were sometimes specified, such as the use of certain proprietory products.

The extent of poor workmanship indicated by our records is somewhat greater than usually reported. The trade mostly responsible was the bricklaying trade. Instances of simple surface patching of cracks rather than raking out cracked mortar and repointing, re-rendering over walls without repairing underlying cracked brickwork and the use of mortars with very different strengths to the original strength were common.

## RECURRENT EARTHQUAKE DAMAGE

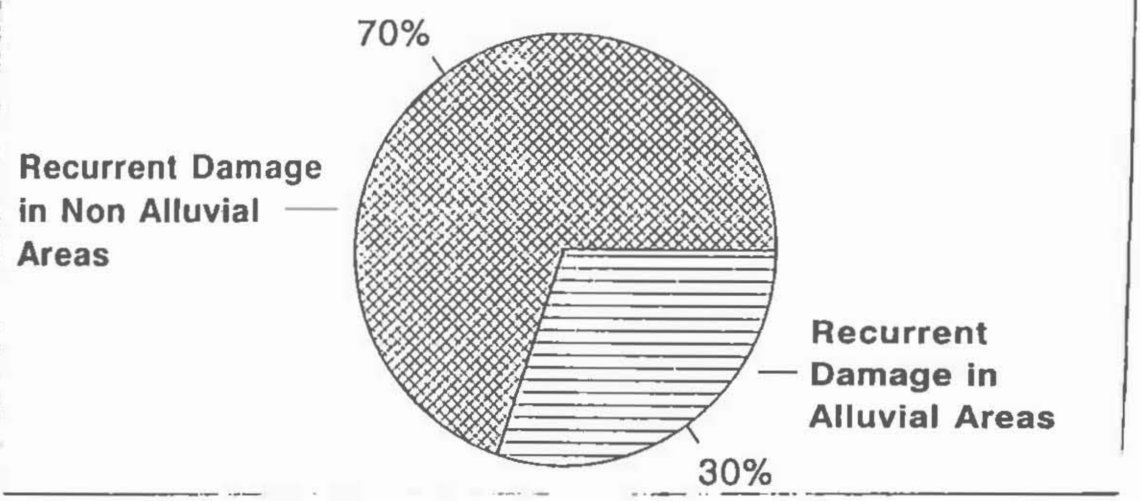
The Building Services Corporation records do not show up this problem since in our experience most cases of poor workmanship went back to the insurance company to be redone.

Figure 3.0 shows the relationship between building foundations and recurrent damage. Note that whilst some 70% of recurrent damage occurred in non-alluvial areas generally underlain by clay soils, 30% occur in alluvial areas where soils are typically sandy and non-reactive. Thus in at least 30% of cases seasonal ground movement cannot be the most influential factor causing building distress.

**RELATIONSHIP BETWEEN FOUNDATION CONDITIONS & RECURRENT DAMAGE**

January 1990 to November 1991

FIGURE 3.0




It has been suggested by Pederson (Ref. 3) that:

> *"Micro-cracking of the brickwork joints, initiated by the earthquake, may result in more distress/cracking in buildings .... due to ground movements and stress relieving in the frames".*

It is difficult to apportion the amount of blame related to this cause due to the constraints of insurance investigations, but it makes up a certain portion of that damage missed during preparation of the specification and repair work.

Microscale damage to geological materials as a contributing factor to the ongoing damage is currently being studied by the Institute of Coal Reseach (Ref. 4). These studies may well add an additional factor causing recurrent damage to the aforementioned reasons.

## DISCUSSION

With hindsight, it is a relatively simple matter to explain why so much of the recurrent damage has been caused by inadequate repairs.

Firstly, it was a learning experienced for all involved and mistakes were bound to occur. There were also time constraints imposed due to the urgency of the situation.

Secondly and importantly, a number of even the most experienced builders had had little exposure to the type of repairs required by earthquake damaged homes. In Newcastle most of the damaged homes were quite old and had been built using materials of inferior quality compared with today. Much of this work requires the skills of an experienced building restorer. These repairs are very different to those involved in erecting new buildings using new materials.

The engineer accepts that cracking to walls of up to 5 mm as acceptable and largely unavoidable. This sort of damage is generally structurally insignificant, however, from the home owners point of view this damage is very significant.

## CONCLUSION

Undoubtedly, the movement of reactive clay soils is a major factor in the ongoing occurrence of damage to homes in the Newcastle region following the earthquake.

However, the quality of repairs and the adequacy of some repair specifications must be seen as equally contributing to the recurrence of damage.

## RECURRENT EARTHQUAKE DAMAGE

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# DYKES IN THE NORTHERN SYDNEY COASTLINE BETWEEN PORT JACKSON & BROKEN BAY

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**Queensland University of Technology**

The basic dykes in the Northern Sydney coastline are of interest mainly because of their distribution, but in addition, the size of the Barranjoey dyke is remarkable, and the composition of the dykes is also noteworthy.

## DISTRIBUTION

Morrison (1904) recorded approximately forty dykes in the nineteen kilometre long coastal strip between Port Jackson and Botany Bay, but only four in the adjacent twenty seven kilometre long coastal strip between Port Jackson and Broken Bay. The writer has walked the entire northern coastline and found another nine dykes, one of which, at Barranjoey, is the largest dyke in the Sydney District (Hamilton, 1965). If the dykes in the Botany Bay to Port Jackson strip average 0.5 metres wide, there is approximately 1 metre width of dyke per kilometre of coastline. This is a minimum figure and does not account for the volcanic plug at Bondi. The northern dykes range from 0.5 to 2.3 metres wide except the Barranjoey dyke which is at least 12 metres wide and possibly as much as 21 metres wide. The average width of dyke per kilometre for the northern coastline is 0.9 - 1.3 metres.

Despite the case made above for some uniformity of intrusion density on a broad scale, the dykes in the northern Sydney coastline are very unevenly distributed. Only four occur in the southern section from Port Jackson to Newport which covers eighteen kilometres or two thirds of the northern coastline. Furthermore, these four dykes have a south-east trend while the more northerly (and southerly) dykes have more easterly trends (apart from three with north-westerly trends). There are large stretches of sand in this southern region (e.g. Narrabeen Beach) and it is possible that some dykes may lack surface exposure here, whereas this is unlikely in the rocky regions.

BARRANJOEY DYKE

The discovery of the Barranjoey dyke was recorded by Hamilton (1965, for location see figure 1). At that time contacts could not be seen and the form of the dyke was inferred form internal structures. Recently, at very low tide, contacts were observed at the western end of the outcrops confirming the dyke shape and orientation. The south western contact is unusual in that it is marked by anatomising apophyses dipping from 20 to 70 degrees to the north and averaging about 10 centimetres thick. The apophyses are weathered (or altered) to clay, and the country rock at the contact is a grey mudstone. The thickness of the dyke is difficult to measure but is probably closer to the 12 metre minimum than the 21 metre maximum previously noted, unless it is thick in the eastern section where it is best exposed. It is a typical teschenite, containing zoned feldspar, titan-augite, olivine, magnetite, ilmenite, analcite, apatite, biotite, chlorite and iddingsite (or clay) with an intergranular to intersertial texture. It is layered at the centimetre to decimetre scale, the layers varying slightly in texture and composition. Robertson (1979) dated the intrusion at 171 Ma (Middle Jurassic) by magnetic means, and Embleton *et al.* (1985) dated it by the K-Ar isotope method as 171 ± 3 Ma from a "basalt" specimen and 173 ± 3 Ma from a "nephelinite" specimen.

LION ISLAND DYKE AND THE PURPLE DYKE

North of the Barranjoey dyke is another teschenite dyke, 2 metres wide, at Lion Island. This dyke has a flow texture and contains grey xenoliths with honeycomb weathering. The xenoliths closely resemble a dyke rock south of Palm Beach described here as the "purple" dyke. The "purple" dyke occupies a vertical fault of 25 centimetres throw, north side up. It is 1.6 metres wide and slightly sinusoidal. It also exhibits honeycomb weathering and has calcite amygdales elongated in a direction inclined slightly with south-west. It consists of orthoclase, hematite and leucoxene in

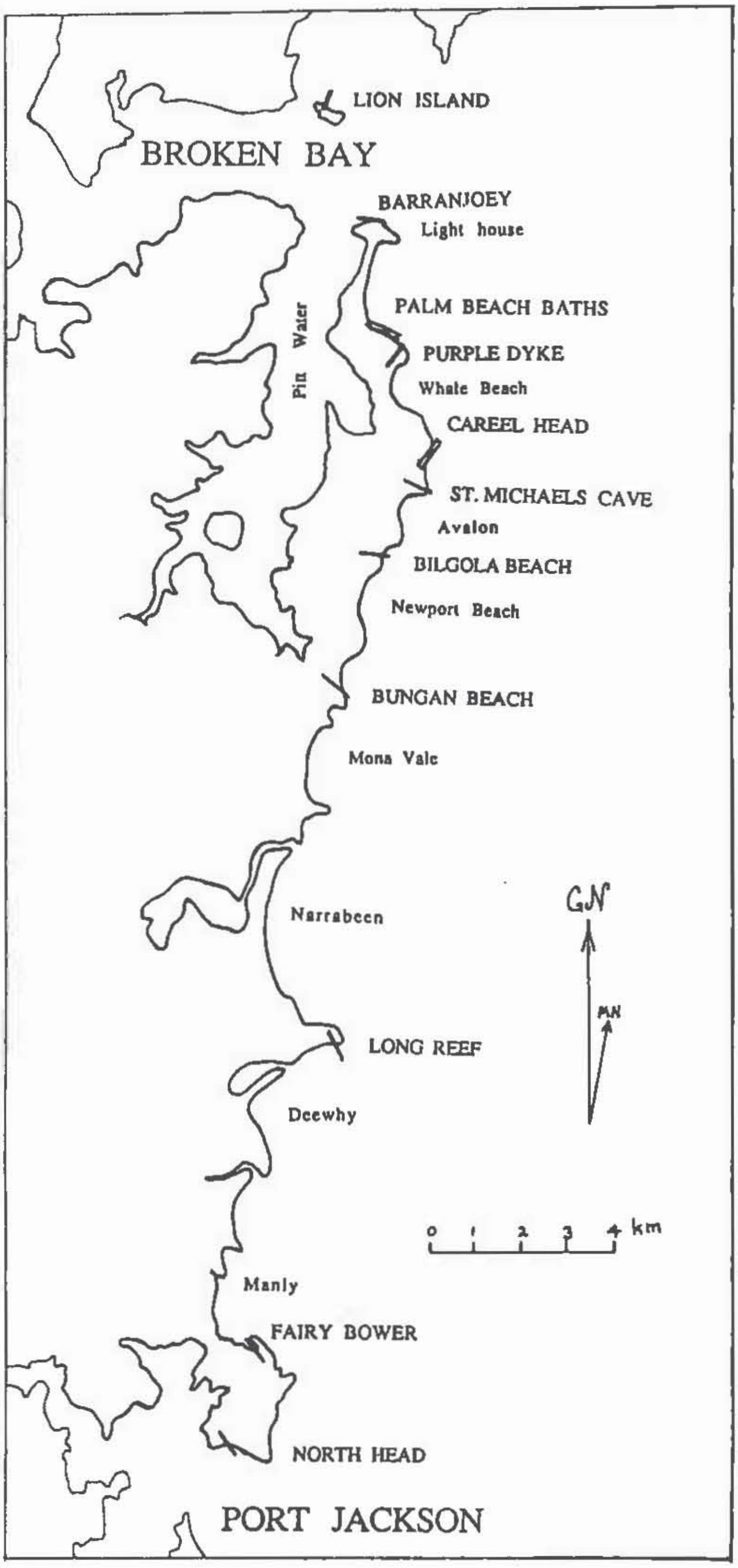


**Fig.1 DYKES IN THE NORTHERN SYDNEY COASTLINE.**

cryptocrystalline material (probably altered devitrified glass) with minor calcite and kaolinite.

## PALM BEACH DYKES

A pair of teschenite dykes about 8 metres apart occur at Palm Beach baths north of the "purple" dyke and south of Barranjoey dyke. One is 1.5 metres wide and the other is 2.3 metres wide.

## CAREEL HEAD DYKES

South of the "purple" dyke, near Careel Head, are two altered and weathered dykes about 30 metres apart. The northerly dyke is the largest and is 0.76 metres wide occupying a fault with a few centimetres of displacement. Both dykes are somewhat irregular in shape, contain carbonate veins, are hosted by carbonaceous shale and terminate within the cliff section. Half of a kilometre south of this pair of dykes is a remarkable breccia dyke at St Michael's Cave near where the "Hole in the Wall" was at Avalon.

## ST MICHAEL'S CAVE BRECCIA DYKE

St Michael's Cave dyke is a vertical body about 0.6 metres wide with vertical foliation expressed by the orientation of fragments and by weak jointing. It is composed of a black mudstone matrix containing quartz pebbles and fragments of shale and sandstone. The palynoflora in the matrix was apparently derived from overlying Triassic strata (Crawford *etal.* 1980). Although it may have been filled with downward circulating material two microscopic fragments of coke found in the matrix indicate some of the material in the dyke may have been in contact with magma. This is not surprising. The Careel Head pair of dykes probably intersect the St.Michael's Cave dyke within a kilometre of their outcrops (Fig.1) but no breccia was found in the Careel Head dykes and no recognisable altered teschenite was found in the St.Michael's Cave breccia. Nevertheless it is suggested that the matrix in the dyke may have formed from a process of delithification caused by hot fluids pulsing in advance of a magma column (Hamilton, 1986) .

## DYKES IN THE NORTHERN SYDNEY COASTLINE

### BILGOLA BEACH DYKE

The dyke at Bilgola Beach is one metre wide and somewhat similar in appearance to the "purple" dyke near Palm Beach. It occurs in a cave within a carbonaceous siltstone. This cave is is 15 metres long compared with the 107 metre long St. Michael's Cave.

### BUNGAN BEACH DYKE

The dyke at Bungan Beach is slightly wider (1.2 metres) than the Bilgola dyke and is less intensely altered. Nevertheless, it is largely altered to carbonate where it is in contact with carbonaceous siltstone and is half carbonate at the centre. It is greyish brown to greenish and this together with the occurrence of labradorite and titan-magnetite suggest it is of mafic composition.

### LONG REEF DYKE

The Long Reef dyke is well known (e.g. Morrison, 1904). This is teschenite up to 1.4 metres wide, described in some detail by Plimer (1965).

### MANLY DYKES

The two remaining dykes, at Fairy Bower and North Head, are weathered to clay and are of relatively small dimensions.

### DISCUSSION AND CONCLUSION

In the Newcastle coastal area the average intrusion density is at least one metre of dyke width per kilometre (K. Moelle pers. comm. 1992 and Williams 1978). If allowances are made for sills, the intrusion density in the Wollongong area is probably greater than the equivalent of one metre of dyke per kilometre. This probably applies to a large part of the Sydney Basin, and has implications for heat flow study as well as structure. It may be that the coastal zone is anomalous, and this remains to be studied, but it must be noted that dykes weather quickly in sandstone host rocks and form very poor outcrops which are difficult to find except on wave-cut cliffs and platforms. Furthermore, the coastal dykes trend, more or less, easterly while the coastline trends, more or less, northerly so by extrapolation they ought to occur with a similar abundance in areas west of the coastline.

In common with other dykes in the Sydney region, those dykes surrounded by sandstone tend to be highly weathered. While those surrounded by shale are relatively fresh they are endometasomatically altered in the presence of carbonaceous matter. Teschenite is the dominant rock and the layering in the Barranjoey dyke indicates at least some slight differentiation of this. The xenoliths at Lion Island also indicate that differentiation has occurred. The "purple" dyke is something of a puzzle in that it could have been produced by differentiation or possibly by intense deuteric alteration. The Barranjoey dyke occupies a prominent location at the extremity of Pittwater Peninsula and may have influenced the geomorphic development of Broken Bay just as the dykes at Manly, Palm Beach baths, Careel Head and Long Reef may have had some influence on the development of the coastline. The petrology of the great Barranjoey dyke and the genesis of the enigmatic St. Michael's Cave dyke await the attention of further research.

With the probability that more than 0.1% of the Sydney Basin is igneous, more attention should be paid to its igneous rocks.

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# HIGH ENERGY SHORELINES AND THE ROLE OF SHALE COMPACTION IN THE FORMATION OF EXTENSIVE COAL DEPOSITS

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**Geological Survey of Canada**

Coal seams that formed on many Cretaceous wave-dominated strandplain sediments in North America are characterised by great lateral continuity (tens to hundreds of kilometres), substantial thicknesses (up to 12 m) and relatively low-ash and low-sulphur contents (Fig. 1). These coals formed behind an active shoreline in areas undergoing subsidence due to shale compaction and dewatering (Fig. 2). The coals formed as part of a high-stand shoreline but the high water table is the result of subsidence caused by the shale compaction. Sea level only indirectly controls peat accumulation. The zone of peat of accumulation was remote from the shoreline and associated storm and tidal inundations. Deltas feeding high-energy shorelines normally have only a few distributaries thereby reducing coarser clastic splits within the peat due to fluvial flooding. If the rate of subsidence was too great, lakes formed and peat did not accumulate. Statistical evaluation of petrographic properties show that the strandplain coals form distinctive petrographic groups that are characterised by relatively low vitrinite contents and high inertinite contents.

The vertical sequence forming the shoreface platform on which the peat accumulates is typically 20 to 30 m thick and consists of sandstone or conglomerate (Fig. 3). Hummocky cross stratification and wave-rippled conglomerate are common.

Comparison of coal facies and depositional environments from Permian coals of Australia show that the Lower Cretaceous strandplain coals have petrographic similarities to coals that were formed under regressive back-barrier conditions in the Permian. Due to differences in nomenclature, previously interpreted regressive back-barrier conditions in the Permian may be similar to the strandplain environments discussed here.

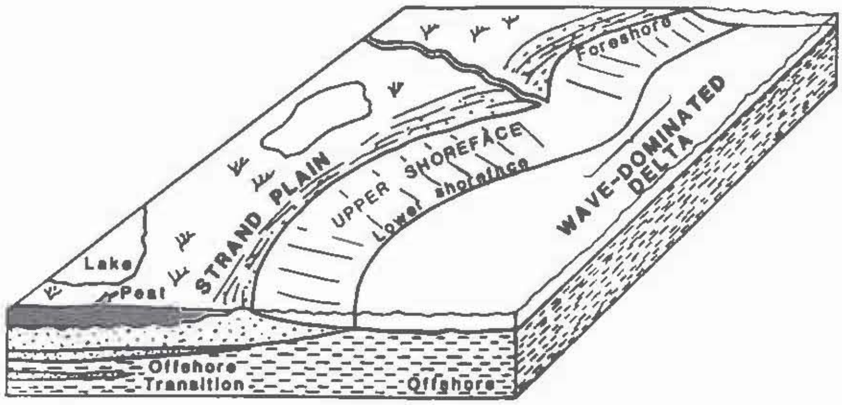


Figure 1. General characteristics of wave-dominated deltas and strandplains which form a laterally continuous sheet of sandstone and/or conglomerate.

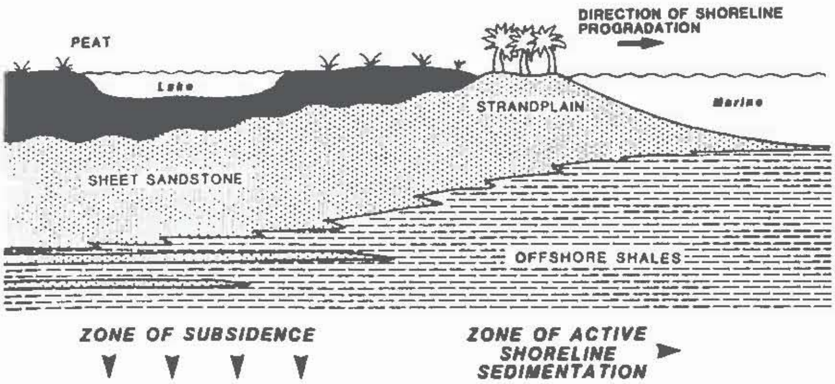


Figure 2. Depositional model to illustrate the formation of laterally continuous coals above regionally extensive strandplain deposits.

COAL, HIGH ENERGY SHORELINES AND SHALE COMPACTION

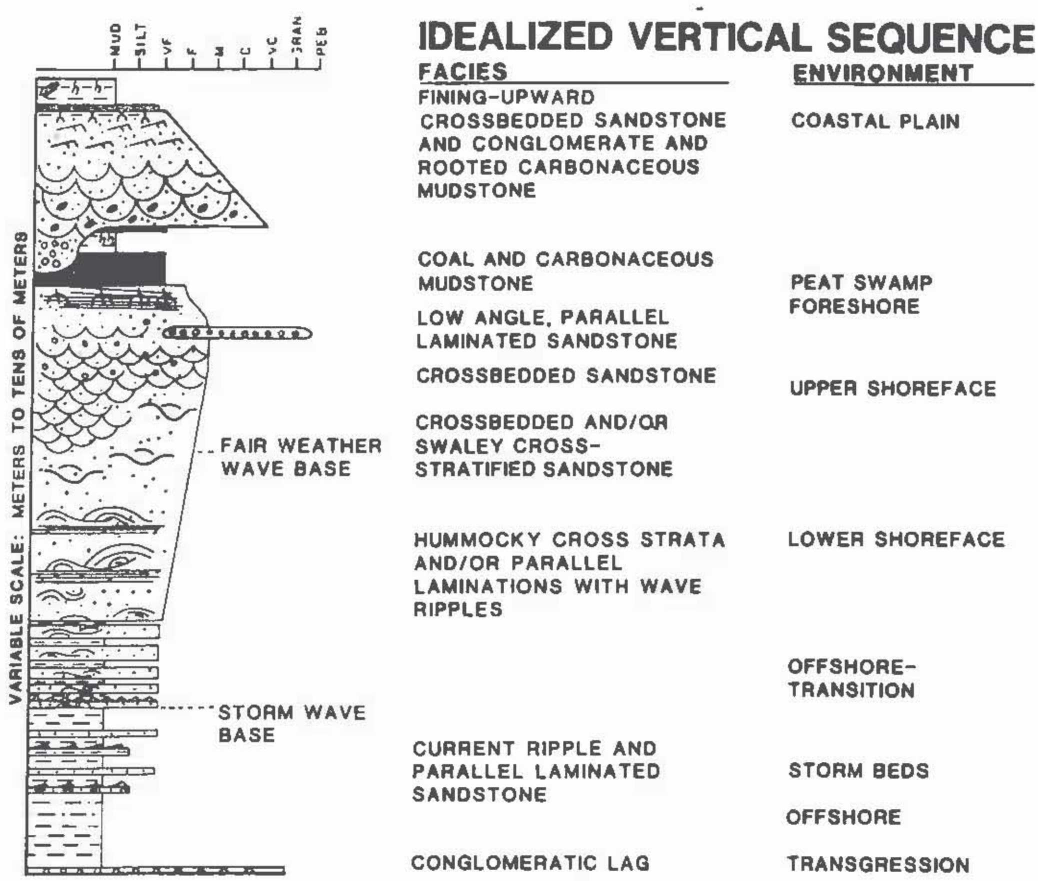


Figure 3. Idealised vertical section of a wave-dominated strandplain sequence.

# STRAND-PLAIN COALS OF THE GATES FORMATION, WESTERN CANADA

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## Western Canada Foreland Basin

The Western Canada Sedimentary Basin is one of the major hydrocarbon bearing basins of the world. It contains extensive reserves of petroleum, natural gas, tar sands and coal. The basin occupies the eastern portion of the province of British Columbia and much of Alberta and Saskatchewan. Coal deposits are widespread, with bituminous coal reserves concentrated in the front ranges and foothills to the east of the Rocky Mountains, (Fig.1). Some 85% of Canada's reserves of bituminous coal, 50% of the total production and 95% of the metallurgical coal production comes from this region.

This foreland basin comprises the Phanerozoic rocks that overlie the Precambrian basement of the North American continent and extend westwards into the eastern Cordillera. In the Late Jurassic, the continental margin transformed, relatively abruptly, from a tectonically quiet platform to a highly mobile region with orogenic uplift in the west (Columbia Orogen) and an associated foredeep to the east. The earliest sediments of the foreland basin were deposited in Middle Jurassic and the basin margin has migrated eastward with the deformation front during the Late Cretaceous and Early Tertiary. Basin fill comprises a sequence of six major clastic wedges formed during successive periods of deformation, loading and subsequent isostatic adjustment and erosion during Cordilleran mountain building.

Extensive deposition of coal bearing sequences accompanied formation of three of these wedges, (Fig. 2). The Upper Jurassic clastic wedge contains substantial coal reserves in the Kootenay Group in the southern Front Ranges and in the Minnes Group to the north, which were deposited during the first major episode of the Orogeny. A second deformation phase was accompanied by deposition of the Luscar Group and correlatives, which include several major coal bearing formations in the mountains and foothills of northeastern British Columbia and west-central Alberta. The Cretaceous-Tertiary clastic wedge includes coal sequences of the outer foothills and Alberta plains, deposited during an early phase of the Laramide Orogeny. These sequences become younger and decrease in rank from west to east.

## STRANDPLAIN COALS

### Coals of the Gates Formation

This study focuses on coals of the Gates Formation in the Lower Cretaceous clastic wedge (Fig. 2). The basal deposits of this wedge (e.g. Cadomin Fm) infill topographic irregularities on the sub-Cretaceous unconformity. The Gething Formation comprises a mainly non-marine, fluvio-deltaic sequence with frequent coal seams, which grades northward into estuarine and open marine sands and shales. A subsequent major transgression pushed the shoreline far to the south and, in the northern foothills region, deposited the dominantly marine shales of the Moosebar Formation.

The Gates Formation consists of several upward coarsening sequences, formed by the repeated northward progradation of sand and gravel rich, wave-dominated deltas and strandplains (Leckie, 1986; Leckie, this vol.) which extended as sheet sands laterally along strike for at least 230km and down dip for up to 90km. These shoreface sandstones are frequently immediately overlain by extensive coal seams up to 12m in thickness. The upper Gates, landward of the shoreline, represents fluvial to upper delta plain environments. Coal seams deposited in these environments are not as extensive as the shoreface coals.

The strandplain coals are thick, laterally extensive with low sulphur and relatively low ash. Thick peat accumulated on a platform created by the sheet sands, but relatively distant from the shoreline, as a result of the early, steady and continuing subsidence due to dewatering and compaction of the underling marine shales. The extent of the coals and the relatively low ash suggests little influence by overbank deposition, wide spacing of major channels and protection from the high energy coastline (Leckie 1986, Kalkreuth & Leckie 1989).

### Seam Petrography

Kalkreuth and Leckie (1989) reported on the sedimentologic and petrographic characteristics of the Gates Formation and contained coal seams from four measured sections of 200 to 400m thickness in the Front Ranges. The coals assigned to the strandplain were found to exhibit a rather limited range of petrographic composition; vitrinite 45% to 66% (mean 47%), inertinite 31% to 53% (mean 42%) and negligible liptinite (mean 2%). Mineral content is relatively low (mean 6%). Within the vitrinite group desmocollinite is dominant and within the inertinite group, semifusinite > inertodetrinite > fusinite. These coals were found to occupy a restricted zone on facies diagrams such as Tissue Preservation Index-Gelification Index (TPI-GI), (Fig.3). This zone lies close to the zone of back barrier coals as defined for the Permian of eastern Australia (Diessel, 1986).

Although the strandplain coals form a relatively restricted zone on the facies diagram, it is not an exclusive zone. In some cases, coals formed in environments other than the strandplain also show petrographic characteristics similar to strandplain coals. In most cases however, coals from other depositional environments plot in zones separated from the strandplain coals on a TPI-GI diagram (e.g. Fig.4).

Seam Profiles

Although the strandplain coals have relatively consistent whole seam compositions, there are marked differences in seam profiles. Seams 4,10 and 11 in the Smoky River Coalfield (Fig. 5) have petrographic compositions typical of these coals, although Seam 11 has an unusually high mineral content (21%).

Seam 11, the uppermost coal, contains numerous clastic partings indicating frequent flooding and generally high water levels during deposition. This profile displays many of the features of parting-rich coals of the Gates Formation; a dominance of brighter lithotypes (banded coal and brighter), variable vertical lithotype successions, dulling-up sequences below partings and relatively bright lithotypes above partings.

Seam 10 contains only one thin clastic bed indicating a relatively long period free from clastic inundation and characterised by a predominance of duller lithotypes (banded coal and duller), common dulling-up sequences within relatively thick coal beds and rare brightening-up sequences.

Seam 4 is transitional between the two extremes of frequent and infrequent flooding as represented by partings. In this seam, banded coal is the most common lithotype, dull coals occur both near partings and in the central portions of relatively thick coal sequences and a variety of lithotype successions occur.

These variations in seam profile are considered to represent the influence of overbank deposition in the precursor mires. At this sampling site, Seam 11 formed closer to distributary channels than did Seam 4 and was subject to more frequent inundation. Seam 4 developed in a zone where relatively long periods of stability allowed build up of the mire to levels higher above the water table than in the case of Seam 11.

Dull Coals

Dull coals occur in two distinctly different associations within these seams; either in close association with clastic beds or atop dulling up sequences in relatively thick sections of parting-free coal. There are two distinct fields of composition:

a) Dull coals associated with clastic partings are characterised by low to moderate vitrinite content, a high content of dispersed macerals (principally inertodetrinite with rare discrete macrinite), inertodetrinite as the dominant inertinite, a relatively low gelification index and high mineral content dominated by rounded quartz.

b) Dull coals occurring in the central portions of thick coal sequences are characterised by a moderate vitrinite content, a low dispersed maceral content (inertodetrinite), semifusinite as the dominant inertinite, the presence of rare groundmass macrinite, a relatively high gelification index and a very low mineral content.

When plotted on a ternary facies diagram (Fig. 6), the mean petrographic composition of each lithotype class indicates a trend from deposition in a wet forest moor toward a drier forest moor for the sequence from bright coal to banded coal.

## STRANDPLAIN COALS

The banded dull and dull coals indicate an increased input by "dispersed" macerals and the influence of higher water levels within the typical Gates mire.

When the dull coals are subdivided as above, it is clear however, that there are two types of dull coals present in these seams; "dry" dull coals occurring in the central parts of relatively thick coals sequences and "wet" dull coals formed in close association with clastic partings. The dry dull coals plot on the trend line from bright to banded dull coals and indicate deposition in a moderately wet forest moor (Fig. 6). The wet dull coals show a very high proportion of component D macerals (principally inertodetrinite) and indicate higher water levels and a strong influence of open moor or marsh environments.

The dull coals also occur atop different types of dulling-up sequences (Fig. 7). Thick sequences in the central portions of seams show increases in both components D & F upward. This trend is considered to reflect drying within a forested environment. Increases in component D represent the inevitable increase in inertodetrinite associated with increases in structured inertinite components. Thin sequences associated with partings show a much more marked increase in "dispersed" macerals reflecting increased water levels and higher contributions by transported inertodetrinite, vitrodetrinite and discrete macrinite and the influence of open moor conditions.

