A NEW LOOK AT THE NEWCASTLE COAL MEASURES - TWO CONTRASTING APPROACHES TO THEIR FORMATION AND SEQUENCE STRATIGRAPHY

Field Trip
Originally held Friday April 3, 1998 for the 32nd Newcastle Symposium
On Advances in the Study of the Sydney Basin

Guidebook by
Ron Boyd, Murray Little
Department of Geology, University of Newcastle
and
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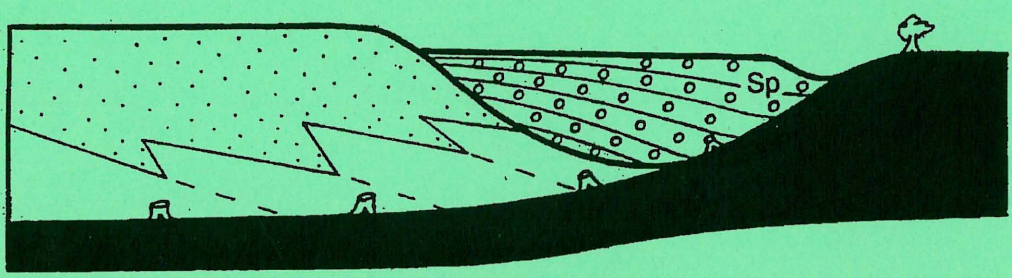

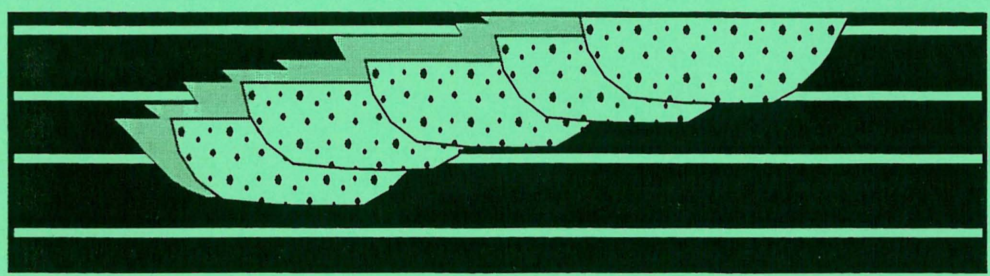

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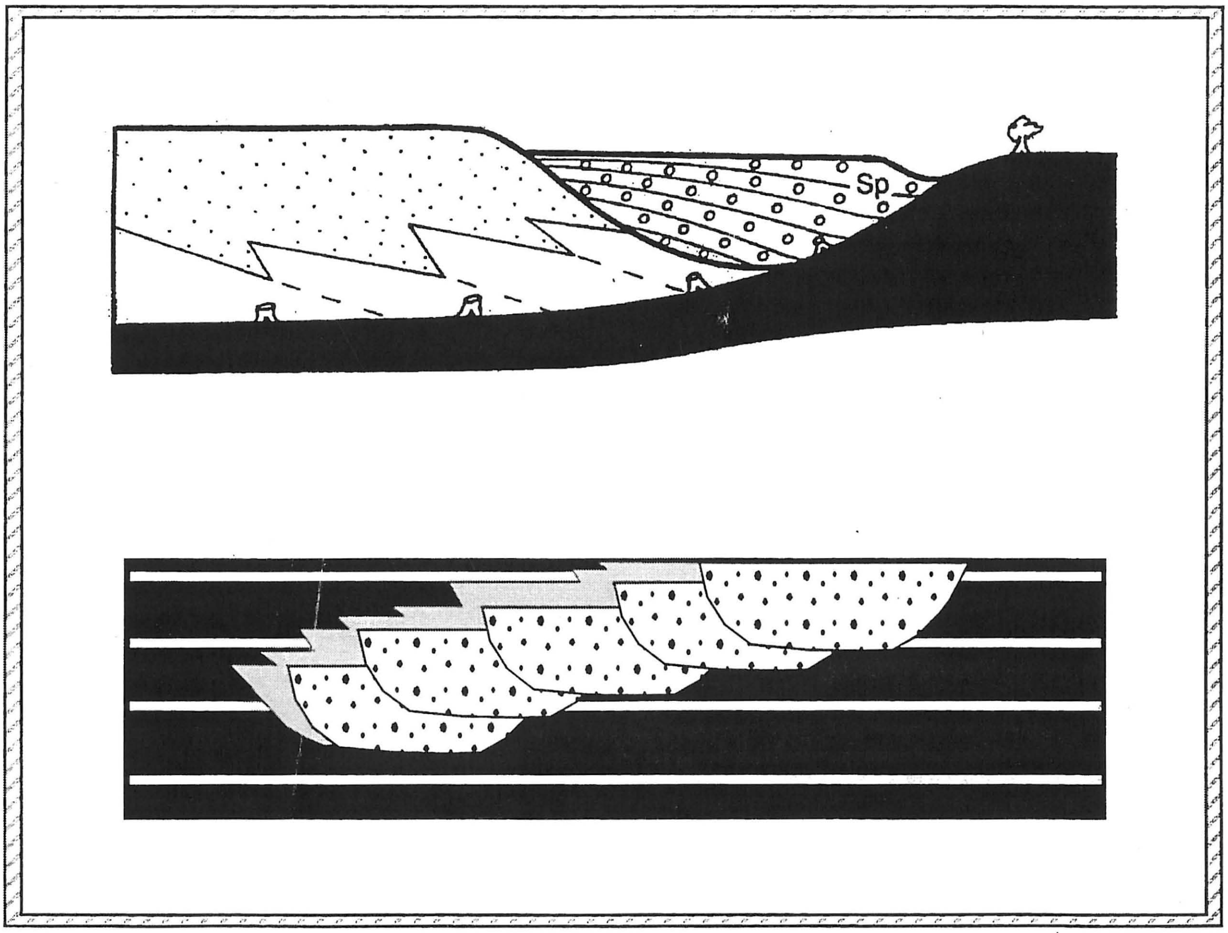


Cover Illustration: Two contrasting views of the Newcastle Coal Measures. Top shows highstand deltas and peat flanked by younger lowstand conglomerates as depicted in Figure 6, p.13. Bottom shows contemporaneous deposition of peat and clastics as shown in Figure 17, p. 32

1998 THIRTY SECOND NEWCASTLE SYMPOSIUM EXCURSION

A NEW LOOK AT THE NEWCASTLE COAL MEASURES - TWO CONTRASTING APPROACHES TO THEIR FORMATION AND SEQUENCE STRATIGRAPHY.

INTRODUCTION.

Welcome to the 1998 32nd Newcastle Symposium Field Trip. This year we are using a slightly different format. We are presenting a topic of current geological interest and providing two contrasting views of it based on examination of outcrop and subsurface information. The topic we have chosen is the depositional environment and sequence stratigraphy of the Newcastle Coal Measures. We have two recent interpretations of the Newcastle Coal Measures. Chris Herbert, one of the field trip leaders, has published several recent journal articles (Herbert 1996, 1995), interpreting the Newcastle Coal Measures to result from deposition over a range of relative sea level conditions. He proposes that an offshore eastern volcanic sediment source was responsible for the progradation of a series of marginal marine deltas westward into the peat-filled Macquarie Syncline at sea level highstand. At lowstand, these deltas were skirted to the west by large incised valley systems which filled with fluvial conglomerate during the following rise in sea level, and hence were not contemporaneous with the preceding delta and peat deposition. One of the key locations to observe the features on which this interpretation is based is the coastal cliffs between Dudley and Redhead Beaches, where the Merewether Conglomerate and the Adamstown Formation are exposed.

A second interpretation is provided by Murray Little and Ron Boyd, the other excursion leaders. This interpretation is based on the regional borehole and outcrop correlations conducted by Murray Little for his PhD thesis, and to revise the stratigraphy of the Newcastle Coal Measures for the Coalfield Geology Council. These interpretations will be fully published soon, but early versions of the data can be found in Little et al., 1996, 7, and Boyd et al 1997. In essence, Little and Boyd suggest that all the sediments of the Newcastle Coal Measures were derived from a general NE source. Once the shoreline of the Waratah Sandstone and associated units prograded SW, the remainder of the Newcastle Coal Measures were deposited under terrestrial (fluvial and lacustrine) conditions. Because of the high volume of depositional space adjacent to the thrust front of the New England orogen, no significant variation in accommodation occurred during the deposition of the Newcastle Coal Measures. Fluvial conglomerates existed contemporaneously and aggraded alongside linked floodplain facies and peat mires. The key location to examine this interpretation is the West Borehole Coal to Nobbys Coal interval of the Lambton Formation at Black Hill. Another example to be presented at this site is the subsurface expression of the Fassifern Coal and the Bolton Point Conglomerate from the Power Coal lease west of Lake Macquarie.

The format of the excursion will be to depart from the University of Newcastle at 9.30 am and proceed to the cliff face south of Dudley Beach. There we will examine 2-3 km of cliff face before ascending the cliff at Redhead. We will have lunch at the park next to Redhead Beach and then continue to the Black Hill Quarry to examine the exposures in three pits and to compare a subsurface correlation from the upper Newcastle Coal Measures. The excursion will conclude around 4.30 pm and return to the University by 5 pm.

The format of the excursion guidebook is to first present some basic information on sequence stratigraphy by Ron Boyd to familiarise participants with terminology and concepts. The second section by Chris Herbert is to introduce his interpretation of the Newcastle Coal Measures and the field stop descriptions for the Dudley-Redhead coast. The third section is by Murray Little and Ron Boyd and covers the alternate interpretation of the Newcastle Coal Measures, and the field stops for Black Hill and the Fassifern-Bolton Point subsurface correlation example.

PART 1: SEQUENCE STRATIGRAPHY

WHAT IS SEISMIC/SEQUENCE STRATIGRAPHY?

☻ Traditional stratigraphy attempts to subdivide, interpret, and correlate sedimentary rocks. Seismic/sequence stratigraphy also has this objective and operates by subdividing sedimentary rocks into units called **sequences** enclosed within **sequence boundaries** (Figure 1). **Sequence stratigraphy** can be defined as the study of genetically related facies within a framework of chronostratigraphically significant surfaces (van Wagoner et al., 1990). The **sequence** is the fundamental stratal unit and can be defined as a relatively conformable, genetically-related succession of strata bounded by unconformities and their correlative conformities (Mitchum et al., 1977). Sequences can be further broken down for detailed mapping into the following successively smaller and shorter time units;**parasequence set, parasequence, bedset, bed, laminaset** and **lamina**. Each of these units above the scale of lamina is a genetically related succession of strata bounded by chronostratigraphically significant surfaces and each surface is a single physical boundary that separates all the younger strata above from older strata below over the extent of the surface.

☻ In particular, **parasequences** are the building blocks of sequences, and are defined as a relatively conformable, genetically related succession of beds or bedsets bounded by marine flooding surfaces or their correlative surfaces. The **marine flooding surface** boundary is defined as a surface separating younger from older strata, across which there is evidence of an abrupt increase in water depth. The stacking pattern of parasequences into parasequence sets defines a number of distinct depositional settings called systems tracts.

☻ We can then use these bounding surfaces for subdividing, correlating and mapping and the units within them for interpretation. Sequence stratigraphy is thus more closely allied with chronostratigraphy than lithostratigraphy. Within each sequence the rocks are deposited contemporaneously in linked assemblages of lithofacies called **systems tracts**. Interpretation of systems tracts provides a framework to predict facies relationships within the sequence.

☻ So you can see that this is a whole new system of stratigraphy, designed specifically for explorationists who use seismic and well logs as well as the outcrop sections on which conventional stratigraphy was based. The beauty of sequence stratigraphy is that it provides an integrated way of studying sediments from the smallest lamina to the largest basin scale. Sedimentologists, geophysicists, biostratigraphers and modellers are no longer independently studying unrelated topics. Sequence stratigraphy has the capability to, as Walther stated in relation to process based studies, "save us from stratigraphy" (the cataloguing of rocks and fossils).

☻ It has also been suggested that this concept of sequence stratigraphy contains the basis for a new **time scale** based on **sea level** and a new mechanism, (?glacial) **eustasy** which controls the development of the sequences and the time scale.

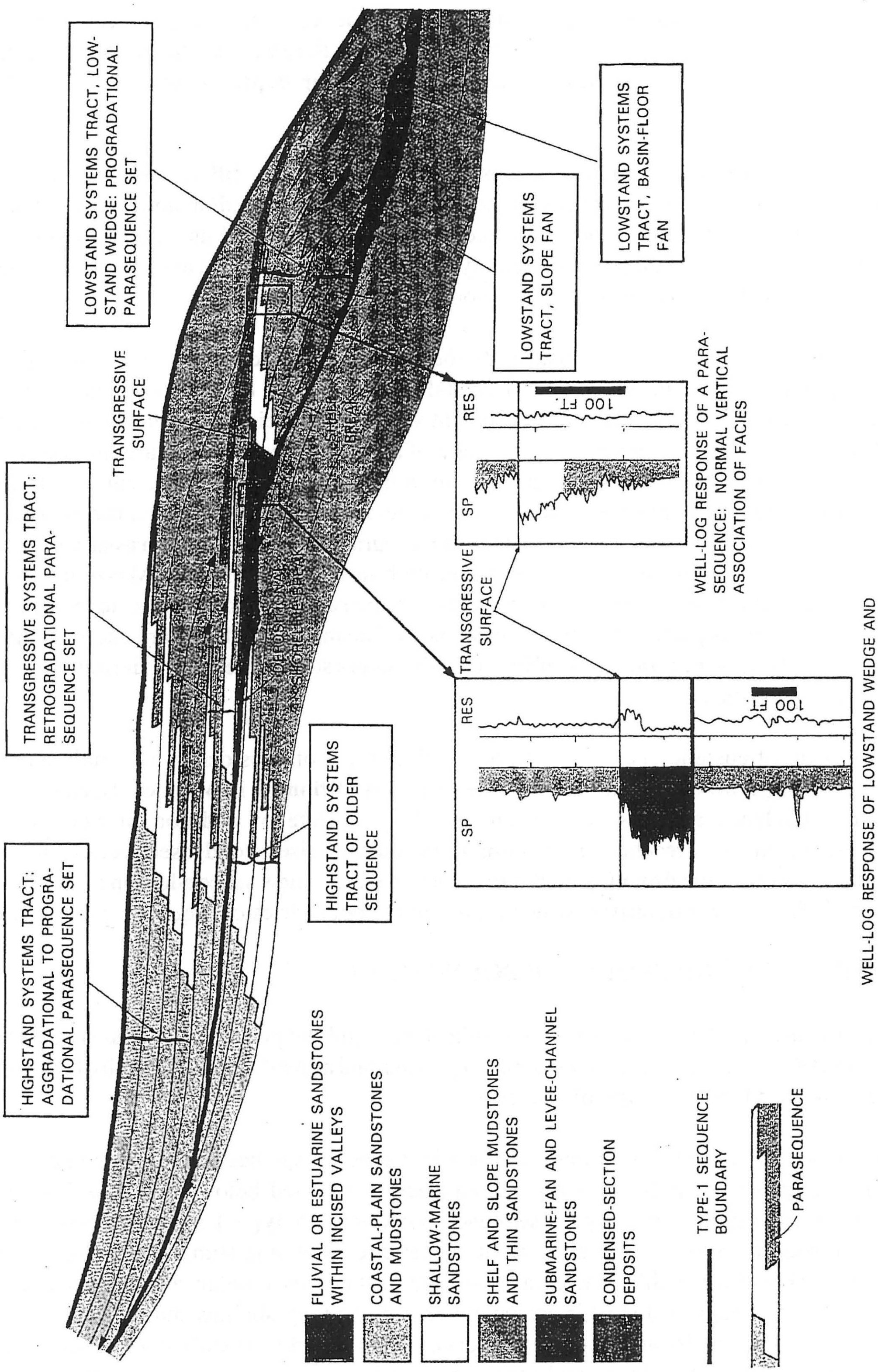


Figure 1. Stratal patterns in a Type-1 sequence deposited in a basin with a shelf break (from Van Wagoner et al., 1990).

BASIC CONCEPTS

☻ Much of the following material is derived from SEPM Special Publication 42 (1988) and particularly van Wagoner et al. and Posamentier et al. therein. **Accommodation** is the space made available for potential sediment accumulation, which is a function of both sea level fluctuation and tectonics (subsidence or uplift). **Eustasy** refers to the position of the sea surface with respect to the centre of the earth. **Relative sea level** is the position of the sea surface with respect to the position of a datum at or near the sea floor and therefore shows local variation. **Water depth** is relative sea level less accumulated sediment.

☻ The geometry of and hence stratal patterns of sedimentary basin fill are dominated by three variables: **eustasy** (global changes in sea level), **tectonics** (subsidence and/or uplift) and **sediment supply.** In developing the following models for sequence stratigraphy and associated systems tract distribution EPR has simplified a complex problem by assuming that sediment supply remains constant and the tectonic component consists only of linear, non-time varying subsidence.

☻ In EPR models, eustatic change is considered to be a curvilinear function punctuated by inflection points (i.e., where the curve gradient changes sign). Stratal patterns depend on the rate that new space has been added and the rate of **sediment supply**. If sediment supply is sufficient (and preferably constant) then as the rate of addition of new space slows the rate of **aggradation** will decrease and the rate of **progradation** will increase. At **inflection points** on the falling limb of the eustatic curve (F), rate of addition of new space is least and little new sediment can be accommodated on the shelf (however it may be deposited beyond the shelf in deeper water). Hence at F progradation or rate of **regression** is greatest and aggradation is least. The opposite is true for rising limb inflexion points (R). Maximum rates of addition of new space at R inflection points commonly results in **transgression** and the development of starved or **condensed sections** particularly in the distal basin. The maximum landward encroachment of the condensed section (**time of maximum flooding**) usually occurs some time after R during the eustatic rise due to the slope of the basin.

