MALCOLM BOCKING

THIRTY FOURTH NEWCASTLE SYMPOSIUM
on
ADVANCES IN THE STUDY OF THE SYDNEY BASIN

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PROCEEDINGS OF THE THIRTY FOURTH NEWCASTLE SYMPOSIUM

on

"ADVANCES IN THE STUDY OF THE SYDNEY BASIN"

Edited by Ron Boyd, Claus F. K. Diessel and Sharon Francis
***The* University *of* Newcastle**

July 6, 2000

NEWCASTLE NSW 2308 AUSTRALIA

CONVENERS
RON BOYD
CLAUS F.K. DIESSEL

PREFACE

Welcome to the 34th Newcastle Symposium and its Proceedings. This year the Symposium continues its tradition of 34 unbroken years of providing a forum for presenting and discussing the geoscience of the Sydney Basin. In keeping with its focus on the Sydney Basin, this year's Symposium was held in Sydney on Thursday July 6th in conjunction with the 15th Australian Geological Convention. The venue was the University of Technology campus on Broadway. The conveners felt that two conferences in the middle of 2000 held close together would dissipate our Sydney Basin presentations. Instead we decided to join forces with the 15th AGC and present a full day feature Symposium (Number 5B).

The concept has worked well and the symposium turned out to be quite a success. One measure of this success is the Symposium Proceedings. This year we have a broad and varied selection of quality papers. These papers cover the range from non-marine sequence stratigraphy to coal geology, regional stratigraphy, hydrogeology and geophysics. In addition we enjoyed two keynote addresses. The first was from Peter McCabe of the United States Geological Survey presenting a vision of global energy in the 21st Century. The second keynote address was the second Kenneth George Mosher Memorial Lecture, sponsored by the NSW Coalfied Geology Council, and this year presented by Colin Ward on the topic of mineral matter in coal. In contrast to previous years, the Proceedings were not completed prior to the Symposium but have been put together subsequently, and published in early 2001. The budgetary position of the Symposium was also different in 2000, in that we did not have registration funds available for printing the Proceedings. In this respect we are grateful to the Geological Society of Australia and the 15th AGC for subsidising printing costs. We are particularly grateful for the assistance provided by the Convention Convener Greg Skilbeck of the University of Technology, and to Colin Ward for his co-ordination of the Sedimentary Basins and Resources Conference Theme.

Ron Boyd and Claus F.K. Diessel
Conveners, 34th Newcastle Symposium

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

ORGANISATION OF NON-MARINE STRATIGRAPHY

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INTRODUCTION

Non-marine stratigraphy has traditionally been a difficult field in which to correlate, interpret, and to construct summary models. This is because individual stratigraphic units are often difficult to distinguish, marker beds are less common and continuous, and chonostratigraphic and biostratigraphic control is frequently lacking or inadequate. In contrast, coastal and shallow marine strata are more distinctive, have better age control and are subdivided by the repetitive passage of the shoreline in transgressive and regressive packages. It is not surprising then, that the advances embodied in sequence stratigraphy (e.g. Posamentier and Vail, 1988, Van Wagoner *et al.*, 1991) were initially applied to coastal and shallow marine strata, and this approach is still being developed for environments furthest removed from the shoreline in terrestrial and deep marine settings.

Nevertheless, the accommodation concept behind sequence stratigraphy offers the best current method to develop an organised approach to non-marine stratigraphy. This is because other approaches such as facies models and architectural element analysis, while offering local methods to interpret non-marine successions, do not provide a unified approach to encompass all non-marine strata and to provide a link to adjacent coastal and marine strata. Numerous studies (e.g. Shanley and McCabe, 1991, Kocurek and Havholm, 1993, Bohacs and Suter, 1997, Legaretta and Uliana, 1998, Diessel *et al.*, 2000) have shown that non-marine strata are not randomly arranged, but occur in an organised succession of units that frequently repeat their characteristics in vertical and lateral sections. Such organised and repetitive characteristics include the geometry and stacking of sandstone bodies, the composition of coal seams and the alternation of diagnostic facies such as aeolian, palaeosol and lacustrine units. In response to these organisational patterns, a number of sequence stratigraphic models have been proposed for non-marine strata. These include generic models such as Wright and Marriott (1993), a model incorporating three systems tracts based on Argentinian basins by Legaretta and Uliana (1998), a model incorporating coal as an integral component (Boyd and Diessel, 1994), a model concerned with the marine/non-marine interface in incised valleys (Zaitlin *et al.*, 1994), and a summary of principles together with a range of models in Shanley and McCabe (1994). However, these early models deal primarily with a single idealised sequence. Most are also based on only one principle field site with relatively uniform tectonic and climatic settings. Most also deal only with clastic sediments and are concerned primarily with only sandstone-shale geometries.

In order to extend these first generation models, the non-marine stratigraphy group at The University of Newcastle together with industry partners conducted studies over a range of accommodation in two separate basins. The objective of these studies was to provide an integrated model of non-marine stratigraphy based on multiple study sites and spanning multiple sequences. The studies also integrated a range of component facies from shoreline to lacustrine, fluvial, palaeosols and coal.

BACKGROUND AND PRINCIPLES OF NON-MARINE STRATIGRAPHY

In marine sequence stratigraphy there are a series of fundamental relationships that underlie the development of strata. The first of these is the idea of a base level, above which sedimentation does not take place. This level in marine environments is sea level. A second relationship is that of a marine profile of equilibrium resulting in a dynamically constructed shoreface or delta front profile. Accommodation, the space made available for sedimentation, is thus defined by these upper and lower surfaces. Transgressive and regressive shoreline translation results from the relationship between the development of accommodation and the sediment flux available to fill that space.

Although the principles differ, analogous relationships control sedimentation in non-marine settings. The basic non-marine principle is that of sediment continuity (see review in Blum and Tornqvist, 2000) in which stream bed elevation depends on the width-averaged sediment transport rate along the channel. Aggradation or degradation of the channel (bed elevation) results from variations in the sediment transport rate, which in turn result from variations in discharge and sediment supply. Like the marine case, the ultimate base level is sea level. The resulting balance between sediment transport and bed elevation is responsible for the graded stream concept (Mackin, 1947). Accommodation in the fluvial environment is determined by the translation of an erosive channel base (lower limit, see Boyd and Diessel, 1994), and the floodplain elevation (upper limit, see Blum and Tornqvist, 2000). In the general case these relationships are dominated by climate and the inputs of runoff and sediment yield in the catchment (e.g. Hovius, 1998). However there is also a contribution to the stream power from the relief of the drainage basin and this latter variable may be influenced by relative sea level changes in the lower stream course near the mouth. Relief is also influenced by tectonic processes throughout the drainage basin (for example by uplift of the source area or subsidence of the receiving basin). The outcome of the balance between aggradation and degradation is the net accumulation of sediment. In the case of fluvial processes, the net sediment accumulated is strongly controlled by the successive passage of erosional channel bases and the difference in elevation between each passage, and this is the practical meaning of accommodation in fluvial sediments. If the next erosional channel base passes by at the same level as the previous floodplain top then the entire succession will be preserved. If it passes at a lower level than the previous floodplain top then partial preservation will result.

Preservation is an important issue in this discussion. While all the principles discussed above are important in controlling fluvial processes, not all locations along a stream profil are equally important in preserving thick non-marine stratigraphy. Hence maximum generation of strata will be in locations where tectonic processes are providing maximum accommodation and this accommodation is being filled with sediment. For example, in a passive margin tectonic setting this location will be seaward of the basin hinge line.

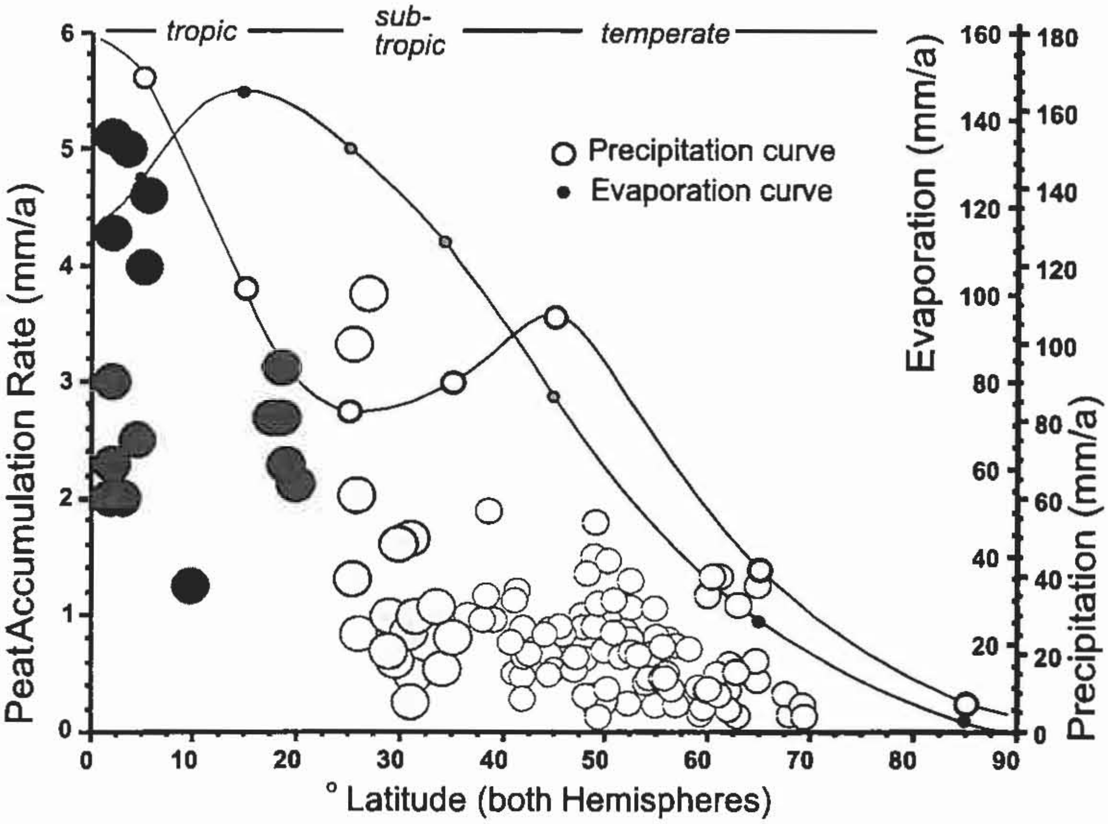

Figure 1. A compilation of Holocene maximum accumulation rates of low altitude peats in relation to geographic latitude, mean annual precipitation and evaporation. Data from various authors and summarised in Diessel *et al.*, (2000).

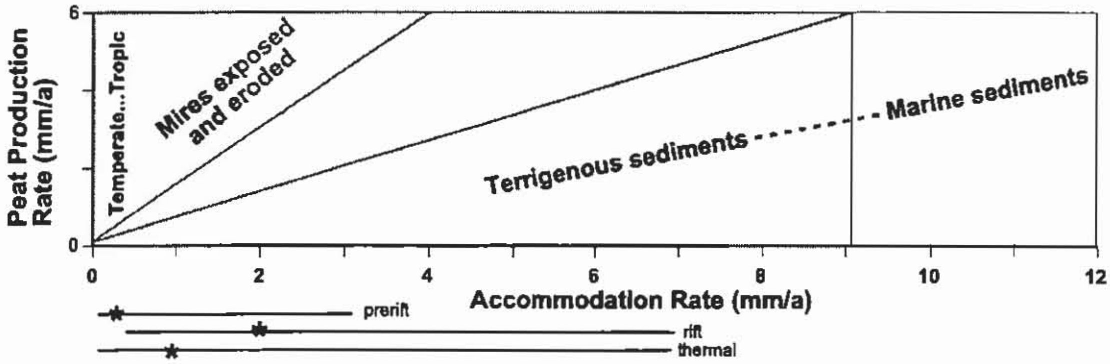

Figure 2. Relationship between peat production rate and accommodation rate. Peat production will vary as a function of climate zone (see figure 1), and accommodation will be influenced by tectonics and relative sea level (example rates from three tectonic settings shown with average values indicated by *). Modified from Bohacs and Suter, 1997.

So while large areas of the drainage basin will be unaffected by marine basin subsidence and relative sea level change, the part of the basin that is accumulating the majority of the sediment will be strongly influenced by these processes.

An equivalent set of equilibrium relationships control organic sedimentary facies production and accumulation. Diessel *et al.*, (2000) have identified a clear relationship

(Figure 1), based on an extensive database, between the rate of peat growth and climate (precipitation/evaporation). This relationship also shows a clear latitudinal dependency with maximum peat production rates in tropical regions and minimum values in polar regions. Bohacs and Suter (1996) detail a similar dependant relationship between rate of accommodation generation and rate of peat accumulation (Figure 2). If these rates are matched, then peat accumulation and preservation is at a maximum and thick coal seams may eventuate. If accommodation is either too great or too little, conditions are not conducive to peat preservation and organic mudrocks will be deposited. The reason for these relationships is the behaviour of the groundwater table. For peat to pass most efficiently from the acrotelm to the catatelm, it requires a constant high water table to preserve the organic matter (McCabe, 1984). If peat growth exceeds the rise in watertable elevation, it will be exposed and oxidised. On the other hand, if the watertable rises at a greater rate than peat growth, the peat will be drowned and subaqueous conditions will ensue. A basic description of peat and coal stratigraphy is included in the following discussion, but a more detailed treatment is provided by Diessel *et al.*, (this volume).

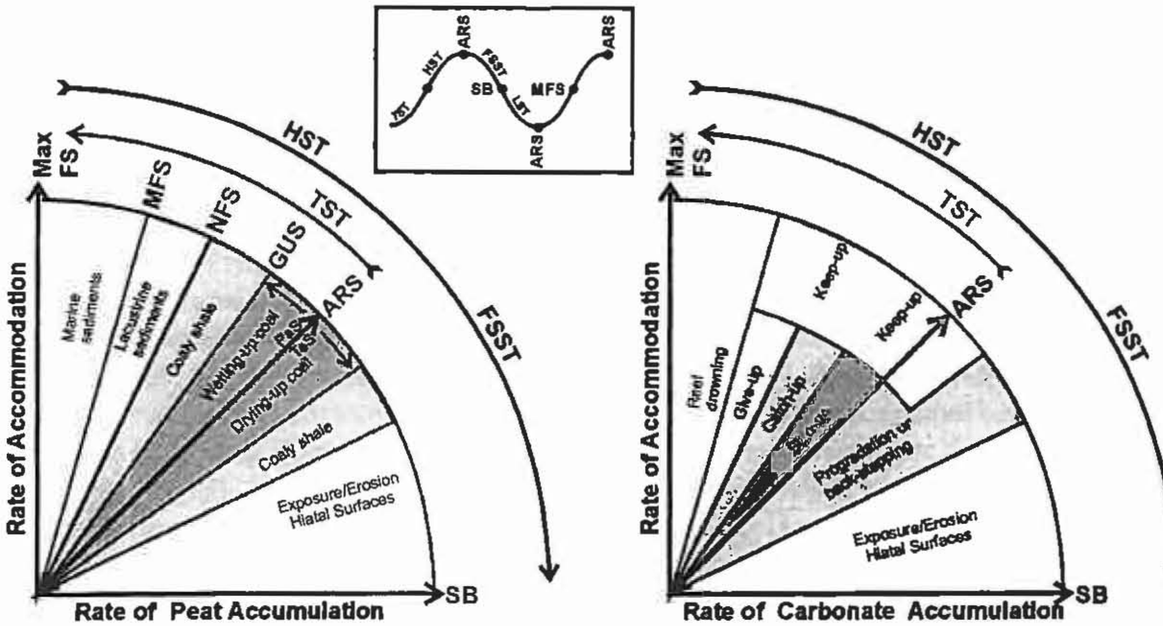

Figure 3. Conceptual diagram comparing peat mires and carbonate reefs. In both settings, the ratio between the rate of sediment accumulation and accommodation space creation is one of the primary controls in the development of facies and significant surfaces. An Accommodation Reversal Surface (ARS) occurs when the direction of accommodation reverses (inset diagram shows relationship between ARS and relative sea level curve). Increasing rates of accommodation relative to peat accumulation result in wetting up coals becoming more shaly and finally becoming flooded. This succession contains the significant surfaces of Give-Up Surface (GUS), Non-Marine Flooding Surface (NFS) and possibly a Marine Flooding Surface (MFS). The equivalent succession in carbonates contains start up, keep up, catch up, give up and drowning responses. Another ARS surface occurs at the transition between highstand and falling-stage systems tracts. At this transition drying upward coals may be produced, eventually become degraded and exposed as base level continues to fall. In the carbonate case reefs are similarly exposed and eroded during falling sea level. PaS = Paludification surface, TeS = Terrestrialisation surface.

In many respects, the situation of peat production and preservation in non-marine environments parallels that of carbonates in the marine realm. In this context, peat mires can be considered as terrestrial reefs, as their relationship to the groundwater table strongly mirrors that of carbonate reefs to sea level (see Figure 3), resulting in analogous strategies of keep up, catch up and give up facies successions in both carbonates (see Jones and Desroches, 1992) and coal (see Diessel, 1998; Diessel *et al.*, 2000).

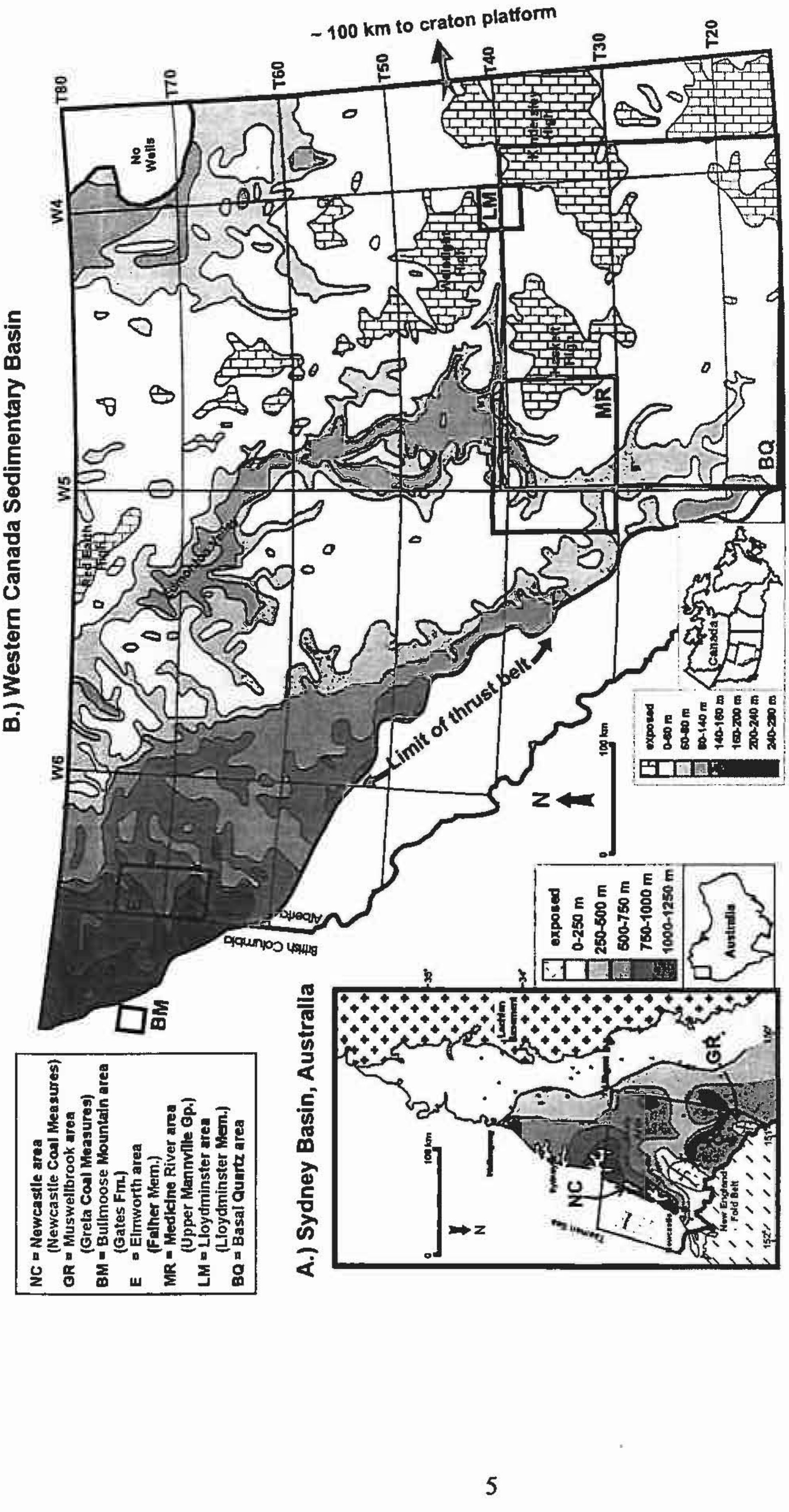

Figure 4. This shows the location of a) The Sydney Basin and b) the Western Canada Sedimentary Basin, at the same scale. Also shown are the field sites.

APPROACH

A review of previous models for non-marine stratigraphy convinced us that the greatest potential for improved models lay in a sequence stratigraphic approach in which we could investigate a spectrum of accommodation under differing climate and tectonic regimes. This was because important variables such as fluvial stacking geometries and peat development responded most clearly to variations in non-marine accommodation, as defined above. In addition, the accommodation approach was close to that employed in marine sediments and offered the best hope for unified correlation in the zone in which sea level influences accommodation and in which the majority of sediments accumulate.

In early formulations of our research project we searched for good ancient examples of single sequences in which the full range of stratigraphic responses to the spectrum of accommodation was present in a single region. It proved difficult to locate such regions and sequences with high quality databases. We then concentrated on locating basins with a range of accommodation, and with a quality database in several field sites spanning the range of accommodation. Our final field site choices were located in the Cretaceous Western Canada Sedimentary Basin (WCSB) and the Permian Sydney Basin of Eastern Australia (Figure 4). Individual studies in a number of these sites have already been published and the remainder are either in press or in preparation. Bibliographic references to the published studies are provided in the following study site descriptions.

In the early Cretaceous, the WCSB (Figure 4) experienced a mid-latitude, warm to humid, temperate climate. This basin was a broad retroarc foreland (Leckie and Smith, 1992) experiencing thrust loading in the Rocky Mountains to the west and flanked on the east by the Canadian Shield. The WCSB contains early Cretaceous study sites that ranged from very low accommodation in the extreme south and south-east of the Basin (e.g. the Success Formation - Leckie *et al.*, 1997, and the Basal Quartz Formation - Zaitlin *et al.*, 2000, Arnott *et al.*, 2000) to intermediate accommodation in the centre of the Basin (Boyd et al., 2000, Chalmers and Boyd this volume) to high accommodation in the NW part of the basin (Diessel *et al.*, 2000, Boyd *et al.*, 2000).

The Sydney Basin (Figure 4) in the Permian was located close to the South Pole around 65° S and experienced a polar climate. The basin was initiated in the early Permian as a back arc basin behind the subduction zone and volcanic arc of the New England Fold Belt (e.g.Collins, 1991). By the late Permian, collision of the New England Fold Belt from the east with the earlier accreted Lachlan Fold Belt in the west transformed the Sydney Basin into a narrow retroarc foreland basin. The three field sites studied in this basin span the transition from early Permian back arc basin (Greta Coal Measures, Boyd and Leckie, 2000; van Heeswijk, 1999; Boyd *et al.*, in press) to late Permian foreland basin (Newcastle Coal Measures, Little, 1995, 2000; Boyd *et al.*, 1997; Little *et al.*, 1996). All studies in the Sydney Basin were in moderate to high accommodation settings adjacent to the basin margin. The following results summarise the outcomes of these studies over the range of accommodation, climate and tectonics in the two basins.

RESULTS

Low Accommodation Conditions

Low accommodation results in low rates of accumulation and preservation of thin stratigraphic units (Figure 5). This in turn results in the erosive migrating base of channel systems returning close to their earlier stratigraphic level, producing a succession that contains numerous erosion surfaces and preferential preservation of the lowermost part of fluvial successions as amalgamated channel deposits. This means that channel lags, cross-bedded basal channel fills and lower bar segments will be the dominant form of sediment preserved. Multiple cycles may be found over a short vertical range of stratigraphy, separated by unconformities (sequence boundaries). The geometry of the preserved fluvial sediments will be that of a sheet sand or an incised valley fill. Zaitlin *et al.,* (2000), based on composition studies, demonstrate the recognition of six separate sandstone units in the Basal Quartz Formation in southern Alberta over a stratigraphic interval of only 20 m. Incised valleys (Zaitlin *et al.,* 1994) are a characteristic basin response to low accommodation. They are formed when a river is forced to locally steepen its base level, for example in response to a relative fall in sea level across a shelf gradient steeper that that of the graded profile (e.g. Talling, 1998), or in response to an increase in discharge or a reduction in sediment flux. (e.g. Blum, 1990). Incised valleys are a ubiquitous feature of Cretaceous sedimentation in the low accommodation regions of the WCSB (e.g. Zaitlin and Schultz, 1984, 1990, Rosenthal, 1988).

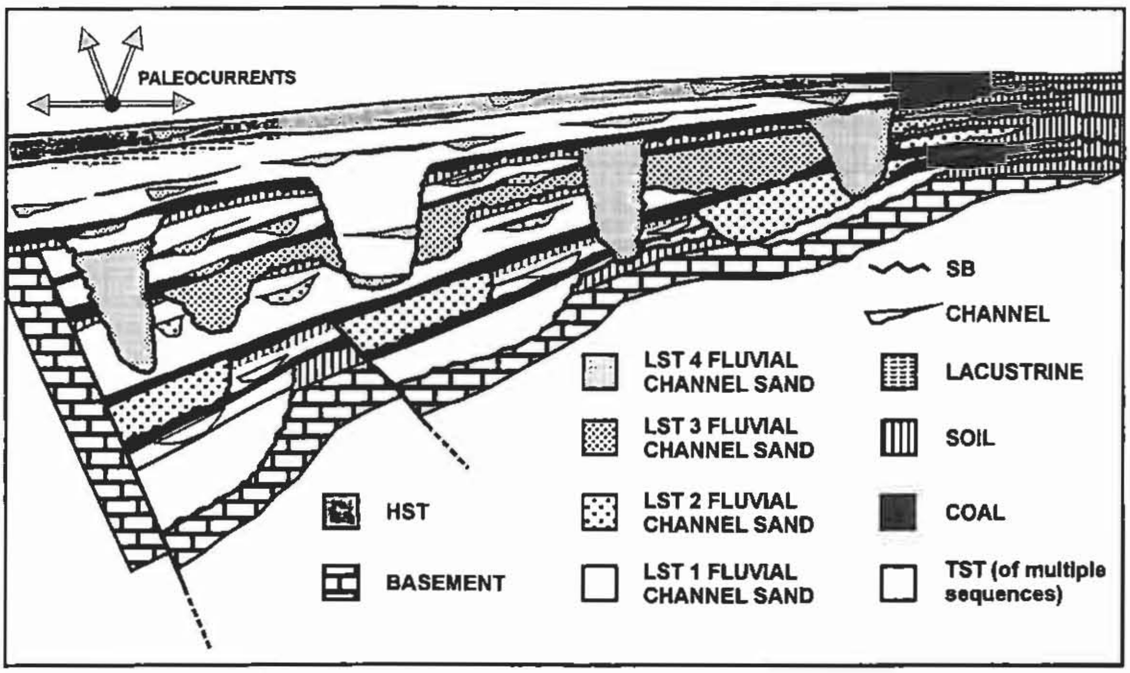

Figure 5. This shows the typical stratigraphy developed in a low accommodation terrestrial setting. Accommodation decreases from left to right. The deposits of four sequences are shown, dominated by closely spaced unconformities and incised valley fills. The influence of structure and paleotopography determines the location and thickness of sedimentation. Soils are well developed in the lowest accommodation settings. Individual sequences can be differentiated on their texture and composition (different fill patterns) and their paleocurrents (overlying arrows show a wide range of vector resultants).

The lack of accommodation to enable vertical accretion results in underlying structure and paleotopography exerting continued control on the site of deposition (exemplified by an asymmetric graben fill in Figure 5). The most common expression of this control is to localise channels and valleys along structural or topographic lineaments (Zaitlin *et al.*, 1999, 2000), and to promote the re-incision of older deposits during subsequent cycles (right hand side of figure 5). This increases the complexity of the sediment distribution pattern and produces rapid lateral changes in thickness (e.g. Leckie *et al.*, 1997). A common expression of low accommodation is the fragmentary nature of the preserved stratigraphic record, often resulting in sections in adjacent valleys containing different units that are difficult or impossible to correlate.

Chalmers and Boyd (this volume) document a case study of high-resolution coal correlation between regions less than 50 km apart that identifies a total of four sequences but only two are present at the ends of the region, and all four vary considerably in thickness and character across the region. This variation is interpreted to result from thin sequences developed in a region of considerable paleotopographic relief and undergoing small-scale contemporaneous structural movements. A further outcome of low accommodation conditions in fluvial deposits close to the shoreline is their high likelihood of reworking by tidal processes during subsequent transgression because of low subsidence between the transgressive and regressive parts of a relative sea level cycle. Many valleys in the WCSB Mannville Group, for example, were initially formed by fluvial processes, but have only a thin fluvial unit preserved at their base or have been completely reworked by tidal channels (e.g. Broger *et al.*, 1997).

Further expression of low accommodation can be seen in the low preservability of organic deposits. In conditions of low accommodation, there will be a transition between regions of lowest accommodation where only paleosols are present (right hand side of Figure 5), through organic rich shales to regions of relatively higher accommodation where peat and coal preservation occurs (left hand side of Figure 5). In the WCSB this north-south transition occurs between the US – Canada border, and approximately township 25 (a distance of around 240 km) in the Basal Quartz interval and a similar transition takes place in the overlying Glauconitic Formation. In the extreme case, oxidising conditions and falling water tables may remove all organic traces resulting in only paleosol formation, especially during depositional hiatuses (e.g. Leckie *et al.*, 1997).

Increasing accommodation will result in preservation of root traces and increased organic content (often expressed as darker colouration), and ultimately result in the development of coal seams. However, when developed, these coal seams may split frequently, with splits that correlate laterally to incised valleys, and the seams may contain internal unconformities that result in compound coals (e.g. Diessel, 1998, Chalmers and Boyd, this volume). Low accommodation is also conducive to the development of multiple deep, long-lived soil profiles. Again, since there is limited aggradation, subsequent cycles of soil development may influence underlying cycles, resulting in compound or amalgamated soils. These soils frequently exhibit well-developed peds and jointing, slickensides, root traces, clay coatings on grains, destruction of primary sedimentary structures, crumbly appearance in core, and presence of authigenic minerals such as pyrite and siderite (e.g. McCarthy and Plint, 1998).

In a sequence stratigraphic context, conditions of decreasing accommodation promote the formation of unconformities, forced regressions and incised valleys (correlative to lowstand system tract deposits). These are preferentially filled in low to maximum rising accommodation conditions (correlative to lowstand to early transgressive system tract deposits), and accumulate in stratigraphically low positions such as the base of incised valleys. These deposits will have high potential for preservation, especially if deposited within backfilling valleys. Deposition in the subsequent lower accommodation parts of a cycle (equivalent to the highstand systems tract) will be more exposed at the top of valley fills and on adjacent interfluves, and subject to removal by subsequent cycles of erosion.

The basic sequence stratigraphic correlation surface in terrestrial settings will be the sequence boundary, often located at the base of incised valleys and correlated laterally onto interfluves at the position of well- developed soil profiles. In active tectonic areas such as the WCSB in the early Cretaceous, variations in basin geometry and source area will promote variations in sediment composition and paleocurrents (top of figure 5) between individual unconformity bounded sequences, permitting their recognition and correlation.

High Accommodation Conditions

Increasing accommodation results in a greater vertical distance between successive lateral migration paths of channel bases. This in turn allows for the greater preservation of higher stratigraphic elements in the fluvial system such as upper bar forms, channel fills and in particular, levee and floodplain deposits (see Arnott *et al.,* 2000, in press). Hence, under increased accommodation conditions, fluvial processes will preserve not only amalgamated channel fills but will show increasing preservation of intervening floodplain facies, making the channel sand bodies less interconnected and more ribbon-like in geometry (Figure 6).

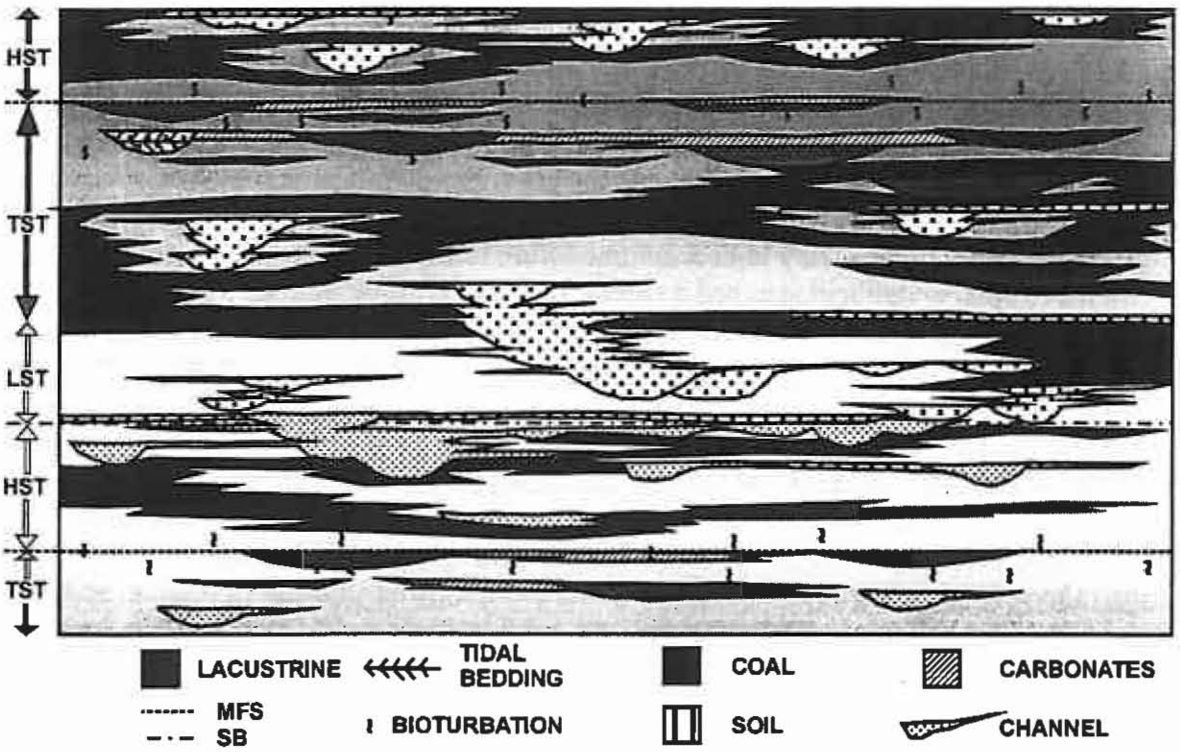

Figure 6. This shows the typical stratigraphy developed in a high accommodation terrestrial setting. The deposits of two sequences are shown. Aggrading channel systems that interfinger laterally with floodplain and coal seams replace incised valleys and lacustrine and carbonate facies may be common near the maximum flooding surface.

Under increasing accommodation conditions, both soils and coals will be less complex. In the case of soils, duration of soil formation will be reduced, soil profiles will be thinner and more widely spaced, decreasing the likelihood of compound soils. Organic content of soils will also increase, and sediment aggradation will produce renewed addition of sediment to the upper soil profile. In the case of coal, the same principles apply. Peat preservation is rare in times of low groundwater table. As water table elevations rise, organic preservation and darker colouration begins and culminates with peat formation when the water table is consistently high. Individual coal units or plies exhibit wetting upward cycles defined by trends of increasing mineral matter and characteristic maceral response. Individual coal seams will have fewer internal hiatuses in higher accommodation settings and will eventually develop a seam for each cycle of accommodation. Even higher accommodation preserves thick multiple seams, such as the Greta Coal Measures in the Muswellbrook region of the northern Sydney Basin, where 12 coal seams are preserved in a single sequence (Boyd and Leckie, 2000) and individual seams exceed 12 m in thickness. Where detailed studies of the internal structure of high accommodation coals has been undertaken (e.g. the WCSB Falher Member - Diessel *et al.,* 2000), both drying upward and wetting upward cycles are preserved in a single seam, separated by an accommodation reversal surface (in contrast to the internal unconformities present in lower accommodatior coals).

Increasing accommodation results in sediment aggradation and the development of thicker stratigraphic sections, in turn removing deposits from the direct influence of underlying structure and paleotopography. Unconformities become less frequent and further apart, as does the vertical separation of incised valleys. Concurrently, the potential for marine influence increases and transgressive and highstand deposits may exhibit brackish influence and possible tidal signatures. Shanley and McCabe (1991) illustrate the interfingering of tidal deposits with the alluvial strata of the Kaiparowits Plateau. If rising water tables exceed the aggradation rate of clastic and organic facies, open water bodies develop and coalesce on the depositional surface, eventually forming lacustrine environments. These settings are suitable for generating a range of characteristic facies ranging from fresh water carbonates to evaporites and algal coals. Creech (this volume) provides an example of very high accommodation in the Newcastle Coal Measures where extensive open water bodies associated with peat mires allow multiple, thin ashfall tuffs, deposited subaqueously, to be correlated for distances of over 30 km. The Newcastle Coal Measures (Little, 2000) also illustrate very high accommodation responses in channel and organic facies. Up to 600 m of sediment, including 10 composite coal seams with over 50 splits accumulated in this unit without evidence of a single unconformity in the Newcastle – Lake Macquarie region. All internal formations in the Newcastle Coal Measures have a similar composition and paleocurrent pattern (Little, 1995, 2000). Here there appear to be no incised valley systems. Rather, sandstone and conglomerate channels 20-108 m thick aggrade vertically and migrate laterally at the same time as adjacent floodplain and mire deposits. This behaviour is identified by crevasse splay deposits interfingering from channel to floodplain (see sandbody geometries of Figure 6), and by ashfall tuff layers onlapping the side of migrating channels.

In particularly high accommodation settings like the Newcastle Coal Measures, traditiona sequence stratigraphic indicators like unconformities and changes in composition betweer adjacent units may not be present. Instead, high accommodation cycles may be marked (figure 6) by clustering of channel bodies in the relatively lower accommodation intervals (e.g., Posamentier and Allen, 1993), and by extensive development of lacustrine, floodplain and high ash coal facies in the higher accommodation intervals, and incursion of marine facies in coastal regions.

CONCLUSIONS

This summary of features exhibited under low and high accommodation provides a framework for developing a model for the organisation of non-marine stratigraphy. The model presented here resulted from a series of detailed field studies in two basins, supplemented by results from additional literature studies in other basins. The model has been expressed as a summary figure for each of the low (Figure 5) and high (Figure 6) accommodation settings.

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SIGNIFICANT SURFACES AND ACCOMMODATION TRENDS IN PARALIC COAL SEAMS

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INTRODUCTION

Paralic coal measures usually occupy ancient coastal regions in which they are part of marine to terrestrial parasequences. Landwards, the marine intercalations wedge out so that formerly separated coal seams amalgamate before they become replaced by terrestrial deposits. This means that successive coal plies in an amalgamated seam are likely to represent the stacked remnants of parasequences. It also means that coal composition should reflect the accommodation trends that were operative in the more fully developed parasequences further basinward.

The numerical limits for the maintenance of a well-balanced accommodation / peat-accumulation ratio have been estimated by Bohacs and Suter (1997) to range from 1 to 1.18. Although this range is relatively narrow, actual peat accumulation rates vary greatly with climate (Figure 1) so that well-balanced accommodation / peat-accumulation ratios can be established under a variety of accommodation rates.

Table 1. The limits of peat accumulation in relation to accommodation /accumulation ratios according to Bohacs and Suter (1997). The ash percentages are by mass.

Accommodation / peat-accumulation ratio	Depositional response
< 0.5	No significant peat formation
0.5 to 1.0	Impure peat due to oxidation and weathering
1.0 to 1.18	Optimum peat stage (< 20% ash)
1.18 to 1.53	Well preserved peaty sediments (25-75% ash)
> 1.53	No significant peat formation

As shown in Table 1, peat can still form outside the optimum accommodation / peat-accumulation ratio, but it will be increasingly contaminated by inorganic sediments. The admixture of mineral matter is not the only characteristic of coals whose precursor peat accumulated outside the optimum range. Although we used variations in the detrital-mineral content as the main criterion for dividing a coal seam into subsections with varying depositional history, the optical and compositional signatures of coal macerals were considered as well. The planes of demarcation between the subsections can be classified

relative to the direction in which the accommodation / peat-accumulation ratio was increas
or decreasing.

Coal-Petrographic Indicators of Ancient Peat-Accommodation Trends

We have used coal-petrographic methods to study accommodation trends in paralic coal seams in Canada, Germany and Australia (Boyd and Diessel, 1994; Diessel, 1998; Diessel and Gammidge, 1998; Diessel, *et al.*, 2000) and found that ancient mires which retain a w balanced accommodation / peat-accumulation ratio (= optimum peat stage in Table 1) for periods of time tend to produce thick coal seams with minimum detrital mineral content a maximum plant-tissue preservation, the latter in the form of structured vitrinite (telovitrini As shown in Table 2, indicators of oxidation such as inertinite and inertodetrinite are rare, the optical properties of telovitrinite, i.e. mean reflectance and fluorescence are a normal reflexion of the thermal history of the coal with little statistical variation about the arithme mean.

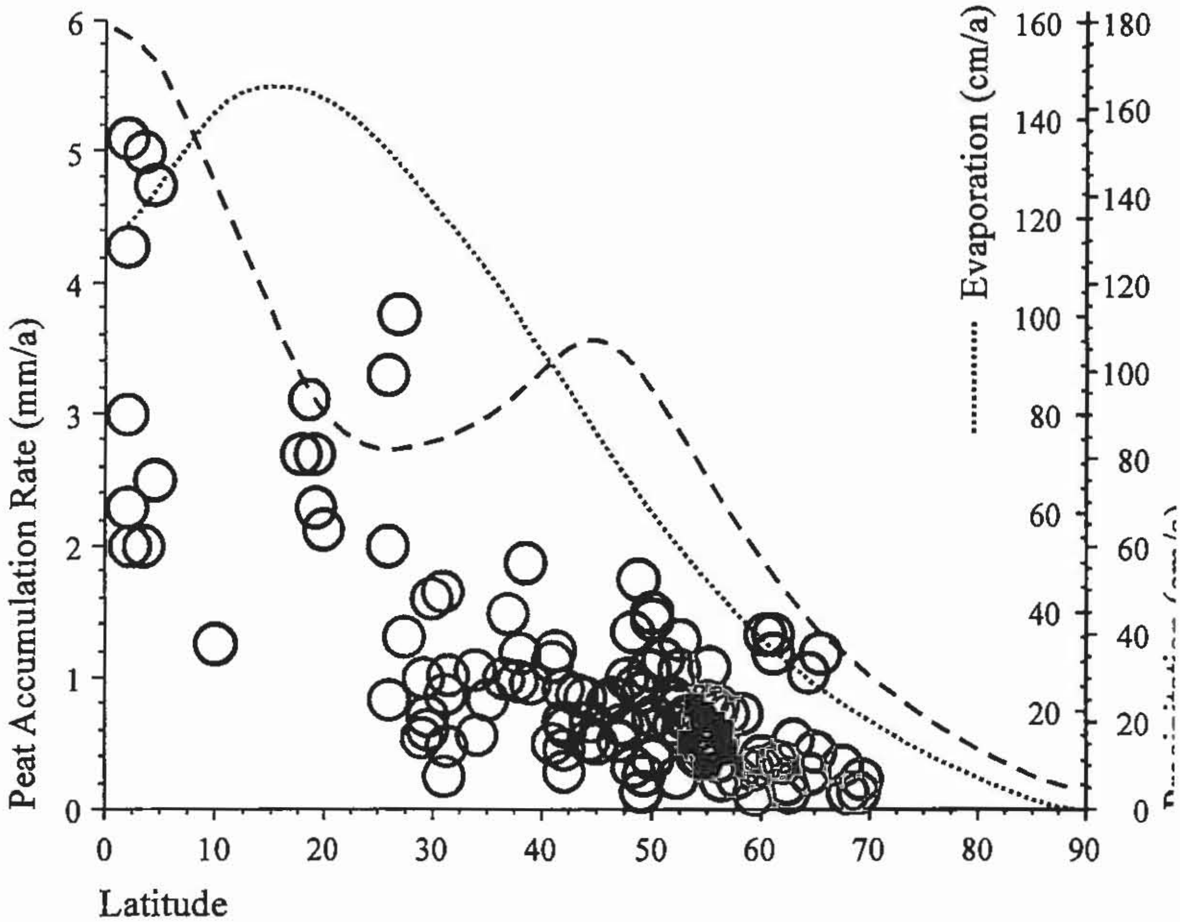

Figure 1. Holocene maximum peat accumulation rates in relation to climate and geograpl latitude. For literature references see Figure 2 in Diessel *et al.*, (2000).

A high accommodation / peat-accumulation ratio (between 1.18 and 1.53) causes frequen flooding of the peat. The plants that grow under such conditions in the mire struggle for survival, but where peat still managed to accumulate under a high accommodation rate, th resultant coal commonly contains a high proportion of detrital minerals due to the frequer of flooding. The proportion of structured vitrinite is reduced because cellulose-destroying bacteria thrive under the low-acidity and often eutrophic conditions in the limnotelmatic environment. The proportion of structured inertinite, i.e. fusinite and semifusinite, is low but its fragmented form, i.e. inertodetrinite, is quite common together with concentrations of other dispersed organics, particularly spores and pollen.

Table 2. Petrographic indicators of accommodation / peat-accumulation ratios in coal.

	Balanced	High	Low
Detrital Minerals (%)	low, often < 10%	high, often > 10%	low, can be enriched by biodegradation
Structured Vitrinite (%)	high	high to moderate	low to moderate
Structured Inertinite (%)	low	low to moderate	high
Inertodetrinite (%)	low	moderate to high	moderate to high
Sporinite (%)	low	moderate to high	low
Telovitrinite Reflectance (e.g. %Rrt)	normal	reduced	enhanced
Telovitrinite Fluorescence (e.g. I 650wt)	normal	enhanced	reduced
Coefficients of Variation of %Rrt and I 650wt	low	high	low to moderate, high in multiple root-derived vitrinites

The high level of bacterial activity in the mire causes the vitrinite precursors to be enriched in lipid-derived hydrogen which causes the telovitrinite reflectance to be lower than normal while its fluorescence is higher. Because of the high watertable and frequency of flooding, there is a great deal of mixing of autochthonous and allochthonous vitrinite precursors. This results in a greater than normal statistical variation of the optical properties of telovitrinite.

A low accommodation / peat-accumulation ratio (between 0.5 and 1.0) causes oxidation and partial combustion of the organic matter. Although the low watertable would reduce the influx of detrital minerals into the mire, the oxidative loss of biomass tends to enrich all inorganic matter. The vitrinite content is generally low but the proportion of structured inertinite as well as its fragmented form may be quite high. The sporinite content is often low, and most spores show signs of corrosion. Telovitrinite reflectance is higher and its fluorescence is lower than normal due to the depletion of hydrogen in the source material. Because most of the vitrinite precursors have been derived from in-situ material, the variation of the optical properties about their respective mean values is usually quite low, but it can be high when the sample contains several generations of root-derived vitrinite. An example was described and illustrated by Diessel and Gammidge (1998) from a sequence boundary at the contact between the Wynn and Bayswater seams at Dartbrook Mine, New South Wales.

The Surfaces Separating Different Accommodation Trends

The application of the petrographic indicators of relative accommodation / peat-accumulation ratios to the vertical profile analysis of coal seams revealed a variety of accommodation trends that made it desirable to define five new surfaces of varying significance in onshore sequence stratigraphy. They are illustrated schematically in Figure 2 and discussed below (also see Diessel et al., 2000).

It has been long known that peat accumulation usually begins by either paludification or terrestrialisation. In the first instance, mire conditions develop above the *paludification surface* (*PaS* in Figure 2) on a formerly dry terrain. Paludification may have various climatic and other causes but if the result is a coal seam, an increase in accommodation is an essential part of the process. The seat earth below the usually hiatal paludification surface is commonly well developed, often with deeply penetrating roots. The basal part of the seam has a low to medium detrital mineral content and a low shoot / root ratio. As the accommodation / peat-accumulation ratio continues to increase through the life of the mire, the peat passes through a phase of optimum accumulation conditions, followed by a decline in biomass production and increasing intermingling of the peat with detrital minerals brought into the mire by flood waters. The result is either a gradual upward increase in the mineral content of the coal, or the upper part of the seam becomes increasingly interbedded with dirt bands. Eventually, peat accumulation ceases and the mire is flooded above a *give-up transgressive surface* (*GUTS* in Figure 2). This surface is a non-hiatal flooding surface which in paralic coal measures may coincide with marine flooding.

The opposite to paludification is terrestrialisation, i.e. the filling of a body of water, such as a lake, lagoon or bay, to the point where peat-forming plants can grow, often following a decrease in accommodation. The floor sediments below the non-hiatal *terrestrialisation surface* (*TeS* in Figure 2) are carbonaceous, and usually contain no or only small roots. There is either a gradual upward decrease in mineral content or an increasing number of coal bands interbedded with floor rock until coal dominates. Above the terrestrialisation surface, the basal portion of the seam, formed under eutrophic limnotelmatic conditions, still contains a medium to high detrital mineral content and a high shoot / root ratio. As the accommodation / peat-accumulation ratio decreases further upward, the mire passes through the oligotrophic phase and, given suitable climatic conditions, may form a raised mire with low detrital mineral content. The contact with the roof is commonly sharp due to renewed flooding above a marine or nonmarine *flooding surface* (*FS* in Figure 2000). This surface may coincide with a break in sedimentation and/or partial peat erosion as has been described by Diessel and Gammidge (1998) from the above-mentioned Wynn/Bayswater seam couplet at Dartbrook Mine in New South Wales.

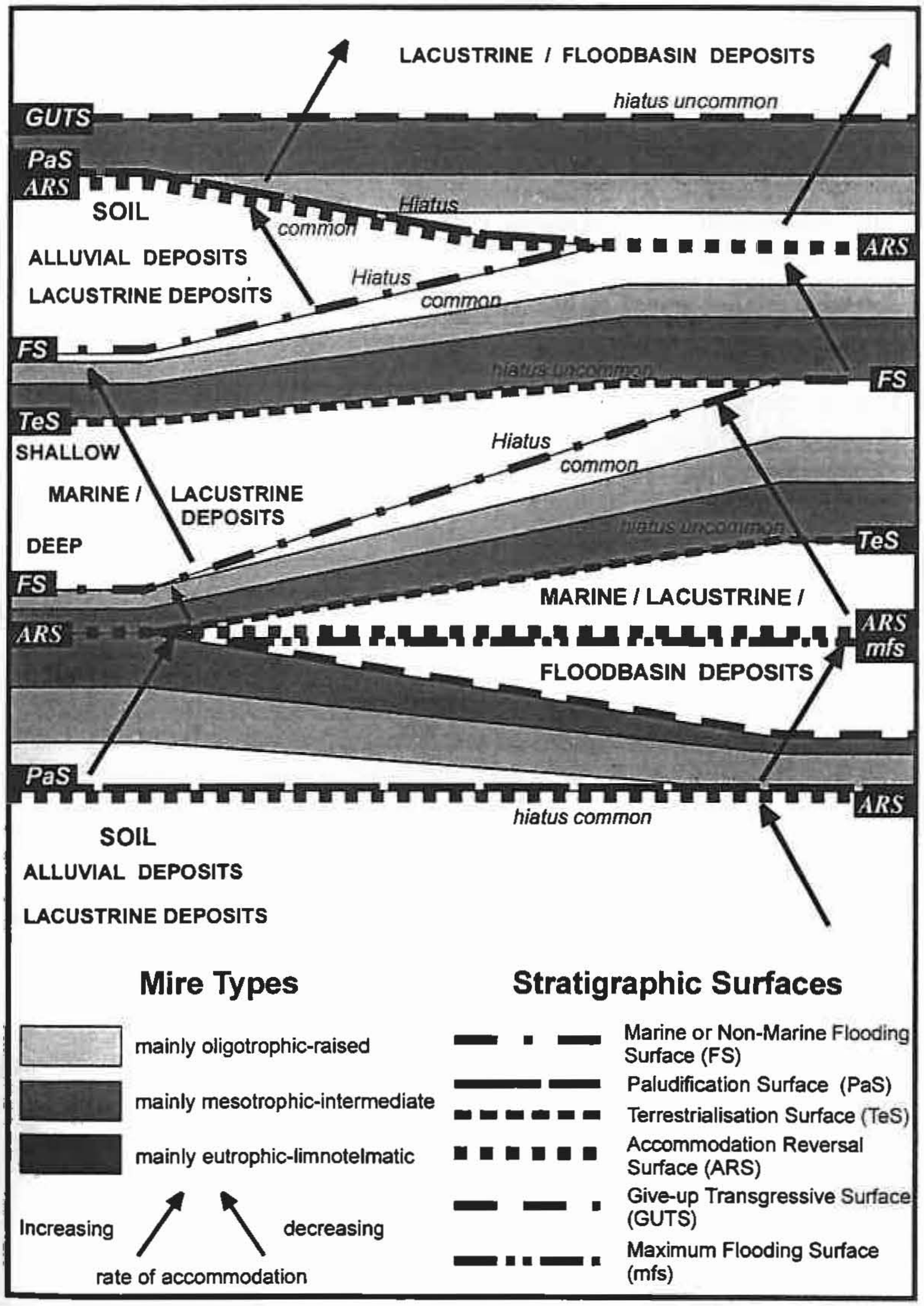

Figure 2. Schematic representation of the main accommodation trends in coal seams and the surfaces separating them.