Based on composition and position within seam successions it appears that the dull coals represent two different phases in mire development. The wet dull coals form prior to and immediately after flooding events and represent the response of mires to the increased water levels at these times. The dry dull coals represent advanced stages of hydroseral successions toward raised bogs in which thick peat deposits have become elevated and are subject to sub-aerial exposure and increased oxidation (Marchioni and Kalkreuth, 1991).

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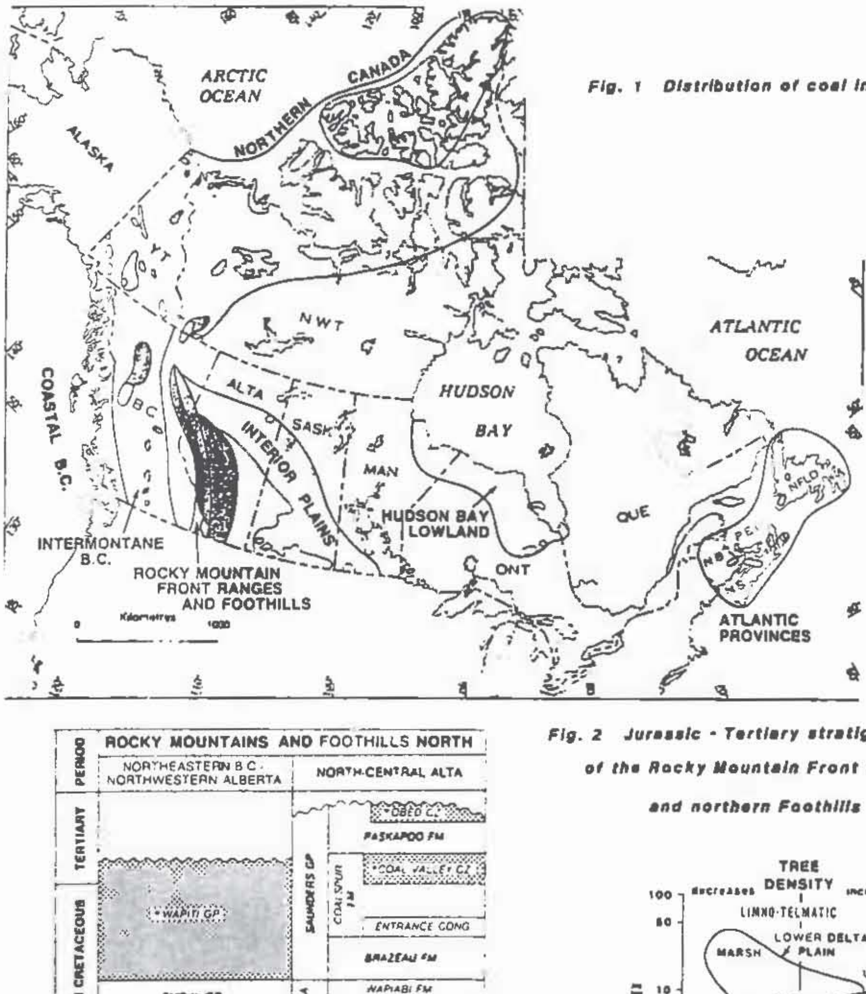


*Fig. 1 Distribution of coal in Canada*

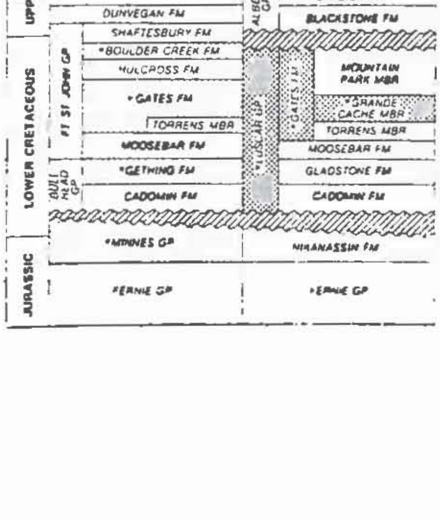


*Fig. 2 Jurassic - Tertiary stratigraphy of the Rocky Mountain Front Ranges and northern Foothills*

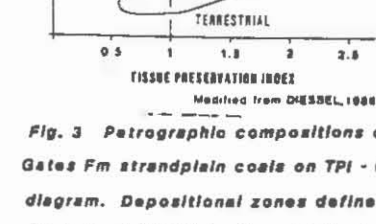


*Fig. 3 Petrographic compositions of Gates Fm strandplain coals on TPI - GI diagram. Depositional zones defined by Diessel (1986) for Permian Coals of Australia*

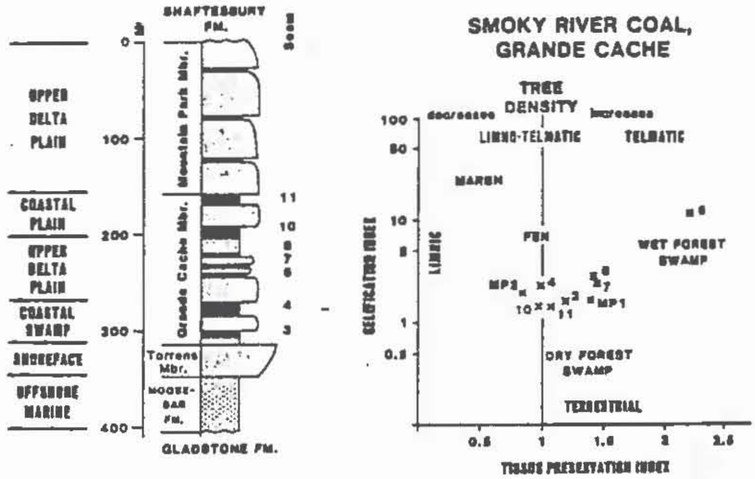


*Fig. 4 Lithologic section of Gates Fm & petrographic compositions of seams, Smoky R. Mine*

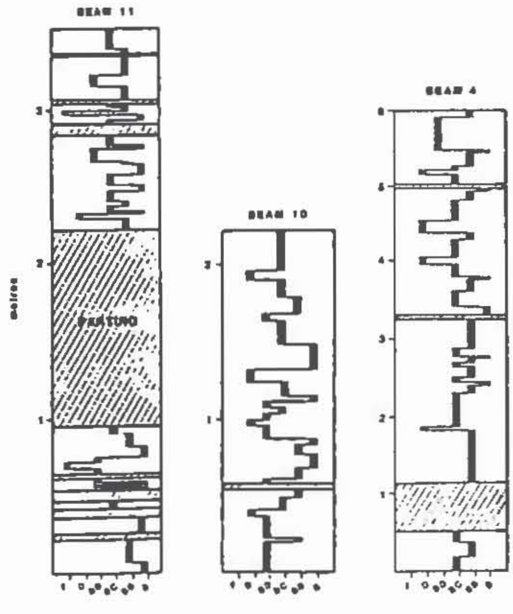

*Fig. 5 Lithotype profiles of seams 4, 10 & 11, Smoky R. Mine*

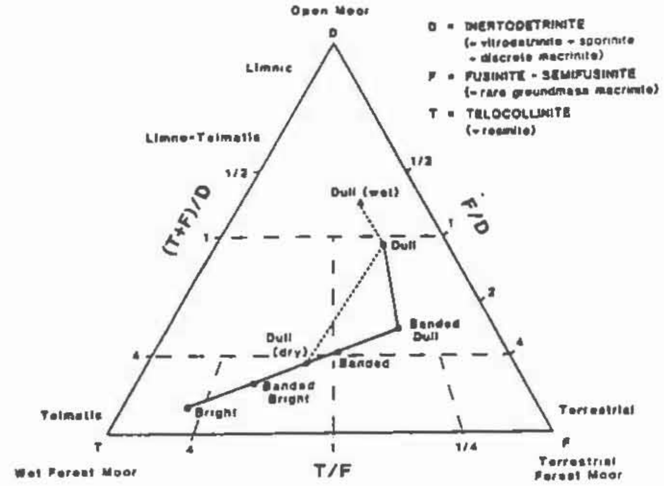


*Fig. 6 Facies diagram of mean composition of lithotypes*

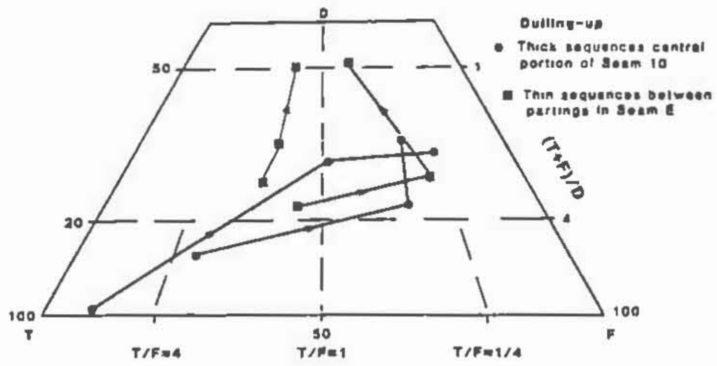


*Fig. 7 Facies diagram of dulling-up sequences*

*(apices of ternary diagram as in Fig. 6)*

# COMPARISON OF MACROSCOPIC & MICROSCOPIC SIZE ANALYSES OF ORGANIC COMPONENTS IN BOTH COAL & PEAT

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**[2] University of Canterbury, New Zealand**

## INTRODUCTION

Modern peat deposits are used as analogues for paleoenvironmental reconstructions of coal seams. Comparisons between peat and coal can be readily made as to areal extent of the deposit, ash and sulphur contents and, with reference to compaction, thickness. However, macroscopic peat types and coal lithotypes cannot be so easily compared because of the different classification systems used for macroscopic analysis.

In modern mire studies, peat types are categorized by particle size and these particles are further identified according to botanical affinities. The size of peat particles are usually measured by sieving and their composition is quantified by either macroscopic and/or microscopic identification of plant parts as well as chemical analyses. The size of particles is controlled both by the amount of microbial and physical degradation occurring in peat. The degree to which the degradation occurs is related to the style of flooding of the mires and also to the mire flora.

In coal studies, the macroscopic character is classified according to the approximate thickness and proportions of bands but these attributes are rarely quantified. Existing macroscopic classification can be used but these are subjective and difficult to reproduce among operators. The bright vitrain bands (also know as xylite) visible in coal are derived from large woody plant parts whereas the attritus between bands (which may be bright or dull) is composed of smaller plant parts as well as decomposed and comminuted plant and fungal material. However, although some of these botanical components are clearly visible in coal and can be related to what is found in modern peat deposits, coal is usually examined microscopically using crushed, volumetrically representative samples. Particle size cannot be measured as crushing will have destroyed the larger plant particles. Maceral terminology is therefore used and, even in conjuction with chemical analyses, usually fails to identify the botanical origin of particles. Standard maceral analysis of crushed coal grain mounts may be appropriate for technological characterisation, but for paleoenvironmental reconstructions, methods which allow identification of botanical attributes have the greatest relationship to the original mire forming environment.

Although both peat and coal are characterised on the basis of macroscopic texture and microscopic composition, rarely are these two attributes considered together for either material nor are they directly compared between peat and coal. If size of particles in both peat and coal is related to composition, and can be used as a generic link between the two materials, then perhaps the distribution of peat types in modern mires can be used as a model for coal lithotypes.

## METHODS

Macroscopic and microscopic size distributions of organic components were determined for a number of peat and coal types, as was the botanical and maceral composition of particles. The distribution of three basic peat types, fibric, hemic and sapric, was recorded in sixteen cores from two deposits, one in Sarawak, Malaysia and the other in Sumatra, Indonesia. These deposits are up to 12 m and 7 m thick, respectively, and were cored in 50cm increments using an Eykelkamp peat auger. This auger provides undisturbed cores but cannot penetrate solid logs. However, their distribution in the deposit was noted.

The three peat types reflect decreasing particle size as the result of more intense decay of plant tissue. Fibric peats are light reddish brown and consist of long slender roots and fibers set in a watery matrix. Hemic peats are reddish brown to dark brown but contain fewer long fibers and greater amounts of wood fragments set in a compacted medium of fine grained particulate matrix. Impenetrable logs were most common in the hemic peats. Sapric peats are dark brown to black, contain little wood, and consist of fine particles of plant organs and tissues, generally unrecognizable, set in a dense, often colloidal matrix. Each increment sample collected was point counted macroscopically at 1 cm spacing and both particle size and general botanical composition (such as wood, roots, leaves) were noted. Particles were measured and placed into one of three size categories: >10 mm, 2 to 10 mm, < 2 mm.

In the laboratory, subsamples of the different peat types were selected, freeze-dried and vacuum-impregnated with epoxy to make 5 x 7 cm polished blocks for microscopic analysis. Particles greater than 10 mm in diameter were excluded from the blocks as the block surface area was too small to adequately assess their distribution. Each block was then point counted at a 1 mm spacing perpendicular to layering and the maceral and plant organ/tissue type or matrix component under the crosshairs recorded. In addition, the size of the plant organ/tissue or matrix component was measured and placed into one of the following categories: 2 mm to 10 mm, 1 mm to 2mm, 1 mm to 0.3 mm, 0.3 mm to 0.1 mm, 0.1 mm to 0.01 mm, < 0.01 mm (Esterle, 1990). These categories were later converted to phi scale as this scale was found by Moore and Ferm (1992) and Lorente (1990) to be the most useful for observing particle size of organic material.

Coal data was collected from banded and non-banded coal types from deposits in New Zealand and Australia. Morley coal at Ohai coalfield (Cretaceous) and the Kupakupa seam at Huntly Coalfield (Eocene) both have bright bands ("vitrain") set in attrital layers which also have a bright lustre (Shearer, 1992; Moore, unpublished data, 1991). By comparison, the Australian Bulli seam (Permian) is well-to non-banded, consisting of bright vitrain bands of varying thickness and freqency in an apparently dull matrix often containing pods and bands of fusain. Vertical profiles through the seams were point counted at the mine face. Within each profile lithotypes were defined and used as the basis for macroscopic size determination and sample collection. Band size within each lithotype was measured by point counting the face of the seam using a string marked off in 1 or 2 cm increments,

dependent on the thickness of the bands. At each intersection the presence or absence of a bright band > 1 mm in width was noted and the width of the bands recorded. At least 50 to 100 measurements were required within each lithotype zone to obtain a distribution.
Replicate block samples of each lithotype were collected and prepared as epoxy-impregnated, polished blocks for microscopic examination. Polished blocks were chemically etched to enhance cellular structure and differentiation between intact plant parts and matrix particles. Blocks were point counted at a 1 mm spacing along traverses perpendicular to bedding. At each intersection, the maceral as well as the plant organ/tissue or matrix component in which the maceral occurred were recorded as was the size of the plant part or matrix component.

The results of the megascopic and microscopic point counts for both peat and coal samples were combined. Thus the sizes of particles in the two materials could be compared at both scales and, because the petrographical analyses were of similar types, their compositions could also be contrasted.

## RESULTS AND CONCLUSIONS

In Figure 1 the combined macro- and microscopic size measurements from the peat deposits (55 samples) and the Kupakupa (13 samples) and Morley (10 samples) coal beds are displayed for all peat/coal types. The most distinctive feature of the size measurements is that in all deposits the size distributions are trimodal, having three distinct size populations. The largest populations have modes of -3 to -1 phi (8 mm to 2 mm) and consist mainly of particles of secondary xylem tissue. The intermediate size populations have modes from 2 to 4 phi (0.25 mm to 0.064 mm) and consist of smaller plant organs and tissues as well as fragments of large organs and tissues. The modes of the smallest size populations range from 8 to 10 phi (0.004 mm to 0.001 mm). This size fraction contains fragments of plant tissues, with minor input from spores, fungal material and completely degraded plant tissues (amorphous humic gel) and lipid-rich material (bitumen) for the peats and New Zealand coals. In Figure 2, the macroscopic size distribution for the Bulli seam is presented for all lithotypes and for each lithotype within a vertical profile at Coalcliff. Although the microscopic size data are not yet completed, the macroscopic distribution of plant parts, or bands, is similar to that of the peats and New Zealand coals.

The similarity of the the widths of the organic components in both peat and coal indicates that little compression of plant material occurred during coalification. Rather, the majority of tissue degradation and compaction occurred in the aerobic zone of peat accumulation and the sizes of organic components changed little thereafter (Moore and Hilbert, 1992). Much of the volume loss during coalification occurs from dewatering of the interparticulate pore space (Teichmuller, 1989, p. 14) resulting in tighter packing. As well as the size distributions, the overall proportions of components in the different peat types and coal beds are also similar; the ratio of plant organs and tissues to matrix components is close to 1.0 in each deposit. The similarity of the types of particles in each size population of the peat and coal studied suggests that composition can, to some extent, be predicted from the size distribution of the material. Thickly banded peat or coal will contain far more secondary xylem than will finely banded material, which will contain mainly small plant organs/tissues and matrix. Non-banded coals will be composed predominantly of matrix.

On the basis of size distribution, thick-, thin- and non-banded coal types can be inferred to have originated from the fibric/coarse hemic, hemic and fine hemic/sapric peat types respectively (Fig. 3). These three peat types commonly occur in mires of the Indo-Malesian region and show distinct distributions relative to the shape and development of the peat deposit. The hemic peat type contains the largest wood fragments greater than 10 mm in width (> -3.5 phi) which are equivalent to the thick bands in coal. However, this peat type still contains abundant fine grained matrix material. In contrast, the fibric/coarse hemic peat type contains woody fragments mostly in the less than 10 to 2 mm size range (< -3.5 to 1 phi) and would result in a coal with only thin bands with variable amounts of matrix. Finally, the fine hemic/sapric peat type has little macroscopic wood content and therefore would result in a non-banded coal.

The spatial distribution of peat types in mires can be mapped by coring (Cameron et al., 1989; Esterle, et al., 1989). For example, a profile from the center of a 12 m thick domed peat deposit in Sarawak varies from decomposed fine grained hemic/sapric peat at the base overlain by a thick central zone of hemic peat containing large pieces of wood and occasional logs and capped by a zone of coarse hemic/fibric peat. The thinned margins of the same deposit are dominated by fine hemic/sapric peat. A suggested model for the resulting coal lithotype distribution would be one in which profiles from the center of the seam varied from non-banded coal at the base, to thick to thinly banded, loosely packed coal in the center overlain by thinly banded, tightly packed coal at the top.

In conclusion, it has been demonstrated that petrographical measurements conducted in a comparable manner can be used to ascertain the similarity or dissimilarity of peat and coal types. Although variation between deposits is inherent, models produced from quantitative data from the modern can provide analogues for the distribution of coal types within a seam, provided coal and peat types are assessed by similar attributes, such as size and/or composition as described in this brief study. Composition is linked to grain size in both peat and coal types; therefore the size and proportions of particles, including the amount and type of macroscopic banding, can be used to predict the composition of the coal in terms of the proportions of secondary xylem, other plant organs/tissues and matrix.

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SIZE ANALYSIS OF PEAT AND COAL

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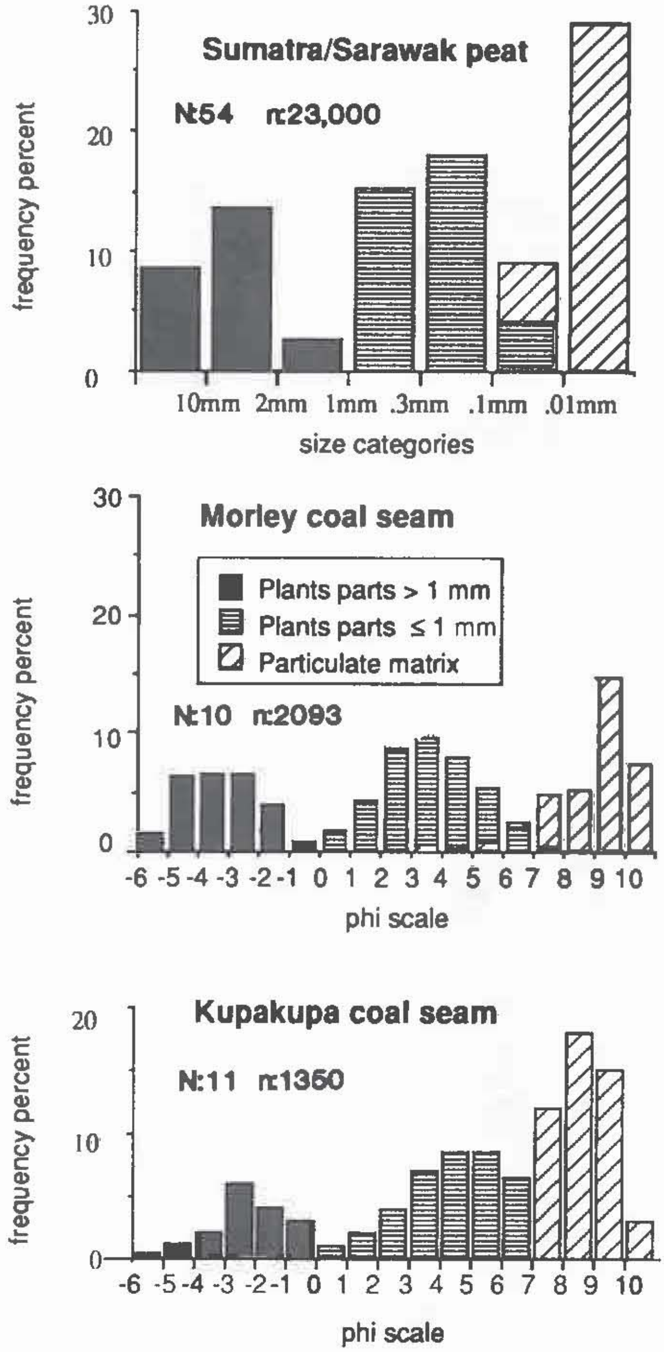


Figure 1. Combined megascopic and megascopic size distributions for the modern peat and New Zealand coals

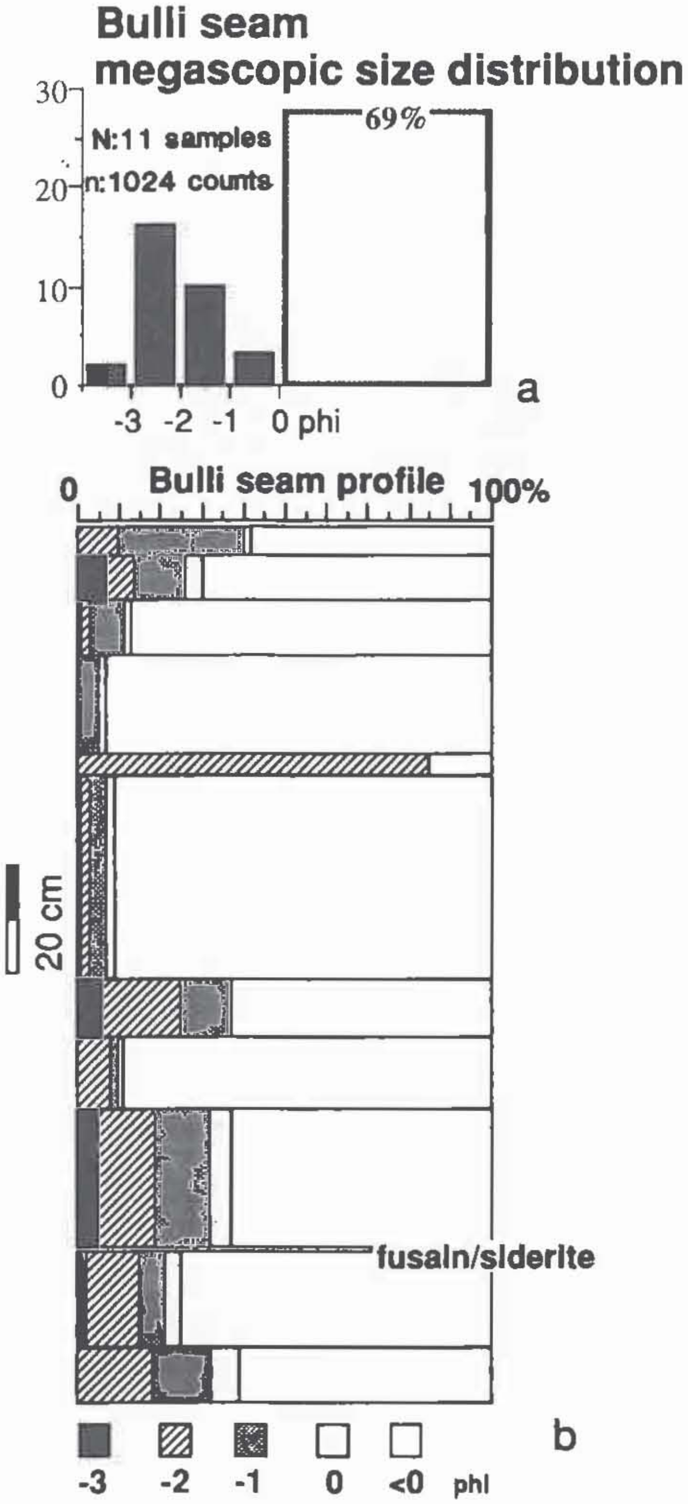


Figure 2. Bulli seam at Coalcliff, NSW.
a. megascopic size distribution; b. seam profile showing megascopic size distributions

SIZE ANALYSIS OF PEAT AND COAL

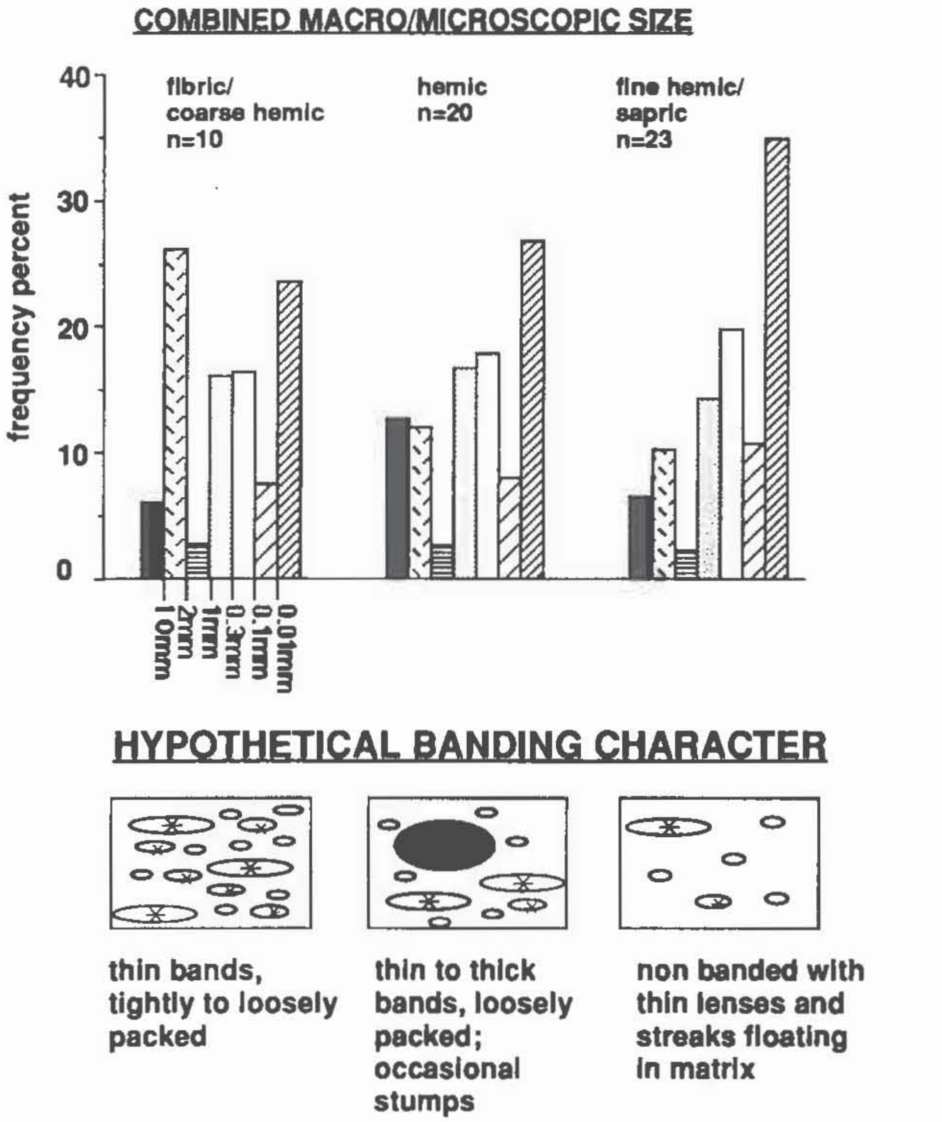


Figure 3. Combined megascopic and microscopic size distributions from peat types occurring in the Baram and Jambi peat deposits and the hypothetical banding character of the coal that might be derived from them.

# VARIATIONS OF BROWN COAL COMPOSITION IN RESPONSE TO RELATIVE SEA LEVEL CHANGES – LA TROBE VALLEY, VICTORIA

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Monash University

Marine ingressions into Victoria's Latrobe Valley brown coal fields have been interpreted by occurrences of marine foraminifera and dinoflagellates in the interseam clays and reservoir sands (Holdgate and Sluiter, 1991).

Figure 1 is a bore hole cross-section between Loy Yang and Sale. This illustrates the relationship between Morwell Formation brown coals, east of which a stacked sequence of Balook Formation sands is clustered against the limestone/marl marine Seaspray Group between Rosedale and Sale.

Ingressions from the main marine edge penetrate up to 30 kilometres inland advancing over pre-existing coal swamps and depositing seaward thickening interseams of clays (muds) and sands. Typically, the mud lithofacies containing marine fossils overlies the preceding coal seam with sharp erosional contact. Subsequent sand lithofacies thicken seawards, and locally may grade up into overlying coal.

Quantitative coal seam pollen data at Loy Yang (Sluiter, 1984) recognizes eight zones of interseam influence (IIZ's) through a 100m thick continuous sequence of the MIB coal seam. Eight interseam clay splits to the MIB coal seam can be recognized east of Loy Yang and are numbered 1 to 8 on figure 1. Of these splits, Nos. 1 and 7/8 are major and represent the boundary clays of the MIB coal seam. The remaining Nos. 2 to 6 die out east of Loy Yang. Nevertheless, they can be traced to Loy Yang, both from quantitative pollen data and coal composition, and demonstrate marine influence extended beyond the extent of the clay splits.

Figure 2 details the physical and chemical properties for the upper 48m of the MIB coal seam at Loy Yang from analysis of bore hole LY 1275 (King et al., 1983). The IIZ zones centred around the bore depths of 36m, 57m and 72m correspond to IIZ's 7/8, 6 and 5 respectively on figure 1. It should be noted the IIZ 7/8 is a composite of two splits, and is the recognized boundary between the MIA and MIB coal seams elsewhere - the two seams being joined in LY 1275.