☻ When the **rate** of eustatic change is summed with the rate of subsidence we obtain a **rate of relative sea level change** which is equivalent to the **rate of addition of new space**. Because of the balance between subsidence and eustasy chosen by EPR this rate of addition of new space is predominantly positive. When it reaches a maximum during eustatic rises, condensed sections form and these are the site of future **seismic downlap surfaces**. When the rate of new space addition is at minimum during rapid eustatic fall, **unconformities** (which represent the boundaries of sequences) are formed.

TYPES OF SEQUENCES AND SEQUENCE BOUNDARIES

☻ The relative rates of change of eustasy and subsidence, and the possibility of insufficient space available on the shelf determine the type of unconformity generated around the falling limb of the eustatic curve inflection point and hence the type of sequence.

☻ A **type 1 sequence** (Figure 1) is bounded below by a type 1 sequence boundary and above by a type 1 or a type 2 sequence boundary. A type 2 sequence is bounded below by a type 2 sequence boundary and above by a type 1 or a type 2 sequence boundary. A **type 1 sequence boundary** is characterized by subaerial exposure and concurrent subaerial erosion and truncation associated with stream rejuvenation, a basinward shift of facies, a downward shift in coastal onlap, and onlap of overlying strata. As a result of the basinward shift in facies, nonmarine or very shallow-marine rocks, such as braided-stream or estuarine sandstones above a sequence boundary, may directly overlie deeper water marine rocks, such as lower shoreface sandstones or shelf mudstones below a boundary, with no intervening rocks deposited in intermediate depositional environments. Sequence boundaries are often further indicated by the presence of lag deposits derived from erosion in incised valleys or from erosion on flooding surfaces coincident with sequence boundaries. A type 1 sequence boundary is interpreted to form when the rate of eustatic fall exceeds the rate of basin subsidence at the **offlap or depositional-shoreline break,** producing a relative fall in sea level at that position (marked by the change in slope in prograding clinoforms).

☻ A **type 2 sequence boundary** is marked by subaerial exposure and a downward shift in coastal onlap landward of the depositional-shoreline break; however, it lacks both subaerial erosion associated with stream rejuvenation and a basinward shift in facies. Onlap of overlying strata landward of the depositional-shoreline break also marks a type 2 sequence boundary. A type 2 sequence boundary is interpreted to form when the rate of eustatic fall is less than the rate of basin subsidence at the depositional-shoreline break, so that no relative fall in sea level occurs at this shoreline position.

PARASEQUENCE STRATIGRAPHY

☻ **Parasequences** are interpreted to result from higher frequency variations in accommodation generated by superimposing eustatic cycles of different order (Fig. 2). Cycles of sea level change which do not include a relative sea level fall result in parasequences. Rather than being bounded by sequence boundaries, parasequences are bounded by flooding surfaces, across which there is a rapid deepening of facies. Likely causes for this time of paracycle sea level behaviour are Milankovich cyclicity based on orbital variability at different frequencies, and episodic styles of melting in high latitude ice shelves.

☻ The result of this variability in sediment supply versus accommodation is to generate **progradational events, separated by transgressive flooding events** which juxtapose more distal facies (e.g., marine shales) above more proximal facies (e.g., coastal plain sandstones). Groups of parasequences are termed parasequence sets and their overall stacking geometry (basinward versus landward) determines whether they occur in progradational, aggradational or retrogradational parasequence sets. The use of parasequence stratigraphy can produce a dramatic contrast in correlation style when compared to a standard lithostratigraphic approach.

DEPOSITIONAL SYSTEMS TRACTS

☻ **Depositional systems** (Fig. 1) were originally defined for use in the Gulf Coast by workers at the Texas Bureau of Economic Geology (Fisher and McGowan, 1967). They are three-dimensional assemblages of lithofacies, genetically linked by processes and are equivalent to the depositional record in any one sedimentary environment such as a river valley, delta, shelf and submarine fan. Contemporaneous linkage of depositional systems often occurs (for example in a river valley, passing seaward into a delta and then a continental shelf). These larger, contemporaneously linked units are called **systems tracts** (Brown and Fisher, 1977) and are basic building blocks of depositional sequences. Systems tracts in the Exxon approach are defined on the basis of bounding surfaces, position within the sequence and parasequence stacking patterns. They are also closely linked to relative sea level behaviour and hence depart in meaning from the original usage by Brown and Fisher, 1977.

☻ The lowermost systems tract is called the **lowstand system tract** if it lies directly on a type 1 sequence boundary; however, it is called the **shelf-margin systems tract** if it lies directly on a type 2 boundary. The lowstand systems tract is formed when a decrease in accommodation causes bypassing of sediment up dip, the formation of an erosional unconformity and accumulation in deeper water down dip where some accommodation can still be found (e.g., beyond the shelf break).

☻ The **lowstand systems tract,** if deposited in a basin with a **shelf break**, generally can be subdivided into three separate units, a **basin-floor fan,** a **slope fan,** and a **lowstand wedge.** The **basin-floor fan** is characterized by deposition of submarine fans on the lower slope or basin floor. Fan

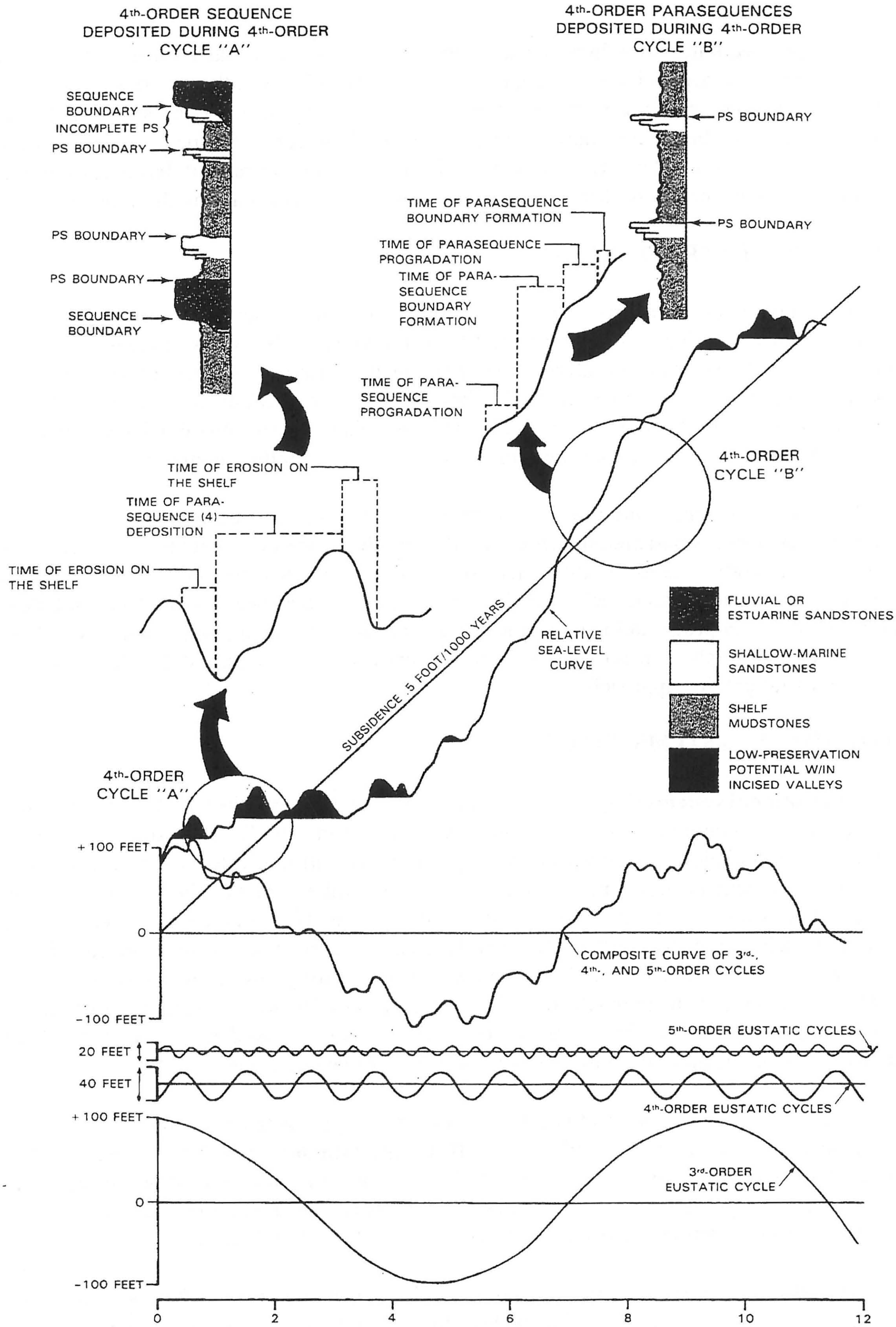


Figure 2. Interaction of eustasy and subsidence to produce parasequences and sequences (from Van Wagoner et al., 1990).

formation is associated with the erosion of canyons into the slope and the incision of fluvial valleys into the shelf. Siliciclastic sediment bypasses the shelf and slope through the valleys and the canyons to feed the basin-floor fan. The base of the basin-floor fan (coincident with the base of the lowstand systems tract) is the type 1 sequence boundary; the top of the fan is a downlap surface. Note that in more recent versions of seismic/sequence stratigraphy there are multiple downlap surfaces and hence associated condensed sections. Basin-floor fan deposition, canyon formation, and incised-valley erosion are interpreted to occur during a relative fall in sea level.

☻ The **slope fan** is characterized by turbidite and debris flow deposition on the middle or the base of the slope. Slope-fan deposition can be coeval with the basin-floor fan or with the early portion of the lowstand wedge. The top of the slope fan is a downlap surface for the middle and upper portions of the lowstand wedge.

☻ The **lowstand wedge** is characterized on the shelf by incised-valley fill, which commonly onlaps onto the sequence boundary, and on the slope by progradational fill with wedge geometry overlying and commonly down-lapping onto the basin-floor fan or the slope fan. Lowstand wedge deposition is not coeval with basin-floor deposition. Lowstand wedges are composed of progradational to aggradational parasequence sets, and reflect increasing accommodation in a location where deposition may be laterally restricted, due to supply being confined through incised valleys. The top of the lowstand wedge, coincident with the top of the lowstand systems tract, is a marine-flooding surface called the **transgressive surface**. The **transgressive surface** is the first significant marine-flooding surface across the shelf within the sequence. Lowstand wedge deposition is interpreted to occur during a slow relative rise in sea level.

☻ The **lowstand systems tract,** if deposited in a basin with a ramp margin, consists of a relatively thin **low-stand wedge** that may contain two parts. The first part is characterized by stream incision and sediment bypass of the coastal plain interpreted to occur during a relative fall in sea level during which the shoreline steps rapidly basinward until the relative fall stabilizes. The second part of the wedge is characterized by a slow relative rise in sea level, the infilling of incised valleys, and continued shoreline progradation, resulting in a lowstand wedge composed of incised-valley fill deposits up dip and one or more progradational parasequence sets down dip. The top of the lowstand wedge is the transgressive surface; the base of the lowstand wedge is the lower sequence boundary.

☻ The **shelf-margin systems tract** is the lowermost systems tract associated with a type 2 sequence boundary. This systems tract is characterized by one or more weakly progradational to aggradational parasequence sets; the sets onlap onto the sequence boundary in a landward direction and downlap onto the sequence boundary in a basinward direction. The top of the shelf-margin systems tract is the transgressive-systems tract. The base of the shelf-margin systems tract is a type 2 sequence boundary.

☻ The **transgressive-systems tract** is the middle systems tract of both type 1 and type 2 sequences. It is characterized by one or more retrogradational parasequence sets. The base of the transgressive-systems tract is the transgressive surface at the top of the lowstand or shelf-margin systems tracts. Parasequences within the transgressive-systems tract onlap onto the sequence boundary in a landward direction and downlap onto the transgressive surface in a basinward direction. The top of the transgressive systems tract is the **downlap surface.** The **downlap surface** is a marine-flooding surface onto which the toes of prograding clinoforms in the overlying highstand systems tract downlap. This surface marks the change from a retro- gradational to an aggradational parasequence set and is the**surface of maximum flooding** . The **condensed section** occurs largely within the transgressive and distal highstand systems tracts. The **condensed section** is a facies consisting of thin marine beds of hemipelagic or pelagic sediments deposited at very slow rates. Condensed sections are most extensive during the time of regional transgression of the shoreline and reflect a removal of the sediment source landward of their place of formation. Because the sediment flux in this location is low biological input can be relatively high, resulting in fauna abundance and diversity peaks also coinciding with the position of the condensed section. The condensed section also shows up on gamma ray logs as a high peak due to the increased organic content, and a resistivity low due to clay content and resulting reduction in porosity.

- The **highstand systems tract** is the upper systems tract in either a type 1 or type 2 sequence. This systems tract is commonly widespread on the shelf and may be characterized by one or more aggradational parasequence sets that are succeeded by one or more progradational parasequence sets with prograding clinoform geometries. Parasequences within the highstand systems tract onlap onto the sequence boundary in a landward direction and downlap onto the top of the transgressive or lowstand systems tracts in a basinward direction. The highstand systems tract is bounded at the top by a type 1 or type 2 sequence boundary and at the bottom by the downlap surface.

PART 2: A SEQUENCE STRATIGRAPHIC MODEL AND FIELD GUIDE FOR THE COASTAL NEWCASTLE COAL MEASURES FROM DUDLEY TO REDHEAD

Chris Herbert

INTRODUCTION

The 400-m-thick Late Permian Newcastle Coal Measures, the underlying Waratah Sandstone, and the 40-m-thick Dempsey Formation form a southwest-thinning siliciclastic wedge of alluvial, deltaic, and marine sediments that prograded across the subsidence axis of the foredeep or retroarc Sydney Basin (Herbert 1980) (Figs 3 & 4). Previous environmental interpretations have assumed continuous deposition with no significant depositional hiatuses, but do not adequately explain the sharp juxtaposition of fluvial gravel, finer-grained, heterolithic, deltaic sediments, and peat mires. I attempt to resolve this difficulty by referring these contrasting depositional environments to differing stages of relative sea-level and applying sequence stratigraphic concepts.

The Dempsey Formation and the Waratah Sandstone comprise stacked, marine shale and shoreface sandstone intervals that downlap to the southwest onto marine maximum-flooding-surfaces (Herbert 1995). Landwards, to the northeast, these marine sediments pass into paralic upward-coarsening deltaic intervals, coal, tuff, and fluvial conglomerate. Thus, the base of the Newcastle Coal

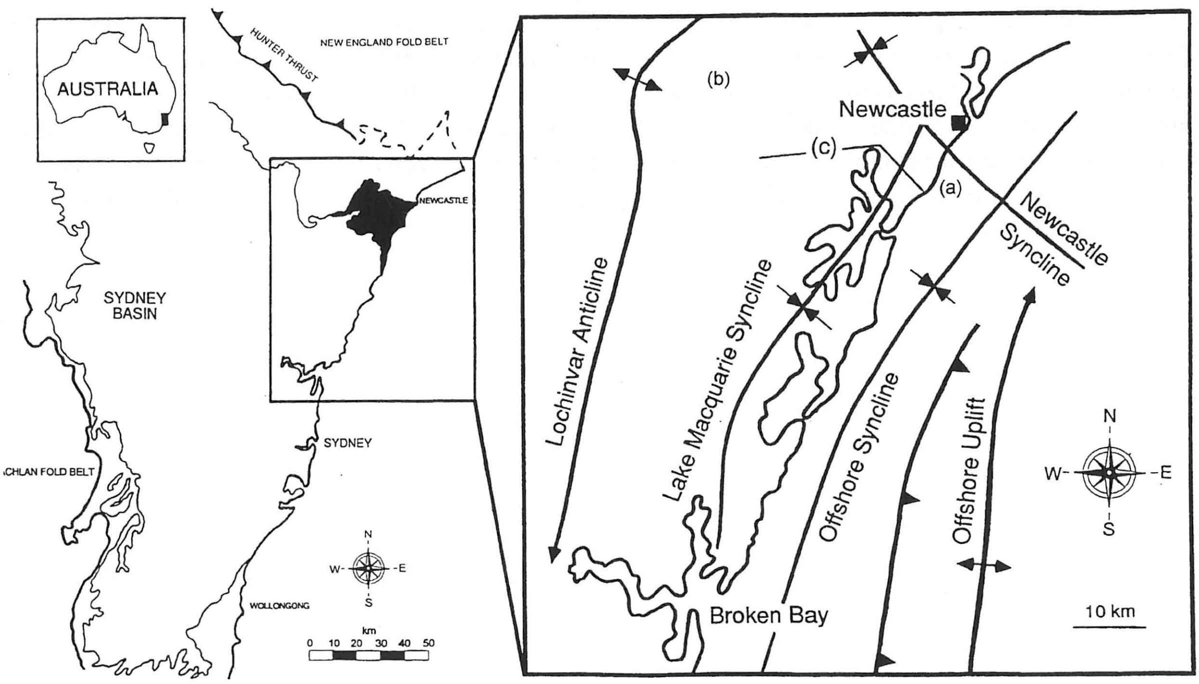


Figure 3. Late Permian Coal Measures were deposited across the entire area of the Sydney Basin shown here. The topmost one third of the coal measures in the proximal northeastern part of the basin are known as the Newcastle Coal Measures (outcrop in black). The coal measures were deposited in a north-south oriented half-graben between the Lochinvar Anticline and the faulted Offshore Uplift in the Lake Macquarie and Offshore Synclines (large inset). (a) Dudley to Redhead, Fig. 10, (b) Black Hill, (c) cross-section in Fig. 6.