The position of some of the surfaces mentioned above, indicates a change in accommodation trends, i.e. from upward shallowing to upward deepening (see direction of arrows in Figure 2) or *vice versa*. This has led to the identification of an *accommodation reversal surface* (*ARS* in Figure 2). This surface may coincide with other surfaces, such as the *maximum flooding surface* (*mfs* in the lower right portion of Figure 2). Because we recognise this surface in nonmarine as well as marine sediments, the use of lower case in the spelling of "mfs" is meant to separate its occurrence in nonmarine sediments from the more common sequence-stratigraphic application of "MSF" to marine settings. We have identified accommodation reversal surfaces also within coal seams by changes in the distribution pattern of detrital minerals, trends in optical properties and maceral combinations. Examples are illustrated in the lower left and upper right portions of Figure 2. In either location, the accommodation reversal surfaces mark the contacts of amalgamation between two coal seams, and are thus correlative the flooding and maximum flooding surfaces, respectively, in the adjacent seam splits. However, this relationship is not obvious if only a section through the amalgamated seam were available. We believe that the identification of accommodation reversals may prove to be an important step forward in onshore sequence stratigraphy.

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CYCLIC CORRELATION AND SIGNIFICANT SURFACES IN LOW ACCOMMODATION COAL

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INTRODUCTION

The recognition that peat-forming environments exhibit sensitivity to high frequency, small-scale changes in groundwater (base) level has led to sequence stratigraphic interpretations of coal-bearing strata (e.g. Diessel, 1992). For peat to preserve and accumulate, the watertable needs to be near or at the mire surface. Organic material requires to settle below the acrotelm/catotelm interface, 5 to 50 cm below the watertable surface, in order to retard biodegradation. The degree to which organic material is degraded depends on the residence time in the oxidative acrotelm, which is dependant on the rate accommodation changes relative to the peat accumulation rate of a particular mire. Optimal peat-forming conditions occur when there is a balance between the accommodation rate and the peat accumulation rate. Outside this coal-forming "window", the thickness and quality of coal produced declines due to an increase in the inorganic content in the peat deposit and the coal becomes progressively inferior (see Bohacs and Suter, 1997). This reduction in coal quality is the result of either an increase or decrease in the accommodation rate. For instance, if the accommodation rate accelerates to the point that peat accumulation cannot keep pace with it, the peat will become progressively flooded, and the mineral content will increase until peat formation terminates with deposition of lacustrine or marine strata. If the accommodation rate decelerates to the point that the accommodation space is filled and the peat becomes exposed, then loss of organic material by oxidation and weathering will occur, enriching the peat with mineral matter.

The balance or imbalance between accommodation and peat accumulation rates is reflected in the variation in petrographic composition within a coal seam. Coal samples can be grouped into cycles depending on the style of peat initiation and compositional trends. Significant surfaces separate coal cycles, which are equivalent to sequence stratigraphic surfaces in down-dip, coeval marine strata. Significant surfaces are summarised by Diessel *et al.* (this volume) and discussed in detail by Diessel *et al.* (2000) using the higher accommodation Gates Formation coal seams in the Mannville Group of the Western Canadian Sedimentary Basin (WCSB).

The non-marine stratigraphy group at The University of Newcastle, Australia is investigating the behaviour of coal seams in a spectrum of accommodation settings. The Lloydminster study area (Figure 1) is a component of this larger study and represents one of the lowest accommodation settings. Wadsworth *et al.* (1998) describe the sedimentary setting of the Lloydminster study area, and identify its low accommodation character.

The major objective of this paper is to investigate wetting-upward and drying-upward cycles in low accommodation coal seams and their associated interseam sediments, in an attempt to correlate coal development across the study area. Another objective is to identify the factors that have influenced the character of these coal seams and to provide a detailed description of coal behaviour in this low accommodation setting.

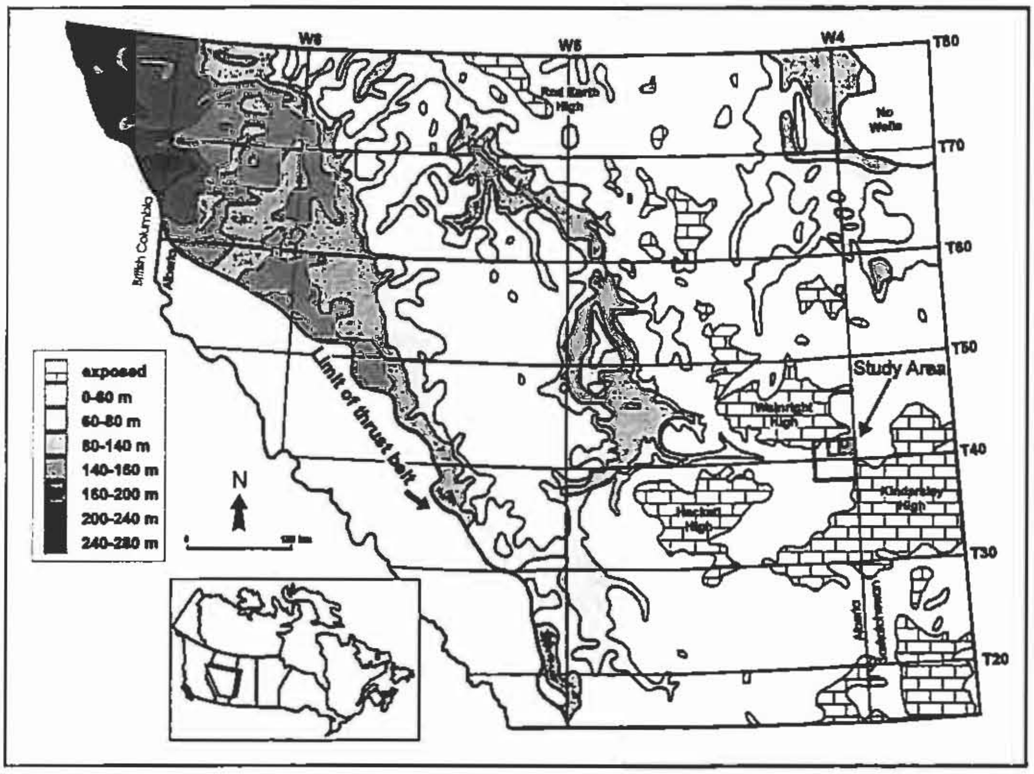

Figure 1: Isopach map of the total thickness of the Lower Mannville Group, illustrating the location of the study areas (LM = Lloydminster study area) and the position of the exposed series of central ridges during the deposition of the Lower Mannville. Inset map shows the location within Canada. Modified from Cant and Abrahamson (1994).

INFLUENCES ON SEDIMENTATION

The coal-bearing strata of the Lower Cretaceous Mannville Group in the Lloydminster heavy oilfield, eastern Alberta (Figure 1) are situated on the cratonic margin of the WCSB. Isopachs of the Lower Mannville Sub-group (Dina and Cummings Members) ir Figure 1 highlight the relatively low accommodation, with thinner and more condensed strata (less than 70 metres) in comparison to the rest of the basin. The area was topographically constrained by the Wainright and Kindersley palaeohighs to the northwest and southeast, respectively. These palaeohighs are a part of a series of Paleozoic ridges that were exposed during sedimentation of the Lower Mannville, forming a partially enclosed sub-basin (Figure 1). The irregular palaeotopography on which the Lower Mannville strata accumulated, resulted from high relief (up to 80 metres; Cant, 1996; Leckie *et al.*, 1997) on the major pre-Cretaceous unconformity. This is a mature erosional surface, developed over a 15-20 Ma period (Cant, 1996).

Another structural control on sedimentation is the syndepositional faulting of the basement, highlighted by the location of incised valleys, coal-seam splitting and local thickening of the sedimentary strata (Figure 2). A change to local accommodation rates results from these structural movements. An increase in the accommodation rate on the hanging wall side of the fault creates thicker deposits, an imbalance between peat accumulation and accommodation rates (coal seam splitting), and determines channel incision locations for incised valleys. Other workers (e.g. Cant and Abrahamson, 1996; Davies *et al.*, 2000, Berger *et al.*, 2000) have traced linear channels of incised valleys in the central WCSB and also shown that syndepositional faulting has influenced drainage patterns and affected the thickness of the Mannville strata.

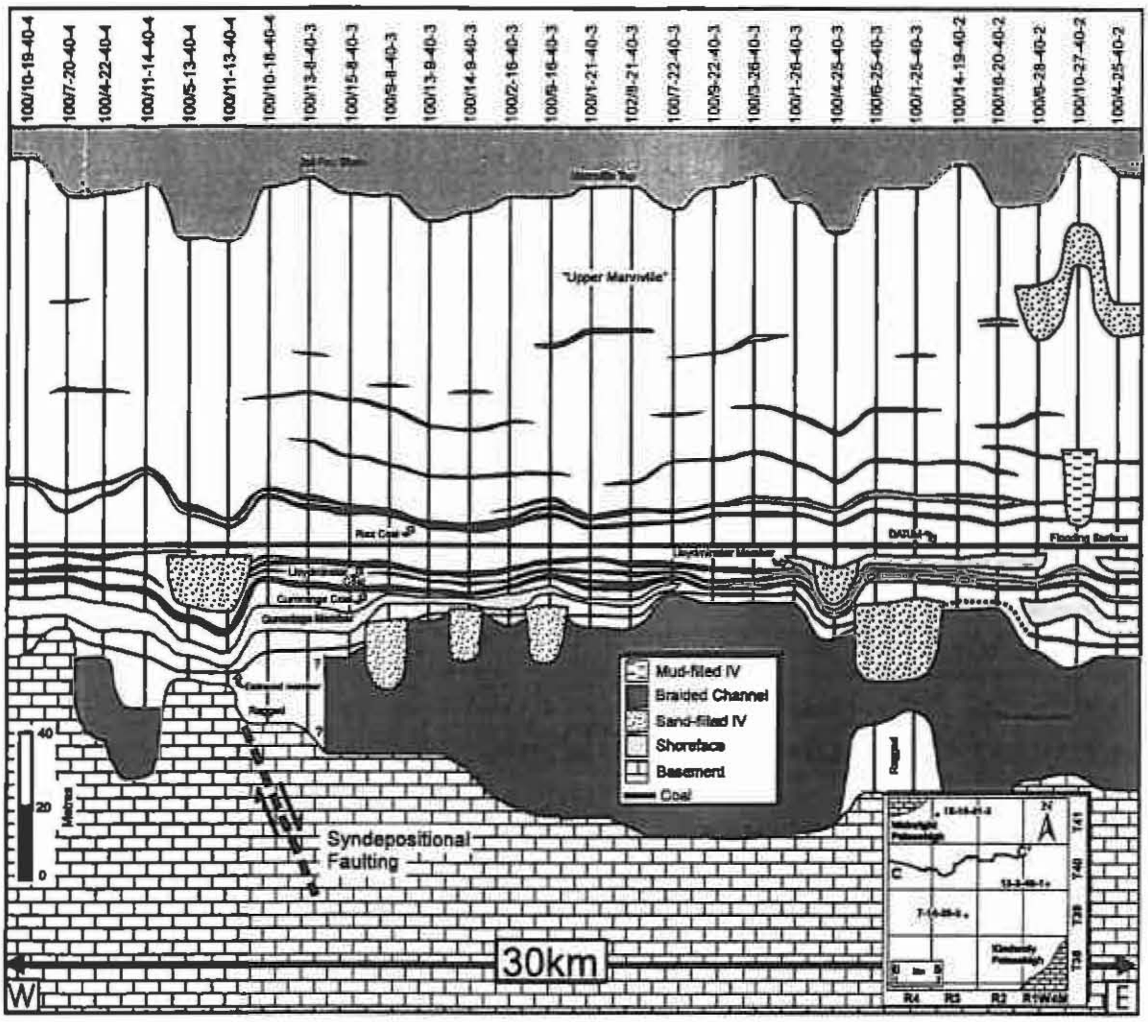

Figure 2: Cross-section C-C' from the Lloydminster study area illustrating the features associated with basement syndepositional faulting during the deposition of the Lower Mannville. These features include: incised valley development, coal seam splitting and local thickening of the whole Mannville Group due to an increase in local accommodation of the hanging wall and a decrease on the footwall side. Inset shows location of boreholes in relation to palaeohighs. Datum is an internal regional flooding surface.

APPROACH

The stratigraphic nomenclature of the WCSB is shown in Figure 3, illustrating the difficulty in lateral correlation of major units due to the lateral variation of facies across the sedimentary basin. The members that contain the analysed coal seams are the Cummings and Lloydminster Members of Eastern Alberta. These two units are coarsening-upward shoreface packages with capping coal seams. The sedimentation of these units is contemporaneous with the coarsening-upward shoreface facies of the Glauconite Formation of the Central Alberta Plains.

Five cross sections (Figure 2 is an example) were constructed from 182 geophysical wire-line logs. The average log spacing is 0.87 kilometres, covering a total length of

160 kilometres. The gamma ray, resistivity and density logs were used to correlate co: seams, shoreface facies and incised valleys within the Mannville Group. Sequence boundaries were identified from the erosive surfaces of incised valleys, their correlations and the juxtaposition of facies across the boundary.

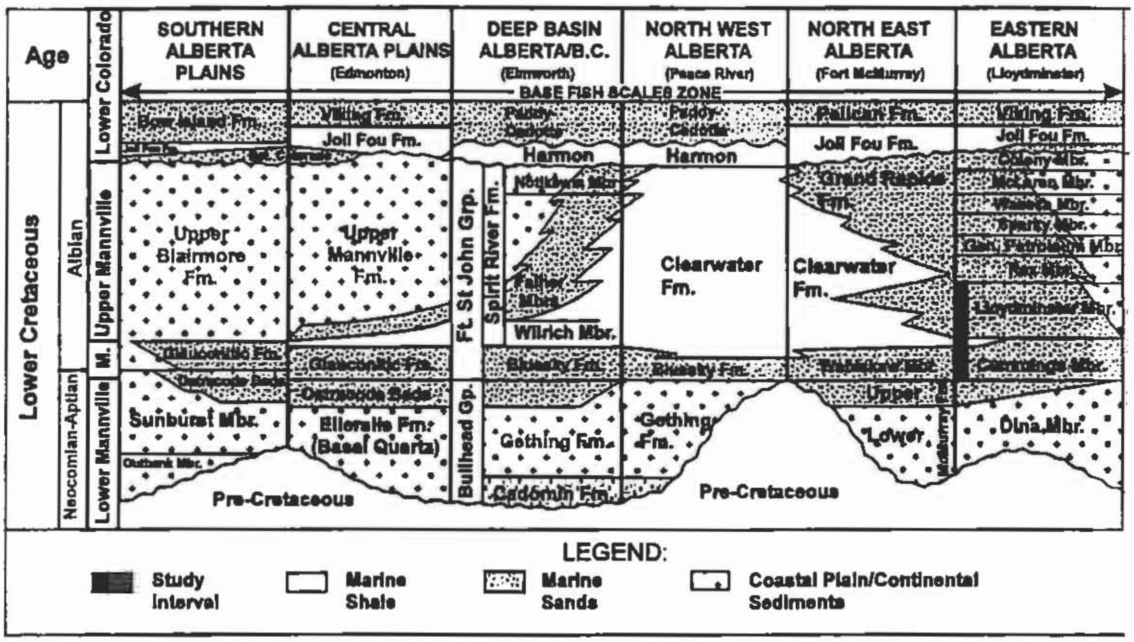

Figure 3: Stratigraphic nomenclature and regional correlation of the Mannville Group across the WCS Modified from McPhee (1994) and Jackson (1985).

Three coal cores 13-3-40-1W4M (Kindersley palaeohigh), 7-14-39-3W4M (palaeolo and 15-19-41-3W4M (Wainright palaeohigh) were prepared for petrographic analyse giving a total of 206 grab and lithotype-based samples. A distance of 28 kilometres exists between the coal cores 15-19-41-3 and 7-14-39-3, and a distance of 26 kilomet between 7-14-39-3 and 13-3-40-1. The length of the 15-19-41-3 coal core logged wa total of 6 metres, with 8 metres for the 7-14-39-3 coal core. Due to the amalgamation the two coal seams, the highest sampling resolution was performed on the 13-3-40-1W4M coal core, with 182 lithotype-based samples being analysed from 3.6 metres c material. This gives an excellent opportunity to examine the anatomy and the behavi of the coal seams at the point of amalgamation.

The internal trends identified in these coal cores reveal accommodation trends or cyc are related to changes to the mire ecosystem – for example, a progression from a flooded carbonaceous shale horizon to a limnotelmatic mire to an ombrotrophic raise mire is termed a drying-upward cycle. The diagnostic feature here is the gradual reduction of detrital minerals and dispersal indicators with a concomitant increase in preservation indices (e.g. tissue preservation index) and the maceral groups of vitrini and inertinite. In contrast, wetting-upward cycles consist of increasing trends of detri minerals and dispersal indicators, with decreases shown in vitrinite and inertinite. Concentrations of dispersal indicators signify an imbalance between the rates of accommodation and peat accumulation, more so in the direction of an increasing accommodation rate. This includes the macerals sporinite and inertodetrinite, and the coefficient of variance for telovitrinite reflectance and fluorescence (Diessel *et al.*, 2000). The tissue preservation index (TPI) is the measure of the degree of humificati the peat has undergone (Diessel, 1992). High TPI combined with low detrital minera content is an indication of raised mire conditions (Diessel *et al.*, 2000).

The recognition of wetting-upward and drying-upward cycles is also dependent on the style of initiation of peat deposition. Peat accumulation can initiate by two methods (see Diessel *et al.*, *this volume*): (1) when base-level rises, dry land is replaced with a mire (paludification); (2) when accommodation and water depth decrease due to continuous sedimentation, peat initiates by the process of terrestrialisation. The boundaries between the floor and the coal seam are termed a paludification and terrestrialisation surface, respectively. The accommodation reversal surface (ARS) and the non-marine flooding surface (NFS) are other significant surfaces identified in non-marine strata. The ARS signifies a change in the accommodation trend, with a shift between balanced and unbalanced accommodation/peat accumulation conditions (Diessel *et al.*, 2000). This surface can either be hiatal or non-hiatal and is the transitional zone separating the wetting-upward and drying-upward accommodation cycles. The NFS is the correlative equivalent of the marine flooding surface when the groundwater table is hydraulically connected to the sea (Diessel *et al.*, 2000). A rise in sea level will translate landward as a weaker rise in the groundwater level, increasing the accommodation and typically ending a drying-upward cycle.

As the total separation of the three coal core sites is less than 50 kilometres, it is expected that a peat mire over this distance will experience similar conditions (i.e. climatic and base-level fluctuations), and respond in a similar and contemporaneous manner. This is the basis of the correlation for the coal seams at this stratigraphic resolution. Therefore, wetting-upward cycles should not be laterally correlated with drying-upward cycles as they represent opposing accommodation trends, which do not occur at the same time on a local scale. Results show that it is not always a simple task to correlate a coal seam across a relatively small area, particularly when developed in a low accommodation setting with active tectonism.

COAL CYCLE CORRELATION

The sequence stratigraphic framework shown in Figure 4 was created in order to put the petrographic data of the two coal seams into context, and illustrate the relationship between the Cummings coal seam, the Lloydminster shoreface and Lloydminster coal seam. There are at least three sequence boundaries identified in only 20 metres of strata, based on tracing incised valley erosional surfaces identified in geophysical wire-line logs. One of these sequence boundaries can be traced into the amalgamated coal seam in the southeast and another lies above the roof of this coal seam. A regional palaeosol at the base of the Cummings coal seam identifies a third sequence boundary. The geometry of coal seams is also illustrated in Figure 4, with the Cummings coal seam splitting into three daughter seams towards the northwest. The Lloydminster coal seam is identifiable on the Kindersley palaeohigh as a single seam, which splits into two daughter seams in the palaeolow area. The upper daughter seam shales out over a short distance with the lower daughter seam continuing only to shale out on the flanks of the Wainright palaeohigh. These seams have been locally eroded by the stratigraphically higher incised valley in the 5-6-40-2 well.

The development of the coal-bearing stratigraphy in this area has been interpreted in terms of wetting-upward and drying-upward cycles (Figure 5), which are separated by surfaces of sequence stratigraphic significance. The underlying presence of a major unconformity surface appears to have had a significant impact on the stratigraphy. Above the first sequence boundary (SB1), deposition of a carbonaceous shale occurs as a wetting-upward cycle (WU1) in the palaeolow (7-14-39-3W4M), and on the Wainright palaeohigh (15-19-41-3W4M). This is an indication that the accommodation rate was too fast for peat accumulation to occur. In the next cycle, the accommodation rate has decreased to the point of becoming balanced with the peat accumulation rate on the Wainright palaeohigh, resulting in thick drying-upward cycles (DU1 & 2) of the Cummings coal seam. During this deposition of the WU1, DU1 and DU2 cycles, the Kindersley palaeohigh (13-3-40-1W4M) appears to be still undergoing palaeosol development (Figure 5). During the deposition of DU1 and DU2, the palaeolow area with slightly higher accommodation rates developed two thinner daughter seams that are separated by a prograding shoreface facies (WU2). The coal seams in these drying-upward cycles are underlain by a terrestrialisation surface (TeS), when accommodation trends changed from wetting-upward to drying-upward cycles. An accommodation reversal surface (ARS1) can also be placed here, due to a reversal from increasing to decreasing accommodation rates. This resulted in more balanced conditions between the rates of peat accumulation and accommodation.

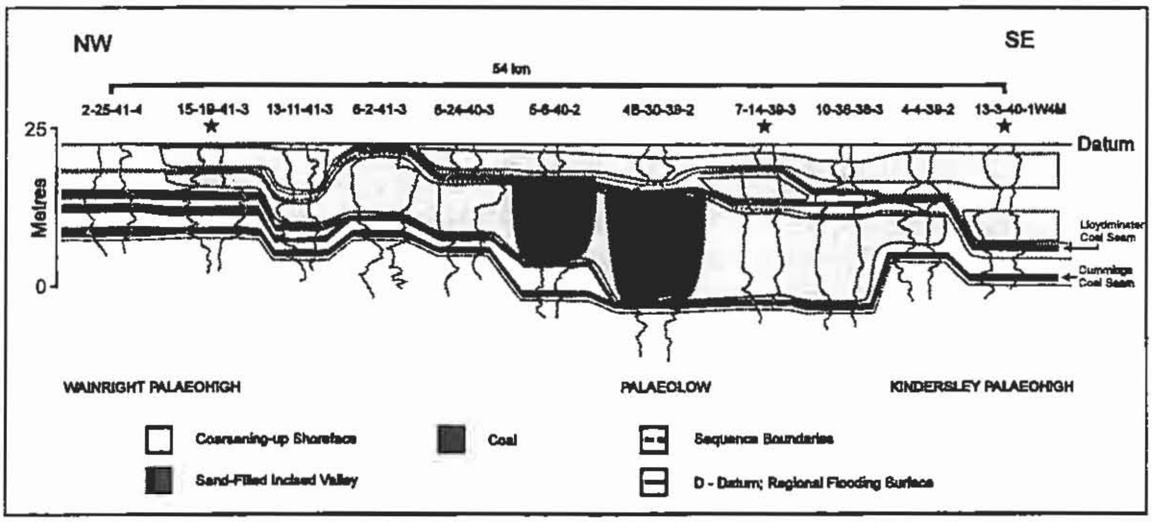

Figure 4: Geophysical log cross-section between the three analysed coal cores (indicated by stars), showing the geometry of the shoreface, incised valley sandstones and coal seams. Gamma ray (left) and neutron density log (right) profiles are shown.

A change occurred following the deposition of drying-upward cycles of DU1 and DU2, with thick wetting-upward cycles (WU3) producing the Cummings coal seam on the Kindersley palaeohigh and the remainder of the upper daughter seam in the palaeolow (Figure 5). The change in accommodation trend from drying-upwards to wetting-upwards between these two palaeohighs is separated by an accommodation reversal surface (ARS3). A paludification surface (PaS) is identified below and an ARS (4) above the Cummings coal seam on the Kindersley palaeohigh. The ARS4 can be correlated to the interseam sediment that separates the upper and middle daughter seams on the Wainright palaeohigh. Above this ARS, the deposition of the rest of the Cummings coal occurred as a series of drying-upward cycles (DU3), but only on the Wainright palaeohigh. The second sequence boundary (SB2) and the ARS4 coalesces with the ARS5 at the top of the Cummings coal seam on the Kindersley palaeohigh, illustrated by the tapering out of the DU3 cycles on the flank of this palaeohigh. During the deposition of the remainder of the Cummings coal seam in the northwest, the southeast appears to have either experienced no deposition, or erosion of this coal. The interseam shale here has developed a palaeosol, showing rootlets and pedogenic textures.

The Lloydminster coal seam is bounded by the second and third sequence boundaries (SB2 and SB3; Figure 5) that correlate laterally with two generations of incised valleys (IV1 and IV2). The Lloydminster coal seam was either not preserved or did not form in the northwest, but only developed on the Kindersley palaeohigh as a series of thick drying-upward cycles (DU6). The coalescence of the second and third sequence boundaries on the Wainright palaeohigh indicates a significant gap in the stratigraphic record, which correlates to the development of the Lloydminster coal seam in the southeast. Similar to the Cummings coal seam, the Lloydminster seam splits into two daughter seams (DU5, WU5 and DU6) in the palaeolow, separated by a coarsening-upward shoreface package. This results from slightly higher rates of accommodation in the palaeolow. A major marine transgressive surface occurs above the Lloydminster coal seam, indicating that increasing accommodation allowed deposition of a shoreface across the whole sub-basin (WU6, DU7, WU7 and DU8).

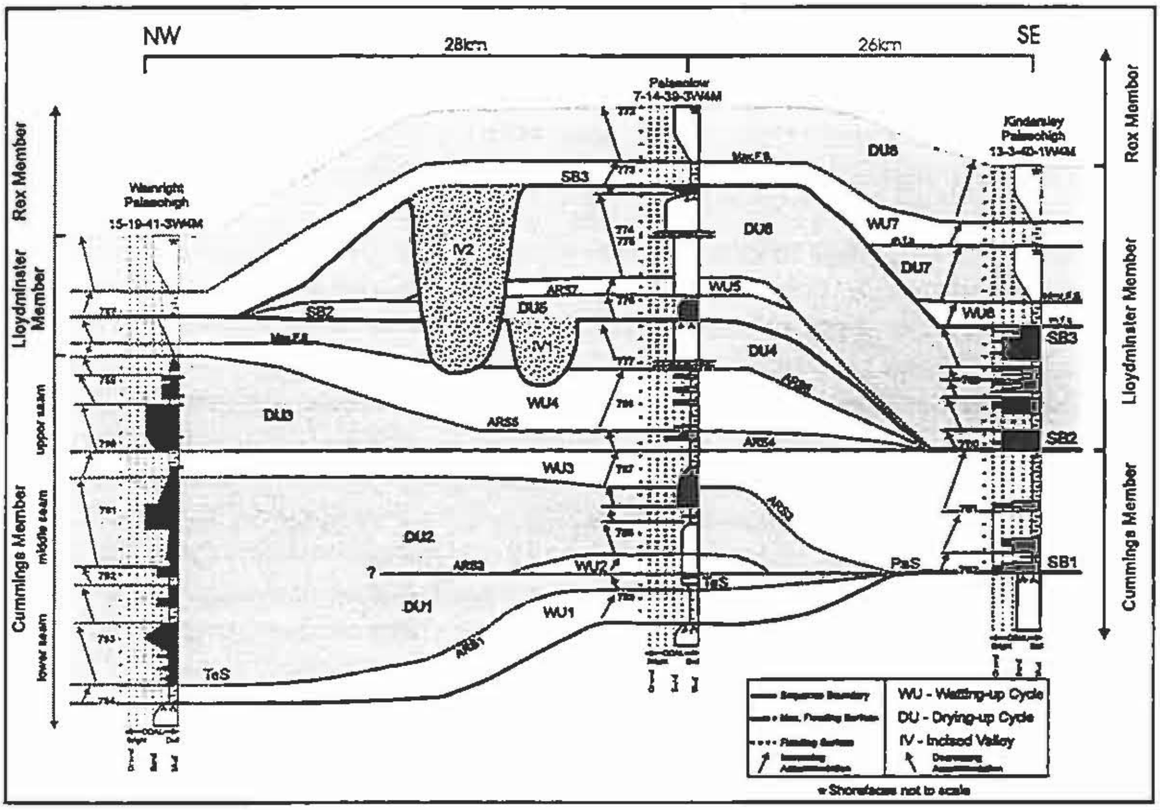

Figure 5: Correlation of the Cummings and Lloydminster coal seams, using wetting/drying-upward coal cycles from three boreholes in the Lloydminster study area. Note: TeS = Terrestrialisation Surface; PaS = Paludification Surface.

DISCUSSION

The results of this study show that the Cummings and Lloydminster coals are characterised by a combination of both wetting-upward and drying-upward accommodation trends. This is not the expected behaviour of low accommodation coals. Theoretically coal seams in a low accommodation setting should be characterised by wetting-upward cycles, where accommodation would only be sufficient at the fastest rates to enable peat to accumulate, i.e. transgressive systems tract time (see Figure 3 of Boyd *et al.*, 2000). In this setting, the drying-upward accommodation trend, commonly forming during a sea-level highstand, would be the period of time that the rates are too slow for the development of coal. The slow rates would cause exposure and ablation of the organic matter. Why is it then that the coal seams in this study show drying-upward cycles? Plausible explanations could include the unique ability of ombrotrophic raised mires to accumulate peat above the groundwater level, although the peat has to eventually be incorporated below the regional base level in order to preserve as coal. Alternatively, the localised increase in accommodation by syndepositional faulting of the basement can allow for the continuation of peat accumulation. On the other hand, active faults could also decrease the accommodation rate and cause localised removal of sediment. Warren (2000) interpreted similar changes to local accommodation to be caused by active faults in the Lower Mannville of south-central Alberta.

The selective removal of material or non-deposition in a local area gives low accommodation coal seams the characteristic of lateral fragmentation. The fragmentary nature of the coal seams is highlighted by the close spacing of significant surfaces, to the point of amalgamation, and the high frequency of palaeosol development within the strata. For example, the amalgamation of the significant surfaces SB2, ARS4, ARS5 and ARS6 above the Cummings coal seam on the Kindersley palaeohigh. These characteristics and the condensed nature of the sediments have made the geophysical correlation of the coal seams extremely difficult. In the 9 Ma it took for the development of the Lower Mannville sub-Group (Leckie *et al.*, 1997), the Lloydminster area only accumulated a maximum of 70 metres of sediment (< 7.8 m/Ma) compared to the Gates Formation of British Columbia, which accumulated up to 280 metres (30.8 m/Ma) in the high accommodation northwest part of the WCSB. In the regional context, unconformities coalesce eastward towards the Canadian Shield due to a combination of erosion and onlap (Cant, 1996), further illustrating the thinning of strata toward the east.

The geophysical log correlation can be referred to as the "external" correlation of the coal seams, with the petrographically-derived wetting/drying-upward cycles as an "internal" correlation. The reason for this is that the geophysical log correlation relies on the surrounding strata to aid interpretation, while the wetting/drying-upward correlation uses the internal characteristics of the coal seams. Although these two methods employ completely different approaches, they show the same results; identifying coal seam behaviour, sequence boundary positions and confirming the complex nature of low accommodation coal deposition.

A major Early-Cretaceous re-organisation event of the WCSB geometry has been identified in the nearby Medicine River area (Rosenthal, 1989; Cant and Abrahamson, 1996; Broger *et al.*, 1997; Karvonen and Pemberton, 1997a,b), and in south-central Alberta (Wood and Hopkins, 1992). This tectonic event occurred during the deposition of the stratigraphically equivalent Glauconite Formation, interpreted by changes to the palaeoslope and the sedimentary provenance. In the Lloydminster study area, the changes to the basin geometry may have caused reactivation of syndepositional basement faults, affecting local accommodation. The change in deposition of the thick cycles that produced the Cummings coal seam on the Wainright palaeohigh to the thick cycles that produced the Lloydminster coal seam on the Kindersley palaeohigh may be a reflection of this major re-organisation event. This event resulted in differential subsidence/uplift between the two palaeohighs, affecting the preservation/accumulation potential during deposition of the Cummings and Lloydminster Members.

CONCLUSIONS

Two approaches to coal seam correlation, based on geophysical log data and wetting/drying-upward cycles, were employed in this study of a low accommodation setting. The first of these utilised geophysical logs to externally correlate the two coal seams across the sub-basin. Both the Cummings and Lloydminster coal seams occur as an amalgamated seam on the Kindersley palaeohigh, with the Cummings coal seam splitting into three daughter seams and the Lloydminster coal seam shaling out as they approach the Wainright palaeohigh. The second approach used wetting/drying-upward cycles based on changes to petrographic composition within a coal seam. Correlation based on these cycles uses the assumption that, during a peat accummulation event, the mire environment is experiencing similar depositional conditions, resulting in the same coal cycles being developed. Wetting/drying-upward cycles have shown that, internally, segments of each coal seam appear to be deposited in different peat-producing episodes. This lateral variation is possibly due to either the whole region accumulating the same coal cycles and then being locally eroded, or a localised area experiencing peat accumulation while other areas are excluded. A third alternative is that the peat has accumulated across the whole sub-basin simultaneously, but due to differential subsidence, both wetting-upward and drying-upward accommodation trends are generated.

Low accommodation settings often occur above major unconformity surfaces. The low accommodation, non-marine strata in this study is characterised by a complex organisation of rock units. As preservation is limited in this setting, sequence boundaries, closely spaced significant surfaces and development of incised valleys and palaeosols are common. The fragmentary nature of the coal seams is caused by a high frequency of seam splitting and amalgamation. This fragmentary characteristic is highlighted by the abundance of significant surfaces found within these coal seams.

Low accommodation continental settings, as illustrated in this study, are strongly influenced by syndepositional tectonism. This includes syndepositional faulting and the major re-organisation of the sedimentary basin geometry, both of which have contributed towards the preferential preservation/removal of strata within this sub-basin.

Coal petrographic-derived wetting/drying-upward cycles were used to determine the depositional history. Consequently, this technique forms a powerful tool for high-resolution correlation of complex coal seams. The above example also illustrates that a coal seam is not always a simple stratum to correlate across a relatively small distance, and that it is not necessarily the ideal datum for all correlation exercises.

ACKNOWLEDGEMENTS

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IN SEARCH OF THE WOONONA SEAM: A REAPPRAISAL OF THE GEOLOGY OF THE SOUTH AND WEST OF THE SOUTHERN COALFIELD

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In early 1999, the Coal and Petroleum Geology Section of the NSW Geological Survey was requested to provide detailed resource information to Government on two separate issues relating to the southern and the western parts of the Southern Coalfield. The first issue was the Southern Comprehensive Regional Assessment (CRA), part of the Regional Forest Assessment process. The Section was required to assess the resource potential of seven State Forests and numerous blocks of Crown Land, and to advise Government whether these areas should be transferred to the National Park estate. The second issue was the mineral resource study of the Wingecarribee Shire commissioned by the Department of Urban Affairs and Planning. The study was intended to provide the Council with up to date information to enable it to review its local environmental plans (LEPs) and to develop a comprehensive plan for future development.

An initial review of Section Southern Coalfield coal and petroleum resource models indicated that the models were inadequate for the intended purpose. Field checking quickly showed that part of the existing stratigraphy (Coalfield Geology Council of NSW, 1999) was incorrect and required modification. A project was initiated to remap the southern and southwestern escarpments of the Illawarra Plateau and to correlate across to the east of the Coalfield using available borehole data.

A fundamental premise of the Southern Coalfield stratigraphy, first suggested in 1961 and accepted by later authors, is that the conglomerate overlying the Shoalhaven Group in the west of the Coalfield is the Marrangaroo Conglomerate of the Western Coalfield. The coal seam directly overlying the Conglomerate has been identified as the Woonona Coal Member, the lateral equivalent of the Lithgow Coal of the Western Coalfield and the Bayswater Coal of the Hunter Coalfield. As a result of the remapping, it can now be shown that the coal seam has been mis-identified.

The coal seam overlying the Marrangaroo Conglomerate, from the southwestern part of the Coalfield near Belanglo State Forest and as far north as the Burragorang Valley mines, is in fact the Tongarra Coal. The sandstone unit overlying the Coal, now named the Wanganderry Sandstone Member, and defined as being laterally equivalent to the Wilton Formation, actually erodes into the Tongarra Coal and is laterally equivalent to the top of the Coal and possibly the lower part of the Bargo Claystone. In this paper, the above conclusions are supported by cross sections across the Coalfield.

STRATIGRAPHY

Figure 1 shows the currently accepted stratigraphy for the Illawarra Coal Measures in the Southern Coalfield (Coalfield Geology Council of NSW, 1999). Figure 2 shows the location of cross sections completed during the current project using measured sections an relevant boreholes across the southern and western parts of the Coalfield. Figures 3-7 are the cross sections. Figure 8 is a diagram in three parts comparing the existing (8a) and the proposed models of the relationship of the major units, west to east across Wingecarribee Shire (8b), and south to north along the western margin of the Shire then extending north to central Burragorang (8c).

Shoalhaven Group

In the southwest and west of the Coalfield, the uppermost unit of the Shoalhaven Group underlying the Coal Measure sequence consists of dirty, bioturbated silty sandstones that are here correlated with the Berry Siltstone (see also Jones, 1990). The unit can be recognised to the east as far as Bundanoon and to the north as far as Mountain Vale (north of Bonnum Pic on the Wanganderry Walls).

East from Bundanoon and north from Mountain Vale, the Berry Siltstone is overlain by a thickening sequence of interbedded sandstones, siltstones and claystones. The sandstones are typically red to orange in colour, medium grained and volcanolithic. The siltstones, particularly at the top of the unit, are dark grey, silicified and very hard. Bioturbation is common throughout and the unit is believed to be the Broughton Formation deposited in a marine shelf environment (Bowman, 1974).

Cumberland Subgroup

Pheasants Nest Formation
The Pheasants Nest Formation conformably overlies the Shoalhaven Group to the east and northeast of Meryla. The sequence comprises thickly bedded red or green volcanogenic sandstones with minor siltstones and claystones. The sandstones lack bioturbation and exhibit features such as trough cross bedding, rip up clasts and ripple laminations consistent with fluvial deposition. Thin coals occur towards the top of the sequence in boreholes east of Moss Vale and in the Robertson area.

The Erins Vale Formation
The Erins Vale Formation has not been recognised in the project area.

Sydney Subgroup

A generalised stratigraphy can be developed for the project area from boreholes such as Austen and Butta Sutton Forest DDH 35A and Armco Illawarra DDH 12 located in the central part of the area. Changes to this stratigraphy do occur towards the Basin margins and towards the Basin centre, however the most significant variation is the erosion of underlying units by the Hawkesbury Sandstone.

This is most pronounced in the southeast and the southwest (see Figure 3). In the far southeast, at Barren Grounds, the Hawkesberry Sandstone unconformably overlies the Kembla Sandstone. To the northwest, it progressively overlies the Wongawilli Coal, the

Eckersley Formation and the Narrabeen Group. In the far southwest, at Wingello State Forest, the Hawkesbury Sandstone unconformably overlies the Berry Siltstone. To the northeast, (see Figure4), it progressively overlies the Tongarra Coal (at Penrose Quarry and Long Swamp Adit), the Bargo Claystone, the Kembla Sandstone (at Southern Colliery), the Wongawilli Coal (at Loch Catherine and Berrima Collieries), the Eckersley Formation (south of Joadja), and the Narrabeen Group (at Basket Creek near Bullio).

The basal unit of the Sydney Subgroup over most of the project area is a previously unrecognised and unnamed sequence of thin bedded sandstones with laminated siltstones and claystones. This unit forms the seat earth for the Tongarra Coal and the upper parts are strongly disturbed, with common root traces. It is up to three metres thick at Southern Colliery and at Hidden Valley west of Emu Creek, but does not occur in the Meryla Forest area nor in the west of the project area. One sandstone towards the base of the unit is characteristic. It is a white, lithic sandstone with abundant ripple laminations and with carbonaceous fragments commonly coating the ripple surfaces.

Marrangaroo Conglomerate

The Marrangaroo Conglomerate is the basal unit of the subgroup in the west of the project area, from Rocklea Quarry in the south to Beloon Pass, on the Wanganderry Walls, in the north (see Figures 3, 4, 7 and 8). At Green Wattle Creek, further to the north of Beloon Pass, there is an uncorrelated coal seam beneath the Conglomerate and above the Shoalhaven Group rocks.

The Marrangaroo Conglomerate occurs irregularly in the far west along the Tugalong Road and at Bullio. At several places, including at Nundialla Mountain and at Pulpit rock, it has been eroded by the overlying sandstones of the Bunnygalore Formation (see below). At Tugalong Station, it is observed to wedge out against the Berry Formation.

The Marrangaroo Conglomerate typically consists of angular to sub-rounded cobbles and pebbles of quartz and acid volcanics with minor amounts of sandstone and siltstone, in a matrix of course to medium quartz lithic sandstone. However, it varies greatly in thickness and composition. At Rocklea Quarry, the unit comprises 3 metres of framework conglomerate with an upper section of pebbly sandstone 1.5 metres in thickness. To the southeast of Tugalong Station it comprises 5 metres of thickly bedded framework and matrix supported conglomerate and pebbly sandstone. At the Joadja Valley Road it comprises 1.5 metres of interbedded matrix supported conglomerate and pebbly sandstone which is almost identical to the overlying sandstones. At Bonnum Pic the unit comprises 1.5 metres of matrix supported conglomerate and 1 metre of siltstone interbedded with six pebble bands, each up to 20 cm thick. At Pulpit Rock it comprises 1.5 metres of framework conglomerate, with the clasts consisting of angular cobbles.

The Marrangaroo Conglomerate can be traced in boreholes through the western parts of Sutton Forest and the Berrima Colliery Holding but there is insufficient evidence of the unit or of distal equivalents of the unit occurring from Mittagong to Moss Vale and across the Coalfield to Robertson in the east (see Figures 8b and 8c).

Tongarra Coal

The Tongarra Coal overlies the unnamed transition unit in the south and centre of the area and the Marrangaroo Conglomerate in the west. It can be traced continuously from Tongarra Colliery in the east (the type section), to Southern Colliery and Penrose Quarry in the southwest, north to Joadja, and further north to the Valley Collieries at the northern en of the Wangandery Plateau (see Figures 3-8).

The unit varies greatly in thickness and composition across the project area but does not occur in the Meryla area where it is here suggested that it was not deposited (see Figure3). The Tongarra Coal is split and in some cases replaced by blue-grey claystones in the southeast and the west, between Joadja and Bonnun Pic (see Figures 5 and 7). The upper part of the unit has been eroded by the overlying sandstone, from Jacky Jackys Creek (nea Bunnygalore) to Bonnum Pic. The oil shale horizon mined at Joadja is contained within the Coal.

Bunnygalore Formation

A thick sandstone unit overlies the Tongarra Coal in the west of the project area from Jacky Jackys Creek in the south to the Valley Collieries in the north. This unit, here name the Bunnygalore Formation, has eroded the Tongarra Coal in the south but appears to be conformable with it to the north of Breakfast Creek. This unit has been mis-identified as the Wangandery Sandstone in the current stratigraphy. The Wangandery Sandstone is defined as occurring below the Tongarra Coal and being equivalent to the Wilton Formation.

The Bunnygalore Formation comprises matrix supported conglomerates and pebbly sandstones in which the constituents are indistinguishable from the Marrangaroo Conglomerate. The unit is split by blue claystone and/or coal between Joadja and Green Wattle Creek (see Figures 5 and 7). It can be traced further east in boreholes near Berrima and beneath Nattai National Park but is not present and has no direct distal equivalents in the centre and east of the project area (see Figure 8).

Bargo Claystone

The Bargo Claystone overlies the Tongarra Coal throughout most of the area but it overlie the Bunnygalore Sandstone in the west, and the Shoalhaven Group near Meryla. The unit comprises blue grey laminated siltstones and claystones with minor sandy laminations. The Huntley Claystone Member, a tuffaceous claystone located towards the base, was readily identified in all cases where there was full exposure of the unit.

Darkes Forest Sandstone

The Darkes Forest Sandstone is not present in the south and west of the area. It appears across the centre of the area and thickens to the northeast. Where present, it comprises sandy laminites and thin bedded sandstones which occur gradationally at the top of the Bargo Claystone.

Allans Creek Formation

The Allans Creek Formation overlies the Bargo Claystone or the Darkes Forest Sandstone except to the south of Meryla and to the west near Rocklea Quarry and Breakfast Creek. Near Rocklea Quarry and at Meryla the unit has been eroded by the overlying Kembla Sandstone. At Breakfast Creek it was not deposited. Over much of the area the unit is composed of the American Creek Coal Member and consists of between 0.5 m and 1 m of coal. To the northeast, the unit thickens and is composed of coal, carbonaceous claystone siltstones and sandstones.

Kembla Sandstone

The Kembla Sandstone overlies the Allans Creek Formation throughout most of the area. It consists of white, medium to course grained lithic sandstone which is medium to thickly bedded and commonly exibits low angle and trough cross bedding. The basal parts of the unit usually contain abundant wood fragments and large claystone rip up clasts. The upper part of the unit commonly comprises a fining up sequence of sandstones and laminites. The laminites are composed of siliceous, tuffaceous, siltstones and claystones, containing numerous plant fossils. This unit has been mis-identified in the past as the Burragorang Claystone. In the west near Basket Creek, the lower part of the unit is missing and there is a gradational change from the Bargo Claystone laminites to the laminites of the upper Kembla Sandstone.

Wongawilli Coal and the upper Illawarra Coal Measures

The Wongawilli Coal is present throughout most of the area except in the southwest as previously discussed. The Eckersley Formation and overlying units occur in the north and northeast of the area but further work is required to accurately understand this part of the sequence.

CONCLUSION

The Woonona Coal Member and the Wilton Formation do not occur in the project area. The seam overlying the Marrangaroo Conglomerate in the west of the area is the Tongarra Coal not the Woonona Coal Member. The Tongarra Coal is now known to extend further than previously thought and to be more variable. The resource potential of the coal must now be revised.

The sandstone unit now known to overly the Tongarra Coal in the west of the area is not the Wanganderry Sandstone. The unit is here named the Bunnygalore Formation. The Woonona Coal Member and the Wilton Formation are known to exist further to the north in boreholes in the area from Picton to Camden. Further work is now being conducted to determine where these units first appear and how they develop.