The IIZ's in the coal can also be mapped in the Loy Yang open cut batters as erosional disconformities between dark lithotype coal infilling and overstepping a bevelled surface on medium light/light lithotype coal. It has been proposed (Holdgate, 1992) that these bevelled surfaces represent the maximum flooding surfaces of sequence stratigraphy, which were cut and later infilled with an allochthonous dark lithotype. Between maximum flooding surfaces (IIZ's) the coals show an upward lightening cyclical pattern. It was concluded that rising sea levels of the transgressive system tracts produced a lightening upwards lithotype cycle culminating in a catastrophic flooding and erosional event when the Balook Formation barrier sands were overtopped. The allochthonous dark coal infilling the eroded surface represents the condensed section, and the subsequent high stand systems tracts are largely absent from the coal sequence, but constitute the rebuilding period of the Balook sands. Hence a new cycle of coal formation did not recommence until the next transgressive period.

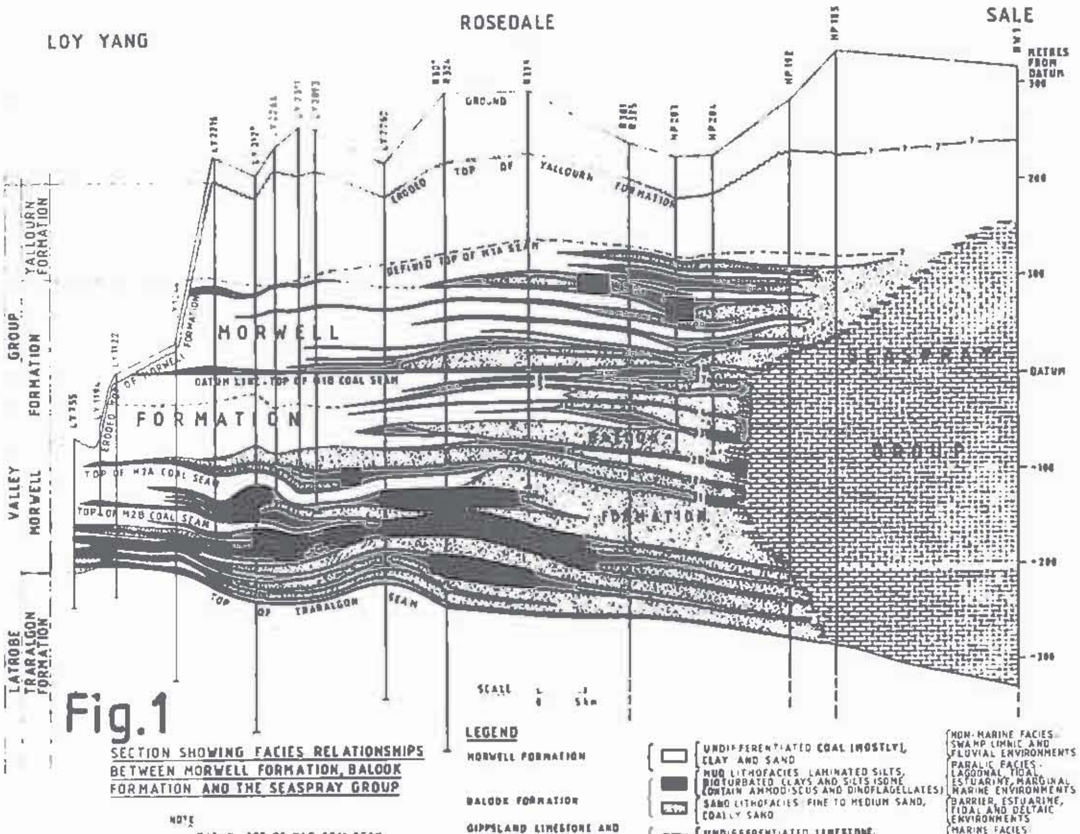


Fig.1
SECTION SHOWING FACIES RELATIONSHIPS BETWEEN MORWELL FORMATION, BALOOK FORMATION AND THE SEASPRAY GROUP

NOTE
DATUM TOP OF M1B COAL SEAM

LATROBE VALLEY COAL COMPOSITION AND SEA LEVEL CHANGES

Associated with these physical coal cycles are coal composition cycles graphed on figure 2. These include:

. Volatile matter tends to increase by 1% to 2% towards the top of each cycle.

. Moisture content decreases by 1% to 2% towards the top of each cycle.

. Sodium content (% dry basis) shows slightly higher values around the top of each cycle superimposed on an overall upwards sodium increase.

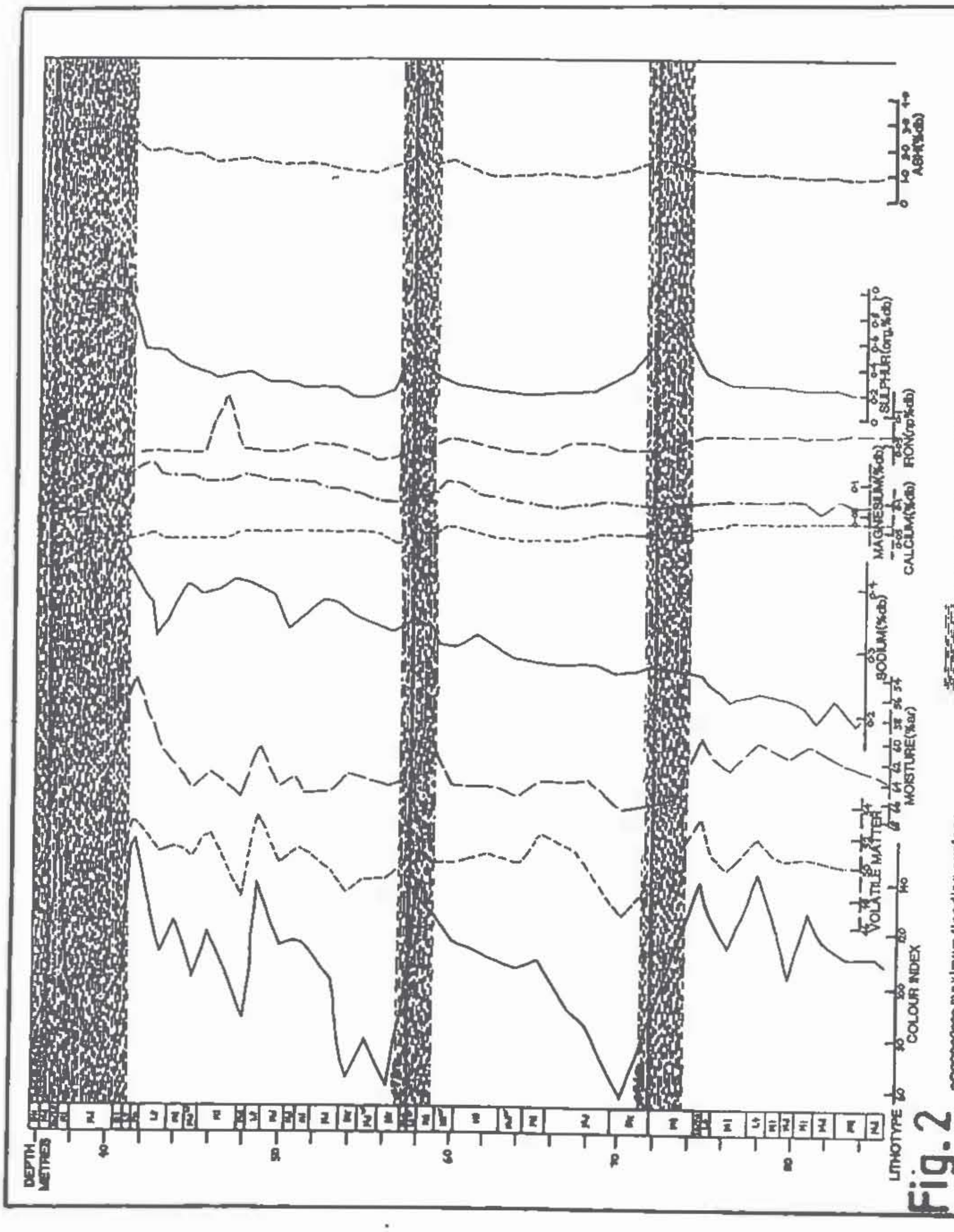


Fig. 2 LY 1275:RELATIONSHIP BETWEEN LITHOTYPE CYCLES, SEA LEVEL HIGHS, & THE DISTRIBUTION OF COAL PROPERTIES, MINERALS & INORGANICS FOR THE UPPER M1B COAL SEAM

. Calcium (% dry basis) shows little influence by the cycles.

. Magnesium (% dry basis) shows a slight rise near the top of the upper two cycles.

. Non pyritic iron (% dry basis) shows minor fluctuations with two peaks in the upper cycle.

. Organic sulphur (% dry basis) peaks occur at each cycle boundary with a major peak of 2.77% on the MIA - MIB boundary.

. Ash (% dry basis) shows minor increases at the lower two cycle boundaries, rising to 4.1% on the MIA - MIB boundary.

Regionally, the above vertical coal variations can be traced eastwards through the Flynn and Rosedale coal fields. Organic sulphur is particularly diagnostic and overall increases, both in maximum peak values and background values towards the marine interface. Moisture content also decreases eastwards and volatile percentage increases as the greater loading factor from the Balook sands becomes important.

West of Loy Yang data is less complete until the Morwell open cut area is reached. Here a small sulphur peak can be identified around the MIA - MIB boundary, but other marine ingressions may not be as obvious due to its remoteness from the marine influence. Nevertheless, the coal lithotype cycles are still recognizable.

In conclusion, it can be said that sea level changes have influenced the physical properties of the Morwell Formation brown coals which, in turn, reflect changes in their chemical properties.

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# THE PROBLEM OF SYN- VERSUS POST-DEPOSITIONAL MARINE INFLUENCE ON COAL COMPOSITION

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## Signatures of Marine Influence

It has been known for a long time that coal seams with marine roof sediments possess unusual properties, including high gas yield, high swelling, high coking pressure, extremely high Gieseler fluidity and dilatation. Some of these properties result from a higher than normal hydrogen content, which, together with the likewise elevated nitrogen and sulphur values, is responsible for a volatile matter yield too high for the degree of coalification of the coal (Teichmüller, 1955, 1962).

A high pyrite content is probably one of the most conspicuous characteristics of marine-influenced coals. The formation of this pyrite follows the reduction of sulphates contained in sea water by the anaerobic bacteria Desulphovibrio desulfuricans and Clostridium desulfuricans (Degens 1965). The process generates H2S which reacts either with organic matter to produce organic sulphur or, when available, with ferrous iron resulting in the syngenetic precipitation of pyrite (Casagrande 1987) or any of the other modifications of FeS2. There is a preference for pyrite to form under neutral to slightly basic conditions, whereas marcasite prefers a more acid environment according to Tarr (1927), Edwards and Baker (1951), Rosenthal (1956), Rickard (1975) and Littke (1985). In particular, the work of Sweeney and Kaplan (1973), Berner (1970), Berner et al. (1979) and Cecil et al. (1979) has shown that framboids of pyrite cannot be generated at low pH conditions, which is supported by Littke's (1985) observation of low framboidal pyrite counts in coal seams or parts thereof assumed to have been formed under acid conditions. Conversely, marine-influenced coal seams are generally high in their content of framboidal pyrite.

Another signature of marine influence is a low sulphur isotope ratio (Kaplan et al. 1963; Kaplan and Rittenberg 1964; Smith and Batts 1974; and Price and Shieh 1979; and others) because hydrogen sulphide formed by the bacterial reduction of sulphates is enriched in the 32S isotope. The ∂34 S values of bacterially concentrated sulphides are therefore lower than the isotope ratio of sea-water sulphate, currently at +20 per mil. Since bacteria have generally a low tolerance to the high acidity of most fresh-water peats, they function better under the slightly elevated pH conditions resulting from the mixing of peat- and sea water. This explains the contrast between Cassagrande's (1987) relatively high ($\partial 34$ S = +9 to +13 per mil) sulphur isotope ratios obtained from low sulphur fresh-water peats of the Okefenokee Swamp and the marine-influenced high sulphur Florida peats which yielded only negative values ranging from -8 to -30 per mil.

Marine influence raises the pH in the peat thus increasing bacterial activity which results also in biodegradation and loss of biomass, while bacteria-derived lipids are added to the humic degradation products (Diessel 1990). Because these bacteria share the same environment and are often associated with the above-mentioned sulphate-reducing bacteria, syngenetic pyrite is often found in coalified cell tissue (Belyaev et al. 1981; Given and Miller 1985). Marin-influenced coals are therefore characterised by low tissue preservation and a high proportion of detrovitrinite, detrital inertinite fragments, and liptinite. The latter tends to decompose under neutral to slightly alkaline conditions which leads to the formation of dispersed liptodetrinite and submicroscopic liptinite impregnations of humic compounds (Taylor and Liu 1987). The incorporation of bacterial lipids and absorbed and otherwise finely dispersed liptinitic material into the variously humified precursors of vitrinite increases the ratio between interstitial (intermicellar) material and the condensed aromatic framework. In terms of optical properties the consequences for marine influenced coals are a reduction in reflectance and an increase in fluorescence intensity of practically all humic degradation products (Lin et al. 1986; Lin and Davis 1988; Diessel 1990).

The high fluorescence and lowered reflectance intensities in coals carrying a marine roof are not evenly distributed throughout the seam profile but are concentrated closest to the source of the marine influence, i.e. in the upper seam section (Stevenson 1991). Excellent examples are the Greta and Pelton Seams in the Hunter Valley and the Eocene Brunner Coal Measures on the West Coast of the South Island of New Zealand. The latter were formed in a satellite rift associated with the opening of the Tasman Sea at a time when the sea began to invade the widening rift zone from the south. Coal formation took place under transgressive conditions such that peat accumulated in a marginally marine environment and was eventually covered by marine sediments. Based on a variety of analyses carried out on seam subsections, Newman and Newman (1982) and Newman (1985) could demonstrate an upward decline in vitrinite reflectance, which is associated with an increase in volatile matter yield and atomic H/C ratio, in spite of a simultaneous rise in inertinite content. Other changes include a marked increase in sulphur underneath the marine roof. Since Newman (1985) attributes these vertical changes to a gradually rising water table, the inertinite is interpreted as allochthonous material, which floated into the mire from peripheral areas during periods of flooding. This is supported by the association of the inertinite with an upward increase in clastic-derived ash, which is the percentage of ash minus ash from authigenic minerals (Newman 1986).

## The Timing of Marine Influence

Although there appears to be little doubt that the marine signatures listed above have been imprinted on the coal during its peat stage, the exact timing of this process has remained unclear. Basically two models can be established:

> Model 1. The peat accumulated in a fresh-water environment near the coast. Peat accumulation ceased by drowning of the seam following a marine transgression which resulted in the peat to be inundated by sea water and covered by marine sediments.
>
> Model 2. The peat accumulated in a coastal setting in contact with brackish or sea water, either on a lower delta plain, in an estuary, or on a tide-affected strand plain. Following its accumulation the peat was inundated by sea water and covered with marine sediments.

In the first model the marine influence affected a fresh-water peat epigenetically, i.e. after the seam was formed either in a rheotrophic or ombrotrophic (raised bog) setting. In the second model rheotrophic peat accumulation was the landward response of the depositional process to the transgression, i.e. the marine influence persisted syngenetically during peat accumulation and increased when the marine transgression began to overroll the seam. While the two cases differ in their respective biochemical environments during peat accumulation, they are subjected to the same post-depositional conditions so that similar, but not necessarily identical, marine signatures are acquired.

## The Significance of Marine Influence for Sequence Stratigraphy

The identification of compositional differences between coals affected by either of the two scenarios has attracted little interest in the past. However, the development of criteria for the distinction between syngenetic and epigenetic marine influence on coal seams would provide a powerful tool to test one of the basic assumption of sequence stratigraphy concerning the status of parasequences.

The basic sequence-stratigraphic units distinguished by Vail et al. (1977; 1987) and van Wagoner et al. (1987, 1990) are the parasequences, which consist of genetically related lithologic successions, such as offshore mud, shoreline sand, strand-plain coal, fluvial gravel and other lithofacies that coexisted within the time frame given by the enclosing stratal surfaces. Each parasequence is assumed to begin with a marine flooding surface along which a rapid landward shift of facies (transgression) has occurred followed by a period of relaxation during which the strandline progrades seaward and most of the sedimentation takes place. In this scenario coal occupies a position near the top of a parasequence (van Wagoner et al. 1990), i.e. the formation of coal occurs within the context of a marine regression. The landward shift of facies at the base of the next overlying parasequence may place the strandline so far inland that the coal at the top of the preceding (i.e. underlying) parasequence is covered by marine sediments and is subjected to epigenetic marine influence according to Model 1. An illustration of this case is given in Figure 1.

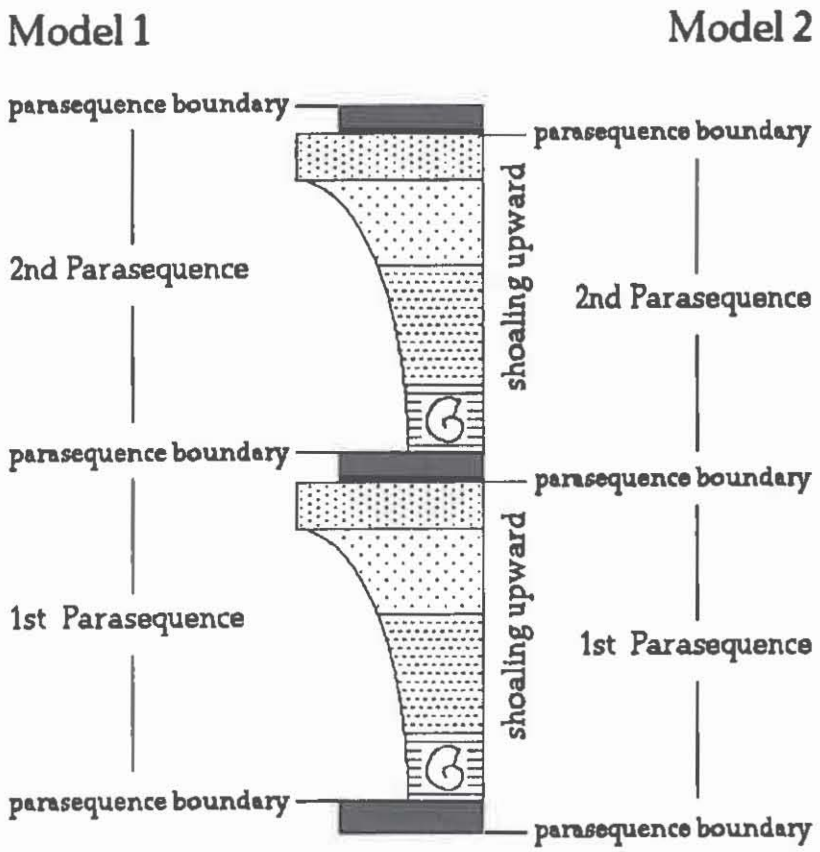


Figure 1. Cartoon illustrating the position of coal either at the bottom (transgressive coal formation) or the top (regressive coal formation) of a parasequence.

towards a drier environment during the actual peat-forming process. This means that fresh-water peat formed under Model 1-conditions would tend to produce a subhydrous coal due a relatively high ~~auto~~chthonous inertinite content. allo-

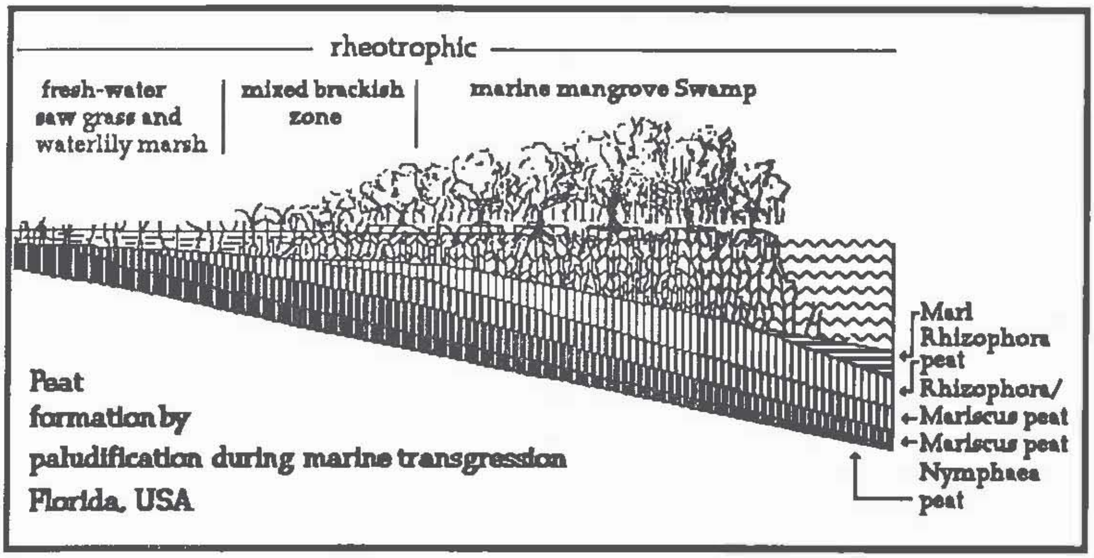


Figure 2. Example of a 4m thick peat seam extending 2.4Km into the Gulf of Mexico. The seam shows upward gradation from fresh-water Nymphaea to marine Rhizophora peat followed by marine roof sediments. Modified after Spackman et al.(1966).

In contrast to the above example of a marine influence causally related to a different parasequence (or sequence), the coal formation in Model 2 is the landward response to the transgression and therefore ushers in a new parasequence. Examples of such transgressive coals are the Greta and Pelton Seams in the Hunter Valley, the Katharina Seam in the Ruhr Basin (Diessel 1961) and the Lower Kittanning Seam (Habib et al. 1966; Ferm and Williams 1979) in the U.S.A., to name just a few examples. Such coals display a high degree of consistency between the various parameters of marine influence which reflect the causal links between seam formation and the marine transgression. The affected coal seams are often relatively thin and contain a high proportion of dispersed components, including alginite, inertodetrinite, framboidal pyrite, and shale bands with a high boron content. A matching set of palaeo-environmental indicators in the interseam sediments consists of clean, even-grained sandstone in the seam floor and bioturbated or fossiliferous shale in the roof.

The consistently wet conditions and increasing flooding of the peat under Model 2-conditions are indicated by a proportion of autochthonous inertinite and often high gelification indices. The latter are based on a high proportion in these coals of detrovitrinite (desmocollinite), probably due to a high contribution to the peat by soft-tissued plants and the high rate of

Peat formation under the transgressive regime at the beginning of a parasequence (Model 2 above and in Figure 1) is a scenario that does not fit easily into a sequence stratigraphic framework because the retrogradation of the strandline is considered to be too fast to leave behind a record of transgressive sediments. Yet, the composition of some coal seams, their field relationships, as well as Recent examples of transgressive peat formation are testimony of the validity of this model. For example, Spackman et al. (1966) describe an up to 4 m thick peat seam from southwestern Florida (Fig. 2) which underlies a 10 to 20 km wide inland zone of fresh-water saw grass marsh (approx. 1 m thick peat) and extends seaward underneath a 1 to 2 km wide brackish mangrove swamp. The seam could be traced up to 2.4 km into the Gulf of Mexico underneath a thickening overburden of marine marls. The seam has been formed over the past 4.5 ka in response to the Holocene marine transgression over the coastal area. Evidence for this is seen in the vertical peat profile consisting of fresh-water-derived saw grass peat at the base followed by brackish and then marine mangrove peat at the middle and upper portions of the seam. The superposition of marine Rhizophora (mangrove) peat on fresh-water Mariscus (saw grass) peat described by Cohen and Spackman (1972) from the Joe River area of southern Florida is likewise indicative of a marine transgression.

## Diagnostic Features of Syn- and Epigentic Marine Influence

The difficulty in making a clear distinction between syn- and epigenetic marine influence on coal composition stems from the fact that the anaerobic bacterial activity responsible for most of the marine signatures persists long into the post- depositional history of the seam. If therefore a fresh-water peat formed, for example, behind a prograding strandline (marine regression) is subsequently soaked in sea water in the course of a marine transgression the effects on coal composition are not dissimilar to an increasing marine influence during peat formation.

In coals formed under Model 1-conditions the marine roof is genetically unrelated to the underlying coal which shows only those criteria of marine influence which could be superimposed on it after peat accumulation had ceased. An example would be a high sulphur content and a concentration of pyrite near the top of the seam from percolating sea water, similar to the enrichment of sulphur found in the fresh-water peats of southern Florida in places where they are overlain by sulphur-rich marine or brackish peats (Cohen et al. 1984, 1987). In view of the ongoing bacterial activity during and after the transgression any remaining unoxidised precursors of vitrinite will be subjected to severe tissue destruction thus raising vitrinite fluorescence and lowering its reflectance, as is also the case in Model 2. At this stage, the main difference to Model 2 appears to be the tendency biodegradation under elevated pH conditions. The tissue preservation index is therefore also low, and there is evidence of a high contribution to the coal of cuticles. These have been partly corroded by the brackish water so that the recorded cutinite percentage probably does not fully represent its original input. Indeed, many marine-influenced coals show a decrease in liptinite due to chemical corrosion (Stach and Michels 1955/56; Teichmüller 1962), which is thought to occur when the pH of the peat water is raised above neutral point during prolonged contact with the alkaline sea water. This notion is supported by Pfaffenberg's (1953/54) observation of the preservation potential of pollen exines in Recent limnic peats. Well-preserved pollen grains and cuticles were always found in strongly acid peats, but their state of preservation deteriorated sharply with increasing alkalinity. Similar effects are common in some Carboniferous coals, particularly in the above-mentioned Katharina Seam of the Ruhr Basin, in which bleaching and corrosion of sporinite and cutinite are widespread.

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# COAL REQUIREMENTS FOR NEW IRONMAKING TECHNOLOGIES


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## 1 Introduction

The advent of new iron making technologies offers opportunities to the coal industry to diversify into new products. A common aim of all of the new processes is the elimination of coke as a reductant. A second motivation, not directly related to coal, is to eliminate the need for extensive iron ore preparation. These aims are in part a response by the steel industry to the economics of raw material supply and in part in anticipation of environmental pressures [1]. As a consequence of eliminating cokemaking the desirable characteristics of a good coking coal are no longer relevant. Indeed some characteristics such as a high volatile content, are actually disadvantageous in some of the new processes.

The properties of coals required for the new technologies relate to the way in which the coal reductant is introduced to the melt. Coal can be fed directly into a liquid iron bath or into slag floating on the surface of the metal. Alternatively carbon can be dissolved by liquid iron which percolates through a bed of coal char. This presentation will focus on the HIsmelt$^{TM}$ Process currently under development in Australia. In the case of the HIsmelt Process, coal is injected by a carrier gas stream directly into a bath of molten iron. Ideally coals for this process must readily dissolve in liquid iron. A further requirement are low levels of undesirable elements which would be carried by the coal into the iron. Tramp elements which may have an impact on process operation and product quality are a problem for all coals used in metallurgical processes.

## 2 A Review of the New Technologies

Progress is evident at several sites around the world in the development of new iron making technologies. There is a high level of activity in Europe, Australia, Japan, South Africa and the USA. Groups engaged in the development of new technologies include HIsmelt in Australia, Voest-Alpine who have installed a COREX plant in South Africa, and nationally coordinated projects in the USA and Japan. COREX, the process most advanced towards a commercial status was developed by Korf Engineering and subsequently commercialised by Voest Alpine. The HIsmelt Process under development in Australia grew out of research efforts in Germany by a partnership of CRA and the German steelmaker Klöckner Werke. Current development is being undertaken by HIsmelt Corporation, a joint venture between CRA Ltd and MIDREX Corporation of the USA.

Only a brief account of the technicalities of the emerging processes can be given here. For a more extensive explanation of the evolution of new ironmaking technologies reference should be made to the publications which are beginning to appear in the open literature [2, 3, 4, 5, 6]. Figure 1 presents an overview of current and potential future process routes to steel. The first route, conventional blast furnace technology, uses coal to produce coke which together with iron ore and fluxes forms the burden charged to the blast furnace. As a mature technology the blast furnace has reached a high level of technical refinement. The inherent counter-current interaction between solids and the gas stream means that high thermal and chemical efficiency is possible. Coke consumption of a modern blast furnace is of the order of 480 kg/tonne of pig iron produced. If the coke breeze used in an associated sinter plant is taken into account the equivalent coal consumption is 700-750 kg per tonne of product. This figure, which is being reduced as a result of further development, sets a fuel efficiency standard against which any alternative process must compete.

Notwithstanding its high fuel efficiency, the blast furnace suffers from a number of disadvantages:

- Iron ore must be in the form of more expensive and less readily available high grade lump or alternatively must be subjected to a preparatory process to turn it into sinter or pellets. This is necessitated by the requirement that the burden be permeable to the rising gas stream. Burden preparation is an added cost to blast furnace operation and presents environmental problems of $SO_x$, $NO_x$ and dust emissions.

- High grade coke is essential for the process. Coal suitable for coke making commands a price premium due to its scarcity and conversion cost and a cokemaking plant is a source of environmental pollution.

- New integrated steelworks are economical only on a large scale of the order of 3 million tonnes per year. Setting up or expanding a production facility is a major investment decision and extensive industrial infrastructure is required.

- The process has restricted operational and materials selection flexibility.

The second and third process routes depicted by figure 1 involve direct smelting of iron ore using coal as a reductant. The goal in developing any new iron making technology is to eliminate the problems associated with the blast furnace. In particular direct smelting processes promise to:

- use iron ore fines without any agglomeration step.
- utilize a wide range of coal types directly without the necessity of coke making.
- be economic at low production rates ranging up from 0.2-0.5 million tonnes per year. The inherently lower capital costs eases production planning decisions. Numerous environmental and social gains are implied by smaller geographically disseminated production units.
- address a growing demand for flexible and fast supply of custom made products for regional and niche markets that would not be large enough to justify traditionally large installations.

Direct smelting processes rely on the fact that carbon dissolved in molten iron or present as char in the slag phase in the practical temperature range of 1300-1600$^0$C forms a strong reducing medium. Air or oxygen blown into a molten bath leads to a reaction between the gas and the carbon present to form carbon monoxide. This reaction is very rapid. Molten iron has a high affinity for carbon and if coal is added to the iron bath its carbon content dissolves but the volatile components escape from the bath and contribute hydrogen and carbon monoxide to the off-gas. Simultaneously dissolving coal in a molten iron bath and oxidizing the dissolved carbon by oxygen injection produces an iron bath coal gasification process. If iron ore or partly reduced iron ore is also injected into the bath, then the process becomes an iron producer provided sufficient energy can be supplied to overcome the endothermic nature of the smelting reactions.