Measures becomes younger to the southwest as it passes laterally into marine sediments. Individual, but repeated, cycles of conglomerate to coal to upward-coarsening heterolithic sediments are interpreted as high-frequency, 4th-order sequences controlled by changes in relative sea-level (Herbert 1997).

PALAEOENVIRONMENTAL INTERPRETATION

Deposition in the Newcastle Coal Measures took place in a complex of coastal plain environments landward of a marine barrier. Upward-coarsening, heterolithic, shale/sandstone intervals, conglomerates, and coals deposited in these environments within the lower Newcastle Coal Measures are discussed below (Fig. 4).

Upward-coarsening heterolithic intervals (Parasequences)

Two types of repeated upward-coarsening, heterolithic, shale/sandstone intervals are interpreted to have been deposited in marine and paralic environments. Stacked marine intervals in the Dempsey Formation/Waratah Sandstone are interpreted as offshore silt/prograding beach ridges bounded by marine flooding surfaces (marine parasequences, not discussed here). Upward-coarsening shale/sandstone intervals in the lower Newcastle Coal Measures are interpreted as crevasse splays, crevasse subdeltas, and small deltas which prograded into shallow, brackish, lagoons and interdistributary bays landward of the Waratah Sandstone barrier islands (paralic parasequences, Fig. 5). Brackish conditions are indicated by sporadic burrows and the occurrence of acritarchs in all but the uppermost Newcastle Coal Measures (McMinn 1982, 1984). Paralic parasequences are sheet-like with gently-inclined heterolithic strata downlapping onto flooding surfaces on top of coals (Fig. 6).

These sediments have generally been interpreted as exposed, to intermittently exposed, floodbasin, levee and crevasse splay deposits related to the conglomerates. However, these intervals do not contain palaeosols, organic horizons, or display roots, but instead have well preserved sedimentary structures, are relatively thick (10-20m), coarsen upwards to shallower facies from prodelta mudstone, through delta front, ripple drift crossbedded, finely interbedded sandstone and shale, to delta platform, crossbedded, fluvial to delta front sandstone. Also, there is no interbedding between these finer-grained sediments and conglomerates; contacts are always sharp. It is apparent that there is no genetic relationship between the two different lithologies.

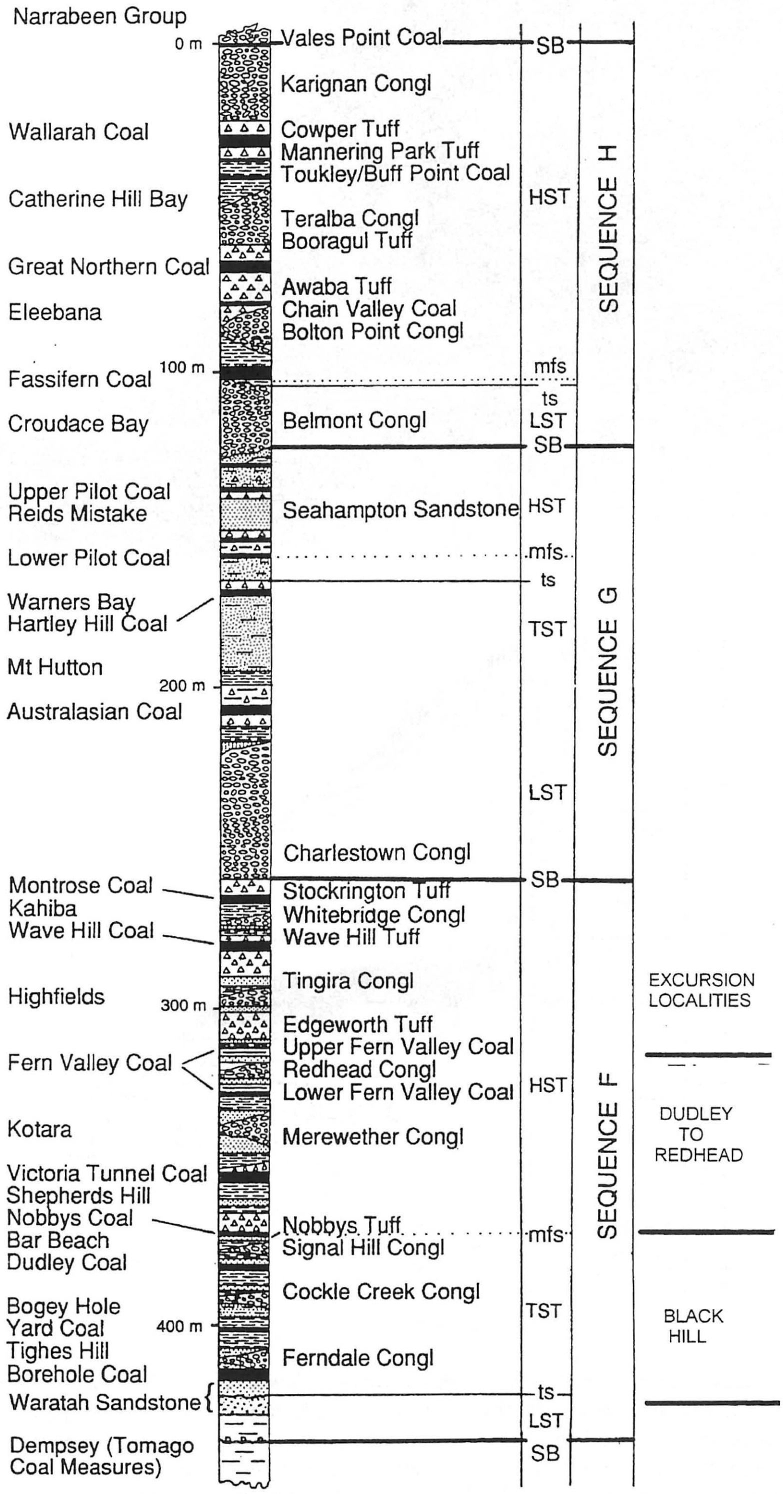


Figure 4. Composite stratigraphic column of the regressive nonmarine/paralic 400 m-thick Newcastle Coal Measures underlain by the marine Waratah Sandstone and Dempsey Formation, modified from McKenzie and Britten (1969). 3rd-order sequences from Herbert (1995). SB=sequence boundary, ts=transgressive surface, mfs=maximum flooding surface, LST= lowstand systems tract, TST=transgressive systems tract, HST=highstand systems tract.

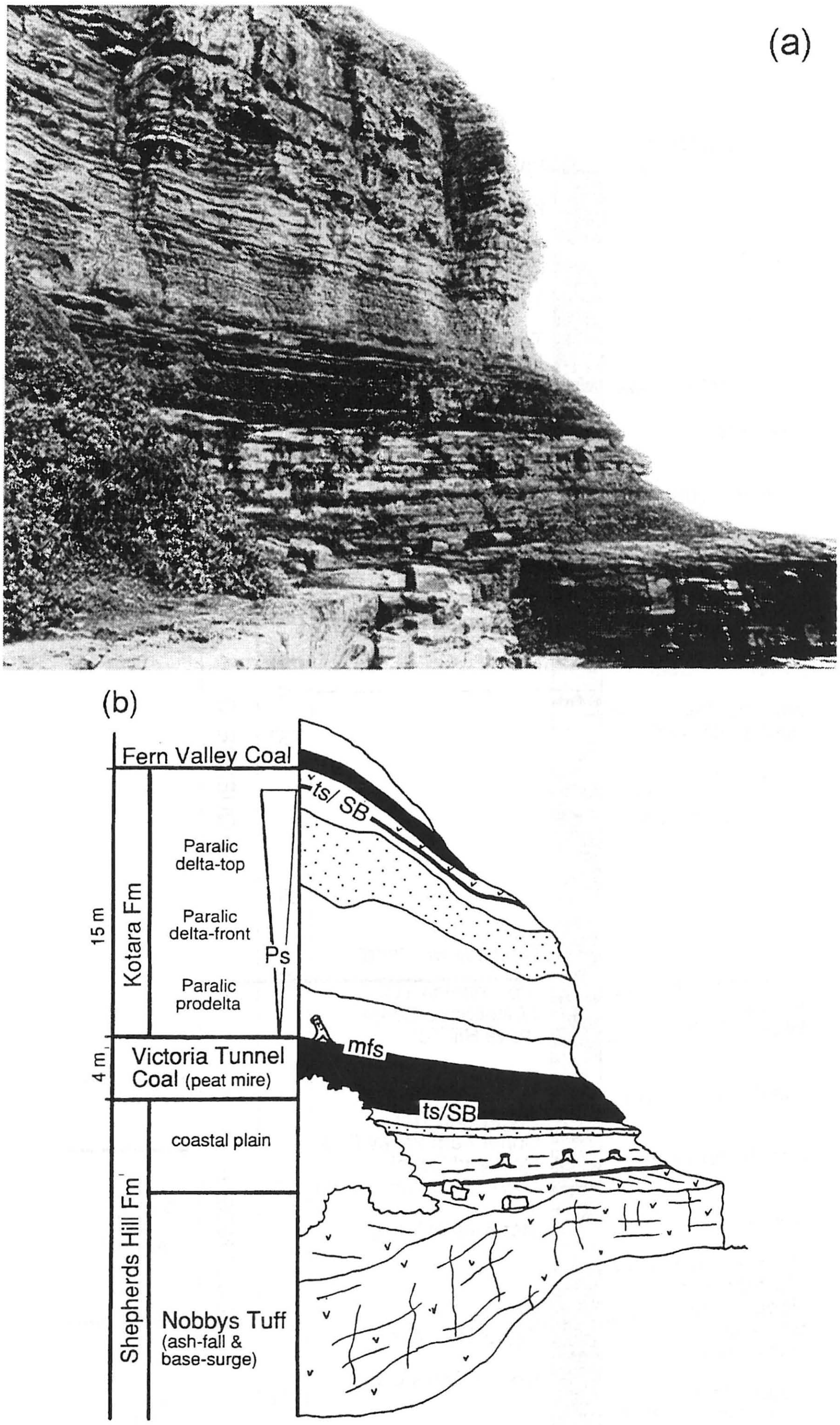


Figure 5. Stop 4. (a) Coastal outcrop of part of the nonmarine/paralic Newcastle Coal Measures at Redhead, from Nobbys Tuff to the Fern Valley Coal. Location in figure 10. (b) Interpretive sketch showing the 4th-order paralic delta parasequence Ps1, about 15m thick, overlying the Victoria Tunnel Coal (4 m). Triangle depicts upward-coarsening trend. Ps1 is bounded, at the base, by a paralic flooding surface, interpreted as a 4th-order maximum flooding surface, (mfs). The surface beneath the Fern Valley Coal and associated tuff is interpreted as a landward correlative of a 4th-order transgressive surface (ts). Note that in this area, where a lowstand conglomerate is not present, the 4th-order sequence includes strata from the base of the Victoria Tunnel Coal to the base of the Fern Valley Coal and the sequence boundary (SB) is coplanar with the transgressive surface (ts/SB). However, the interval above parasequence Ps1 may be a little more complicated because the thin, shaly, southernmost pinchout of Ps2 may also be present between Ps1 and the Fern Valley Coal. Note in situ tree stumps above and below the Victoria Tunnel Coal indicating subaerial conditions.

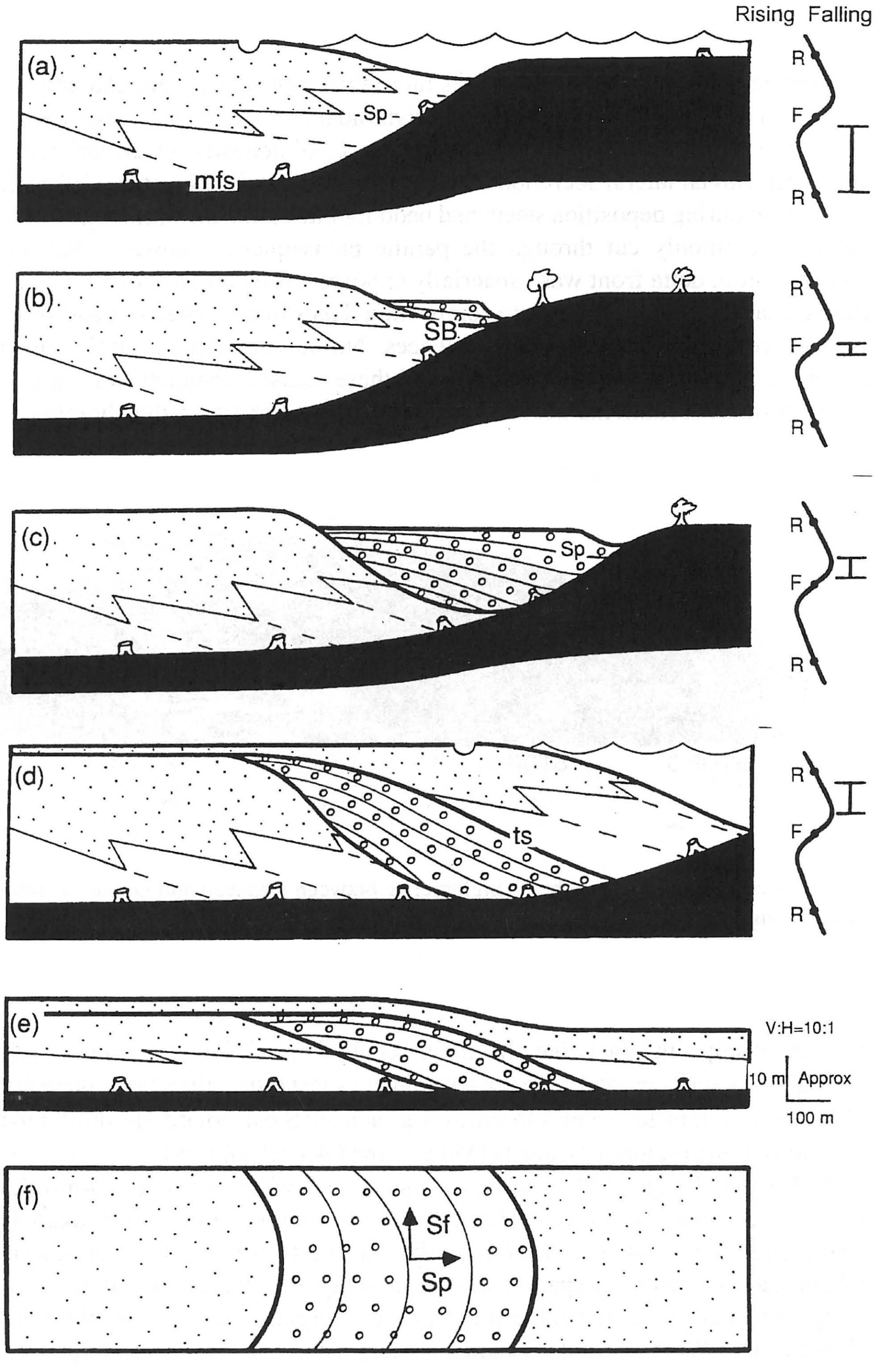


Figure 6. (a)-(d) Schematic sections showing the deposition of 4th-order paralic delta parasequences and an alluvial incised-valley-fill (circles) in Sequence F during progressive peat compaction and changing relative sea level. Relative sea level curve at right of each panel shows the rising (R) and falling (F) inflection points and range of relative sea level (vertical line between horizontals). Horizontal to slightly inclined principal bedding surfaces (Sp) steepen as the underlying peat compacts during siliciclastic deposition. (e) Fully compacted section based on the Merewether Conglomerate and parasequences Ps1 and Ps2 in Fig. 10. (f) Plan view showing the orientation of the principal bedding planes (Sp) and internal foresets (Sf) in the conglomerate, after Diessel (1992, p. 334). Note that sediment supply for the paralic deltas is east to west (left to right) whereas the supply for the alluvial incised valley fill is at right angles, i.e. north to south.

Conglomerate

Fluvial conglomerates, up to, and in some places more than, 60 m thick, are characterised by inclined bedding planes, with dips up to 45° which impart a sigmoidal shape to each conglomerate body (Fig. 7). Diessel (1992, fig. 6.50) inferred that the principal surfaces of deposition were originally deposited as more gently inclined fluvial lateral accretion beds, and agreed with Britten et al. (1975) that compaction of the underlying peat during deposition steepened bedding into forms that mimic giant crossbeds. Basal erosional surfaces commonly cut through the paralic parasequences down to the underlying coal, suggesting that the entire delta front was subaerially exposed to stream incision by a fall in relative sea-level. The fluvial channels were directed into compaction moats formed ahead of, and around, abandoned paralic delta-fronts composed of paralic parasequences. No substantial adjacent floodplain deposits can be identified and it is apparent that overtopping of these incised channels was rare. The channels functioned only to funnel sediments across the coastal plain directly to the shoreline via entrenched streams.

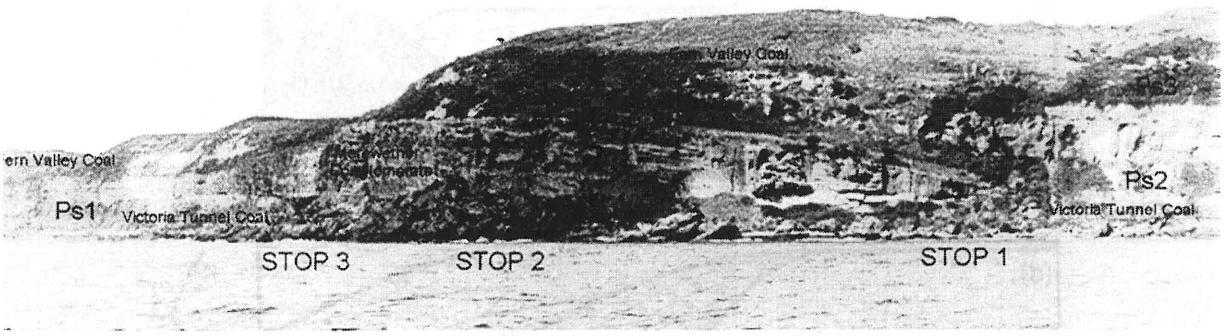


Figure 7. Coastal outcrop of the Merewether Conglomerate between Redhead and Dudley as represented in Fig. 10. Note the overall sigmoidal shape and inclined bedding planes which resemble giant crossbeds.