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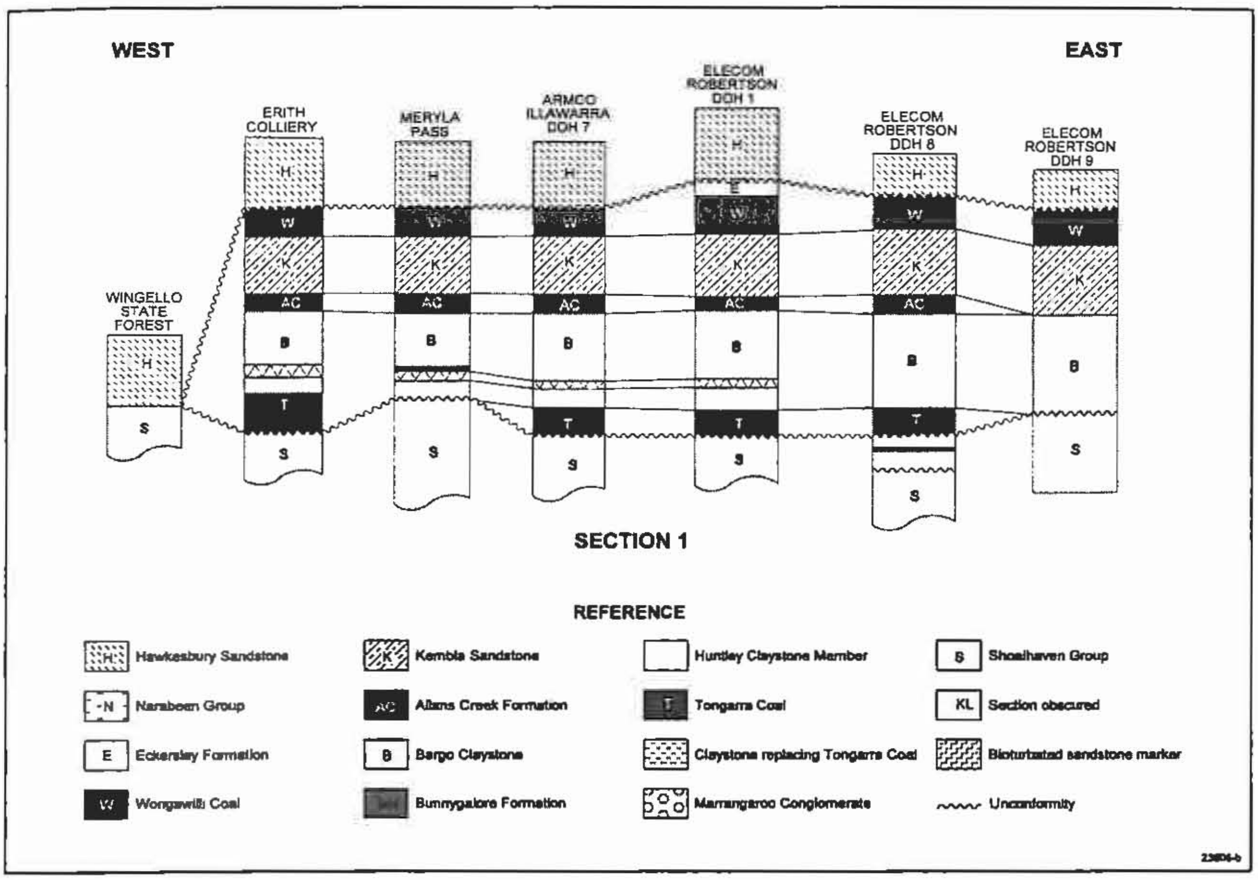
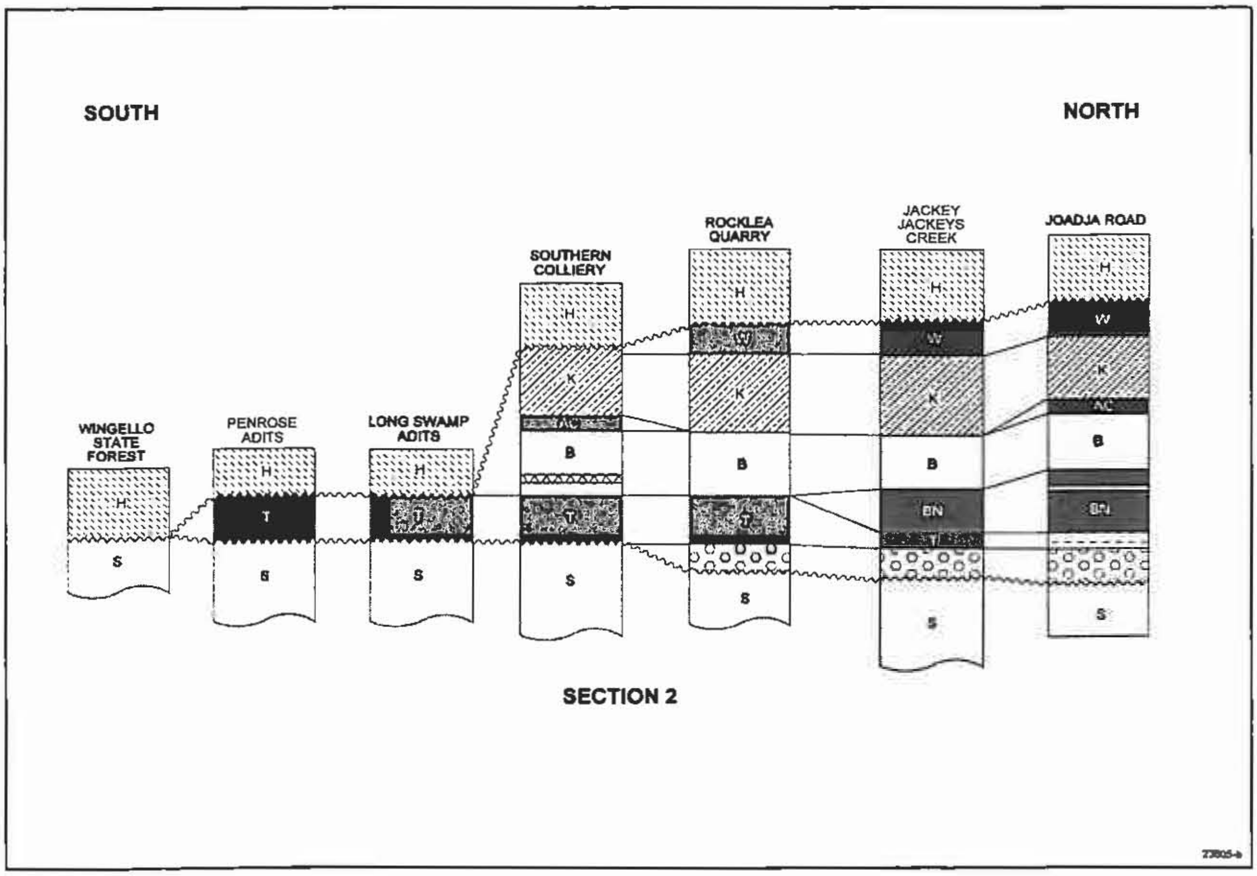


Figure 3



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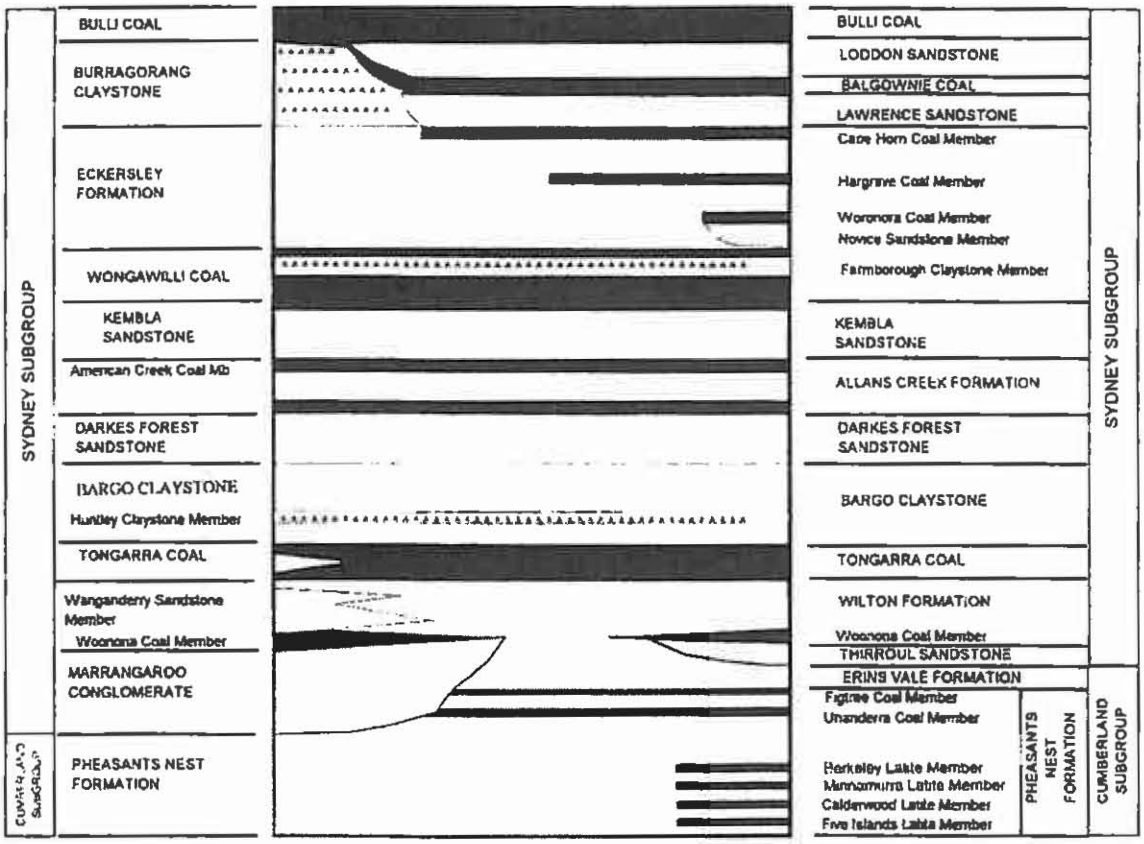


Figure 1 Stratigraphy of the Illawarra Coal Measures (Coalfield Geology Council 1999)

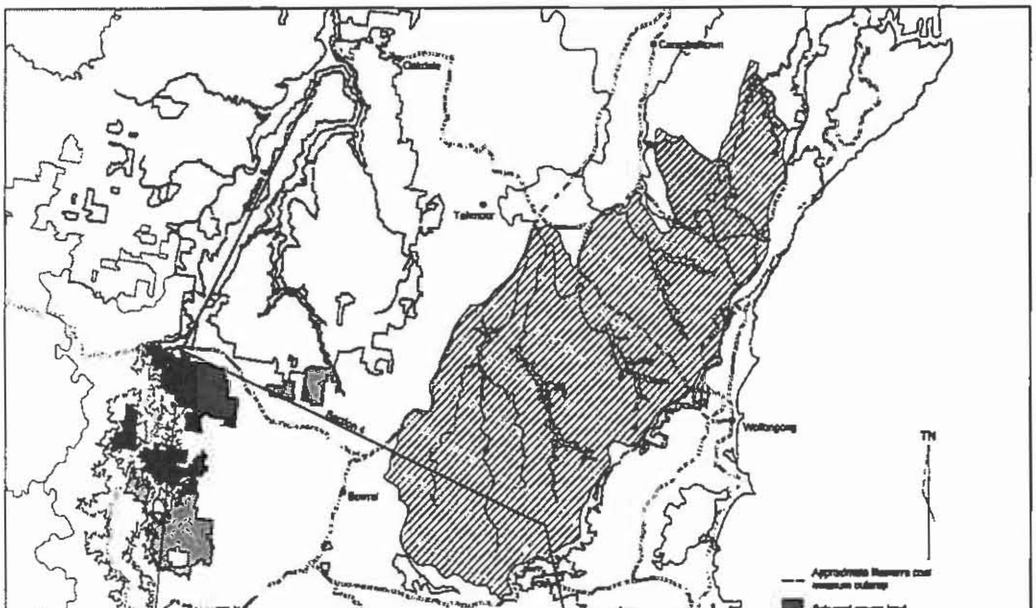


Figure 2 Locations of cross sections

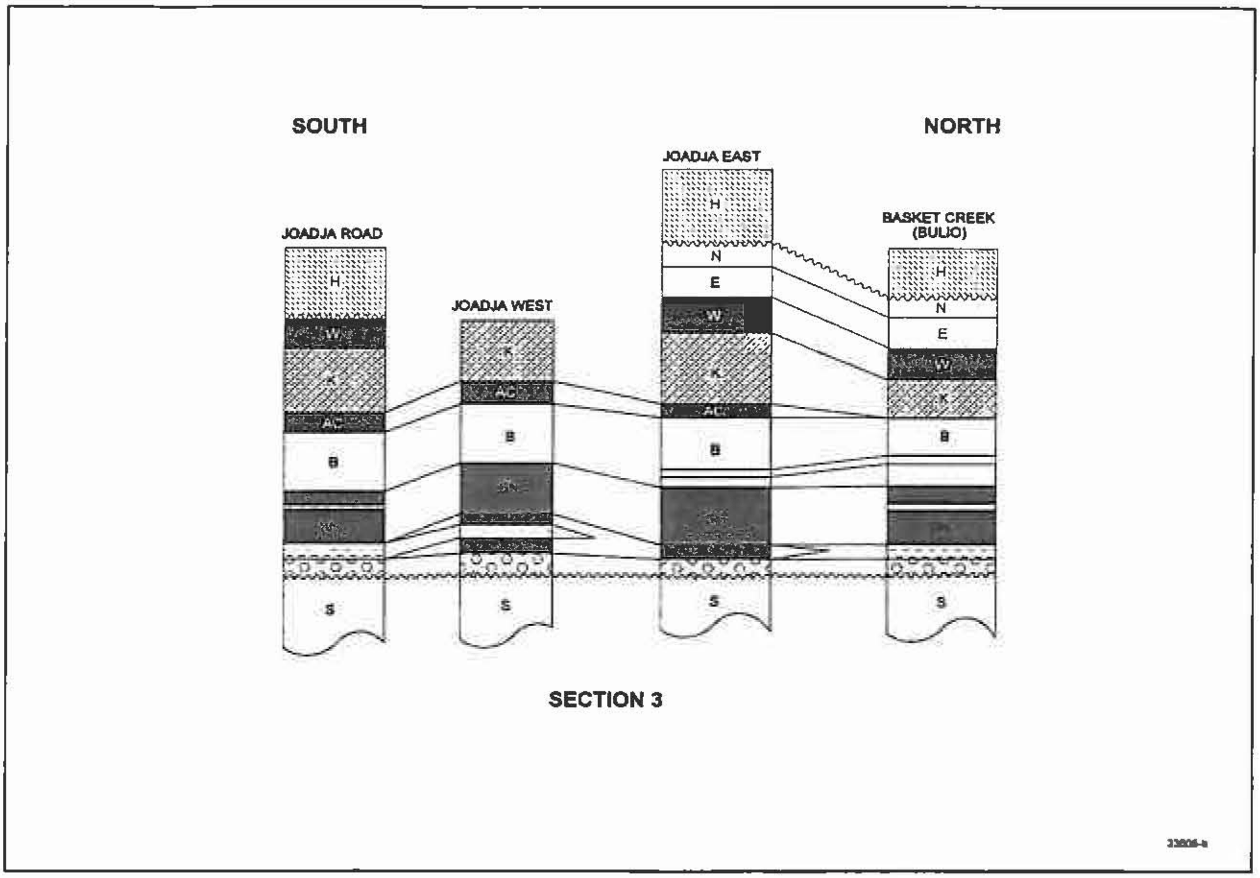


Figure 5

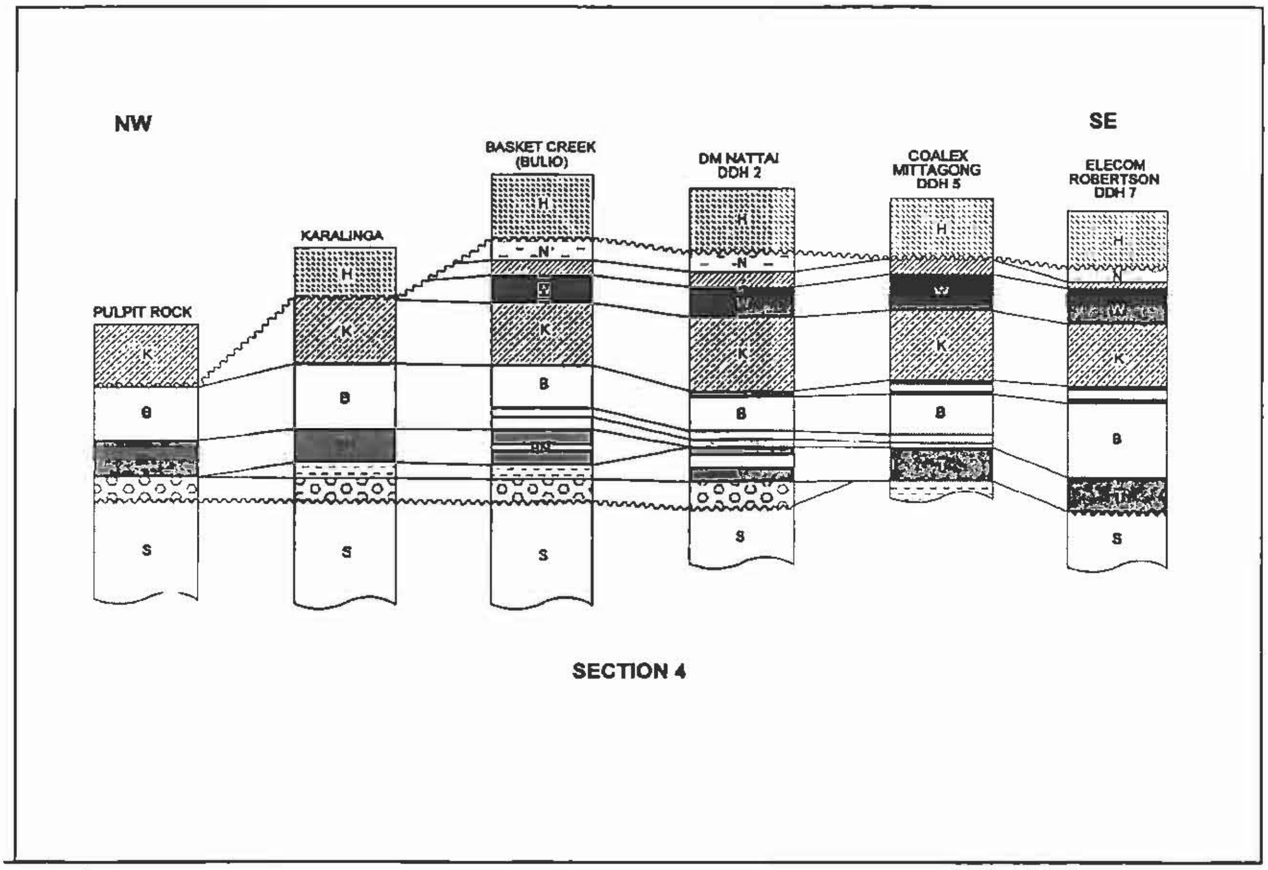
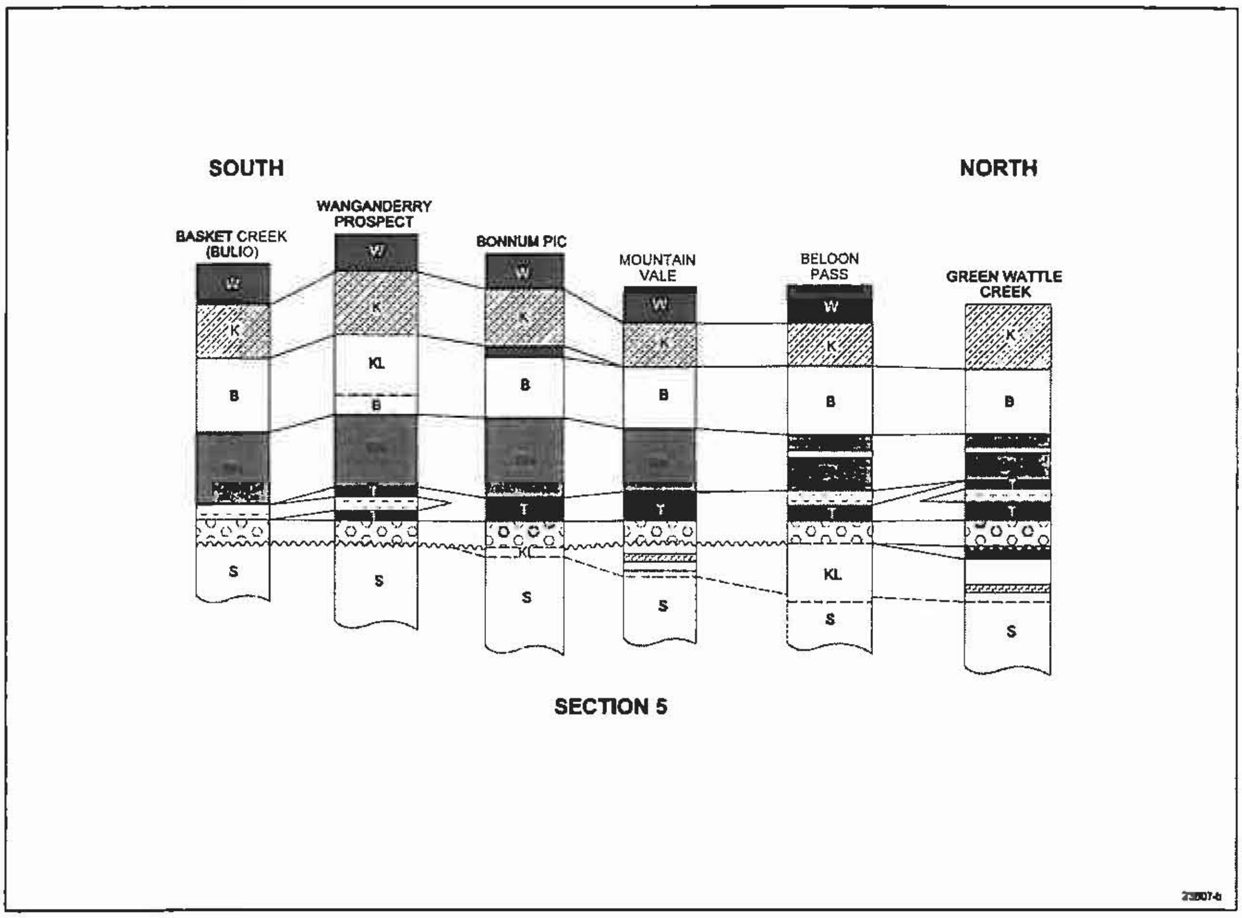


Figure 6


SOUTH
NORTH
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WANGANDERRY PROSPECT
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MOUNTAIN VALE
BELOON PASS
GREEN WATTLE CREEK
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SECTION 5

Figure 7

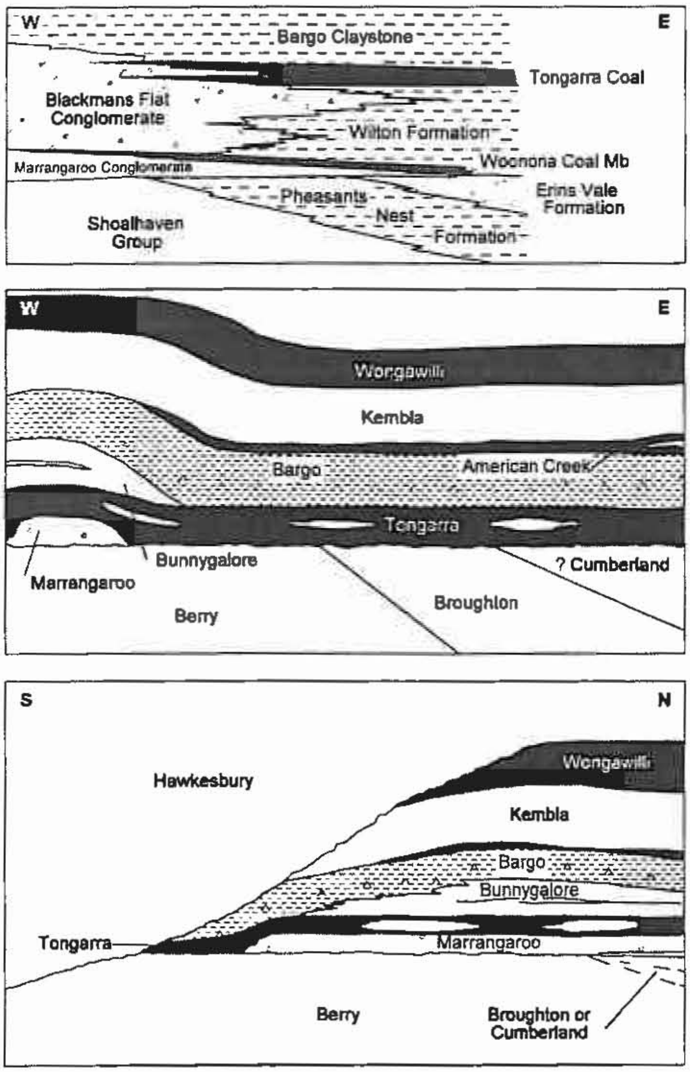

Figure 8 Comparison of the existing (upper) and proposed (centre and lower) models of the relationships between the major stratigraphic units in the lower part of the Illawarra Coal Measures in the southern and western parts of the Southern Coalfield. The existing model is taken from Coalfield Geology Council of NSW, 1999.

SO HOW DOES YOUR PEAT GROW?

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michaelc@powercoal.com.au

A database consisting of 1200 boreholes, spanning the entire Newcastle Coalfield (NC) provides a unique opportunity to travel back in time to when the Great Northern and Fassifern seams were accumulating (Figure 1). The correlation of numerous tonstein bands within the Fassifern seam allows the sequential viewing of several plies of the seam accumulating through time (Figures 2,3 & 4). The overall scene is similar to previous studies (Bocking et al 1988) including areas of peat accumulation seperated by several fluvial channel systems and an extensive braidplain/delta to the southwest. However viewed sequentially the lateral migration of these channels can be seen, as well as the periodic termination of peat by the much broader areas of braidplain/deltas. These channels are contemperaneous to peat formation as the channel edges include complex seam splitting and intercalations of clastics and coal bearing strata. The structural control on the drainage pattern can be seen reflecting the NE-SW and WNW-ESE jointing which dominates the east coast of Australia.

The numerous tonstein bands within the Fassifern seam display remarkable continuity and can be mapped across the entire coalfield using 5mm isopachs (Figure 5 – Ply FCR). Such preservation suggests a subaqueous deposition where the ash falls are protected from redistribution by rainfall and runoff. These tonsteins are also almost devoid of any tree preservation or vertabraria (Figure 6). Indeed by far the largest exposure of a seam (Fassifern) terminated by a tuff (Awaba Tuff) in the Newcastle Coalfield has been at Westside Opencut. In the several years of its operation no trees have been found preserved in the roof of the seam. Although rare trees are preserved at specific horizons, their almost complete absence in intraseam tonsteins requires explanation.

In contrast the claystone deposited on the roof of the GT Northern seam preserves both topographic relief (Figure 5 – GNYS) and numerous tree trunks. This claystone achieves a maximum thickness in excess 7 metres, whereas Ply FCR averages 7cm and almost all the data points range between 1 and 12cm. Recent drilling at Broke by the DMR, and at Denman by Powercoal have identified the same tonstein over 100 km from the NC, at equivalent thicknesses.

Boron seam profiling has found that the upper plies of the Gt Northern seam are depleted in boron, a marine indicator. This may be the result of the seam becoming exposed, enabling trees to become established over a large area. This depletion in boron is unique compared with other seams profiled by the author and is not repeated adjacent to other tonsteins (Creech 1998), suggesting that trees are growing in an atypical peat situation. In addition chemical and maceral studies in proximity to these tonsteins have not found any evidence of flooding, but indicate they have been deposited in the normal peat environment (Creech 2000).

The Awaba Tuff, a thick volcanoclastic deposit, dominates the interval between the Fassifern and Great Northern seams. This unit varies considerably in thickness across the NC achieving a maximum of up to 30 metres and averaging 8 metres (Figure 4). This variation could be due to either compaction of the underlying peat, proximity to the source or variation in topographic relief. Although thicker portions do occur over the best developed peat, differential compaction alone cannot account for the observed distribution. Similarly, the variation in thickness cannot be accounted for by proximity to the source. Redistribution due to topographic relief is inconsistent with the preservation of the tonsteins unless both the tonsteins and the Awaba Tuff were deposited in water bodies of variable depth. This interpretation is also consistent with sedimentary features such as water escape features and synaeresis cracks, indicating that the thicker intersections of the Awaba Tuff were laid down in brackish water. Determining the depth of water is problematic due to the effects of differential compaction and dewatering during deposition, however it could well be measured in metres.

It has been argued that these bands are being preserved only when the peat was flooded and dormant. Such an argument does not explain the lack vertabraria once peat is reestablished on the upper surface of the tonstein. Also if the distribution of the Awaba Tuff reflects topography then peat accumulating under the thickest sections (in a topographic low) should contain extra tonsteins preserved in the profile as these areas would be below the water table more often.

The numerous pyroclastic units in the NCM indicate widespread peat and tuff accumulation in a subaqueous environment and challenge conventional views on coal formation in the Sydney Basin. Such an environment may involve raised mires restricting channel locations at the margins, but whose central portions are below the water table (Figure 7). This implies that tree growth is restricted to the margins and to horizons where the peat becomes more generally exposed. The consistent thickness of coal plies across apparently variable water depths suggests that the predominant supply of plant material are plants capable of growing subaqueously and not large enough to be preserved by the numerous ash falls. Such a model of coal formation may also be appropriate in coals displaying similar features preserved by pyroclastic strata.

The author would like to thank the Dept. Mineral Resources, Powercoal, COAL and Oceanic Coal for access to this data.

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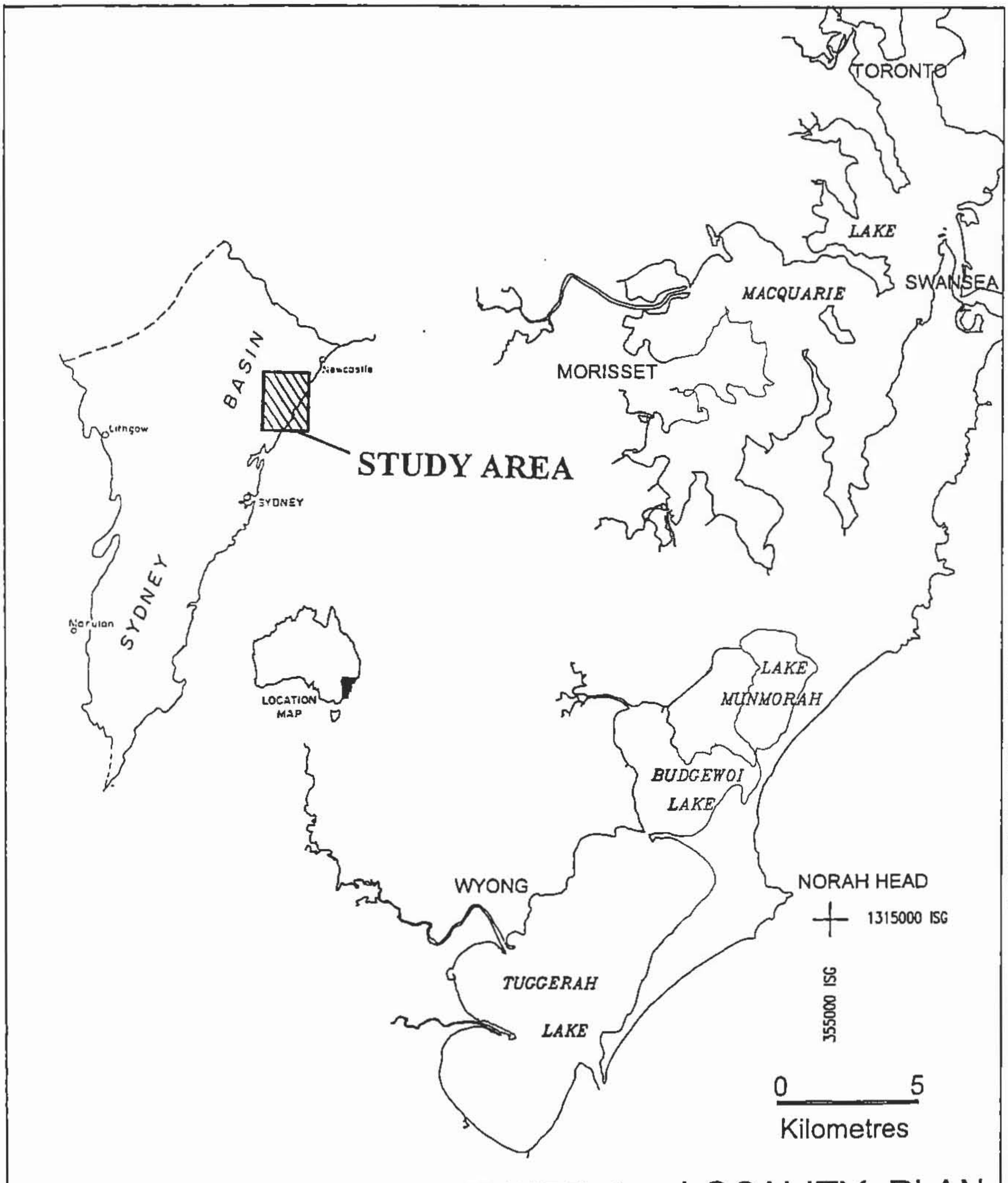
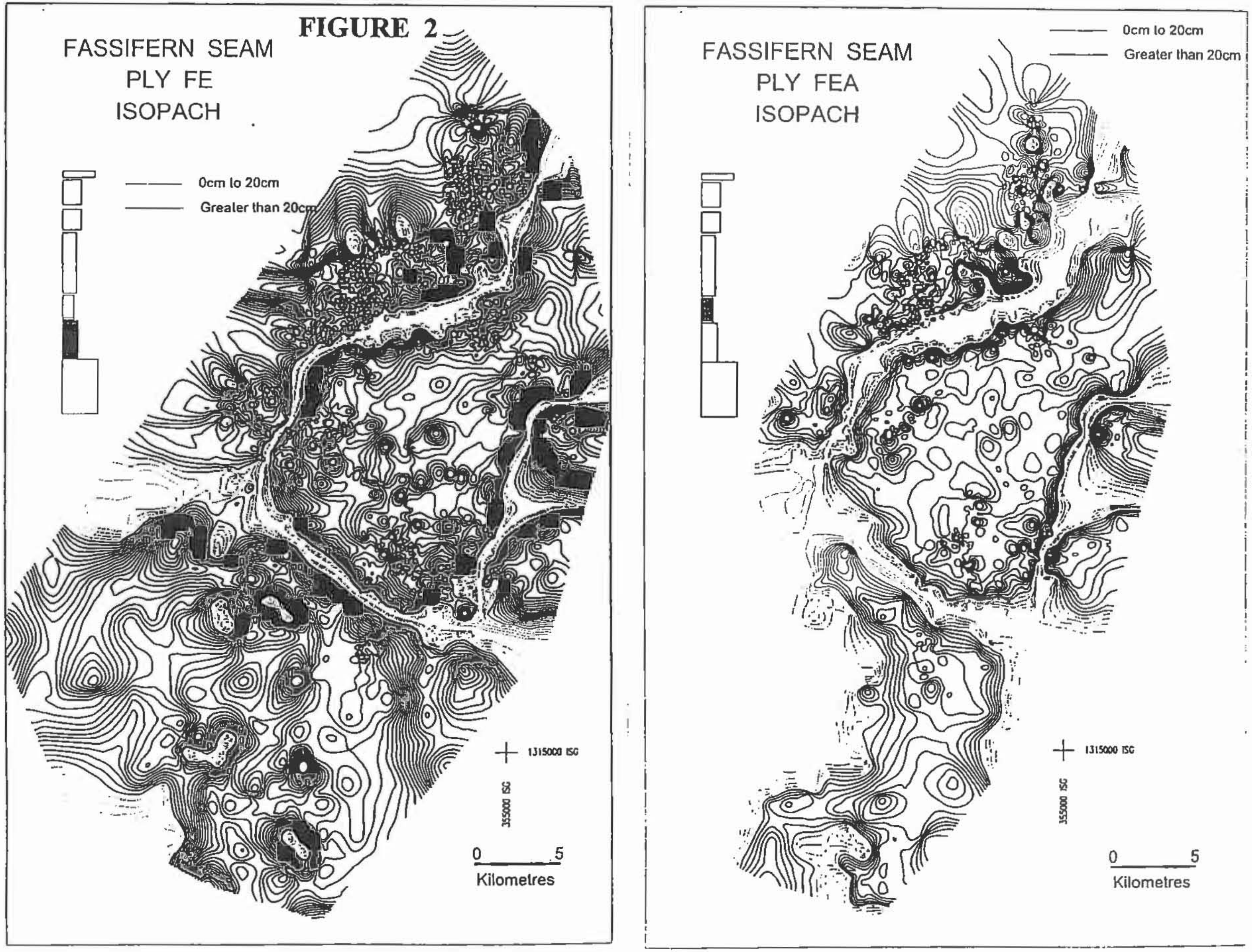


FIGURE 1 LOCALITY PLAN

FIGURE 2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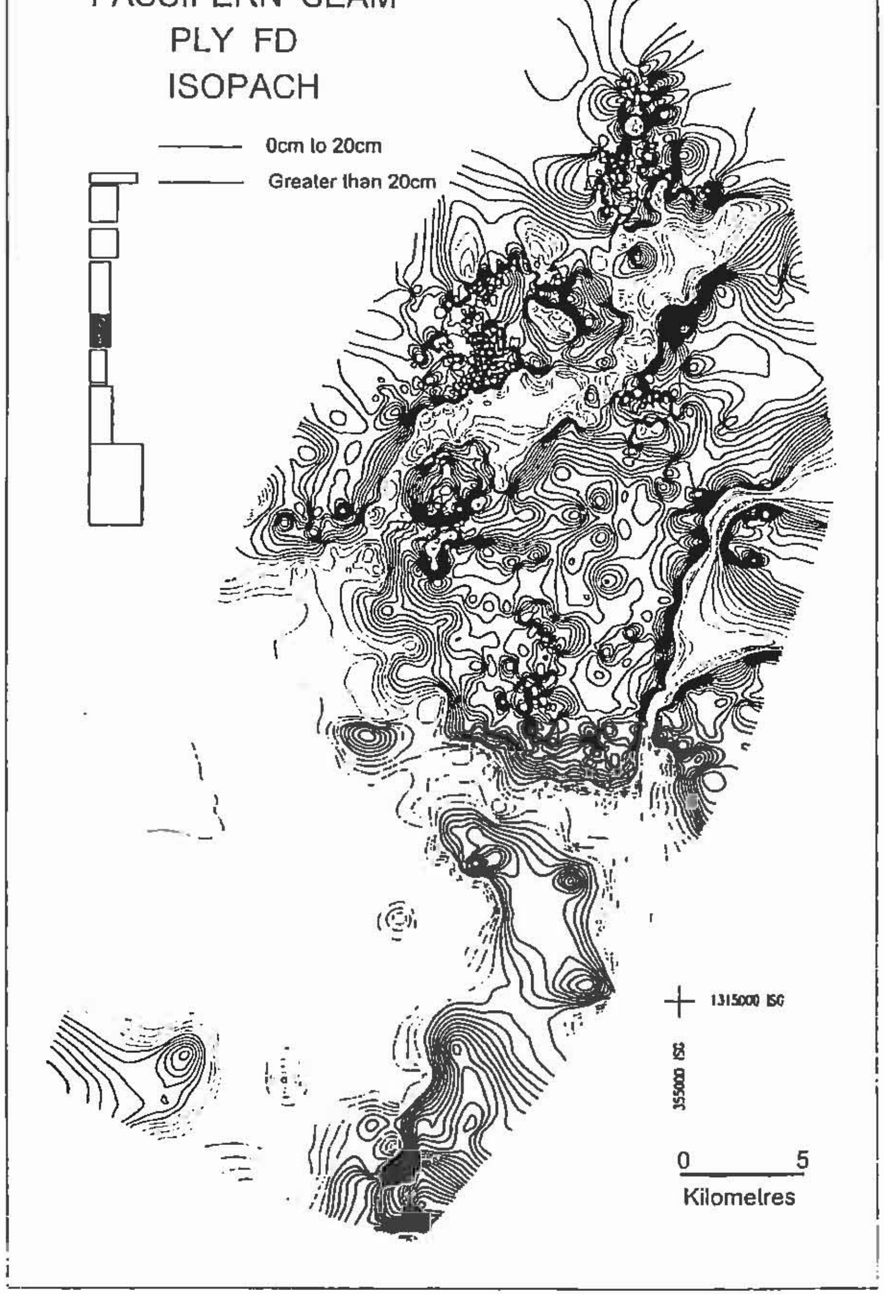
Kilometres

FIGURE 3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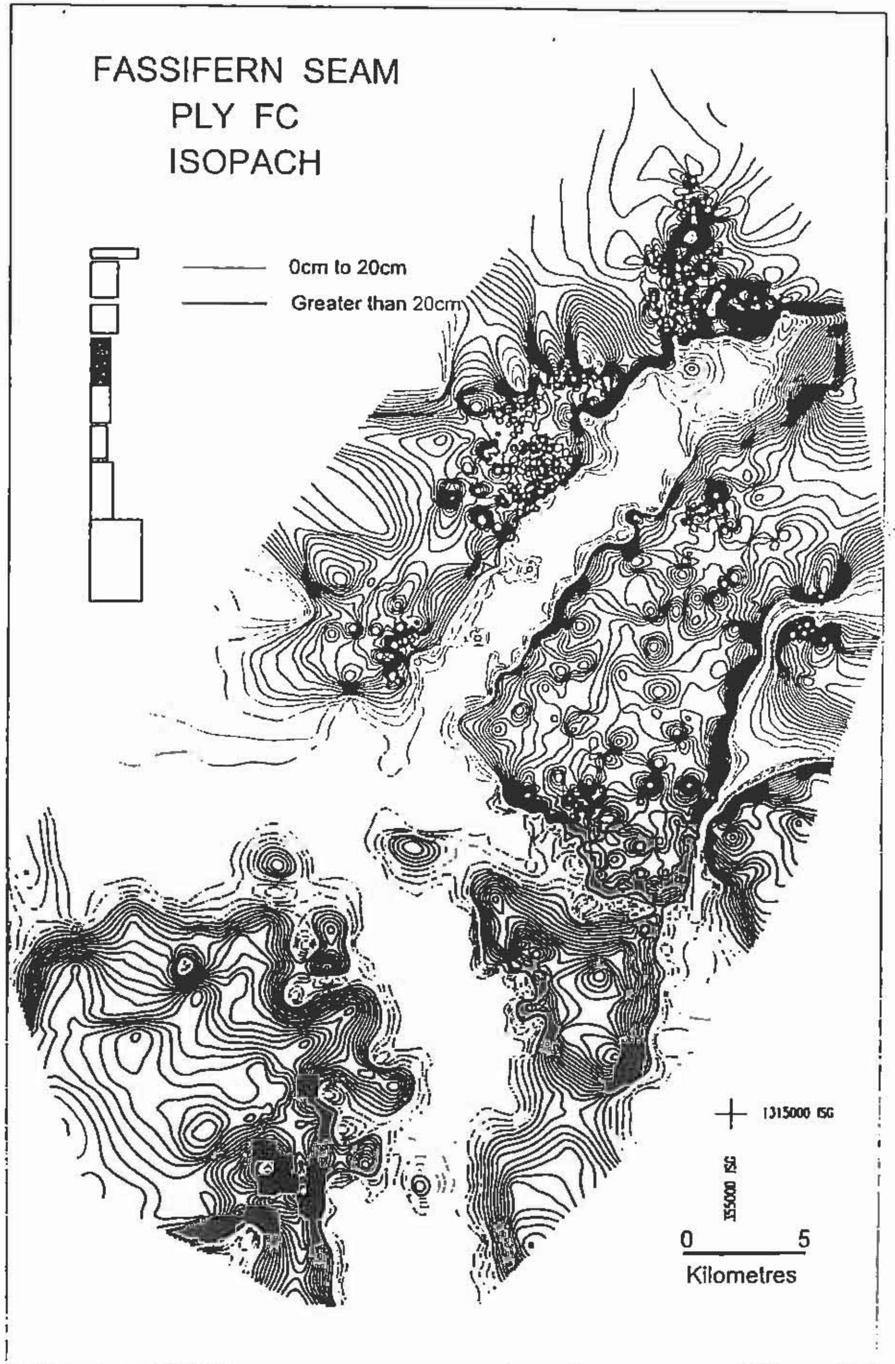
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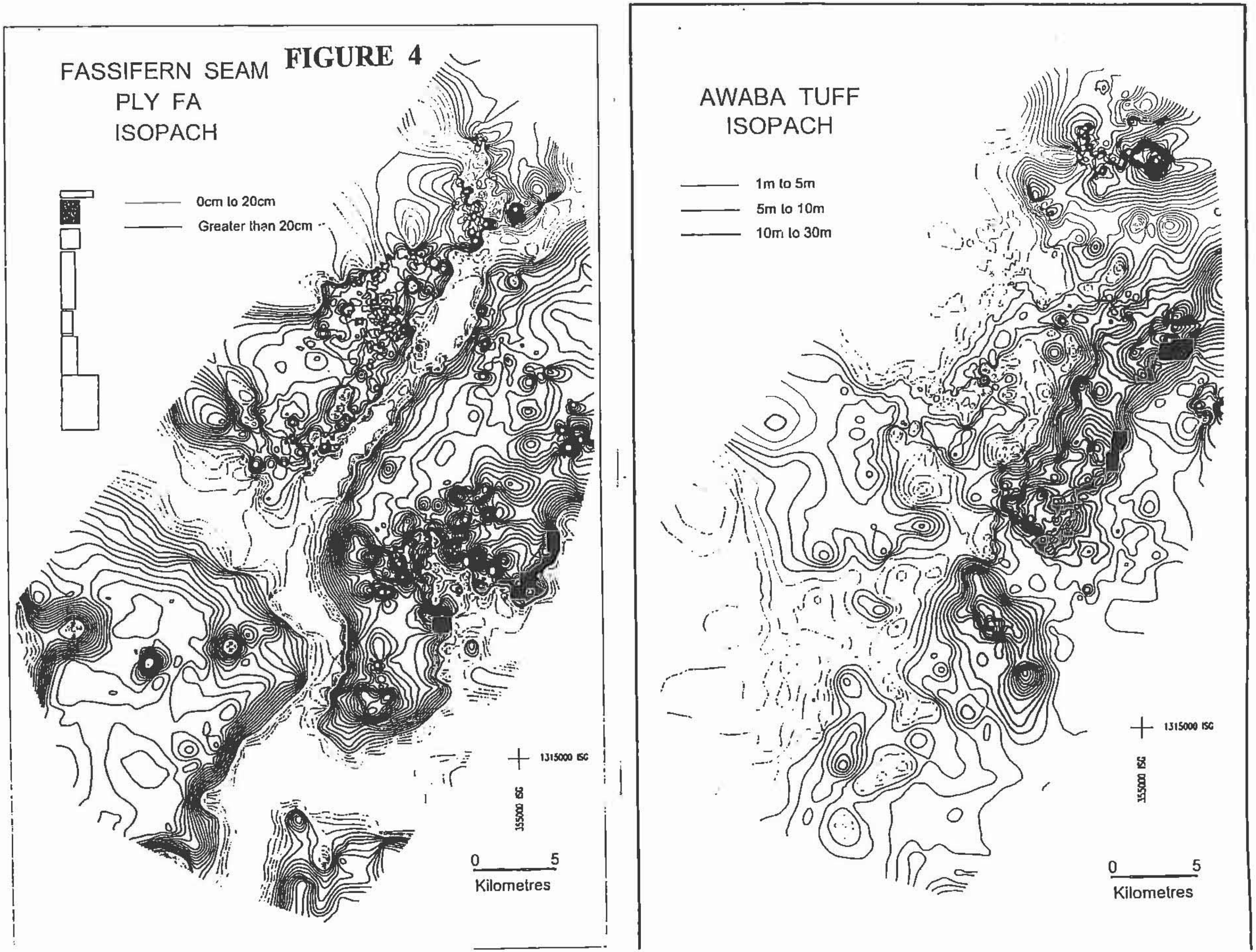
FIGURE 4


FASSIFERN SEAM
PLY FA
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0cm to 20cm
Greater than 20cm
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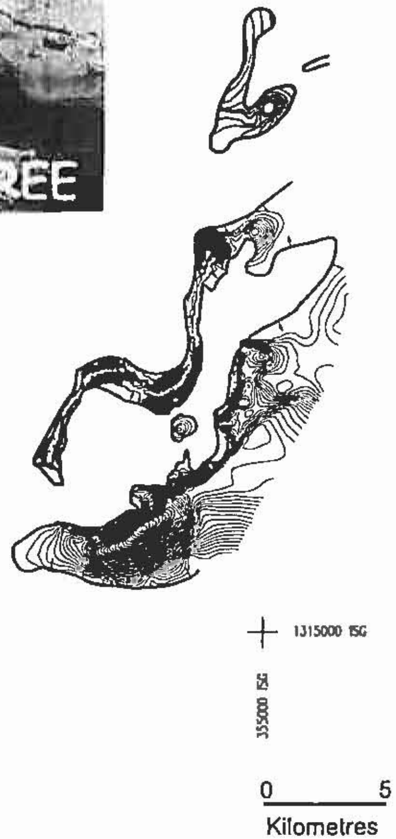
AWABA TUFF
ISOPACH
1m to 5m
5m to 10m
10m to 30m
1315000 ISG
355000 ISG
0
5
Kilometres

FIGURE 5

GREAT NORTHERN SEAM

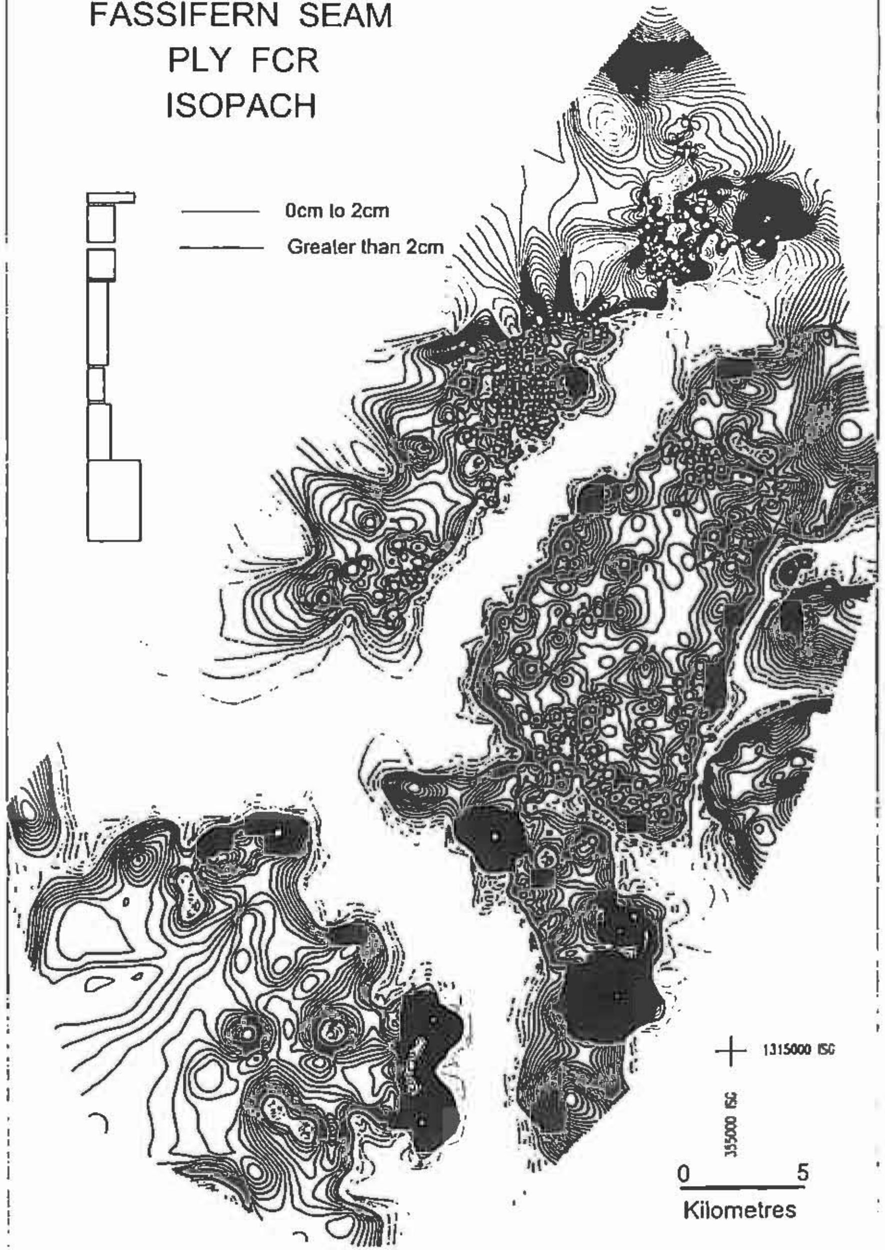
CLAYSTONE ROOF



FASSIFERN SEAM

PLY FCR

ISOPACH



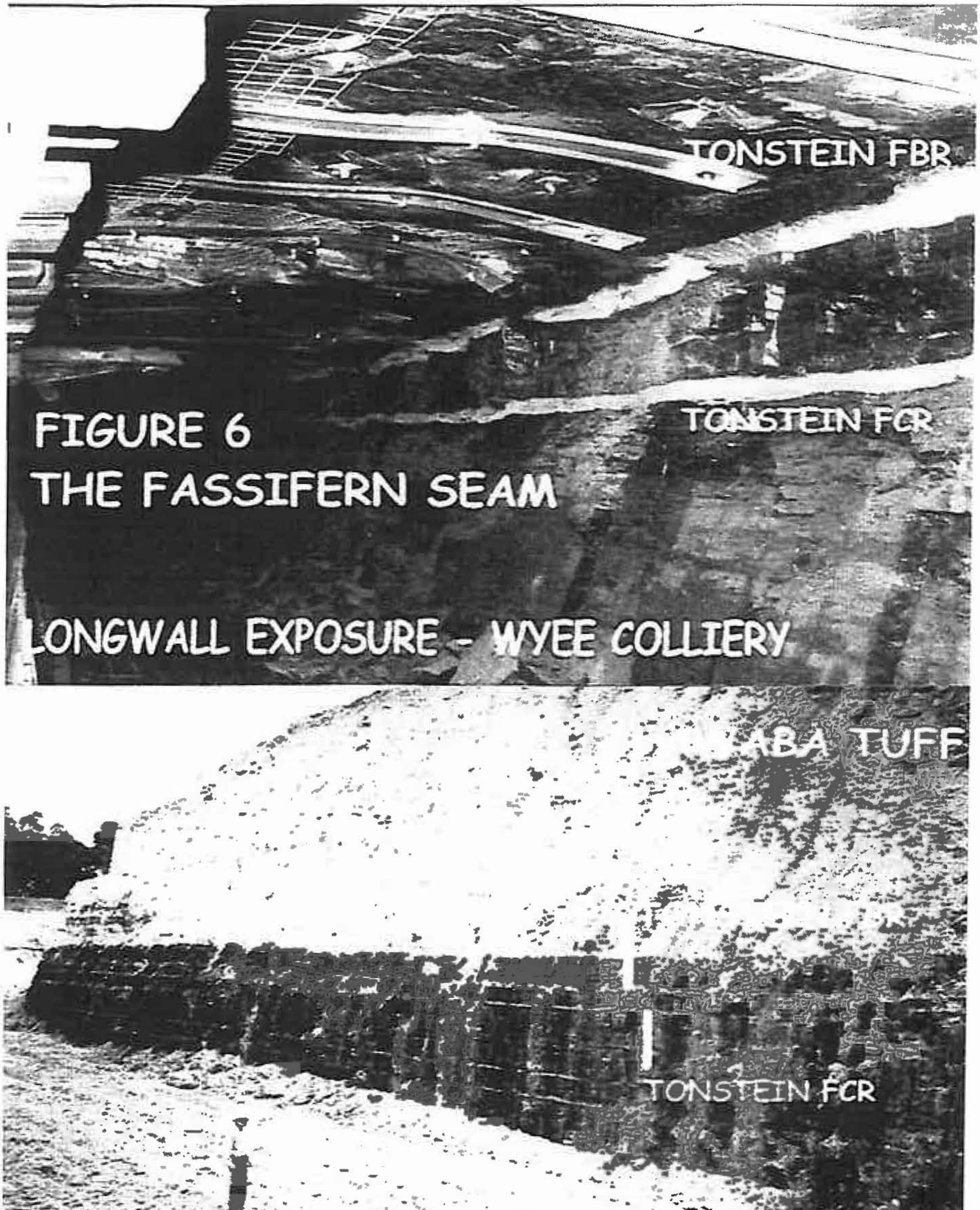
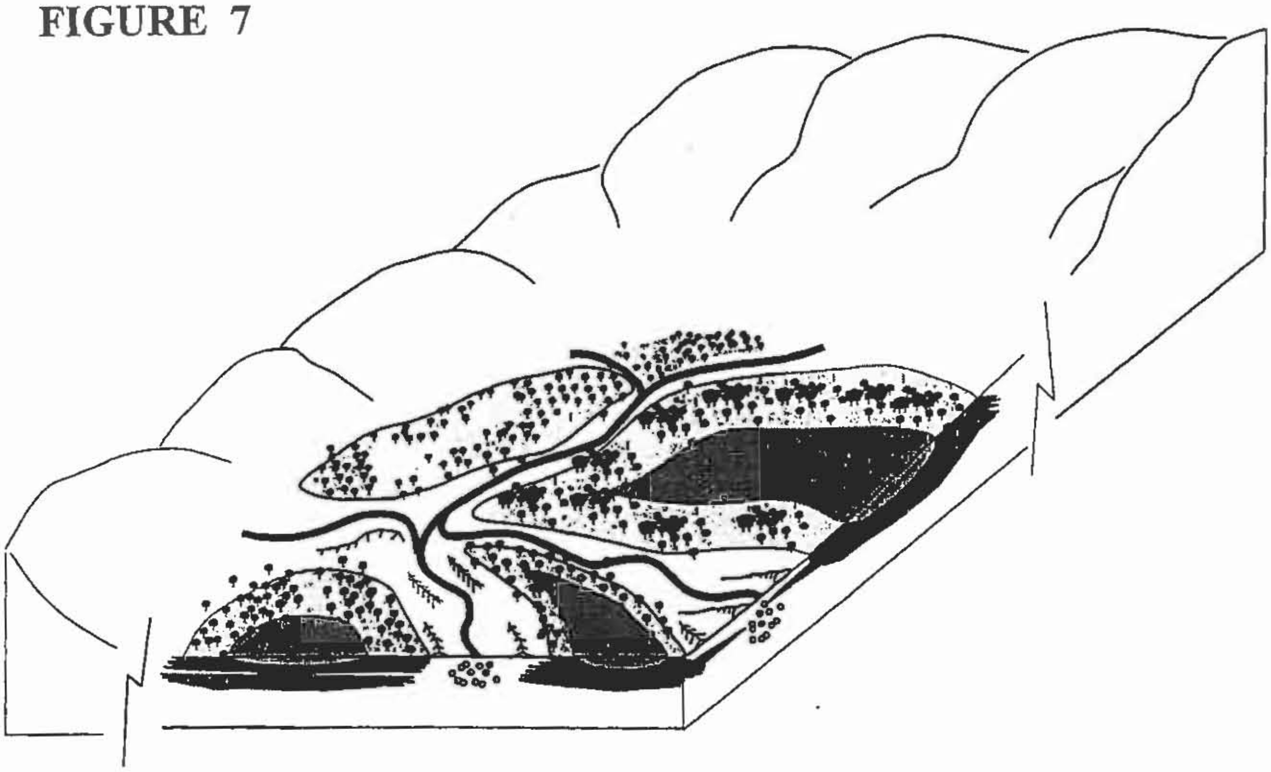

TONSTEIN FBR
FIGURE 6
THE FASSIFERN SEAM
TONSTEIN FCR
LONGWALL EXPOSURE - WYEE COLLIERY
ABA TUFF
TONSTEIN FCR

FIGURE 7



SCHEMATIC DIAGRAM
ENVIRONMENT OF FASSIFERN SEAM

THE EVOLVING GLOBAL ENERGY MIX

KEYNOTE ADDRESS

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Denver, Colorado 80225, USA

INTRODUCTION: THE ENERGY MIX

For much of human history, energy was derived from renewable sources such as wood, dung, animal oils, waterpower, and wind power. Even today the majority of the energy consumption of forty-five poorer countries still comes from such traditional sources. Coal became a major energy source with the industrial revolution. By the beginning of the 20th century over 90% of the world's energy supply was from coal. Through that century there was a tremendous growth in the world's energy demand as the world became more industrialized and, in many regions, richer. Energy demand was also driven by population growth: there was a fourfold increase in the world population within the century. Coal lost its dominant position in the middle of the century as it lost market sectors to other fuels (Figure 1). Natural gas, and to a lesser extent oil, have largely substituted for coal in the domestic heating and manufacturing sectors. The transport sector largely ran on coal at the beginning of the century but the newly invented automobiles, trucks and airplanes ran on oil. During the early part of the century oil also substituted for coal in the steamships and later on the railroads. Despite the loss of market sectors, coal is still an important part of the energy mix because of its use in electrical generation, a sector that had only just emerged at the beginning of the century. World coal production reached all time highs just before the collapse of the Soviet empire. Currently oil accounts for about 38% of the world's energy consumption. Coal accounts for 23.5% and natural gas 22.5%. The remaining 16% of our energy supply is derived from non-hydrocarbon sources, predominantly from hydro and nuclear power plants.