The engineering necessary to convert these chemical facts into a practical technology can be described by four basic process flowsheets. These flowsheets are presented in figure 2.

1. **Single stage process: Iron bath coal gasification** (Figure 2 A )
   All reactants are injected into the iron/carbon bath. If the iron ore is excluded, then the process is a coal gasifier. Pyrolysis of coal following injection into an iron bath is an endothermic process. The injection of oxygen through different tuyeres leads to the oxidation of dissolved carbon, a strongly exothermic reaction. By balancing the rates of coal and oxygen injection it is possible to maintain a constant bath temperature. The gasification process is a cooling mechanism, so the higher the volatile content of the coal, the greater is the consumption of coal to maintain a constant temperature. If a low volatile coal is used, then another means of cooling such as the injection of steam is used. In this case heat is absorbed by the endothermic reduction of steam to hydrogen and carbon monoxide. Only high grade coals produce surplus energy under coal gasification conditions.

   A single stage iron bath gasification process using high quality anthracite requires a minimum 2600kg of coal per tonne of iron produced if iron ore

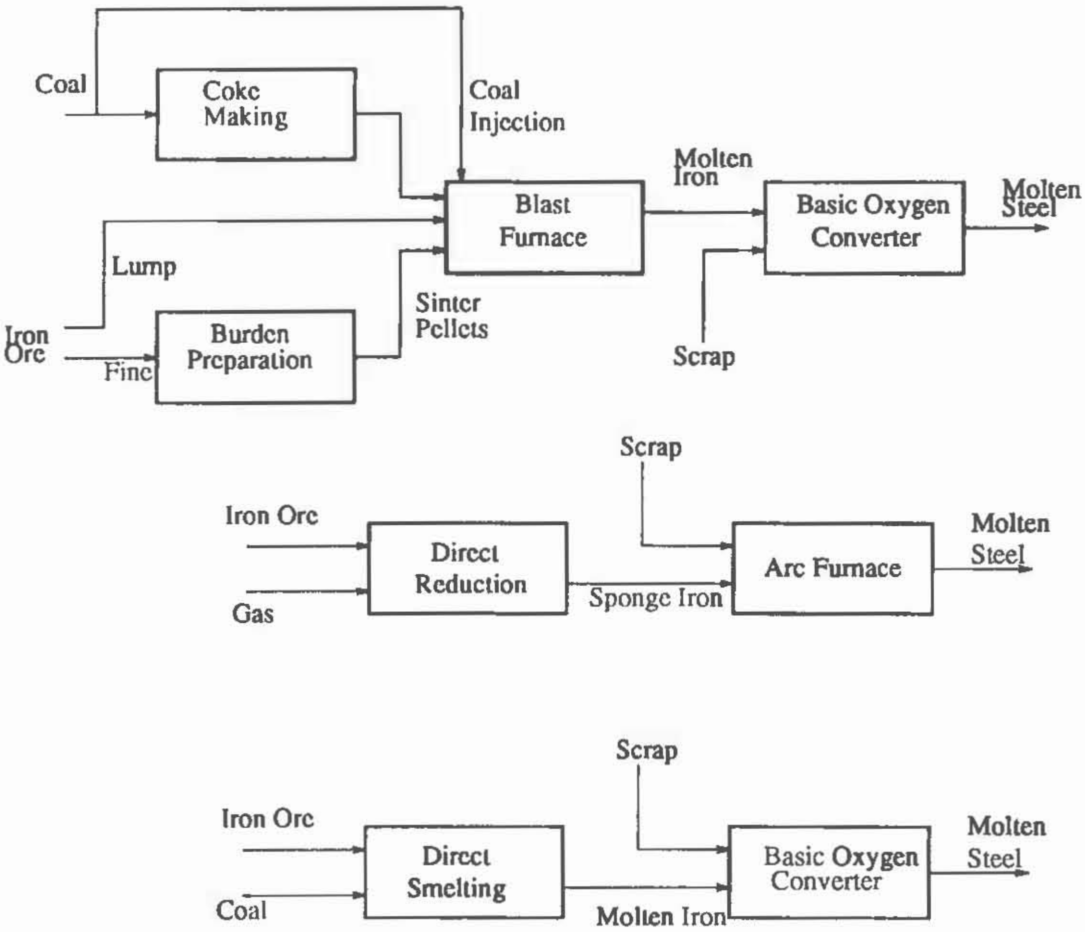


Figure 1: Block diagram illustrating various process routes to steel

is injected. Such a fuel requirement implies that a single stage process can only be justified economically as a gas producer. Klöckner Werke and CRA developed such a process for large scale coal gasification. KHD also had a similar process called MIP ( Molten Iron Puregas ). The motivation was to trap the sulphur content of the coal in the slag, metal and dust in response to the acid rain problem. With falling natural gas prices in Europe 1982 these projects did not proceed. A joint project by British Steel, ICI and the British Department of Energy to investigate the use of iron bath coal gasification as a source of feedstock for chemical synthesis was also discontinued.

2. **First Generation Smelting Reduction** (Figure 2 B )
   Instead of recovering the chemical energy of the carbon monoxide leaving the iron bath by post combustion it can be used to partially reduce or metallise the incoming iron ore feed stream. In addition some of the sensible heat of this gas stream must be used to pre-heat the ore for acceptable thermal efficiency.

   The linking of a coal gasification vessel with a Midrex type DR shaft implies a balancing between the use of chemical energy between the two stages.

COAL REQUIREMENTS FOR NEW IRONMAKING TECHNOLOGIES

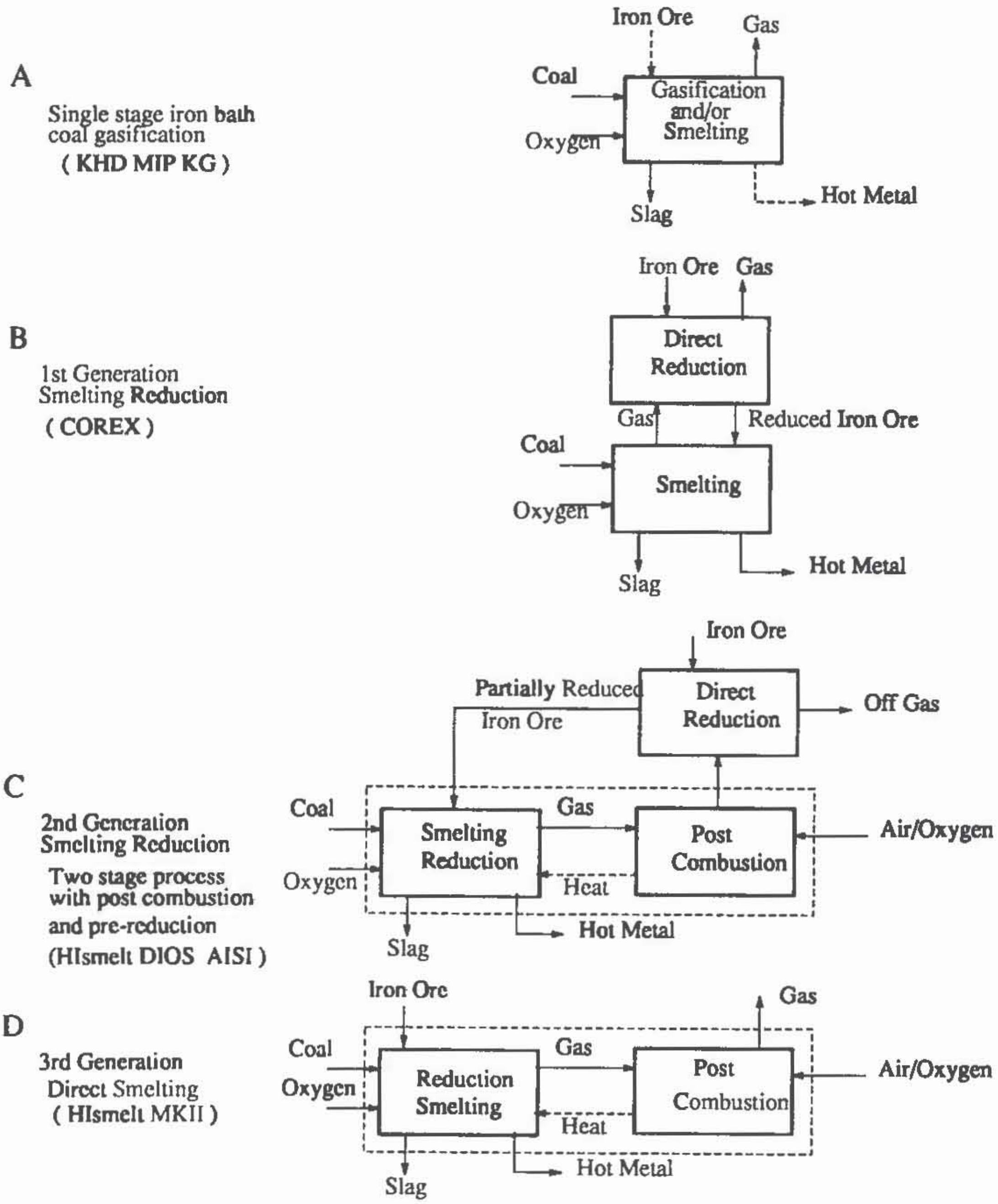


Figure 2: Evolution of a fuel efficient direct iron making process

Computer simulation indicates that the coal consumption decreases with both increasing degrees of pre-reduction and decreasing volatile content of the coal fed to the gasification vessel. Blast furnace equivalent coal consumption is only possible with a pre-reduction degree >90% and coal volatiles of <10%. Chemical equilibrium constraints link such a high degree of pre-reduction with a high residual fuel value of the process off-gas. This means that this approach is most attractive in situations where there is a market for the excess gas. The COREX process which will be described in more detail later is based on two stage smelting reduction without post combustion.

3. **Second Generation Direct Smelting** (Figure 2 C )
If there is no requirement for excess energy in the process off gas then it is logical to convert as much energy as possible within the smelting operation. The combination of post combustion with a pre-reduction step allows this to be done. Post combustion is the process of injecting air or oxygen into the topspace above the iron bath. Provided the heat generated from post combustion of gases liberated by the bath can be transferred back into the bath, large savings in fuel are possible. The fuel saving arises from the release in energy through the oxidation of the carbon monoxide generated within the bath to carbon dioxide. Under the conditions within an iron carbon melt, carbon monoxide is in chemical equilibrium but if this species leaves with the off gas only about 15% of the chemical energy available from the full oxidation of carbon is liberated. By aiming at an intermediate degree of pre-reduction it is possible to operate with a far lower residual fuel value in the gas leaving the process. This means that energy can be extracted from the gas stream through post combustion in the smelting vessel. The HIsmelt, DIOS and AISI processes are based on this approach. Computer optimization studies indicate that by operating the plant with 55% post combustion and 22% pre-reduction coal consumption rates comparable to the blast furnace can be realized. Pilot plant operation has been consistent with these predictions [3, 4]. The low residual fuel value of the off-gas can be used to advantage to pre-heat the air for post combustion and so contribute further to fuel economy.

4. **Single stage direct smelting with post combustion** (Figure 2 D )

The practical outcome of post combustion is a substantial reduction in the consumption of coal per tonne of hot metal produced. If both a high degree of post combustion and heat transfer efficiency could be realised it would be possible to dispense with a pre-reduction stage. To achieve the coal consumption equivalent of a typical blast furnace a single stage direct smelting process would need to operate with at least 60% post combustion and 85% heat transfer efficiency. This level of performance is based on the retention of an ore pre-heating stage although pre-reduction is eliminated. Research directed at these targets is underway and if realized a single stage direct smelting process

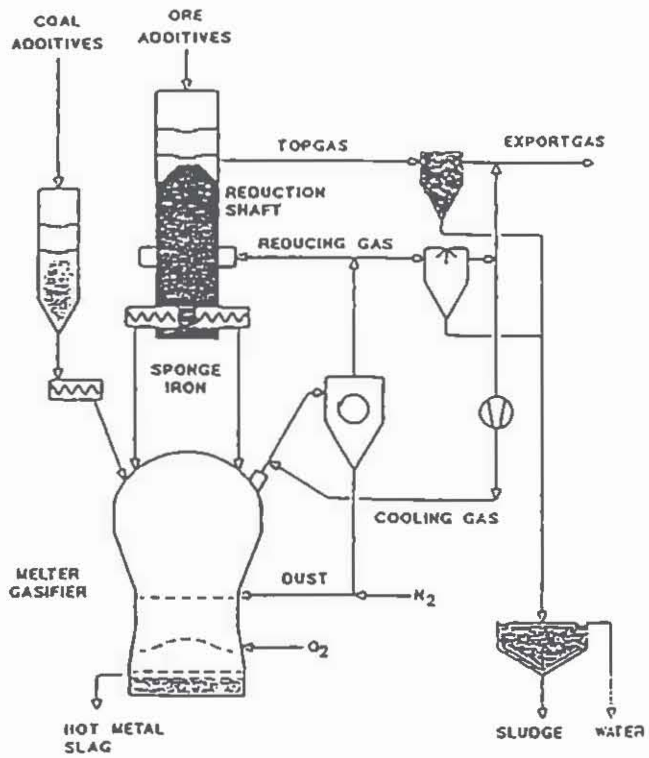


Figure 3: COREX Plant configuration

based on post combustion would be a simple and effective rival to the blast furnace.

## 3 Emerging Processes

### 3.1 COREX

COREX is a two stage process without post combustion. Figure 3 gives a simplified outline of a COREX plant [5]. Coal is fed to a melter-gasifier where it reacts with oxygen to produce gas rich in carbon monoxide. Some of the carbon content of the coal is dissolved by liquid iron percolating through the moving bed of char. The gas from the melter-gasifier is used to reduce the raw ore feed in a direct reduction shaft. The ore is almost completely reduced to metallic iron (93% oxygen removal) before being fed to the melter-gasifier. To achieve this degree of pre-reduction the gas entering the shaft must have a high reducing potential. Even though the shaft is a counter-current reactor not all of this chemical energy can be recovered by reduction and the gas leaving the shaft has a high residual fuel value. It follows that economic operation of a COREX process depends on a market for this gas.

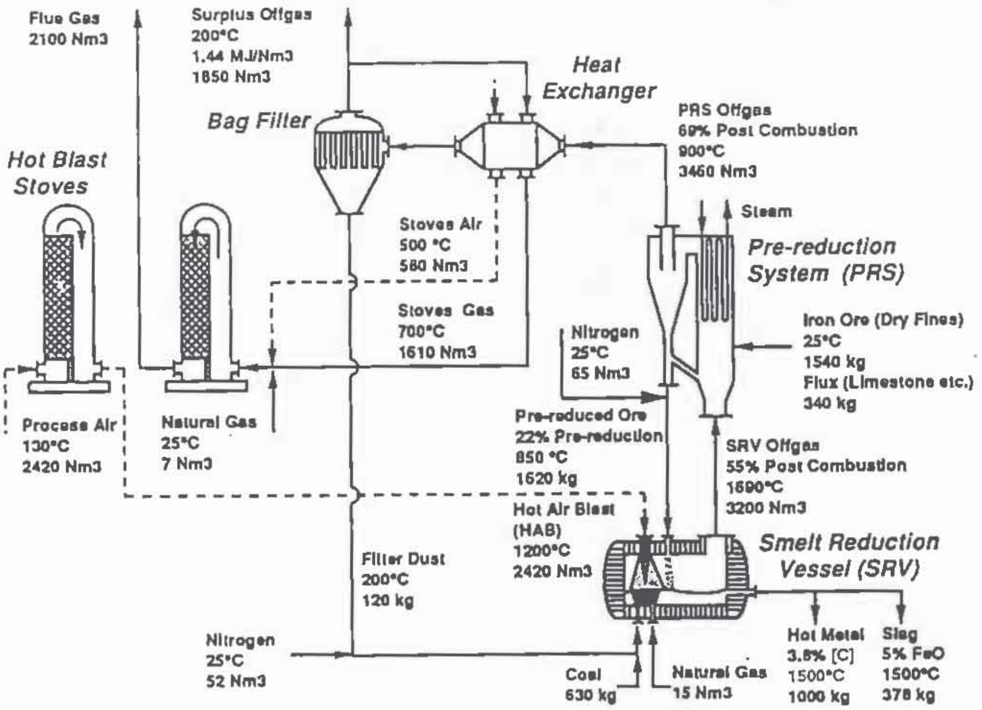


Figure 4: HIsmelt Process flowsheet

### 3.2 HIsmelt

The HIsmelt Process is based on two steps. Fine coal and ore are injected into a liquid iron bath in a **S**melting **R**eduction **V**essel (SRV). A high degree of post combustion takes place in the top space above the bath due to a jet of pre-heated air or oxygen [4]. Much of the sensible heat and chemical energy remaining in the offgas stream is recovered in a circulating fluidized bed pre-reduction system (PRS). The degree of post combustion in the SRV means that approximately 20% pre-reduction occurs but the gas leaving the PRS has a lower fuel value. The key to successful operation of HIsmelt is to achieve a high degree of post combustion (>50%) and heat transfer efficiency (85%) in the SRV.

### 3.3 The DIOS and AISI Experimental Programs

As the DIOS project in Japan and the AISI project in North America are less developed than COREX there is less information published about either. In HIsmelt the simultaneous realization of high post combustion and heat transfer efficiency is dependent on careful attention to the fluid mechanics in the SRV. An alternative approach utilised by both the DIOS and AISI projects involves the use a deep slag layer in a steel converter type SRV as a medium for heat transfer and chemical reactions. So far as coal suitability is concerned there is are significant differences

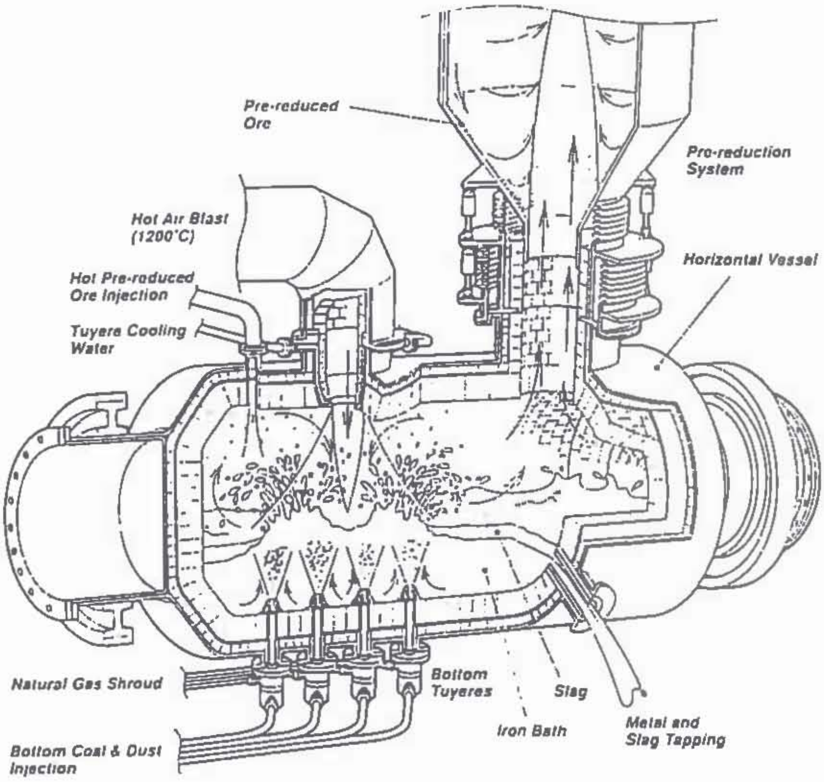


Figure 5: HIsmelt smelt reduction vessel

between COREX, HIsmelt and the DIOS-AISI approaches. In DIOS or AISI coal is introduced into slag rather than liquid metal with HIsmelt and a moving bed as is the case with COREX.

## 4 Discussion of Coal Requirements

COREX and HIsmelt have undertaken pilot plant trials to test a variety of coal types. Pilot plant and laboratory studies have established a preliminary coal specification for COREX [6].

For both COREX and HIsmelt the volatile content of the coal is an important consideration. The gasification of high volatile coals absorbs heat energy which would otherwise be available to the process. This gasification energy leads to a higher consumption of coal per tonne of product with COREX due to a reduced smelting capacity in the melter-gasifier. The achievement of high post combustion values in direct smelting processes means that a large portion of the energy used in gasification can be recovered. This means that high post combustion processes are less sensitive to coal volatile content and can operate satisfactorily as demonstrated by pilot plant trials [3]. Ash content increases coal consumption in all smelting processes, however smelting and fluxing gangue components does not have the same influence as volatile content. This is a consequence of heat and mass balance considerations. This trend is clear in figures 6 and 7 which summarise the performance of both processes with a range of coal types. The requirement for a low volatile content in general translates to high rank in traditional coal classification.

The differences in the way in which coal is introduced into the various processes are reflected in the priority attached to some mechanical properties.

For COREX the coal particles must be smaller than 50mm but an excessive proportion of fine particles less than 2mm has an adverse effect [6]. The proportion of such fines should not exceed 10% . It is interesting to speculate that the resistance of the coal char to slumping in the melter-gasifier is important but there does not seem to by any reference to this requirement in the literature on the process.

In HIsmelt the coal is injected into the iron bath with an inert carrier gas stream. This means that the coal must be reduced to a particle size less than 2mm. In this respect the situation is the opposite to COREX, the fines content is not a problem but there is a need to grind the coal.

For both COREX and HIsmelt high ash is undesirable for the following reasons:

1. The ash component of the coal lowers the available carbon.
2. Not only must energy be expended in fusing the ash and raising it to slag temperature but the problem is compounded by the need to inject additional fluxing agents to keep the slag composition within desired limits.
3. In both processes, some components of the coal ash may be incorporated into to product which implies more expensive refining operations downstream.

The deep slag based processes, DIOS and AISI have less information published about coal requirements. It is natural to assume that dropping coal into a layer of slag will lead to different coal requirements than injection into liquid metal or pyrolysis followed by absorption of carbon by percolating liquid iron. There may be some benefit in volatile content in helping to promote a degree of foaming of the slag layer. DIOS are pursuing an offgas reforming step where coal fines are injected into the offgas stream. The aim is to char the coal, reform the volatile components and cool the offgas below 1200°C.

## 5 Conclusions

The developers of new iron making processes have realized the goal of avoiding dependence on coking coal. In the case of COREX parameters that define a good coking coal are of little relevance. The same can be said to apply to HIsmelt. No doubt as these processes gain commercial acceptance and effort is directed at optimizing their performance, significance will be attached to subtle differences in ash chemistry, mechanical properties, and maceral content at a given rank.

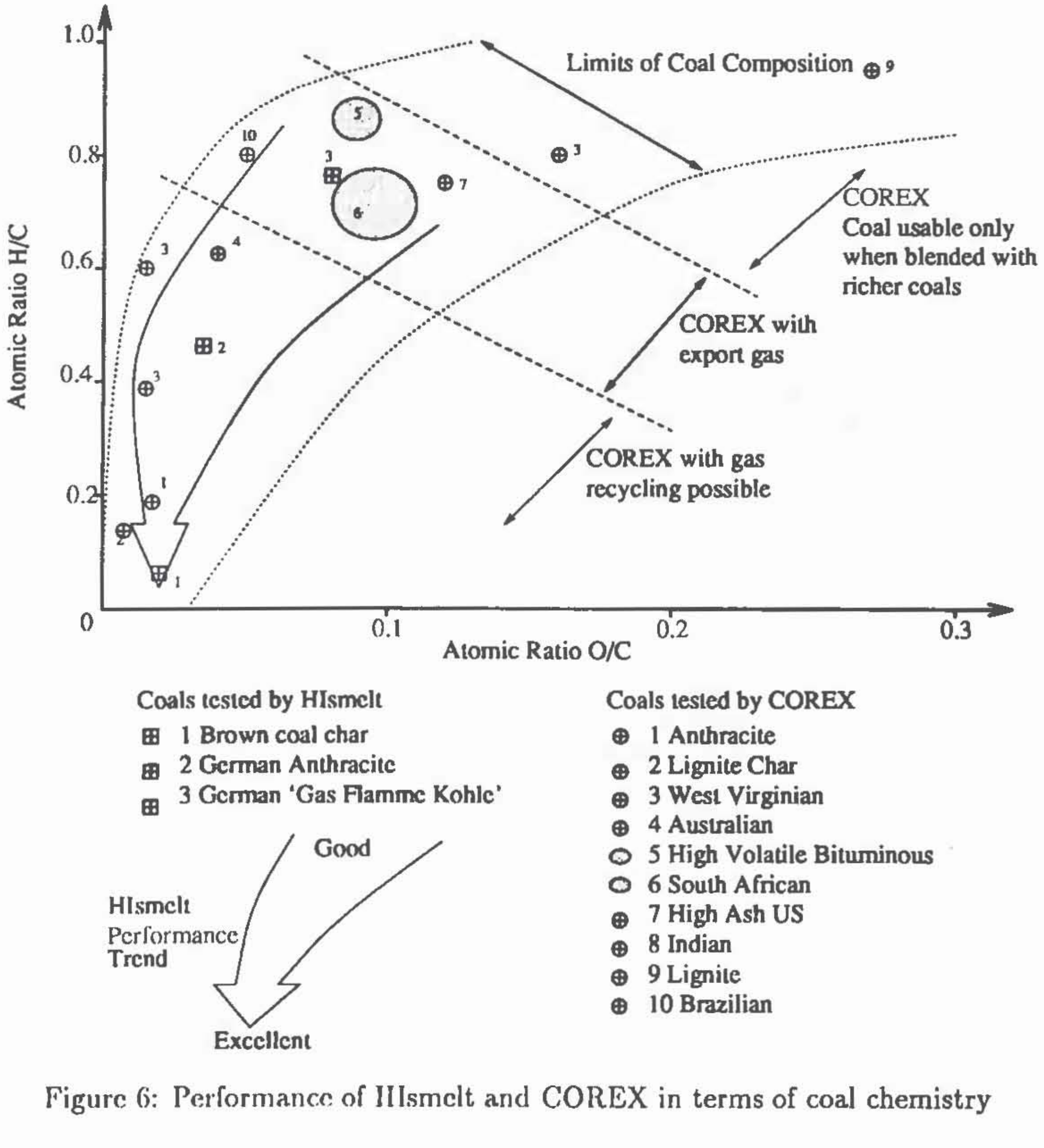


Figure 6: Performance of HIsmelt and COREX in terms of coal chemistry

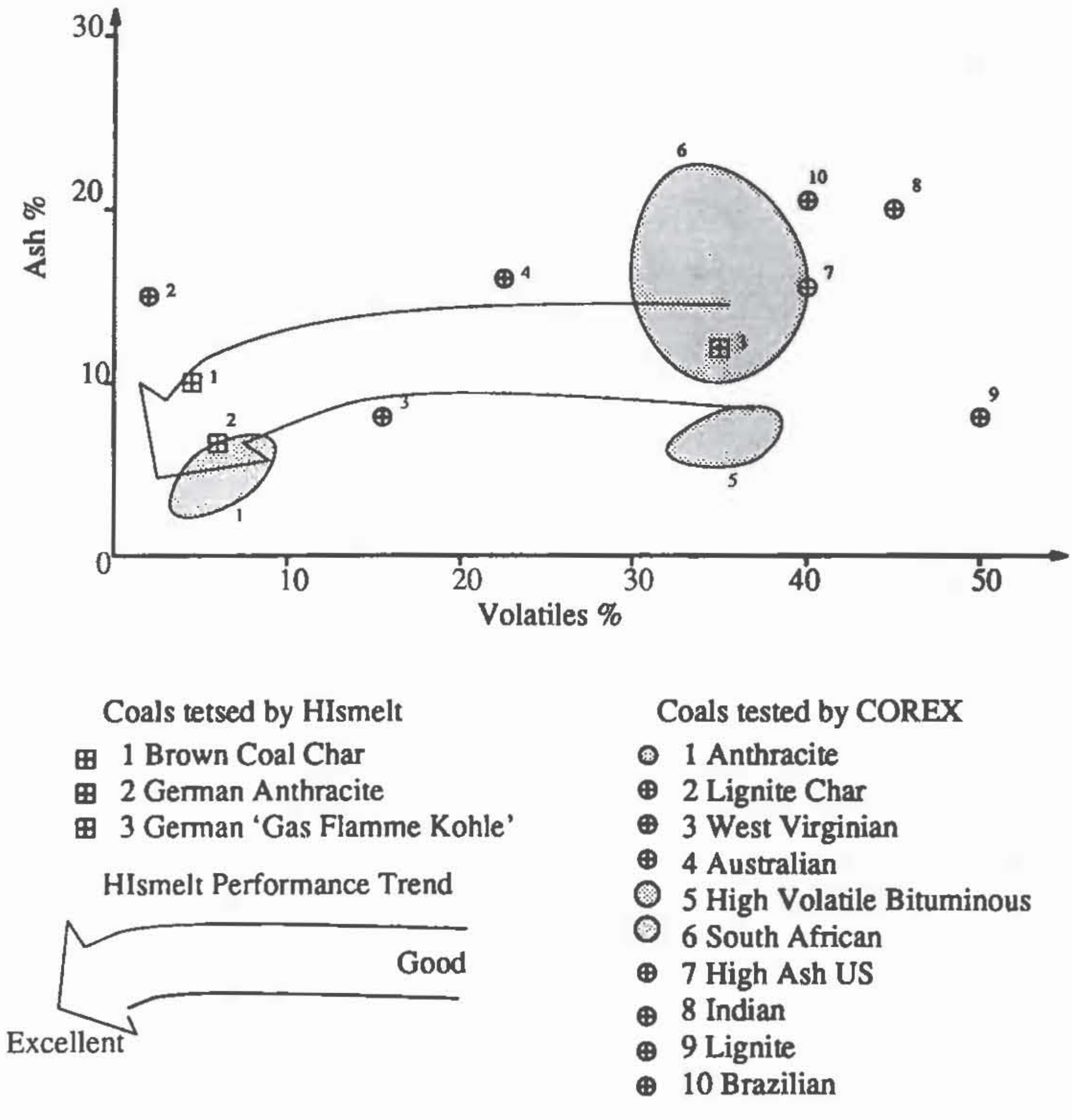


Figure 7: Performance of HIsmelt and COREX in terms of coal ash and volatiles content

## 6 Acknowledgments

The authors are indebted to Dr. D.S. Conochie of CRA and Mr. G.J. Hardie of HIsmelt for technical discussions concerning the influence of coal type on smelting reduction process performance. Dr J.K. Wright gave valuable guidance in the drafting of this paper. Technical information supplied by the HIsmelt Corporation was used in the preparation of this paper.