Coal

Stratigraphic relationships indicate that the major coals formed from peat mires which blanketed *abandoned* sedimentary surfaces, and were not coeval with substantial siliciclastic deposition. Peat mires were probably woody, in rain-fed (ombrotrophic) bogs at a 70° S palaeolatitude similar to those forming today in the boreal wetland regions of Canada (Martini and Glooschenko 1985). A 10:1 compaction ratio for peat to coal (Ryer and Langer 1980) implies decompacted, originally 20- to 50-m-thick peats, which probably built up the highest surfaces on the coastal plain reducing or totally excluding associated siliciclastic sediments. Seam convergence lines define the westward extent of clastic sedimentation and outline the lobate shape of successive paralic delta fronts (Fig. 8 & 9c). Repeated delta progradation and subsequent draping by peat mires led to the successive convergence of the Borehole, Yard, Dudley, and Nobbys Coals to form the West Borehole Coal in the western more slowly subsiding part of the Newcastle Coalfield (Fig. 8).

SUBSURFACE RELATIONS

The complex splitting and coalescing of coal seams between coastal outcrops in the Lake Macquarie Syncline, near Redhead, and the flank of the Lochinvar Anticline defines the geometry of interbedded clastic sediments. This added dimension can be observed in an east-west cross-section shown in figure 8. The Borehole, Yard, Dudley and Nobbys Coals encase parasequences stacked in a retrogradational, backstepping-to-the-east, pattern. Erosionally-based, sigmoidal bodies of conglomerate define the western pinchout of each parasequence. Each parasequence/conglomerate couplet is draped by a coal seam which converges and coalesces with previously deposited coal seams to the west to form the West Borehole Coal. Isopach maps (Branagan and Johnson, 1970) indicate that the conglomerates fill channels which outline the convex-to-the-west terminus of each parasequence (Figs 9a & c). Two or more bodies of conglomerate may occur between major coals, e.g., two Cockle Creek Conglomerates in the Bogey Hole Formation, and two or three Merewether Conglomerates in the Kotara Formation, as mentioned previously. The thick pyroclastic-surge Nobbys Tuff caps the retrogradational parasequence set which can be interpreted as the transgressive systems tract of a 3rd-order Sequence (Figs 2, 8). The two parasequences capped by the Victoria Tunnel and Fern Valley Coals downlap onto the Nobbys Tuff as part of a progradational parasequence set and can be interpreted as the lower part of the 3rd-order highstand systems tract (Figs 2 & 8). Conglomerate (Barnsley Member) again marks the western terminus of these progradational, paralic parasequences. The Victoria Tunnel and Fern Valley Coals cap parasequences and coalesce westwards with the West Borehole Coal as did previous coal seams. Thus, the thickness of clastic interseam sediments decreases westwards from the more rapidly subsiding Lake Macquarie Syncline towards the more slowly subsiding Lochinvar Anticline.

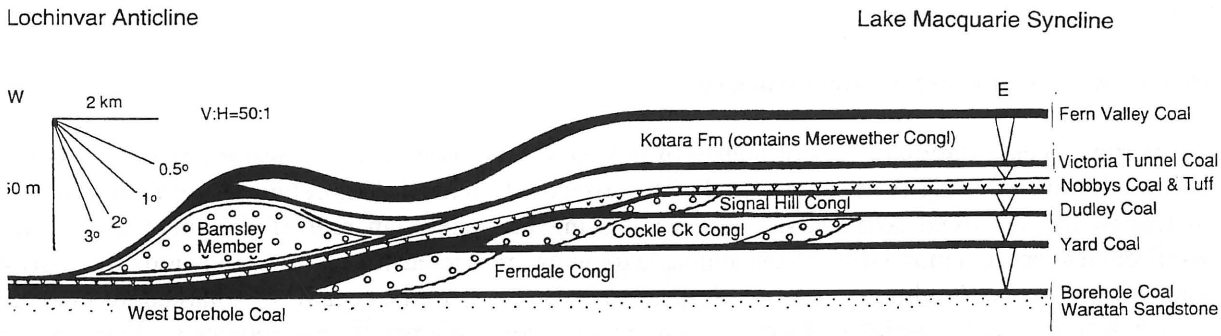


Figure 8. Subsurface cross-section of the lower part of Sequence F, from the flank of the Lochinvar Anticline (west) to Redhead (east), (c) in Figure 3. Modified from Diessel and Warbrooke (1987) by reducing vertical exaggeration to 50:1, leveling on the Borehole Coal, and smoothing thickness variations. Note the: (1) backstepping or retrogradational pattern of paralic delta parasequences from the Borehole to the Nobbys Coal (3rd-order transgressive systems tract); (2) Nobbys Tuff in position of 3rd-order maximum flooding surface/condensed section at change of parasequence stacking from retrogradational to progradational; (3) progradation and downlap of paralic delta parasequences onto Nobbys Tuff (3rd-order highstand systems tract); (4) location of conglomerate members at the distal terminus of each parasequence (high-frequency, 4th-order, incised-valley-fills); and (5) coalescence of coals westwards. High-frequency, fourth-order sequence boundaries occur at the base of each conglomerate, and continue at the boundary between coalesced coals, and at the base of coals which overlie parasequences with no intervening conglomerate.

RELATIVE SEA-LEVEL CHANGE

Deposition during one of the many 4th-order relative sea-level cycles within the lower Newcastle Coal Measures is discussed below (Figs 6 & 9).

Relative sea-level fall

A fall in relative sea-level terminated the progradation of a previous highstand paralic delta (parasequence) and exposed the coastal plain. Lower base-level rejuvenated streams draining the New England Orogen where a repository of gravelly alluvium had accumulated during the highstand. Hinterland tributaries incised the alluvium and flanking piedmont fans to provide immediately available detritus for transport to the basin. Tributaries merged into a single trunk stream before they entered the Newcastle half-graben from the northeast (Fig. 9a). Finding the lowest topography, the trunk stream was deflected around the abandoned, western extremity of the exposed delta-front in a moat created by compaction of the underlying peat. The gravelly fluvial sediments crossed the coastal plain in confined channels that fed directly to the marine shoreline. The abundant sediment supply to the shoreline initiated seaward progradation of the upward-coarsening shoreface intervals of the Dempsey Formation/Waratah Sandstone

Rising relative sea-level

Rising relative sea-level caused as much as 60 m of gravel to aggrade in the channel incised during the previous fall. As the rise accelerated, the locus of alluvial deposition migrated upstream, north of the basin, to be confined to fringing piedmont fans and hinterland valleys in the New England Orogen. Correspondingly, sediment supply to the marine shoreline declined and the Waratah Sandstone beach ridges were transformed into transgressive barrier islands above a transgressive surface. After alluvial sedimentation ceased in the Newcastle sub-basin, the coastal plain landward of the sandy barriers (Fig. 9b) was entirely covered by forested, rain-fed (ombrotrophic) peat mires whose growth was stimulated by the rising water-table.

Maximum rate of rising relative sea-level

The vertical accumulation of tens of metres of peat kept pace with the rising water table induced by a favourable rate of rising relative sea-level. This effectively inhibited shoreline transgression and the encroachment of fluvial sediments. However, during the maximum rate of rise, peat growth was insufficient to prevent inundation by expanding lagoons and restricted marine bays landward of the barrier complex. A paralic flooding surface which spread across the top of the peat mire is marked by an abrupt transition from coal to prodelta siltstone, initiating deposition of a paralic parasequence. This flooding surface is interpreted as the back-barrier equivalent to a marine maximum flooding surface. Trees growing on the surface of the peat mire were drowned and preserved in growth position or as fallen logs. At this time, or during the next phase, the sandy marine barriers may have been submerged as shoals, but still protected the coastal plain from open marine processes.

Relative sea-level highstand

During relative sea-level highstand, lagoons and restricted bays landward of the marine barrier shoreline, or shoals, provided sufficient accommodation space for small paralic deltas to prograde westwards from the Offshore Uplift (Fig. 9c). Explosive volcanoes from this area not only showered the coal measures with air-fall and base-surge ash but also provided volcano-lithic detritus by the erosion of its associated ignimbrite sheets (Jones et al. 1987). High relative sea-level caused the impounding of coarse, pebbly alluvium in hinterland valleys of the New England Orogen allowing the finer-grained, volcano-lithic sediment to be deposited and trapped on the coastal plain; in effect, starving the marine shoreface and shelf (Waratah Sandstone and Dempsey Formation).

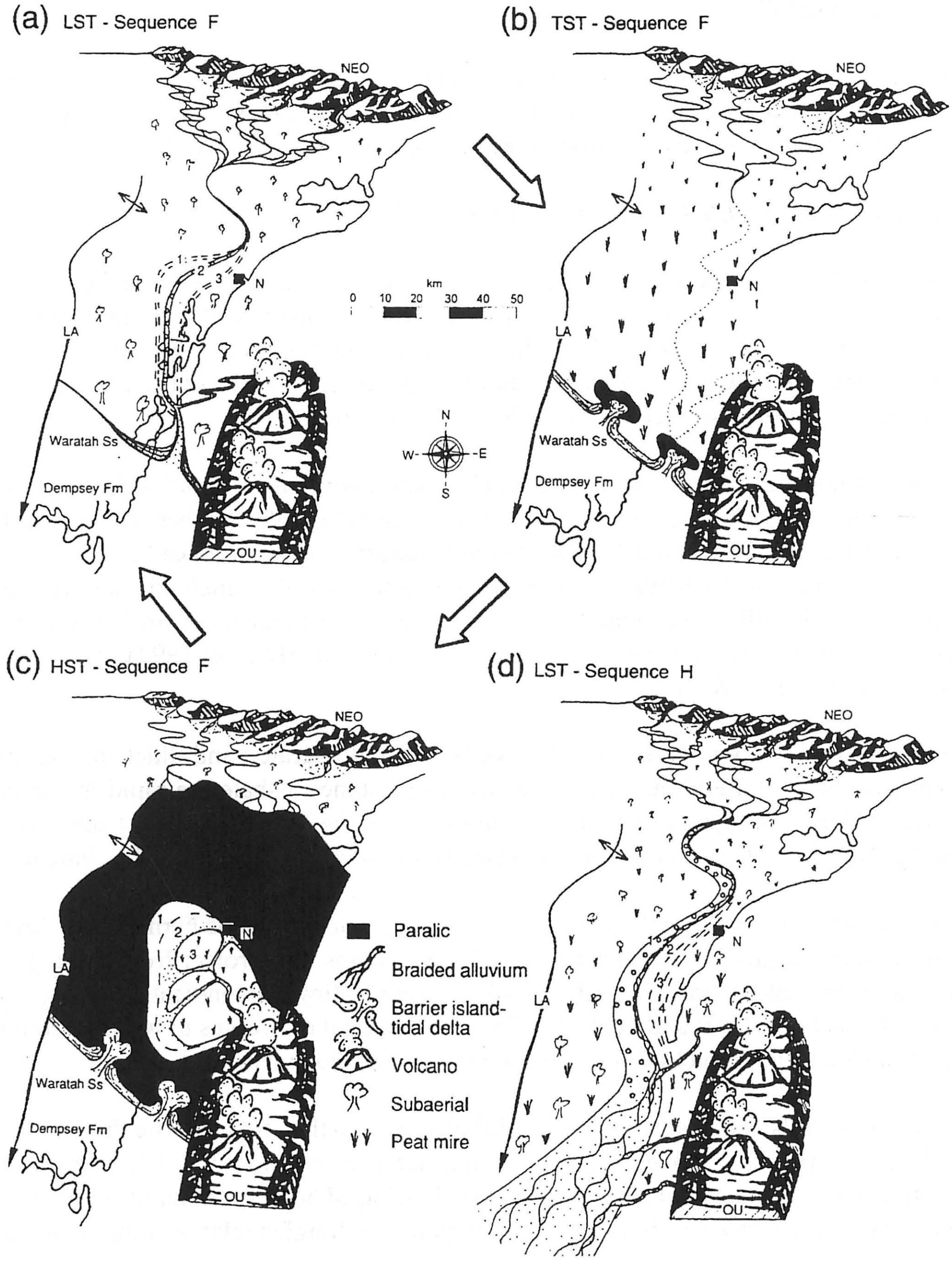


Figure 9. Palaeogeographic reconstructions for a single representative 4th-order sequence within the larger 3rd-order Sequence F (a-c) during one cyclical 4th-order change in relative sea level (large arrows depict cyclicity) and Sequence H (d) during a 4th-order lowstand. The marine shoreline prograded southward during lowstands, and the paralic delta complex prograded westward during highstands. N=Newcastle, NEO=New England Orogen, LA=Lochinvar Anticline, OU=Offshore Uplift. (a) Relative sea level lowstand to initial rise (lowstand systems tract). 1=Ferndale Conglomerate, 2=Cockle Creek Conglomerate, 3=Signal Hill Conglomerate. (b) Early relative sea level rise to maximum rate of rise (transgressive systems tract). (c) Slowing rates of relative sea level rise to early fall (highstand systems tract). Location of backstepping paralic delta fronts based on seam convergence lines from Branagan and Johnson (1970), Warbrooke (1981), Bowman and Whitehouse (1984). 1=Borehole/Yard Coals, 2=Yard/Dudley Coals, 3=Dudley/Nobbys coals. (d) Relative sea level lowstand to initial rise (lowstand systems tract). Location of main fluvial channel based on Bolton Point Conglomerate. 1=Bolton Point Conglomerate, 2=Teralba Conglomerate, 3=Marks Point Conglomerate, 4=Karignon Conglomerate.

Relative sea-level fall

Falling relative sea-level at the start of another cycle terminated the deposition of paralic deltas, exposing the entire back-barrier coastal plain to local fluvial incision (Fig. 9a) and initiating another high-frequency, 4^{th}-order sequence of conglomerate-coal-paralic parasequence.

REDHEAD TO DUDLEY COASTAL TRANSECT

Cliffs between Redhead and Dudley (Fig. 10) expose an imbricate set of 3 paralic parasequences (Ps1-Ps3) and the Merewether Conglomerate Member which constitute the Kotara Formation. Ps1 is a parasequence that coarsens upward from shale to sandstone (Fig. 6) to form a mound-shaped body with inclined bedding that downlaps southwards and northwards onto the top of the Victoria Tunnel Coal. The southerly inclined, upper surface is draped by the Fern Valley Coal.

The Merewether Conglomerate, about 12 m thick, occurs above an erosional surface that cuts through Ps1 down to the top of the Victoria Tunnel Coal. The inclination of the erosive surface is subparallel to the slope of bedding in Ps1. Similar bodies of conglomerate at Little Redhead (3 km to the north) and at Shepherds Hill, also in the Kotara Formation, are exposures of a single channel (Diessel, 1992a), or alternatively, may be different channels separated by deltaic parasequences. Inclined bedding, interpreted as giant crossbeds (Conaghan, 1982) or lateral accretion beds (Diessel 1992), imparts a characteristic sigmoidal shape (Figs 6 & 7).

Parasequence Ps2 drapes over the Merewether Conglomerate, and thickens northwards as the conglomerate thins. Lateral facies changes from sandstone to shale are rapid in places. Fossil tree stumps as much as 6 m high, with their roots in the top of the Victoria Tunnel Coal have been buried by Ps2 and by Ps1. Sand-filled scours around some of the stumps indicate rapid sediment accumulation.

Parasequence Ps3, abruptly overlies Ps2. Tuffaceous sediments and the Fern Valley Coal drape Ps1 and Ps3 and the Merewether Conglomerate. Fossil tree stumps that project from the top of the inclined, mound-like surface of Ps1 into the tuff beneath the Fern Valley Coal indicate subaerial exposure of Ps1 before the deposition of tuff and peat. The Fern Valley Coal converges to within a couple of metres of the top of the Victoria Tunnel Coal at the southern end of the outcrop.

Note that although Ps1 and Ps2 are identical lithologies, and they both overlie the Victoria Tunnel Coal, it would be incorrect to correlate them. This mistake is a common pitfall for subsurface correlations where intercalated conglomerates are depicted as 'U'-shaped bodies instead of sigmoidal-shaped bodies that intercalate with adjacent sediments in an offlapping or shingled relationship, as shown by this coastal transect.