The energy mix will almost certainly continue to evolve during the 21st century. On the supply side, the mix will be determined by the availability and price of various fuels. On the demand side, the mix will be determined by economic prosperity, environmental concerns, and development of new technologies. This paper aims to give a short overview of some of those factors that will help determine the interaction of supply and demand.

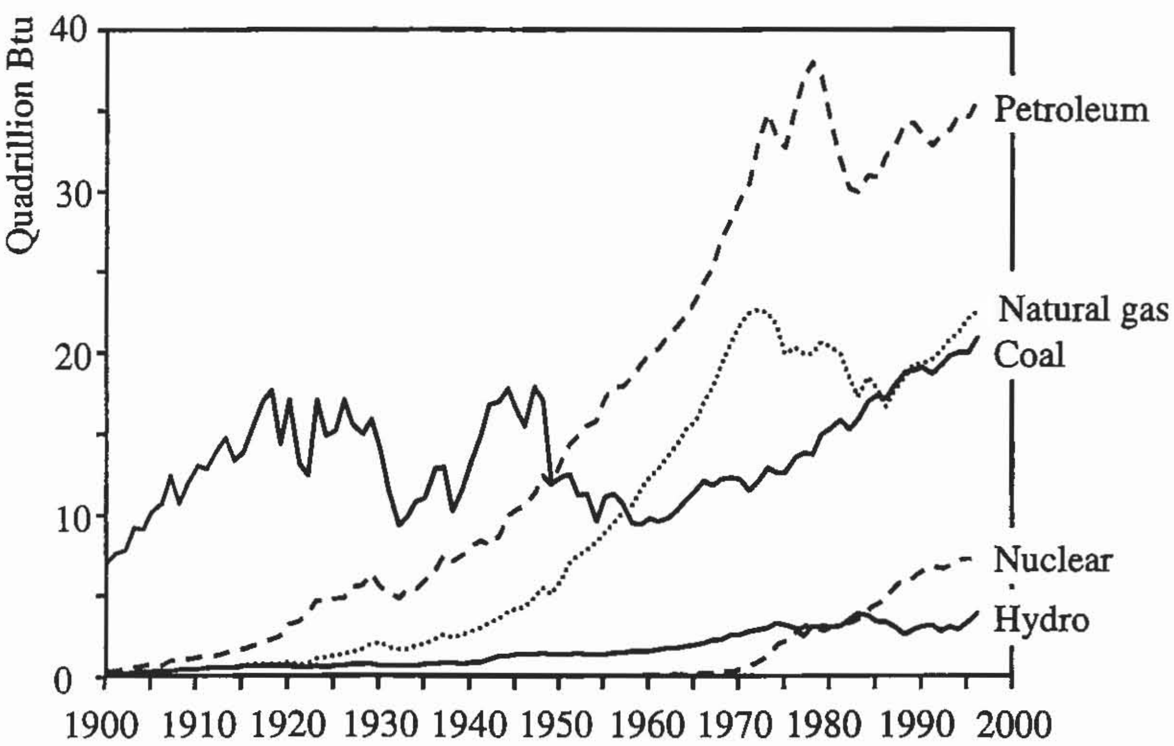

Figure 1: Plot showing the evolution of the energy mix in the United States during the 20^{th} century. Coal was the dominant source in the first half of the century but lost the transport (steamships and railroads) and domestic heating markets. Coal use, however, has increased steadily since 1960 for use in electrical generation. Petroleum and natural gas use rapidly increased until the energy crisis of the mid1970s. The world energy mix had a similar pattern of evolution though currently there is slightly more coal used than natural gas.

NEOMALTHUSIANS AND CORNUCOPIANS

Currently there is much speculation as to how the energy mix will evolve over the coming decades. Predictions range from a neoMalthusian perspective of an imminent peak in oil production, with subsequent dire consequences for the world economy, to a cornucopian perspective of low energy prices due to technological advances (McCabe, 1998). The neoMalthusians correctly say that Earth's resources are finite and that if we continue to use those resources at the present rate or at an increasing rate, then we will inevitably run out of those resources. The question is: when will that time come? Most neoMalthusians in the last 50 years have followed a methodology developed by King Hubbert (1956). The methodology predicts future production of a fossil fuel by an analysis of the production history to date plus knowledge of the amount of the remaining resource. The recent predictions of Campbell (1997) using this methodology predict a peak in world production within the next few years. By contrast cornucopians do not foresee any shortage of fossil fuels. They believe that, because of man's ingenuity, an abundant and cheap supply of fuel will always be available. History certainly seems to be on the side of the cornucopians: the long-term trend for fossil fuels, as with other nonrenewable resources, has been for lower prices over time (McCabe, 1998).

In some ways, the neoMalthusian and cornucopians viewpoints are basically the pessimistic versus the optimistic perceptions of the future of technology. Critical to the current debate, however, are the concepts of resources and reserves about which there is considerable misunderstanding. Resource or reserve numbers are not a measure of the ultimate amount available for development. As resources or reserves are depleted over time, additional amounts of fossil fuels are inventoried (Figure 2). These new resources or reserves tend to be those that are progressively of lower quality or less easy to extract and get to market. Despite that, these new resources/reserves tend to be available at similar or even lower costs over time because of advances in technology. Throughout most of the 20th century crude oil reserves in the United States represented about a 12 year supply. For the last 50 years, estimates of undiscovered crude oil in the U.S. have represented about a 40 year supply. For the world, estimates of undiscovered oil have represented about a 50 year supply (Δt in Figure 2). Estimates of resources and reserves can therefore be considered as inventories of the amount of fossil fuel perceived to be available over some future period of time.

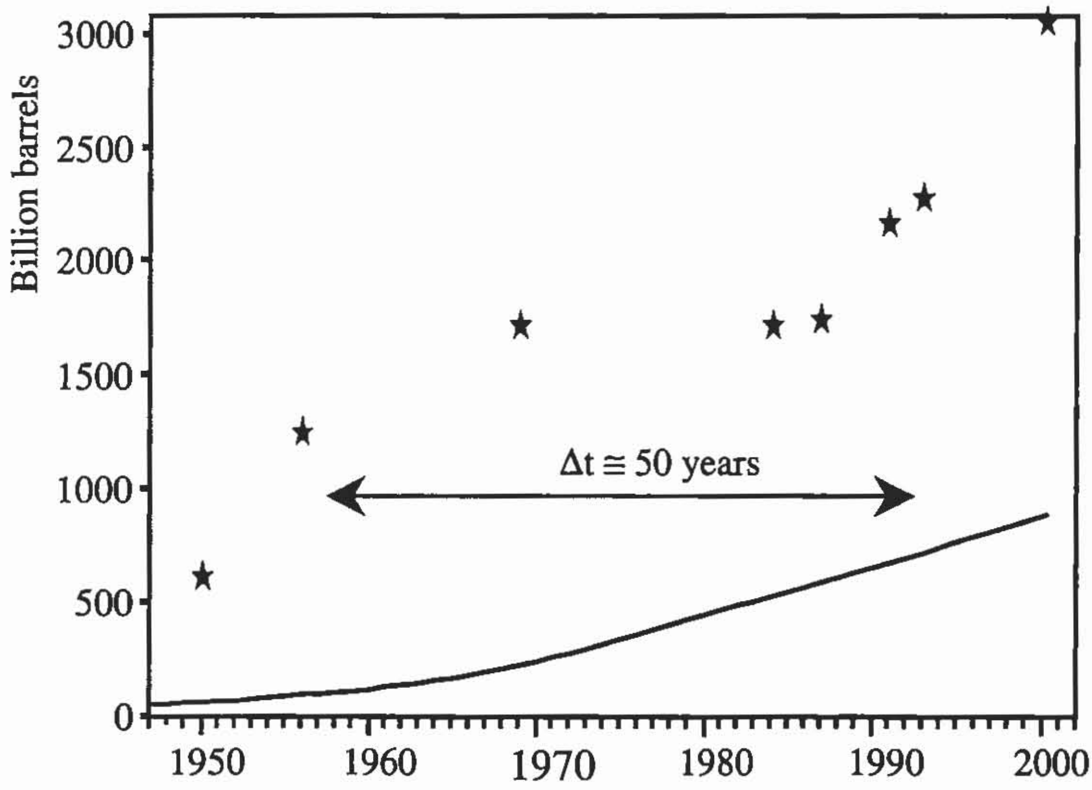

Figure 2: Cumulative production of crude oil in the world (curve in lower part of plot) and successive estimates (stars) of the ultimate resource (that is the cumulative production to date plus the estimated remaining resources). Based on McCabe (1998). Note the recent estimate of the U.S. Geological Survey World Energy assessment Team (2000) at upper right.

Because reserve and resource estimates are not a measure of an ultimate amount and the numbers are added to through time, it is futile to divide such numbers by current or projected annual consumption to determine the time at which a fossil fuel will be depleted

Likewise, Hubbert-style predictions are based on the false premise that we now know the ultimate amount of any fossil fuel that will be available for production.

Two conceptual models that relate production to price can be considered (Figure 3). The closed-market model assumes that there is only one source of energy available. Although the price initially may fall because of economies of scale, long-term prices rise as the energy source is depleted and it becomes progressively more expensive to extract. In this model the peak of the production curve comes close to a midpoint in production of the fuel. This is the model that Hubbert and his followers believe. By contrast, the open-market model assumes that there are a variety of available energy sources and that competition among them leads to long-term stable or falling prices. Peak production of a fuel in this model is at a time when cheaper substitute fuels become available. Under this model, the production history is determined by the interaction of supply and demand and is not related to the ultimate amount of fossil fuel left in the ground. Examination of some energy resources with well-documented histories suggests that production of all fuels to date more closely approximate the open-market model (McCabe, 1998). British coal and Pennsylvania anthracite, for example, peaked production when substitutes (oil and natural gas) became available at cheaper prices in various market sectors. Both now are mined at very low levels compared to the peak production despite the fact that there is much more coal left in the ground than has been mined to date.

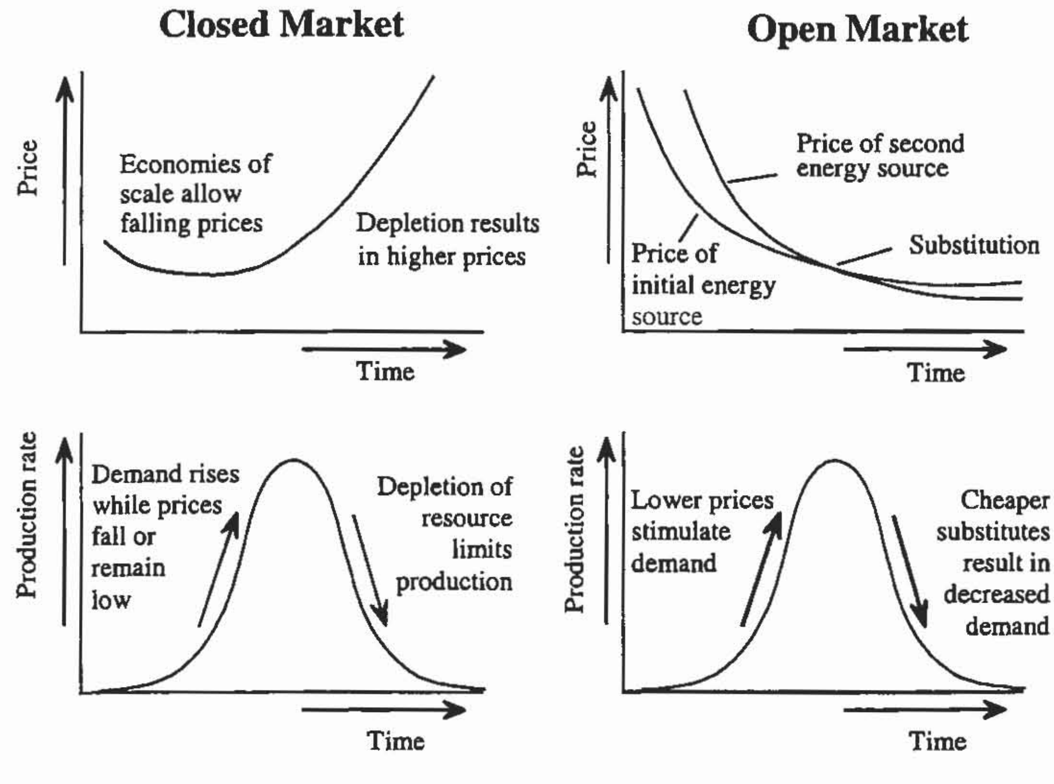

Figure 3: Idealized relationship between price and production of an energy resource in a closed (left) and open (right) market. In a closed market only one fuel is available whereas in an open market two or more fuels are available and substitution of one fuel for another can take place. From McCabe (1998).

The supply side: how much fossil fuel is left?

The U.S. Geological Survey recently released a new World petroleum assessment (U.S. Geological Survey World Energy Assessment Team, 2000). This suggests that there are 2311 billion barrels of remaining producible crude oil left in the ground in contrast to the 710 billion barrels that have been produced to date. The remaining oil consists of 891 billion barrels of remaining reserves, an estimated 688 billion barrels that will be derived from field or reserve growth, and 732 billion barrels that is estimated to be undiscovered. Furthermore, this assessment did not encompass many smaller producing regions, such as the Taranaki Basin of New Zealand, or any unconventional oils such as the oil sands of Alberta.

The same assessment (U.S. Geological Survey World Energy Assessment Team, 2000) also suggests that there is 13,649 trillion cubic feet of remaining natural gas left in the ground in contrast to the 1,752 trillion cubic feet that have been produced to date. Again these figures do not include the vast unconventional resources of natural gas or the accumulations in many of the smaller basins in the world.

The Energy Information Agency (2000) estimates World recoverable coal reserves as 1,087,185 million short tons, which are equivalent to a 200 year-supply at today's production levels. Again this figure assumes current technologies and excludes large amounts of coal that are currently considered uneconomic.

Given the numbers above, it would appear that one would have to be an end-member pessimist to suggest that the World is about to run out of fossil fuels. Even for crude oil the numbers suggest that we are a long way from reaching a midpoint in producing what is available with current technologies. Future technologies will almost certainly make even more fossil fuel available - if we need it. However, the abundant resource base does not necessarily translate to an abundant rate of supply. The development of new resources often requires a large amount of investment in exploration and development and infrastructure to get the fuel to market. It can also take several years or even decades before discovered resources reach the market.

The demand for fossil fuels: how much and what will people want?

The demand for various energy sources is driven by growth and competition in the various market sectors. Within a single market sector substitution of one fuel by another may take place over a decade or less. For example, in many countries the transition from coal to natural gas as the dominant fuel for domestic heating took place in less than 10 years. The substitution occurred when natural gas became cheaper and, incidentally, more convenient for heating homes. Changes in the future energy mix will occur as technological advances change the relative costs of fuels in different market sectors. As in the past, government policies will also influence the energy mix. Future policies may well be implemented because of the perceived environmental and strategic costs of certain fuels.

At the turn of the millennium we are witnessing a convergence of factors that in combination will most likely lead to a revolution in the pattern of the World's energy demand. These factors include: (1) Rapid growth in energy demand in many underdeveloped countries. This is especially true in many Asian countries and in South America. However, that growth in demand is contingent on energy prices energy prices remaining at affordable levels. (2) Increasing environmental concern. There is a demand in many countries, rich and poor, for ways to reduce air pollution. There is also growing concern about the perceived danger of global warming resulting from anthropogenic emission of greenhouse gases. (3) Power industries in many countries are being deregulated and/or denationalized. This is forcing companies to become more cost competitive and it gives them more freedom to choose alternative fuels and technologies that may enhance their profits. There is a trend away from big regional power plants to smaller neighborhood plants. (4) New technologies are being developed that may allow production from many accumulations of natural gas that are currently uneconomic to develop. Costs for liquefied natural gas (LNG) facilities and transportation have fallen and LNG trade between countries has almost doubled in the last 10 years. Gas-to-liquid conversion technology is also widely touted as a way to bring so called "stranded" gas accumulations to market in the future. (5) New technologies are being developed that give much greater fuel efficiencies. Automobiles powered by hybrid technologies, for example, allow cleaner burning and much greater fuel efficiency. The efficiency of combined cycle gas turbines for power generation has increased substantially. Potentially the most important future technology will be fuel cells that could bring about the end of the internal combustion engine in vehicles and may make it economic for small companies, apartment buildings, and even homeowners to generate their own electricity. Fuel cells would also help solve many environmental problems because they are essentially emission-free.

Time will determine which of the above factors will be the more important in determining the future energy mix. Perhaps other technological advances or events will overshadow all of them. It seems likely, however, that the convergence of increased concern about global warming and the new technologies, that may help make natural gas more competitive, could produce a surge in demand for natural gas in the early decades of the new century. In particular, demand for natural gas may benefit from political pressures to reduce coal use in power generation and oil use in the transportation sector. Clean coal technologies and nuclear reactors may eventually offer cheap, clean, and reliable electrical supply but it would appear that changes in public perceptions are needed before substantially more coal and nuclear power plants are built.

Renewable sources of energy offer promise for the long term but at present only 1.4% of the World's power production is from biomass, geothermal, solar and wind sources combined. Hydroelectric capacity may increase somewhat because of more efficient turbines but the interest in building new dams has decreased substantially in the last couple of decades.

Renewable energy is likely to remain only a small fraction of the total energy mix for some time to come and the demand for energy will largely be met by fossil fuels.

CONCLUSIONS

At the moment, the world energy markets approximate the open-market model and there appears little reason to suspect that long-term price trends for fossil fuels will rise significantly over the next few decades. Short periods of relatively high or low prices may exist due to imbalances in either supply or demand. Such periods, however, probably cannot be sustained for more than two or three years because the higher prices would stimulate new exploration and production and lower prices would drive marginal production from the market.

It looks likely that natural gas will take a greater share of the energy mix over the next couple of decades especially in the electrical power sector. Although the demand for energy will likely continue to rise from many underdeveloped countries, that rise may be counterbalanced by increased energy efficiencies. Emergent technologies promise substantial increases in energy efficiency especially in the transport and electrical power generation sectors. Renewable energy will likely play an increasing role in the energy mix but is unlikely to be a major part of the mix until the middle of the century.

Australia seems well positioned in terms of fossil fuels for the foreseeable future. The assessment of the recent US Geological Survey World Energy Assessment Team (2000) suggests that there is about 5 billion barrels of undiscovered oil and 105 trillion cubic feet of natural gas in Australia mainly offshore of the northwest coast. It is likely, therefore, that Australia can continue to produce the majority of its oil needs over the next two decades. Increases in global gas demand may well make the extensive gas accumulations of the Northwest Shelf a more viable resource in the coming decades. As the World's largest coal exporter, Australia has a high stake in how coal will fare within the energy mix. Future levels of concern about global warming, advances in clean coal technology for power generation, and changes in technology for steel making will determine the future demand for coal exports.

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STRATIGRAPHY AND CORRELATION OF THE GRETA COAL MEASURES

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INTRODUCTION

The Greta Coal Measures are the lower of the two main coal-bearing intervals in the Permian northern Sydney Basin. They crop out around Cessnock, Maitland and Muswellbrook in the Hunter Valley and in the adjacent Cranky Corner Basin outlier (Figure 1). Subsurface correlations indicate that the Greta Coal Measures occur throughout the Hunter Valley between Muswellbrook and Newcastle, and thin southward from the Hunter Thrust towards the centre of the Sydney Basin (Basden, 1969). The Greta Coal Measures had great economic significance in the first half of the twentieth century when intensive underground mining occurred on the eastern limb of the Lochinvar Anticline in the Maitland to Cessnock area. Today only one operating mine remains. In the latter part of the twentieth century mining focus shifted to the Muswellbrook Anticline, where three large open cut mines continue to operate. In the Muswellbrook area, the Greta Coal Measures crop out along the crest of the Muswellbrook Anticline (Beckett, 1988). In this region a high quality geological database exists from high wall exposures in the mines and continuously cored boreholes from earlier exploration. As part of a larger study of the application of sequence stratigraphic methods to understanding deposition of terrestrial and coaly rocks, we investigated the Greta Coal Measures in the Muswellbrook area. These strata had not previously been subjected to a sequence stratigraphic analysis and our preliminary investigations suggested the presence of a high accommodation setting. Application of sequence stratigraphy to terrestrial sedimentation is reviewed in Boyd *et al.*, (this volume).

Results from the Greta Coal Measures provide data on a high accommodation end member in a spectrum of accommodation settings being investigated by the non-marine stratigraphy group at the University of Newcastle. Other comparative studies into high accommodation examples such as the Newcastle Coal Measures, and low accommodation examples in the Western Canada Sedimentary Basin, are ongoing and will be published elsewhere (e.g., Chalmers and Boyd, this volume, Diessel *et al.*, this volume). Additional significance of this study derives from the likely future decline of mining in the Muswellbrook area and hence a loss of important data, together with the possibility of the Greta Coal Measures being a petroleum exploration target in the zone adjacent to the Hunter-Mooki Thrust.

Our approach to the Greta Coal Measures in the Muswellbrook area was to measure in detail six fully cored boreholes from the Savoy (south) and Skeletar (north) regions (see

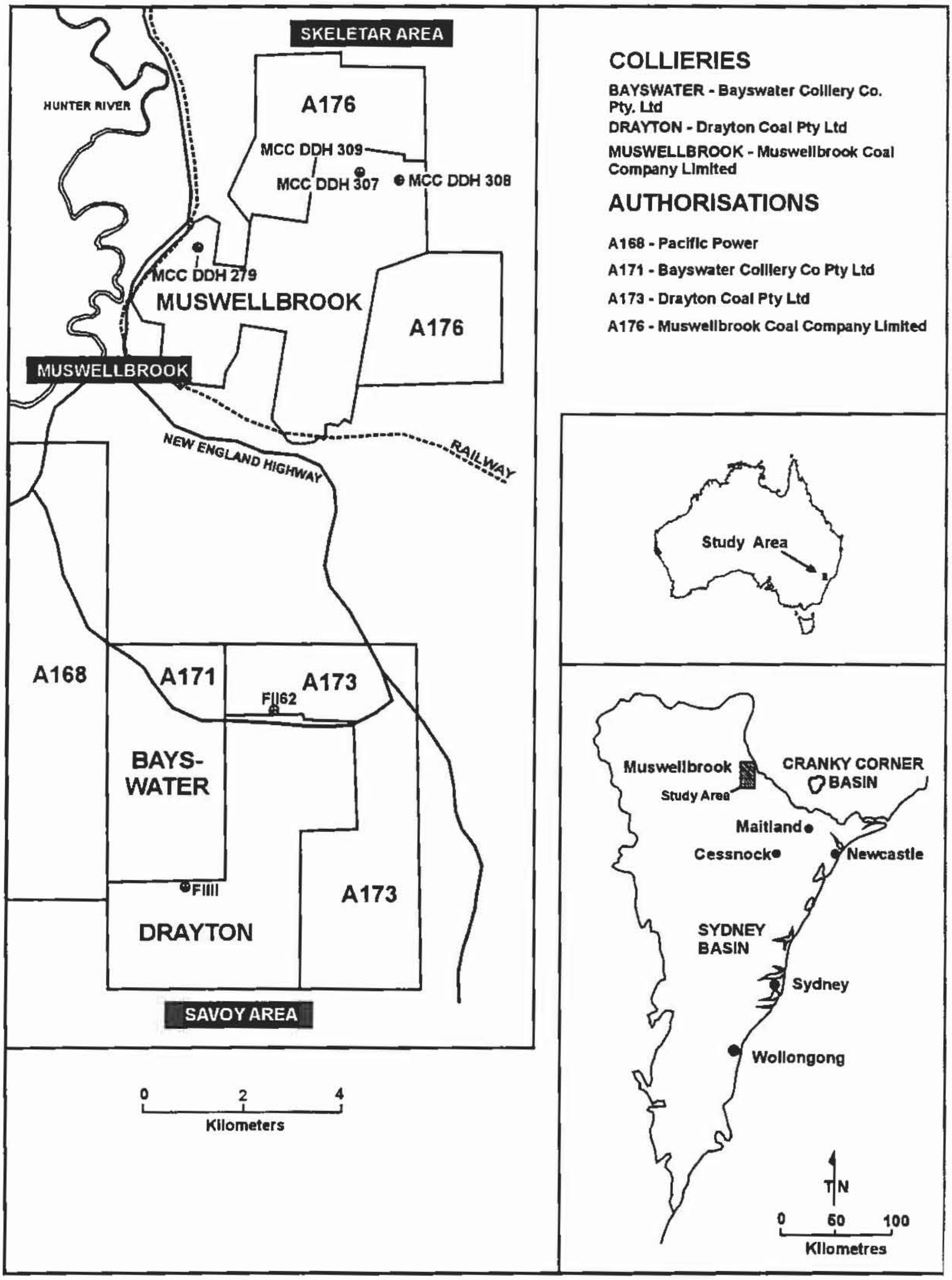

Figure 1. Greta Coal Measures in the Hunter Valley of the northern Sydney Basin, study location of the Muswellbrook anticline area, location of the collieries where highwall outcrops were described, and location of the boreholes described in the text.

Figure 1) and apply a sequence stratigraphic approach to the interpretation of their facies, sedimentation history and stratigraphy. We supplemented core examination with site investigations of the highwall geology in three mines (Muswellbrook Coal Company, Bayswater Colliery Company, and Drayton Coal Pty. Ltd), and a limited correlation of geophysical logs in the common highwall area at Bayswater and Drayton. Investigations were conducted on Drayton cores at the Drayton core shed on site, and Muswellbrook Coal Company (MCC) cores at an adjacent property. No cores were available from the Bayswater Colliery. Detailed core descriptions and interpretations are provided in Boyd and Leckie (2000).

REGIONAL SETTING AND PREVIOUS WORK

Early stratigraphic assessments of the Muswellbrook Anticline (see Figure 2) identified a "Lower Marine" equivalent unit below the Greta Coal Measures, containing amygdaloidal basalts and felsites, rhyolite and rhyolite breccia and termed the Gyarran Volcanics (e.g., Raggatt, 1938). The overlying Greta Coal Measures were divided into a lower "Skeletar Stage" of rhyolites, rhyolite breccias and interbedded white shales containing *Glossopteris* and *Gangamopteris* leaves, and an upper "Muswellbrook Stage" of coal, interseam clastics and volcanics. Current usage follows that of the Standing Committee on Coalfield Geology of New South Wales (SCCG, 1994), which recognised a restricted Skeletar Formation

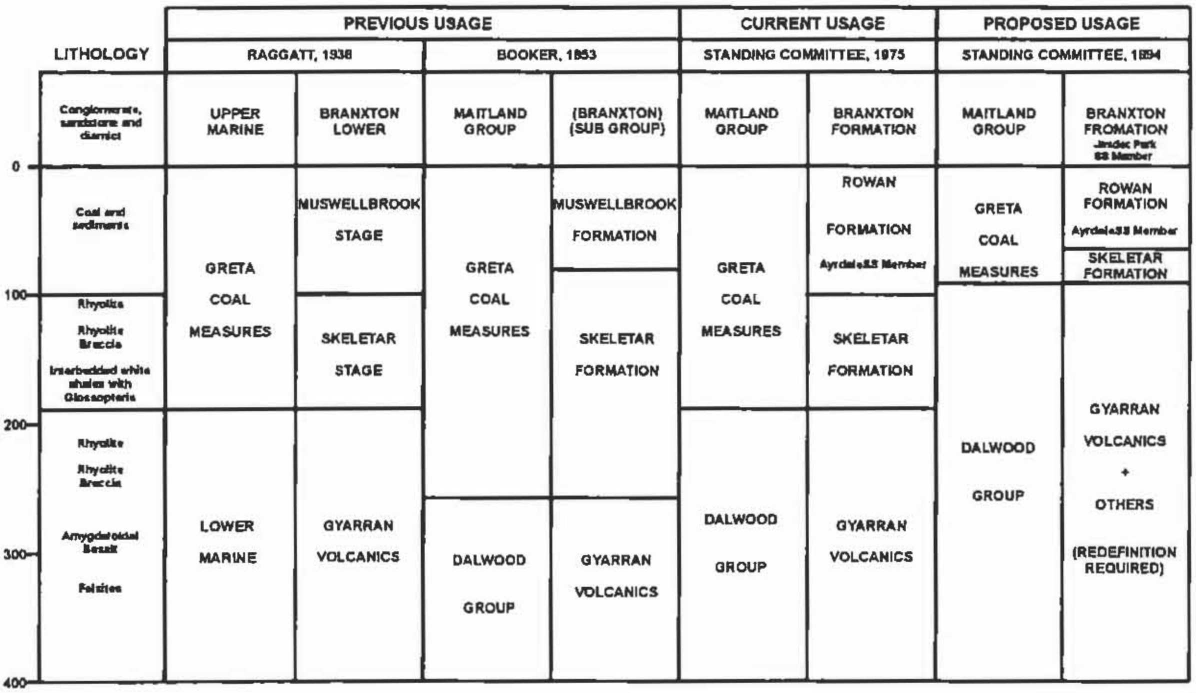

Figure 2. Stratigraphic usage in the Greta Coal Measures (after SCCG, 1994).

consisting of colluvial/alluvial mudstones, sandstones and conglomerates containing pelleted kaolinitic clasts and intercalated, generally dull coal seams. The overlying Rowan Formation contains the remainder of the Greta Coal Measures, consisting of brighter coal seams, igneous intrusives, fine-grained interseam sediments and a number of coarser clastic sand bodies including the Ayrdale Sandstone Member. The underlying Dalwood Group contains the Gyarran Volcanics, consisting of dark grey marine siltstones in the NE and coarse immature volcanolithic clastics in the SW. Overlying the Greta Coal Measures is the Branxton Formation of the Maitland Group containing the laterally persistent Jasdec Park Sandstone Member (SCCG, 1994). The Jasdec Park Sandstone Member is overlain by the paraconglomerates or diamictites that make up the remainder of the marine Branxton Formation. The SCCG (1994) was unable to recommend a precise correlation between individual coal seams in the Savoy and Skeletar areas but proposed a subdivision of 6-7 informal seams and a reference section for each area (see Figure 3).

The Rowan Formation represents a fluvial interval of deposition according to Tobin (1980) and Diessel (1992). Hamilton (1986) considered it to have been deposited in an upper to lower delta plain, with the Ayrdale Sandstone Member as a distributary sand body flanked by interdistributary bays. Tobin (1980) suggested that the Ayrdale Sandstone Member, which occurs only in the Savoy area, had marine features including bioturbation, and interpreted it as having formed in an estuarine setting. Both Tobin (1980) and Hamilton (1986) also interpreted clastic sand bodies in the Savoy area, such as the Brougham sandstone (informal unit) of the upper Rowan Formation, as fluvial in origin.

Age of the Greta Coal Measures on the Muswellbrook Anticline.

The Greta Coal Measures are Lower Permian sediments of Artinskian-Kungurian age. Underlying the Greta Coal Measures and the Dalwood Group in the Muswellbrook area are the Gyarran Volcanics (Figures 2, 3), which contain a *Glossopteris* and *Gangamopteris* flora indicating they are of Permian age. The Dalwood Group contains acritarchs and an Early Permian Stage 3a (Sakmarian) palynoflora (McMinn, 1981) at a position 30m below the base of the Greta Coal Measures in Muswellbrook Coal Company DDH 309. The basal Greta Coal Measures on the Muswellbrook Anticline are of palynofloral Stage L4 age (see Figure 3). Previous work (e.g. McMinn, 1980; Roberts *et al.,* 1996) identified the Greta Coal Measures as diachronous, with the top substantially younger in the Muswellbrook Anticline area than in the type section on the Lochinvar Anticline in the lower Hunter Valley. The Greta Coal Measures near Muswellbrook contain *Praecolpatites (*al. *Marsupipollenites) sinuosus* in the "Muswellbrook coal" (=St Heliers coal? - Balme and Hennelly, 1956). As *P. sinuosis* defines the base of the Upper Stage 4a (U4a) palynofloral zone, the Greta Coal Measures can be divided into an older unit of Lower Stage 4 (L4) age that extends from the Skeletar Formation up to the St Heliers seam of the Rowan Formation, and a younger unit of U4a age that contains the remainder of the Rowan Formation, from the Muswellbrook seam up to the boundary with the Branxton Formation. Roberts et al. (1996) report a SHRIMP zircon date (Z1842) from a tuff in the Rowan Formation between the Fleming and Hilltop seams with an age of 268.9+/-2.0 Ma. The overlying Branxton Formation contains *Eurydesma* 24m above the "Greta" (= St Heliers?) seam, indicating a position in the uppermost *Echinalosia maxwelli* brachiopod zone (Roberts *et al.,* 1996), and palynofloras spanning the U4a and lower Stage 5 (L5a) zones. The Branxton Formation first contains diagnostic L5 palynofloras at a level 200m above its base in DM Brougham 1 (McMinn, 1980).

Problems of age interpretation for the Greta Coal Measures result from the finding by McMinn (1980) of *Praecolpatites (*al. *Marsupipollenites) sinuosus* 28m below the top of the Rowan Formation in DM Brougham 1. J. Rogis (pers. comm., 1998) has found that this interval corresponds to the intersection of the Aberdeen Thrust with the borehole. A separate "East Greta" block has been thrust over the "West Greta" block, probably using the base of the Greta Coal Measures as a glide plane. Although confirming that some of the Greta Coal Measures are of Upper Stage 4a age, McMinn's (1980) correlation introduces a measure of uncertainty into the exact positioning of the Stage L4/U4a boundary resulting from the potential for contamination along the fault plane. In addition, detailed correlations of the Greta Coal Measures across the Aberdeen Thrust have not been reported, leaving open the exact affinities of the material above the thrust in DM Brougham 1. A second problem exists at the base of the Greta Coal Measures where palynofloral Stage 3b was not encountered in boreholes such as MCC DDH 309. Either palynofloral Stage 3b is located within an unsampled 30m of core at the top of the Dalwood Group or there is a significant hiatus between the Dalwood Group and the Greta Coal Measures (as suggested by Roberts *et al.,* 1996).

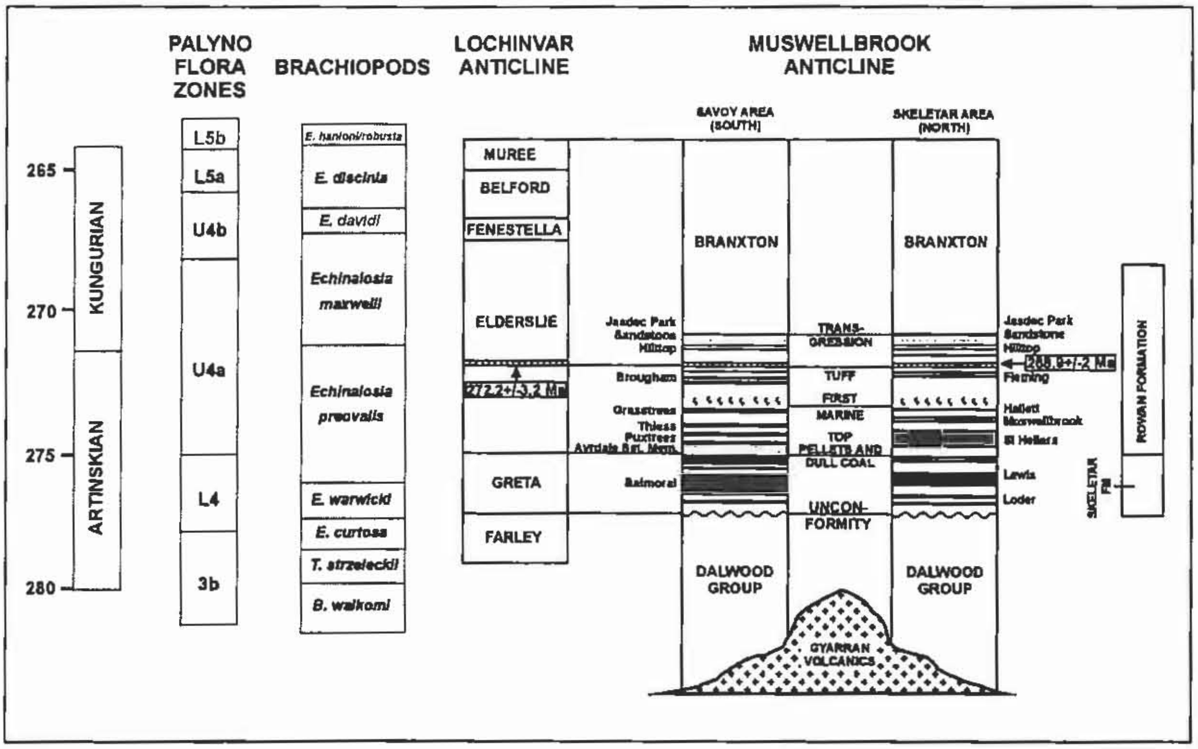

Figure 3. Stratigraphic relations of lower Permian strata from the Hunter Valley (partly derived from Roberts et al. 1996 and SCCG, 1994) showing correlations from the lower Hunter Valley (Lochinvar Anticline in the Maitland-Cessnock area) to the southern (Savoy) and northern (Skeletar) sides of the Muswellbrook Anticline.

Correlation of the Greta Coal Measures from the Muswellbrook Anticline to the Lochinvar Anticline and the Cranky Corner Basin

Beneath the Greta Coal Measures in the Lochinvar Anticline lie the Rutherford and Farley Formations of the Dalwood Group; beneath the same unit in the Cranky Corner Basin lie the Cranky Corner Sandstone and the Billy Brook Formation. The Farley Formation contains the *E. Warwicki* Zone (equivalent to the lower palynofloral L4 Stage) while the Billy Brook Formation contains the 3b palynofloral Zone (Roberts *et al.*, 1996, unpublished data). The Homeville (lower) and Greta (upper) seams of the Greta Coal Measures in the Lochinvar Anticline lie in the L4 Stage (Balme and Hennelly, 1956), as does the lowest part of the Greta Coal Measures in the Cranky Corner Basin (Roberts *et al.*, unpublished data). This suggests a conformable transition from the Dalwood Group to the Greta Coal Measures in these two areas, and reinforces the possibility of a thin or missing Stage 3a equivalent in the Dalwood Group of the Muswellbrook Anticline. The lower parts of the Greta Coal Measures in all three areas are time equivalent and of Stage L4 age. However, van Heeswijck (1999), assessed the stratigraphy of the Greta Coal Measures in the Cranky Corner Basin and described the presence of an additional lower sequence (the Mirannie Sequence). In this interpretation, although of Stage L4 age, the progradation of the Mirannie Sequence of the Greta Coal Measures began in the proximal Cranky Corner area in the north and continued southward, depositing the next (Gillieston) sequence before becoming transgressed by the overlying Branxton Formation. The Greta Coal Measures contain a much thicker succession in the Cranky Corner Basin, and the lower Mirannie units are of markedly different conglomerate clast lithology and geophysical log response to the overlying Gillieston units.

The Branxton Formation overlies the Greta Coal Measures in the Lochinvar Anticline; it contains the *E. preovalis* and *E. maxwelli* Zones, and upper Stage 4a palynofloras (Roberts *et al.*, 1996). A SHRIMP zircon date from a tuff 12 m above the Greta seam and in the lowermost Branxton Formation on the Lochinvar Anticline returned an age of 272+/-3.2 Ma (Roberts *et al.*, 1996). This date and the palynofloral correlations have been taken to indicate a diachronous relationship between the top of the Greta Coal Measures in the Lochinvar and Muswellbrook Anticline areas. Our interpretation is consistent with this view. However, based on an assessment of the stratigraphy of the two regions and information on the sources of the two tuff samples (J. Rogis and D. Stevenson pers. comm., 1998), it seems likely that these dates are from the same tuff. This is because the error ranges (272+/-3.2 Ma and 268.9+/-2.0 Ma) of the dates overlap, and because this stratigraphic interval is otherwise relatively free from evidence of vulcanism. These are the only tuffs to occur in the two anticline regions, hence they are likely to be from the same eruptive event.

These data therefore indicate the Greta Coal Measures in the Lochinvar Anticline around Cessnock and Maitland are equivalent to the lower part of the Greta Coal Measures in the Muswellbrook area. The most likely correlation is between the Homeville, Greta and Paxton seams on the one hand and the Loder, Lewis and Balmoral seams on the other (Figure 3). This correlation is strengthened by the presence of sandstones containing pelletal claystone clasts in the Skeletar Formation and at one level in the Greta seam (Oatmeal Band, Stevenson, 1991). The transgression that terminated the Greta Coal Measures in the lower Hunter may thus be equivalent to the transgression that produced the estuarine Ayrdale Sandstone Member in the southern Savoy area of the Muswellbrook Anticline. The St Heliers and Puxtrees to Hilltop seam interval of the Muswellbrook Anticline is equivalent to the lowermost Branxton Formation in the lower Hunter Valley. The Branxton Formation at Muswellbrook is around 240m thick (Tobin, 1980), which is less than 20% of the thickness at the lower Hunter type locality (1300m; Beckett, 1988). This indicates either much slower sedimentation rates or a missing section in the Muswellbrook Anticline area, consistent with the biostratigraphic and chronostratigraphic correlations. Due to a lack of equivalent data, the upper Greta Coal Measures of the Cranky Corner Basin cannot yet be correlated with the units on either the Muswellbrook or Lochinvar Anticlines. However, the overall succession indicates an initiation of terrestrial sedimentation in the northern, Cranky Corner Basin area, and a gradual southward progradation towards the Lochinvar Anticline. The Muswellbrook area had extensive local relief in early Greta time and the marine regression appears to have progressed from a southern volcanic highland towards the north. Following sedimentation in the Muswellbrook area, relief diminished by Ayrdale Sandstone time and the ocean and estuarine valleys opened up toward the south. The final transgression that terminated Greta Coal Measure deposition originated in the south, first submerging the Lochinvar Anticline area, and then the Muswellbrook area and presumably also the Cranky Corner Basin.

RESULTS AND DISCUSSION

Revision of stratigraphic correlations in the Muswellbrook Anticline area

The 1994 revision of stratigraphy by the Greta Working Party of the Standing Committee on Coalfield Geology (now Coalfield Geology Council of New South Wales) provided a sound basis for stratigraphic nomenclature in the Muswellbrook Anticline area. Our investigations allow for minor modifications to the Standing Committee's revision. It was not clear in the 1994 revision whether the relationship between the Dalwood Group and the Greta Coal Measures is a conformable one. Evidence from MCC DDH 309 suggests that some section is missing at this level, and that the contact is erosional. Underlying units are marine, glacially-influenced and characterised by coarsening upward grainsize trends. Overlying units are terrestrial, fining-upward, and characterised by kaolinite pellets that are missing below. The age relationships suggest that there is one palynofloral zone either missing or thinly developed. This evidence suggests that there is a hiatus between the Dalwood Group and the Greta Coal Measures.

The 1994 stratigraphic revision suggested that the boundary between the Skeletar Formation and the Rowan Formation be "the top of the dull coal section of the seam directly overlying the topmost pelletal claystone sequence". However, we have observed kaolinite pellets right up to the seam splits below the Ayrdale Sandstone unit, and hence the boundary should be placed at this level.

In the Rowan Formation there is a good case for correlation of a bentonite 5-10 m above the Fleming and Brougham seams in the Skeletar and Savoy areas. This interpretation is strengthened by correlation of the first appearance of bioturbation and a change in sedimentation style at the Hallett-Grasstrees seam level. The tentative Rowan Formation correlations identified in the Greta Working Party 1994 document are thus supported by the present study.

Our investigation of the transition from Rowan Formation to Branxton Formation suggests that it is more complex than that defined by the SCCG (1994). The basal Jasdec sandstone unit has an erosional boundary and a dramatic change of sedimentation style from the underlying Rowan Formation. However it is not a marine unit, but a braided fluvial deposit. As such, it is distinct from the overlying transgressive lag and shoreface to shelf transition of the other two Jasdec Park Sandstone units. Although retaining the Jasdec Park Sandstone Member as a distinct lithological unit seems feasible, it should be recognised that the Member is complex and consists of three subunits with different depositional settings. The base is interpreted as an unconformity while the upper boundary is gradational.

Sequence Stratigraphic Interpretation of the Lower Permian in the Muswellbrook Area

Based on analysis of core and outcrop of the Gyarran Volcanics to Branxton Formation interval in the Muswellbrook area, at least four sequences and three sequence boundaries are thought to be present (Figure 4). The lowermost sequence boundary (SB1) developed on the Gyarran Volcanics as a long-lived weathering surface on the exposed volcanics, resulting in transformation of the volcanics to a kaolin-dominated soil profile. Paleogeographic reconstructions of the Sydney Basin at this time (e.g. Eyles *et al.,* 1998) indicate that the soil formation occurred in a polar climate. An extensive hiatus is indicated in order to form the soil profile, and this boundary between the Gyarran Volcanics and the overlying units of the Dalwood Group is interpreted as the basal sequence boundary in the Lower Permian. Despite the likely occurrence of an extensive hiatus, it is paradoxical that kaolinite soil development, which requires a high degree of leaching, is interpreted to have developed in a polar climate.

The next sequence boundary (SB2) occurs between the upper Dalwood Group and the Skeletar Formation. This interpretation is based on regional evidence for an erosional contact at the boundary, a distinct change in sediment composition and provenance across

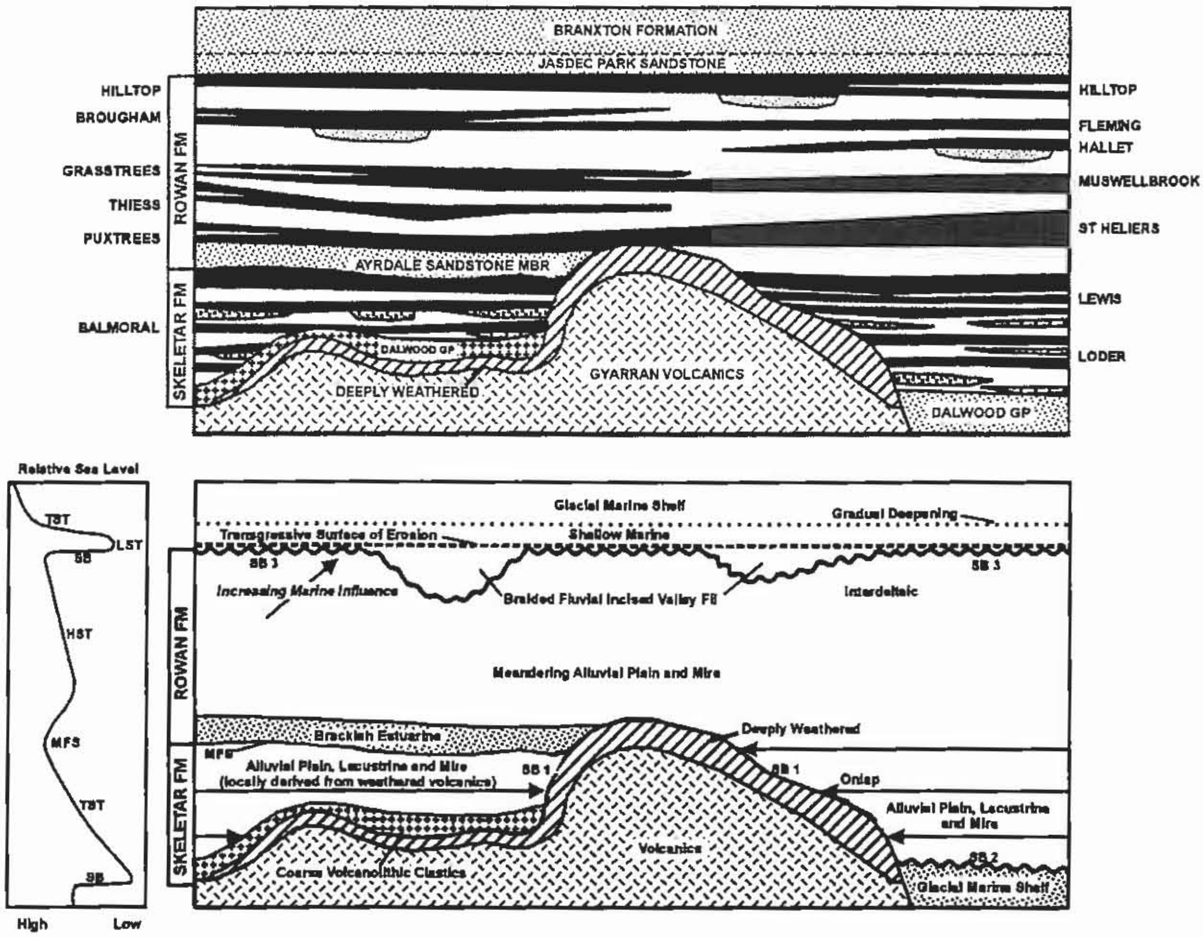

Figure 4. a) Upper shows a regional cross section of the lithostratigraphy of the Gyarran Volcanics to Branxton Formation interval in the Muswellbrook area. b) Lower shows the sequence stratigraphic and depositional environment interpretation for the same interval. SB = sequence boundary, MFS = maximum flooding surface, TST = transgressive systems tract, HST = highstand systems tract and LST = lowstand systems tract. Note the influence of the Gyarran Volcanics paleotopographic high up to the deposition of the Ayrdale Sandstone.

the boundary (particularly the appearance of pelletoidal beds), and a basinward shift in facies from coarsening upward marine parasequences to alluvial channel and flood plain facies. The marine parasequences of the upper Dalwood Group are progradational and contain increasing upward evidence of bedding and plant remains. This suggests that they occupy a highstand systems tract under a rising relative sea level.

The overlying Skeletar and Rowan Formation sediments do not contain obvious sequence boundaries. Rather, this interval represents continuous sedimentation in which sediment supply and subsidence were roughly balanced and underwent only minor fluctuations. The main fluctuation is the marine transgression that resulted in deposition of the Ayrdale Sandstone Member (see Figure 4). The penetration of marine to brackish water is indicated by the presence of a relatively coarse clastic unit with different provenance, bidirectional paleocurrents, tidal bedding and extensive bioturbation occurring in a valley-shaped geometry. This suggests an estuarine setting and the presence of a maximum flooding surface (MFS) at this stratigraphic level (c.f., Shanley and McCabe, 1991). The non-marine sediments (including coal) of the Skeletar Formation do not fit easily into any sequence stratigraphic model, but the upward increase in accommodation with thicker coal seams, such as the Lewis seam, suggest that it is best fitted into a transgressive systems tract. Hence no lowstand systems tract was observed in the Skeletar Formation.

The alluvial to paralic sediments of the Rowan Formation fit a highstand systems tract above the maximum flooding associated with the Ayrdale Sandstone Member. The single sequence that contains the majority of the Greta Coal Measures is relatively thick (up to 110m for the Rowan Formation and up to 33m for the Skeletar Formation), and includes at least 14 recognisable coal seams plus many additional splits. Coal composition is relatively constant, both within seams and from one seam to the next, in both the Skeletar Formation and the Rowan Formation, although a gradual change does take place between the two formations. Low energy fluvial sedimentation predominated throughout the Greta Coal Measures with average fluvial channel depths of around 3-4m. These characteristics place the Greta Coal Measures in a high accommodation setting throughout, with a sediment supply that varied but roughly balanced the rate of accommodation generation.