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# CALCULATING RESERVES – A MATTER OF SOME GRAVITY

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## SUMMARY

Determination of the in-situ density of coal from borecores is essential for the accurate estimation of reserves, especially for low rank (high bed moisture) coals. There is a confusion of terminology describing different types of density, and a wide range of opinion on the relevance of each type to the subject of reserves.

In the past laboratory results, determined on air-dry coal, have been used as the relative density of bed moist coal in situ, with obviously erroneous results.

A study carried out by Quality Coal Consulting for Pacific Coal concluded that, providing the bed moisture and the moisture of the analysis sample are accurately known, the density of the coal in-situ can be determined with acceptable accuracy from the relative density determined using the density bottle method, providing that the basis is changed as follows:

Relative density (in-situ) = $\{RD_{ad} \times (100\text{-}M_{ad})\} / \{100 + RD_{ad} \times (TM - M_{ad}) - TM\}$

## 1 INTRODUCTION

The relative density of coal is a fundamental physical parameter which should be well understood by geologists, who need to know the in situ relative density of coal for use in reserve calculations.

In spite of this, the relative density of coal appears to be a subject which is poorly understood. The literature is of little assistance, with virtually no practical definitive work on the subject having been identified, apart from that of Smith (1991). Hence the application of relative density in reserve calculations is often at best uncertain, at worst incorrect.

A study by Quality Coal Consulting Pty Ltd, for Pacific Coal Pty Ltd, aimed to identify a method for estimating the in situ relative density of coal, so that it can be reliably used in determining coal reserves. Ancillary study aims were to obtain a better understanding of the subject, the terms used, tests applied, and the causes of variability in results. Paramount in the study was consideration of the relationships between coal density, coal porosity and moisture.

This paper discusses some of the major findings of the study.

# 2 OBSERVATIONS

## 2.1 Porosity

It is well established that coal is a porous substance, and that both the pore size distribution and total pore volume (porosity) vary, depending on a number of factors.

The pore sizes have been conveniently grouped into three types, by a number of researchers:

| | |
|---|---|
| • Large pores | with diameters greater than 30 nm (30-3000 nm) |
| • Intermediate size pores | with diameters of 1.2 to 30 nm |
| • Micropores | with diameters less than 1.2 nm in size. |

Sub-bituminous and lower rank high volatile bituminous coals tend to be relatively high in total porosity and have a high proportion of intermediate size pores. High rank bituminous coals have no intermediate size pores and appreciable microporosity (>50%). Lignites have little pore volume in the intermediate sizes, and have high levels of macroporosity.

## 2.2 Definitions

### *2.2.1 Density*

The density of a material is its mass per unit volume, usually quoted in $kg/m^3$ or $g/cm^3$. Prior to metrication, this property was known as specific gravity.

### *2.2.2 Relative Density (RD)*

The density of water is 1.0 $g/cm^3$ at a temperature of 5°C. So the relative density of a material is its density, relative to the density of water at 5°C (taken as 1.0). This property is a ratio and is, therefore, dimensionless. It is numerically equivalent to the value of the density of the material.

Clearly all determinations of relative density require the mass and volume of a sample to be measured. The mass determination is always simple. However the volume determination is the one which causes problems, both of measurement and of understanding, in heterogeneous materials such as coal. This relates especially to the porous nature of the coal and the variable degree to which the different methods cope with this aspect of the determination.

## 2.3 "Types" of Relative Density Determinations

### *2.3.1 "True" or "Absolute" Relative Density*

These terms should only be used to describe the relative density of a unit volume of dry, pore-free coal. In practice coal may exist dry, but it is never pore-free. *Pore-free in this sense means that in determining the volume of the sample, the medium used must occupy all pores.* In practice this is difficult. The helium density method is the recognised method for determination of this parameter. Helium, being the smallest atom, has the best chance of penetrating the greatest number of pores, although it is recognised that there are some pores that even helium does not penetrate.

Because coke has very large pores, the results obtained in water by the density bottle method are said to give the "true" relative density. Unfortunately, many results determined in the past on coal by this method have also been (incorrectly) referred to as "true" relative density.

The availability of consistently reliable true or absolute relative density values for coal would make the estimation of in situ relative density a relatively straightforward process.

*2.3.2 "Apparent" Relative Density or "Coal Particle" Relative Density*

This term describes the relative density of lump coal which may contain pores, fissures and moisture. The degree of preservation of these features in the actual sample can be variable. Because of this fact, and the relative imprecision of the method (displacement of water by lump coal in a bath), the results are regarded as relatively unreliable. The method is described in AS1038.21 Item 5.

A more precise method of determination exists, namely the mercury density method. However, like the helium method, it is not available on a routine basis. If the method was generally available and the sample condition known to be similar to that in situ, (particularly regarding moisture), then this method could be used to directly estimate in situ relative density. Unfortunately this is not the case.

*2.3.3 In Situ Relative Density*

This refers to the relative density of coal in the ground. The coal, under confining pressure, contains pores and fissures filled with water and dissolved gases. The relative density of the coal in-situ is the value required for estimating coal reserves. It may be readily calculated from length (in-situ), diameter and mass of impeccably preserved core lengths.

*2.3.4 Relative Density "AS1038.21 Item 4"*

The most common method of determining coal density is by use of this Australian Standard method. Most coal geologists have vast sets of relative density measurements of this type. Whilst the method is cheap and easy to apply, the state of the sample, when tested, does not simulate the in-situ condition of the coal. That is to say, the sample is:

- ground to -212 μm size, thereby removing fissures and some pores
- air-dried i.e. retaining some, but not all of, its in situ moisture.

The method involves measuring the amount of liquid displaced by the coal, either in a density bottle or in a volumetric flask, and hence determining its volume. This is then related to the original weighed mass. The major problem with the method is the inability of the liquid (either water and wetting agent under vacuum, or methylated spirits) to occupy all pores within the coal i.e. to displace all air and water.

The result gives neither absolute relative density nor in situ relative density. However it probably approaches the former more closely than the latter. For example, experiments carried out by Ettinger and Zhupakhina (1981) compared the results obtained for coal using the density bottle and helium porosimetry methods. In the former test, the coal was ground more finely than usual, and the water and wetting agent boiled to facilitate pore penetration. Agreement between the methods was excellent, for a wide range of coal types and ranks. Thus, under certain rigorously controlled conditions, the Standard density bottle method may give results closely approximating the "true" or absolute relative density for coal (expressed on the air-dry basis).

Prior to the publication of the Australian Standard method of determining relative density using the density bottle, the method commonly used in Australia was the NCB Analyst's Handbook Method, on which the current Standard is substantially based. (NCB was the British "National Coal Board", now British Coal).

Note that the top size of the test sample is 212 µm, while the diameter of a typical macropore is only 0.01 mm. Clearly, whilst much of the test sample is finer than 212 µm, many of the pores are much finer than the particles. Some of the pores are removed in grinding; some are not.

For purposes of further discussion the relative density value determined according to the AS1038.21 Part 4 procedure will be referred to as the standard relative density.

## 3.3 Relative Density Values NOT to Use in Determining Coal Reserves

### *3.3.1 Standard Relative Density*

As noted, these relative density values are cheap and plentiful. It could be claimed that this abundance gives a wide lateral and vertical picture of any coal seam and hence the values are statistically significant i.e. a lot of incorrect values are better than a few correct ones.

However, the standard relative density does not replicate the conditions which need to be met in a determination of in situ relative density. In simple terms, the sample tested is on the air-dry basis, whereas the reserves of coal in situ are not. Consequently the result should not be used for coal reserve calculations.

Use of the standard relative density in reserve calculations is estimated to result in an overstatement of reserves of 2.5 - 4.5%.

### *3.3.2 Standard Relative Density - Adjusted UP for Moisture*

Some reserves estimators have recognised the fact that the values determined by the Standard method are reported on an air-dry, rather than in situ, moisture basis. To compensate for the lower moisture value of the sample, they have made a moisture adjustment in much the same way as coal masses are factored up to allow for moisture increases. Thus, the erroneous calculation has been made as follows:

RD in situ = RD air dried x (100 - Moisture air dried) / (100 - Moisture in situ)

This process increases the relative density but incorrectly so. It is based on the premise that adding water to the coal must make it more dense. This would be true if water could be added without any increase in volume i.e. that the number being adjusted (RD air dried) represents a state where pores, fissures etc. are preserved but are only partly water filled. This is not the case. The coal in the Standard test has much of its pore space and contained moisture removed. The remaining moisture is contained in closed pores or bound to the margins of pores. The moisture lost on air drying cannot be added without first 'adding' the pores back in, thereby increasing volume.

Adjustments of this kind can easily add an error of 4 - 6% to an already overstated relative density figure.

### 3.4 The Change of Basis Equation

The correct equation to use for the conversion of coal relative density from one moisture basis to another is:

$$RD_2 = RD_1 \times (100-M_1) / (100 + (RD_1 \times (M_2 - M_1) - M_2))$$

| where | $RD_1$ = old RD | $M_1$ = old moisture |
|---|---|---|
| | $RD_2$ = new RD | $M_2$ = new moisture |

When considering how to convert coal relative density from the Standard basis to an in-situ basis, it is instructive to first consider what happens to the coal when being processed in the opposite direction, i.e. when it is converted from in-situ to Standard basis. The following processes are believed to occur:

- Fissures are removed by grinding, and any contained water is drained or driven off in the drying steps.
- With the exception of micropores, all other open pores (i.e. pores intersected by coal particle faces) are either removed or opened to penetration by the displacement fluid. Contained water is driven off during air drying.
- Closed pores are retained, together with their contained water.
- Some open micropores are removed, and their water driven off. Many lose some of their water in air drying, and possibly some of their volume. These pores may not all be filled by displacement fluid and therefore their volume may not be entirely lost.

In the process of converting a coal sample to a ground, air-dry, state the volume is reduced by removal of pores and contained water. This reduction in volume has a greater effect on the relative density than has the loss of mass held in that volume. Thus the relative density of the sample is effectively *increased* by this process. More simply put, as voids and contained water are removed, the density of the sample trends towards the absolute density of the coal.

The estimation of in situ relative density, from values determined by AS1038.21 Part 4, involves reversal of the process described above. The voids must be 'restored' to their original state and refilled with water. In doing this both the mass and volume of the sample will increase, but the volume will increase at a greater rate than mass. Hence, sample density will *decrease*, trending towards 1 (the relative density of water).

The process of restoring the voids and refilling them with water is simulated by the change of basis equation.

In conclusion, it is considered that the change of basis equation, given reliable input, will enable relative density of coal to be converted from one basis to another. In particular it is the appropriate formula for estimating in situ relative density from standard relative density.

## 4 PRACTICAL APPLICATION

The AS1038.21 Item 4 method of relative density determination should continue to be carried out routinely. As previously noted it is cheap and readily available and therefore does allow a large spread of results to be obtained. Boiling should be used by the laboratory, instead of evacuation, to maximise pore penetration by the test water.

It is also important to acknowledge that:

- the method is relatively precise,
- it is an good indicator of relative density variations resulting from mineral matter content (on the air-dry basis),
- it is the reference point from which the in situ relative density can be estimated.

Clearly estimation of in situ relative density from the above requires accurate determination of in situ moisture. This is not an easy property to measure. However it should not be omitted because of this fact. Knowledge of in situ moisture is important both to density calculations (hence reserves, coal handling mass calculations, etc.) and to estimation of product coal total moisture.

It is recommended that for all deposit evaluations, particularly where it appears that a significant resource may exist, a systematic effort to determine in situ moisture should be made.

Sufficient samples should be taken to represent the normal range of ash values. If there are significant rank and/or type variations these should also be represented in the sampling. In general, it is thought that sampling should be done by coring; chip samples are too finely divided and will contain free moisture. Coring by clean water circulation will probably be necessary to avoid air blast drying of the coal. Prompt bagging and sealing of the core, and total reclamation of the moisture at the laboratory, will be necessary.

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# ON ASPECTS OF STRATA CONTROL IN COLLIERIES OPERATING IN THE SYDNEY BASIN

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ABSTRACT

The technical term "strata control" has been part of the mining engineering and rock mechanics nomenclature for more than 50 years, and is now regarded as a standard term by many researchers. It generally describes scientific and engineering efforts to understand, and to devise means for the control of energy release processes in coal seams and in their floor- and roofstrata in response to disturbances by mining. It may also be useful to regard the term as a description of engineering measures and actions to prevent the occurrence of irreversible deformation and failure in the floor- and roofstrata of coal seams.

The control of strata behaviour during development and extraction operations in modern collieries is of great importance, as their economic success depends on the predictability of the floor- and roofstrata's responses to either partial or total mechanical extraction of coal seams.

The mechanical response of floor- and roofstrata to mining is governed by the interaction of inherent and mining induced stresses, the existing fabric patterns and mechanical properties of the strata, geometry and mode of formation of the mine openings, as well as by the type and timing of engineering support measures. It is possible to modify the properties of floor- and roofstrata by mechanical means to large extents, especially when the nature of the strata is well understood. The identification and definition of geological attributes of strata, mechanically affected by coal extraction, must form an integral part of the analytical procedures leading to the establishment of mining design criteria. Geological features cause the unpredictability of strata behaviour and thus pose as great a danger to the safety and stability of underground openings as stress concentrations and inadequate structural design criteria. The system "floor-seam-roof" is either in a stable or unstable equilibrium prior to mining; that fact is regarded as an important rock mechanics consideration.

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Modern exploration methods and techniques seek relevant data for strata control design work from borehole geophysical tests and also through various laboratory analyses of borecores. Results from a recently completed research project show that a mechanical disintegration of the fabric of immediate roofstrata occurs due to low frequency cyclic loading. This is a load application type that has previously not been considered in the standard tests for strata control purposes. The demonstrable effects of low frequency cyclic loading on sedimentary fabrics can be used to lower their coherence potential and, if required, to induce goafing by controlled disintegration of strata.

## INTRODUCTION

The safe and controlled mechanical extraction of a coal seam from a layered sequence of different sedimentary rocks is a difficult engineering process that frequently results in complex energy release patterns in the rockmass affected. The different forms of instability portrayed by floor- and roofstrata are often difficult and complex manifestations of disturbances of existing equilibria in the rockmass. The instability is commonly the result of loss of coherence in the fabric of the individual strata under load and their inability to form beams between abutment zones. The degree of anisotropy developed in the individual strata during deposition and subsequent tectonic events, determines their mechanical response to stress applications to a significant extent. The existing anisotropies influence the propagation of mining induced stresses and their concentration patterns within the strata, as well as the interaction of inherent tectonically derived stresses with induced loads. The 'control' of usually complex response mechanisms of strata brought about by mining operations can become a difficult task , but can be achieved by a number of support and mine layout measures. The coal mining operations conducted at great depths in Europe require extraordinary and expensive physical supports for all roadways and faces, stress relief drilling and special layout designs for effective strata control. Conversely the safety of the relatively shallow workings of collieries in the Sydney Basin is best achieved by supports and layouts selected for the locally prevailing conditions, which require primarily the recognition of existing strength anisotropies and the definition of the interaction of stress regimes in the rockmass with induced stresses for the design of effective strata control measures.

The term 'strata control' now has a variety of meanings for workers and researchers in various fields of rock mechanics, mining engineering and engineering geology, indeed, even its concept appears to change as different disciplines develop specific working methods and techniques for strata failure risk assessment and the predictability of areas and types of failures. A combined effort by all interested disciplines toward the solution of unsolved problems could probably best achieve the desired targets.

STRATA CONTROL IN COLLIERIES

It seems important that all researchers and 'practitioners' recognise the significance of the fact that the formation of coal measures is a geological, biological and ecological peculiarity which creates strong mechanical anisotropies. The extraction operations create a mining induced stressfield that disturbs an existing stable or unstable equilibrium in the rockmass. The superposition of the mining induced stresses on the existing regional and local stressfield s strongly influences the mechanical response of a rockmass to the extraction processes.

## STRATA CONTROL—A GENERAL SCIENCE AND ENGINEERING CONCEPT

The requirements for effective strata control in pillar extraction operations vary typically from those in longwall panels, as dimensional as well as time effects become important rock mechanics and design considerations.

The depth of mining operations, the geometry of the openings and the mechanical specifications of the support systems are as important for strata control purposes, as the geological attributes of the succession of strata that is to be controlled.

In this context it is useful to examine what it is, precisely, that is to be controlled. The ideal situation for coal mining operations can be readily defined as having predictably stable roofstrata, no floorheave in any form, good pillar and rib stability, and absence of geological surprises, igneous dykes , faults and gas outbursts from the designated extraction area. The ability to predict mining conditions accurately is today of major significance for the planning and development of modern longwall collieries, and also for the design of safe and economical pillar extraction operations in previously developed panels. The occurrence of fatalities and serious injuries due to roof failure in pillar extraction operations are now as unacceptable as ever; the modern means of investigation and the available testing facilities are powerful tools to eliminate accidents in such operations. The increasing sophistication and versatility of mining equipment have led to high degrees of operational control and have enabled the operators to achieve significant increases in output under safe conditions. The increased output from Australian longwall faces and the improved safety records testify to much improved mining conditions and to the ability to control the forms and rates of energy release. The meaning of the term 'strata control' is thus frequently expanded to embrace the predictability, the control and maintenance of the physical environment of mining operations, and leads to the question: "to what extent can the geological system 'floor-seam-roof' be quantitatively assessed and subsequently engineered?"

In addition to the 'strata control' requirements in the different types of extraction panels (longwall, miniwall, Wongawilli Method, and conventional pillar extraction) it is of considerable economic significance to minimise the need for medium and high density support in development roadways. The erection and installation of support systems, as required in gateroads, for instance, do retard the progress of continuous miners and other roadheading machines, but they are currently the only means that allow some control over the response of the roofstrata to the extraction process.

New concepts in strata control measures should always be considered for the future development of Australian longwall mining; it is now possibly more than ever necessary to bring geological and engineering expertise together for the achievement of safe and economic development and extraction conditions. Very high production levels have been achieved in several modern Australian collieries, often by co-operative efforts of geoscientists and engineers at various levels; increasing sophistication of mining machinery, increases in the dimensions of extraction panels, better training of personnel and improved analytical tools and techniques will undoubtedly lead to even higher productivity, providing the understanding of the mechanical attributes of the rockmasses is improved and brought to a level of quantification where engineering control of energy release modes and rates can be achieved.

## THE COAL MEASURES—MODE OF FORMATION

The development of coal measures results from a chance interplay of events in the geological development of sedimentary basins. A peculiar sequence of geological, chemical and biological processes in a distinct ecological setting produces vegetable matter accumulations that subside in a finely balanced environment of water table levels, availability of nutrients, climatological conditions and a specific range of plants. As such, coal seams and their host rocks reflect the input of this highly diverse range of features.

Paralic coal deposits especially are the product of a range of depositional systems influenced by wide sedimentary control and variable tectonic subsidence and/or eustatic sea level changes. These combine to produce strongly heterogeneous coal measure sequences in which the proportion of coal is usually small compared to the volume of inorganic sediments.

The supply of clastic sediments into the depositional area is principally controlled by tectonic activity and the prevailing lithologies in the source area, the type and rate of erosion, mode of transportation of sediment between the source area and the nature of the depositional area. The setting and geometry of the accumulating area has a controlling effect on the development of primary anisotropies, that reflect the mode of deposition, syn-depositional tectonic events, volcanic activity, compaction features and a host of other sedimentary structures. The development of primary mechanical anisotropies in the accumulating sediment occurs on different scales. Current and gravity are the dominant vectors acting on the suspended sedimentary particles during transportation. As a result the fabric of most fluvially deposited sandstones and siltstones is characterised by preferred orientation of clasts according to dimension, and also by imbrication and subsequently formed differential compaction textures. On a larger scale, primary mechanical anisotropies occur in the form of fore-set beds, mostly orthogonally arranged joint sets, lenses, bedding planes and erosional structures. The ratios, types and size classes of clasts, matrix and cement components in the interseam sediments have a decisive influence on their mechanical behaviour when loads are applied as a result of extraction processes.

The heterogeneity and anisotropy of the fabrics of the sedimentary strata in the floor and roof of the extracted seams significantly influence the storage of inherent stress, the modes of propagation of induced stresses, and most importantly, the response of the strata to an inevitable disturbance of existing equilibria by mining operations. Consequently it is important to recognise that the response of the strata that we attempt to control is not only stress-strain dependent, as is occasionally assumed, but also structure- and history dependent.

## MECHANICAL ATTRIBUTES AND PROPERTIES OF COAL MEASURES STRATA

The floor- and roofstrata in operating bord-and-pillar, miniwall and longwall panels are brittle materials that have frequently been modelled as isotropic, homogeneous and linearly elastic substances. The mode of deposition in coal-bearing environments and other contributing factors, however, have created largely heterogeneous and anisotropic tabular bodies, whose mechanical properties depend to a large extent on the frequency and geometrical attributes of primary anisotropies, the release modes and rates of stored strain energy, and the interaction of tectonically derived inherent stresses with mining induced stresses. Elastic theory is an important consideration in the development of so-called "strata control guidelines," but it is not the only important aspect of physics required to understand the complex processes that determine the response of strata to an extraction process sufficiently well to write valid "rules" for the conduct of strata control practices.

There are numerous examples of relatively simple roof failures in first and pillar extraction workings, clearly attributable to bed separation, parting along erosional contacts between two different lithologies and to physical weakening of one particular stratum in a succession of strata with markedly different mechanical properties. In many instances a detailed map of an erosional river system, or a record of very different lithologies occurring in close vertical succession, could have conceivably prevented the experience of a roof failure. In the opposite case, where problems have been encountered with strata that tend to overhang, efforts to control the response of strata may be enhanced by cyclic loading of those strata in order to achieve a disintegration of the fabric by the creation of a damage pattern that closely resembles a fatigue failure. Results from a recently completed project have shown that a disintegration of highly bonded and strongly cemented fabrics in sedimentary rocks can be achieved by cyclic loading at relatively low frequencies.

This experimental study has identified several important mechanical behaviour aspects; damage development in tested anisotropic sandstones invariably exhibited a strong dependence, not only on the maximum stresses applied, but also on the cyclicity of the stresses. Cyclic loading has been shown to be a very effective way to induce damage on the micro scale. Crack growth in the tested sandstones was extremely sensitive to the variations of the cyclic range of stresses in the existing crack-tip region. Minor magnitude changes in the cyclic stress range have caused the crack growth rate to vary by orders of magnitude. This means that a controlled and rather"insignificant" variation of certain procedures in the mining operation can dramatically change the behaviour pattern of the immediate roofstrata which are subjected to low frequency cyclic loading by the periodic advance of the support systems. The study has also identified the peculiar and controlling effects of the petrographic and petrological attributes of the sandstones on the damage development during cyclic loading; in the unloading phase of the tensile loading cycle, a compressive stress field developed at the tip of propagating induced fractures. The occurrence of such a compressive stress during unloading is due entirely to the heterogeneity and anisotropy of the tested rocks. The externally applied cyclic tensile loads generate an internal stress field alternating from tension in loading to compression during unloading, or from compression in loading to tension in unloading in a cyclic compressive loading process.

Such a peculiar stress configuration sequence has caused very complex local rigid-body motions, which are, again, controlled by the heterogeneity and anisotropy of the tested sandstones, leading to severe and pervasive cyclic damage occurrences in the clasts' boundary areas, cement or matrix, and ultimately to the disintegration of the affected rock fabric.

The findings of this project also have considerable implications for the design of support systems, as it can be shown that compressive stresses are created at the tips of mining induced fractures and cracks within sedimentary fabrics, when the hydraulic support systems are lowered and moved forward. The ability or inability of strata to form beams depend on the internal make-up of the strata, and on the miner's ability to reinforce the inherent stability attributes, which are very often directionally controlled. The miner can only act to prevent failure, and to control energy release rates and modes, if the mechanical complexities of the strata are understood. It is thus logical to study the geological details and to design the support measures accordingly, rather than to assume that geological strata are materials that can be engineered like specified concrete, steel or other construction materials. Prudent engineers would never allow materials with as many defects and variables as those found in geological bodies to be considered for a designed structure. It is the understanding of the variables, flaws and defects in geological bodies that allows us to modify the mechanical properties of the strata where that is economically feasible, or to design support measures that allow degrees of strata control.

## SUPPORT SYSTEMS AND OTHER STRATA CONTROL MEASURES

Modern support systems are designed to provide safe working environments, a high degree of flexibility and ability to deal with a considerable variety of geological environments. Hydraulically operated breakerline support systems have made pillar extraction operations much safer and more efficient. The electronic control systems available today for the longwall supports allow the most efficient use of the advanced technology built-in to the chocks, chock-shields and shields. It is now possible to select appropriate support systems for even very difficult geological conditions. The high degree of mechanical engineering sophistication characteristic for modern support systems allows a wide range of operations and affords the ability to exercise a considerable amount of control over the strata's response patterns . This ability to control is enhanced if the compatibility of the geological setting and the support system is high. It is very important to know the likely failure modes of the strata and to be able to design or to select the most efficient support systems to counteract the weaknesses and to reinforce the inherent strength of the strata in the most effective and economical fashion.

The established forms of strata control by using roofbolts to transform several weak strata into an artificially strengthened mechanical beam are an integral part of support measures and thus very important for strata control ; the advent of cable bolts has been a major development in strata control. The yielding arch concept of support in difficult areas provides today solutions to instability problems in certain areas, together with timber chocks, concrete bag and other temporary supports that can be rapidly deployed as the needs arise. It is important in all situations to understand the mechanical properties of the rockmass involved and to select the most appropriate support system.

The most economical and efficient support system is the inherent capacity of the floor- and roofstrata to maintain structural integrity and to form safe beams across mine openings. The directional stability features that are found in many roofstrata allow the cost-effective and efficient development of bord and pillar panels and of gateroads and faces in longwall panels. The demonstrable reduction in support requirements in panels laid out and developed according to the 'directional mining' or directional stability concept has made such operations safer and more economical to conduct.

## SUMMARY AND CONCLUSIONS

Equipment, techniques and methods for the analysis and assessment of mechanical properties of floor- and roofstrata are available to geoscientists today that permit a reasonably accurate prediction of the likely energy release modes and rates under extraction conditions. The rock mechanics and mining engineer can base their assessment of the instability risk and the calculations of support requirements on the results obtained by the sedimentologists and petrophysicists. The designs of support systems appropriate for specific localities should be researched and designed for each major application, as the geological conditions may vary to such an extent that the mechanical response of strata is significantly different.

For the achievement of 'strata control' it is necessary for geoscientist and engineers to co-operate closely, as an investigation of isolated aspects and elements of the mechanical properties of the geological system "floor-seam-roof" is unlikely to be successful. A considerable body of knowledge of the geotechnical, engineering geological, rock mechanics and engineering aspects exists for the coal measure sequences of the Sydney Basin; when seen, treated and used in combination it will provide a powerful tool for the improvement of mining practices and for achievement of higher safety standards.

# GEOLOGICAL INTERPRETATION OF RADIO-WAVE TOMOGRAPHY

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## Introduction

Coal seams act as a natural waveguide for electromagnetic waves due to the large conductivity contrast between coal and the overlying and underlying strata. The Radio Imaging Method (RIM) utilises this property for detecting changes in the geology of the coal seam. Because the seam is acting as a waveguide, most of the energy is confined to the seam itself. This not only increases the range of the radio waves but also simplifies the imaging problem as the image is reduced to only two dimensions.

The attenuation rate of the signal propagating through the coal seam is determined by the waveguide properties of the seam. These properties include the conductivities of the coal and the surrounding rock, and the thickness of the seam. The presence of a geological disruption changes the waveguide properties, typically the conductivity of the coal seam.

This paper examines the use of radio-wave tomography from RIM surveys as a means of evaluating geological features in coal seams. It also demonstrates the use of 'hypothesis testing' as an aid in the geological interpretation of tomographic images, thus improving the prediction of geological hazards in coal mines.

## Data Acquisition

The RIM system is comprised of two units, a transmitter and a receiver. In the case of RIM I, the transmitter is a simple loop antenna with a power source which generates a magnetic dipole moment through the axis of the loop. The receiver is a loop antenna attached to a digital display which monitors the received signal strength.

The RIM I transmitter and receiver units are very mobile underground because of their light weight and compact size and require only two operators to carry out a survey. Both operators use stopwatches to synchronize their movement along the longwall, thus ensuring that their positions relative to each other are maintained. With the station spacing surveyed beforehand and clearly marked in the maingate and tailgate roadways, a set of measurements can be carried out quite efficiently with readings taken every 40 seconds in most cases. At this rate, a direct-ray survey can be conducted along a 2 km longwall, with measurements every 10 m, in less than 2 hours and 15 minutes.

In a direct-ray survey, the two operators are positioned on either side of the coal panel so that an imaginary line joining them is perpendicular to the roadways. The transmitter and receiver antennas are aligned with their loops in a vertical coplanar orientation which ensures maximum coupling with the waveguide and between the antennas. The operators travel along the panel, moving both the transmitter and receiver units. An alternative is the diagonal-ray survey, in which the two operators are positioned at a fixed offset so that the imaginary line joining them is at an angle to the roadways. This angle is chosen based on the expected orientation of the target in order to maximise the information gathered.

Since direct-ray and diagonal-ray surveys only measure the average attenuation rate of the coal seam between the transmitter and receiver, they can only indicate the presence of an anomaly but not its spatial extent and magnitude. To get a more complete picture of the anomaly, a tomographic image must be produced which requires a fan-ray survey to be carried out. This increases the number of raypaths travelling through the coal panel in different directions.

The RIM II system consists of two 4 m borehole probes linked by fibre optic cable to a central control unit. Each probe is attached to a calibrated winch which allows the probes to be moved to a specific position in the borehole. The RIM II equipment is less mobile than RIM I but is useful when access to the survey area is limited to boreholes. Surveys can be conducted from the surface between vertical boreholes or underground between horizontal boreholes. In the case of horizontal boreholes, a pulley is attached to a casing which is inserted into the hole. Kevlar string is attached to the end of each probe and fed around the pulley, enabling the operator to pull the probe along the hole.

## Principles of Tomographic Imaging

Tomographic imaging is based on the fundamental assumption that the measured signal can be expressed as a line integral in the following form:

$$d = \int_{\Gamma} \alpha(\mathbf{r}_0) dl.$$

Here $l$ represents the distance along the raypath and $\Gamma$ the raypath itself. In the case of RIM, the input data $d$ are the measured data corrected for spreading losses and for the 'c' factor, while the unknown $\alpha$ is the attenuation rate (see Thomson et al. 1990). Assuming straight raypaths and complete data coverage, this can be solved by an exact inverse transform.

However, in geophysical imaging it is usually impossible to gather a complete data set. This is because access is restricted to the available roadways and boreholes, and measurements are typically restricted to three sides, two sides or even only one side of the target area. Because the source and receiver arrays cannot completely surround the target area, the measurements are not recorded for a complete set of view angles. Thus only partial information is available for the inversion problem.