Stop 1

Northern pinchout of the Merewether Conglomerate (Figs 7 & 10). Note the sharp, inclined top of the sigmoidal-shaped conglomerate body, a formerly horizontal bedding plane which has been tilted by compaction of the underlying coal (Fig. 6). This slope parallels inclined bedding within the conglomerate making it appear to consist of giant crossbeds. Shale of parasequence Ps2 overlies the conglomerate and the Victoria Tunnel Coal with no interbedding. This contact is interpreted as a paralic flooding surface. Parasequence Ps2 pinches out to the south, over the top of the thickening conglomerate. The base of the conglomerate is erosional into the underlying parasequence Ps1 and is interpreted as a high-frequency, 4^{th}-order sequence boundary. Note that Ps1 also sharply overlies the Victoria Tunnel Coal and buries in-situ fossil tree stumps which project several metres above the

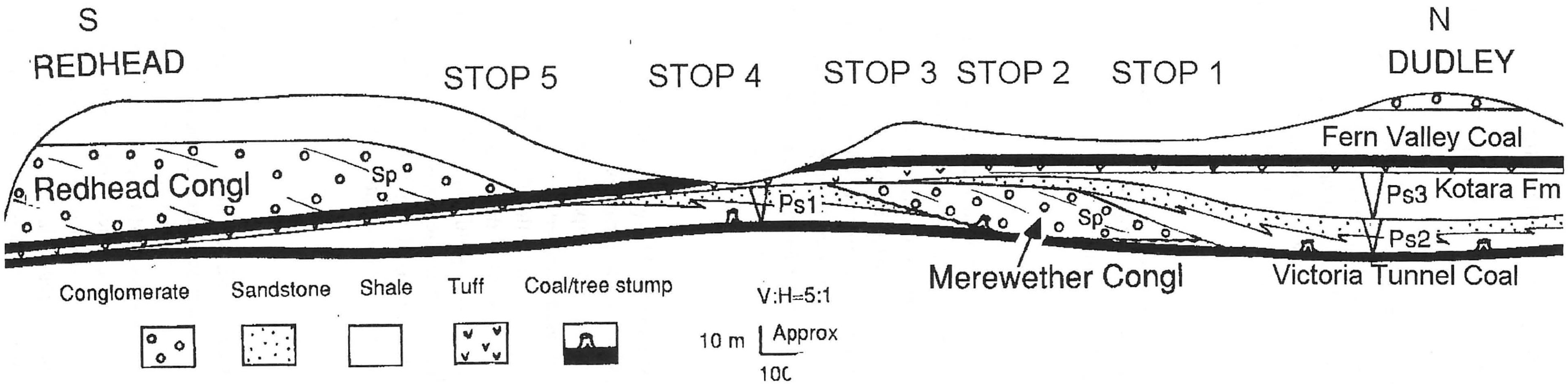


Figure 10. Sketch of coastal outcrops of the nonmarine/paralic sediments in the Newcastle Coal Measures from Redhead to Dudley, (b) in Fig.3. Offlapping paralic delta parasequences (Ps1-Ps3) in the Kotara Formation intercalate between sigmoidal fluvial conglomerate bodies (dashed lines depict principal bedding planes, Sp, see Fig. 13). Triangles depict upward-coarsening trends. Note in situ tree stumps on top of Victoria Tunnel Coal. In the subsurface, if the Merewether Conglomerate was not intersected or incorrectly interpreted, Ps1 would be correlated incorrectly with Ps2. However, in this continuous coastal exposure the two parasequences are seen to be separated by a 4th-order sequence boundary at the base of an incised-valley-filling conglomerate (Merewether Conglomerate). All these sediments were deposited on the coastal plain landward of the marine shoreline.

underlying coal (some with attached branches). This contact is interpreted as an older flooding surface.

Stop 2

The 4th-order sequence boundary at the base of the conglomerate is spectacularly exposed here. Transported logs can be seen in the basal few metres in addition to in-situ fossil tree stumps which project several metres into the conglomerate. Radial roots are located in sandy and shaly sediments immediately below the basal erosional surface and indicate subaerial exposure of the paralic parasequence Ps1 before gravel deposition. This implies a substantial relative sea-level fall after the deposition of parasequence Ps1.

Stop 3

This is a brief stop to view the southern pinchout of the Merewether Conglomerate and the full thickness of parasequence Ps1. In the distant headland it can be seen that the sandstone dominated top of Ps1 is sharply overlain by what may be a southern shaly continuation of Ps2 before it passes upwards to tuffaceous sediments and the Fern Valley Coal

Stop 4

A complete section through a paralic parasequence can be observed here overlying the Victoria Tunnel Coal (Fig. 5). Note the upward coarsening character of this heterolithic, shale to sandstone parasequence. In-situ fossil tree stumps with their roots in the top of the Victoria Tunnel Coal, have been buried by the prodelta shale indicating that this is a flooding surface caused by inundation. Note that, at this location, a thin, shaly, southern continuation of parasequence Ps2 overlies the sandy top of Ps1, but both the previously intervening Merewether Conglomerate and the overlying parasequences Ps3 are absent. This implies a considerable hiatus between the deposition of parasequence Ps1 and both Ps2 and the overlying Fern Valley Coal at this location. The deposition of, at least, 12m of parasequence Ps1 implies a relative sea-level rise.

Stop 5

Parasequence Ps1 is seen here to consist of gently inclined bedding which downlaps onto the top of the Victoria Tunnel Coal (poorly exposed just above rock platform level). The inclined bedding probably resulted from a combination of gentle sedimentary dip and compactional tilting caused by underlying peat compaction (a similar mechanism for the exaggerated inclined bedding in the conglomerates) (Fig. 6). The parasequence pinches out to the south (where the Fern Valley Coal converges to within a few metres of the top of the Victoria Tunnel Coal) and is interpreted as the delta front terminus of a paralic delta. Note the in-situ fossil tree stumps projecting into overlying tuff under the Fern Valley Coal at the top of the parasequence indicating exposure. The Redhead Conglomerate is spectacularly exposed here, clearly displaying steeply inclined internal bedding surfaces as it pinches out to the north, similar to the Merewether Conglomerate. The underlying erosional surface is interpreted as another 4th-order sequence boundary.

CONCLUSION

(i) Most models of coal-measure deposition regard alluvial, peat mire, deltaic, and shoreline environments as coeval, laterally equivalent facies. However, it is proposed here that the juxtaposition of three disparate lithologies in the Newcastle Coal Measures, such as coal, fluvial conglomerate, and upward-coarsening siltstone/sandstone deltaic, paralic parasequences was caused by changes in relative sea level which initiated deposition of these facies at different times. In Sequence F, back-barrier paralic deltas prograded during 4th-order relative sea level highstands and alternated with coarser-grained alluvial deposition during lowstands. Most thick peat mires developed as bogs, blanketing abandoned sedimentary surfaces between times of alluvial and paralic delta deposition, coincident with a siliciclastic hiatus and stimulated by a rising water table.

(ii) Fourth-order depositional sequences commenced with subaerial erosion surfaces (sequence boundaries) and were overlain by channelised fluvial conglomerate deposited in incised-valleys in lowstand systems tracts (Fig. 6). Following lowstand fluvial deposition, peat mires extended over the entire non-marine area of the Newcastle Coalfield in transgressive systems tracts. In Sequence F, maximum flooding surfaces developed by submergence of peat mires and were overlain by prograding crevasse splays, crevasse subdeltas, and small deltas which extended into lagoons and lakes in highstand systems tracts. Marine shoreface parasequences were deposited during relative sea level lowstands, out of phase with paralic delta parasequences which were deposited during relative sea level highstands. In Sequence H topographically higher areas, too far landward to be reached by paralic transgressions, supported peat mires which developed throughout both the transgressive and highstand systems tracts and were crossed briefly by streams which deposited gravelly alluvium in lowstand systems tracts.

(iii) Two source areas supplied sediment into the Newcastle half-graben. During highstands, an easterly source on the Offshore Uplift shed sandy and muddy, dominantly volcanic, detritus into the Newcastle Coalfield via streams feeding paralic and lacustrine deltas. During lowstands, a northern source in the New England Orogen shed gravelly volcano-lithic detritus via rejuvenated, braided streams, flowing in 4^{th}-order incised valleys.

(iv) Multiple 4th-order sequences constitute three 3rd-order depositional sequences, which in turn constitute the Newcastle Coal Measures (Fig. 4).

(v) All of the Newcastle Coal Measures was deposited during 2nd-order falling relative sea level, reflected in an overall upward regressive trend of increasing thickness and coarseness of fluvial conglomerate, and a corresponding decrease in intercalated coastal plain facies. Increasing up-sequence evidence for oxidation during peat mire development, producing duller coals, is consistent with lower water tables as a result of regional regression.

(vi) The Newcastle Coal Measures was deposited on the tectonically active side of a foreland basin where more rapid subsidence rates created greater amounts of subaerial accommodation*landward* of the marine shoreline leading to the deposition of a thick non-marine/paralic section and a relatively thin coeval marine section (the reverse situation to a seaward subsiding and thickening shelf basin). In addition, high rates of peat aggradation probably inhibited the marine shoreface from transgressing the coastal mires. These combined effects led to the accumulation of as much as 400 m of siliciclastic sediments and peat in alluvial and paralic environments with no open-marine intercalations, and a correspondingly thin (about 40m) laterally equivalent marine interval.

PART 3: THE NEWCASTLE COAL MEASURES - CONTEMPORANEOUS DEPOSITION OF CLASTIC AND COAL MEASURE STRATA IN A HIGH ACCOMMODATION SETTING

Murray Little and Ron Boyd

The Newcastle Coal Measures (NCM) consist of proximal non-marine coal-bearing strata that provide an opportunity to conduct research in the fields of lithostratigraphy, and the still developing field of non-marine sequence stratigraphy. The NCM has the uncommon characteristic of containing a considerable proportion of organic sediment that has been preserved adjacent to coarse conglomerate units and interbedded with a significant proportion of tuff/tuffaceous strata. The abundance of tuff markers provides an excellent opportunity to conduct high resolution lithostratigraphic and chronostratigraphic correlation of non-marine sediments, and to compare this approach with that of sequence stratigraphy in proximal coal-bearing non-marine sediments.

The maximum thickness of the NCM is 412.8m in DM Awaba DDH3. The NCM are notably different from other Sydney Basin units due to the presence of large proportions of tuff and tuffaceous sediment, and the fact that coal is preserved alongside significant proportions of conglomerate. Diessel (1980) calculated that the NCM have an average composition of 29 % conglomerate, 23% sandstone, 17% shale, 19% tuff and claystone, and 12% coal.

PAST AND PRESENT STRATIGRAPHY OF THE NEWCASTLE COAL MEASURES

The stratigraphic division of the NCM that many geologists will be familiar with is that of the Standing Committee on Coalfield Geology of N.S.W. (1975, see Figure 11). A revised stratigraphic nomenclature has been published by the by the Standing Committee on Coalfield Geology of N.S.W., Newcastle Coalfield Subcommittee (1995). This stratigraphic revision was undertaken to address the difficulties of the stratigraphy of McKenzie and Britten (1969) and later amendments made by the Standing Committee on Coalfield Geology of N.S.W. (1975). An example of these problems is the assignment of the type section for the Australasian Coal and Hartley Hill Coal to the same unit. This error has lead to misnaming of the coal seams and the associated interseam sediment (Standing Committee on Coalfield Geology of N.S.W., Newcastle Committee 1995).

Significant changes have been made to the stratigraphy of the NCM in the 1995 version. The more notable changes include: 1) Waratah Sandstone is no longer part of the NCM as the top of the Waratah Sandstone marks the base of the NCM. 2) The top of the NCM was defined as the top of the Vales Point Coal. 3) Internally, the NCM are divided into seven formations. 4) Three formations consist of the Nobbys Tuff, Warners Bay Tuff and Awaba Tuff. The tuffs are now used to divide the stratigraphy as they can be correlated consistently over large areas.

These changes represent a major difference to the 1975 (Standing Committee on Coalfield Geology of N.S.W.) stratigraphy which divided the NCM into four subgroups, using coal seams (which are not as extensive as the tuff units) as boundaries. In the 1995 stratigraphy all of the

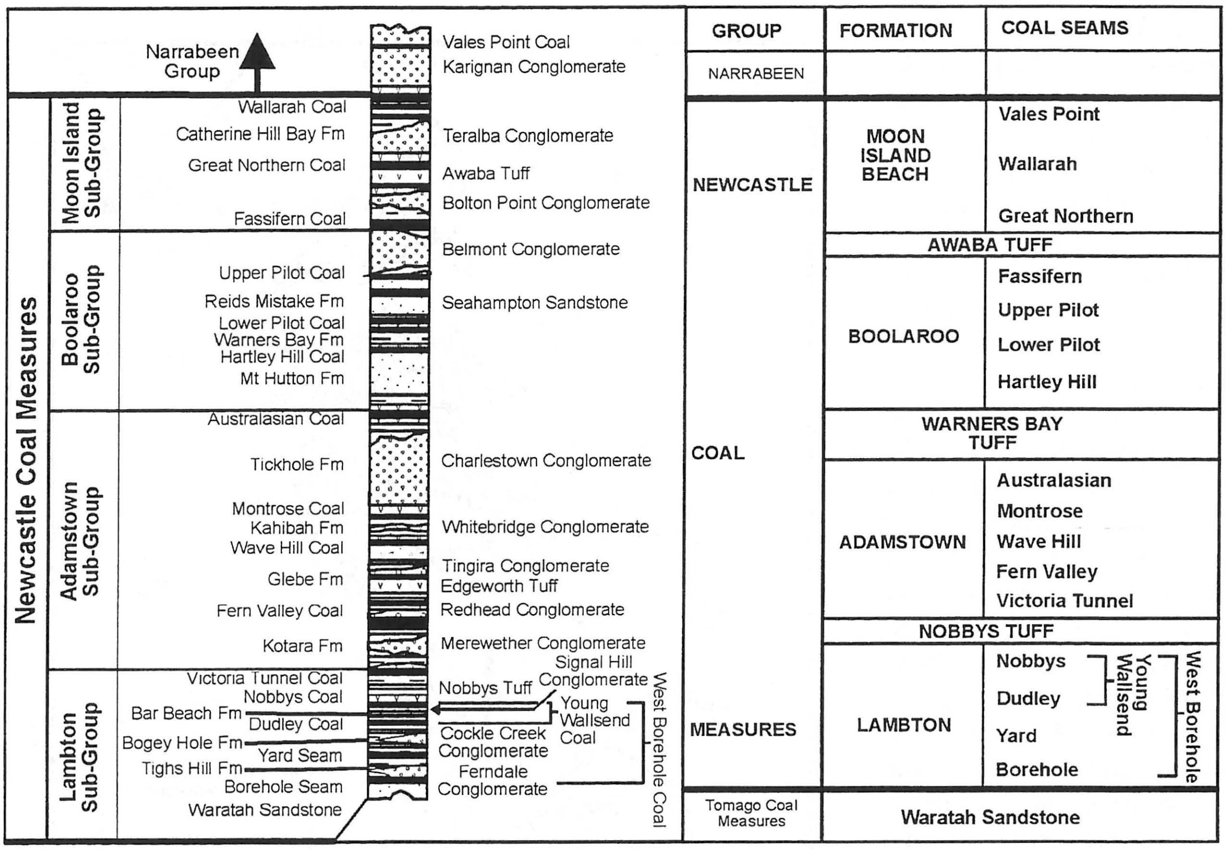


Figure 11. Previous stratigraphic division of the NCM (on the left, Standing Committee on Coalfield Geology of N.S.W. 1975) and current stratigraphic nomenclature of the NCM (on the right, Standing Committee on Coalfield Geology of N.S.W., Newcastle Coalfield Subcommittee 1995).

coal seams and the remaining clastic and pyroclastic strata are divided by the three tuffs into the Lambton, Adamstown, Boolaroo and Moon Island Beach Formations (see Figure 11). The coal seams and clastic units are named on an informal basis, using the names from the stratigraphy of the Standing Committee on Coalfield Geology of N.S.W. (1975), pending further review.

Current Stratigraphic Review of the Newcastle Coal Measures

Currently the stratigraphy of the NCM is undergoing review by the NSW Geology Council, Newcastle Coalfield Committee. This revision also represents a significant section of the PhD study of Little (in prep). This stratigraphic revision was based on correlation of 137 stations (see Figure 12 for locations). Out of the 137 stations, 136 were borelogs (bores N114 and N1524 were supplemented by coastal outcrop sections). The borelogs were complimented by a measured section at Black Hill. The correlations extend 70km from north to south, from Black Hill to Terrigal. A borehole framework that covers approximately 1000km^2 has been used for correlations. The authors proposed stratigraphic review is illustrated in Figure 13.

Tuffs Defined as Formations, Members and Beds

The above-mentioned correlations have confirmed that the three formation status tuffs of 1995 stratigraphy are present on a regional basis. In total, seven tuffs can be correlated over the study area (Figure 12). In ascending order these tuffs include: the Nobbys Tuff, Murdering Gully Tuff Member, Edgeworth Tuff, Buttaba Tuff, Warners Bay Tuff, Reids Mistake Tuff, and the Awaba Tuff. Six of these tuffs are suitable to be named as formations, and to divide the NCM into additional formations. The six tuffs are designated to formation status because: a) they are marker horizons that can be easily delineated on cross sections on a regional basis; b) the tuffs are the only units in the NCM that continuously divide the coal seams over the entire borehole suite; c) they are relatively thick (mostly between 1-22m). The Murdering Gully Tuff Member is the only regional tuff not suitable to be named at formation status. The reason for its unsuitability is that this tuff is relatively thin and is usually separated from the Edgeworth Tuff by less than one metre of coal or coaly shale. Nonetheless, the Murdering Gully Tuff is an important stratigraphic marker as it aids the identification of the Edgeworth Tuff. It is suggested that the Murdering Gully Tuff should be elevated to member status.