The next overlying sequence boundary (SB3 - Figure 4) is at the boundary between the Rowan Formation and the Jasdec Park Sandstone Member. This is also a regional surface, seen in both the Savoy and Skeletar areas, and has extensive relief probably in a valley form. The sequence boundary is overlain by the coarsest grainsize encountered above the Dalwood Group. This coarser unit is interpreted as a lowstand systems tract deposited in a braided fluvial environment and contains a characteristic lithology of extra-basinal volcanic and chert clasts, as contrasted with the muddy intraclasts in the Rowan Formation.

The rest of the Jasdec Park Sandstone Member was deposited in a transgressive systems tract. Jasdec subunit 2 is separated from subunit 1 by a transgressive surface of erosion (TSE or wave ravinement surface), representing the erosional passage of the base of the shoreface. Subunit 2 is the lag deposit sitting on the TSE. Jasdec subunit 3 and the remainder of the lower Branxton Formation represent the continued transgression associated with the transition from shoreface to shelf in the deepening transgressive systems tract.

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THE WOLLOMBI COAL MEASURES – REFUGEES FROM NEWCASTLE

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The Wollombi Coal Measures (WCM) are the uppermost coal bearing sequence within the Hunter Valley Coalfield (HVC) and to date have been considered uneconomic due to their banded nature and poor continuity. They have long been recognized as stratigraphically equivalent to the better known Newcastle Coal Measures (NCM) from east of the Lochinvar Anticline (Figure 1), however this association has not been fully appreciated until recently. The Core Display Day (Beckett et al 1999) held in conjunction with the 1999 Newcastle Symposium exposed many local geologists to the similarities present between these coal measures.

Recent exploration by Powercoal at the western extremity of the Hunter Valley has identified a large resource of both the Great Northern and Fasssifern seams 100km west of their Newcastle home. These seams were recognized at Broke (Stevenson, 1999) approximately 40 km west of the Newcastle Coalfield (NC), however the Fassifern seam is split at this locality. The high resolution correlations which can be seen between the WCM and NCM are highlighted by the numerous pyroclastic units throughout both coal measures (Figure 2). The occurrence of the Awaba Tuff at the roof of the Fassifern seam and the Teralba Conglomerate at the roof of the Great Northern seam have implications for the processes responsible for the deposition of these units in both coalfields.

Correlation of NCM units west of the Lochinvar Anticline and across the HVC has implications for exploration of the WCM and also current ideas on coal formation in the Sydney Basin. By utilizing known NCM relationships when assessing the WCM, it can be deduced that the economic targets are restricted to the upper seams (including the Great Northern and Fassifern seams) and the lower West Borehole seam (WBH) and its equivalents. All but a hand full of bores drilled in the HVC have intersected the upper seams of the WCM, requiring collaring of the hole in Triassic strata. Economic sections of the lower seams have not been located to date indicating development of these seams is poor to the south, in a similar fashion to their restricted development in the northern NC. A low interest in the WCM is understandable if one imagines correlating widely spaced bore holes collared below the Fassifern seam located in the southern Newcastle

Coalfield where the WBH is not well developed. The intervening seams (Pilot to Fern Valley seams) are all banded, high ash, laterally discontinuous and of limited prospectivity.

The identification of the Anvil Hill Exploration Area (north of Denman) as prospective for Powercoal came as a result of long distance correlations of the Fassifern seam across the HVC by the author. The distinctive profile of this seam is easily recognized throughout the NC, west to Broke (though split) and further west again to Denman (Figure 3). The coal plies divided by the numerous tonsteins also show a consistent ash content over both coalfileds, including high ash bands such as the uppermost FAA ply which averages over 55% ash. Such a distribution is inconsistent with a fluvial origin suggesting instead an airborne flux of volcanic ash and wind blown dust. This is consistent with the ash in the coal being very similar in chemistry to the intervening tuffs. Due to the ash source being independent of other features of the peat forming environment any detailed coal profile study should not automatically conclude that an increase in ash is the result of flooding of the peat. Other supportive evidence should be sought to confirm such a proposition, such as reflectance data.

The numerous tonsteins within this seam also present a unique opportunity to study the peat-forming environment in detail over a 100km distance. Each tonstein represents a time line enabling the author to select for analysis three 10-20cm thick coal plies, bounded by the same correlatable tonsteins (Figure 4). It can be concluded that each ply has formed as peat simultaneously over 100km apart. The similarity in maceral abundances (mmf – Figure 5), TPI (Figure 6), and chemistry (B & S – Figure 7) indicate that the environment of peat formation and supply of plant material was almost identical between these sites. This is despite the fact that the two sites were isolated by the Lochinvar Anticline, which was active during sedimentation.

This work also indicates that the tonsteins do not transgress the coal seams even at scales of centimetres over 100 kilometres. Therefore any model of coal formation implying a laterally migrating peat is not valid in this instance. In addition there is no evidence for flooding of the peat adjacent to tonsteins in either the maceral data, chemical data or reflectance (Figure 6). This suggests that these tonsteins preserve the normal peat environment, which the author suggests is predominantly subaqueous. Such a notion is consistent with their lateral continuity (preserved from redistribution by rainfall and runoff) and the lack of tree preservation and vertabraria (Creech 1998). It is also consistent with the high resolution correlations of coal and carbonaceous shale plies between the two coalfields.

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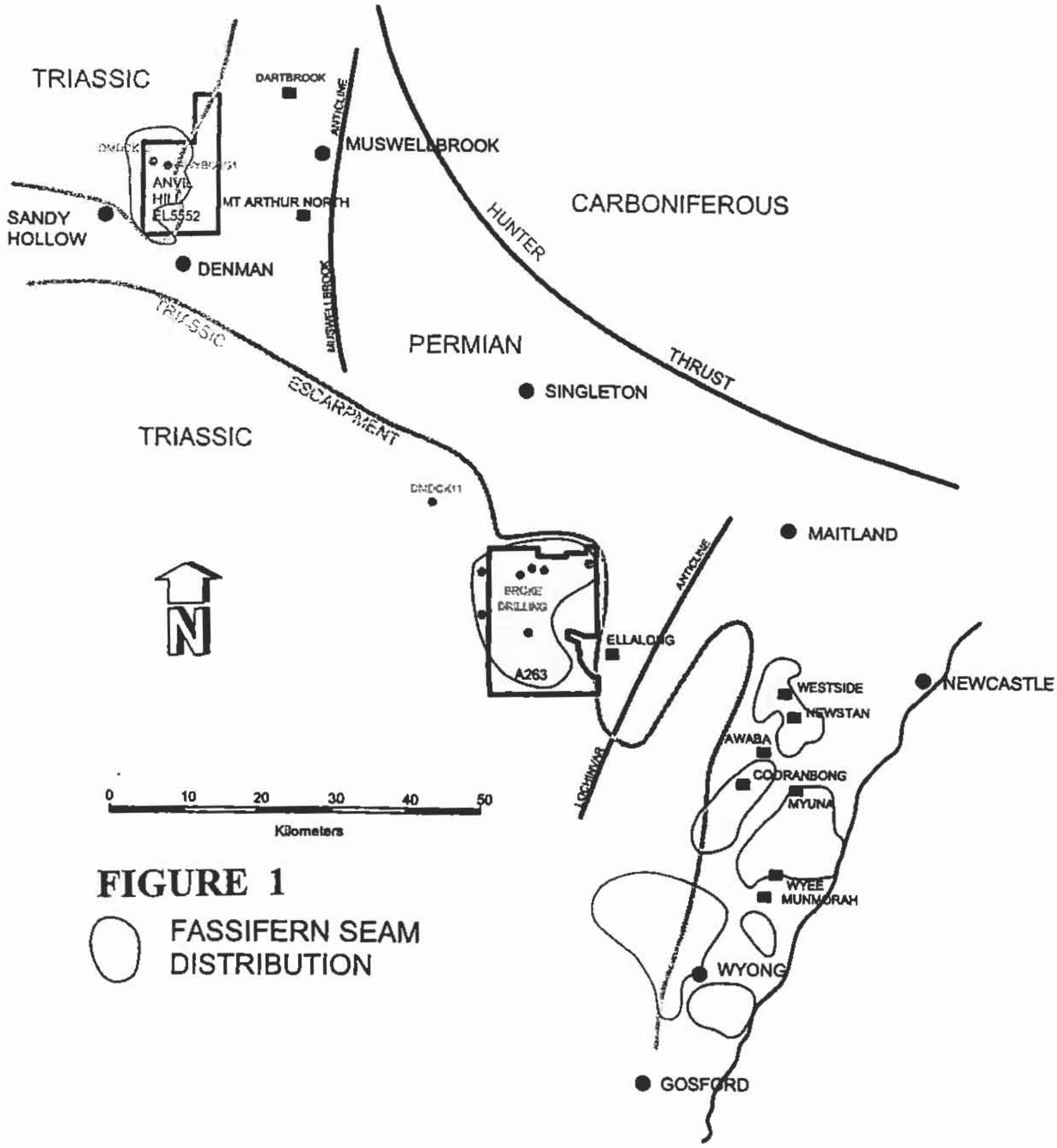
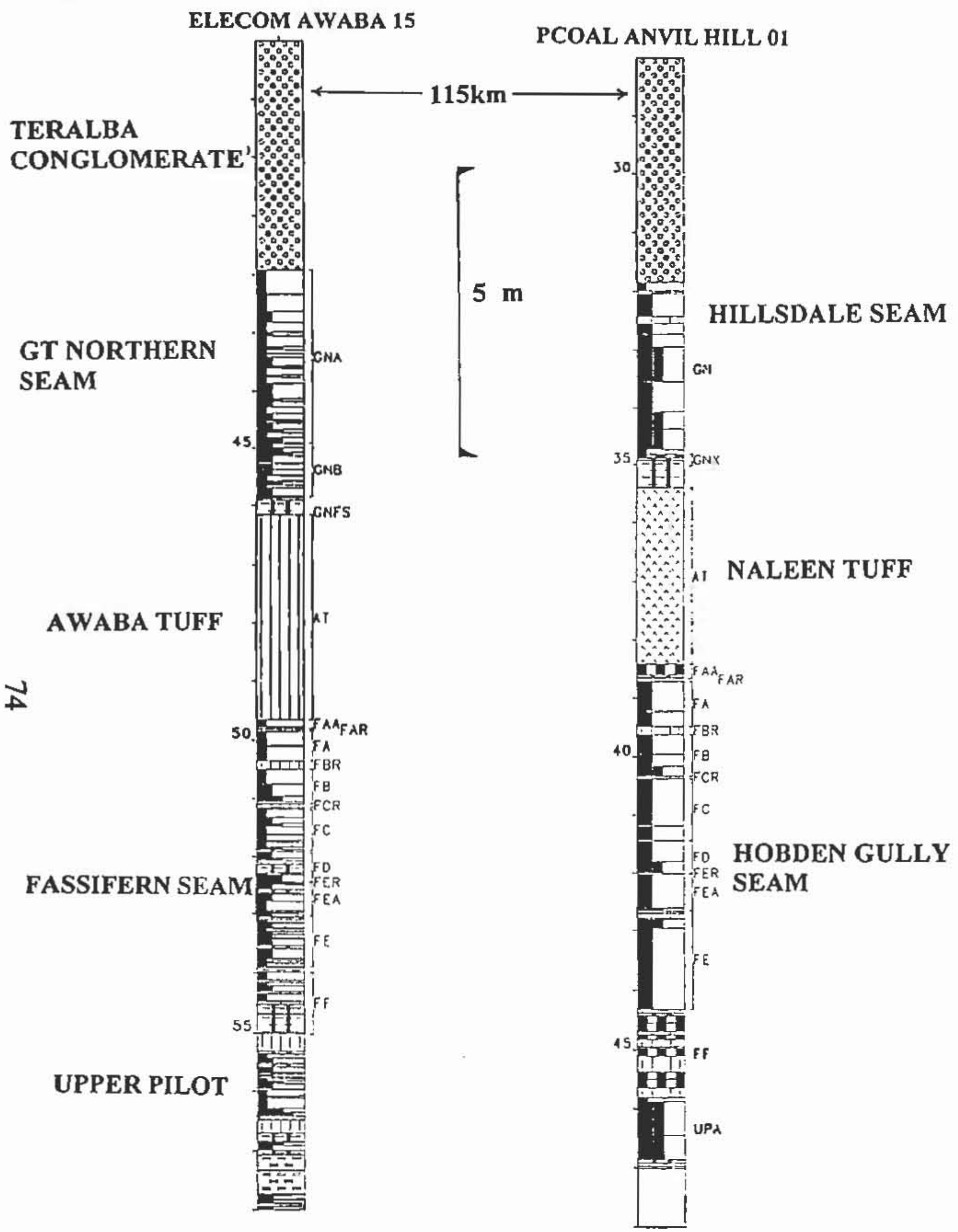
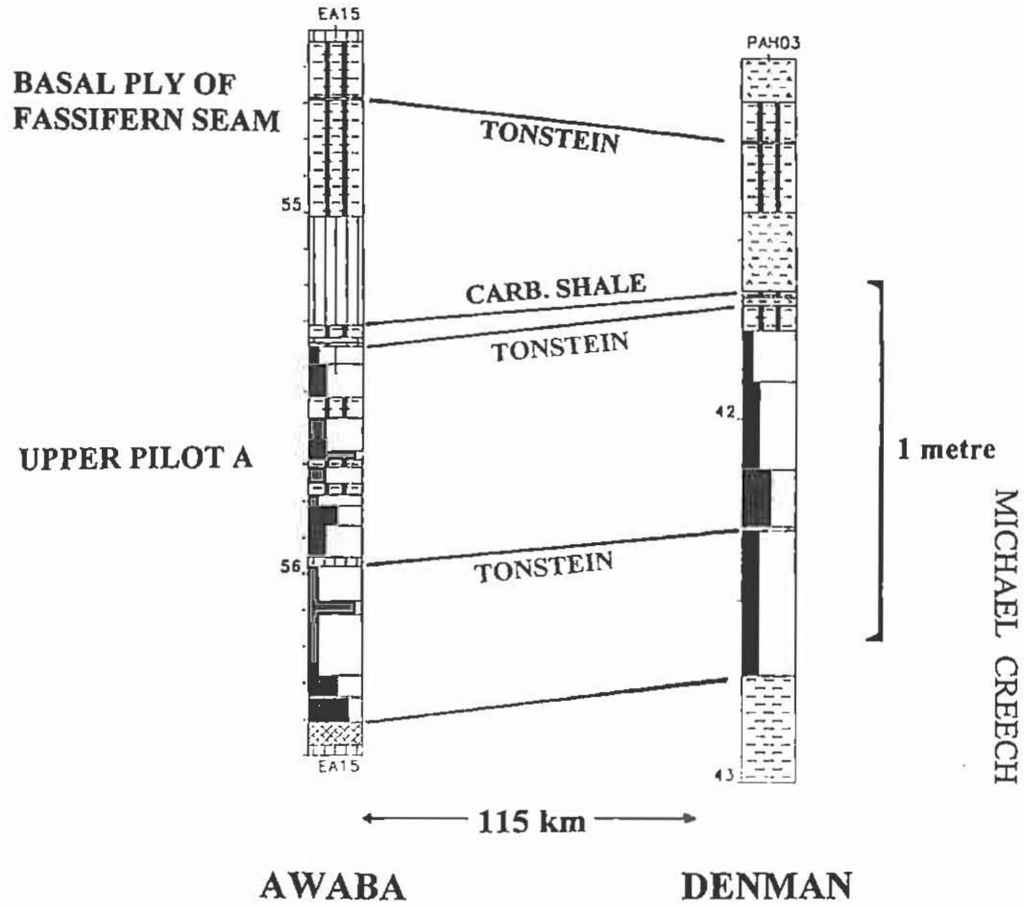


FIGURE 1

FASSIFERN SEAM DISTRIBUTION

FIGURE 2 HIGH RESOLUTION CORRELATION





MICHAEL CREECH

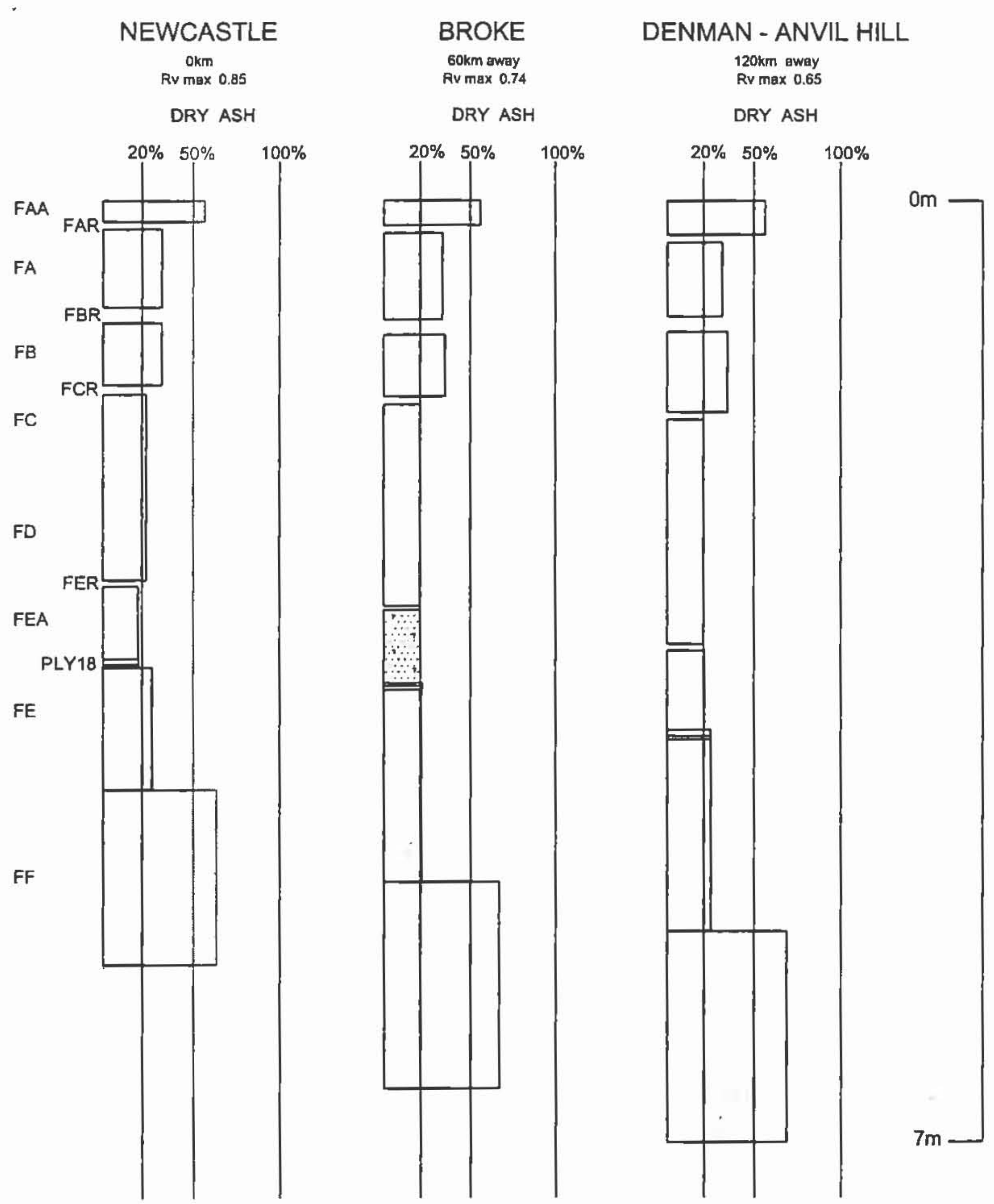
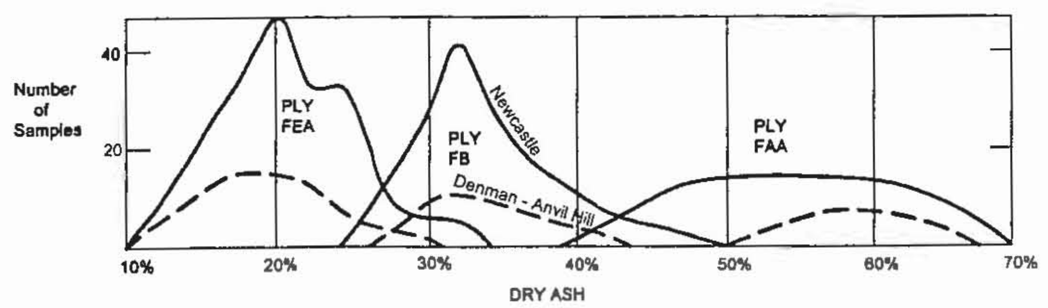


FIGURE 3

THE FASSIFERN SEAM - Vertical Profiles across the width of the Sydney Basin



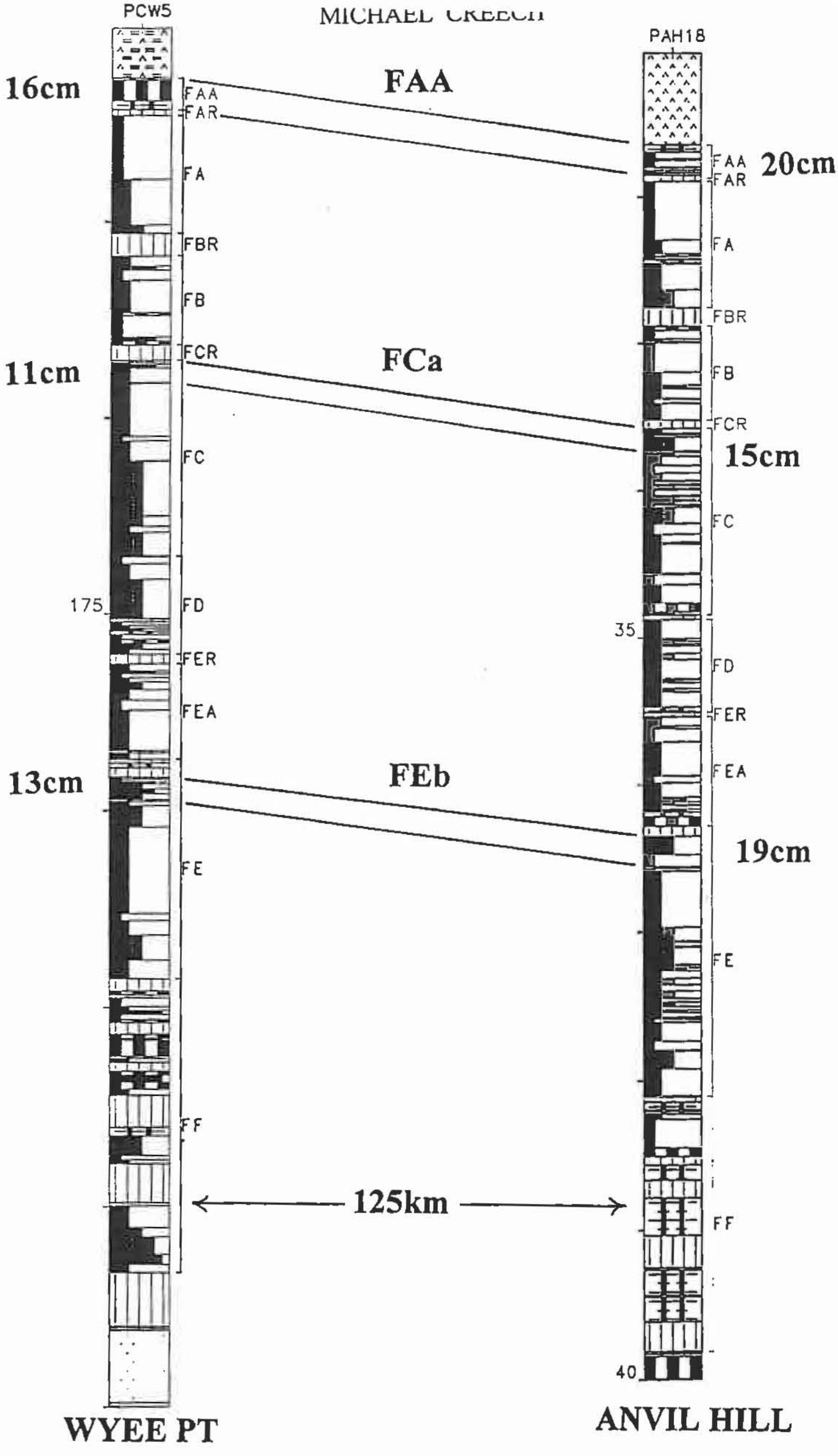


FIGURE 4 FASSIFERN SEAM
PLY SELECTION – MACERAL ANALYSIS

FIGURE 5

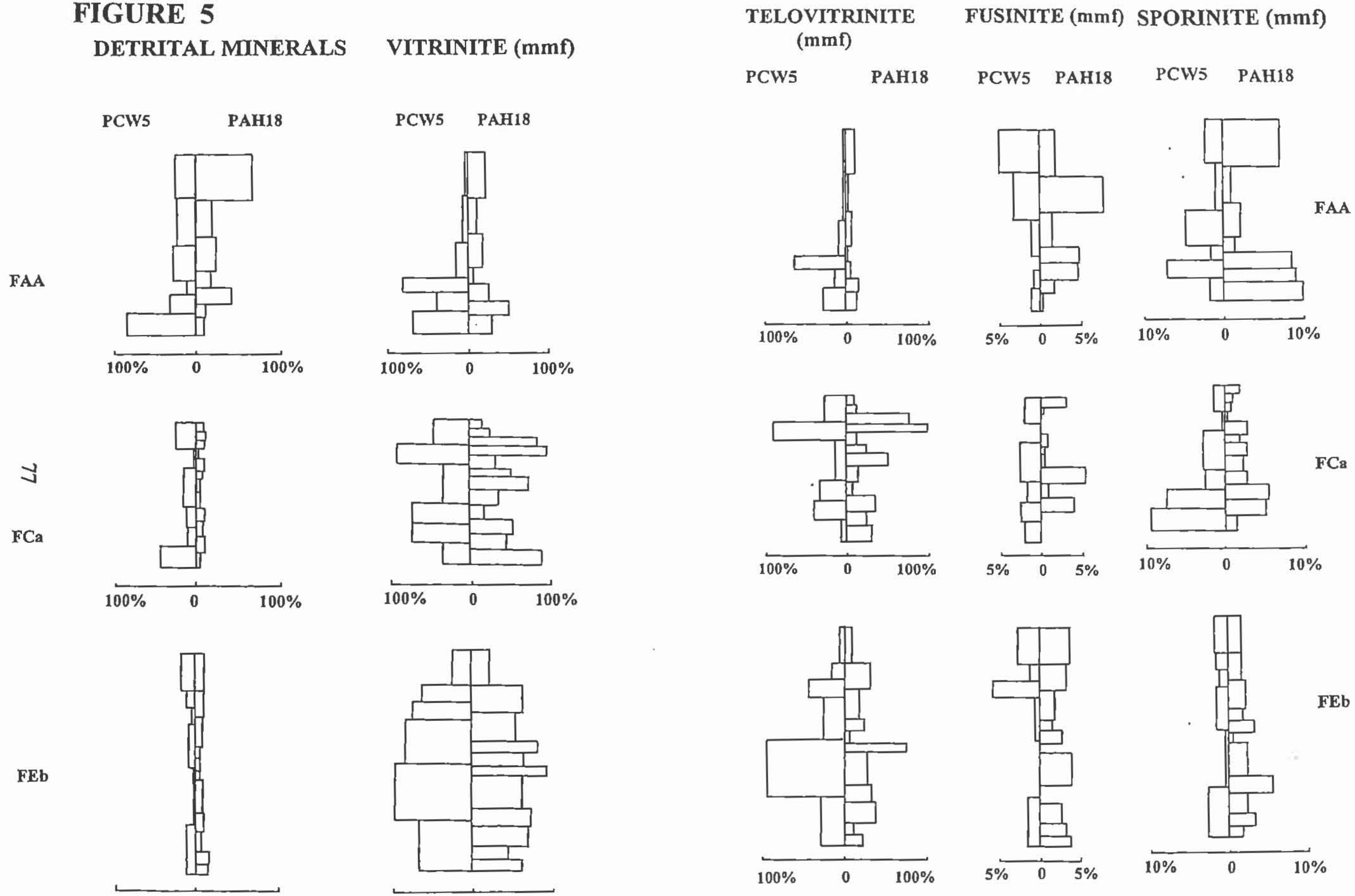
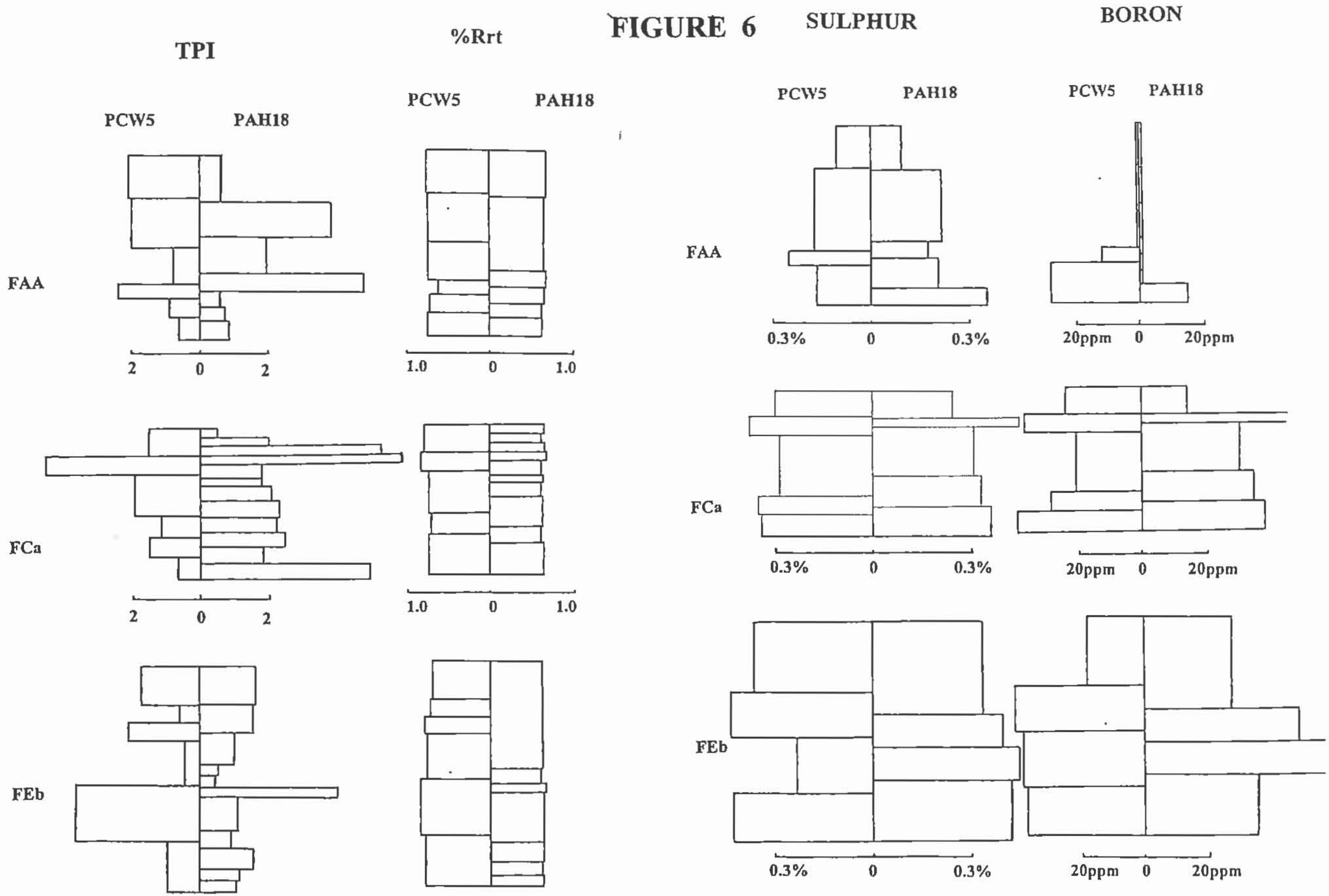

DETRITAL MINERALS
VITRINITE (mmf)
TELOVITRINITE (mmf)
FUSINITE (mmf)
SPORINITE (mmf)
PCW5
PAH18
FAA
FCa
FEb
100%
0
100%
5%
0
5%
10%
0
10%

FIGURE 6


TPI
%Rrt
SULPHUR
BORON
PCW5
PAH18
PCW5
PAH18
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FAA
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FEb
2 0 2
1.0 0 1.0
0.3% 0 0.3%
20ppm 0 20ppm
FAA
FCa
FEb
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COAL AND CONGLOMERATE - LATERAL FACIES OR COEVALLY UNRELATED?

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INTRODUCTION

The study area is located on the Central Coast of NSW, midway between Sydney and Newcastle (Figure 1). It consists of two coal exploration licences held by Coal Operations Australia Limited (COAL); one to the west of Wyong township and another over Tuggerah Lake. Together, they cover approximately 250 sq. kms. Data consists of approximately 85 bores drilled in, or adjacent to, the exploration licences prior to 1990 and approximately 260 bores drilled by COAL since 1996.

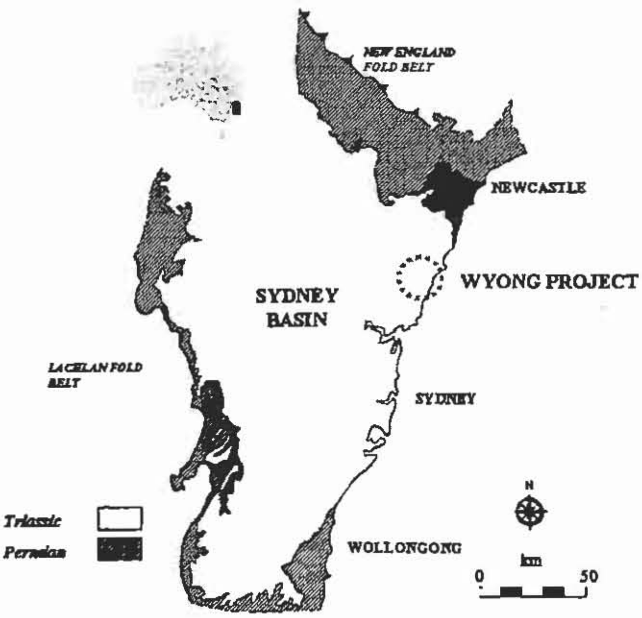


Figure 1. Locality map.

In the Central Coast region of the Sydney Basin the top-most coal in the Late Permian Newcastle Coal Measures is as much as 8m thick (Figure 2). In places, coarse siliciclastic bodies, such as the Karignan and Teralba Conglomerates, divide this coal into separately named seams, namely the Vales Point, Wallarah, and Great Northern Coals (Figure 3). These sediments are the culmination of a 400m-thick regressive interval grading from marine shoreface facies in the Tomago Coal Measures, upwards, into the terrestrial Newcastle Coal Measures.

The Newcastle Coal Measures was deposited in a north-south half-graben, about 50 km wide, situated between the synsedimentary flexural Lochinvar Anticline (Herbert, 1993) and the Offshore Uplift (Bradley, 1993a & b). The western part of this half-graben is preserved on the Central Coast where the coal measures thicken eastwards into the Macquarie Syncline and thin westwards onto the more slowly subsiding flank of the Lochinvar Anticline. Herbert (1995) divided the Newcastle Coal Measures into three, 3rdorder sequences, the latest sequence containing the Great Northern, Wallarah, and Vales Point Coals. Conglomerates within this interval were considered to have been deposited in incised valleys above high-frequency, 4th-order sequence boundaries. These boundaries could also be traced through the adjacent, unsplit coal seams. This concept is supported and discussed further herein.

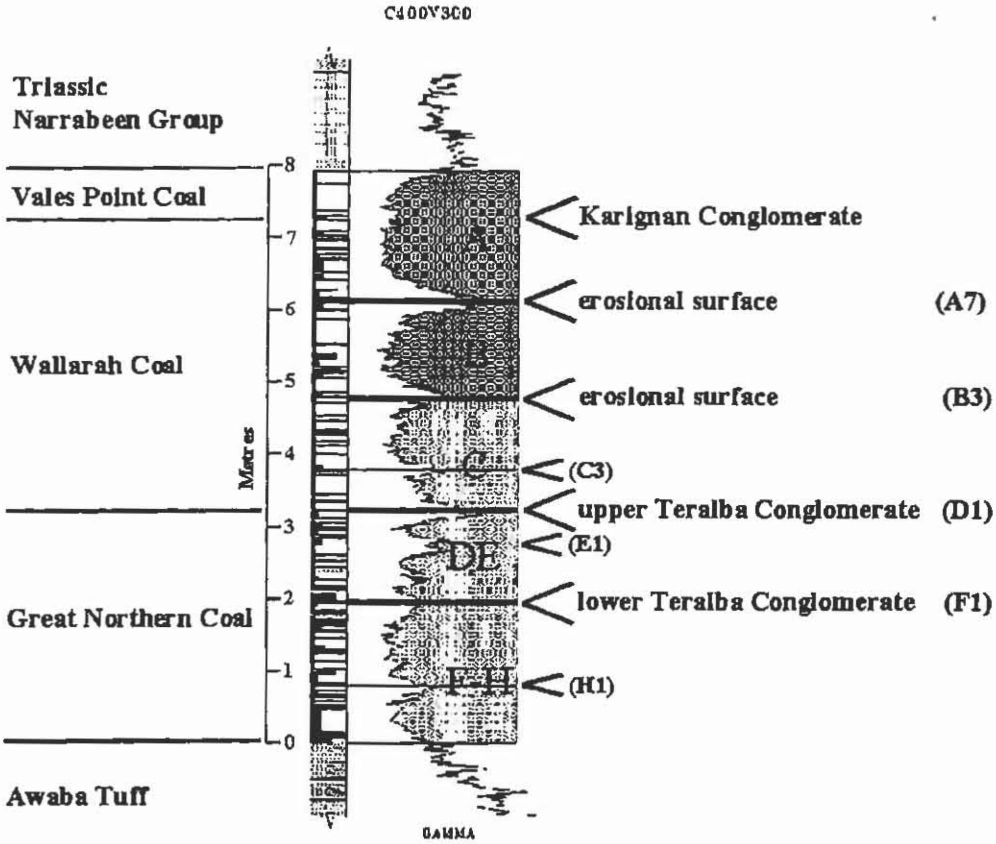


Figure 2. In the central part of the area all three seams coalesce into a single seam nearly 8m thick. Coal plies and horizons are shown in capital letters. The position of siliciclastic splits and erosional surfaces that occur to the east and west are shown by horizontal V's.

Coal is generally considered to have formed from low-lying peat mires which developed at the same time as, and adjacent to, areas of active siliciclastic sedimentation (eg. Diessel, 1992). However, stratigraphic relationships in the Late Permian of the Sydney Basin indicate that major coals were formed from extensive peat mires that blanketed *abandoned* sedimentary surfaces during a substantial decline in siliciclastic deposition (Warbrooke, 1981, Bamberry *et al.*, 1989) and that they were formed from raised mires, not low-lying swamps (Herbert, 1997). According to Bocking *et al.* (1988), conglomerates at the top of the Newcastle Coal Measures were deposited in braided alluvial channels as lateral facies equivalents of raised peats but with ... "a notable absence of overbank sediments". We agree with their environmental interpretation, but argue herein, that the facies were never coeval and laterally equivalent. This is indeed suggested by their observation that overbank sediments interbedded with coal are absent.

At the top of the Newcastle Coal Measures coal seams are in the order of a few metres thick, whereas conglomerate splits within the coal are of the order of a few tens of metres thick. There appears to be a dilemma here concerning accommodation space. This problem is largely resolved by applying a 10:1 compaction ratio for the conversion of peat to coal (Ryer and Langer, 1980). Thus it is apparent that the maximum thickness of conglomerate is roughly equivalent to the maximum thickness of peat before compaction (Figure 6,o). Therefore, there is adequate accommodation space for coarse clastic sediments given sufficient erosion into the peat, especially when augmented by compaction of underlying peat and sediments under the load of accumulating gravel.

COAL STRATIGRAPHY

Coal seams within the area comprise variously split and coalesced combinations of the Great Northern, Wallarah and Vales Point Coals (Figure 2). The seam is underlain in places by the Awaba Tuff, a widespread volcanoclastic unit up to 12m thick, and in other places, by the Karingal Conglomerate. The Dooralong Shale, of the Triassic Narrabeen Group, unconformably overlies the seam. The combined Great Northern/Wallarah/Vales Point seam varies in thickness, up to a maximum of 8m within the study area (Figure 3).

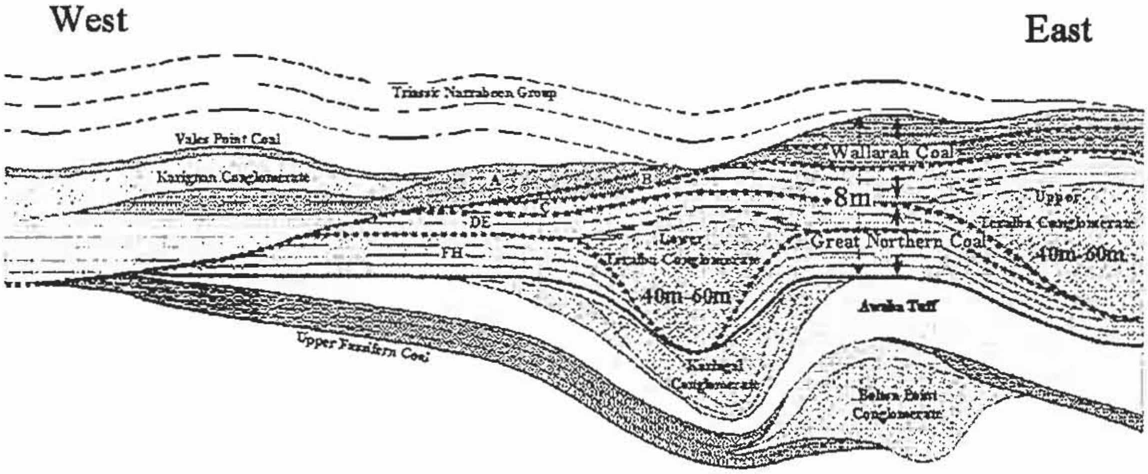


Figure 3. Rock relationship diagram. The scale of the siliciclastic units has been reduced as compared to the coal. Note that there are two Teralba Conglomerates within the Great Northern/Wallarah Coals.

The coalesced seam is predominantly a relatively dull coal, forming a series of dulling-up cycles, each cycle in many cases culminating in a mudstone penny band. The lower part of the seam contains a greater proportion of bright coal than the upper part and contains most of the clastic bands, usually mudstone penny bands (Figure 2, F, H). Thick dull coal zones with fewer clastic bands characterise the middle part of the combined seam, which has a lower average ash content (Figure 2, D, E). Whereas the upper portion of the seam contains some brighter units, it also has thick, dull coal intervals with a canneloid appearance and an even lower ash content (Figure 2, A, B).

The seam was originally subdivided into plies for coal quality sampling based on brightness profiles and claystone bands. However, after examining geophysical data, gamma-ray logs were subsequently used to refine correlations over distances of at least 25kms. Gamma-ray traces show a very distinctive character with a series of correlatable spikes at intervals of 0.5m to 1.0m through the seam indicating markedly higher radiation levels than the generally low background levels of the coal. The gamma-ray peaks are a response to a concentration of radioactive minerals which are not necessarily associated with any macroscopically visible increase in mineral matter in the coal but is often associated with thin claystone bands or zones of diffuse clay pellets in dull coal. Detailed correlations reveal a complex series of up to 7 extensive correlatable surfaces within the coal seam. These are essentially conformable in the coalesced coal seam. However, the upper two surfaces are strongly erosional over the western half of the study area, cutting down through the complete seam into the underlying Awaba Tuff to the west (Figure 3, A7, B3).

SILICICLASTICS SPLITS

Where present, the Teralba Conglomerate separates the Great Northern Coal from the overlying Wallarah Coal. Where the conglomerate is absent, the stratigraphic subdivision of the coalesced Great Northern/Wallarah Coal is cryptic, but can be identified as a peak on gamma-ray logs. This study has defined an additional conglomerate at a lower horizon within the Great Northern Coal, and a few kilometres to the west. These two are referred to, in this study, as the upper and lower Teralba Conglomerate. They are multicoloured, clast supported, pebble conglomerates composed of a variety of rock types ranging from black, green and red cherts to acid volcanics, all derived from the orogenic New England Fold Belt in the north. They are north-south oriented, slightly sinuous, channel-like bodies with sharply defined edges.

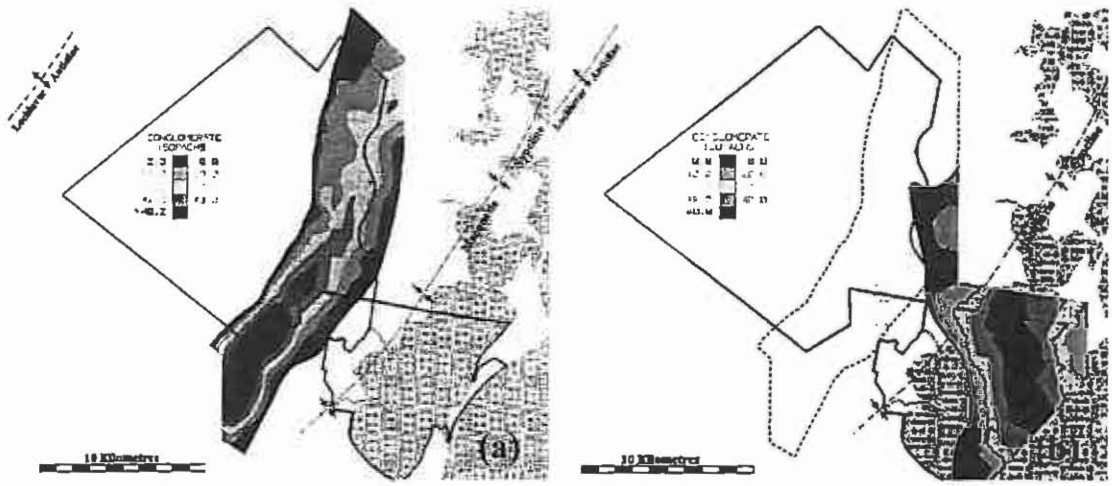


Figure 4. Upper (a) and lower (b) Teralba Conglomerate isopachs. Contours are at 10m intervals and show each conglomerate thickening along their north-south axes.

The lower Teralba Conglomerate can be more than 40m thick and about 5km wide while the upper Teralba Conglomerate can exceed 60m in thickness and is about 7km wide (Figure 4). Basal contacts are sharp and erosional into underlying coal, or into underlying clastic sediments in the thickest areas where the coal has been completely eroded. At the top, each conglomerate grades rapidly into a few metres of sandstone, mudstone, and carbonaceous mudstone, before passing up to coal (Figure 3).

The Karignan Conglomerate splits the Vales Point Coal from the top of the Wallarah Coal. In the north, where it outcrops near Catherine Hill Bay, it is a pebble conglomerate identical to the Teralba Conglomerate. Here on the Central Coast, it is dominantly a sandstone with minor conglomeratic phases. It is as much as 20m thick, but has not yet been sufficiently defined to comment on its distribution.

RELATIONSHIP BETWEEN COAL AND CONGLOMERATE

Detailed correlations have established clear relationships between the siliciclastic splits and the coal seam within which they occur. The coarser grained conglomeratic, siliciclastic units can be *related to hiatal surfaces* within the unsplit coal, *not to plies* of coal as has been thought in the past. Layers or zones of pelletal claystone usually define the surfaces, which can also be recognised by a prominent gamma-ray spike on geophysical logs. The most significant surfaces usually overly thick, dull coal.

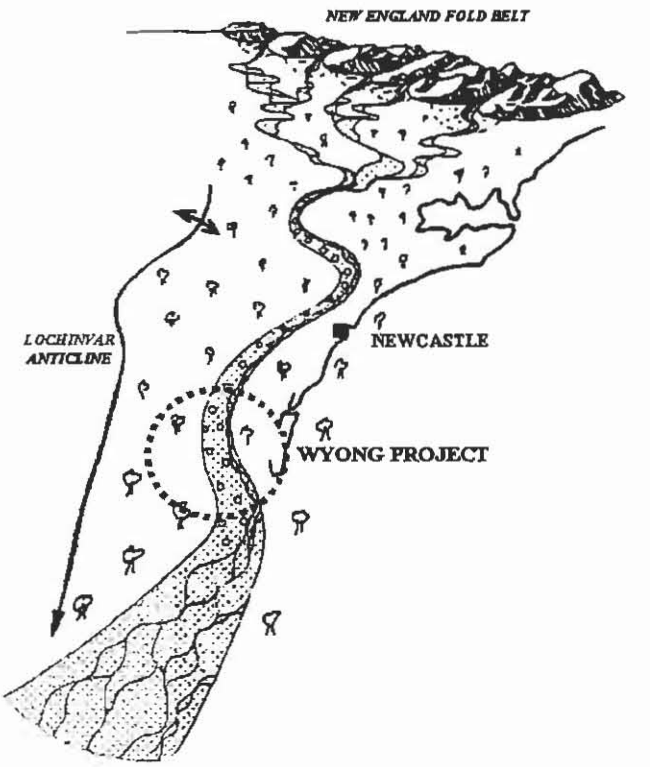


Figure 5. Palaeogeography depicting each conglomerate to have been deposited in braided fluvial, gravel-filled, incised-valleys fed from the active New England Fold Belt.

The lower Teralba Conglomerate can be related predominantly to the F1 horizon (Figure 2). However, there is evidence that the lower part of the conglomerate is equivalent to the H1 horizon. The upper Teralba Conglomerate can be related to the D1 horizon. However, there is also evidence for the lower parts of the conglomerate to be equivalent to the E1 and C3 horizons. These are identifiable, in places, owing to the presence of thin coal and shale units believed to be the D2 and C4 horizons within the upper Teralba Conglomerate.

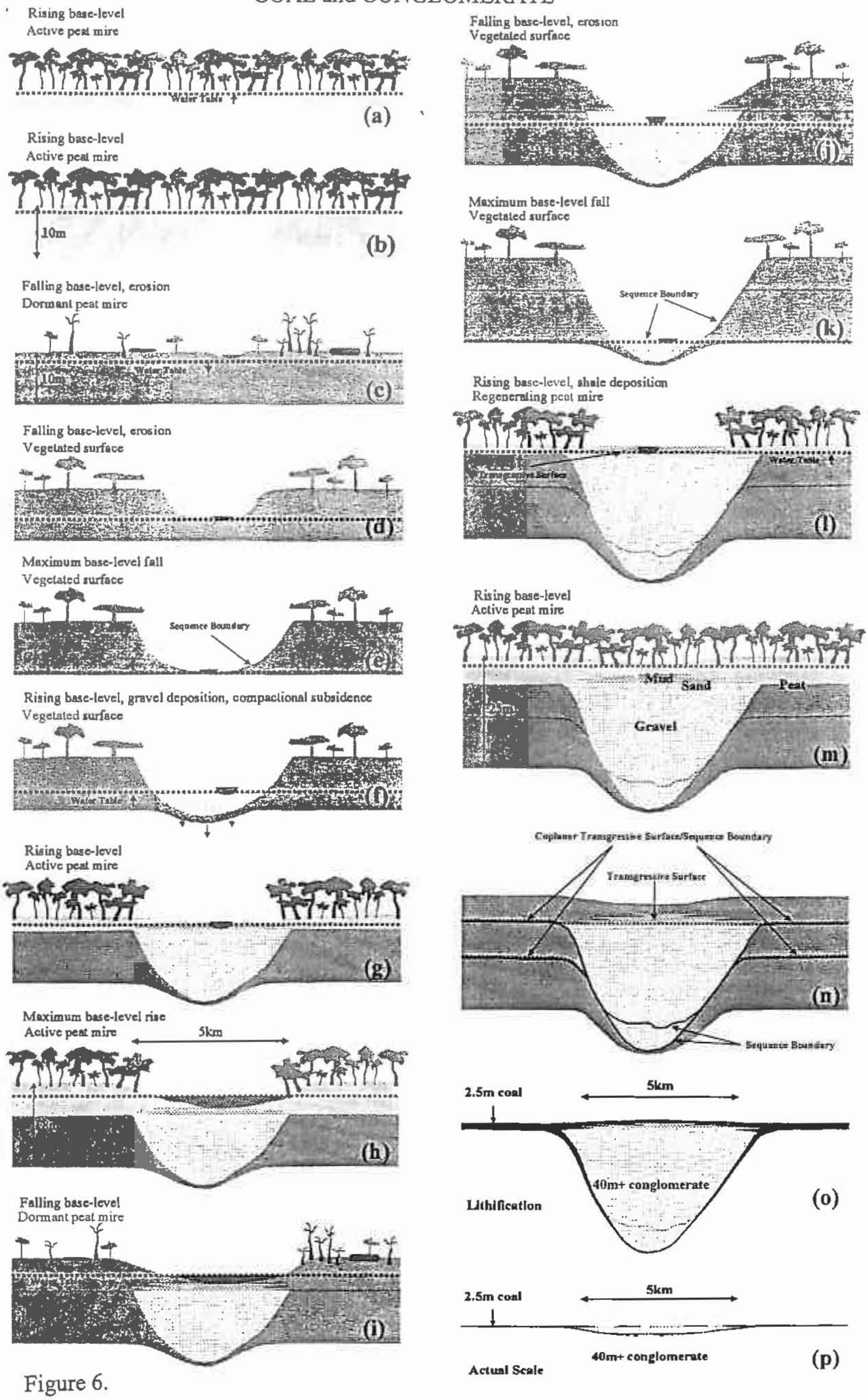
The contact between conglomerate and underlying coal is always erosive. In places, along the axis of maximum conglomerate thickness, the coal has been completely removed by erosion. Coal plies immediately overlying each of the conglomerates tend to grade laterally into shale.