The simplest approach to the incomplete data problem is to assume that the missing data values are zero and to use a standard reconstruction algorithm as if one had a complete data set. Because this solution is not necessarily physically valid, it usually results in images with severe artefacts. It is necessary to introduce additional information in order to constrain the solution and to increase the stability of the reconstruction problem.

One approach is to use this additional information to attempt to expand the limited data set before performing the reconstruction step. This is the philosophy behind the reconstruction algorithm known as YOULA which was developed at CSIRO Division of Radiophysics. YOULA combines iterative extrapolation of the measured data with a standard direct Fourier reconstruction method (Rogers et al. 1987). In addition to the measured data, YOULA uses available information (both physical and mathematical) to specify constraints on the solution, such as smoothness and limits on the image bounds. YOULA differs from other tomographic reconstruction algorithms such as ART and SIRT in that it operates in the data domain rather than in the image domain (see Rogers et al. 1987).

## Hypothesis Testing

As explained in the previous section, the data are used in conventional imaging as input to a reconstruction algorithm, with any available information used to constrain the inversion to a unique solution. Alternatively, the data can be regarded as a means of testing hypotheses about the geology of a region. This can be done in two ways:

- forward modelling through a trial model and the results compared with the measured data;
- using a reconstruction algorithm to produce an image which is consistent with the measurements and any available constraints, and which is also 'close' in some sense to the hypothesized model.

Iterative tomographic reconstruction algorithms, such as YOULA and ART, require a starting model of the geology. As the imaging problem is usually underdetermined to some extent, the final solution obtained in an iterative reconstruction is dependent on the initial model. Normally, a uniform starting model is sufficient, based on the average attenuation rate over all of the raypaths. Alternatively, a trial geological model can be used. The reconstruction algorithm produces an image which is close in some way to the starting model but which is still consistent with the observed data, a way of testing the hypothetical model.

Any geological data that are available, for example from mapping, regional trends and borehole cores, can be used by an experienced interpreter in conjunction with 'eyeballing' the data to obtain a reasonable first estimate of the model. Thus it is important to include the most qualified expert on the local geology (i.e. the mine geologist) in the interpretation step.

## The Imaging System

To be able to carry out hypothesis testing effectively, the interpreters should be able to experiment with geological models, following intuitions quickly and naturally. This requires a facility for constructing hypotheses in graphical form using a 'paint' facility.

An image display and processing system was developed at CSIRO Division of Radiophysics to support the RIM program. The interactive image processing and graphics operations associated with image interpretation and hypothesis testing have been incorporated in a software package which we call DISPLAY. The DISPLAY program allows geological models to be quickly entered using interactive drawing facilities.

The need to involve the mine geologist in the reconstruction procedure means that at least some of the processing be done on-site in conjunction with the survey, creating the need for a portable imaging system. On-site processing is also vital for quality control of the data and for defining areas which may indicate the need for further data measurements.

Taking into account the factors of cost, portability and the ability to display images in colour, the most attractive platform for our imaging system, at the start of the project in 1989, was a Commodore Amiga 500 personal computer. Although its processor has limited power, it does have several custom graphics chips which enable speedy graphics operations. The Amiga is very user-friendly as it has a mouse-driven, window-based operating system.

The more computationally intensive operations of tomographic reconstruction and forward modelling are carried out on a mainframe computer. At remote locations, data and images are transferred between the Amiga at the mine office and the mainframe computer located in Sydney, across telephone lines using a modem. Both the imaging and reconstruction software are presently being ported to UNIX workstations and to IBM compatible PCs to provide a stand-alone system, taking advantage of advances in computer technology.

## Geological Interpretation

Figure 2(a) shows the results from a RIM I tomographic survey targeting a dolerite sill. The survey was conducted between parallel roadways across a longwall panel, as shown in Figure 1. The areas of black, which indicate zones of relatively higher attenuation rates, correspond to the sill, and tie in with an outcrop of the sill in the top roadway. The initial reconstruction had no geological constraints applied.

For this survey, hypothesis testing was used to validate the shape and extent of the sill. Figure 2(b) shows a geological model used to simulate a worst-case mining scenario in which the spatial extent of the sill has been increased. This hypothesis

## RADIO WAVE TOMOGRAPHY

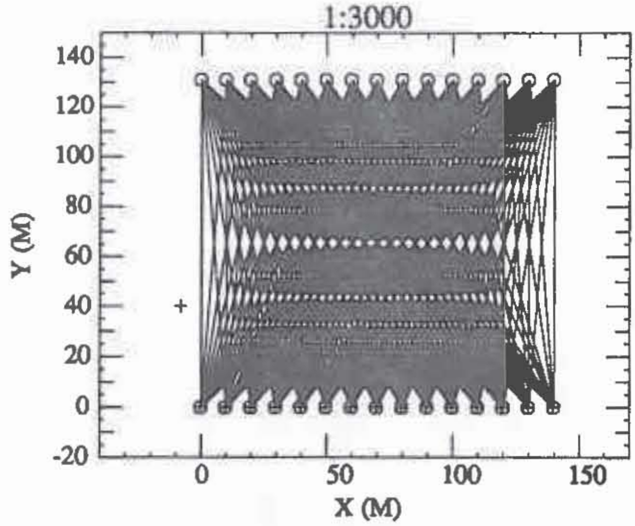


Figure 1: The ray coverage for a RIM I tomographic survey between parallel roadways. (+ = Transmitter; O = Receiver)

was used as a starting model in a tomographic reconstruction. The resultant image, shown in Figure 2(c), shows virtually no change from the original image, indicating that the hypothesis is incompatible with the observed data. This gives us more confidence in the initial tomographic image.

In the example just described, the geometry of the survey in relation to the target produced a relatively unambiguous result, as confirmed by the hypothesis testing. However, in some cases, access to the area is restricted in such a way that the RIM measurements alone cannot specify the target uniquely. More than one interpretation can be applied to the data. The number of possible scenarios satisfying the data can be reduced by applying geological constraints through hypothesis testing.

The tomograms in Figure 4 illustrate an extreme example of non-uniqueness in imaging. This survey was conducted as part of the initial trials of the RIM II equipment in Australian coal mines. The measurements were taken between two parallel boreholes (see Figure 3). The geological target is a dyke which was predicted to run parallel to the boreholes. The dyke outcrops in the roadway, midway between the two boreholes. With this survey geometry, the attenuation rates measured will remain the same regardless of the position of the dyke between the boreholes. In addition, there is a tradeoff between the thickness and the conductivity of the dyke.

Figure 4(a) is the initial tomogram produced using only the measured signal strengths. Some linear features appear in the image but they do not follow the orientation of the dyke. To assist the reconstruction, it was necessary to add information about the position of the dyke and either its thickness or conductivity. This was achieved by postulating a geological model (Figure 4(b)), based on knowledge of the site. Figure 4(c) illustrates how applying the hypothesis has changed the image. Both Figures 4(a) and 4(c) are theoretically correct images of the data, but 4(c) is closer to geological reality.

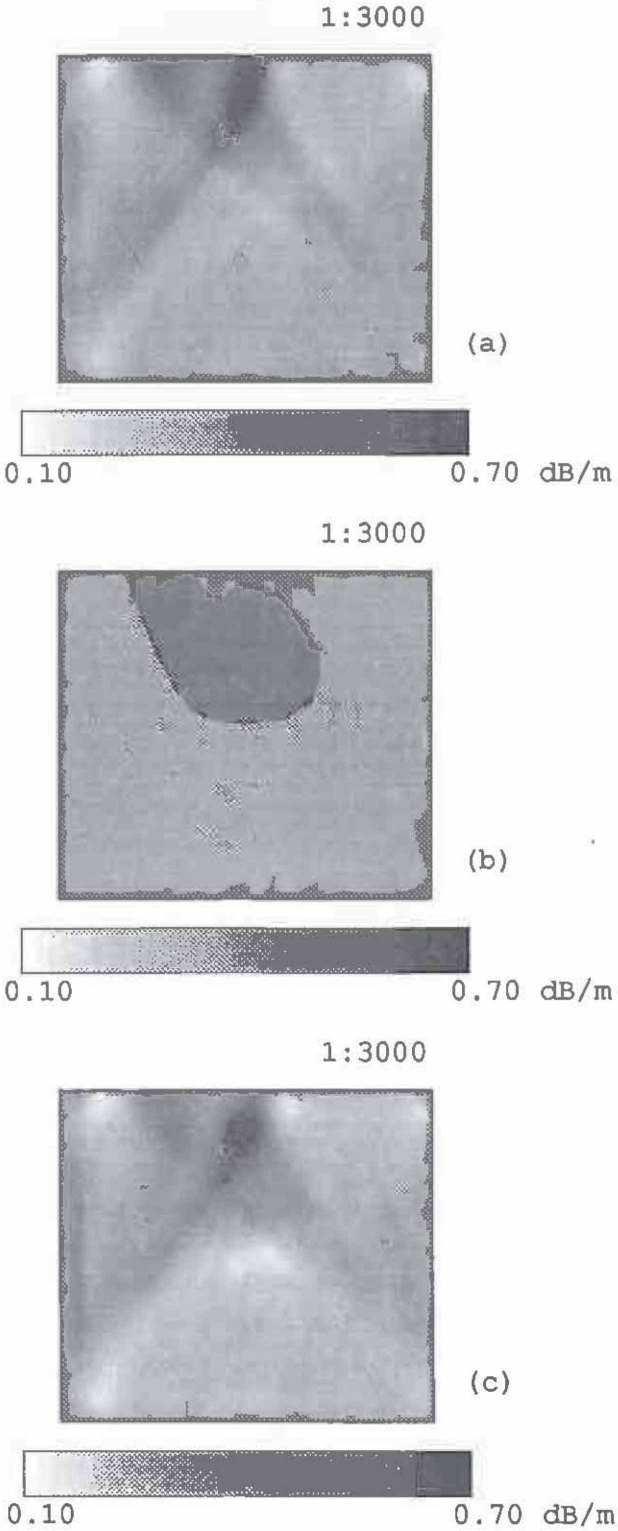


Figure 2: (a) Initial tomographic image. (b) Trial geological model. (c) The tomographic image obtained using this hypothesis.

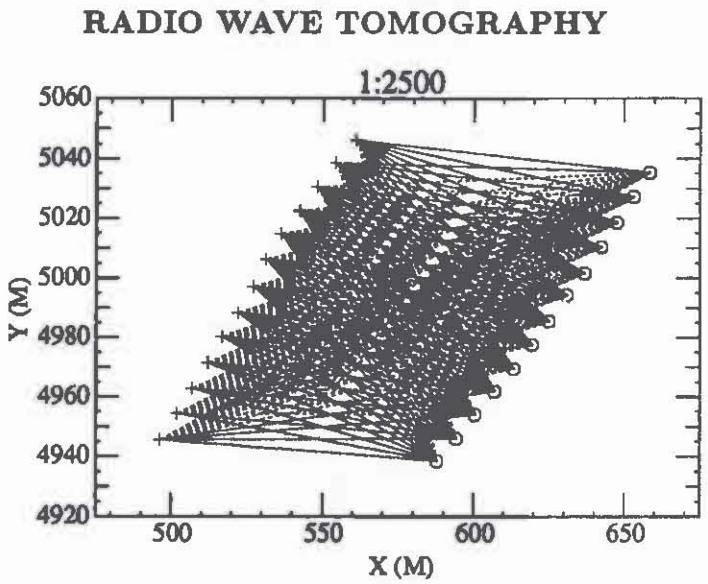


Figure 3: The ray coverage for a RIM II tomographic survey between parallel boreholes. (+ = Transmitter; O = Receiver)

## Conclusions

RIM is a powerful geophysical tool which is simple to implement. It is possible to detect and delineate a range of geological features within a coal seam with a high degree of resolution.

Interpreting RIM geologically can be improved by applying local geological knowledge to test the applicability of various hypotheses to the measured data set. An imaging system has been developed which can be used by the mine geologist as a tool in the interpretation process. By combining geological input and advanced imaging procedures, we have improved confidence in geological hazard prediction from RIM surveys.

## Acknowledgments

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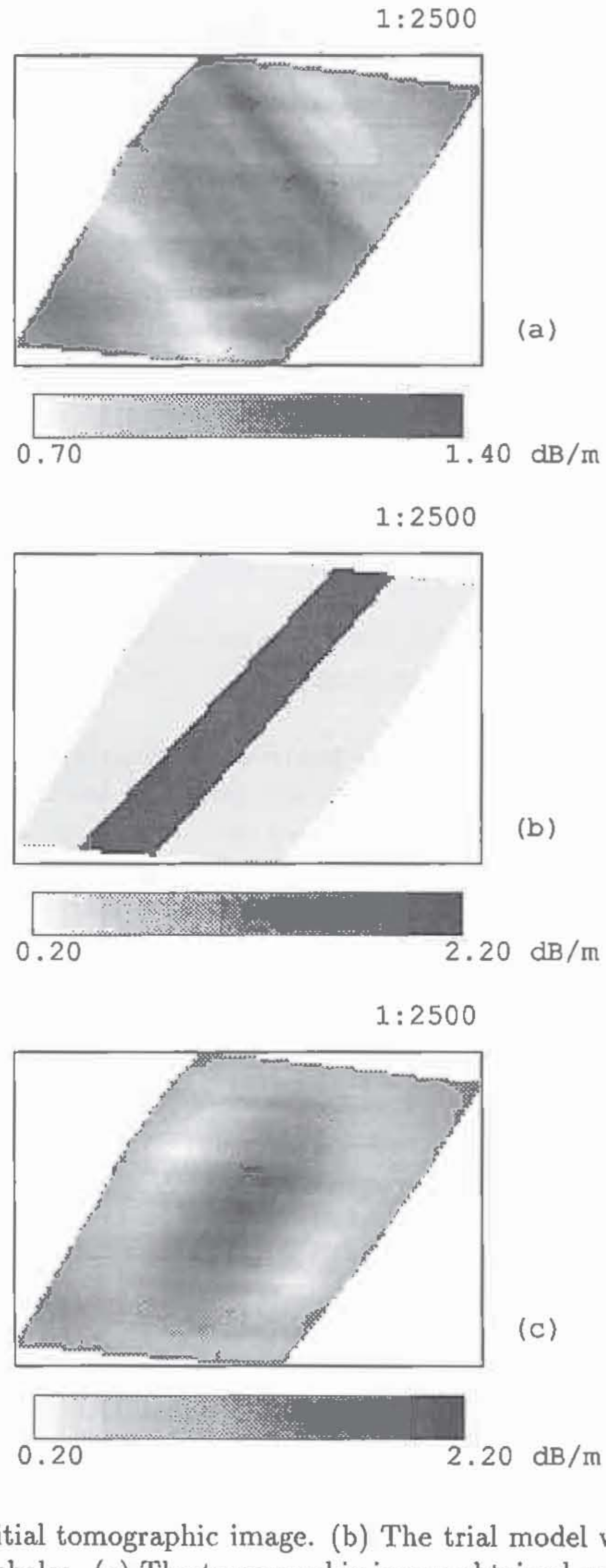


Figure 4: (a) Initial tomographic image. (b) The trial model with a dyke midway between the boreholes. (c) The tomographic image obtained using this hypothesis.

# APPLICATION OF THE RIM TECHNIQUE FOR WATER INFUSION ANALYSES AT APPIN COLLIERY

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SUMMARY

Three different methods of water infusion were studied to ascertain the most appropriate for the prevailing conditions at BHP Steel's Appin Colliery. This project demonstrates an innovative application of RIM which has been used to better understand the migration of water during the infusion process.

INTRODUCTION

At Appin Colliery an extensive pattern of methane drainage holes is utilised to reduce the content of in-seam methane. This drainage also reduces the moisture content of the coal. Because the coal is then dryer, it is also dustier during the extraction process. In an effort to lower dust counts water infusion has been initiated at the colliery with some success. The geophysical technique known as RIM (Radio Imaging Method) has been used in an attempt to: quantify the extent of water infusion; determine the effectiveness of the different methods and to improve the understanding of water infusion technology. A description of the RIM technique is given in Thomson et al. 1990.

During a routine RIM survey of Longwall 22, results were observed to be highly erratic across a zone of water infused coal (Doyle 1991). As a result of this observation a special survey was commissioned to cover an area of water infusion to determine the extent and the rate of water migration. An area of Longwall 22 was set aside to be water infused using three different techniques.

Following this survey a second set of surveys was undertaken on Longwall 23. During this second survey only two of the techniques were compared.

WATER INFUSION TECHNIQUES

The first RIM survey (17/11/91 to 6/12/91) covered an area of three borehole fans. Each fan covered different areas ranging from about 120 to 170 metres, multiplied by the longwall width of 200 metres. The layout of the test areas can be seen in Figure 1. The three different techniques used were described as the "non-bagged", "semi-bagged" and "fully-bagged" methods.

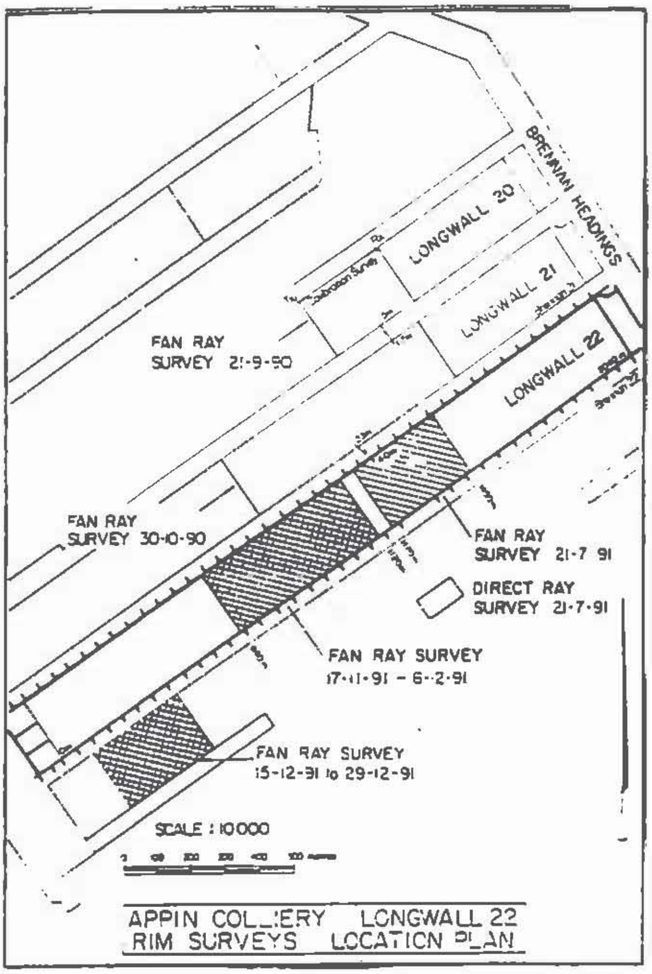


Figure 1. Mine & Survey Layout.

The "non-bagged" method basically consists of pumping water into a bore and sealing only the extremities of the holes. It appears to be an inferior technique because water loss is experienced into the roadways via the ribs.

Appin Colliery had developed a method of infusion that was quite novel. The "fully-bagged" method of water infusion involves the sealing of boreholes off over distances of 2m at spacings of approximately 16 to 20m down the borehole. This grouting procedure effectively installs obstacles in the path of the water. It was suggested that the water is forced out into the coal around these bags continuing downhole and at the same time further out into the block.

Appin Colliery wished to collect evidence to prove how effective the fully-bagged method actually was. There was no clear quantitative or qualitative analysis to determine if one technique was in fact better than the other. When considering the cost of installation in labour and materials, the "fully-bagged" method needed to be proven to be a better technique than the others or abandoned.

## APPLICATION OF RIM FOR WATER INFUSION ANALYSIS

The "semi-bagged" method involved the sealing of the borehole at approximately 15 to 20 metres from both ends of the hole. This left the rest of the bore open. This method had no leakage into the gateroads.

### GEOLOGICAL CONDITIONS WITHIN THE TEST AREAS

The two areas tested (Longwall 22 and Longwall 23) contain some minor geological features such as jointing and strike slip faults. The structures appear to affect different areas within the longwall differently, whereas cleat appears to be consistent throughout both test areas. In Longwall 22, these features appeared to affect the areas covered by the semi and non-bagged methods more than the fully bagged area which was relatively free from geological structure. In Longwall 23, geological structure appears to affect the area covered by the fully-bagged technique, more than the semi-bagged area.

### RIM SURVEYS - THE FIRST CAMPAIGN

A series of three tomographic RIM surveys were undertaken over a period of four weeks. The results from the previous direct ray survey conducted in July 1991 were used as a base line. As each week's survey was conducted the direct ray results were extracted from the tomographic results and used to check the progress of water infusion over the three different techniques.

### DIRECT RAY RESULTS

Figure 2, shows the results of the direct ray readings over the campaign. The initial results in July show a relatively even attenuation rate of between 15 and 20 dB/100 m. After the first tomographic survey the results indicated a dramatic increase in attenuation response in the area of the "fully-bagged" method. A small increase in attenuation was observed for both of the other techniques. The first survey of the water infused area was undertaken 3 days following the commencement of infusion on the 17/11/91.

On the 24/11/91 a further RIM survey was conducted. The direct ray results generally showed a dramatic across the board increase in attenuation rate. The semi-bagged method shows a steep gradient over half of its curve before reaching the level of the fully-bagged results.

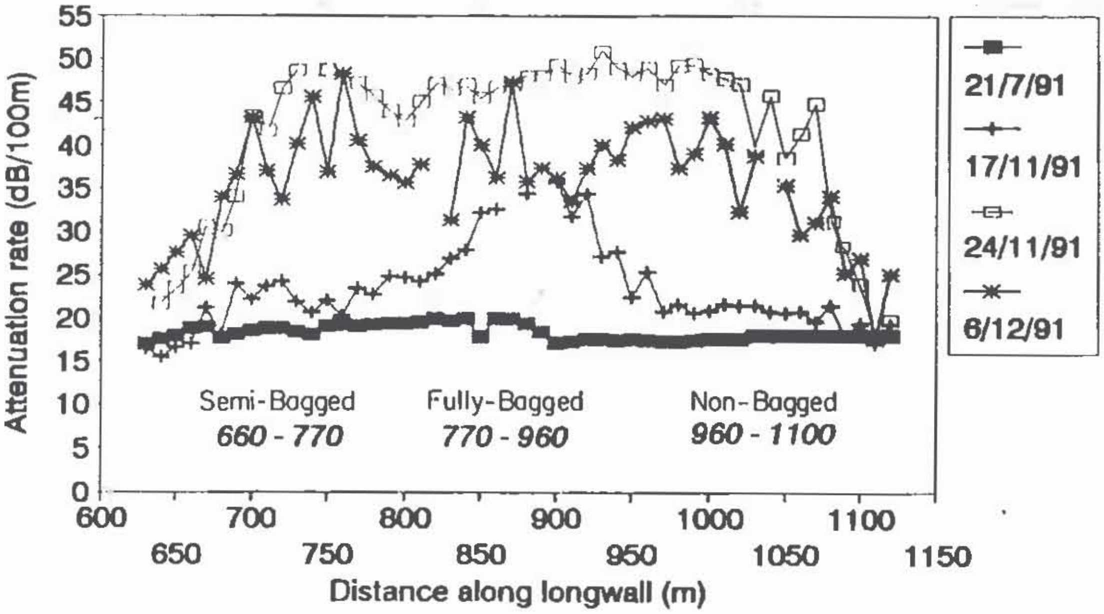


Figure 2. Longwall 22, Direct Ray Path Surveys.

The fully-bagged area shows a relatively even level of results which were believed to be on the limit of the measuring equipment and in the area of background noise. The non-bagged area tended to mirror the semi-bagged results. The steep gradients of the semi and non-bagged areas may reflect either the fact that there was no adjacent water infusion holes and/or the symmetry of the boreholes.

The third survey in this series was conducted on the 6/12/91 and produced erratic results. Electromagnetic noise appears responsible for the spurious readings. For this reason little significance has been attached to these results. Nevertheless, the two ends of the survey run were relatively equal in their responses.

WATER VOLUME

From the start of this project, water meters were used to measure the exact amount of water placed into each fan system so that a fair comparison could be made (see Table 1 below). The table shows the increase of water with time. Comparisons are also made with the total length of boreholes and the total volume of coal around the respective methods. The ratio of Coal Volume/Water Volume shows (for the semi-bagged area) that for every 40 cubic metres of coal 1 cubic metre of water has been pumped in.

## APPLICATION OF RIM FOR WATER INFUSION ANALYSIS

| Techniques | 17Nov | 24Nov $H_2O$ $m^3$ | 6Dec * | Bore Length Total m | Coal Vol $m^3$ | Ratio $H^2O$ $m^3$* /Bore L | Ratio Vol/ $H_2O$ $m^3$ | Ratio Vol/ Bore L |
|---|---|---|---|---|---|---|---|---|
| Fully Bag | 220 | 910 | 1250 | 1450 | 85000 | 0.86 | 68 | 58 |
| Semi-Bag | 200 | 975 | 1500 | 1000 | 60000 | 1.50 | 40 | 60 |
| Non-Bag | 250 | 775 | 1200 | 1250 | 75000 | 0.96 | 63 | 60 |

Table 1
Flow Rates For Water Infusion and Associated Ratios.

## TOMOGRAPHIC RESULTS

Figure 3, shows the tomographic image after 3 days of water infusion. It shows the initial response (lighter shades) of the area covered by the "fully-bagged" method, while the rest of the test areas were relatively unaffected. Figure 4, after 10 days of infusion, shows a water saturated area dominated by geological control.

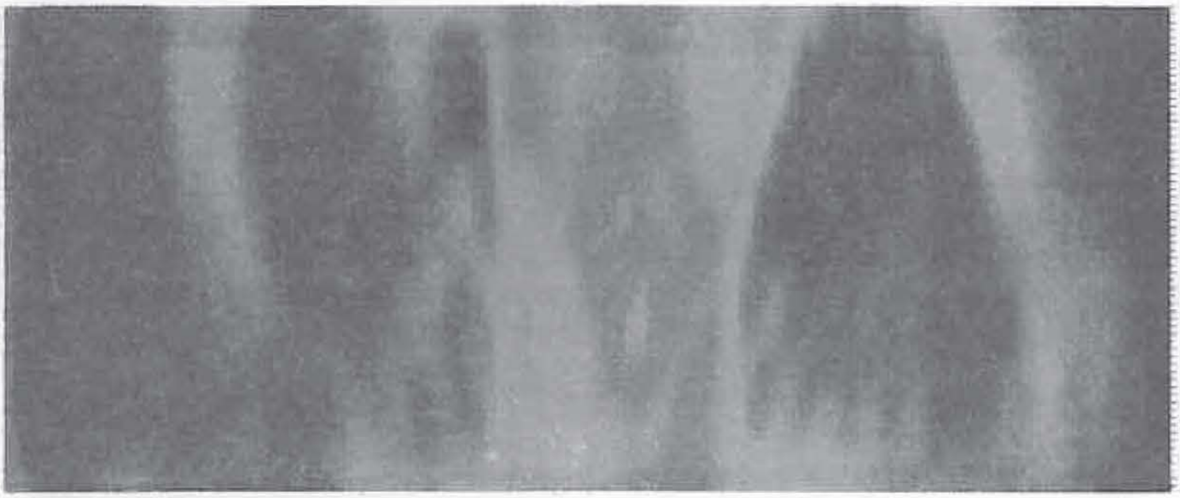

Figure 3. Tomographic image 17/11/91

Figure 4. Tomographic image 24/11/91

Following the completion of this stage of testing it appeared that the fully-bagged method was a quicker technique for raising the moisture content of the coal. But with time the semi-bagged method would allow greater volume and further migration of water through the longwall block. This is highlighted by the ratio of water input divided by borehole length, see Table 1. The geological structure particularly the cleat is believed to have affected the results by preferentially steering the water along its planes within the test area.

The results did not give sufficient information to ascertain individual borehole performance. It was decided that the "snapshots" taken by RIM had been spaced too far apart in time. To this end another program of water infusion was planned, with more survey runs conducted over a shorter period of time.

## THE SECOND CAMPAIGN - DIRECT RAY RESULTS

The second series of tests focussed on comparing the "fully-bagged" and the "semi-bagged" methods by infusing water into a single borehole within a fan. A set of seven tomographic runs were conducted from the 15/12/91 to the 29/12/91, covering an area of Longwall 23. Figure 5, shows a comparison of the direct ray survey results, raw field data plotted as signal strength. Despite logistical problems and the loss of some data over the semi-bagged area, the results indicate a more intense infusion and a broader spread in the semi-bagged area.

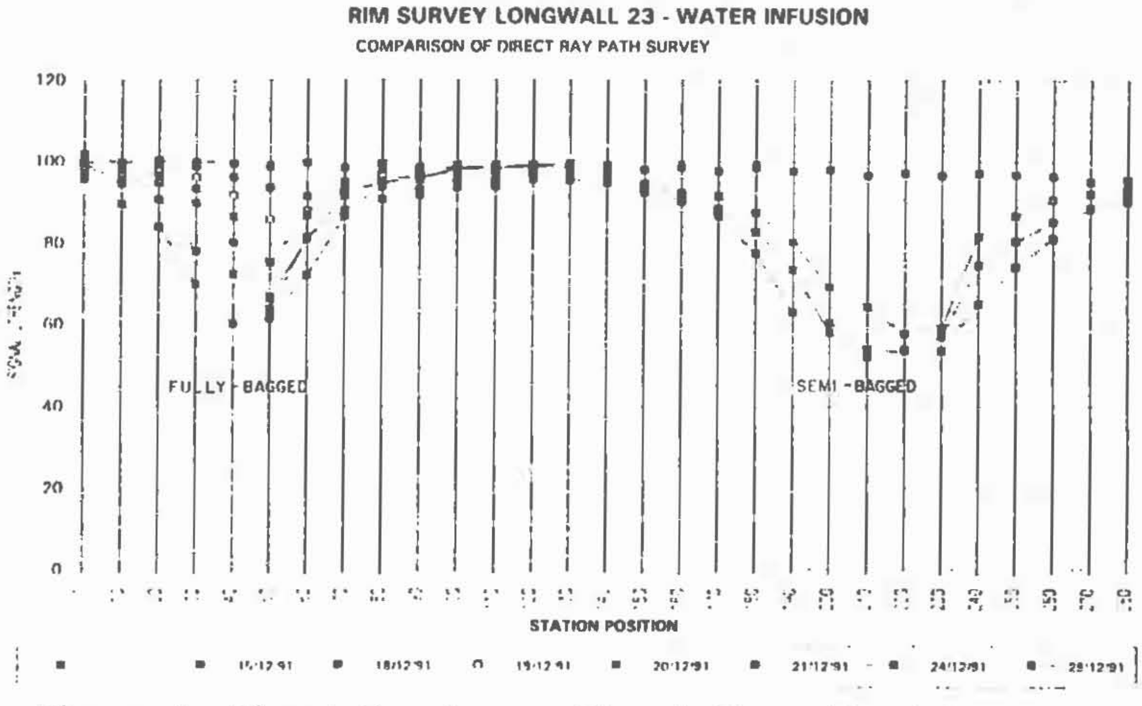


Figure 5. Direct Ray Survey Signal Strength Field Data.