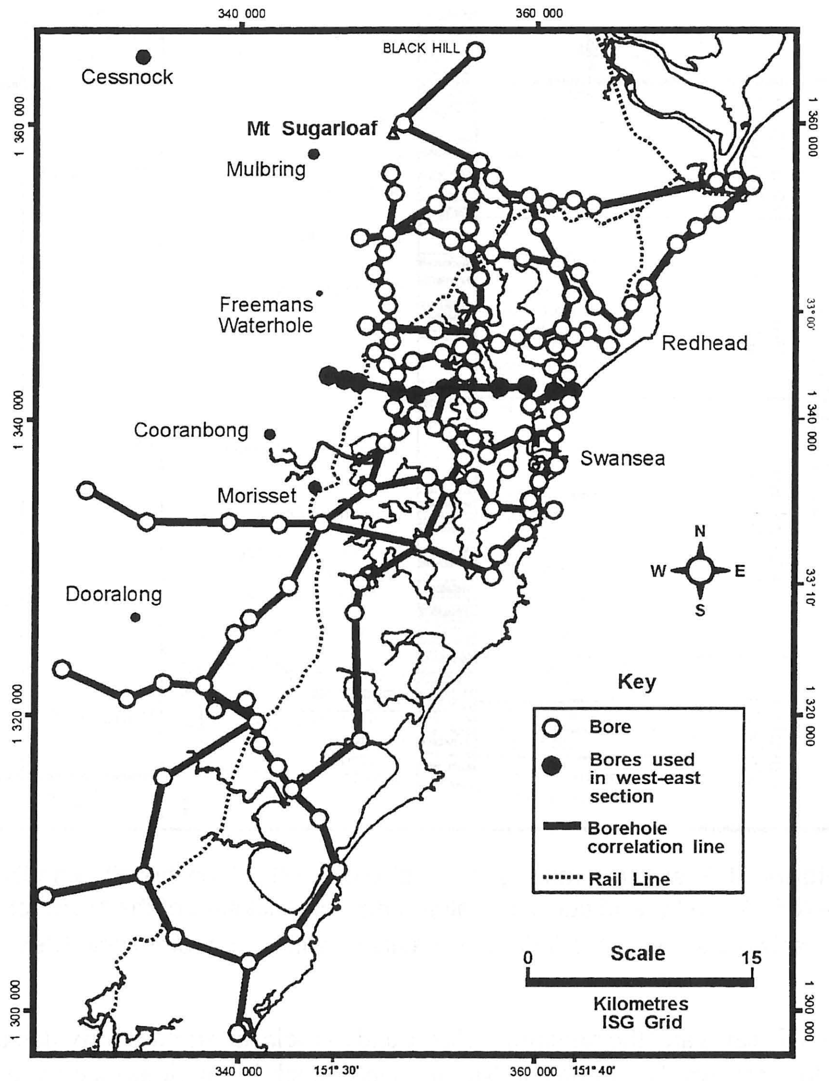


Figure 12. Location of boreholes and outcrop sections used in regional correlations of the NCM.

Other tuffs provide valuable stratigraphic markers, but are not as extensive or as thick as the above mentioned six regional tuffs. The thin marker tuffs that have proved to be useful for correlation over large areas, and identification of the formation status tuffs, are now formally named as beds (e.g. Seven Foot Bed and Eight Foot Six Inch Bed in the Victoria Tunnel coal seam). There are additional marker tuffs that are not formally classified as beds (e.g. Ten Foot band of Warbrooke 1981) but are not formally named as beds because they were not necessary or useful for correlation purposes across the entire study area. It is acknowledged that some of the tuff markers that are not proposed to be formally named may be useful for correlation purposes.

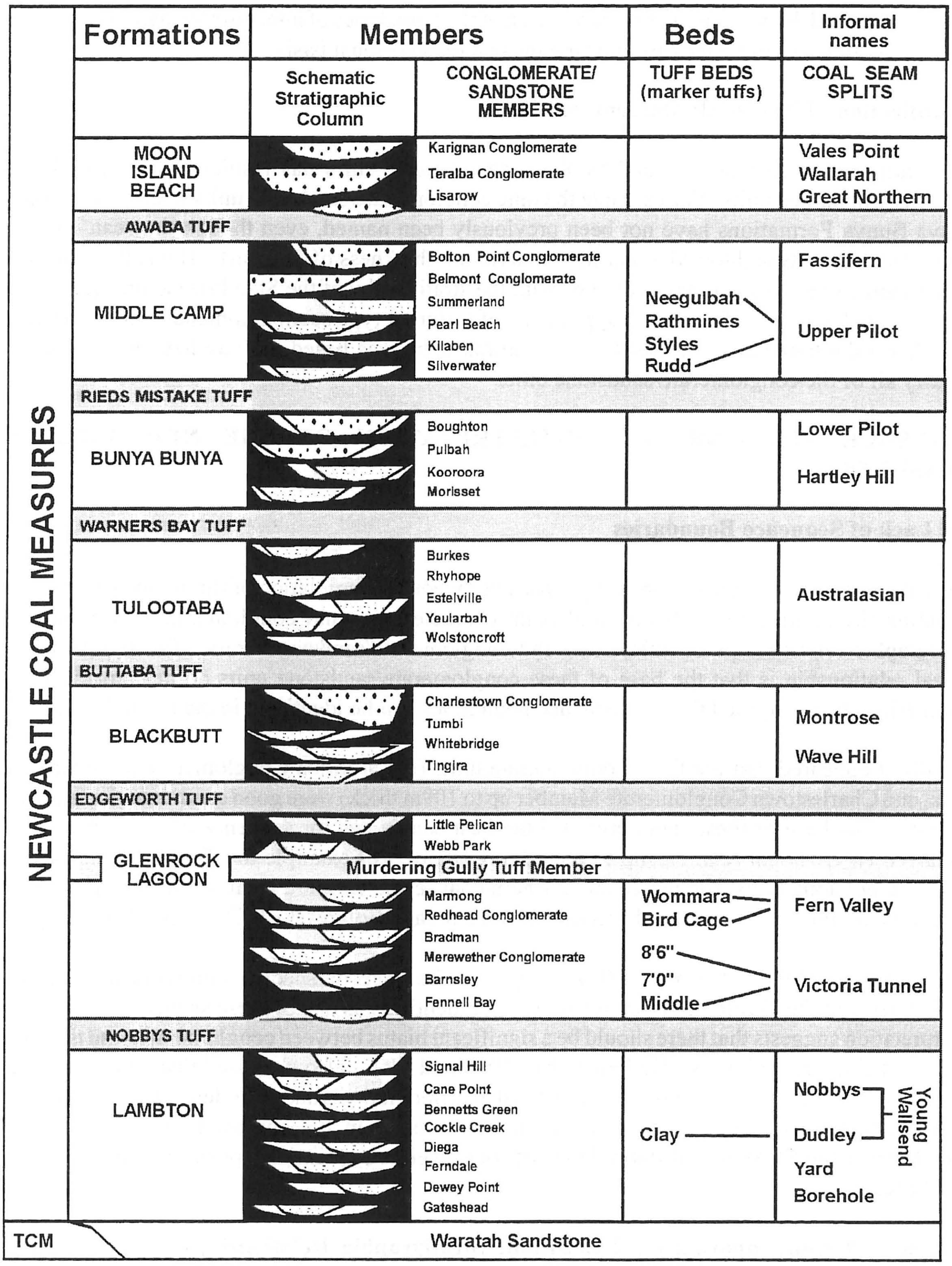


Figure 13. Proposed stratigraphic revision of the NCM.

Inter-Tuff Formations

The intervals between the regional tuffs (which also contain thin discontinuous tuffs) are classified at formation status. These inter-tuff units are designated as formations because: a) is not possible to further divide them into additional formations on the basis of lithology as the clastic units do not form continuous layers, and the coals split and coalesce around the clastic units; b) the tuffs provide boundaries that are readily identified, hence making the recognition of the boundaries of inter-tuff formations easy to identify on cross sections; c) the inter-tuff units are present on a regional basis.

Identification of Previously Unidentified Units

The stratigraphic control provided by the seven regional tuffs has resulted in the identification of previously unnamed units. For example the nine conglomerate/sandstone units within the Tulootaba and Bunya Bunya Formations have not been previously been named, even though they can be up to fifty metres thick (e.g. Boughton Member has a maximum thickness of 53.94m). The lack of identification of these units may be due to the problems with the stratigraphy of the Standing Committee on Coalfield Geology of N.S.W. (1975), such as application of different type section nomenclature to the same unit. In addition the borehole suite that the 1975 stratigraphy was based on may have been insufficient to identify all of the conglomerate/sandstone units.

SEQUENCE STRATIGRAPHIC INTERPRETATION OF THE NEWCASTLE COAL MEASURES

The Lack of Sequence Boundaries

There is substantial evidence supporting contemporaneous accumulation of fluvial and peat mire systems including the relationship between coal seam characteristics and conglomerate/sandstone units, and stratigraphic relationships of tuffs, coals and conglomerate/sandstone units. The significance of this coeval relationship is that the base of these conglomerate/sandstone units do not represent sequence boundaries. It is proposed that no sequence boundaries can be identified in the entire NCM.

Initially it appeared that the thick conglomerate units (e.g. Teralba Conglomerate Member up to 40m thick, and Charlestown Conglomerate Member up to 109m thick) were good candidates for incised-valley systems. The base of these units provided the best candidates for sequence boundaries as they often displayed an erosional relationship to underlying strata. For example the Teralba Conglomerate was known to erosionally overlie the Great Northern coal seam. In some locations the Great Northern coal seam was thought to be completely eroded in some areas (Ziolkowski 1978, Spoon Rocks region).

Later Herbert (1994, 1995 and 1997) interpreted the base of specific conglomerates as sequence boundaries, but the Teralba Conglomerate was not identified as one of these sequence boundaries. This interpretation suggests that there should be a significant hiatus between conglomerates and the underlying coals and fine-grained units. Herbert (1994, 1995 and 1997) also proposed that coals, conglomerate, sandstone and fine-grained units were deposited at different times and their deposition was controlled by relative sea-level changes. Therefore a significant issue in the approach to identifying sequence boundaries in the NCM is the differentiation of coeval verses sequential deposition of fluvial systems and peat mires.

Evidence of Contemporaneous Deposition: Stratigraphic Relationships Between Coals, Tuff Markers, Fine-grained Units and Conglomerate/Sandstone Units

An excellent example that illustrates the contemporaneous deposition of coal, tuff, fine-grained facies and conglomerate/sandstone units is provided by detailed subsurface correlations of the Bolton Point Conglomerate, Fassifern coal seam, and tuff markers.

The correlations of the Bolton Point Conglomerate and Fassifern coal seam are illustrated in Figures 32 and 33. These correlations are constrained by eleven tuff markers, including the Awaba Tuff. The Fassifern coal seam and intervening tuff markers onlap the Bolton Point Conglomerate on its northern and northwestern margins (first noted by Mr Malcolm Ives, Powercoal). At the opposing margins of the Bolton Point Conglomerate, tuff markers and sections of the Fassifern coal seam are terminated at the base of the Bolton Point Conglomerate.

But is this relationship between tuffs, coals, fine-grained facies, and conglomerate/sandstone units comparable to the characteristics of incised-valley systems? Zaitlin*et al.* (1994) provided identification criteria of incised-valley systems. The criteria of Zaitlin *et al.* (1994) included: 1) The valley is a negative (ie. erosional) palaeotopographic feature, the base of which **truncates** underlying strata including any **regional markers**. 2) The base and walls of the incised-valley system represent a sequence boundary that may be correlated to an erosional (or hiatal) surface outside the valley (ie. on the interfluve areas). On the interfluves the exposure surface may be characterised by a soil or rooted horizon. 3) The base of the incised-valley fill exhibits an erosional juxtaposition of more proximal (landward) facies over more distal deposits (ie. a "basinward shift in facies" Van Wagoner *et al.* 1990). 4) Depositional markers within the deposits of the incised-valley fill will onlap the valley walls.

The model of incised-valley fill systems presented by Zaitlin*et al.* (1994) suggest that if the Bolton Point Conglomerate represented an incised-valley system, then the Fassifern coal seam sections and interbedded tuff markers should be truncated on both sides of the Bolton Point Conglomerate. Onlap of markers onto the margins of an incised-valley systems does not occur. When compared to the criteria of Zaitlin*et al.* (1994) the Bolton Point Conglomerate does not represent an incised-valley system as the coal seam sections and interbedded tuff markers onlap the Bolton Point Conglomerate on its north/northwestern side. Although nondeposition and/or truncation of tuff markers and coal occurs along the southern/southeastern margin, the criteria for incised-valley identification indicates that truncation should occur along both margins of the valley.

The onlapping stratigraphic relationship between coal, tuff and conglomerate/sandstone units indicates that the deposition of fluvial and systems and peat mires was coeval. Unlike incised-valley systems fill, such as those described in Dalrymple *et al.* (1994), the conglomerate/sandstone units in the NCM have accumulated at the same time as the mire systems that bound them. Incised-valley systems differ to units such as the Bolton Point Conglomerate, as the incised-valley fill is separated from underlying and laterally adjacent strata by the chronostratigraphically significant surface of an erosional unconformity. Due to the significant difference of the characteristics of an incised-valley system (as outlined in Zaitlin*et al.* 1994) the conglomerate/sandstone units of the NCM cannot be interpreted as incised-valley systems, and the bases of these units do not represent sequence boundaries.

Depositional Model of the Bolton Point Conglomerate

Analysis of outcrop and subsurface correlations indicates that the Bolton Point Conglomerate was deposited as a shallow gravel ("Scott type") to deep gravel ("Donjek type") braided fluvial system (interpretation based on the fluvial style classification system of Miall 1996). The unit as a whole (maximum thickness of 77m, and width of 7km) does not represent a single channel fill, but is made up of vertically and laterally stacked channels as illustrated in Figures 32 and 33.

The onlapping relationship between the Fassifern coal seam, intervening tuffs and the Bolton Point Conglomerate is interpreted as a result of coeval mire and fluvial deposition where the fluvial system dominantly migrated towards the south/southeast. Where the channel-system was active peat and ash falls could not accumulate. But along the channel margins peat mires and tuffs could be preserved (see Figure 14). As the channel system migrated towards the southern/southwestern side, areas that were previously occupied by the active channel became abandoned so that peat and tuffs were able to accumulate and be preserved in these abandoned zones. This migration resulted in the onlap of tuffs, and coal seam sections onto the Bolton Point Conglomerate. As the channel system migrated towards the south/southeast, peat and tuff accumulation was progressively halted (nondeposition) in the active channel zone. This migration resulted in the termination of coal sections and tuff markers at the southern/southeastern base of the conglomerate. It is likely that some erosion of the already deposited Fassifern coal seam and tuff markers occurred, as braided river channel systems are characterised by their erosional relationship between in-channel and overbank deposits (e.g. Ashmore 1993, Siegenthaler & Huggenberger 1993, Miall 1996).

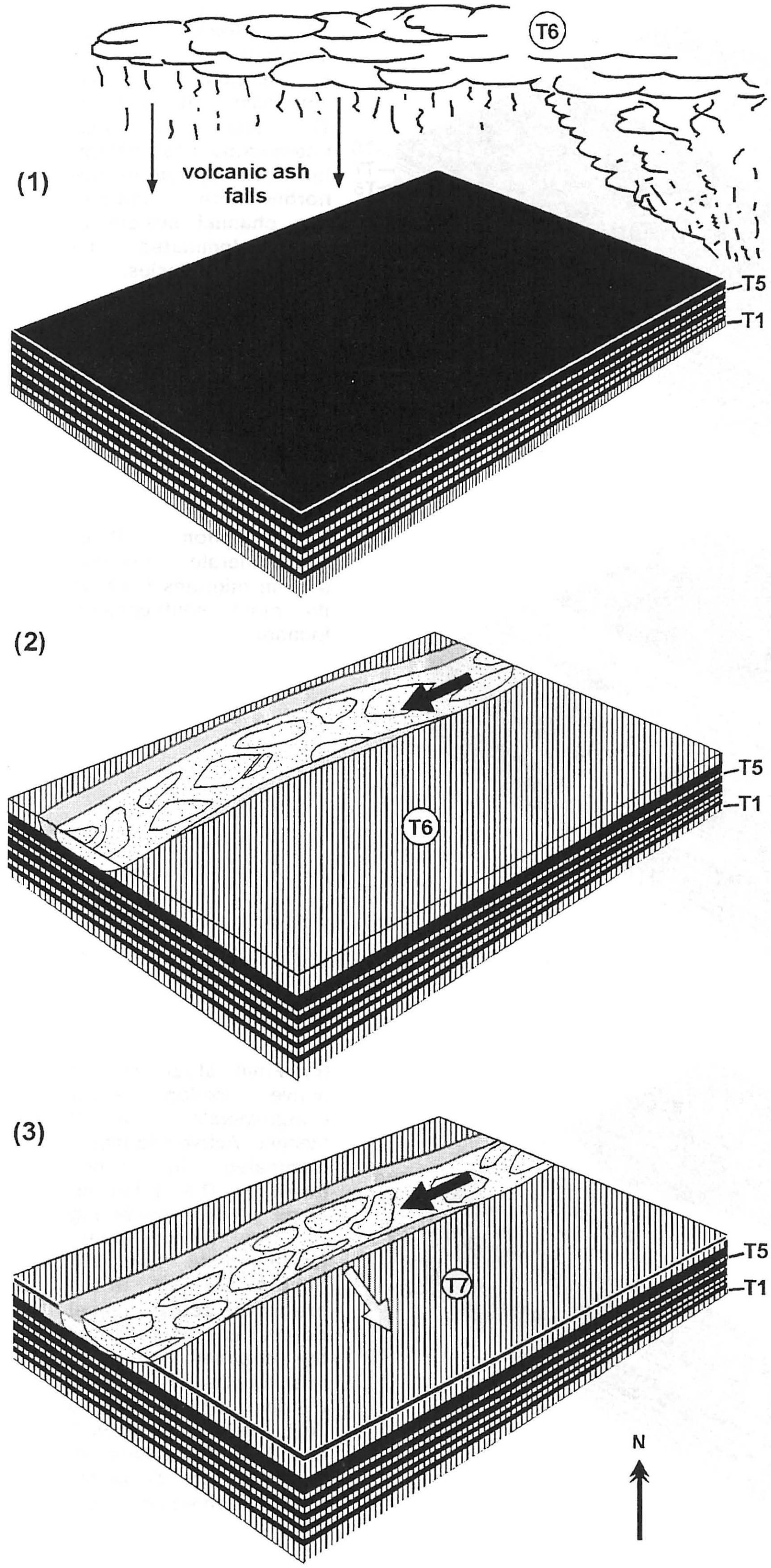
Significant changes in the position of relative sea-level (accommodation changes) are not required for fluvial erosion to occur. The diverging and converging of channels around bars in braided river systems results in the presence of scour pools at anabranch confluences, and cutbanks and associated bend scours on either side of mid channel bars (see Ashmore 1993, Siegenthaler & Huggenberger 1993, Bristow & Best 1993, and Miall 1996 for examples). A good example illustrating the degree of erosion associated with braided river channels is provided by Best and Ashworth (1997) who conducted a study on the Jamuna River (one of the worlds largest modern braided river systems). Best and Ashworth (1997) noted an outer bend scour (15m deep), on an anabranch of the Jamuna River, that migrated laterally by 1km over the 28 month study period. This braided river channel erosion occurred without any significant changes in the position of relative sea level (Best & Ashworth 1997).