PALAEOGEOGRAPHY

During the closing stages of Newcastle Coal Measures deposition, regression had pushed the Late Permian shoreline outside the present limits of the Sydney Basin so that paralic transgressions rarely reached the Newcastle Coalfield (Herbert 1997). At times of low relative sea-level, incised valleys up to 7km wide were eroded into extensive peat mires (Figure 5). These valleys were back-filled with gravel derived from the eroding New England Fold Belt as relative sea-level began to rise again. Coarse, pebbly sediments were confined to incised valleys in the more rapidly subsiding northern Sydney Basin, close to the orogenic margin of this foreland basin. However, downstream in the less rapidly subsiding part of the southern Sydney Basin, the gravels in each incised valley passed into coarse sand with minor gravel and spread out as unconfined braidplains. This ultimately produced stacked, blanket sandstone bodies between coals. At times of high relative sea-level, raised peat mires expanded basin-wide, interrupted only where flooded, sediment-filled incised valleys remained.

RELATIVE SEA LEVEL CONTROL ON DEPOSITION

It is paradoxical that thick, extensive, and siliciclastically uncontaminated coal seams occur in lithological contact with thick, conglomeratic, obviously high energy, fluvial sediments if it assumed that they were deposited simultaneously in laterally adjacent environments. However, the paradox is resolved by assuming that peat accumulation and coarse clastic deposition were *not* coeval and that deposition was controlled by changes in relative sea-level which in turn influenced base-level. In coastal plain environments, cyclical changes in relative sea-level must also effect the height of the water-table and thus effect peat accumulation and the style of sedimentation for a considerable distance upstream. It is suggested that mire growth and the accumulation of thick peat could be sustained only when relative sea-level, and hence the water table, was rising at a sufficient rate to preserve the biogenic productivity (Figure 6a, b). Conversely, following a subsequent base-level fall the water table would also fall and would no longer be capable of sustaining mire growth (Figure 6c, d). The exposed mire would become dormant, and start to degrade, producing a widespread hiatal surface across the peat (high-frequency sequence boundary). Falling base-level would simultaneously initiate erosion of the dormant mire in the topographically lowest areas to produce, in the case of the lower Teralba Conglomerate, a 5km-wide, north-south oriented, incised valley, subparallel and to the west of the axis of the Macquarie Syncline (Figure 6e). This erosion surface is a continuation of the sequence boundary/hiatal surface above the dormant peat. Vigorous braided streams then deposited gravel in the incised valley during the early part of the subsequent relative sea-level rise (Figure 6f). When the water table returned to the top of the dormant peat and the top of the incised valley, the mire re-established above a transgressive, or paludification, surface and peat accumulation resumed (Figure 6g, h). Simultaneously, gravel deposition waned to sand and then mud deposition as the locus of gravel deposition was pushed further upstream. The now full incised valley probably resembled a shallow, suspended-load estuary with peat mire encroaching from either side. Peat accumulation continued as long as relative sea-level was rising, but ceased when falling relative sea-level, again, induced a falling water-table (Figure 6i). This literally left the mire high and dry. Degradation would then have been the most likely process to effect the peat mire. If the stream was still located in the same area, falling base-level would induce erosion of the previously deposited fluvial gravel in the incised valley and, depending on the magnitude of the relative sea-level fall, all or only some of the sediment may be removed (Figure 6j, k). If, as suggested above, the conglomerates were deposited as composite bodies, two cycles of relative sea-level rise and fall may have occurred to deposit the lower Teralba Conglomerate (Figure 6l, m). To produce the upper Teralba Conglomerate, which occurs at a higher stratigraphic position in the Great Northern/Wallarah Coal, the stream needed to shift its course only a few kilometres to the east during another relative sea-level fall. This was obviously a topographic low where the subsidence rate was probably greater, closer to the axis of the Macquarie Syncline. Subsequent cyclical changes in relative sea-level would produce identical peat accumulation/degradation processes and siliciclastic deposition/erosion.



Rising base-level
Active peat mire
Water Table
(a)
Rising base-level
Active peat mire
10m
(b)
Falling base-level, erosion
Dormant peat mire
Water Table
10m
(c)
Falling base-level, erosion
Vegetated surface
(d)
Maximum base-level fall
Vegetated surface
Sequence Boundary
(e)
Rising base-level, gravel deposition, compactional subsidence
Vegetated surface
Water Table
(f)
Rising base-level
Active peat mire
(g)
Maximum base-level rise
Active peat mire
5km
(h)
Falling base-level
Dormant peat mire
(i)
Falling base-level, erosion
Vegetated surface
(j)
Maximum base-level fall
Vegetated surface
Sequence Boundary
(k)
Rising base-level, shale deposition
Regenerating peat mire
Water Table
(l)
Rising base-level
Active peat mire
Mud
Sand
Peat
Gravel
(m)
Coplanar Transgressive Surface/Sequence Boundary
Transgressive Surface
Sequence Boundary
(n)
2.5m coal
5km
40m+ conglomerate
Lithification
(o)
2.5m coal
5km
40m+ conglomerate
Actual Scale
(p)

Figure 6.

CONCLUSION

Peat mire growth was *not* coeval with coarse, siliciclastic deposition. Gravel was deposited in lowstand, incised valleys eroded into peat mires that were dormant at the time, and probably degrading, because of exposure caused by low relative sea-level. This is suggested as the main reason for producing the dull, inertinite-rich coal that is typical for these topmost Late Permian coal seams. At times of rising and higher relative sea-level, mires extended basin-wide, peat accumulating and being preserved by the high water-table in the transgressive systems tract.

Peat was formed in raised mires, not low-lying swamps, thus preventing siliciclastic contamination from adjacent fluvial facies that were confined to incised valleys at a lower topographic level.

The proposed mechanism for alternating biogenic and siliciclastic deposition was cyclical changes in base-level caused by relative sea-level changes. This produced 4th-order, or high-frequency, sequences.

Sequence boundaries are located at the base of conglomerates and at prominent correlatable erosional surfaces within each conglomerate (Figure 6n). These sequence boundaries pass into unsplit coal, adjacent to the conglomerate bodies, at the boundaries between coal plies. Prominent gamma-ray spikes identify the location of these sequence boundaries within the coal. Thus, the conglomerate bodies are lowstand stratigraphic equivalents of the hiatus between coal plies, *not to the coal itself.* Transgressive surfaces are located at the top of conglomerates where they grade up through sandstone into mudstone. This surface is probably best positioned where the topmost sandstone passes up to mudstone, in many places a sharp boundary. Equivalent transgressive surfaces in coal are coplanar with the sequence boundaries at the hiatal surface between coal plies.

ACKNOWLEDGEMENTS

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MINERAL MATTER IN COAL SEAMS: FOREIGN INVADER OR INDIGENOUS COMMUNITY?

KENNETH MOSHER MEMORIAL LECTURE

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ABSTRACT

Mineral matter in coal embraces dissolved ions in the pore water, inorganic elements associated with the organic compounds, and crystalline or true mineral particles. Even a relatively low-ash Australian bituminous coal contains approximately 15% inherent mineral matter. This means that the New South Wales coal industry currently produces more than 15 million tonnes per year of mineral material, a fraction about which surprisingly little is known. Mineral matter represents the source of most of the problems associated with using coal, and thus has significant implications for the mining, preparation, and marketing of Australian coal deposits.

Based on the processes that form them, the minerals and other inorganics in coal can be identified as either *foreign invaders* (introduced contaminants) or *indigenous communities* (inherent peat-swamp components) with respect to the sediment that makes up the coal seam. The minerals in Australian coals include quartz and a range of clay minerals (especially kaolinite), along with different types of carbonates, sulphides, phosphates and other constituents. Their mode of occurrence within the coal and their three-dimensional distribution in the seam allows the different minerals and non-mineral inorganics in individual seams to be identified as combinations of:

- biogenic constituents (e.g. diatoms, phytoliths);
- organically-associated inorganics (e.g.dissolved salts, exchangeable ions);
- chemical precipitates (e.g. petrifactions, nodules, cleat infillings);
- detrital or pyroclastic contaminants.

The minerals in coal can be identified by X-ray diffraction, scanning electron microscopy and related techniques. Modern developments allow these methods to be used for quantitative assessment of mineral proportions, as well as simply for mineral identification. The quantitative results have been found to be consistent with the chemical composition of the ash derived from the same coal samples. The mode of occurrence of the different non-mineral inorganics can be investigated by selective chemical leaching techniques.

Especially with the capacity for quantitative assessment, mineral matter studies are being used to investigate problems in coal handling and preparation, or in marketing and utilisation for combustion and coking applications. They can also be used as an aid in seam correlation. The abundance of particular trace elements can be related to particular minerals in the coal seam, allowing mineral matter studies to play a significant role in assessing the environmental impact of coal mining, utilisation and waste disposal.

Modern methods of investigation, coupled with recent advances in the understanding of coal-forming environments and sedimentary basins, allow geologists to make new and increasingly valuable contributions to coal deposit evaluation, and to the understanding of coal formation processes. These advances, many of which have been sourced from Australia, are helping to perpetuate the long and outstanding contribution of Ken Mosher as a leader in the application of geological science to the Australian coal industry.

INTRODUCTION

In its simplest sense coal consists of two classes of material: a collection of organic components referred to as macerals and a collection of inorganic components referred to as mineral matter. The organic components represent the preserved and coalified remains of different types of plant debris, most of which probably grew in or close to the swamp, bog or mire in which the original peat accumulated. Changed in various ways by processes associated with burial, the organic components are at the core of coal utilisation processes, and indeed are the very reason why coal is the mainstay of the world's energy-based industries. All the benefits derived from coal, including its contribution to metallurgical processing, its potential as a hydrocarbon source and its capacity for in-situ methane absorption, as well as its energy output on combustion, are derived from the maceral constituents.

The inorganic fraction, however, typically contributes little if anything to the value of the coal in any of these activities. At best it is a diluent, displacing more useful organic matter with a non-combustible component that leaves an ash residue when the coal is burned, or that needs to be removed as slag from the blast furnace during metallurgical processing. It can, however, also be a source of unwanted stickiness, abrasion, corrosion or pollution associated with coal handling and use. Most of the problems associated with coal utilisation arise in some way from the incorporated mineral matter, rather than directly from the maceral components.

THE NATURE OF MINERAL MATTER

The material classed as mineral matter in coal embraces three different types of inorganic constituents, namely:

- Dissolved ions and other inorganic substances in the coal's pore water;
- Inorganic elements incorporated within the organic compounds of the coal macerals, and
- Discrete crystalline inorganic particles or true mineral components.

The first two types of mineral matter, best described as *non-mineral inorganics*, are dominant in lower-rank coals, such as brown coals, lignites and sub-bituminous materials. Reductions in moisture content and changes in the nature of the organic matter with rank advance, however, mean that they are virtually absent from higher-rank materials, such as bituminous coals and anthracites. Crystalline inorganic constituents, or *minerals*, may be present in both lower-rank and higher-rank coals, but in the absence of other inorganics they are the dominant if not the sole component of the mineral matter in higher-rank deposits.

Depending on the seam geology and the extraction method, mined coals typically contain additional fragments derived from discrete intra-seam bands of non-coal material, as well as possibly a certain amount of non-coal rock from the roof or floor strata. These fragments are usually removed by cleaning processes in any coal preparation plant associated with the mining operation. Notwithstanding the efficiency of modern coal cleaning processes, however, there is still typically a significant level of mineral matter, sometimes referred to as *inherent* mineral matter, that cannot effectively be removed preparation and that remains incorporated in the coal when it is ultimately used. This is an unavoidable part of even the best coal product, and must be taken into account along with the macerals in assessing the coal's behaviour in handling, storage or utilisation.

METHODS FOR STUDYING MINERAL MATTER

Some of the mineral matter in coal seams is readily visible in outcrops, drill cores and mine exposures, occurring as bands, lenticles, cleat infillings and other megascopic masses. In the brown coals of the Latrobe Valley, for example, these can also include partly mineralised wood fragments. Other mineral matter can be seen with a hand lens or in X-radiographs of drill cores. Mineral matter originally dissolved in the pore water (including water in cleats and other fractures) is also sometimes precipitated when the water evaporates in fissures or on exposed coal faces.

Much of the crystalline mineral matter in higher-rank coals occurs in masses too small to be seen with the naked eye, but in a form that can be seen under the optical or electron microscope. This includes fine laminae and other masses intimately intergrown with the maceral components, as well as discrete mineral fragments or crystals and a range of nodules, lenticles, veins, pore infillings and cell replacement structures. The identity of the minerals is not always apparent from optical studies, but the textural relationships often indicate how the mineral material may have formed or how it might respond to coal preparation and utilisation processes.

More definitive identification of the minerals in coal can be obtained by optical staining methods, or by using accessory X-ray fluorescence facilities to identify the elements in particular mineral masses in polished or broken coal sections under the electron microscope. The identity of minerals can also be investigated by subjecting powdered coal samples or minerals isolated from the coal to study by X-ray diffraction techniques.

Although some success can be achieved by oxidising the coal with hot, concentrated hydrogen peroxide (Ward, 1974), the minerals can most effectively be isolated from coal by destroying the organic matter at relatively low temperature (around 120°C) under vacuum in an oxygen plasma, excited by a radio-frequency electromagnetic field

(Gluskoter, 1965). This technique leaves the minerals essentially unaltered, including the clay minerals, and in a form that can be readily studied by X-ray diffraction methods. Many of the non-mineral inorganics in lower-rank coals, however, interact with the organic sulphur during low-temperature ashing, forming crystalline products such as bassanite ($CaSO_4.½H2O$); these are not present as such in the coal, but are mineral artifacts produced by the low-temperature, plasma ashing process.

Chemical analysis of the coal, the coal ash, or of various coal leachates, can also be used to investigate mineral matter. This can include studies of trace elements, as well as the major elements in the coal sample. Selective leaching with water (to extract water-soluble ions), ammonium acetate (to liberate exchangeable ions attached to the organic compounds) and hydrochloric acid (to extract any acid-soluble organometallic complexes), combined with analysis of the respective leachates, can also be used to study the non-mineral inorganics in lower-rank coal samples (Ward, 1992). The leached coal can then be subjected to low-temperature ashing, isolating the minerals without the addition of mineral artifacts derived from the non-mineral inorganic constituents.

FORMATION OF MINERAL MATTER

The minerals in coal include quartz, clay minerals (especially kaolinite and interstratified illite/smectite), carbonates such as siderite, calcite and dolomite, feldspars, and sulphide minerals such as pyrite (Table 1). Minor but sometimes significant accessories include phosphate minerals such as apatite or alumino-phosphates of the crandallite group (Ward et al., 1996), titanium minerals such as anatase, and alumino-carbonates such as dawsonite. Iron sulphate minerals such as coquimbite ($Fe_2(SO_4)_3.9H_2O$) may also be found; these usually represent oxidation of sulphide components during coal exposure or storage.

The minerals in coal form by a range of different processes. These can be summarised as follows:

- **Biogenic minerals** - minerals resulting from biological activity in the peat swamp, such as shells from diatoms, molluscs and other organisms, minerals formed within living plant tissues (e.g. phytoliths), and possibly minerals deposited as faecal pellets.

- **Detrital minerals** – minerals washed or blown as fragments into the accumulating peat deposit. These include components introduced from river water and flood inputs, from airborne dust and from pyroclastic debris.

- **Authigenic precipitates** – minerals forming by crystallisation in place, either within the peat deposit (primary precipitates) or in the cleats and fractures of the coal after compaction and probably rank advance (secondary precipitates). Primary precipitates include nodules (commonly of siderite), microcrystalline pyrite framboids, and a range of cell and pore infillings (typically kaolinite, quartz, phosphate minerals and pyrite). Cleat infillings can include calcite, dolomite, ankerite and siderite, as well as pyrite, marcasite, apatite, dawsonite, illite and chlorite.

Table 1. Principal minerals found in coal and oxygen-plasma ash (Ward, 1999).

Silicates		**Carbonates**	
Quartz	SiO_2	Calcite	$CaCO_3$
Chalcedony	SiO_2	Aragonite	$CaCO_3$
Clay Minerals:		Dolomite	$CaMg(CO_3)_2$
Kaolinite	$Al_2Si_2O_5(OH)_4$	Ankerite	$(FeCaMg)CO_3$
Illite	$K_{1.5}Al_4(Si_{6.5}Al_{1.5})O_{20}(OH)_4$	Siderite	$FeCO_3$
Smectite	$Na_{0.33}(Al_{1.67}Mg_{0.33})Si_4O_{10}(OH)_2$	Dawsonite	$NaAlCO_3(OH)_2$
Chlorite	$(MgFeAl)_6(AlSi)_4O_{10}(OH)_8$	Strontianite	$SrCO_3$
Interstratified		Witherite	$BaCO_3$
clay minerals		Alstonite	$BaCa(CO_3)_2$
Feldspar	$KAlSi_3O_8$		
	$NaAlSi_3O_8$	**Sulphates**	
	$CaAl_2Si_2O_8$	Gypsum	$CaSO_4.2H_2O$
Tourmaline	$Na(MgFeMn)_3Al_6B_3Si_6O_{27}(OH)_4$	Bassanite	$CaSO_4.½H_2O$
		Anhydrite	$CaSO_4$
Sulphides		Barite	$BaSO_4$
Pyrite	FeS_2	Coquimbite	$Fe_2(SO_4)_3.9H_2O$
Marcasite	FeS_2	Szomolnokite	$FeSO_4.H_2O$
Sphalerite	ZnS	Natrojarosite	$NaFe_3(SO_4)_2(OH)_6$
Galena	PbS	Thenardite	Na_2SO_4
Millerite	NiS		
		Others	
Phosphates		Anatase	TiO_2
Apatite	$Ca_5F(PO_4)_3$	Rutile	TiO_2
Goyazite	$SrAl_3(PO_4)_2(OH)_5.H_2O$	Boehmite	$Al.O.OH$
Gorceixite	$BaAl_3(PO_4)_2(OH)_5.H_2O$	Goethite	$Fe(OH)_3$
Crandallite	$CaAl_3(PO_4)_2(OH)_5.H_2O$	Zircon	$ZrSiO_4$

It is perhaps useful to think of the minerals in coal as representing either *foreign invaders* (minerals introduced from outside the peat-forming mire) or an *indigenous community* (minerals inherent to the peat-forming process). Detrital minerals are clearly representatives of the foreign invaders, and biogenic components obvious examples of an indigenous community within the coal seam.

Precipitated materials, which form the bulk of the minerals in many better-quality coals, are not so easily differentiated. The elements that formed them may have been derived from dissolution of shells or breakdown of plant tissue (i.e. re-distribution of indigenous material) or from alteration and solution of detrital contaminants (re-precipitation of invaders). Other possible sources include reduction of seawater entering (invading) the peat by swamp-dwelling (indigenous) bacteria (the source of much pore-filling and framboidal pyrite), and non-mineral inorganics expelled from the (indigenous) macerals during rank advance. Groundwater and geothermal fluids entering the coal after burial, and fluids from coal or magma associated with igneous intrusions, can also give rise to mineral formation through what are clearly a later generation of foreign invader processes.

MINERALOGICAL ANALYSIS

Mineralogical analysis is a different process from chemical analysis, especially when applied to the mineral matter of coal samples. Chemical analysis of coal or coal ash has a long history of application to the coal industry. Mineralogical analysis, however, is a more difficult task, especially if the relative mineral proportions are required in quantitative form.

Techniques used for mineralogical analysis include normative computations based on ash analysis data, optical microscopy and point counting, and quantitative analysis of elemental associations using a computer-controlled scanning electron microscope system (Creelman and Ward, 1996). With advances in processing technology, X-ray diffraction has also changed from being a qualitative tool for mineral identification to one that provides quantitative data on mineral proportions.

The SIROQUANT XRD analysis system (Taylor, 1991), has been successfully tested on a range of Australian coals by Ward and Taylor (1996) and Ward et al. (1999). As part of this process the chemistry implied by the mineral proportions indicated by SIROQUANT analysis of plasma ash residues was compared to the ash composition determined directly by independent chemical analysis (Figure 1). Good agreement was found in most cases; the limited disagreements that did arise were mainly due to differences between the composition of the actual minerals in the coal (e.g. Fe in dolomite) and the stoichiometric compositions used for the comparison process.

APPLICATIONS OF MINERAL MATTER STUDIES

Mineral matter can impact in different ways on the behaviour of coal in mining, handling and use (Ward, 1999). Quartz, for example, can be excessively abrasive in grinding of coal for pulverised fuel combustion, and also abrade the boiler tubes within the furnace when the coal is burned. Quartz impregnations in coal can give rise to frictional ignition of methane during underground coal mining, and provide a silicosis hazard that adds to the pneumoconiosis risk associated with mine dust inhalation. Pyrite, long recognised as a source of unwanted sulphur and SO_2 in different branches of coal utilisation, can also contribute to frictional ignition of methane, and can give rise to acid generation from seam exposures, stockpiles and preparation refuse emplacements.

The clay minerals in Australian coals include smectite and interstratified illite/smectite, as well as a very abundant kaolinite component. The first two minerals, especially the smectite, are very cohesive when wet, and may be associated with stickiness in coal handling processes. Smectite is also dispersive in water, and may be difficult to remove from suspension in the clarification of preparation plant tailings or mine and stockpile runoff waters.

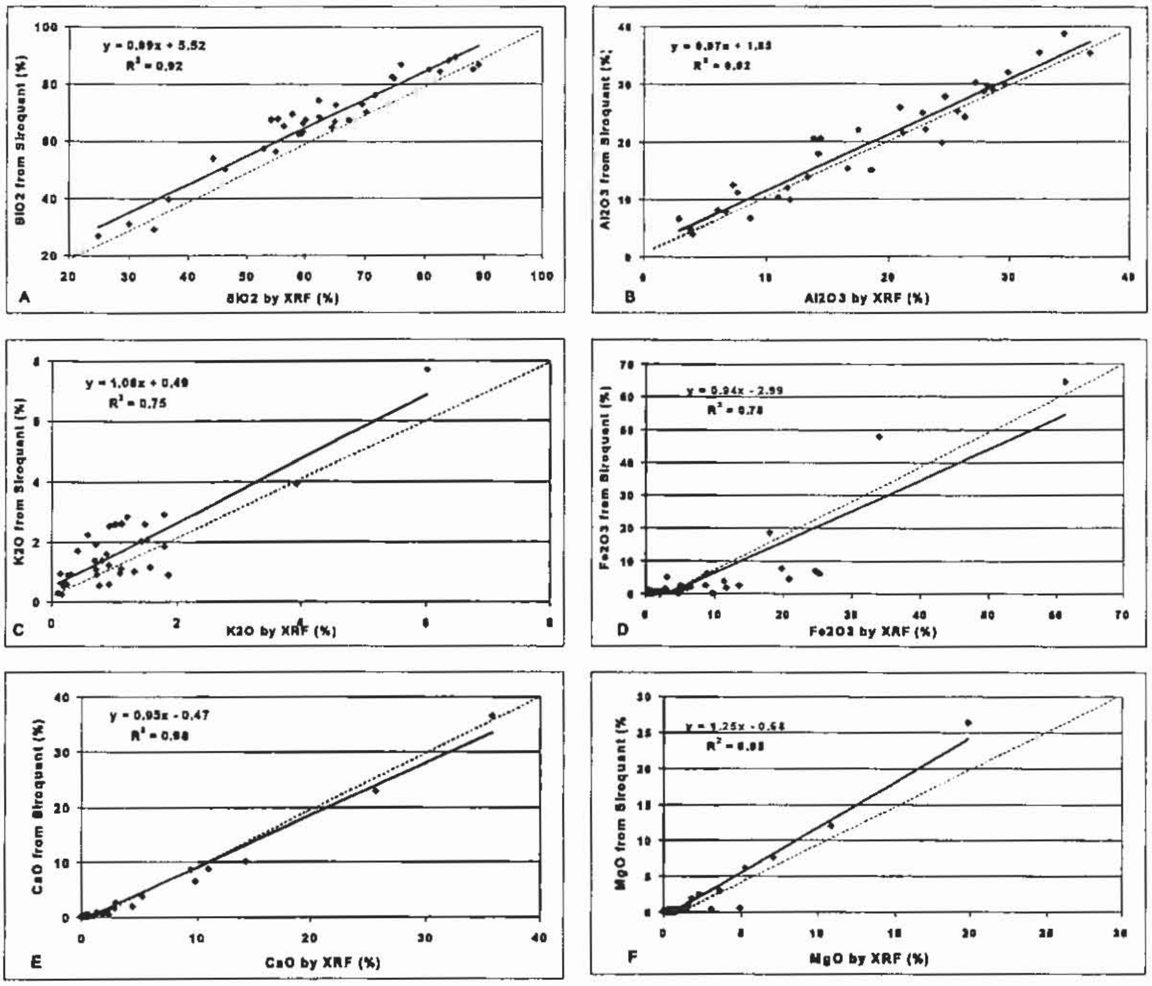

Figure 1. Correlations between chemical composition of coal ash inferred from SIROQUANT mineralogy of plasma ash residues of Gunnedah Basin coals and composition of the same coal ash determined by direct chemical analysis (Ward et al., 1999). A: SiO_2; B: Al_2O_3; C: K_2O; D: Fe_2O_3; E: CaO; F: MgO.

Kaolinite is a very refractory clay, remaining solid even at the high temperatures encountered in modern combustion plants. The other clays, however, are less refractory, and may melt or fuse at these temperatures and give rise to furnace slagging problems. Calcium, magnesium and iron from carbonates or other minerals can also become incorporated in the slagging reactions, lowering the ash fusion temperatures of the coals concerned. Calcium and similar elements incorporated in the organic matter are also released when the coal is burned; these are often more reactive in generating slags than the same elements released from carbonates, since they are liberated from the coal in elemental rather than oxide form.

Geologists need to be aware of the minerals in and associated with individual coal seams as part of the deposit assessment and mine planning process. An understanding of the distribution of the different minerals in the seam is important to identify and allow for potential mining, preparation, marketing, utilisation and waste disposal problems. Pressure on product quality, combined with the need to work progressively more difficult coal seams, is increasing the need for coherent mineral matter studies, and providing yet another avenue through which geologists can contribute in a practical way to the Australian coal industry.

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INVESTIGATIONS INTO THE PREDICTION AND MODELLING OF TOTAL SULPHUR IN COAL SEAMS, GERMAN CREEK MINES, CENTRAL QUEENSLAND.

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BACKGROUND

The German Creek Formation contains five laterally persistent coal seam intervals known as the German Creek, Corvus, Tieri, Aquila and Pleiades in ascending order. The principal seam is the German Creek seam but the Aquila seam and, to a lesser extent, the Tieri seam have also been the focus of past open cut mining operations (see Figure 1). The coal measures dip generally eastwards at 1^0 to 6^0 and the German Creek seam reaches depths of 600m to 800m at the eastern lease boundary. The majority of German Creek's production is from the German Creek seam, an ortho-bituminous, low ash, medium rank, hard coking coal, primarily for export. Most of the shallow coal in the German Creek sequence has been mined except in the north of the leases where thinner seams remain. Present day production is from three separate mines, German Creek Open-cut, Central and Southern Collieries (see Figure 2).

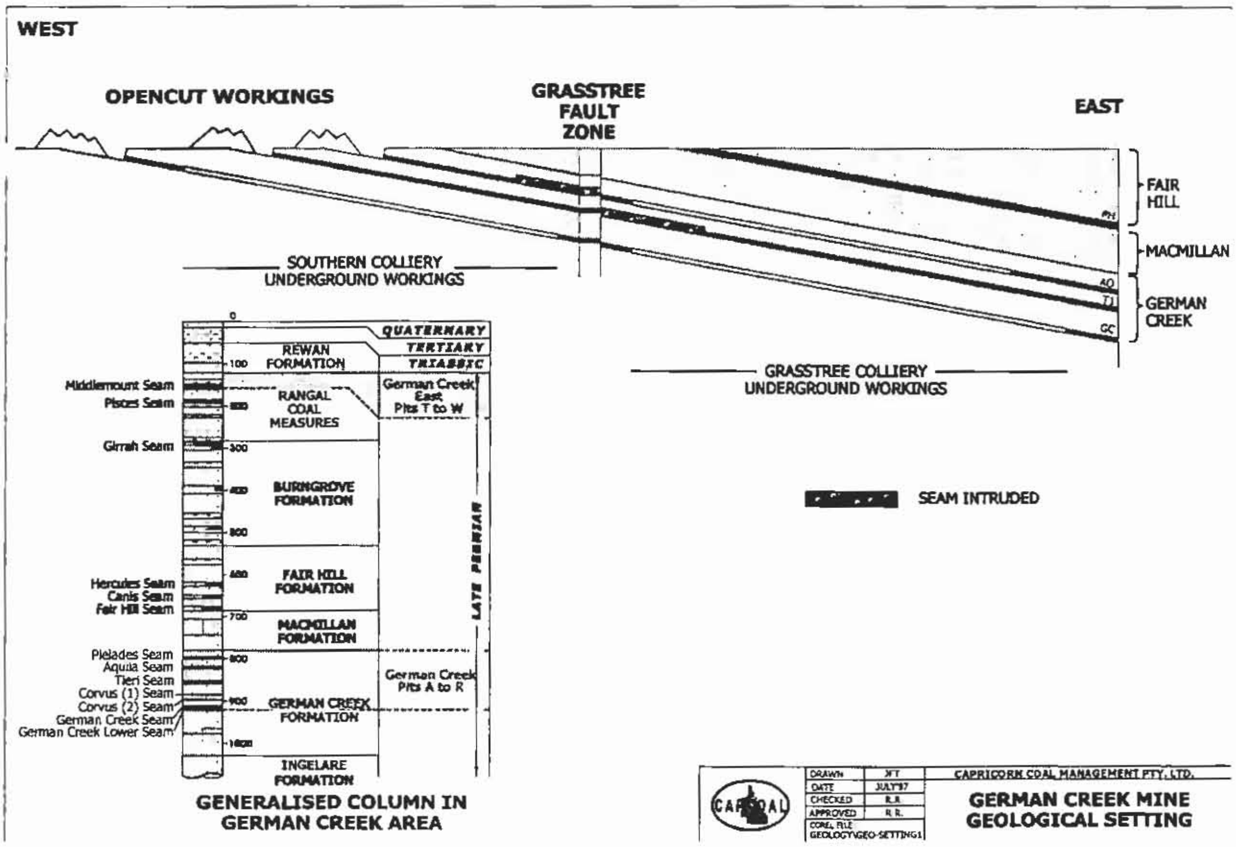


Figure 1 Typical Cross-section and Stratigraphic Column, German Creek Mines.

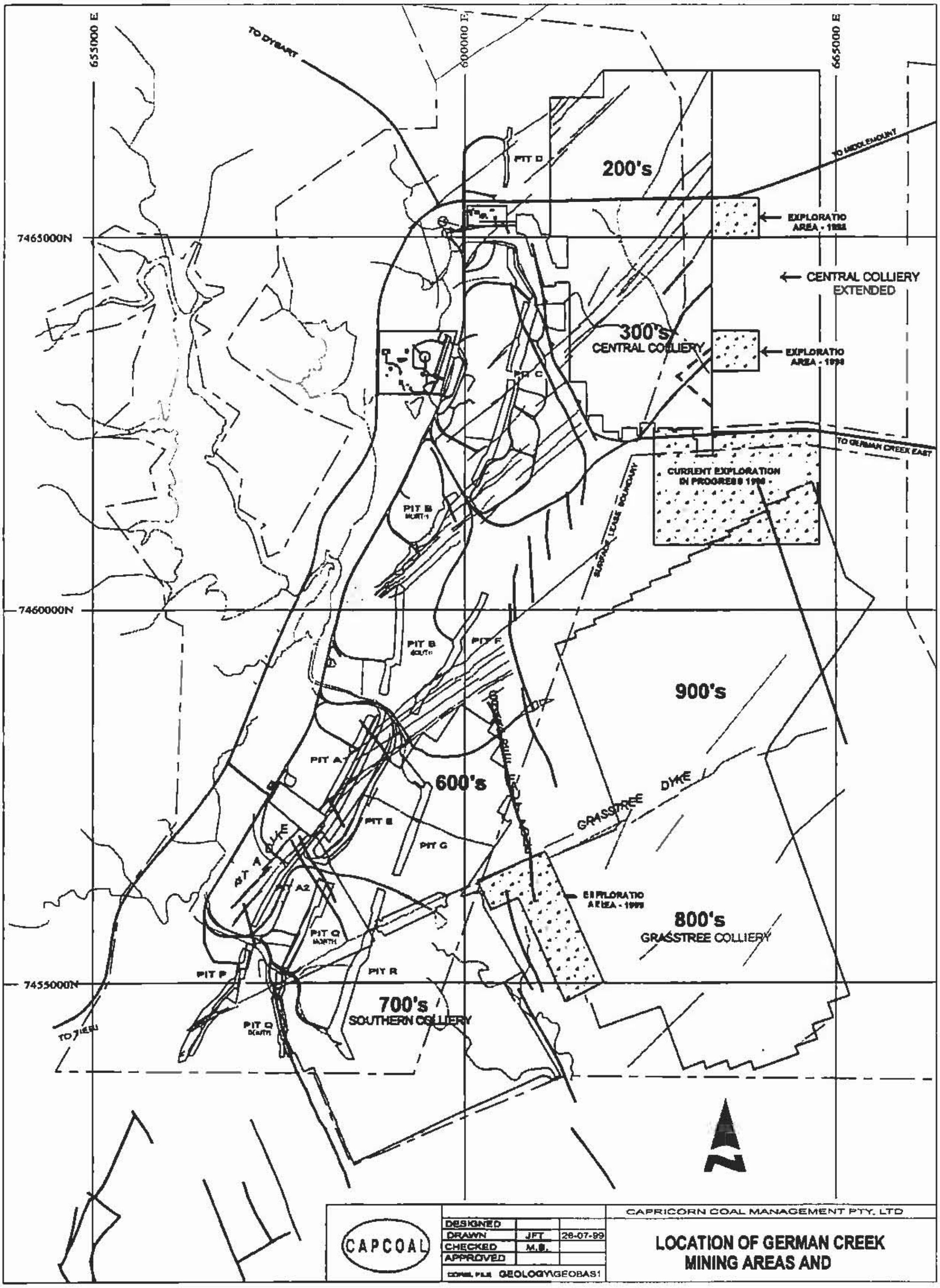


Figure 2 Location of German Creek Mining Areas and Current Exploration

STATEMENT OF THE PROBLEM

There is a systematic variation in rank across the German Creek mining lease, which is exemplified by a regular increase in vitrinite reflectance in the coal from southwest to northeast. Because many of the coal's coking properties are governed by rank, there is a long-range reduction of coking parameters, such as fluidity and dilatation, towards the northeast. By comparison, the sulphur content of some coal seams can, on occasions, widely vary in both a vertical and lateral sense within and between seams, particularly near dykes and seam washout areas. This short-range variability creates problems in predicting the sulphur content of washed product coal, with the possibility of coal shipments to customers being rejected if sulphur levels exceed pre-defined limits. Therefore, if patterns in this variability could be determined and related to some geological property or process of formation of the coal seams, then areas of high sulphur might be predicted in advance of mining.

STUDY METHODOLOGY

In order to study the problem the author instigated a wide-ranging study that has as its main elements:

- Rigorous statistical analyses;
- Spatial continuity testing;
- Background coal characterisation study;
- Trial of downhole geophysical logging (CSIRO's Sulphalog sonde), and;
- Computer-based grid modelling and prediction.

This paper concentrates on providing a summary of work conducted to satisfy the first two elements, statistical analysis and spatial continuity testing. Various modelling methodologies were employed, ranging from geostatistics (ordinary kriging) to polygons of influence so as to best represent the short-range variations present in the seam data sets.

STATISTICAL ANALYSES

Standard statistical analysis tools are always essential as a first pass to characterise sulphur values, spot outliers and typographical mistakes that may have been introduced during encoding. Normally 1-5 ply samples of the raw coal from the target seam are taken and analysed (to the relevant Australian Standards) for relative density, proximate, crucible swell number, hardgrove grindability index, total phosphorous, and forms of sulphur. A clean coal composite of the seam is produced after processing of the laboratory float/sink washability testing. Total and forms of sulphur are one of the analyses performed on this composite (see Ward, 1984 and Lowe, 1996 for a discussion on testing for sulphur). Modelling techniques such as kriging can be used from various mine planning packages to produce grid models by seam or working section for the various forms of sulphur. Though this proved moderately satisfactory for raw insitu data, the influence of core diameter and float/sink washing in organic liquids was also examined, as it was found that borecore size can influence the clean total sulphur result.

Discrepancies between raw and clean sulphur values from the models so constructed still need to be reconciled, as shown by Figure 3. This figure also demonstrates that the overall variation in clean sulphur values, as compared to its raw component also reduces. Washing the coal reduces both the sulphate and pyritic sulphur contents (Figure 4 demonstrates the graphical relationship between raw and clean sulphur for the Aquila seam).

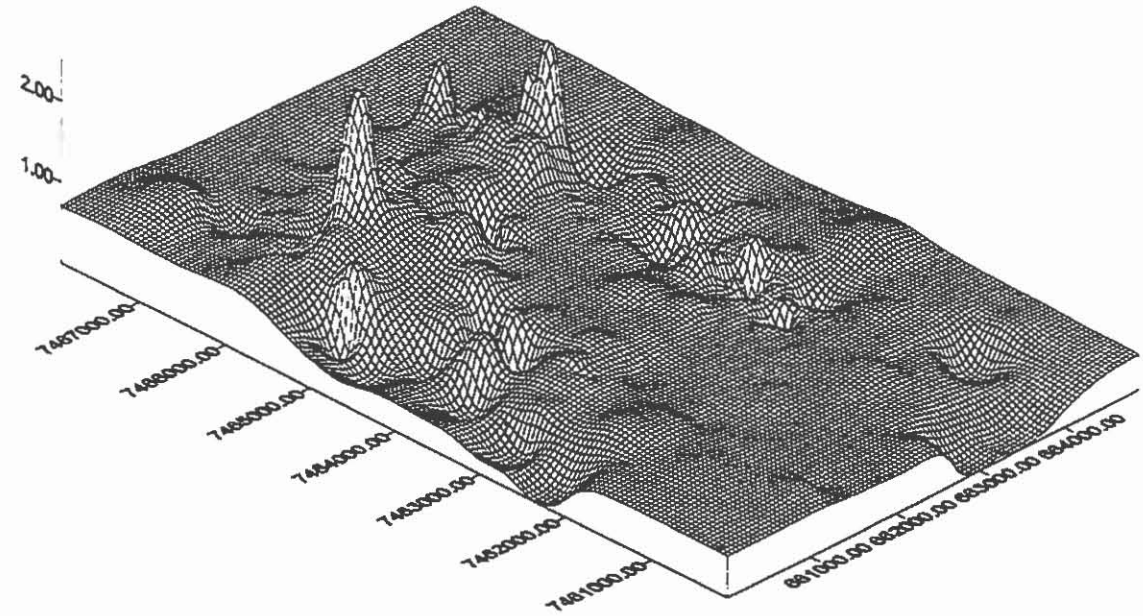
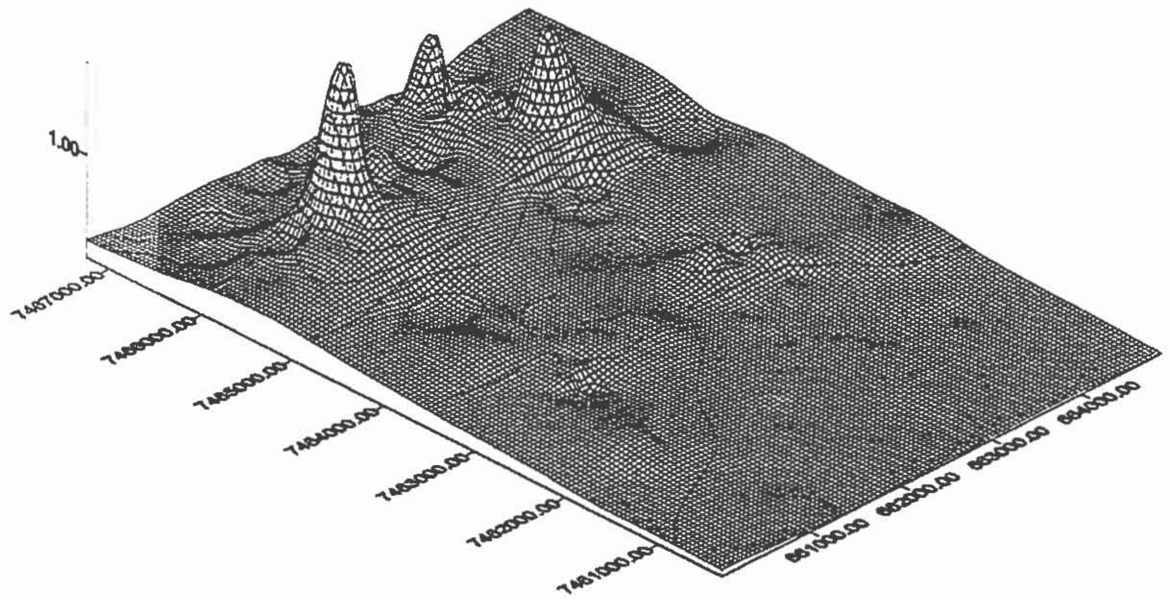


Figure 3 Comparison of ordinary kriging of raw (top) and clean (bottom) total sulphur (%adb) using the same area using the same borehole sample points. Note the reduction and variability in the clean grid.



SPATIAL CONTINUITY TESTING

Not only is it important to characterise the distribution of analysed sulphur values, but of equal importance is the spacing and spatial continuity of the sample points. It is often possible to make crude classification of deposits based on domain geometry and grade continuity, using the experience from modelling a great variety of deposits. The advantage of this approach is to establish some guidelines for what is required to build valid models for each type of deposit.

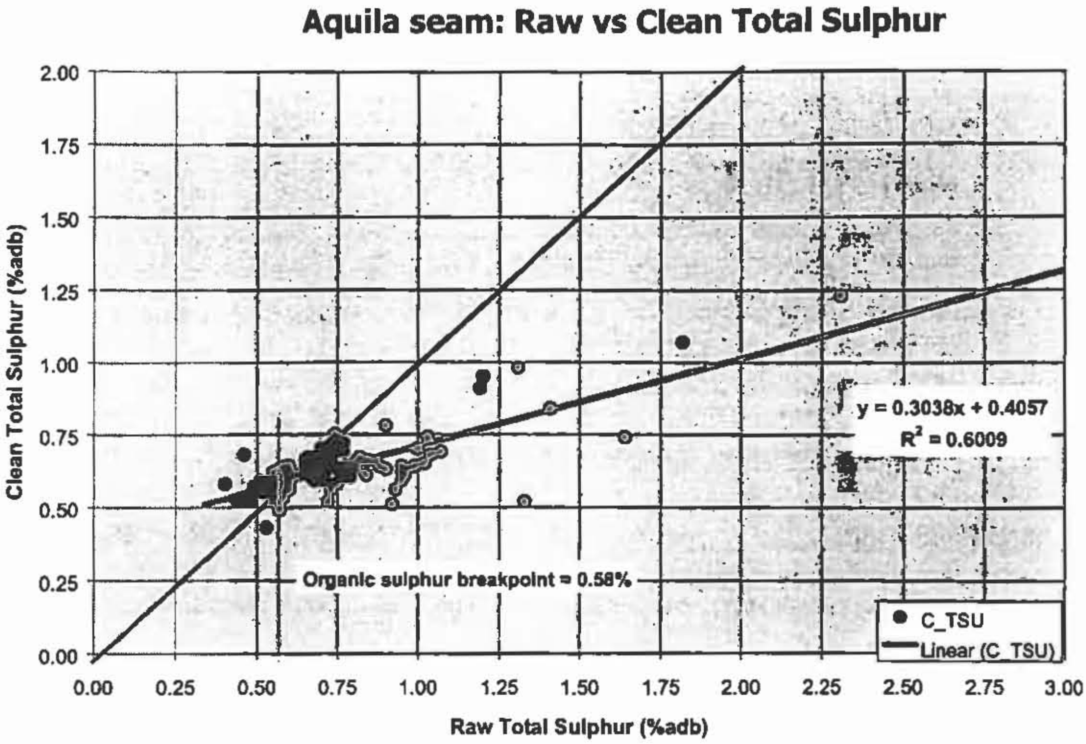
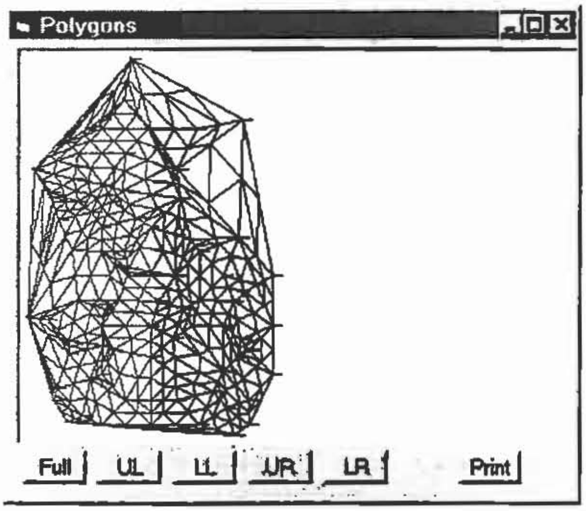


Figure 4 Correlation between Raw and Clean total sulphur for the Aquila seam. The organic sulphur breakpoint shown represents the lowest raw value at which washing will not reduce the clean sulphur value.

This has implications both for the density of data required and the modelling methods likely to be employed. Coal from a domain sense can be regarded as highly continuous with sharp domain boundaries (Duke and Hanna, 1997).

Integral to effective coal quality modelling in this environment are techniques that have been developed to assess the adequacy of exploration borehole coverage over the lease. Borehole spacing in the Central Colliery area is 250m for structure and 450m for coal quality such as sulphur. At Southern Colliery and Grasstree it is generally 150m for structure and 350m for quality.

Considerable thought has been given to methods to characterise the borehole coverage for structure, thickness and coal quality variables with descriptions more constructive than just holes per km^2. Two approaches were adopted. The first approach was to generate voroni tessellations (simple polygons of influence) for each borehole that intersected the Aquila seam for raw and clean coal composite total sulphur. Figure 5 displays a plan view of the polygons generated and histogram distribution of the longest diagonal and area of each polygon.



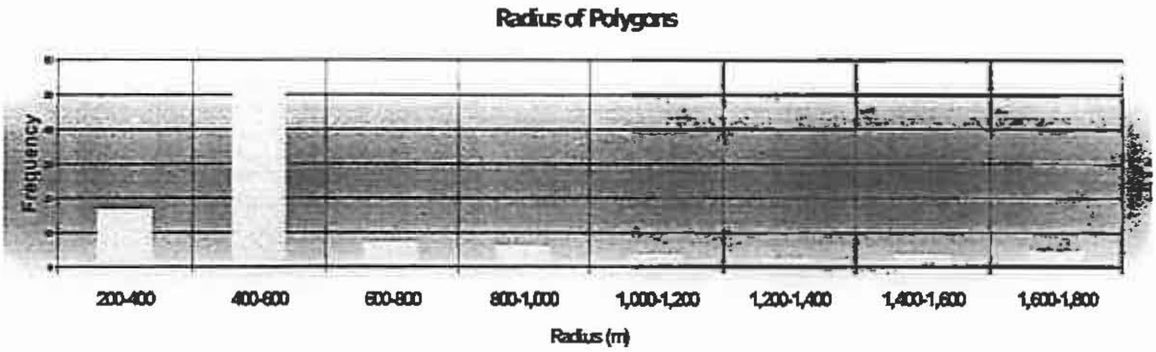


Figure 5 Aquila seam raw total sulphur, histogram of polygons of influence radii.

The second approach was to use a set of descriptive tests devised by Swan and Sandilands (1996) to characterise data density, augmented by some tests devised by Thomas and Taylor (2000). These are generally one-sided hypothesis tests, examining the acceptance, or not, of critical chi-squared, poisson or student-t distributions. These are separately testing for the following characteristics:

- Uniformity;
- Randomness;
- Clustering and regularity;

The following sections provide some background information on the tests for data density characterisation described above.

Testing for Uniformity

Uniform distributions have points distributed with constant density over the area, they therefore show homogeneity (points per unit area). Uniform distributions contrast with clustered distributions, in which the density of points varies significantly around the study area. Uniformity is usually a desirable property of a sampling scheme, it assures that all parts of the area are represented and that there is no bias due to over-representation in some areas.

The test statistic used for uniformity has a chi-squared distribution and is computed as the sum of the square of the difference between expected count and actual count over all included cells. The Null Hypothesis is that the points have a uniform distribution. The alternate Hypothesis is that the points don't have a uniform distribution. The program computes the critical Chi-squared value for 4 levels of significance. The results for Aquila raw total sulphur are shown on Figure 7. If the data is not uniformly distributed then holes/km^2 is meaningless as a deposit-wide value.

Testing for Randomness

Randomness in geological point phenomena, like uniformity, implies effective homogeneity of the geological medium, but additionally implies independence of points from each other. The geological process determining position of points is blind to the positions of other points. Truly random natural point phenomena are probably rare in geology, but randomness in geochemical survey sample site distribution is often advocated. The distribution of random points on a plane has much in common with random points along a line, and hence with point events through time the characteristics of the distribution can be fitted to a Poisson model.

Whereas, with events through time, the time line is divided up for analysis into equal short intervals, with point distributions the area must be divided into equal, small quadrat sub-areas. The number of these is normally more than would be used for the uniformity test. As is usual for this type of test, the number of sub-areas is large. The number of sub-areas with zero points is counted, and then one point, two points and so on. The resulting profile can then be compared with a Poisson model, for which expected frequencies are calculable. Significant departure from the model implies non-randomness; this can be in the direction of greater homogeneity (uniformity) or heterogeneity (clustering).

The test statistic has a chi-squared distribution and is computed as the sum of the square of the difference between expected frequency and actual frequency for all non-zero frequencies. The Null Hypothesis is that the points are randomly distributed. The alternate Hypothesis is that the points are not randomly distributed.

Testing for clustering and regularity

There is a spectrum of possible point distributions ranging from clustered to random to uniform to regular. The hypothetical end member at the clustered end has all points coincident; at the regular extreme, there is perfect equilateral spacing between data points. Clustered natural point phenomena demonstrate heterogeneity of the geological medium: the heterogeneity is in the distribution of probability as well as of points. It would be no surprise to find grains of a certain mineral clustered in xenoliths, fossil sessile organisms to be clustered on local hard substrates or hydrothermal ore deposits clustered around intrusions. The probability of a point forming is not constant over the whole area in these circumstances. Conversely, regular distributions are rare and imply strong constraints on point distribution.

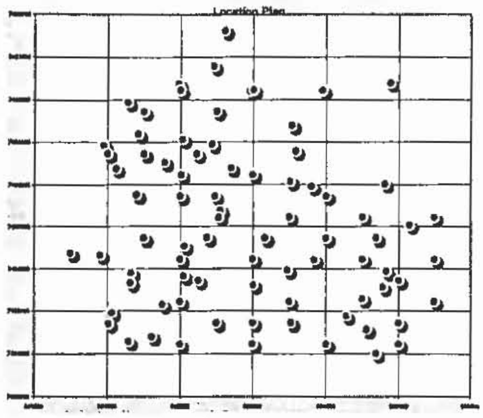
This is a composite test and is based on the average distance between data points. Clustered data will show a predominance of closely spaced data whereas regular data will have a much larger average distance. Unlike previous tests that were single-sided tests, here we can place different interpretation on the results of test depending on which tail the test statistic lies. In comparison to the previous two tests, if we fail to reject both tests, then we can conclude that the data has no regularity and is not clustered. The output also includes a histogram of distance to nearest neighbour.

Hole Density and Monte Carlo Test

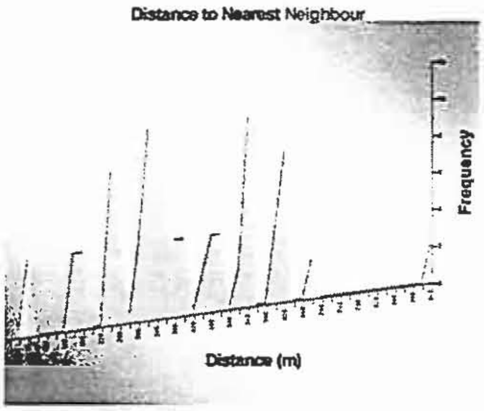
Additionally the software has additional output to calculate density (holes/km^2), histograms of distance to the nearest neighbour, and cell hole density. The last test to examine hole density produces some interesting results. The essence of the test is that some optimum grid placement can be found to maximise the number of cells that have no holes, with the resultant giving a figure of merit as to how well the area is covered. The two main difficulties are deciding what cell size should be used and what is the optimal cell placement?

The technique adopted here is a variation on a Monte Carlo simulation. A cell of required size is added to the map area at the minimum Easting and Northing corner and then within this cell, a point at random is chosen. This point becomes the origin.