## APPLICATION OF RIM FOR WATER INFUSION ANALYSIS

### WATER VOLUME

Flow rates into the single borehole during the course of the survey show that the semi-bagged method accommodated in excess of 100% more water than the fully-bagged method, 650 $m^3$ compared with 300 $m^3$. The explanation considered most plausible for this is the presence of the grouted sections, effectively blockages in the "fully-bagged" boreholes hindering the transmission of the water. Ratios of water input divided by total bore length are 0.38 and 0.65 for the fully and semi-bagged techniques respectively. This indicates a much better overall performance of the semi-bagged method.

### THE SECOND CAMPAIGN - TOMOGRAPHY RESULTS

Seven tomographical images were produced over a period of 14 days. This set of images shows the progressive and gradual change in moisture content of the longwall. They also clearly demonstrate the inherent difference in the two infusion techniques used. Three of these images are included to show the changing nature of water in the coal.

Figure 6, shows the background attenuation rate of the area tested. The minor variation in response is believed typical of an area drained of methane.

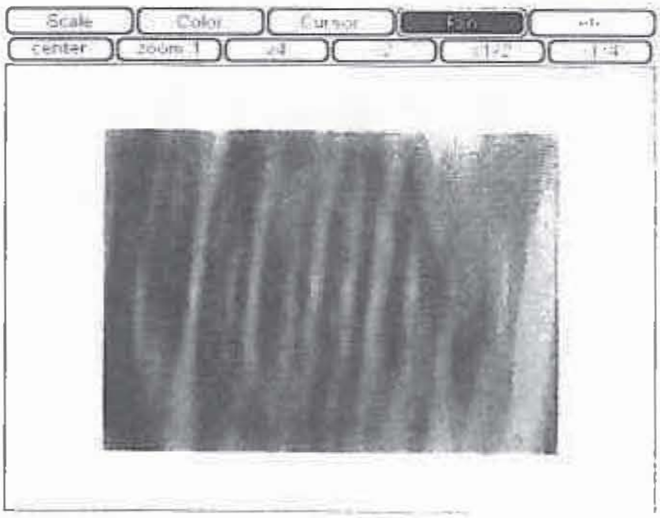


Figure 6. Background Attenuation Rates.

Figure 7, highlights the two techniques the semi-bagged on the left and the fully-bagged on the right. In this image individual boreholes can be identified.

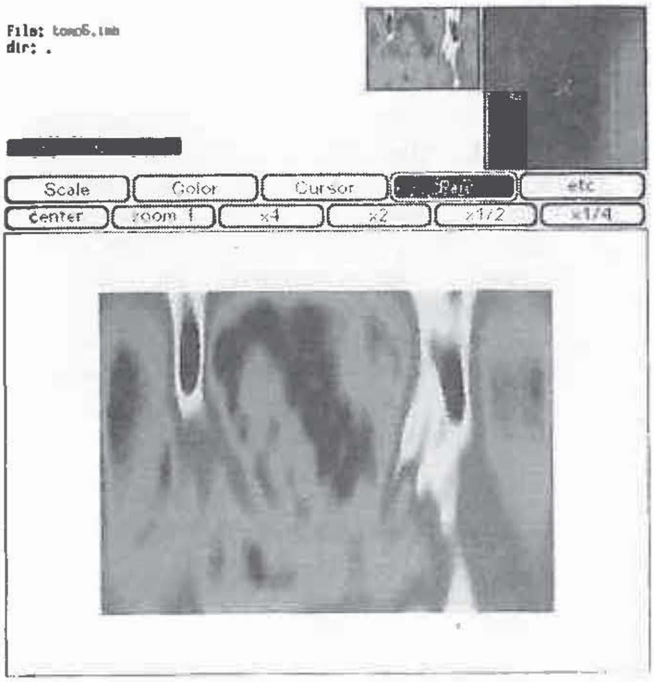


Figure 7. Tomographical Image From Survey Dated 21/12/91.

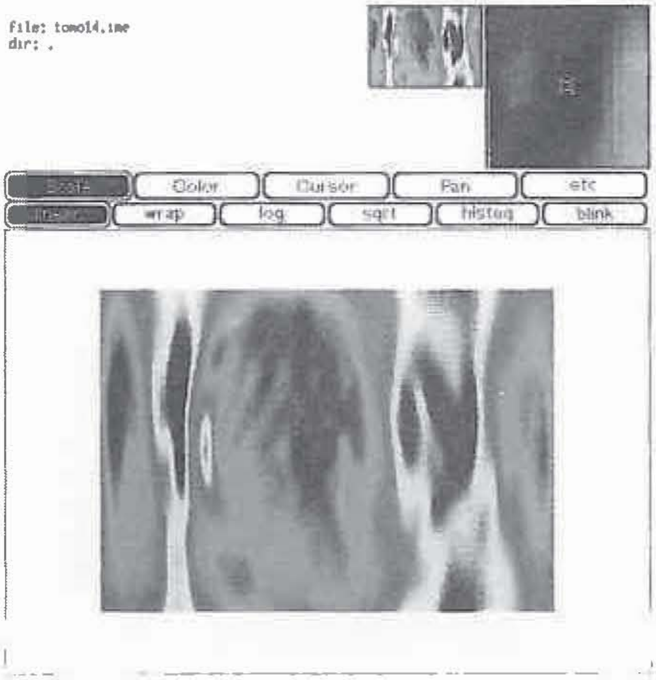


Figure 8. Tomographical Image From Survey Dated 29/12/91.

Figure 8, represents an almost blanket saturation of the respective test areas. The semi-bagged has a more intense and broader pattern of infusion compared with the fully-bagged area. This is contrary to the initial hypothesis for the fully-bagged technique of water being forced out of the hole and into the block.

APPLICATION OF RIM FOR WATER INFUSION ANALYSIS

## CONCLUSIONS

The purpose of this project was to attempt to evaluate how the water in the water infusion process migrated. Appin Colliery was using the fully bagged technique and fulfilling statutory requirements in regard to dust counts. However, it wasn't enough to just pump the water in and hope for the best, the process needed to be proved and improved. This project has allowed the performance of the different water infusion techniques to be measured. The use of RIM has allowed "snapshots" of water infusion to be taken and compared.

By performing this study a modified technique, the "semi-bagged", has proven to be more successful. This conclusion is expected to result in a saving of time, labour, resources and expenditure. The project illustrated the potential of RIM as an analytical tool for the evaluation of water content in coal seams.

## ACKNOWLEDGMENTS

The authors wish to thank BHP Steel Collieries Division for permission to present this paper. The authors would like to express their appreciation to their colleagues, Paul Maddocks who had the foresight to link RIM and in-situ water, Bernie Gray-Spence, who had the initiative to push the project to a commencement. The work force at Appin assisted at all times, in particular Paul Thompson. Downunder Engineering designed and manufactured the bags used for grouting of the boreholes. The service, discussions and assistance from the METS team is gratefully acknowledged. The image processing capability of CSIRO Division of Radiophysics played an important role in the success of the project.

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# EXTRACTION OF BULK SUBSURFACE COAL SAMPLES BY 'KEYHOLE MINING'

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## 1 INTRODUCTION

Bulk sampling is an important aspect of coal exploration, especially in the latter stages of the program. By this time preliminary mining and preparation methods have been decided on, together with the most likely target seam, mining section and market products. All of these decisions have been based on the results of tests and analyses carried out on bore core samples, with slim cores being in the majority.

The mass of samples available from cores varies from about 4 kg/lineal metre for HQ core (61 mm diameter) to about 45 kg/lineal metre for 200 mm diameter core. 400 mm diameter core, uniquely offered by Keyhole Mining Services, yields about 180 kg/lineal metre.

Often tonnage samples are required during the latter exploration stages, for example for carrying out a trial wash. They may also be required for carrying out a test burn in a pilot combustion facility or preparing a batch of coke in a test oven. Collection of the sample by aggregating large diameter (200 mm diameter) bore cores is expensive, even for shallow deposits, and out of the question for coal to be mined by underground methods.

Where deposits are shallow, bulk samples are often taken from a trench or box cut. This method is also relatively expensive, even with shallow cover, because the sample mass required is usually in tens of tonnes, rather than in thousands of tonnes.

Generally, therefore, much essential testing is foregone until the actual mining takes place, and the bulk sample can be taken from an exposed face. Often, this is too late.

Keyhole Mining Services is a joint venture between Mosslake Mining Pty Ltd, with specialist drilling expertise, and Quality Coal Consulting Pty Ltd, with special knowledge of coal properties and testing. It offers a unique service for the taking of subsurface samples, in bulk. The method is summarily described in this paper.

## 2 THE BULK SAMPLING METHOD

Mosslake have developed a bulk sampling system for coal which involves the fracturing of the coal by blasting in the drill hole, followed by the recovery of the broken coal through the drill hole using hydraulic mobilisation and lifting. The technique developed from work on a foundation improvement project for the North Rankin 'A' Gas Production Platform.

BULK SAMPLES BY 'KEYHOLE MINING'

The system for taking the bulk samples proceeds in the following steps:

1 *Exploration Drilling* - the exploration bore, which is generally of small diameter (say HQ size or 61 mm diameter) is completed in the normal manner to identify seams and gather any other relevant data.

2 *Preparation of Drill Hole* - the hole is opened out to allow the emplacement of an outer casing, the depth of which is determined by air lift requirements. The hole to the top of the seam is then opened to accommodate the sample transfer pipe.

3 *Initial Seam Fracturing* - an explosive charge, designed according to the physical characteristics of the coal and stone bands in the seam, is introduced into the bore hole within the seam. The resultant blast introduces a fracture pattern into the seam.

4 *Jetting and Removal of Coal to the Surface* - high pressure water jetting is employed to further fracture and fluidise the coal material. This material is transferred to the surface by an air lift recirculation procedure. Samples are collected by an air knockout cyclone into collection containers, with the fines from the overflow water being removed by a classifying cyclone prior to reuse of the water down the hole. The sample may be taken a section at a time, thus allowing separate assessment of different mining horizons.

5 *Grouting of Sampled Area* - cement slurry is pumped in to fill the void and the drill area.

After the sample has been taken, the shape of the mined space can be examined by a down hole calliper log. Studies by Keyhole Mining Services have shown that a relatively even cross section is possible, over the full seam height, by proper design of the explosive charge.

## 3 CASE HISTORIES

### 3.1 Coal Exploration Area - Western Australia

In the second half of 1988, Mosslake Drilling Services Pty Ltd were engaged in a coal exploration drilling program in Western Australia, drilling core sizes ranging from HQ3 (96 mm hole, 61 mm core) to 16" diameter (600 mm hole, 400 mm core).

Preliminary discussions on further exploration drilling indicated the need for bulk samples of coal from seams at depths in excess of 400 m. Large diameter core drilling (400 mm and 200 mm core) is difficult and expensive at this depth, and other options such as wedging for multiple cores were unsatisfactory in respect of sample volume.

It was decided to perform a trial bulk sampling program in a shallow (150 m) seam in a different location, to determine the viability of the jetting techniques in a coal seam sampling operation.

After preparatory work in Perth, the equipment was mobilised to site in September 1988. A bulk sample was collected, sufficient to fill thirty three sample drums of two hundred litre capacity - approximately 6.5 cubic metres of sample volume (9 tonne) from a 6 m seam.

The technique was still under development for this sampling exercise and the annular conduit for extracting coal restricted the top size to around 16 mm. Comparison of the size distribution of the coal sample obtained and that predicted for the run-of-mine coal led to the following comments:

- The slope (n value) of the size distribution obtained by *keyhole mining* is similar to that expected, based on previous coal testing.
- The restriction of sampling topsize to 16 mm resulted in the generation of a finer size distribution, with a characteristic size (xbar) of 3 mm instead of the expected 8 mm.
- The larger sized particles were somewhat rounded confirming that a tumbling process had taken place to reduce these particles to less than 16 mm.
- An apparent loss of fines may have occurred during the dewatering and recovery process.

It was concluded that increasing the size of the sample transfer pipe would enable larger pieces of sampled material to be introduced into the transfer pipe and carried to the surface.

### 3.2 Proposed Underground Coal Mine - New South Wales

In July 1991, Mosslake entered into a contract to provide a bulk sample from a coal seam at approximately 200 m depth through a 200 mm cored hole. A local drilling contractor was sub-contracted to drill the cored hole and subsequently provide a nominal 310 mm hole to target depth.

Three strings of steel pipe and a high pressure air line were tripped into the bore hole in a single pass operation, and the seam was sampled as previously described.

Approximately 8 tonnes of material were obtained from a 4 m seam, ranging in size from colloidal fines to 100 mm x 150 mm elongated pieces.

As the sample obtained is the subject of current commercial negotiations, no sizing or general analysis data can be included in this paper. It will be made available at a later date.

## 4 THE CONDITION OF THE SAMPLE

To date, little definitive data is available on the nature of the size and washability of the samples generated. The blasting and transport of the samples causes appreciable breakdown of the coal, and it is most likely that sufficient energy is provided to reach the "stabilised" size distribution (1), with the action of water and transport assisting in the production of an "in-plant" wet sizing.

Moderate, confined blasting of the coal should produce a breakage pattern akin to drill and blast operations in open cut mines. Underground mining operations should also be modelled adequately and reference is made to the work of Bennett (2) who compared the size distributions for shot fired, continuous miner and longwall mining methods.

The correspondence of the type of samples generated by "keyhole mining", to those generated by the process of mining, handling and preparation, needs to be studied. The strong potential exists for the derivation of samples that will properly model characteristics found in mining operations.

## 5 MATTERS FOR FURTHER STUDY

The technique is still in its infancy and the major efforts to date have been the procurement of tonnage samples. Rigorous assessment of the nature of the samples generated, compared to those achieved under normal operations, is required to fully exploit the technique.

Particular matters for investigation are:

1. Regularity of the section mined, i.e. under what conditions of blasting and recovery can all levels of the seam be mined/sampled evenly?

2. How does the size distribution obtained compare to run-of-mine, plant feed and in-plant size distributions?

3. Does the material generated have the same washability and size/density characteristics as found in a coal preparation plant?

4. Is the technique reproducible, and how do operational factors impact on the sample size distribution?

5. Can a simple, portable, pilot scale preparation plant be developed to directly treat samples obtained from "keyhole mining"?

The whole question of the generation and modelling of coal size distributions is currently being studied by a major R&D project funded by NERDDC (3) and it is suggested that this project team could make a significant contribution to the progress of any study of the "keyhole mining" technique.

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NERDDC Project 1290; grantee Coal & Allied Operations Pty Ltd.

# IDENTIFICATION OF THE SOURCES OF CONTAMINATION IN PRODUCT STREAMS IN A MINERAL SANDS PROCESSING PLANT

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## 1. INTRODUCTION

The major products of the mineral sands industry in Australia are rutile, zircon and ilmenite. In 1991, Australia earned $M 498 from the export of these minerals (ABARE 1991). Table 1 gives a breakdown of the production and export figures for these minerals for the same year. Exports to Japan accounted for 16.4, 17 and 37.7 % of the total rutile, ilmenite and zircon exported from Australia.

**Table 1**
**Production and Export of Mineral Sands Products from Australia — 1991**

| | kt — fiscal year 1991 | | | Value |
|---|---|---|---|---|
| Mineral | Production | Export | Exports to Japan | total exports A$M |
| Rutile | 184 | 195 | 32 | 155 |
| Ilmenite | 1200 | 1045 | 180 | 72 |
| Zircon | 329 | 326 | 123 | 271 |

Increasingly the demand for rutile is exceeding world production and consequently, there is an increase in the amount of ilmenite being chemically converted to rutile. This product is generally termed "synthetic rutile". In fiscal year 1991, 43% of the ilmenite produced in Australia was processed domestically to produce synthetic rutile. All of the synthetic rutile and most of the native rutile (>95%) are used in the production of $TiO_2$ paint pigments.

The production of synthetic rutile and the processing of either synthetic rutile or rutile to $TiO_2$ pigments, produces waste streams in which any of the minor elements occurring in the minerals are concentrated. In addition to the more commonly known impurities, the ilmenite and rutile contain varying levels of naturally-occurring uranium and thorium. Uranium and thorium present in rutile and ilmenite concentrates can occur either as uranium and thorium incorporated within the crystalline structure of these minerals or as minor minerals that can have higher uranium and thorium contents. When mined, the radionuclides in the uranium and thorium decay chains are usually in secular equilibrium (i.e. the specific activity (radioactivity per gram) of each daughter in the ore is the same as its parent). Processing of ilmenite and rutile results in the radionuclides partitioning into the waste streams.

Problems associated with the disposal of this waste have not been considered until recently when importing countries have realised that in addition to the mineral they are importing a waste disposal problem. Recently, Japan in particular, has tightened regulations governing the disposal of waste from pigment production plants and the US and European Community are also looking at tighter regulations. The regulations (Nippon Keizai Shinbun 1991) affect Japanese pigment manufacturers by limiting the radioactivity that can be contained in waste that is allowed to be disposed of in landfill facilities. These new regulations mean that, depending on the process being used for pigment manufacture, the total U+Th that can be contained in ilmenite should be less than 50 ppm. Japanese pigment manufacturers are being encouraged to only import feedstocks that result in wastes that can satisfy the new disposal regulations.

Most Australian ilmenite concentrates contain far greater amounts of U+Th than 50 ppm. For this reason, it has become increasingly important for mineral sands producers to maintain important, existing markets, particularly in Japan, to reduce these levels to values as low as possible. The effect of the new waste disposal regulations has to a certain extent made problems associated with other impurity levels, like chromium, relatively less important.

We have undertaken a number of studies to help one east-coast mineral sand producer define and reduce levels of uranium and thorium in their ilmenite and rutile products. These studies have been aimed at elucidating the source of uranium and thorium in their rutile and ilmenite products and measuring the distribution of uranium and thorium in process streams in their physical separation plant.

## 2. EXPERIMENTAL

Uranium and thorium in the rutile and ilmenite products and in all the processing streams in the physical separation plant have been measured using $\gamma$-spectrometry. In addition, samples of the processing streams have been characterised by scanning electron microscopy (SEM) and the $\alpha$-track technique. These methods are described below.

Gamma-spectroscopy was carried out on the solid samples using an EG&G Ortec, GAMMA-X detector. Large volumes of solids were counted in a "re-entrant" container (commonly referred to as a Marinelli beaker) and smaller samples were counted using a smaller flat container. Results from this technique gave the activity of each $\gamma$-emitter in the uranium and thorium decay chain and allowed the activity of uranium and thorium to be inferred from their daughter decay products. Concentrations of uranium and thorium were calculated from their activity.

SEM was used to determine the mineralogy of the samples. Specimens examined by SEM were mounted in epoxy resin, ground and polished to reveal cross sections through the grains.

The SEM used was a JEOL JXA 840 fitted with an energy-dispersive X-ray spectrometer (EDS) and a Tracor Northern X-ray analysis system. EDS quickly and easily determines the elemental composition of mineral grains, from which mineralogy may be implied. Spectra collected can be quantified using the Tracor Northern's commercial software package. Grain counts were carried out on the specimens to determine the relative proportions of the minor minerals.

The α-track technique was used to measure the distribution of α-activity of the minerals in the grain mount. This was done by placing the grain mount in close contact with a strip of CR39 plastic detector for about two weeks. Alpha-particles emitted from the surface grains create minute damage tracks in the plastic. These tracks were enlarged to a width of about 15 μm by etching in caustic soda solution and then their distribution on the plastic was examined using SEM. By correlating the tracks on the plastic with the same area on the grain mounts, it is possible to get a visual impression of the distribution of the activity in individual grains and to identify the mineralogy of the individual grains with the highest α-activity. It is not possible using this technique to identify the radionuclide giving rise to the α-activity.

## 3. RESULTS

Initially, the distribution of thorium and uranium contamination in the product streams was investigated. Table 2 summarises the distribution of minerals identified from the grain mounts of the ilmenite and rutile products.

The distribution of α-tracks and the mineral grain distribution were matched-up with grain mounts of the rutile ilmenite concentrates. The rutile grains have a fairly even distribution of α-tracks; the only dense clusters of tracks are due to some of the zircon grains. The uranium and thorium contents of the zircons appear to be highly variable.

Similar investigations of the ilmenite concentrate revealed that the level of uranium and thorium in the ilmenite grains was very low and a significant proportion of the uranium and thorium in this material was associated with the grains of monazite. Although only two monazite grains were located in this sample, if it is assumed that the monazite contained 6 wt% thorium (a typical value for east coast monazites) then these grains account for 70% of the thorium in the concentrate measured in the concentrate.

**Table 2**

**Estimated Number of Minor Mineral Grains per 10,000 Grains of Concentrate**

| | Rutile Concentrate | Ilmenite Concentrate[1] |
|---|---|---|
| Zircon[2] | 80 | 8 |
| Rutile | - | 41+ |
| Ilmenite | 10 | - |
| Monazite[2] | <1? | 2 |
| Xenotime[2] | not found | inclusion in one zircon |
| Spinels[3] | 14 | 800+ |
| Quartz | <1 | <1 |
| Quartz-rutile intergrowths | 18 | <1 |
| Nb & Ta rutiles | 2+ | 2 |
| Cassiterite | 10 | 2 |
| Magnetite | <1 | 4 |
| Marcasite | <1 | 8 |
| Tourmaline | <1 | 2 |

1 Much of the ilmenite has undergone partial alteration to leucoxene, although there is wide variation in the extent of alteration of individual grains.

2 Major hosts for uranium and thorium.

3 Most of the spinel grains contain a significant amount of chromium.

These results established that the matrix concentration of uranium and thorium in the rutile and ilmenite concentrates was relatively low and focussed attention on the need to reduce or eliminate contaminant minerals, like monazite and zircon, from the products. Consequently, a mass balance was carried out on the physical separation plant by company personnel to measure the mass flow and to take a sample from each process stream. Bulk uranium and thorium levels were measured in each of these samples.

For the purposes of this paper, the results for the initial first high tension separator only will be presented. Figure 2 describes the streams entering and leaving this unit. Uranium and thorium analyses of these streams showed that the conductors/non-conductors stream had a thorium concentration 12 times higher than the conductor/conductor stream. Grain mounts were made of the conductors/non-conductors and the conductor/conductor streams and the differences in mineralogy between these two streams were studied.

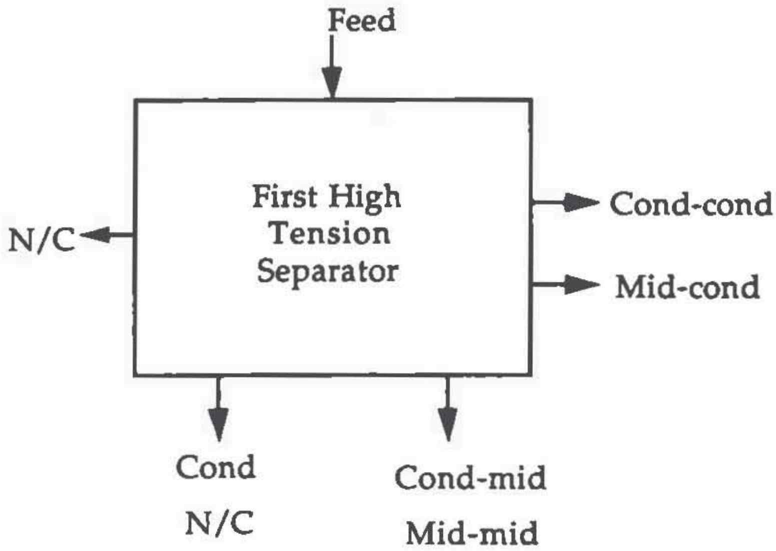


Figure 2 Processing Streams Associated with the First High Tension Separator

Table 3 compares the number of grains of the minor minerals counted in the conductors/non-conductors and the conductor/conductor streams. The minerals which are hosts for uranium and thorium are monazite and thorogummite. In addition to these minor minerals, the other major contributor to uranium and thorium levels is zircon in the conductors/non-conductors stream.

The total thorium content of the samples was calculated from the estimated proportions of all the minerals in the mounts, and the measured or assumed (see above) concentration of thorium in the respective minerals. This calculation agreed, within ± 40%, with the levels of uranium and thorium measured by $\gamma$-spectrometry.

**Table 3**
**Minor Minerals Occurring in the Grain Mounts of Samples from the Process Streams Leaving the Rougher HT**

| | conductor/conductor | conductors/non-conductors |
|---|---|---|
| Total Grain Count | 12200 | 16400 |
| Monazite | ND | 71 |
| Thorogummite | ND | 1 |
| Cassiterite | 2 | ND |
| Baddeleyite | ND | 1 |
| RE-rich Sphene | 1 | ND |

ND Not Detected

As a result of these measurements, the flowsheet of the physical separation plant has been changed and the small mass associated with the conductors/non-conductors stream is being stockpiled. Continuing measurements on the levels of uranium and thorium in ilmenite and rutile product streams are being carried out to assess if this change leads to a reduction in the level of contaminants in the ilmenite and rutile products.

## 4. CONCLUSIONS

This study has identified that the major source of radioactive contamination in ilmenite and rutile products, from a NSW physical separation plant, is associated with the carryover of thorium- and uranium-rich minerals, such as monazite, thorogummite and zircon.

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# SEDIMENTARY FLUID INCLUSION STUDY OF LOWER PERMIAN SEDIMENTS, GUNNEDAH BASIN : PREPARATION, MICROTHERMOMETRIC ANALYSIS, INTERPRETATION

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## INTRODUCTION

Microthermometric data from authigenic inclusions within Permian sandstones of the Gunnedah Basin are presented. These data are interpreted to determine the trapping conditions and fluid type of authigenic fluid inclusions present in the sandstones. This paper presents some of the findings of a wider investigation (McDonald in prep.) of the Permian sediments comprising the "Porcupine - Lower Watermark marine depositional episode" of Hamilton, 1987. Further work combining the fluid inclusion results with vitrinite reflectance and structural data will enable a model for the burial history and hydrocarbon maturity of Gunnedah Basin strata to be presented.

Recent work (McDonald & Skilbeck, 1991) has revealed a lithological heterogeneity in the Porcupine Formation that was not previously recognised. Hamilton et. al. (1988) suggested regional source and reservoir potential of the interval was poor. Wilga Park-1 drilled in 1985, by a Consolidated Petroleum Australia N.L. joint venture, and located in the north of the basin flowed gas at sub-economic rates from sandstones in the Porcupine Formation.

Volcanolithic arenites are the dominant sandstones in the Porcupine Formation, lithologies previously considered unsuitable for fluid inclusion study; however, the proven presence of hydrocarbons within the Porcupine Formation formed a compelling rationale for undertaking such research. The main aims for a fluid inclusion study of Gunnedah Basin sediments are to prove that meaningful and consistent thermometric data can be gathered for lithic sandstones and to collect data that will be used to construct burial history and thermal maturity models for the Gunnedah Basin strata.

## SAMPLE MATERIAL

Material for this study was collected from the fully-cored boreholes; Brigalow-2, Brown-1, Gunnedah-1, Howes Hill-1 and Tullamullen-1. Those boreholes were drilled between 1976 and 1982, during the D.M.E. Gunnedah Basin regional coal assessment program. Samples were taken at two depths from D.M.E. Bellata-1, a fully cored stratigraphic and wildcat exploration well, drilled in 1986. Samples were also collected from the cored interval of C.P.A. Wilga Park (1985), together with ditch cuttings from both Wilga Park and C.P.A. Nyora (1987).

A petrographic thin-section was prepared for each sample, and the thin-sections then evaluated to select those with optimal authigenic quartz overgrowth and porosity, and minimal detrital and authigenic clay content (Fig. 1). Examination of three hundred thin sections of Porcupine sandstones with a basin wide distribution, provided few samples for fluid inclusion analysis. This is due to the predominantly volcanolithic and poorly sorted nature of sediments in the southern and central basin. Sandstones from the north and west basin, e.g. those from Wilga Park, have a more significant quartz content and consequently provided the most suitable materials, of "at least marginal to fair reservoir-grade sandstones" (Eadington 1990, pers. comm.) for the analysis of fluid inclusions. Sandstones from formations other than the Porcupine Formation were selected; Howes Hill 130m is from the Triassic Napperby Formation, and Bellata 986m from the Maules Creek Formation. These samples were analysed primarily to maximise the opportunity of locating authigenic inclusions from sandy intervals, but also - in the case of Bellata - to compare the microthermometric results of one sandstone interval to another.

## RESULTS

### The Measurements

Combined measurements of homogenisation temperature (Th) and freezing data (Tfm and Tml) were collected on forty-eight inclusions from ten samples. A further nine Th-only measurements were taken from inclusions too small for observed freezing behaviour (Fig. 2).

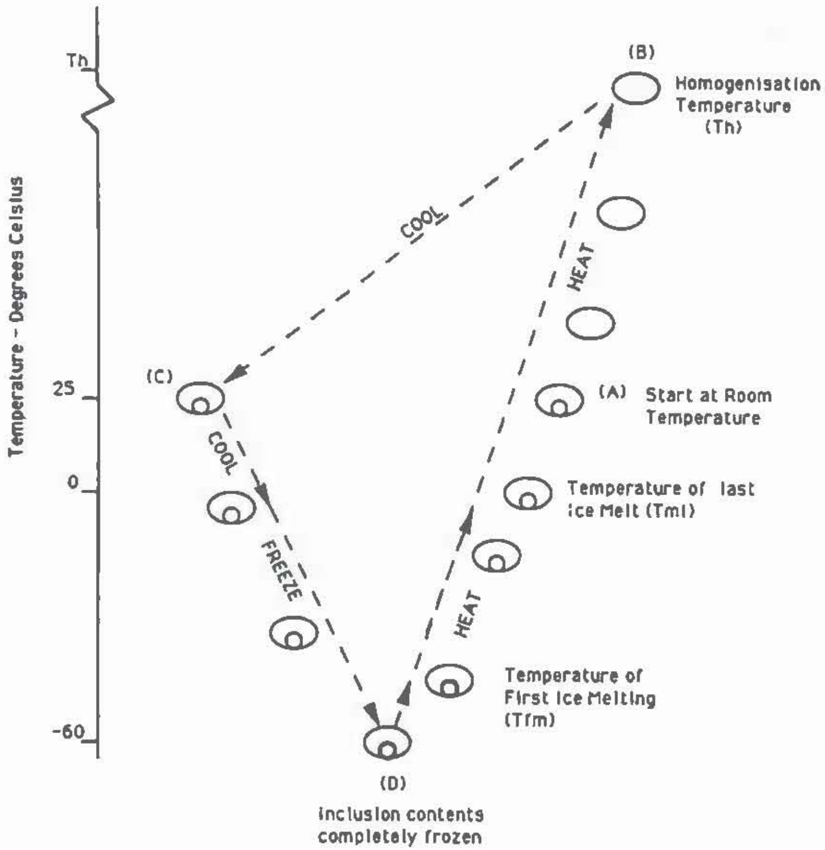


**FIGURE 2.** Typical heating-cooling cycle (A-B-C-D-A) for a two-phase aqueous inclusion. The important phase changes (TFM, TMI, TH) are indicated. Note that the salinity measurements are taken between (D) and (A) rather than on cooling from (C) to (D).