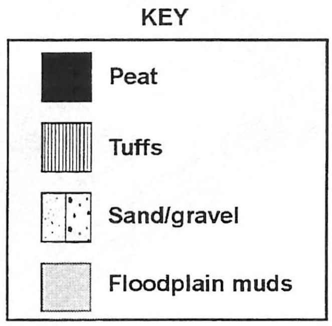
Stratigraphic Relationships between other Coals and Conglomerate/Sandstone Units

The coeval relationship between coal seams, tuff markers and conglomerate/sandstone units is best illustrated by the example of the Fassifern coal seam, intervening tuff markers, and the Bolton Point Conglomerate that has been correlated with closely spaced boreholes. Regional correlation of the NCM indicates that the contemporaneous relationship between coal seams, tuff markers and conglomerate/sandstone units applies to the rest of the NCM as the stratigraphic arrangement of these units is similar to the Bolton Point Conglomerate (compare other conglomerate/sandstone units with the Bolton Point Conglomerate in Figure 15). Subsurface correlations indicate that the majority of the conglomerate/sandstone units do not extend completely through the underlying coal seams, but are often completely surrounded by coal. Some sections of the coal seams are absent below the conglomerate/sandstone units, but this is interpreted to be mainly a result of nondeposition due to the presence of a fluvial system that did not permit peat accumulation in the active channel zone. Some erosion of the underlying coal has occurred, but this is due to the erosive nature of braided river systems rather than significant coal erosion resulting from a major decrease in the available accommodation space. The erosional bases of conglomerate/sandstone units in the NCM do not represent a significant hiatus in sedimentation, and are the product of normal fluvial activity where no significant changes in accommodation space have occurred. Throughout the entire accumulation of the NCM the deposition of the peat mires and fluvial systems was contemporaneous. The only interruption to clastic and organic sedimentation was from the volcanic ash falls that produced the thick regional tuffs (e.g. Nobbys, Edgeworth and Awaba Tuffs).

Evidence for Coeval Deposition: Coal Seam Characteristics

Coal seam characteristics (e.g. seam thickness, ash of cumulative floats at 1.60 density) change as conglomerate/sandstone units are approached. These changes are interpreted to result from the influence of the syndepositional affects of fluvial systems on mire environments. There are several examples from the NCM of coal seam characteristics changing as the conglomerate/sandstone units are approached. These include the example of the Great Northern Coal seam decreasing in thickness and increasing in ash (CF1.60, db) as the Teralba Conglomerate is approached (see Figure 16). Warbrooke (1981) and Warbrooke and Roach (1986) also provided examples from the lower NCM of coal characteristics changing as clastic splits are approached. Ash of cumulative floats at 1.60 density were chosen as tests at this density remove the distorting effects of stone bands.





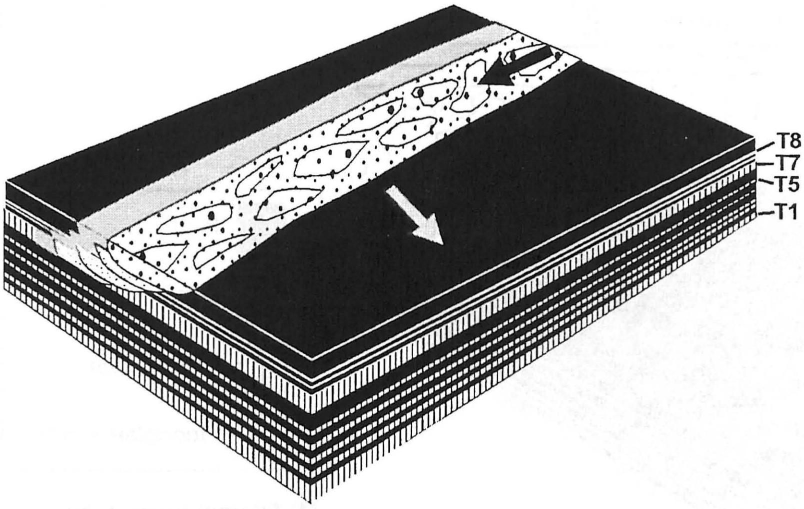
(1) Alternating peat mire and volcanic ash layer accumulation (producing tuff markers).

(2) Fluvial system of the Bolton Point Conglomerate formed during or shortly after the deposition of the T6 tuff marker. T6 tuff marker is eroded by the Bolton Point Conglomerate channel system as it migrates towards the southeast. Overbank fines are mostly eroded on the southeastern margin due to the channel migration.

(3) T7 blankets the area, but is not preserved in the region of the active channel system. Between T6 and T7 the peat mire regrows over T6, but no peat can accumulate in the position of the active channel system. Channel system continues to migrate towards the southeast. Overbank fines are mostly eroded on the southeastern channel margin. Floodplain deposits are best preserved on the northwestern channel margin.

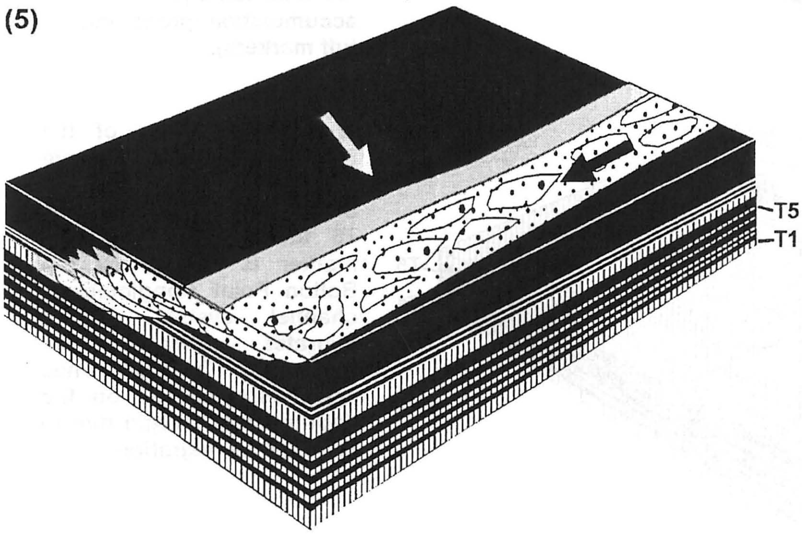
Figure 14. Depositional evolution of the Bolton Point Conglomerate and Fassifern coal seam.

(4)



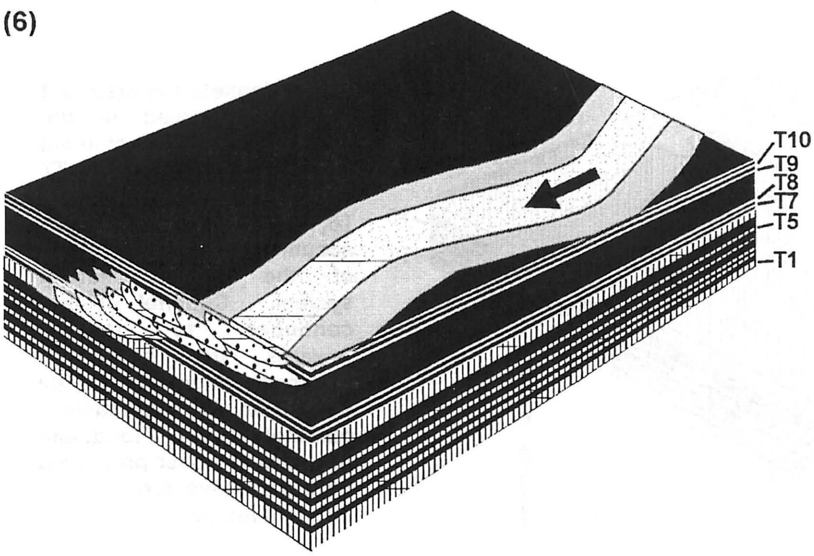
(4) Bolton Point Conglomerate continues to migrate to the southeast. Tuff markers T7 and T8 and interbedded peat onlaps the fluvial system on the northwestern margin. The channel system is now dominated by conglomerate facies.

(5)



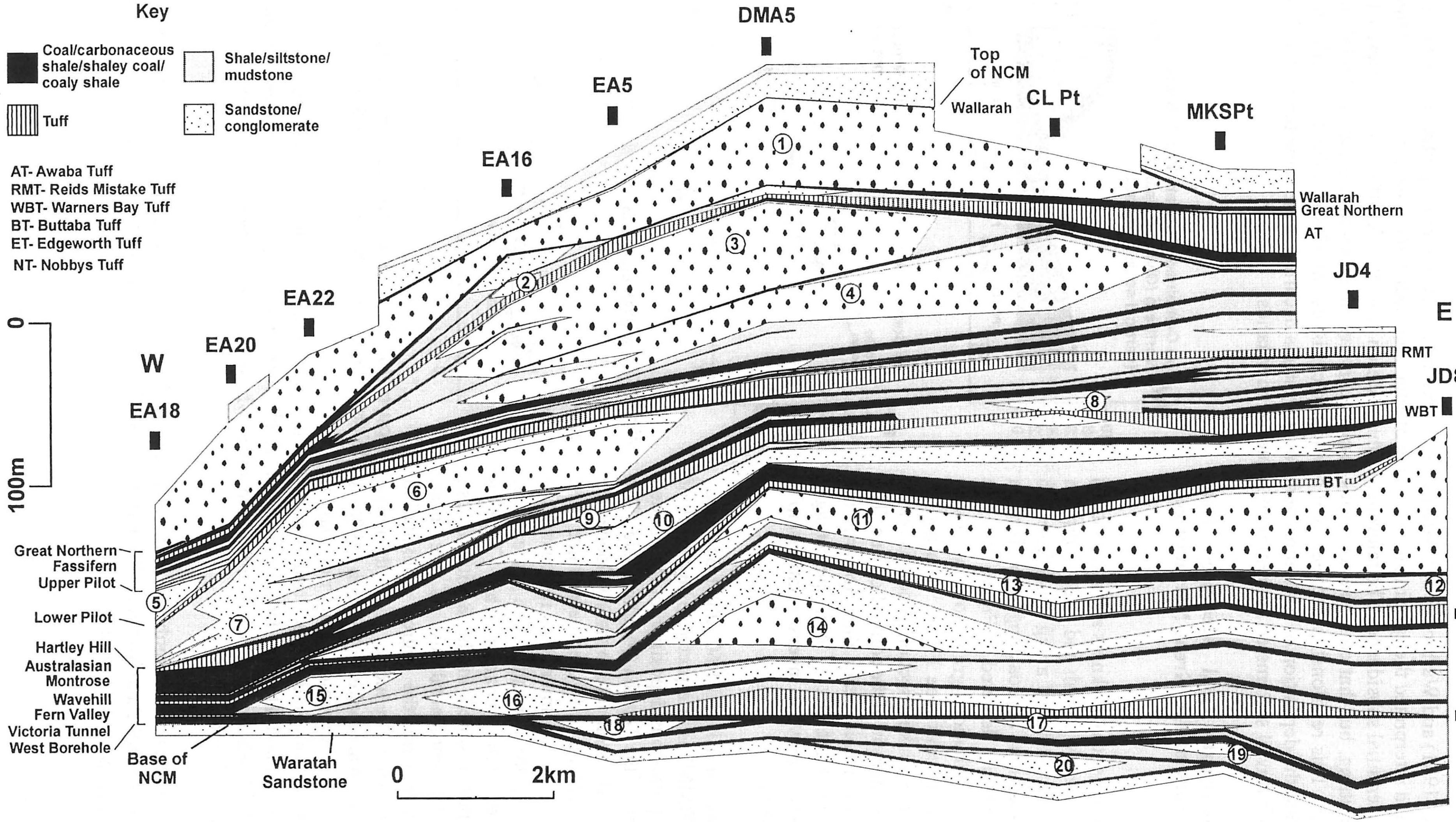
(5) Bolton Point Conglomerate channel system migrates towards its most southeasterly location.

(6)



(6) Final stage of the active Bolton Point Conglomerate fluvial system. Active channel is dominated by sandy facies. The following stage is the smothering of the Bolton Point Conglomerate by the thick Awaba Tuff. In the area of the active channel no peat is preserved and the channel system in this location is directly overlain by the Awaba Tuff. Between stages 5 and 6, tuff markers T9 and T10 are deposited with intervening peat layers.

Figure 14. Depositional evolution of the Bolton Point Conglomerate and Fassifern coal seam.



Conglomerate/sandstone Members

1- Teralba Conglomerate 2- Lisarow 3- Bolton Point Conglomerate 4-Belmont Conglomerate 5- Silverwater 6- Boughton 7- Pulbah 8- Morisset 9- Burkes 10- Rhyhope 11- Charlestown Conglomerate 12- Whitebridge 13- Tingira 14- Redhead Conglomerate 15- Merewether Conglomerate 16- Fennell Bay 17- Signal Hill 18- Cockle Creek 19- Ferndale 20- Gatehead

Figure 15. West to east section of the NCM

Warbrooke (1981) and Warbrooke & Roach (1986) presented evidence for the splitting of coal seams in the NCM and interpreted the splitting to be a result of either autosedimentational activity or tectonically induced differential subsidence. The relevance of this research is not the identification of different types of seam splitting, but that coal characteristics display changes in values as the clastic fluvial split is approached. This relationship between coal seam characteristics and clastic splits is significant as it indicates that the deposition of peat mires and fluvial systems occurred at the same time, therefore the base of such fluvial systems do not represent sequence boundaries.

Upper Newcastle Coal Measures: Coal characteristics of the Great Northern coal seam

Coal characteristics (thickness and ash content) of the combined Wallarah and Great Northern coal seam are displayed along a northwest to southeast section approaching the Teralba Conglomerate are depicted in Figure 16. The thickness distribution graph of the Great Northern coal seam (see Figure 16 a and b) shows that the thickest section of coal is on the northwestern margin of the correlation line. The Great Northern coal seam thins towards the Teralba Conglomerate. Ash percentages (Figure 16 c) displays an inverse relationship to coal thickness.

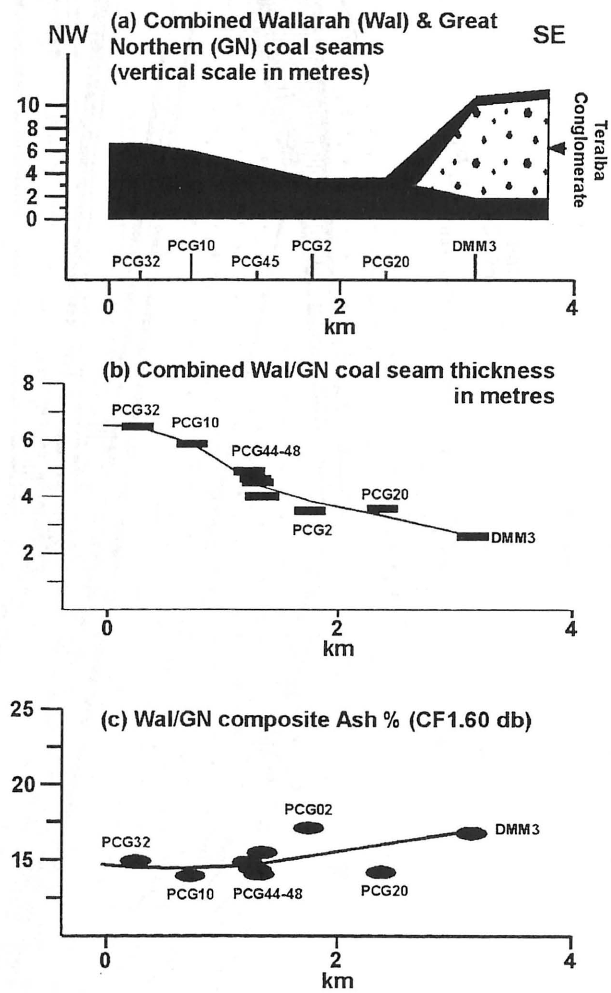


Figure 16. Coal characteristics of the combined Wallarah and Great Northern coal seams.

The increase in ash (CF1.60, db) from bores PCG32 to DMM3 is interpreted to be a result of the contemporaneous deposition of the braided river system of the Teralba Conglomerate. The braided fluvial system intermittently flooded the proximal sections of the peat mire and introduced clastic sediment thus increasing the ash (CF1.60, db) content. The increase in clastic sediment nearest the Teralba Conglomerate resulted in the additional ash reducing the compactability of the peat, therefore increasing the degree of oxidation which ultimately reduces coal thickness. According to Warbrooke and Roach (1986) a proportion of inorganic plant material is insoluble (e.g. SiO_2 and Al_2O_3) and remains in the peat until it forms minerals such as quartz, montmorillonite and feldspar. These minerals are finely disseminated throughout a coal and are reflected in the CF1.60 ash trend which increases in areas where peat desiccation was a significant factor (Warbrooke and Roach 1986).

The characteristics of the combined Wallarah and Great Northern coal seam in Figure 15 are consistent with what Warbrooke and Roach (1986) termed as "sedimentary splitting" (referred to by Diessel 1992 as autosedimentational splitting).