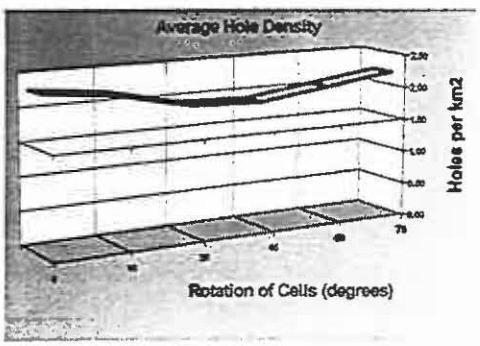
Figure 7 AQUILA SEAM RAW TOTAL SULPHUR ANALYSIS



Standard Statistics	
Statistic	Aquila seam raw total sulphur
Number	80
Minimum	0.34
Maximum	3.00
Mean	0.74
Standard Deviation	0.40
Coefficient of Variation	0.55
Median	0.60
25% Hinge	0.55
75% Hinge	0.79

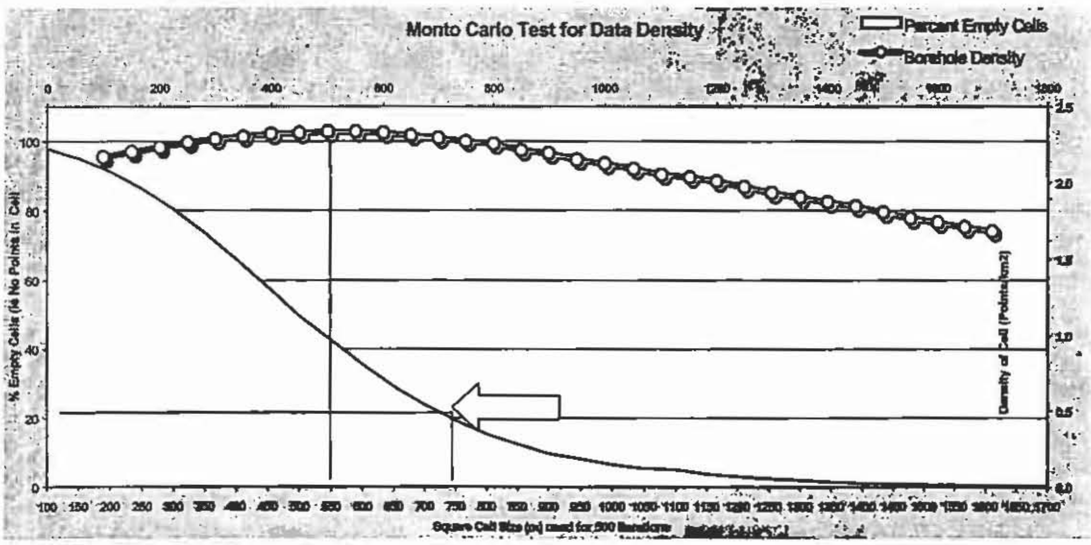


Point Distribution Tests		
Test	Result	
1.) UNIFORMITY	*Cannot Reject null hypothesis*	
	Uniformly distributed	
	Confidence of Test	Marginal
2.) RANDOMNESS	*Cannot Reject null hypothesis*	
	Randomly distributed	
	Confidence of Test	Marginal
3.) CLUSTERING & REGULARITY		
	Reject null hypothesis	
	Regularly Distributed	
	Confidence of Test	Very Good
Significance Level =	0.050	



Data Density (holes per m2)		
Test	Average	Std Dev
Holes Evenly Distributed	1.46	
Actual	2.30	1.69
Exclude Zero Cells	2.98	1.29

Nearest Neighbour		
Test	Average	Std Dev
Average Distance	384.55	170.30
Minimum Distance	54.64	
Maximum Distance	923.38	



By repeating the operation many times (500), the optimum grid arrangement can be established. One of the outputs of this test is the ratio of cells with no holes/cells with > 1 hole per cell size (see Figure 7). This ratio is a measure of how much the reviewer may need to interpolate into empty areas and the smaller this value, the better the coverage of the project area. This value, along with the average minimum borehole spacing, is a good indicator of the density of drilling. An example of the descriptive output of these series of tests is given as Figure 7. From analysis of the program's output, Thomas and Taylor (2000) have commented upon the characteristics of the data in general:

- On the assumption that drillhole data is non-uniform, an unqualified holes/km2 value is meaningless;
- The density distribution can be obtained by gridding the area of interest and calculating the density in each cell. The results are dependent on the cell size chosen;
- The cell size needs to be at least 5 x average minimum hole spacing for a reasonable set of data. Smaller than this results in too many cells with zero data;
- A cell size beyond 10 x average minimum hole spacing is too coarse and the results are little more informative than just quoting an overall density;
- The number of cells with no holes is important;
- A percentage area greater than a nominated density can be obtained from the histogram outputs of the program.

CONCLUSION

When it is completed, the characterisation study (XRD, SEM, geophysical logging) of exploration and channel samples will enable significant updating of the existing quality database to occur. This should in turn enhance the rigorous statistical analyses of available values (by seam) carried out to date and described in brief in this paper. The combination of knowing the distribution and nature of the sulphur mineralisation and having a detailed appraisal of the spatial continuity of the sulphur sample points are essential building blocks to allow areas of high sulphur to be predicted in advance of mining. Eventually, a methodology for predicting sulphur mineral concentrations in advance of mining and reconciling "as-sold" coal quality to that predicted will be developed. These prediction theories will be assessed at the coalface as mining progresses through high-sulphur zones.

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MODELLING A COAL SUBCROP USING THE IMPEDANCE METHOD

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INTRODUCTION

When a radio wave from a distant transmitter strikes the surface of the earth, part of the wave is reflected from the surface while the rest of the wave is refracted vertically into the earth. A vertically polarised radio wave, such as a very low frequency radio wave, incident upon the surface of the earth will induce a horizontal electric field component E_x in the earth, in the direction of propagation. For an earth that is uniform, the ratio between this field component and the primary magnetic field component H_y of the incident radio wave is defined as the surface impedance (Figure 1). The value of the surface impedance is dependent upon the electric and magnetic properties of the earth and is given by the relations

$$Z_s = \frac{E_x}{H_y} = \sqrt{\frac{i\omega\mu}{\sigma + i\varepsilon\omega}}$$

where $i = \sqrt{-1}$, ω is the angular frequency of the radio wave ($2\pi f$), μ is the magnetic permeability of the earth, σ is the conductivity of the earth (reciprocal of the resistivity) and ε is the dielectric constant of the earth. Since surface impedance is a complex quantity, it can be easily expressed with a magnitude and phase (angle) component. The phase is the angle difference by which the electric field component leads the magnetic field component in a cycle. For a uniform earth, the phase will always equal 45° when σ is much larger than $\varepsilon\omega$. When the earth is not uniform, for example if the earth were horizontally layered, the phase will depend upon the impedances and thicknesses of the subsurface layers and will vary from 45°. Also, if the earth is horizontally layered, the surface impedance magnitude will be modified by a factor Q that depends on the impedances and thicknesses of the subsurface layers. For example, if the earth consists of a horizontal layer of thickness h_1 with impedance Z_1 overlying a uniform earth plane of infinite depth and impedance Z_2, the surface impedance on the upper surface of the top layer is given by

$$Z_s = Q\,Z_1$$

where $$Q = \frac{Z_2 + Z_1 \tanh(u_1 h_1)}{Z_1 + Z_2 \tanh(u_1 h_1)}$$

and u_1 is the complex propagation coefficient of an electromagnetic wave in the earth (Wait, 1970).

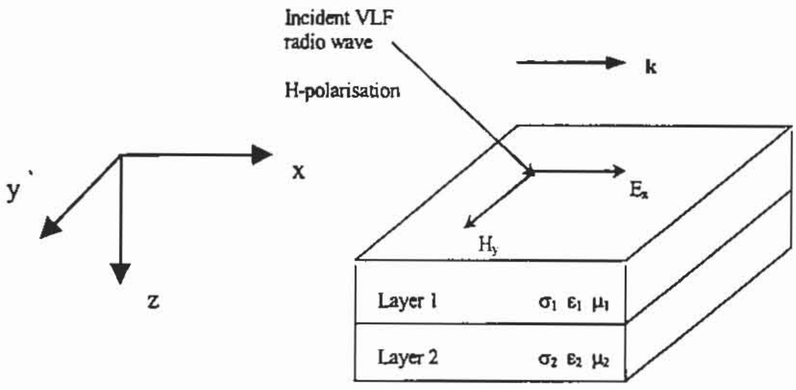

Figure 1 Schematic representation of a VLF radio wave incident upon the earth showing the primary magnetic field component Hy and the secondary electric field component Ex. In this example, the earth consists of two layers with specific conductivities σ, permeabilities μ and permittivities ε.

Surface impedance measurements have been used in the Bowen Basin coal deposits of Eastern Central Queensland for over 10 years (Biggs, 1990; Thiel, 1987) utilising the VLF radio waves generated at 19.8 kHz from a VLF transmitter at Exmouth, Western Australia, used for submarine communication and navigation. The technique has been successfully used for identifying the lateral extents of faults (Nichols, 1996), intrusions (Thiel, 1990) and coal subcrops (Nichols, 1995). VLF radio waves have a nominal depth of penetration ranging from 20 metres to 100 metres, depending upon the resistivity of the local Earth. This makes VLF surface impedance measurements ideally suited to locating relatively shallow geological structures that exhibit distinct resistivity changes at their lateral boundaries. Prior to Thiel and Mittra (1997), techniques for modelling the surface impedance of geological structures were limited to several ideal cases where the geological structures had simple shapes and hence analytical solutions could be obtained. Examples of this include the already discussed uniform, horizontal layers (Wait, 1970) and vertical discontinuity's (d'Erceville and Kunetz, 1962). When the earth is complex however, with discontinuities in both the vertical and horizontal directions, these analytical solutions can not be applied. Hence, in the past, the surface impedance technique has relied on curve shape for qualitative interpretation of geological structures. A number of numerical modeling tools have been applied to surface impedance data. The finite-difference time-domain (FDTD) method was assessed by Thiel and Mittra (1997) was computationally intensive and suffered from some modelling inabilities. Recently, a new and efficient computational technique has become available for the forward modelling of surface impedance data in the frequency domain. The impedance method was derived as a low frequency eddy current modelling technique to map volume currents generated by mains power in the human body. James *et. al.* (1999) detailed an extension and application of the technique to enable the calculation of the surface impedance for a horizontally stratified earth and in the vicinity of lateral dislocations. Recently, Thiel and Mittra (2000) extended the technique to a self-consistent formulation. When using the Impedance method, a two dimensional section of the Earth, called a solution space, is considered.

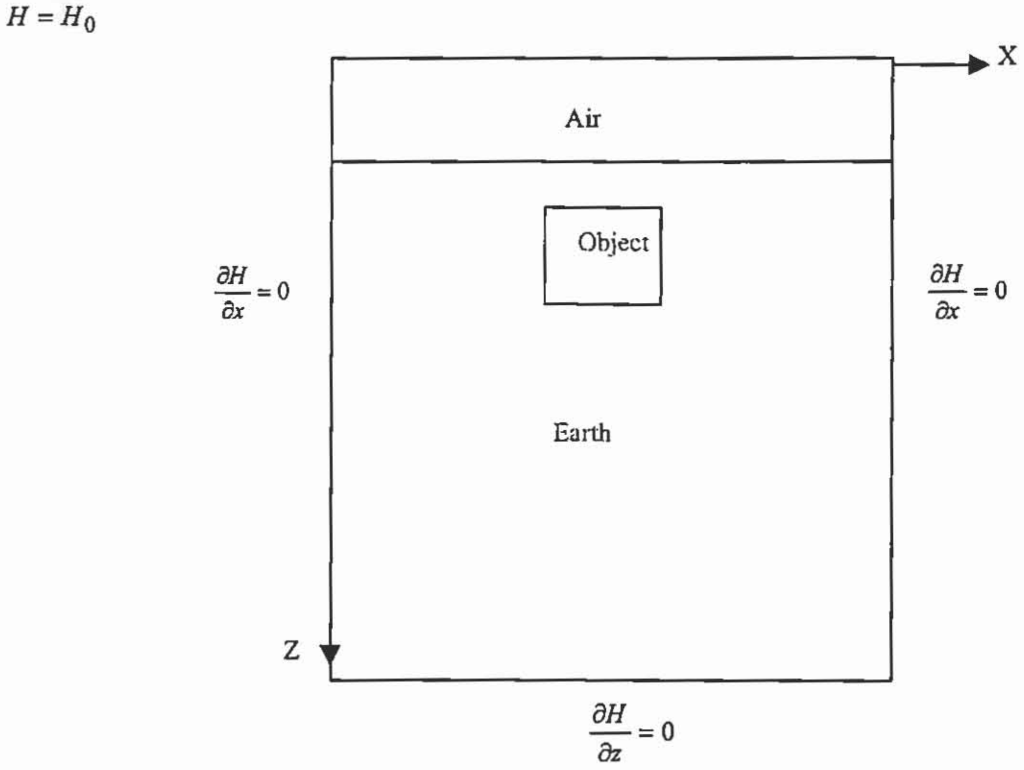

Figure 2 Solution space for the Impedance Method. Note the presence of the air cells at the top of the model to simulate free space conditions.

This solution space is divided into a regular mesh that consists of impedance elements. The impedance of these elements in each cell is determined by the size and the electrical and magnetic properties set when the model is created. The magnetic field is calculated by solving the impedance matrix with a given applied magnetic field distribution. The magnetic field component at the surface of the earth model is calculated using this process and the electric field component is calculated from the current through the impedance elements. Hence the surface impedance can be calculated for each surface cell. There are requirements in the impedance method for the depth of the model to be sufficiently large and that the cell size be sufficiently small to ensure relatively accurate surface impedance data to be calculated.

IMPEDANCE MODEL VALIDATION

The validity of the Impedance method is determined by comparing results from the Impedance models with their respective analytical solutions although this is limited to only a few ideal cases, it is sufficient to validate the technique. Thiel and Mittra (2000) present comparisons between impedance and analytical models for a uniform earth, a horizontally layered earth and a vertical contact between different earth materials. Thiel and Mittra (2000) also demonstrate the use of the impedance method for modelling the surface impedance response above a small, discrete buried object.

COAL SUBCROP MODELLING

Relatively large resistivity contrasts occur where coal subcrops against the surrounding, conductive sediments of a basin margin making this geological feature an ideal target for VLF surface impedance mapping. The accurate location of the coal subcrop is necessary for box cut and initial open cut pit designs. The surface impedance can be quantitatively measured using a Thiel Surface Impedance Meter (TSIM) which simultaneously measures the primary magnetic field component and the secondary electric field component and the phase difference between them. Nichols (1995) presented results from the utilisation of the TSIM for qualitatively identifying the positive lateral location of a coal subcrop in the Eastern Hillside deposit of Callide Coalfields. These results were used for targeting exploration drill holes, which resulted in considerable time and cost savings. Presented here, surface impedance data was collected along a single traverse above two Triassic coal subcrops in the Biloela area. The coal seams observed have a resistivity of approximately 900 Ωm. The overburden and basement have a resistivity of approximately 150 Ωm. Information of these resistivities was obtained from focused resistivity logs of boreholes in the area. The coal seams investigated have thicknesses of approximately 4 m and depths of 12 m and 20 m, so the impedance model was generated on a 40 cell by 40 cell solution space, where each cell had dimensions of 4 m by 4 m. The impedance model showing the current vectors is shown in Figure 3 and the surface impedance response is shown in Figure 4 as the magnitude and in Figure 5 as the phase. From Figures 4 and 5, the impedance model results do correlate favourably with the field results obtained although there are some discrepancies such as the loss of sharp surface impedance peaks when compared to the field data. In a later section of this paper, the causes of these differences is discussed.

In the case of coal subcrops in the Bowen Basin near Middlemount, Eastern Central Queensland, the Permian coal subcrop is overlain by an unconforming, conductive Tertiary sequence of coarse argillaceous sandstone, sandy claystone and conglomerate (Day *et. al.*, 1982) which varies in thickness from 8 m to 15 m. The effect of this sequence on surface impedance measurements is the masking of the underlying, more resistive Permian sequence since the depth of penetration of VLF radio waves decreases as the resistivity decreases.

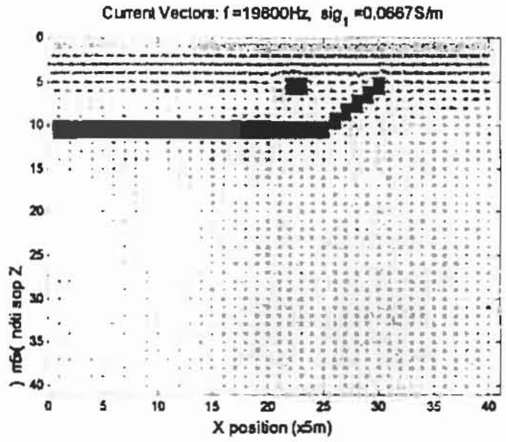

Figure 3 Impedance model of the Biloela coal subcrops showing the current vectors.

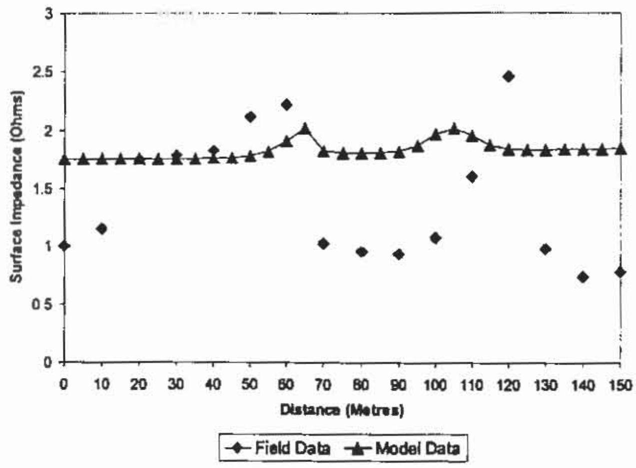

Figure 4 Comparison between the Impedance method and field results from the Biloela coal subcrop for the surface impedance magnitude.

Both the Tertiary and Permian sequences exhibit lower than normal resistivities due to a once shallow and very saline water table. Common resistivity values obtained from focused resistivity logs of boreholes in the area suggest a coal resistivity of approximately 400 Ωm, Permian sediment resistivity of approximately 40 Ωm and a Tertiary sediment resistivity of approximately 10 Ωm. Due to the unconforming nature of the Tertiary sequence and the geometry of the coal subcrop, the location of the coal subcrop from the surface impedance data using simple two layer inversion algorithms such as Wait (1970) is impossible.

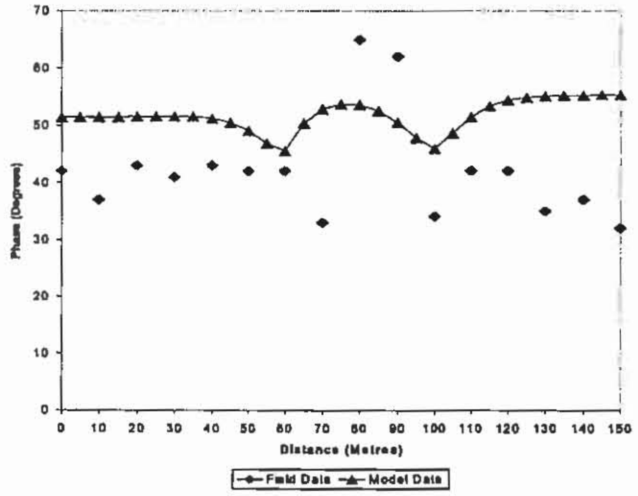

Figure 5 Comparison between the Impedance method and field results from the Biloela coal subcrop for the surface impedance phase.

The coal seam investigated has a thickness of approximately 2 m so the impedance model was generated on a 40 cell by 40 cell solution space where each cell had dimensions of 2 m by 2 m. In this model, the Tertiary layer was given a thickness of 10 m above the coal subcrop and increased to a thickness of 14 m beyond the coal subcrop. The impedance model with the current vectors is shown in Figure 6 and the surface impedance response is shown in Figure 7 as the magnitude and in Figure 8 and the phase. Figures 7 and 8 indicate the impedance model results do compare with the field results obtained although there are some discrepancies.

DISCUSSION

In both the coal subcrop case studies investigated, there are discrepancies between the impedance model data and the corresponding field data. These discrepancies have several sources. Due to the solution space consisting of a relatively large grid size (4 m), the sharp surface impedance magnitude and phase peaks observed at the Biloela coal subcrop could not be replicated in the impedance model. This same modelling difficulty occurs in the Middlemount coal subcrop, which was modelled with a medium grid size (2 m). The difference in the phase between the impedance model and the field data, particularly in the Middlemount coal subcrop example, results from imperfect depth boundaries in the modelling process. Also, the effects of three-dimensional structures are not evident in two-dimensional models. Corrections to this are being investigated. Another reason for the difference between model and field data not related to the modelling process is that the measuring instrument may exhibit non-linearity in its instrumentation at certain Earth resistivities. Attempts are currently be made to address these issues.

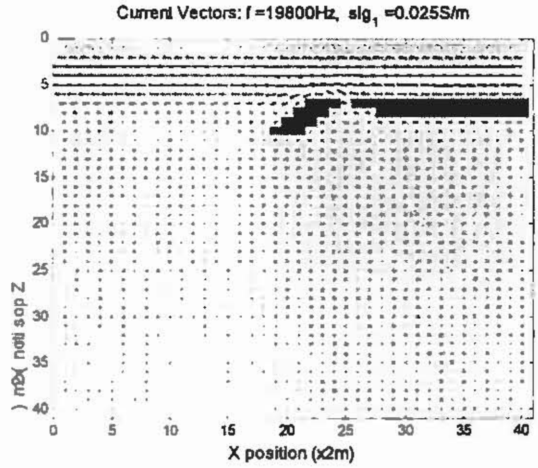

Figure 6 Impedance model of the Middlemount coal subcrop showing the current vectors.

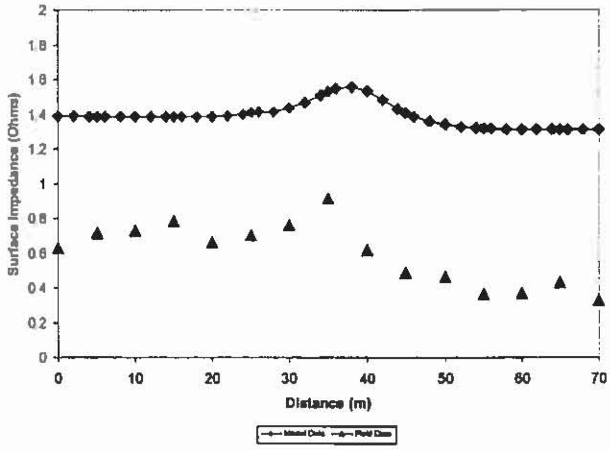

Figure 7 Comparison between the Impedance method and field results for the Middlemount coal subcrop for the surface impedance magnitude.

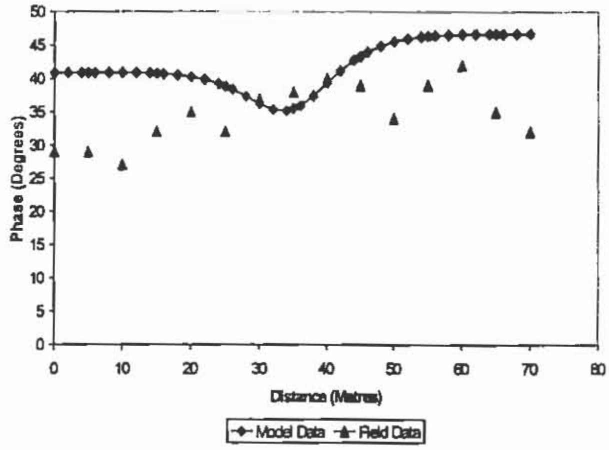

Figure 8 Comparison between the Impedance method and field results for the Middlemount coal subcrop for the surface impedance phase.

CONCLUSION

The impedance method has been demonstrated to satisfactorily model the surface impedance response of coal subcrops in two dimensions. The models developed compared favourably with field results from coal subcrops in the Callide and Bowen Basins of Eastern Central Queensland. Some discrepancies do exist between the model and field data and these have been related to discretization of the solution space in the impedance model, difficulty in using the lower boundary condition, no possible consideration of the effects of the three dimensional physical nature of coal subcrops and non-linearities in the response of the surface impedance meter used to collect the field results. Work is continuing to address these issues.

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THE ONSET OF PERMIAN VOLCANISM IN THE SOUTHEASTERN SYDNEY BASIN

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Early Late Permian (Kungarian - Kazanian) volcanism provided a significant source of sediment, together with tuff beds and lava flows, during the deposition of the upper Shoalhaven Group in the southesatern part of the Sydney Basin. In the Late Permian to Middle Triassic the Sydney-Bowen Basin was a classic foredeep or foreland basin of the New England Fold Belt, flanked to the west by the Lachlan Fold Belt and to the east by a newly resurgent and emergent volcanic arc (Veevers *et al.*, 1994). This volcanic arc, referred to as the Currarong Orogen (Jones *et al.*, 1984), acted not only as a provenance for epiclastic material and a centre for latite extrusions, but also it represented a barrier behind which longshore currents prevailed and periodic restricted anoxic conditions occurred. Thus it controlled deposition and overall development of the Sydney Basin from Early Permian times (Evans, 1991).

The first documented sign of an emergent volcanic chain is a tuff emplaced in the upper Wandrawandian Siltstone at Penguin Head (Veevers *et al.*, 1994) and Green Point, northeast Jervis Bay (Runnegar, 1980). However, Tye *et al.* (1996) suggested the Currarong Orogen developed as an uplifted barrier to the east during the deposition of the upper Snapper Point succession based on the change from a storm-dominated open coastal environment to one dominated by northward-directed longshore currents.

By the Late Permian, volcanic extrusive and associated tuffaceous deposits swamped the southeastern Sydney Basin, with lava flows and intrusions typical of the shoshonitic rock association (Carr, 1998). These formed the Broughton Formation that represents the last phase of deposition of the predominantly marine Shoalhaven Group.

STRATIGRAPHY OF THE COOLANGATTA MOUNTAIN AREA

The coastal stratigraphy in the Coolangatta Mountain area (Black Head, Gerroa, to Kinghorn Point southeast of Nowra) starts with the upper Wandrawandian Siltstone and passes up to the Blow Hole Latite Member of the Broughton Formation (Fig. 1). In this coastal area only the eastern edge of the Nowra Sandstone is present (Le Roux and Jones, 1994) and at Kinghorn Point the offshore deposits of the Wandrawandian Siltstone pass conformably and gradationally up into the Berry Formation (Bann and Jones, 2000a). All of these units are fossiliferous and were deposited under shallow marine conditions.

PERMIAN SHOALHAVEN GROUP	Broughton Formation	Jamberoo Sandstone Member
		Bumbo Latite Member
		Kiama Sandstone Member
		Blow Hole Latite Member
		Coolangatta Latite Member
		Koo-Lee Tuff Member
		Back Forest Tuff Bed
		Westley Park Sandstone Member
	Berry Formation	
	Nowra Sandstone	
	Wandrawandian Siltstone	
	Snapper Point Formation	
	Pebbley Beach Formation	

Fig. 1 Stratigraphic units in the Shoalhaven Group, southeastern Sydney Basin

Igneous units within the Berry Formation and Westley Park Sandstone Member

Carr (1983) remapped and clarified the stratigraphic nomenclature of the lower Broughton Formation and Gerringong Volcanics. He suggested the Blow Hole Latite Member was the first flow of nine within the Gerringong Volcanics and that it outcropped on Coolangatta Mountain, rather than the Bumbo Latite as previously suggested by Harper (1915). The present mapping has defined a number of new units on Coolangatta Mountain in and above the Westley Park Sandstone Member (Bann and Jones, 2000b).

A thin tuff bed, composed predominantly of relict glass shards, was identified within the lower Westley Park Sandstone Member on Coolangatta Mountain (Back Forest Tuff Bed, Bann and Jones, 2000b). Also on Coolangatta Mountain, lensoidal porphyritic igneous units are interbedded with sandstone beds, extrusively and contemporaneously, between about 50 m and 190 m a.s.l. (Bann and Jones, 2000b). The Koo-Lee Tuff Member crops out in gullies at about 120 m, is 2-3 m thick and contains abundant well-preserved relict glass shards (Bann and Jones, 2000b). Fossils found within this ash have been identified as the small marine gastropod *Warthia stricta*. At about 190 m a.s.l. a 30 m-thick dark grey trachytoid porphyritic latite extrusion, with plagioclase phenocrysts up to 4 cm in length, has been named the Coolangatta Latite Member (Bann and Jones, 2000b). A breccia unit is developed at the base of the flow where it overlies a sandstone bed at the top of the Westley Park Sandstone Member. A second latite unit (15 m thick) with a prominent foliation but no large plagioclase phenocrysts overlies the basal latite extrusion and is interpreted as the Blow Hole Latite Member.

The first documented evidence of penecontemporaneous volcanic activity (other than ash deposits) in the southeastern Sydney Basin occurs at Kinghorn Point where andesitic lava has intruded into wet unconsolidated silty sediment (Bann and Jones, 2000a) at the base of the Berry Formation. This dyke/sill predates any previously documented lava flows in the southern Sydney Basin. It has a porphyritic texture with stumpy plagioclase phenocrysts and is similar to other andesite units within the Gerringong Volcanics.

SEDIMENTOLOGY

Wandrawandian Siltstone

The Wandrawandian Siltstone crops out at Crookhaven Heads, Penguin Head and Kinghorn Point and consists predominantly of light to dark grey, fine- to coarse-grained, quartzofeldspathic siltstone overlain by thin lenses of Nowra Sandstone. It generally contains a rich fossil assemblage, including large crinoid stems, brachiopods and bryozoans. Glendonites are preserved at Crookhaven Heads, and are abundant in a number of horizons. Pale fine-grained clay beds, up to 15 cm thick, resemble ash deposits but they have undergone extensive weathering which hinders an accurate diagnosis. Similar strata at Penguin Head have previously been interpreted as ash by Conaghan (in Veevers *et al.*, 1994). Clasts within the Wandrawandian Siltstone (dropstones) consist of pre-Permian dacite, ignimbrite and meta-sediment derived from the Lachlan Fold Belt.

Nowra Sandstone

The Nowra Sandstone lenses out in the coastal area, where it occurs as storm-sand beds and distal turbidites interposed between the Wandrawandian Siltstone and Berry Formation (at Crookhaven Heads, Penguin Head and Kinghorn Point).

Berry Formation

The Berry Formation comprises the majority of exposure throughout the Coolangatta Mountain and Kangaroo Valley area. Most localities contain massive, indistinctly bedded (often as a result of biogenic homogenisation) to flat-bedded, mid- to dark-grey siltstone and very fine-grained feldspathic litharenite. Thin fine-grained light-grey to light-brown sandstone lenses are interdigitated with the siltstone and they become thicker as they grade into the overlying Broughton Formation. The basal parts of some sandstone beds contain clasts and body fossils and they are interpreted as mass-flow deposits. The sandstone throughout the unit (including the basal part of the succession at Kinghorn Point) consists predominantly of quartz, plagioclase and rare K-feldspar, volcanic rock fragments, clay minerals and cement. Pebbles up to 12 cm in diameter, composed mainly of basic to intermediate volcanic rock and fine-grained quartzite, occur sporadically throughout the middle and upper parts of the unit but are rare at the base. Glendonites occur in the basal part of the formation (e.g. Kinghorn Point) where they are associated with abundant bioturbation.

Bioturbation and body fossils range from abundant body fossils with little bioturbation to abundant bioturbation with rare body fossils preserved. Body fossils generally increase in abundance towards the top of the formation but an abundant assemblage was found in the central portion of the formation at Nowra Hill, and includes brachiopods (*Notospirifer, Spirifer*, productids, *Ingelerella*), gastropods (*Platyschisma, Warthia*), conulariids, bivalves (*Pyramus, Myonia, Mourlonopsis*), bryozoans (fenestellids, *Polypora, Stenopora*) and crinoid stems. The most abundant trace fossil identified was *Zoophycos* isp.

The Berry Formation was deposited in a low-energy marine environment, probably around or slightly below storm wave-base. Increased anoxic conditions within the formation are indicated by fewer fossiliferous horizons with a lower faunal diversity (Jones *et al.*, 1986). This restricted marine fauna may have been influenced by reduced circulation caused by rapid growth of the mid-Permian volcanic island chain to the east (Jones *et al.*, 1986). The mass-flow deposits and very rare hummocky cross-stratified beds reflect a minor input of storm-sand into the silty environment. Alignment of crinoid stems suggests at least periodic northward-trending longshore currents.

Westley Park Sandstone Member

The lowermost member in the Broughton Formation, the predominantly grey/green bioturbated volcarenite of the Westley Park Sandstone Member, conformably and gradationally overlies the Berry Formation at various sites in the study area (e.g. Bolong, Kangaroo Valley and sites around Berry) as previously noted by Bowman (1974) and Jones *et al.* (1986). No sign of the sequence boundary described by Arditto (1991) was seen. On Coolangatta Mountain the base of the member is defined at the start of volcaniclastic beds more than 25 cm thick. Most sandstone beds are massive as a result of bioturbation but a few graded sandstone beds and rare cross-stratified beds are also present. Conglomerate lenses within the sandstone succession contain abundant rounded volcanic clasts. Abundant body fossils are preserved at a few locations within this member, especially at Black Head, Wattamolla and Coolangatta Mountain. Fossils include brachiopods (*Ingelerella*, productids), bivalves (*Megadesmus*) and bryozoans (*Stenopora crinita*).

Strata within the basal exposures of the Westley Park Sandstone Member are composed dominantly of immature basaltic and andesitic detritus of similar composition to the Gerringong Volcanics (Raam, 1968; Bull and Cas, 1989). This implies that volcanism had started and was contributing particulate material to the sedimentary system well before emplacement of the first outcropping latite flow of the shoshonitic Gerringong Volcanic Facies (Harper, 1915; Carr, 1983, 1998).

The upper Westley Park Sandstone Member at Black Head is interpreted as a lower shoreface environment where rapid deposition was influenced by northward-directed longshore currents moving sediment from an area of relatively continuous volcanic activity to the south and/or southeast (Hitchin, 1997). Carr and Jones (2000) suggested the uppermost Westley Park Sandstone Member in the Gerroa-Kiama area represents deposition probably above fair-weather wave base in water depths of about 20m, under the action of a northward flowing, tide-generated long-shore current.

Volcanic dropstones are common in the Westley Park Sandstone Member and the high rate of supply of volcanic detritus swamped any craton-derived sediment. Andesite and basalt are the most common igneous clasts. Although clasts range from angular to well rounded, most are subrounded and they generally exhibit a high degree of sphericity. Andesitic clasts were found to have characteristic, stumpy plagioclase phenocrysts. Relatively large angular clasts of highly vesicular basalt are preserved at a number of sites in the east of the study area. Three extremely weathered clasts found at Black Head have a porphyritic trachytoid texture of large tabular plagioclase phenocrysts (up to 3 cm) in a fine-grained groundmass that appears to be identical to the Coolangatta Latite Member. Clasts at Black Head reach a maximum of 1.4 m in length (average is 14 cm) and the shape and size of the clasts suggests that they are the product of ice-rafting into the marine environment. The larger dropstones are all composed of latite that is similar in appearance to the overlying latites of the Gerringong Volcanics.

Thick tuff deposits, lava flows and large volcanic clasts (dropstones) were absent from the Westley Park Sandstone Member in the Kangaroo Valley area to the west. In this area the unit is predominantly composed of heavily bioturbated, fine- to coarse-grained sandstone containing quartz, plagioclase and (latitic) volcanic material.

DISCUSSION

Sedimentology

Sedimentary units within the Wandrawandian Siltstone, Berry Formation and Broughton Formation are characterised by an abundance of bioturbation and the presence of variable quantities of body fossils. The finer units represent slow deposition below storm wave base in a shallow marine shelf or seaway. The presence of occasional thin coarser sandstone beds at the junction between the Wandrawandian Siltstone and Berry Formation at Kinghorn Point indicates derivation from two distinct source areas. The rare quartz-rich beds were derived from the eastern margin of the Nowra Sandstone and represent detritus from the Lachlan Fold Belt whereas the more common lithic sandstone beds contain feldspar and volcanic detritus and were derived from the Currarong Orogen and its associated volcanic centres. They are interpreted as probable distal mass flow deposits derived from the flanks of a volcano situated to the south (i.e. a predominant northerly current flow direction given by crinoid stems). The inclusion of quartz in the sandstone beds may reflect a source influence from the Lachlan Fold Belt to the west, but more probably it was derived from earlier sedimentary strata uplifted along the Currarong Orogen. These beds represent the first reworked volcanic detritus in the southern Sydney Basin, as opposed to the airfall ash recorded from the top of the Wandrawandian Siltstone (Runnegar, 1980). The presence of glendonites suggests quiet frigid conditions prevailed for part of this depositional period. The frequency of the event beds decrease upwards through the Berry succession, which may reflect a minor eustatic rise in relative sea-level (transgression) with less storm material being supplied to the environment.

The central part of the Berry Formation accumulated below storm wave base but still received occasional mass flows of lithic sand. The relatively anoxic bottom conditions restricted the faunal diversity and may reflect poor circulation caused by volcanic accumulations restricting the entrance to the seaway west of the Currarong Orogen.

Towards the top of the Berry Formation the quantity of sandy volcanic detritus increases, heralding the rapid progradation of the volcanic apron forming the thick southern portion of the Westley Park Sandstone Member. This succession was mainly deposited by mass flow mechanisms into a shallow marine environment where much of it has been strongly bioturbated. Sandstone deposition was periodic and it may have been influenced by the cold climate with winter sea ice. Rapid deposition is also reflected by the greater proportion of bivalves in the fossil assemblage. Longshore currents had again become active and are represented by an increased faunal diversity and occasional cross-stratified sandstone beds. Within the uppermost Westley Park Sandstone Member the succession became shallower and cleaner but it also showed a distinct deepening towards the north (Carr and Jones, 2000).

Glendonites

Glendonite crystals (pseudomorphs after ikaite, Carr *et al.*, 1989) are present in all three formations in the study area. They indicate cold palaeoclimatic conditions (possibly periglacial and under a cover of sea ice) that continued for long enough to enable the repeated growth of crystals without inversion to calcite (i.e. < 5°C).

Dropstones

Previous authors have discussed the occurrence of large dropstones within the succession at Black Head (e.g. Harper, 1915; Raam, 1968; Bowman, 1974; Hitchin, 1997). The only plausible explanation for the presence of the megaclasts (dropstones) is from ice rafted debris carried into the marine environment by sheet-ice released from seasonal melting of shore and/or river ice. It is suspected that prior to incorporation into the ice rafts, the boulders and clasts originated became rounded in a high-energy environment following derivation by debris or lahars flows from the flank or cone of an adjacent volcano. Raam (1968) recognised at least five different volcanic lithologies from the included clasts and dropstones. Andesite was most common, followed by latitic, trachytic and doleritic varieties. These volcanic components comprised more than 95% of the lithic clasts. The occurrence of up to five different latite varieties together suggests that the material was either derived from a composite subaerial volcano that erupted lavas of slightly different composition through time, or from a number of smaller volcanoes erupting lavas with slightly different compositions.

Clast distribution

Porphyritic andesite clasts are scattered throughout the study area, which suggests that their source is a reasonable distance away. The highly vesicular basalt located in the coastal area suggests a more proximal source due to its larger clast size and the more restricted nature of its occurrence. These basaltic clasts were only found within a small stratigraphic interval at the top of the Berry Formation and at the base of the Westley Park Sandstone Member. This may suggest a proximal subaerial basaltic eruption towards the end of Berry Formation deposition. No large clasts or dropstones of this particular basalt were found at Black Head, suggesting that this basaltic flow had been eroded by this period of deposition or, alternatively, Black Head was more distal from the source.

The reason very few volcanic clasts were found in the Kangaroo Valley area was due to its distal location from the active volcanoes and the prevalence of northward palaeocurrents during deposition. The presence of a small percentage of granitic intraclasts indicates a minor influence from the west and suggests that the longshore currents may have controlled the distribution of volcanic clasts. The palaeocurrent flow direction also suggests that the volcanic centres lay to the south or southeast of the study area.

Volcanic Activity

The presence of ash bands within the Wandrawandian Siltstone provides the first positive evidence of volcanic activity within the study area. Volcanic influences are not obvious in the Nowra Sandstone where longshore currents reworked quartzose material from coastal fluvial deposits derived from the Lachlan Fold Belt to the west. This suggests that any lava extrusions were a significant distance from the western coast and were not affected by the active longshore currents. The presence of latitic clasts and thin tuff beds in the Berry Formation suggests extrusive volcanism (both andesitic and basaltic) was occurring regionally during its deposition.

The 2 m-thick pyroclastic Koo-Lee Tuff Member and latite lenses in the lower Westley Park Sandstone Member at Coolangatta Mountain suggests that the tempo of volcanism increased or that the eruptions became more proximal. This is confirmed by coastal strata in the Westley Park Sandstone Member between Coolangatta Mountain and Black Head being swamped by volcanic detritus. The presence of *Warthia* within the Koo-Lee Tuff Member suggests that the source location was proximal and the animals were buried either *insitu* or only transported a short distance (cf. Lockley, 1990). Consistent predominant northerly-directed palaeocurrents and the reduction in volcanic clast abundance from east to west, suggests that the volcanic source lay to the south or southeast. An easterly source can be ruled out due to the fact that both the Berry and Wandrawandian Siltstones thicken to the east where water levels were deepest during their deposition.

Andesitic latite was the predominant extrusive rock produced by eruptive volcanism during the early phases of deposition of the Gerringong Volcanics. Trachyte and basalt are also common. Eruption of fluidal mafic magma would have been less violent than the phreatomagmatic explosions associated with deposition of the pyroclastic tuff beds.

Volcanic source location

The Westley Park Sandstone Member in the Coolangatta Mountain area is interpreted as a sedimentary apron about a volcanic vent(s) on the northwest edge of the magmatic arc of the Currarong Orogen. It is also likely that the described deposits represent a small or distant component of a much larger volcaniclastic apron surrounding a vent located about 50 km to the southeast. The relative thickness of the Westley Park Sandstone Member on Coolangatta Mountain (i.e. >160 m), compared to elsewhere (maximum 45 m), suggests that the local units represent high-energy (shallow water) deposition. Abundant volcaniclastic material would have been shed northwestwards off the volcano into the basin as lahars, debris flows and turbidites forming a prograding volcaniclastic apron.

Geophysical evidence, combined with sedimentological data, indicates that volcanic vents were generally located in a north-northwest trending volcanic arc associated with a subduction zone to the east. All magnetic anomalies within the southern Sydney Basin strata (Bembrick and Holmes, 1976) are circular in shape, suggesting they are ancient stocks, plugs or even shallow sub-volcanic magma chambers. These anomalies may be interpreted as the volcanic centres responsible for the deposition of at least the southern Gerringong Volcanics. An anomaly 40 km southeast of Jervis Bay, and a possible smaller vent situated at Jervis Bay, may have been the source of the volcanic detritus identified in this study. It is possible that only the larger anomalies (i.e. >5200nT) represented active and eruptive volcanoes, whilst the smaller anomalies may reflect small intrusions associated with these volcanoes. These suggested volcano locations, and their distance southeast, corresponds with the suggestions of previous authors that the source of the volcanic material composing the Westley Park Sandstone Member was in this general locality (e.g. Harper, 1915; Raam, 1968). This is in contrast to the western source suggested by Bull and Cas (1989).

The authors found no evidence for eruption of any of the earliest flows to have come from a westerly or northwesterly vent location, as suggested by Carr (1983) and Bull and Cas (1989) for the Blow Hole and younger flows. Carr and Jones (2000) also placed the vent location of the Blow Hole Latite Member to the west or southwest of Kiama based on the flow thickness and the easterly flow direction shown by the lava tubes, as well as the presence of fluvial deposits and a palaeosol (Retallack, 1999) to the southwest.

Palaeogeography

The palaeogeography of the Coolangatta Mountain area during the mid-Permian was dominated by volcanic activity on the Currarong Orogen that extended along the Panthalassan margin of Gondwana, behind a subduction zone located to the east. The Sydney Basin was a sediment trap between the contemporaneously forming orogen to the east and older cratonic rocks of the Lachlan Fold Belt to the west. All sedimentological, geophysical and volcanological evidence suggest that a large subaerial volcano lay to the south-southeast at a distance of about 50 km. This volcano was erupting latitic (predominantly intermediate) lava, some of which was subsequently eroded and deposited in the Coolangatta Mountain area. Vent location may have moved north-northwest to Jervis Bay with a smaller vent possibly located at (or near) the Currumbene Intrusion. Sedimentation was influenced drastically by these southerly and southeasterly volcanoes, not just by the supply of huge amounts of volcanic material (swamping the craton-derived quartzose sediment from the Lachlan Fold Belt), but in creating wave and current deflectors and dampeners. Sediment movement would have also been affected by a seasonally cold climate (dropstones, glendonites and permafrost palaeosols – Retallack, 1999) with sheet ice in winter and rapid sediment movement from the volcanoes during spring thaws. Sea-level changes previously attributed to glacio-eustatic sea level transgressions and regressions (i.e. Milankovitch Cycles) were overprinted by the influence of volcanism in the upper Shoalhaven Group in the southeastern Sydney Basin.

CONCLUSIONS

Volcanism on the Currarong Orogen in the southeastern Sydney Basin started during the mid Permian deposition of the uppermost Wandrawandian Siltstone. Volcanic activity was contemporaneous with deposition of the lower Berry Formation and contributed a large quantity of detritus in the eastern part of the basin. A latitic dyke/sill located at Kinghorn Point, intruded into wet unconsolidated sediment during deposition of the lower Berry Formation, had a similar texture to other rocks of the Gerringong Volcanics. The upper Berry Formation was swamped with volcanic detritus including larger trachyte, basalt and andesite clasts, shed off a volcanic centre as turbidity currents. Ice-rafted dropstones are also prevalent. This unit grades upwards gradationally and conformably into the overlying Broughton Formation.

Three new volcanic units were recorded in the Westley Park Sandstone Member on Coolangatta Mountain. The Back Forest Tuff Bed at the base of the unit and the Koo-Lee Tuff Member indicate that some of the eruptions were explosive. Extrusive events formed lenses of porphyritic latite in the lower part of the member and produced a thick flow, the Coolangatta Latite Member, at the top of the member. These represent new units within the Gerringong Volcanics.

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SEDIMENTOLOGY OF THE SHOALHAVEN GROUP, WESTERN MARGIN, SYDNEY BASIN

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ABSTRACT

The Sydney Basin is one of two major coal-producing basins in the eastern half of the Australian continent. Correspondingly, most sedimentological studies relating to the Permian sequence of the Sydney Basin have concentrated on the Illawarra Coal Measures and little attention has been given to the older Shoalhaven Group. It is generally recognised that the Permian sequence of the Sydney Basin represents cyclic deposition corresponding to transgressive-regressive sea level changes. In the southern part of the Sydney Basin, recent studies have shown that the Shoalhaven Group can be divided into five depositional systems (with two systems containing coal-forming stages, Clyde Coal Measures and Yarrunga Coal Measures) representing transgressive and regressive stages. Along the western margin of the Southern Coalfield, the sequence is much thinner and the five depositional systems cannot be clearly defined.

Facies variations along the western margin of the Southern Coalfield indicate a major marine transgression with basal conglomerates grading upwards through near shore sandstone and finally bioturbated shelf siltstones containing dropstones indicative of a glacial environment. Basement topography influenced the depositional styles and consequently the facies types. The deposition of the Marrangaroo Conglomerate, the lowermost unit of the Illawarra Coal Measures in this area, indicates the marine transgression was abruptly halted.

INTRODUCTION

A combination of factors, including lack of economic resources, has resulted in the lowermost stratigraphic unit of the Permian Sydney Basin sequence, the Shoalhaven Group, being largely ignored in recent geological studies, particularly along the western margin of the Sydney Basin. Excellent outcrop of the Shoalhaven Group is exposed to the west of Mittagong, along Wombeyan Caves Road, Bullio, and Joadja. Northwest of Mittagong, around the old mining ghost town of Yerranderie, good outcrop is in cliff sections.

The coastal stratigraphy of the Sydney Basin is markedly different to the marginal stratigraphy. Most coastal sequences wedge out from east to west before the basin on-laps the stable Lachlan Fold Belt. Tye (1995) and Tye *et al.* (1996) published the most recent review of the Shoalhaven Group stratigraphy (Fig. 1). In this review, Tye recognized five depositional systems:

Shoalhaven Group Upper Nowra Sandstone-Berry Siltstone	nearshore marine-offshore coastal (DS5)
Lower Nowra Sandstone	nearshore marine and coastal (DS4)
Snapper Point Formation-Wandrawandian Siltstone	fluvial and coastal-nearshore marine (DS3)
Yadboro/Tallong Conglomerates-(Yarrunga Coal Measures)-Pebbly Beach Formation	basin margin alluvial apron-nearshore marine (DS2)
Talaterang Group Clyde Coal Measures-Wasp Head Formation	alluvial valley fill-nearshore marine (DS1)

The lowermost member of the Shoalhaven Group cropping out on the western margin of the basin has been termed the Hawkshill Conglomerate. It lies unconformably over granitic and folded metasedimentary basement rocks. The Snapper Point Formation and/or the Berry Siltstone are reported to overlie the Hawkshill Conglomerate. The Hawkshill Conglomerate has been related to other basal Sydney Basin conglomerates including the Yadboro Conglomerate, Tallong Conglomerate and Megalong Conglomerate that also occur along the western extremities of the basin.

In this paper we review the geology of the Shoalhaven Group along the southwestern margin of the Sydney basin, suggest factors that influenced deposition and suggest depositional environments.

SOUTHWESTERN MARGIN OF THE SYDNEY BASIN

For this paper the basal section of the Permian sequence was examined in the Bullio-Joadja area, the Marulan area, and at Yerranderie. In describing the sequences the following facies are used:

Facies Code	Lithology	Sedimentary Structures
Dms	poorly sorted boulder conglomerate	horizontally stratified, random clast orientation, matrix supported
Cph	pebble to cobble conglomerate	clast supported, horizontally stratified
Sm	fine to coarse sandstone	massive
Shc	fine grained to silty sandstone	hummocky and swaley cross stratification
Smb	siltstone	massive, bioturbated

Bullio-Joadja Area

1. In the Bullio-Joadja area, the basal unit is characterised by facies Dms. In the valley of Joadja Creek , a highly irregular, poorly- to very poorly-sorted polymict conglomerate with a silty sandstone matrix comprising 30 and 80% of the rock is exposed. The largest clast size was 1.5m in diameter but clasts up to 90cm are

common. The predominant size is between 25-50cm. The conglomerate overlies the granite basement rocks of the Lachlan Fold Belt.

In the Wingecarribee River a similar conglomerate is found although the clasts are smaller with the maximum diameter of 60 cm. At both localities, the clasts appear to have been derived from the nearby basement rocks.

A similar large boulder conglomerate was reported by Feldtmann (1991), Feldtmann and Hutton (1993) and Hutton and Feldtmann (1996) along the Great Western Highway, west of Lithgow. In that area the lithology was interpreted as a fan delta complex. A similar origin is suggested for the unit at Bullio-Joadja.

2. Also outcropping in the Bullio-Joadja area is Facies Sm, consisting of massive, structureless, fine to coarse-grained sandstone with sporadic pebbles, cobbles and boulders throughout. The clasts occurred isolated, in clusters and in layers. The facies is interbedded with facies Shc. An example is in Joadja Creek valley where cross bedding is evident in some beds of Sm.

Organ (1985) described a section at Nundialla Hill that is interpreted as consisting of Facies Sm and Feldtmann and Hutton (1991) also recorded the same facies in the Lithgow area.

Facies Sm was interpreted by Feldtmann (1991), as representing a near-shore marine environment, with two main points of evidence for this interpretation – the interbedded nature of Sm and Shc, and the pebble beds that are well sorted and segregated into laterally continuous, distinct uniform layers, that is characteristic of marine worked gravels.

Feldtmann (1991) stated that the medium to coarse grained sandstone, typical in the foreshore to backshore zone, does not have wave-generated structures because of the well-sorted and coarse-grained nature of the sand. A similar origin is suggested for Facies Sm and Shc in the Bullio-Joadja area. The wide variation in these facies, particularly around Joadja and Nundialla Hill, is due to local source variations, in combination with basement irregularities that have influenced the type of depositional mechanisms.

3. By far the thickest unit in the Bullio-Joadja area is a bioturbated siltstone (Facies Smb). This unit occurs above the sandstone facies and is overlain by basal conglomerates of the Marrangaroo Conglomerate that is the oldest unit of the Illawarra Coal Measures in this area.

Facies Smb is composed of pale-dark grey sandy micaceous siltstone or silty fine sandstone. The unit appears massive due to the bioturbation throughout the sequence. The bioturbation ranges from moderate to intense. At one locality west of Wombeyan Caves Road, numerous brachiopod, pelecypod and bryozoans were found.

The facies contains pebbles, rarely boulder, clasts at all localities examined. The composition of the clasts is always either granite or quartzite and both types are commonly well rounded.

A quiescent environment is suggested for Facies Smb because of the absence of sedimentary structures. The abundance of bioturbation also supports prevailing quiet conditions and slow sedimentation rates, allowing the burrowing organisms to thoroughly disrupt bedding at some localities. The thickness (possibly up to 120m at Bullio and Joadja) and nature of this facies at certain localities, indicates that these conditions were prevalent for an extensive period of time.