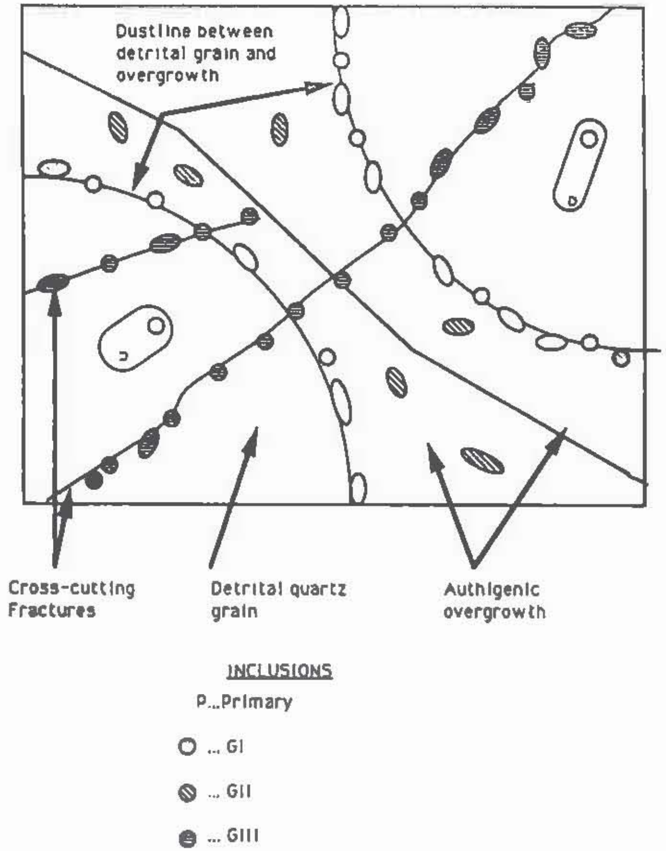


**FIGURE 1:** Schematic representation of primary (P), GI (along dustlines), GII (authigenic overgrowths) and GIII (cross-cutting fractures) fluid inclusions.

Total homogenisation results are presented in Fig. 3, and characteristics of the measured inclusions summarised in Table 1. All homogenisations occurred with a transition to a monophase liquid from co-existent liquid and vapour phases. The majority of homogenisations (from all inclusions) occurred between 90°C and 120°C the range of Th values, from 60°C to 140°C, is characteristic of inclusions in diagenetic mineral phases.

Figure 10 shows that, from within any given sample, homogenisation temperatures cluster with a restricted range. With the exceptions discussed below, inclusions from the three generations, and comprising up to all four recognised types show Th distribution between 5°C and 10°C.

## FREEZING MEASUREMENTS

### First Melting Temperatures

Melting behaviour of the forty-four inclusions measured at low temperature are presented in Fig. 4. First melt temperatures (Tfm.) range from -70°C to -30°C, but the majority of data plot between -55°C and -37.5°C.

Hydrocarbon-bearing inclusions were observed to undergo Tfm. at lower temperatures than neighbouring aqueous inclusions. The presence of methane has been documented as the cause of lowered phase-change temperatures. Significantly, five of the lowest eight Tfm measurements were of hydrocarbon-bearing inclusions. As an qualitative function, Tfm. depression from an aqueous correlative appears to increase with an increasing hydrocarbon content.

### Ice Melting Temperatures

The ice melting temperature (Tml) is that at which the last ice in an inclusion is seen to melt to the aqueous phase. Tml can be used to derive the salinity of a given fluid. Pure water freezes at 0°C, and systematic depression of the freezing point is a function of an increasing salinity. Freezing measurements are not conducted on cooling, due to super cooling and the persistence of metastable water below 100°C. The Tml from a frozen inclusion is equivalent, however, to the freezing point depression. This therefore indicates bulk salt concentration, which is expressed as equivalent weight

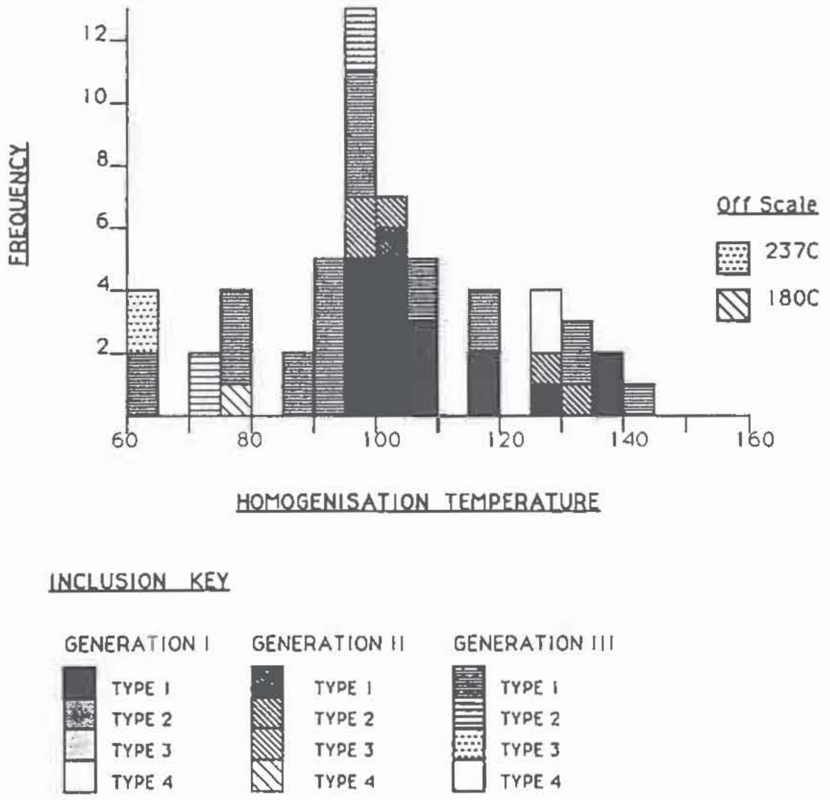


FIGURE __. Total Th frequency distribution for all measured inclusions

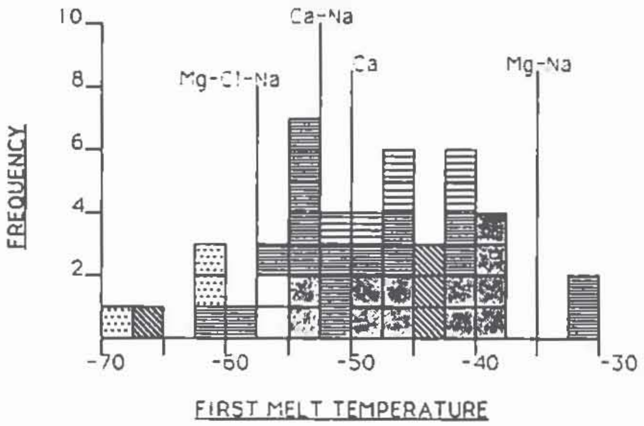


FIGURE ___ Total frequency plot of First Melt Temperatures Key as for Figure 9. Eutectic temperatures of major chloride salt systems are indicated over the first melts

percent NaCl. Most inclusions reached Tml between -1.0°C and 0°C and these measurements equate to salinities from less than 0.5% to 1.5% (Equiv. wt. % NaCl). The range of interpreted salinities is from a large cluster of results around 1%, to the maximum observed in samples from Gunnedah-1, with 13 percent equivalent weight NaCl salinity. The implications of varying salinities of the migrating fluids is discussed below.

## DISCUSSION

### Occurrences

From the observed occurrence and co-existence of inclusion type and generation, hydrocarbon migration is interpreted as having taken place during late stages of fluid migration. Hydrocarbon-bearing were most commonly observed in the quartzose sandstones comprising the Porcupine Formation in the northern basin.

Sediment lithotype is interpreted as the main control over hydrocarbon migration. Distribution of hydrocarbon-bearing inclusions is restricted to those sandstone samples with a modal quartz component of over 30%. In clay-rich samples the later fluids had migratory pathways occluded by authigenic overgrowth and cementation. Authigenic porosity reduction of later fluid migration is interpreted as the main reason for the absence of hydrocarbon-bearing fluid inclusions in volcanolithic samples.

Homogenisation measurements of inclusions from the earlier inclusion morphologies suggest that the sediments from the Porcupine Formation, barren of hydrocarbon inclusions, reached marginal to mature generating temperatures.

### Homogenisation temperatures

A cluster of Th data plots for each sample is interpreted as representing the maximum burial temperature for that sample. This may involve the heating and thermal resetting of cooler, early inclusions. Some inclusions from the same generation and type as others in a field of view do not homogenise until much higher temperatures. These increased values are interpreted as the result of necking-down or leakage during formation, although such evidence was not observed. Manifestations of leakage (increased size of vapour bubbles) are obviously difficult to detect in very small examples. Higher Th observations of leaked inclusions are unsupported by measured vapour-phase ratios.

The scatter of basin wide Th values above an expected sedimentary to diagenetic range may suggest proximity to one of numerous Tertiary dyke swarms, but partial leaking or necking down is invoked as the more likely cause (Roedder 1984). Maximum burial depths of the Porcupine Formation throughout the Gunnedah Basin were sufficiently variable to provide the observed (non-leaked) range of homogenisation temperatures.

## FLUID INCLUSIONS, PORCUPINE FORMATION

Homogenisation temperatures of measured inclusions are higher than a temperature gradient of 33 C/km would yield at the current depths of Porcupine Formation intersections. The average crustal value is that used for the sediments of the Sydney and Gunnedah Basins (Eadington et. al., 1989). Higher Th values are the result of either a higher heat flow than that which currently exists, or greater depth of burial followed by the erosion of an unknown thickness of sediment.

Bai et. al. (1990) studied diagenetic fluid inclusions in the Narrabeen Sandstone from the Sydney Basin, currently buried at around 500 metres. They suggested that the restoration of between 500 and 1000 metres of eroded section would produce formation temperatures in quartz overgrowths of between 102°C and 130°C. Extrapolation of their calculations to a Gunnedah Basin model suggests that the homogenisation temperature range (from 60°C to 140°C) is the result of burial to maximum depths between 1000 and 1800 metres. Homogenisation temperatures from the Porcupine Formation, with a current basin wide distribution from outcrop to burial at 990 metres, suggest the loss of between 500 and 1000 metres of overlying section.

Middleton and Schmidt (1982) proposed the loss of between 500 and 1000 metres of sediment thickness in the Sydney Basin, through erosion following uplift. Vitrinite Reflectance values indicate rapid cooling, suggesting uplift, at 100-70 Ma. Reports by Hamilton (1987), among others, indicate that the results of this major tectonic event in basin evolution are recorded the sediments of the Gunnedah Basin. The "Mid - Permian diastrophism" which occurred between deposition of the Upper Watermark - and Lower Black Jack-

Formations resulted in the loss of sediment thickness up to 1000 metres. Migration of the fluids in the latest inclusions must, by thermometric evidence, have pre-dated Mid - Permian diastrophism.

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# WRENCH FAULTING IN THE WESTERN COALFIELD, NSW.

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## ABSTRACT

The advent of longwall mining in the Lithgow Coal, the basal seam in the Western Coalfield of N.S.W., combined with extensive pillar panel mining in the upper Katoomba Coal, has provided information allowing further development of a structural model for the Coalfield. Episodic basement wrenching and uplifts are proposed in the additional components of this model.

## BACKGROUND

The Western Coalfield of the Sydney Basin is located on the Blue Mountains Plateau and extends from the south of Lithgow north to Ulan. Its western edge lies unconformably on folded and faulted Lower/Middle Palaeozoic metasediments and a number of Carboniferous granites and granodiorites. Geographic location is shown in Figure 1.

The extent of the Western Coalfield has been defined by Branagan (1960) as all the Permo-Triassic rocks of the Blue Mountains Plateau west of a meridian through Katoomba and south of Rylstone. This describes a rough rectangle about 50km by 60km. Topography is that of an undulating plateau surface between 900m and 1300m above sea level and deeply stream-dissected into entrenched cliff-lined river canyons. Drainage eventually flows into the Nepean /Hawkesbury river system.

Morris (1975), Bembrick (1981) and Ward and Morris (1981) have described and reviewed the stratigraphy of the Illawarra Coal Measures in the Western Coalfield. In a Permo-Triassic sequence between 100-400m thick and dipping NE at about 2 degrees, there are five coal seams of economic interest within the Permian strata (In ascending sequence):

a) Lithgow Coal - the basal seam in the sequence, it has been exploited for over 100 years in both open cut and underground mines;

b) Lidsdale Coal - this split from the Lithgow Coal has a limited geographical distribution within the western section of the Coalfield and is of inherently high ash content;


FIGURE 1: Sydney Basin Boundaries

c) Irondale Coal - this seam is relatively thin and high In ash;

d) Middle River Coal - this is a thick seam of high ash thin coal plies interbedded with claystone and shale bands;

e) Katoomba Coal - the uppermost seam in the Coalfield, it is well developed to the NE of Lithgow where it is currently being mined.

Geographically, mines in the Lithgow Coal are concentrated on the western edge of the Coalfield for reasons of outcrop entry and coal quality, while the two mines currently operating underground in the Katoomba Coal are located to the centre-east where the seam is best developed.

## REGIONAL STRUCTURE

A number of studies (Branagan 1960, Morris 1975, Finlayson et al. 1980, Shepherd et al. 1981, Shepherd and Huntington 1981, Poppitt 1984) have reported on structural models for the Western Coalfield. As information has accumulated from fracture mapping and seismic/ magnetic surveys, all at various scales, these models have evolved into a series of tectonic and magmatic events yielding a cumulative structural pattern. Much of the current discussion centres on the temporal relationships of these events - the core of the models is a dissection of the cumulative pattern into a chronological sequence.

Components of the structural models are summarised in the following paragraphs. This paper has some additional information and comments on a number of these components, and as such may have some bearing on the relative timing of various tectonic events.

The essential structural characteristics of the Western Coalfield are listed as:

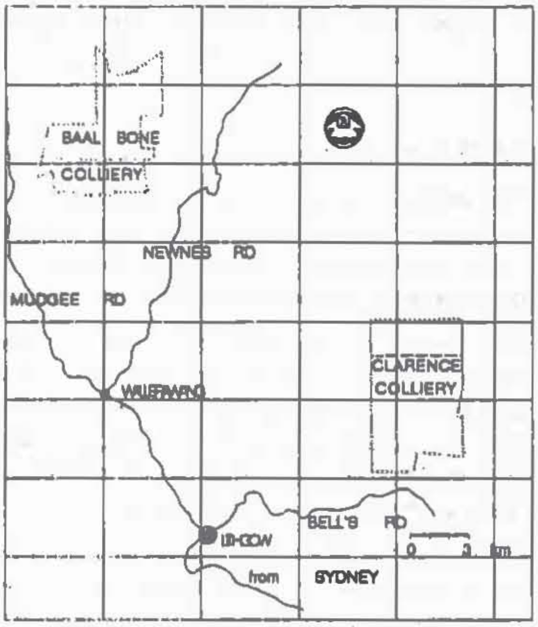


FIGURE 2. Lease locations

a) NNW and ENE regional fracture trends.
Most background jointing sets correspond to these directions (within about a 10 degree

range), although spacing is not regular, and there is no vertical persistence of fractures through the Triassic-Permian boundary;

b) minor normal faulting (throw 1m or less) generally trending NNW in zonal swarms;

c) mild thrust folds containing minor thrust (0.1-0.4m) and strike-slip fault swarms generally trending north, but with considerable variation in strike along their length. To date, intersections of these zones in mining are limited to the basal coal seams in the western section of the Coalfield;

d) significant normal and graben faulting ranging in throw from 4m to over 20m with a general NNW trend. To date, intersections of such faulting in underground mining are limited to the eastern section of the Coalfield in the Katoomba and Middle River Coals;

e) NNE-trending lineaments with considerable strike lengths (perhaps up to 50km) and a periodic spacing of about 5km across the Coalfield. These are visible at air photo and satellite scale as topographic features;

f) Cainozoic uplifts (Wellman 1979, Jones and Veevers 1982) forming highlands and reactivating existing fractures;

g) aero-magnetic basement lineaments with a NNE trend that suggest differing basement lithologies across lineament strike.

## STRUCTURAL PATTERNS FROM MINES IN THE LITHGOW COAL

The concentration of Lithgow Coal mines in the western section of the Coalfield has yielded a pattern of N-trending zones with very difficult mining conditions. These zones may be up to 100m wide with variable spacing across the Coalfield. Reports from Shepherd et al. (1979), mining records and routine personal mapping present a picture of zones containing joint and minor fault swarms of high frequency (spacing less than 1m). The faulting is a mix of normal dip-slip, strike-slip and minor thrusting and bed shearing, with the latter two being predominant. Most of the pillar panel mines in the Lithgow Coal reacted to these zones by leaving them virtually unmined, but the advent of longwall mining required different responses.

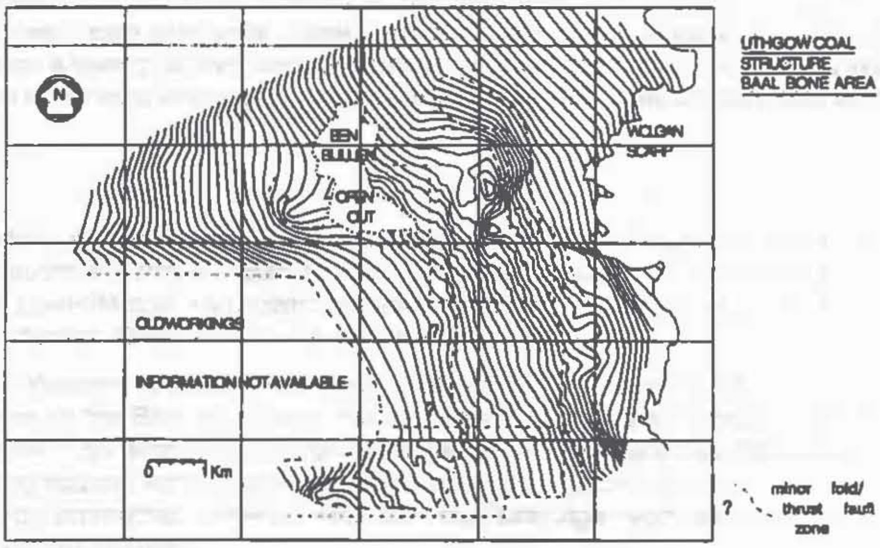


FIGURE 3: Lithgow Coal floor contours

Longwall mining at Baal Bone Colliery (Figure 2 locates the Colliery lease within the district) has intersected two of these zones to date. One of them, on the eastern edge of the mine workings, is quite severe (Cox's River Structure) while the other has been completely penetrated now by seven sets of gateroads. The latter zone has proved relatively mild so far and has yielded some clear detailed exposures within such a zone.

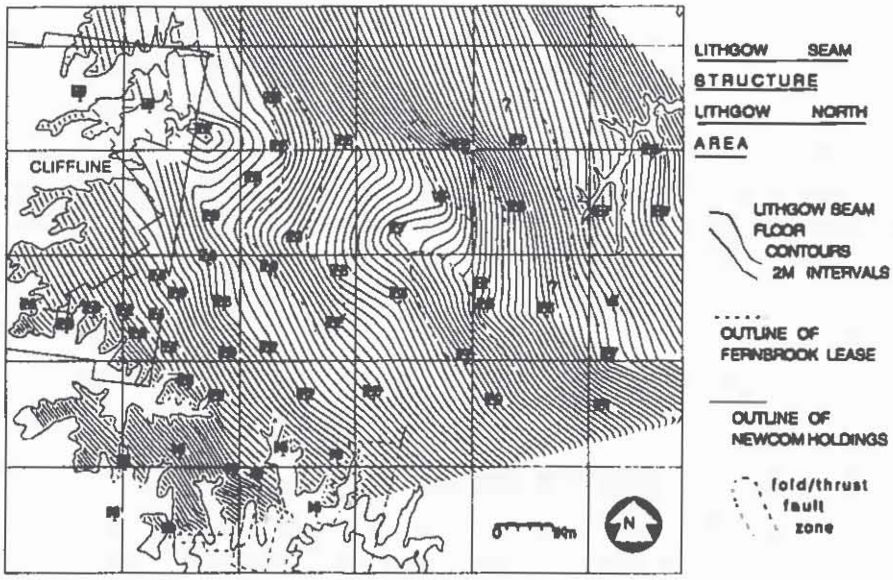


FIGURE 4: Lithgow Coal floor contours

Structure contours were generated across the Baal Bone district for Lithgow Coal floor with every possible verifiable point included. The result of this modelling, which now uses over 7000 points, was to highlight the mild monoclinal thrust fold nature of the two zones discussed above. Although the thrusting that caused these structures was not severe, it was sufficient to cause swarms of strike-slip and thrust shearing within the relatively weak mudstone roof and floor plies of the Lithgow Coal. The coal seam itself shows minor throws along the thrust planes ranging from almost zero to 0.4m. Figure 3 shows the structure contour set for the Baal Bone area. Mapping from Western Main, Wallerawang, Fernbrook, Hermitage and Angus Place Collieries shows a similar pattern within their "slackey rolls".

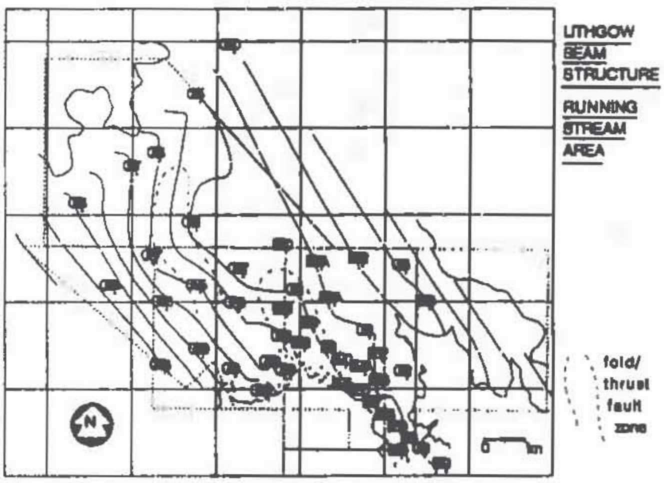


FIGURE 5: Lithgow Coal floor contours

Figures 4 and 5 show respectively Lithgow Coal floor contours for the Lithgow North and Running Stream areas. These maps were generated from drillhole data as no significant mining activity has yet occurred. Similarities in the contour patterns to those from the Baal Bone area are clear - interpretation of these patterns as monoclinal thrust folds is proposed as one of the points of this paper.

Detailed observation of gateroad exposures within the zones at Baal Bone and across the longwall face has shown a chronological relationship between minor normal faulting and the mild thrust deformation. While the zones contain mostly strike-slip and minor thrust faulting, some exposures contain minor normal faulting that has been reworked. Perhaps the clearest expression of this is in 13 East gates cut-through 3, where a minor (0.4m) graben has been gently folded by a later thrust. Figure 6 shows a diagram of this detail.

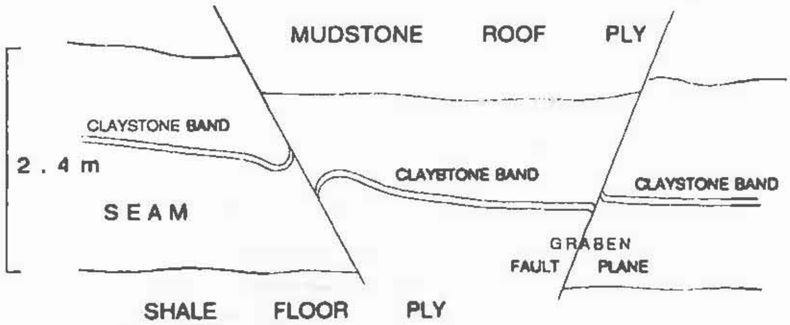


FIGURE 6: Lithgow Coal 13 East C/T 3 fault detail

A road cutting on the Portland Road adjacent to Ivanhoe Colliery has exposed a thrust fold/fault in the Irondale Coal with about 2m amplitude (roughly seam thickness). Background jointing in this exposure is seen to rotate and flex through the axis of the fold, giving a clear time relationship between jointing and thrusting. This exposure is about 20m above the Lithgow Coal.

The pattern for the basal seams in the western section of the Coalfield is one of mild compression overprinted on existing minor normal faulting and jointing. Placement of expressions of compressional folding (colloquially named "slackey rolls") may be lithologically controlled.

## STRUCTURAL PATTERNS FROM MINES IN THE KATOOMBA COAL

Shepherd et al. (1979) describe a series of minor normal faults trending NNW in the Katoomba Coal in Grose Valley Colliery. It was noted that this swarm is striking parallel to the primary jointing of the regional set.

Clarence Colliery, immediately adjacent (NW) to Grose Valley Colliery, has intersected considerable normal faulting along the NNW strike, some of which have significant throws (over 20m). Poppitt (1984) reported a high incidence of in-filled jointing in the fault zones, together with some strike lengths of 5-6km. The faulting has a pronounced en-echelon characteristic. Mine workings have demonstrated the graben nature of this faulting together with the hinged nature of throws along strike. Figure 7 shows significant fault traces overlaid on mine workings.

To date, no thrust folds or faults have been observed in Clarence Colliery, which now has extensive mine workings. Almost all of the intersected faulting and primary jointing trend NNW within a 10 degree variation. Considerable thicknesses of gouge are observed on most fault planes and on some joint faces within joint swarms. This gouge, together with oblique-slip slickensides on exposed fault planes gives a picture of faulting with a strike-slip

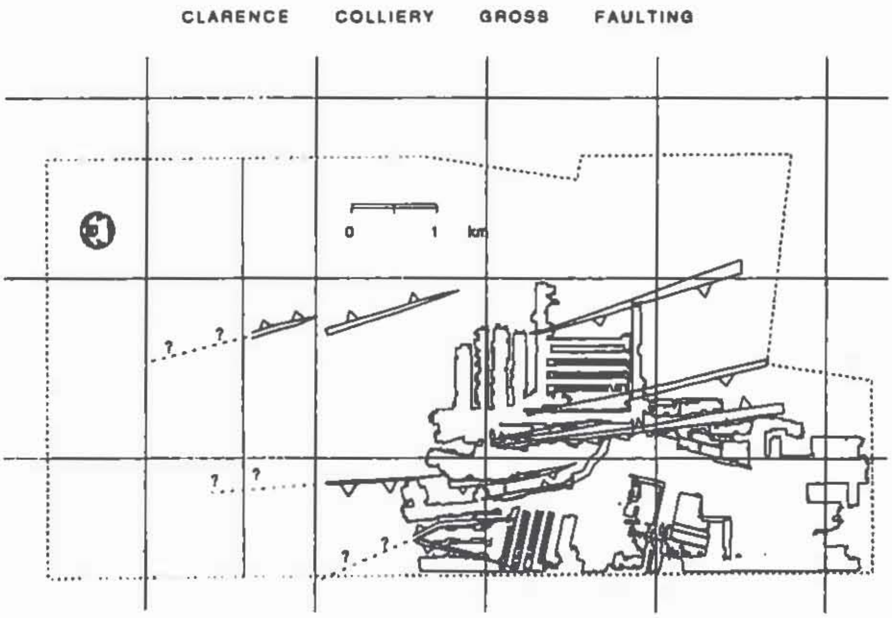


FIGURE 7: Graben faulting in the Katoomba Coal

or oblique-slip component. Groundwater movement through the strata is controlled by this fracturing, as the water make from the roof during formation of mining goaf demonstrates. Seam caverns and oxidisation show heavily fluctuating groundwater levels along the NNW fracture trend.

Most fault ends exposed so far start within a NNW joint zone - just one more joint amongst many, so to speak. Slickensides on NNW joint faces within a fault zone suggest that the faulting postdates joint formation, and it may be that fault strikes are controlled by pre-existing joints being reactivated.

The pattern for the Katoomba Coal is one of tensional faulting forming grabens with significant displacements, perhaps along pre-existing reactivated joints. A significant strike-slip component is present.

## TOWARDS A COMMON STRUCTURAL MODEL

Finlayson et al. (1980) proposed a sinistral wrench model for the regional fractures mapped on the surface in the Clarence area and for the minor normal faulting intersected in the Grose Valley Colliery. Poppitt (1984) developed this model with additional information from significant graben faulting intersected in Katoomba Coal mine workings. The NNE-trending Lineaments mapped across the Clarence Colliery holdings were considered possible last-stage surface expressions of wrenching. Although this model did not include any compressional components and did not assess the impact of Cainozoic uplifting(s), wrenching episodes composed of divergent, sinistral basement movements form a workable model for graben formation (Wilcox and Harding 1972).

Branagan (1960), Morris (1975) and Shepherd et al. (1981) described models for the basal seams of the Coalfield that essentially required minor deformation of the western edge of a basin with N to NNE-trending zones of difficult mining conditions formed from joint and minor fault swarms. An additional proposal for this model from this paper is the location of these "slackey rolls" along monoclinal thrust folds of relatively minor amplitude.

Combining a tensional, graben-forming model for the upper seams of the Coalfield with a compressive, fold-forming model for the basal seams is of some interest. Although a number of syntheses are possible, including a geographical separation of tensional and compressional events, a model that appears to fit is based on Shepherd and Huntington's (1981) proposal for a sequence of geological events affecting the Sydney Basin.

The model proposed for the Western Coalfield in this paper comprises the following sequence:

a) early joint formation (Permian), perhaps through early sinistral N-S basement wrenching, with later joint/coal cleat formation during the Triassic;

b) Early Cainozoic normal faulting related to the Lapstone Monocline/Kurrajong Fault formation, showing in the Lithgow Coal in the western section as minor normal faults. Graben formation from sinistral N-S wrenching episodes reactivating existing joints could be invoked here;

c) Mid-Cainozoic thrusting, perhaps as basement wrenching became convergent at places along strike, showing in the basal seams as N-trending small amplitude monoclines, minor thrust and strike-slip fault swarms ("slackey rolls"). This mild compressional component is expressed in the Katoomba Coal mine exposures as strike-slip faults along reactivated joints;

d) Late Cainozoic differential uplifts, reactivating the graben faulting in the centre of the Coalfield, forming the faulting pattern now observed in the Katoomba Coal mines and entrenching the canyon topography. Relaxation from uplift allowed the NNE-trending lineaments to be expressed across the surface topography.

## ACKNOWLEDGMENTS

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