The extensive bioturbation suggests deposition of this facies on a shallow marine shelf, below storm wave base where no sedimentary structures from wave and current mechanisms could develop. The extensive bioturbation and large clasts (dropstones) throughout the Smb facies also supports this interpretation for deposition.

Marulan

In the Marulan area, especially at Red hill, the basal unit is dominated by facies Cph. Individual beds are commonly 20 to 50cm thick and have large scale cross bedding. Also channels with basal lag layers have south to southeasterly palaeocurrent directions. There is also a general dip of the crudely stratified beds of approximately 5 to 10^{o}, in a southeasterly direction. This outcrop was described Tye (1995).

This unit represents a more distal facies of the boulder conglomerate. Hutton and Feldtmann (1996) also described a similar unit in the Lithgow area.

Yerranderie

In the Yerranderie area only Facies Smb was observed.

Palaeotopography

Feldtmann and Hutton (1996) noted that the topography of the basement was a major influencing factor in the deposition of the Shoalhaven Group in the Lithgow area. In the Bullio-Joadja to Marulan area, the topography of the basement is also a major influencing factor in the deposition of the Shoalhaven Group.

A summary of the stratigraphy of the southwestern margin of the Sydney Basin is shown in Figure 2.

SUMMARY

The Shoalhaven Group along the southwestern margin of the Sydney Basin is a transgressive sequence with the rise in sea probably a result of ice thaw due to an ameliorating climate although some influence from passive thermal subsidence cannot be ruled out.

The Shoalhaven Group along the southwestern margin of the Sydney Basin is a much condensed sequence compared to that outcropping along the coast.

Palaeotopogragphy was a major control on deposition. Two significant palaeohighs are located where the western margin basin crosses the Wombeyan caves Road, at Bullio, and also adjacent to Joadja Creek . It is suggested that the western margin of the Sydney Basin did not extend much further west from where it is now located because both at Bullio and Mudgee, basement rocks are exposed many tens of metres above the Illawarra Coal Measures as well as the Shoalhaven Group.

The conglomerates represent an alluvial apron of debris moving off the elevated landmass to the west. The sandstone is possibly equivalent to the Nowra Sandstone and represents a minor progradational mass flow deposit that was possibly reworked before the onset of the Berry Siltstone depositional stage. The bioturbated siltstone is equivalent to the Berry Siltstone of Tye (1995) and represents a major transgressive regime with shoreline retreat.

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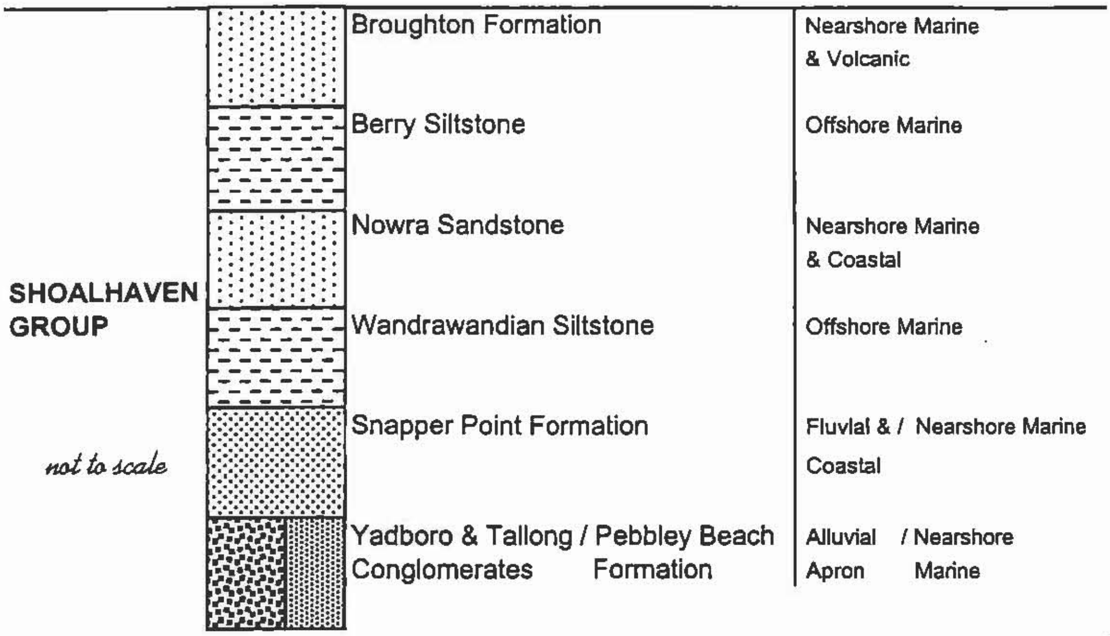

Figure 1. Stratigraphy of the Shoalhaven Group, coastal area (after Tye, 1995)

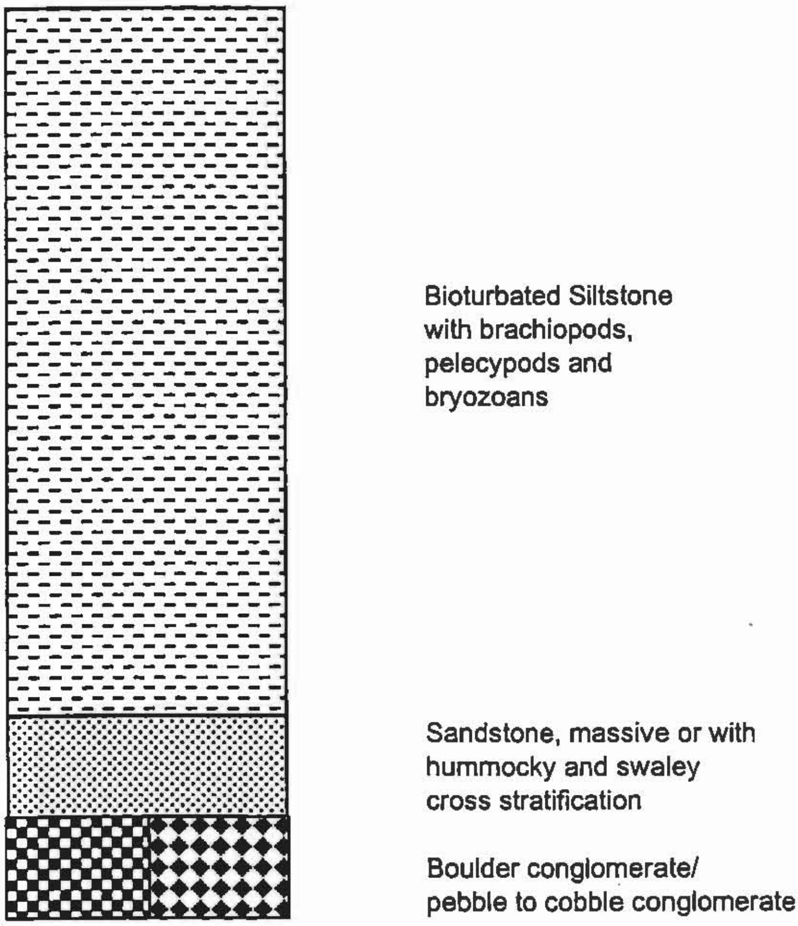

Figure 2. Stratigraphy, southwestern margin of the Sydney Basin

HYDROGEOLOGY OF THE HAWKESBURY SANDSTONE IN THE SOUTHERN HIGHLANDS OF NSW IN RELATION TO MESOZOIC HORST – GRABEN TECTONICS AND STRATIGRAPHY

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ABSTRACT

Recent hydrogeological investigations for groundwater supplies in the southern part of the Sydney Basin have resulted in the delineation a complex horst–graben structural corridor that extends 50 km along a northwesterly trend, transected by conjugate northeasterly trending faults. The zone with associated Jurassic intrusives and extrusive Tertiary volcanics characterise a regional uplift of 200 m coincident with the Mittagong Ranges. Bounding structures are both concealed beneath Tertiary volcanics, and masked by Wianamatta Group shales within areas of elevated topography and poor outcrop. Interpretation of published regional airborne magnetic data suggests that basement faulting control the structural corridor. Structural trends with similar northwesterly orientations form both important structural boundaries and monoclines to the south and north of Mittagong.

Systematic geophysical well logging and stratigraphic analysis along and adjacent to this corridor have been successful in defining the primary groundwater controls which are both structural and stratigraphic. Stratigraphic log analysis has resulted in the subdivision of the Hawkesbury Sandstone into three mappable lithofacies, correlable over an extensive area, and extending into the depocentral part of the basin. Upper and lower facies are dominated by 'clean' medium to coarse quartzose sandstones having high porosity and permeability, separated by a sequence characterised by interbedded clayey fine grained sandstones and shales. Facies modelling of the sandstone bodies and their depositional environments have provided evidence of significant vertical differentiation of the sequence. Alluvial depositional environments vary, ranging from riverine braided, meandering, to distributary mouth bar deposits. Regional correlations reveal the presence of both intraformational disconformities and local erosion at the top of the sequence.

Excellent groundwater potential generally exists in both the upper and lower parts of the Hawkesbury Sandstone associated with increased sandstone porosity and permeability. The middle part of the sequence is considered to be an important confining layer. Increased rates of groundwater recharge are expected within the lower part of the sequence, which subcrops over extensive areas, and from within fracture zones and faults. Water quality generally deteriorates where the overlying Wianamatta Group sequence of shales is preserved, and within the deeper parts of the basin.

INTRODUCTION

Many workers have studied the Triassic Hawkesbury Sandstone of the Sydney Basin, where detailed investigations of discontinuous outcrop have provided various evidence for an understanding of the depositional environment and gross characteristics of the formation. Although numerous coal and petroleum exploration boreholes have been drilled in the basin, the economic attention has been principally directed to the Permian sequence. Consequently, the Hawkesbury Sandstone has been largely ignored from a subsurface stratigraphic perspective. This paper summarises a subsurface analysis of the sequence using geophysical well log records collected from some 60 bores in the Southern Highlands of NSW and 40 wells in the Sydney region. Stratigraphic analysis has provided consistent evidence of a vertically differentiable sequence comprising three basin-wide mappable lithofacies.

The detailed correlability afforded by excellent gamma log signatures and well control has resulted in the clear identification of a complex horst-graben structural corridor in the Mittagong region. The Mittagong Horst-Graben Complex (Figure 1) is of regional significance, and represents a zone of previously unrecorded faulting in the Sydney Basin.

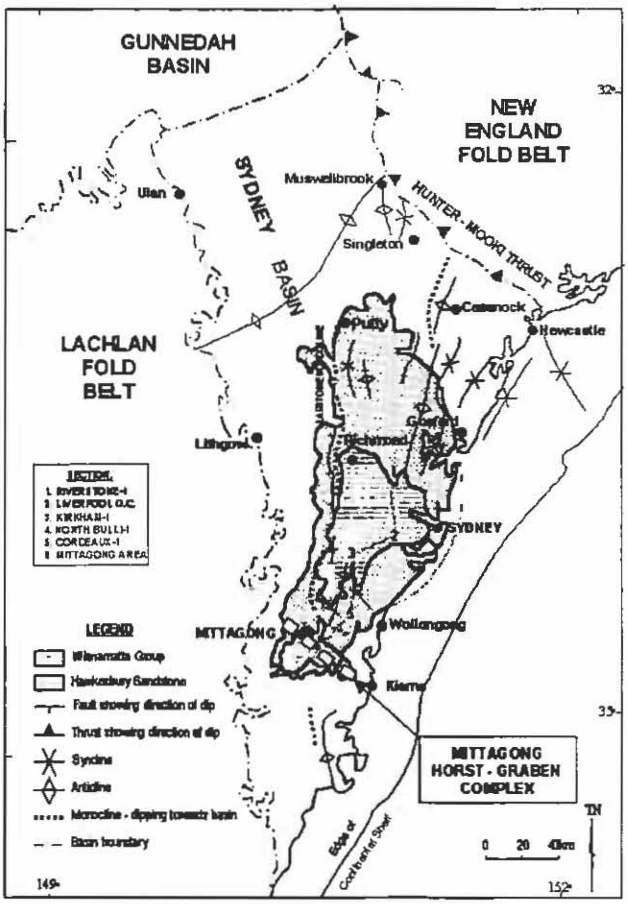

FIGURE 1 Structural framework of the Sydney Basin showing the distribution of the Triassic Hawkesbury Sandstone, Wianamatta Group, and location of the Mittagong Horst–Graben Complex.

Records from hundreds of bores in the Department of Land and Water Conservation (DLWC) database have provided supplementary groundwater and stratigraphic information. Groundwater controls are closely associated with both lithofacies and structure, and as a consequence, increased confidence in the delineation of economic groundwater resources has been established within the region.

In the Mittagong District a condensed, but complete sequence of the Hawkesbury Sandstone is recognised. High-sensitivity digital tools have facilitated geophysical log analysis of numerous rotary percussion-drilled bores. Gamma ray, caliper, self potential, single point resistance, fluid conductivity and temperature logs, have provided the key to an improved regional understanding of the sedimentology, structure and hydrogeology, supplemented by outcrop mapping and aerial photographic interpretation. Hydroilex has largely acquired the data from private groundwater investigations, which are being synthesised as part of an on-going research project.

PREVIOUS INVESTIGATIONS

Studies of the Hawkesbury Sandstone, restricted to detailed outcrop mapping and facies differention have been conducted by various workers (Standard, 1964, 1969; Conolly, 1969; Conolly and Ferm, 1971; Conaghan and Jones, 1975; Ashley and Duncan, 1977; Conaghan, 1980; Jones and Rust, 1983; Rust and Jones, 1987). The conclusions and consensus reached by the more recent workers is that the sequence was deposited in an extensive fluvial braided river environment. The most comprehensive work on the Sydney Basin has been documented in Herbert and Helby (1980). Herbert (1997) has also documented a sequence stratigraphic analysis of Triassic sedimentation.

Recent documented geological investigations in the Mittagong District have been limited to site-specific studies. Both Government authorities, and industry explorationists have largely neglected the region. Taylor and Mawson (1903) provided an interesting insight into the district structural geology, significance of various intrusive and extrusive rocks, and groundwater controls in the origin of the Fitzroy Iron Deposit. Regional mapping by the Geological Survey of New South Wales, Wollongong 1:250,000 sheet (Rose, 1966), and Southern Coalfields Regional Geology 1:100,000 sheet (Moffitt, 1999) provides the most recent formal mapping, without the identification of significant structure in the region.

To date, there has not been a *detailed* regional hydrogeological evaluation undertaken in the Southern Highlands. The DLWC have recently completed a groundwater management plan for the region (DLWC, 1999). McKibbin and Smith (2000) have prepared a general review of the sandstone hydrogeology of the Sydney Basin, with reference to the Southern Highlands region.

REGIONAL GEOLOGICAL SETTING

The Hawkesbury Sandstone of the Sydney Basin is an early Middle Triassic (Anisian) alluvial formation which crops out over an area of approximately 20,000 km^2, extending from the Southern Highlands to the Putty area in the north, and to the lower Blue Mountains (Figure 1). The formation crops out extensively along the Sydney coastline, and continues several kilometres offshore. The original area of deposition is likely to have been significantly greater. The preserved area of distribution is arcuate in form, with the depocentral area being close to the central part of Sydney. The provenance of Hawkesbury Sandstone sedimentation was principally from the southwest (Standard, 1964; Jones and Rust, 1983). The sequence ranges in thickness from approximately 160 m in the Mittagong region to approximately 250 m in the Sydney region. In the depocentral part of the basin, the Hawkesbury Sandstone is overlain by the 300 m-thick Anisian to Ladinian shale-dominated Wianamatta Group, and underlain by the 800 m-thick lithic and quartzose, Scythian to early Anisian Narrabeen Group. These Triassic sediments are underlain by up to 2,000 m of Permian sediments comprised of volcanics, clastics and coals. The total sedimentary thickness in the Sydney region is approximately 2,500 m (Kirkham-1, 2,547 m, Woronora-1, 2,278 m), thickening in the offshore region to between 5,000 m and 6,000 m (Mayne *et al.*, 1972). In the Mittagong region, the Narrabeen Group is effectively absent, and the total sedimentary sequence is approximately 600 m thick.

The Sydney Basin forms the southern part of an elongate foreland structural trough which extends northwards to the Gunnedah and Bowen Basins along a 1,200 km corridor bounded to the southwest by the Lachlan Fold Belt, and by the New England Fold Belt / Tamworth Arc to the northeast. A passive depositional margin is recognised in the west, with increased depositional thickening along the Hunter Mooki Thrust, bordering the New England Fold Belt. Quartzose sediments were principally derived from the foreland, and labile sediments from the arc (Conaghan *et al.,* 1982). The eastern margin of the basin has been rifted at the edge of the continental shelf, resulting in the separation of the Lord Howe Rise from the east coast of New South Wales (Falvey and Mutter, 1980). Several thousand metres of probable Jurassic and Cretaceous cover have been removed by erosion, as evidenced from vitrinite reflectance data.

Compared with other basin-margin areas of the Sydney Basin, the subcrop geology of the Southern Highlands district is uniquely characterised by areas of extensive Jurassic and Tertiary basalts, thick preserved sequences of Wianamatta Group shales, and syenitic intrusions of Late Triassic to Early Jurassic age (McDougall and Wellman, 1976).

GENERALISED STRATIGRAPHY OF THE SOUTHERN HIGHLANDS

A composite summary of the stratigraphy of the Southern Highlands is shown in Figure 2. Cainozoic basalts (30-54 Ma) (McDougall and Wellman, 1976), attain thicknesses of up to 80 m, and based on geophysical log responses from several bores, comprise three to four flows up to 20m thick. Sand and gravel deposits are commonly associated with palaeo valley-fill flows.

The Wianamatta Group comprising Ashfield Shale, Minchinbury Sandstone and Bringelly Shale attains 160 m in thickness along the northern down-faulted margin of the Mittagong Horst. The sequence demonstrates excellent correlability with Wianamatta Group sequences to the north in the Camden area. It is also notable that the locally preserved thickness of the Wianamatta Group in the Mittagong area is comparable to that in the Camden area, within the axis of the Camden Syncline.

The Mittagong Formation, a transitional unit at the contact between the Wianamatta Group and Hawkesbury Sandstone ('Passage Beds' of Lovering, 1954) has been variously assigned to both sequences. Herbert (1976b) has interpreted the sequence to represent the preserved floodplain deposit of the last depositional cycle of the Hawkesbury Sandstone. In the subsurface, the unit has limited stratigraphic value. The author favours a genetic relationship to the Wianamatta Group.

The Hawkesbury Sandstone attains approximately160 m thickness in the area, and can be subdivided into three distinct lithofacies, which are herein described as Units 'A', 'B' and 'C'. The sequences have approximate maximum thicknesses of 70 m, 50 m, and 40 m respectively, characterised by quartzose sand facies in the upper and lower units, and a middle unit dominated by clayey-silty facies. A more detailed description is provided later in the text. The Narrabeen Group is generally not recognised in the region, and Hawkesbury Sandstone rests directly on the Permian Illawarra Coal Measures. This sequence is approximately 60 m thick, and underlain by the approximately 80 m thick Berry Siltstone, where measured in the Canyonleigh area. Minor thicknesses of the fluvial Megalong Conglomerate, and glacial Tallong Conglomerate are recognised in areas along the basin-margin. Basement rock sequences are dominated by Silurian metasediments.

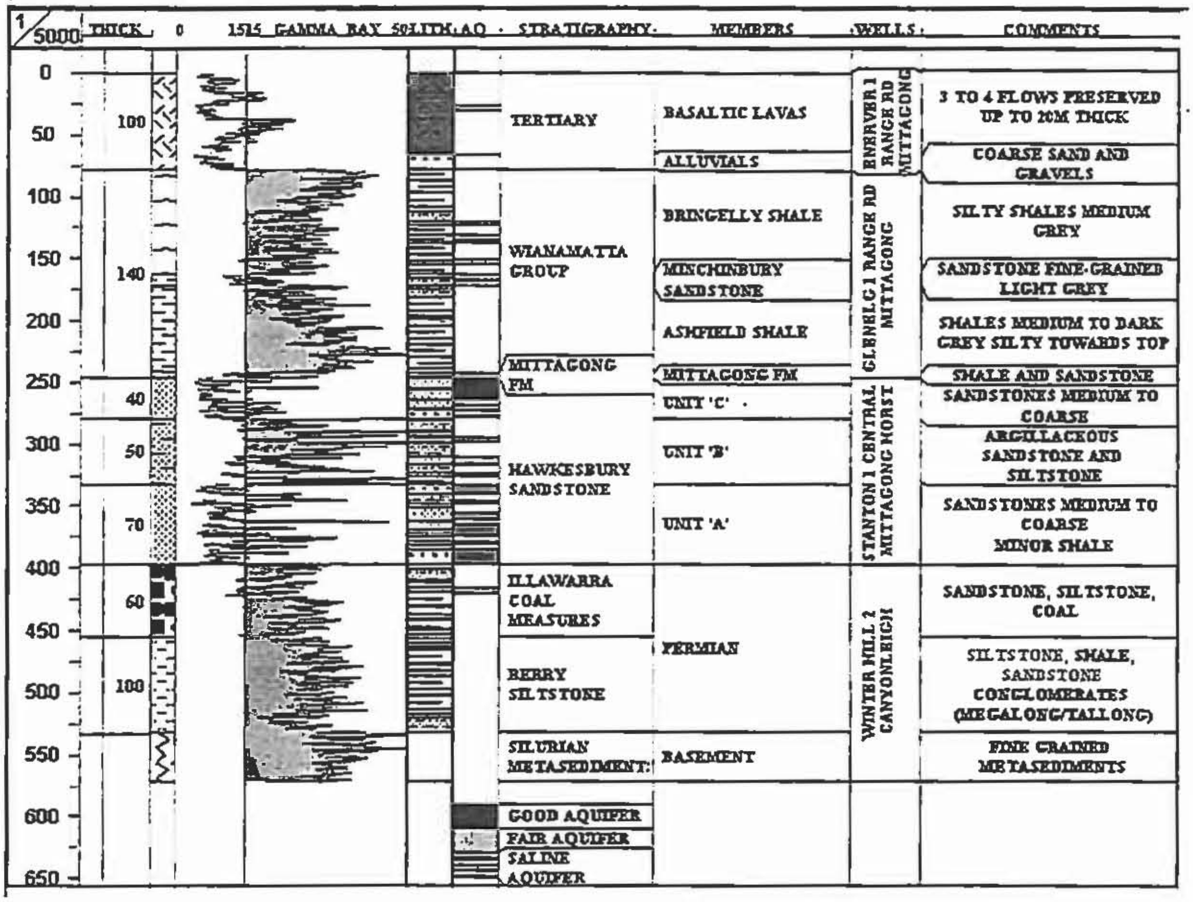

FIGURE 2 Stratigraphy of the Sydney Basin in the Southern Highlands Region, showing approximate maximum stratigraphic thickness, gamma-ray log character, and distribution of aquifers.

STRUCTURAL GEOLOGY OF THE MITTAGONG HORST-GRABEN COMPLEX

The northwest trending Mittagong Horst-Graben Complex and associated lineament is defined as a structural corridor which can be traced over 50 km from Werri Beach, south of Kiama, through Robertson, and along the Mittagong Ranges to the Joadja region (Figure 3). Published aeromagnetic data clearly demonstrates the regional significance of major intrabasement faults that control the feature (Figure 4). Structural uplift in the central part of the zone is approximately 200 m (Figure 5), juxtaposing thick sequences of Wianamatta Group shales against Permian sediments and Hawkesbury Sandstone. The width of the structural corridor varies from 2 to 5 km, with conjugate northeast trending faults forming the bounding structures between the horst-graben compartments. Although the northeasterly faults are mainly confined to the main corridor, the persistence of associated sub-parallel fractures and joints are believed to be controlling influences on both the Nepean River drainage and Illawarra escarpment. The northern margin of the Complex has previously been identified as the Mt Murray Monocline, and other sub-parallel monoclinal features are recognised. Mapped faults, such as the Macquarie Fault have a similar orientation. The attitudes of the fault planes are not known, but are inferred to be near vertical. A number of domal features have been mapped in the region, some of which are associated with horst blocks.

The Mt Gibraltar intrusive of syenitic composition has been emplaced in the central part of the Complex along a northeasterly trending horst-graben bounding fault. In contrast, the Mt Misery Complex is a lopolith, and has been intruded along the southern 'main' bounding fault, extending laterally along the Wianamatta Group–Hawkesbury Sandstone contact. Other intrusives in the area, for example, Mt Jelore and Mt Broughton are likely to be associated with major faults. Jurassic and Tertiary basalts form extensive areas of 'blanket' cover. Along and adjacent to the Mittagong Horst-Graben Complex, the distribution of the Tertiary basalts is significantly controlled by palaeo-valleys that have formed along the main fault traces.

The Mittagong Horst-Graben Complex is clearly associated with a northwesterly structural orientation, an important Palaeozoic trend which is parallel to the Lachlan Lineament (Scheibner, 1974), the Hunter-Mooki Thrust, the Nepean, Alpine and Mt Murray Monoclines to the immediate north, and the southern margin of the Illawarra Plateau (Herbert, 1972).

The region is characterised by significant stratigraphic thinning of the Permian section, and minimal or non-deposition / erosion of the Narrabeen Group, which in the adjacent area to the north, thickens rapidly (480 m in Kirkham-1, in the Camden area). There is no significant evidence for structural growth during the Hawkesbury depositional cycle, except for localised erosion, apparent at the top of the sequence.

The timing of the main episode of uplift associated with the creation of the Mittagong Horst–Graben Complex is considered to be coeval with the emplacement of syenitic intrusions, that is in the Early to Middle Jurassic (Figure 6).

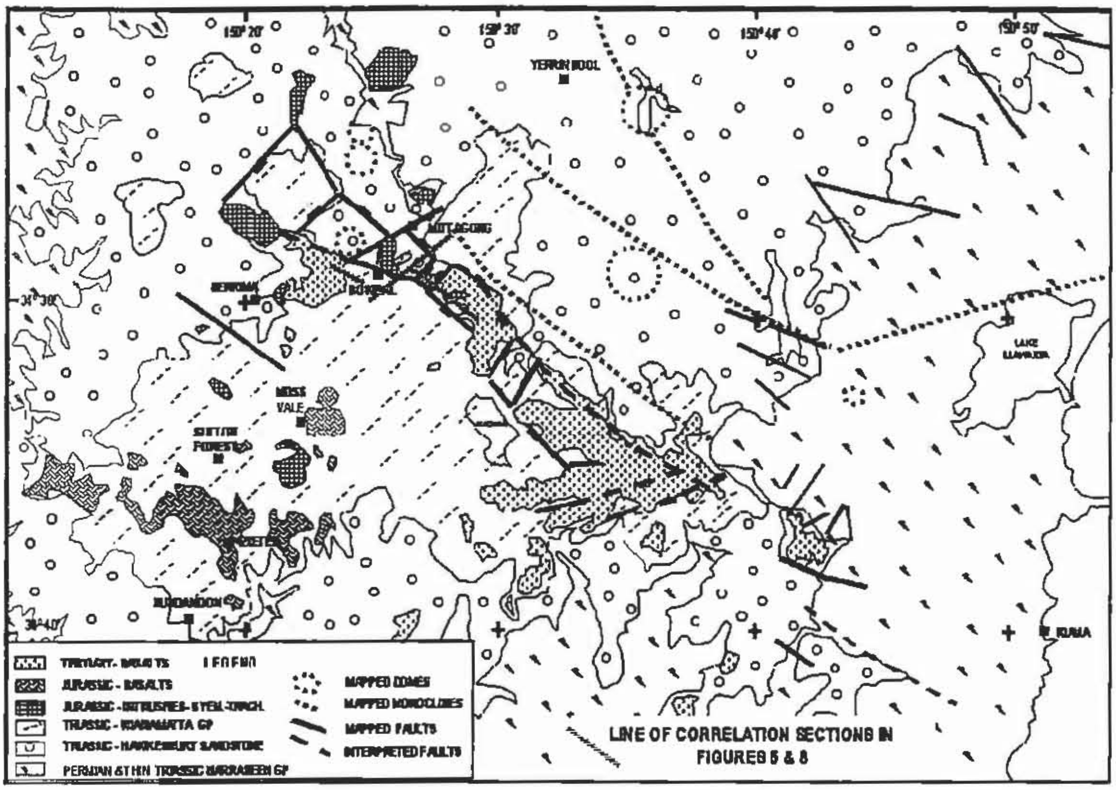

FIGURE 3 Geology of the Southern Highlands Region showing the main structures associated with the Mittagong Horst–Graben Complex. Base geology modified, after Moffitt, 1999

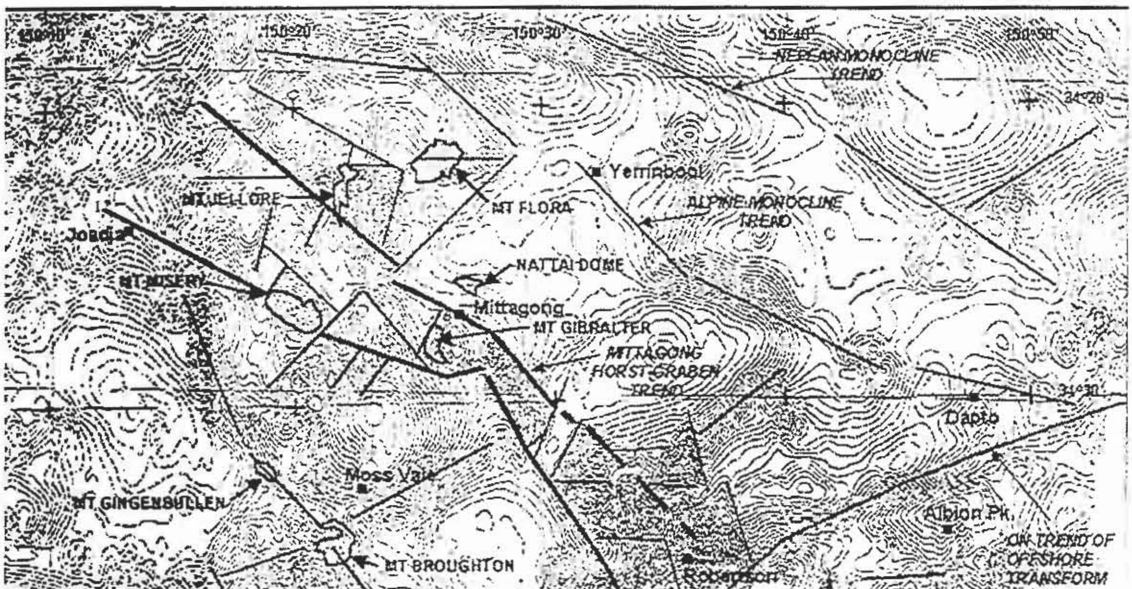

FIGURE 4 Aeromagnetic signature of the Mittagong Horst–Graben Complex, showing the main interpreted structures and intrusives. Data source – Dept. Min. Res. 1984, 1,500 m line spacing.

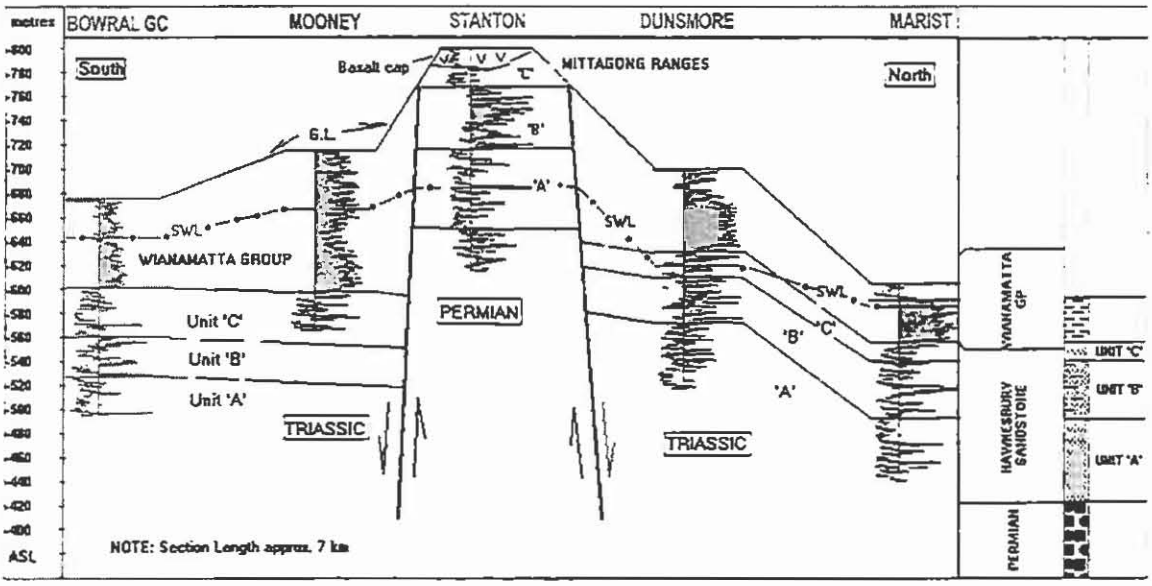

FIGURE 5 North-south gamma-ray log correlation across the Mittagong Horst-Graben Complex, showing 200 m uplift zone juxtaposing Triassic Wianamatta Group and Hawkesbury Sandstone against Permian, elevated Static Water Level (SWL) on southern margin, and thinning / erosion of Unit 'C' on north margin. Note: Gamma-ray threshold level in all correlations figures is 15 cps (~ 5 API). Line of section shown in Figure 3.

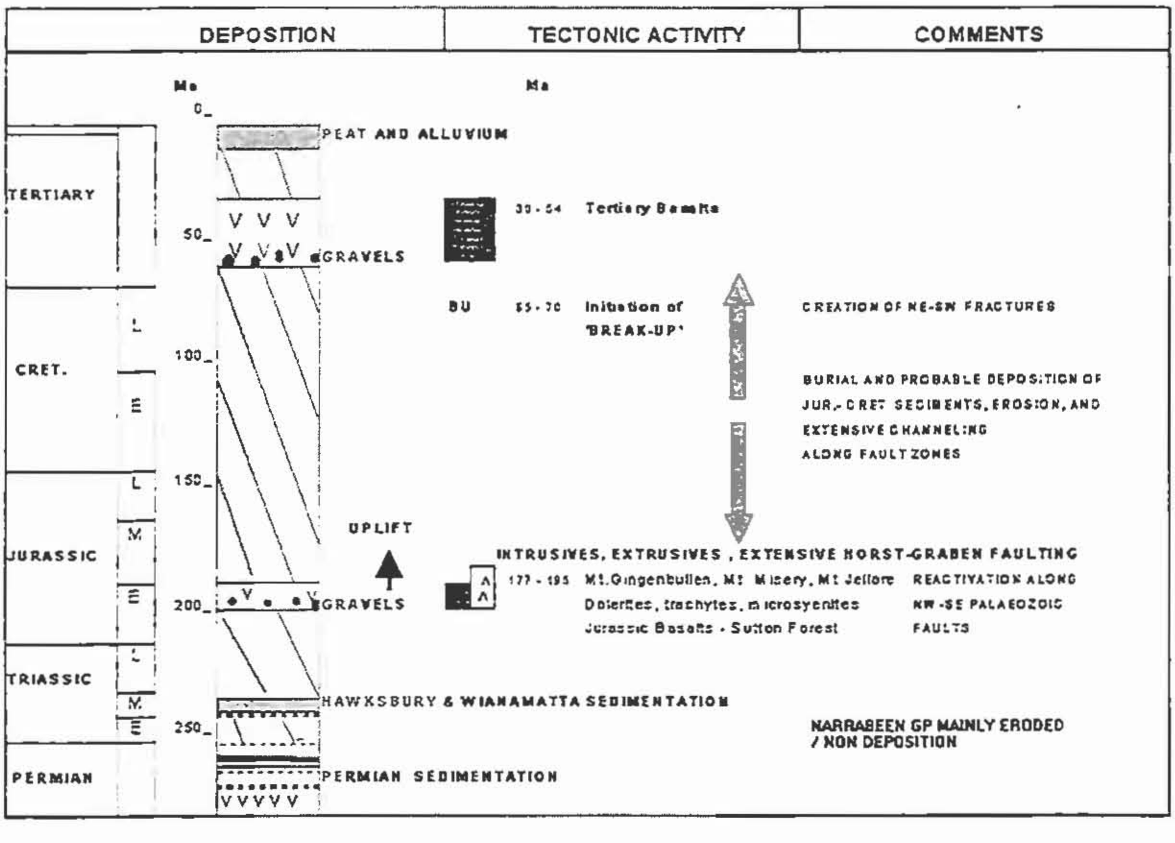

FIGURE 6 Proposed tectono-stratigraphic history in the southern part of the Sydney Basin.

STRATIGRAPHIC FACIES RELATIONSHIPS OF THE HAWKESBURY SANDSTONE

An informal three-fold stratigraphic subdivision of the Hawkesbury Sandstone has been adopted, based on the recognition of lithofacies differentiation over an extensive region of the Sydney Basin, extending from the Southern Highlands to the central part of the basin. Units 'A', 'B' and 'C' have both distinctive gamma-ray signatures and lithological characteristics (Figure 7). Local and regional correlations of the Hawkesbury Sandstone are illustrated in Figures 8 and 9 respectively (refer to section locations in Figure 1).

The lowermost sequence, Unit 'A' is dominated by medium to coarse quartzose sandstones, generally white in colour, with lesser shales. Massive sandstone bodies attain ten metres in thickness. Sand/shale ratios are typically 4:1. Both coarsening upwards and fining upwards clastic cycles are evident, and environments of deposition are considered to be dominantly fluviatile, varying from meandering to braided systems. The distinctive coarsening upward cycles, typical of Unit'A', are more likely to be associated with distributary bar complexes. The sequence has high porosity and permeability, and consequent good groundwater storage and flow potential.

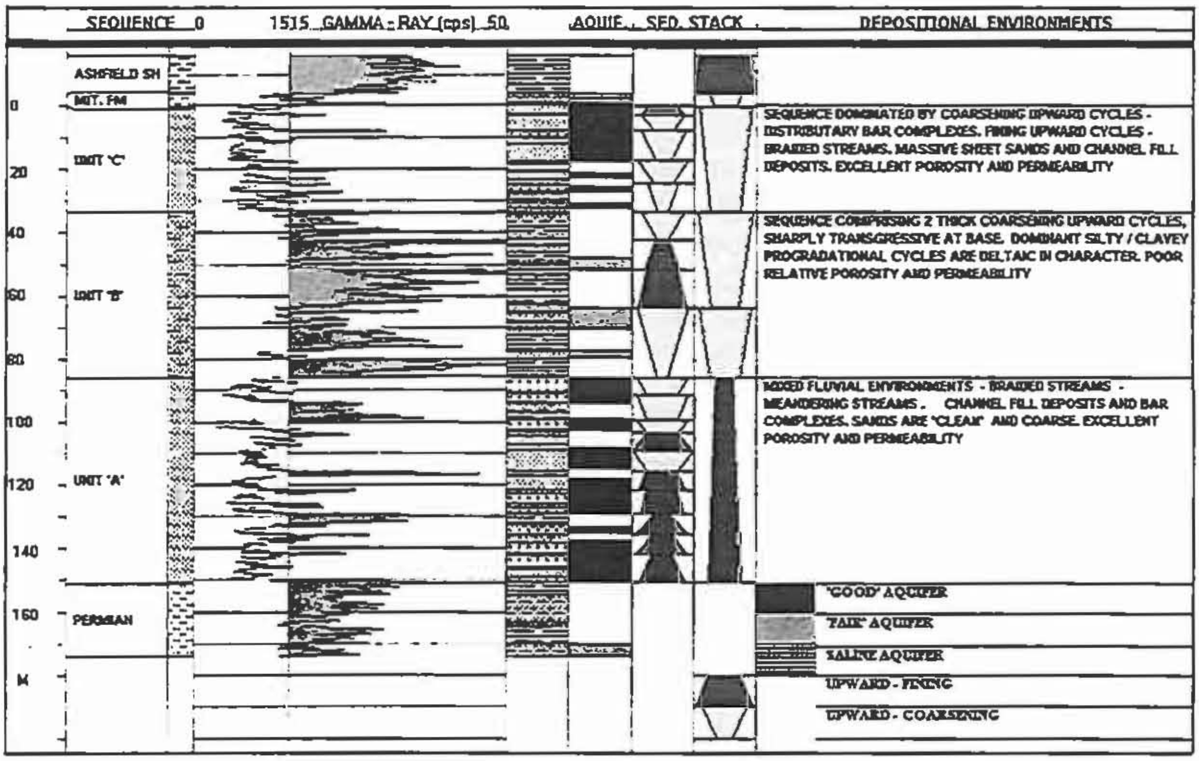

FIGURE 7 Stratigraphic characterisation of the Hawkesbury Sandstone in the Southern Highlands Region.

Unit 'B' is characterised by clayey sandstones, siltstones and shales. The basal contact is usually marked by a sharp transgressive event, which is the most important 'mappable' contact identified by geophysical logging. The sequence marks a significant change in depositional environment, associated with an eustatic rise in base level. Eustatic controls on Australian Triassic clastic sequences are well documented (Gorter, 1994). The sequence is often characterised by a lower, massive, upward coarsening cycle, overlain by an upper fining upwards cycle. The sequence was possibly deposited in a deltaic sedimentary environment. Unit 'B' has low porosity and permeability, and has poor groundwater potential. It is considered to be an important regional confining layer that partitions groundwater systems within Unit 'A' and Unit 'C'.

Unit 'C' possesses similar characteristics to Unit 'A', dominated by massive 'clean', medium to coarse sandstones, with minor shale and siltstone. Similar depositional environments are also recognised. Sand bodies attain up to 20 m thickness. In the Southern Highlands region, the base of the sequence is frequently marked by an upward coarsening cycle, and a blanket sand body which is locally incised into the underlying Unit 'B'. Excellent groundwater potential is recognised within this part of the sequence.

The Wianamatta Group overlies the Hawkesbury Sandstone. A transitional sequence, the Mittagong Formation, up to 6 m thick, is comprised of interbedded sandstone and shale. The unit, which has questionable formation status, is not clearly recognised in the subsurface, and for practical purposes is included within the Wianamatta Group. The Ashfield Shale, a dark grey shale and laminate, prodelta to delta-front sequence at the base of the Wianamatta Group is *generally* conformable on the underlying Hawkesbury Sandstone. Significant channelling at the base of the Wianamatta Group in the Liverpool area has however been recognised by recent drilling.

GROUNDWATER OCCURRENCE AND CONTROLS IN THE SOUTHERN HIGHLANDS

A stratigraphic and structural understanding of the subsurface geology of the southern margin of the Sydney Basin has enabled a better understanding of the hydrogeology of the region. Aquifers having a dominant stratigraphic control are associated with increased porosity and permeability in the upper and lower parts of the Hawkesbury Sandstone. The production potential of these aquifers is enhanced within zones of major fracturing and faulting associated with the Mittagong Horst–Graben Complex, with resulting yields up to 50 L/sec. Jurassic and Tertiary basalt lavas are secondary targets for groundwater associated with intra-basalt flows (vesicular basalts, flow contacts, fractures), and 'deep lead ' alluvial deposits.

Water quality is generally excellent within the sandstone aquifers in the Southern Highlands. Elevated salinity exists within the Wianamatta Group, and reduced water quality in the underlying Hawkesbury Sandstone is well recognised where natural leakage or mixing occurs within the porous Unit 'A'. The preservation of water quality by the isolation and pressure cementing of the overlying Wianamatta Group is an important bore construction issue in the region. Enhanced water quality, and yield, is usually expected in Unit'A', in the lower part of the Hawkesbury Sandstone.

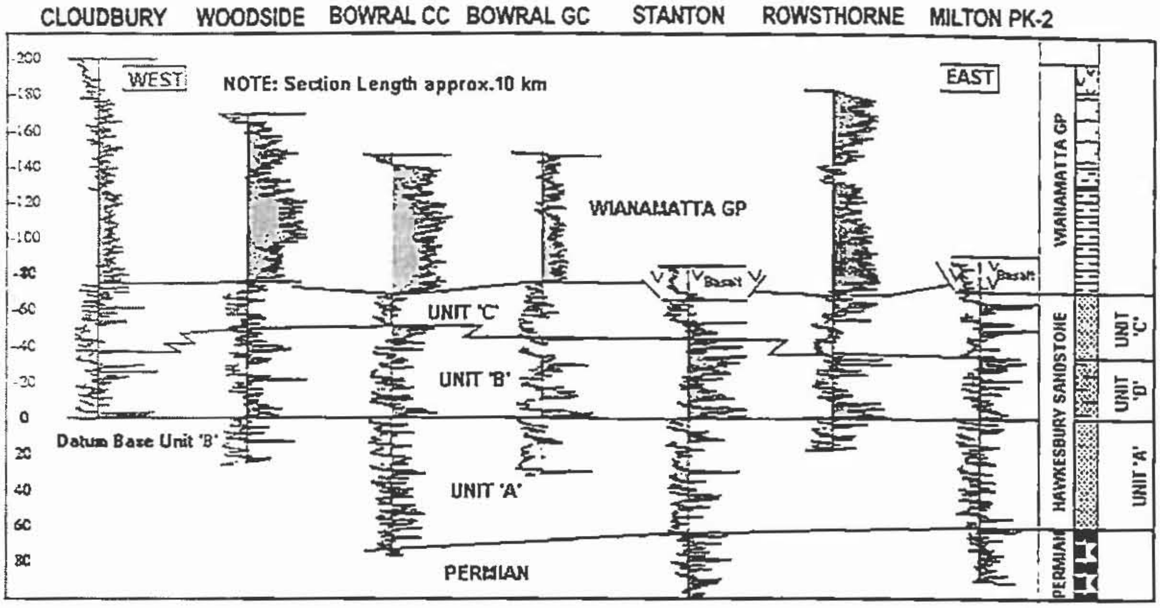

FIGURE 8 Gamma-ray log correlation along the southern margin of the Mittagong Horst – Graben Complex. Refer to Figure 3 for section location. Datum is base Unit 'B'.

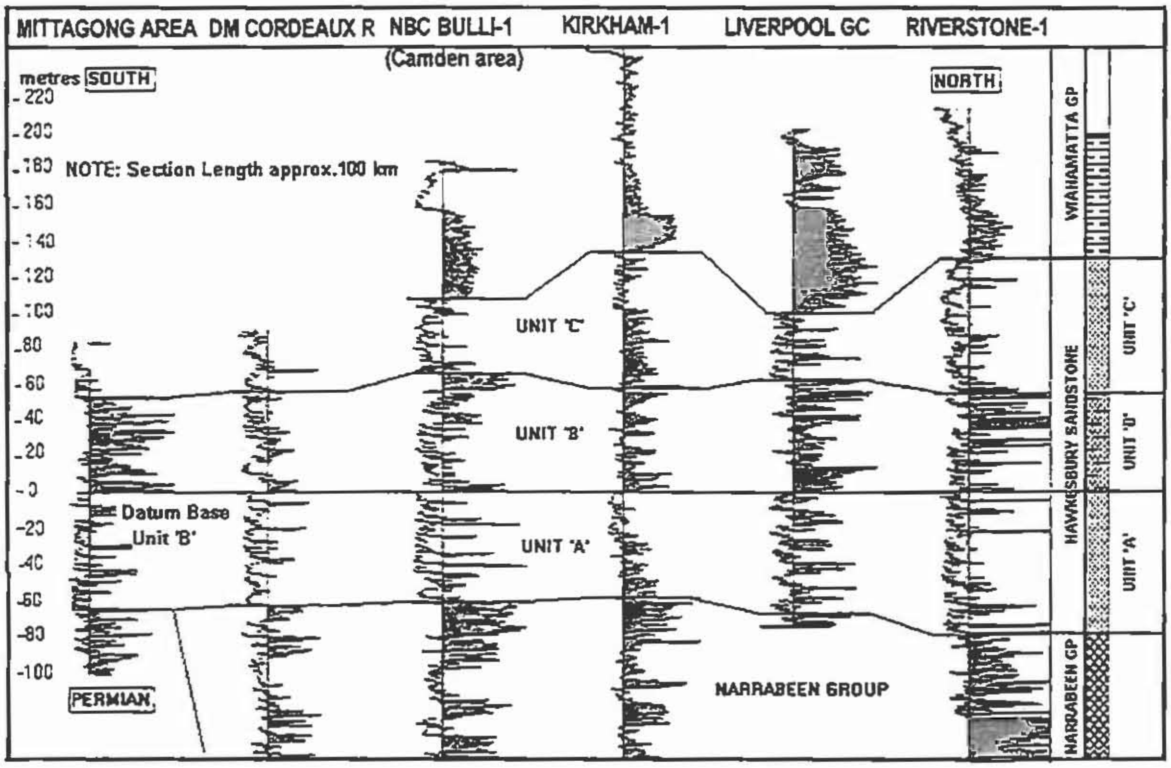

FIGURE 9 Gamma-ray log correlation; Mittagong to Riverstone / Sydney Region, demonstrating excellent stratigraphic correlation of Units 'A', 'B' and 'C'. Datum is base Unit 'B'. Refer to Figure 1 for section location. Note apparent channelling of Wianamatta Group.

Elevated levels of iron are common within the Hawkesbury Sandstone, and although the geological relationship remains unclear, the primary associations are clearly of stratigraphic origin, with secondary controls related to both intrusives and structure.

The lower part of the Hawkesbury Sandstone (Unit 'A'), which subcrops as a rim around the southern margin of the basin, is considered the primary recharge belt (Figure 10). However, groundwater flow into the basin is however restricted by the Mittagong Horst–Graben Complex, which forms a major barrier. Groundwater discharge is expected to disperse laterally along the southern margin of the Complex.

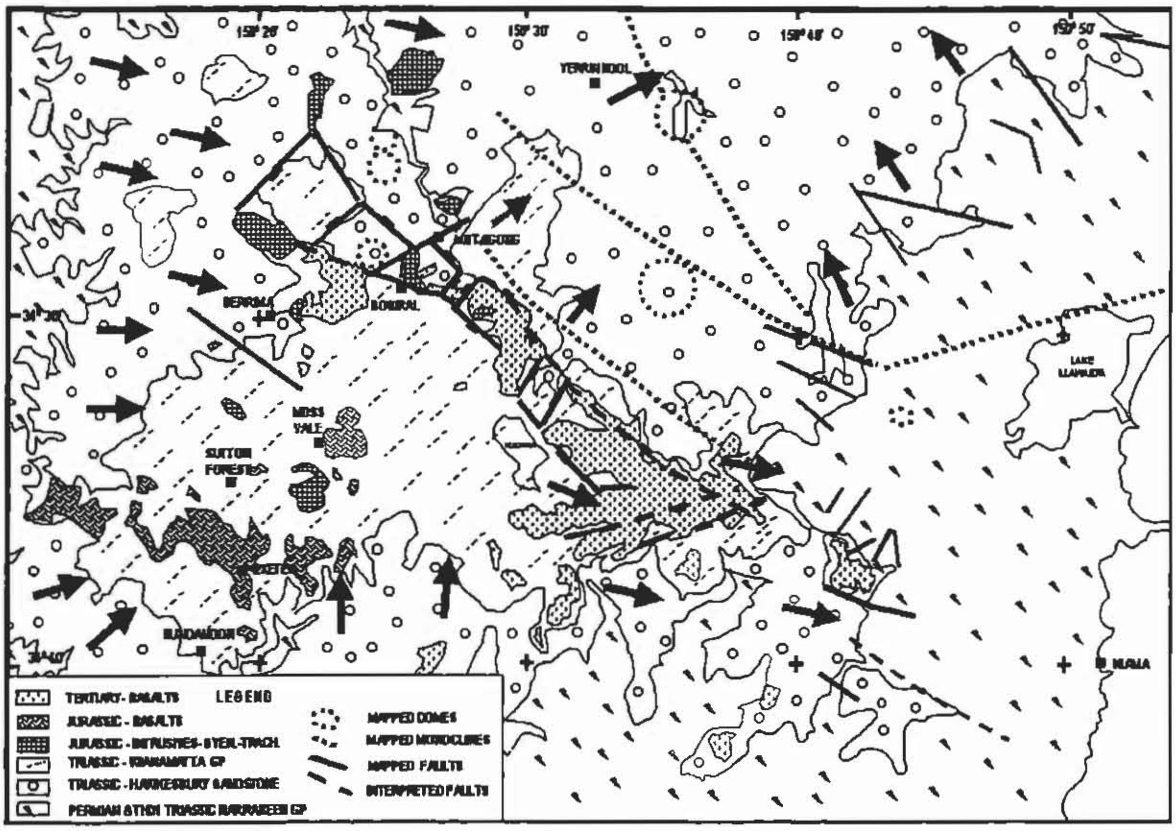

FIGURE 10 Predicted groundwater recharge and discharge trends in the Hawkesbury Sandstone in the southern part of the Sydney Basin.

SUMMARY

Systematic borehole geophysical logging, stratigraphic analysis, and geological mapping in the Southern Highlands district has revealed a number of significant structural, stratigraphic and hydrogeological findings:

1. The identification of a regional uplifted belt coincident with the Mittagong Ranges – the Mittagong Horst–Graben Complex.
2. Stratigraphic differentiation of the Hawkesbury Sandstone into three lithofacies which are widely correlable across the Sydney Basin.
3. Identification of the main groundwater controls within the Hawkesbury Sandstone associated with upper and lower permeable clastic lithofacies.

The comprehensive and significant database being acquired in the region provides an excellent opportunity to enable detailed facies mapping, and modelling of sandstone depositional environments.

ACKNOWLEDGEMENTS

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