The Contrasting Criteria for the Identification of Coeval from Sequential Deposition of Fluvial and Mire Facies

Based on the above examples of coeval deposition of fluvial and mire facies in the NCM the following criteria are suggested to identify contemporaneous deposition of coal and fluvial facies: 1) Onlap of tuff markers/coal seam sections onto the fluvial channel system may occur on the side that the active channel is migrating away from; 2) Truncation of tuff markers/coal seam sections may occur along the margins of the channel system along the side that the active channel is migrating towards; 3) Coal characteristics, such as ash values (from washed fraction CF1.60) and seam thickness, will display consistent changes

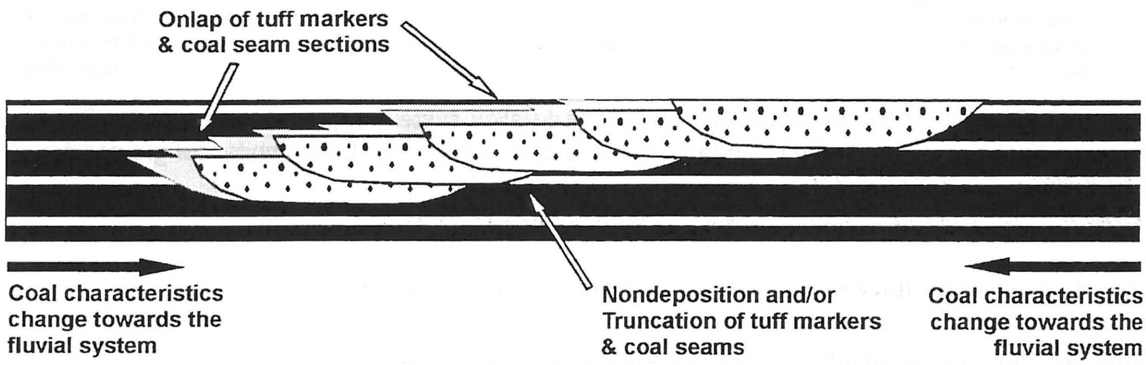


Figure 17. Summary model of characteristics that indicate contemporaneous fluvial and peat mire deposition. The base of the channel system is not a sequence boundary. Coal= black, floodplain shale= grey, tuffs= white, conglomerate= dotted pattern fill.

as the fluvial channel system is approached. For example, in the case of autosedimentological splits, ash values of a coal will increase towards the clastic split, but for differential splitting the ash content of a coal will decrease. In the case of autosedimentological splits, coal seam thickness will decrease towards the clastic split. For differential splitting seam thickness will increase towards the clastic split. The above mentioned criteria for the identification of coeval fluvial system and mire deposition are summarised in Figure 17.

In the case of sequential deposition of fluvial channel systems and coal seams the relationship between these units will be completely different. In the sequential model of deposition the base of the channel system is a sequence boundary, and the channel system represents an incised-valley. The identification criteria for such a system will include those listed by Zaitlin*et al.* (1994), which are listed in section on the Bolton Point Conglomerate. An additional criterion for the identification of incised valleys that are preserved adjacent to coal-bearing strata includes that coal seam characteristics, such as ash (CF1.60) and thickness, should display no consistent relationship to the margins of the incised valley. These criteria of the identification of incised-valleys in coal-bearing strata are summarised in Figure 18.

Comparison of Sequence Stratigraphy to Lithostratigraphy as a Means of Correlation in the Newcastle Coal Measures

As no sequence boundaries can be identified in the NCM, sequence stratigraphy does not provide an alternative method of stratal correlation. As stratigraphic and chronostratigraphic control is provided by the numerous tuff markers, lithostratigraphic concepts still provide the most effective means of correlation in the NCM.

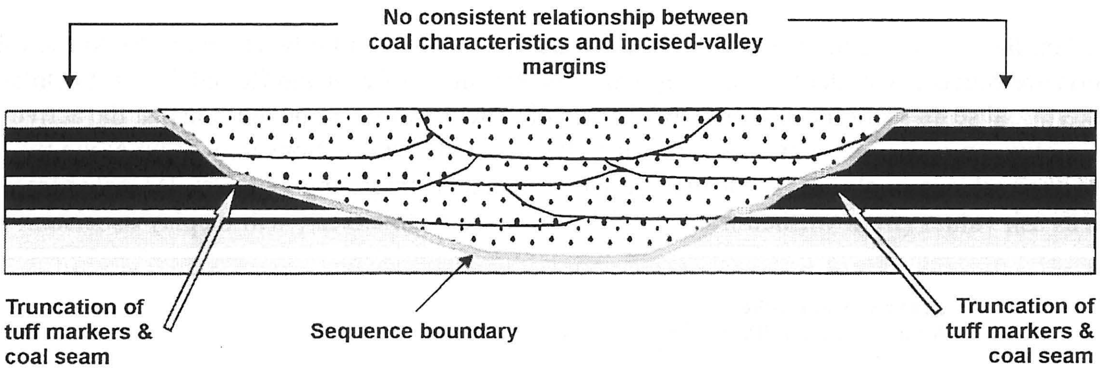


Figure 18. Criteria for the identification of an incised-valley system in coal-bearing strata. The base of the incised valley is a sequence boundary. Coal= black, shale=grey, tuffs= white, conglomerate= dotted pattern fill.

What do Incised-Valleys Systems in Coal-Bearing Strata Look Like?

Although no incised-valley systems and sequence boundaries can be identified in the NCM it is not suggested that such features will not be identified in other coal -bearing strata. Incised-valleys have been identified in other coal-bearing strata. Figure 19 illustrates some examples of incised-valley systems in coal-bearing strata from the Mannville Group, Alberta Basin, Canada. These incised-valleys systems completely erode through coals seams that are up to 12m thick. In some locations the incised valleys erode through split coals.

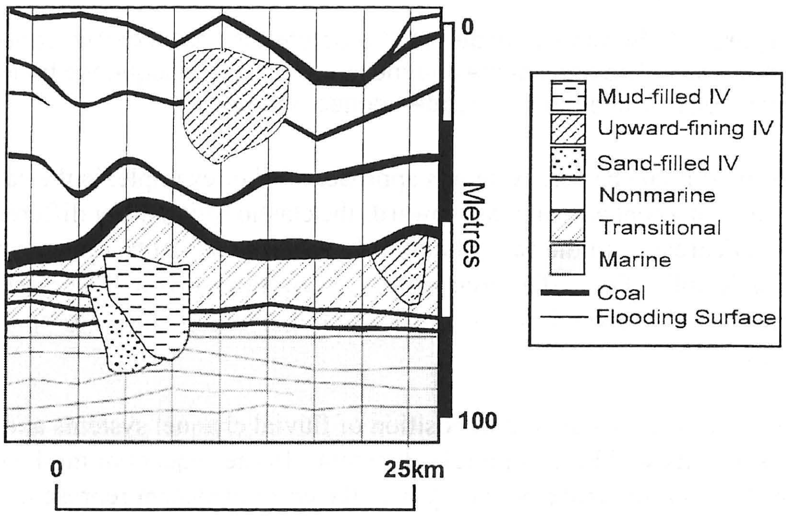


Figure 19. Examples of incised valleys (IV) in coal bearing strata from the Mannville Group, Alberta Basin, Canada (after Wadsworth, unpublished data).

FIELD STOP: VICTORIA TUNNEL COAL SEAM, MEREWETHER CONGLOMERATE, FERN VALLEY COAL SEAM TO REDHEAD CONGLOMERATE INTERVAL EXPOSED AT THE DUDLEY TO REDHEAD CLIFF SECTION

The interval between the Victoria Tunnel coal seam and Fern Valley seam contains the in-channel fluvial deposit of the Merewether Conglomerate and the contemporaneously deposited fine-grained floodplain units (siltstones, shales and fine sandstones). Herbert (1994, 1995, 1997) suggested that fine-grained units are the product of deltaic deposition, but we interpret these fine-grained units as coeval floodplain/basin deposits of the Merewether Conglomerate. Therefore the base of the Merewether Conglomerate does not represent a sequence boundary.

Geophysical logs that correlate to the fine-grained section of the outcrop interval indicate that this section typically consists of both fining and coarsening upward sections (see N1739 in Figure 20). Coarsening upward intervals are interpreted as lacustrine deposits. Very few geophysical logs of this interval only display an overall coarsening upward signature. The majority of geophysical logs display both coarsening and fining upward signatures. The alternating coarsening and fining upward signature indicates the intermittent presence of lakes occupying sections of the floodplain. Fining upward intervals are interpreted as fluvial channel systems. In DM Awaba DDH2 the Merewether Conglomerate is not present as a conglomerate but is a fining upward interval of sandstone and shale (Figure 20). The fining upward geophysical signature suggests fluvial deposition.

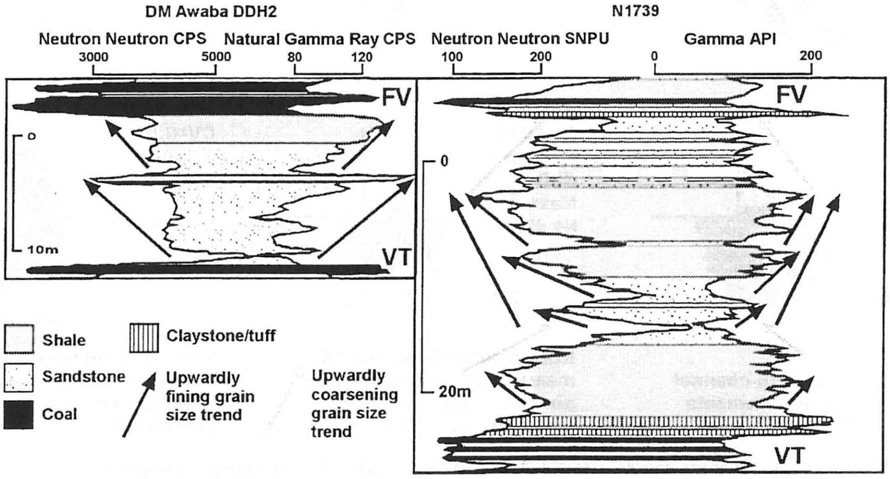


Figure 20. Geophysical response of Victoria Tunnel to Fern Valley coal seam interval. Note the upwardly fining intervals in DM Awaba DDH2 and interbedded coarsening and fining upward intervals in N1739. Upwardly fining sections are interpreted as fluvial channels, coarsening upward sections are interpreted as lacustrine units.

Palaeocurrent measurements in Figure 21 indicate that the mean flow direction of fluvial channels (towards 201°) roughly matches the mean palaeoflow direction for measurements taken from floodplain units (towards 208°). Palaeocurrent measurements of the Merewether Conglomerate and adjacent fine-grained floodplain facies also display a similar pattern. Measurements of directional indicators (e.g. cross bedding) from in-channel units indicate a palaeoflow direction towards 231°, and linear indicators (e.g. logs, plant fragments) suggest a palaeoflow towards 252° (see Figure ?.?). Directional indicators from floodplain facies indicate a mean palaeoflow direction towards 198°. These measurements do not support Herbert's (1994, 1995 & 1997) theory that fluvial channel sediment was derived from the north while the fine-grained "deltaic" facies (interpreted here as floodplain facies) were derived from an easterly location.

Facies studies of outcrop do not indicate the dominance of deltaic facies. Outcrops are dominated by floodplain facies which include crevasse splays and floodplain fines. Some sections display lacustrine facies, but these do not dominate the entire fine-grained section of the cliffs between the Victoria Tunnel and Fern Valley coal seams.

No bioturbation indicating brackish environments can be observed on the cliff sections between Dudley and Redhead. The mere presence of bioturbation does not indicate brackish, lagoonal or estuarine environments. Specific trace fossils such as *Teichichnus* and *Terebellina* are needed to identify such environments (Pemberton 1992). Both *Teichichnus* and *Terebellina* have been identified the estuarine/brackish shales above the Borehole coal seam but cannot be identified in the outcrop between Dudley and Redhead.

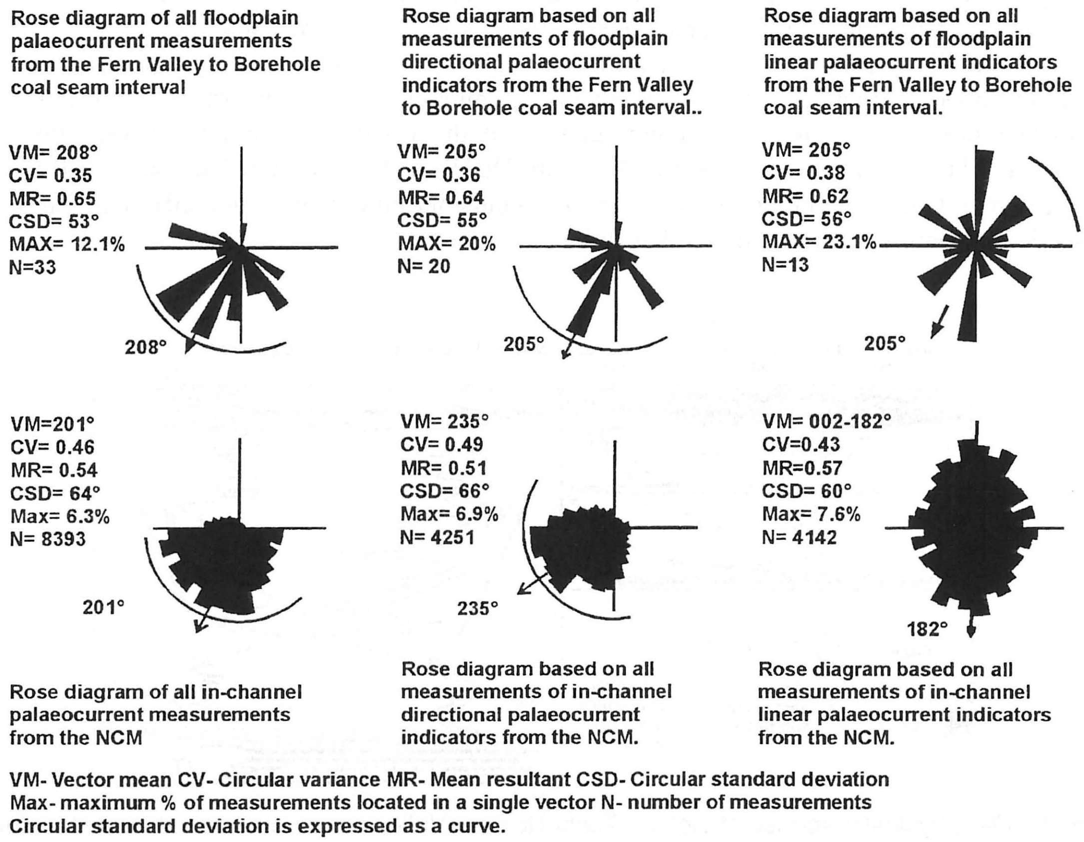


Figure 21. Comparison of palaeoflow directions from in-channel indicators and those measured from floodplain units. Data from field measurements and from previous thesis work (e.g. Holmes 1978 and Warbrooke 1981).

FIELD STOP: GEOLOGY OF BLACK HILL

Aim: To demonstrate a field examples of: 1) evidence of contemporaneous deposition of in-channel and floodplain facies; 2) vertical channel stacking; 3) concave-up fluvial channel margins.

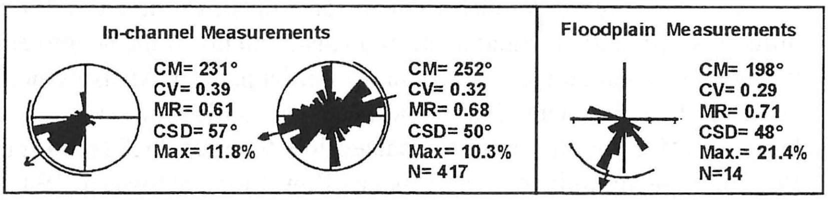


Figure 22. Rose diagrams illustrating palaeoflow directions of in-channel Merewether Conglomerate and floodplain facies.

Black Hill Stratigraphy

Approximately 100m of strata from the lowermost NCM and uppermost Tomago Coal Measures are exposed at Black Hill outcrop. The interval exposed includes strata from the Waratah Sandstone to the Redhead Conglomerate (see Figure 23). The interval of interest on this field excursion is the Signal Hill Member located between the Nobbys coal seam and the remainder of the West Borehole coal seam.

Fluvial Style of the Signal Hill Member at Black Hill

The Black Hill outcrop is dominated by large scale fluvial channels. These channels are often separated by fine-grained floodplain deposits. Facies and architectural elements present in the Signal Hill Member are listed in Figures 24 and 25. The dominant architectural elements are sandy bedforms (SB) and gravel bars and bedforms (GB). Element GB is typically made up of fine-grained conglomerates, usually granule or fine pebble conglomerates. Architectural elements SB and GB often have erosional tops and bases, and display lens, wedge, triangular and rectangular geometries. Elements SB and GB are often interbedded. This lateral variation in texture is interpreted to result from constant changes in sediment-transport patterns. Conglomerate facies (in element GB) at the base of channels sometimes contain abundant siltstone rip-up clasts.

An overall fining upward grain size trend is often present in the coarse-grained channel units (see Figure 23). Accompanying the upward decrease in grain size is an upward change in bedform types from planar crossbeds at the base to climbing ripple laminations in the upper sections. Lateral facies changes from conglomerate to sandstone dominated sections also occur.

Lateral (LA) and downstream accretion macroforms (DA) are not common in the Black Hill exposure. Due to the lack of palaeocurrent data available these elements are recorded as composite LA/DA elements. Element LA/DA display triangular geometries (interpreted 3-d geometry as wedges) and have erosional tops and bases. This element consists of inclined layers of sandstone, or inclined layers of interbedded conglomerate and sandstone.

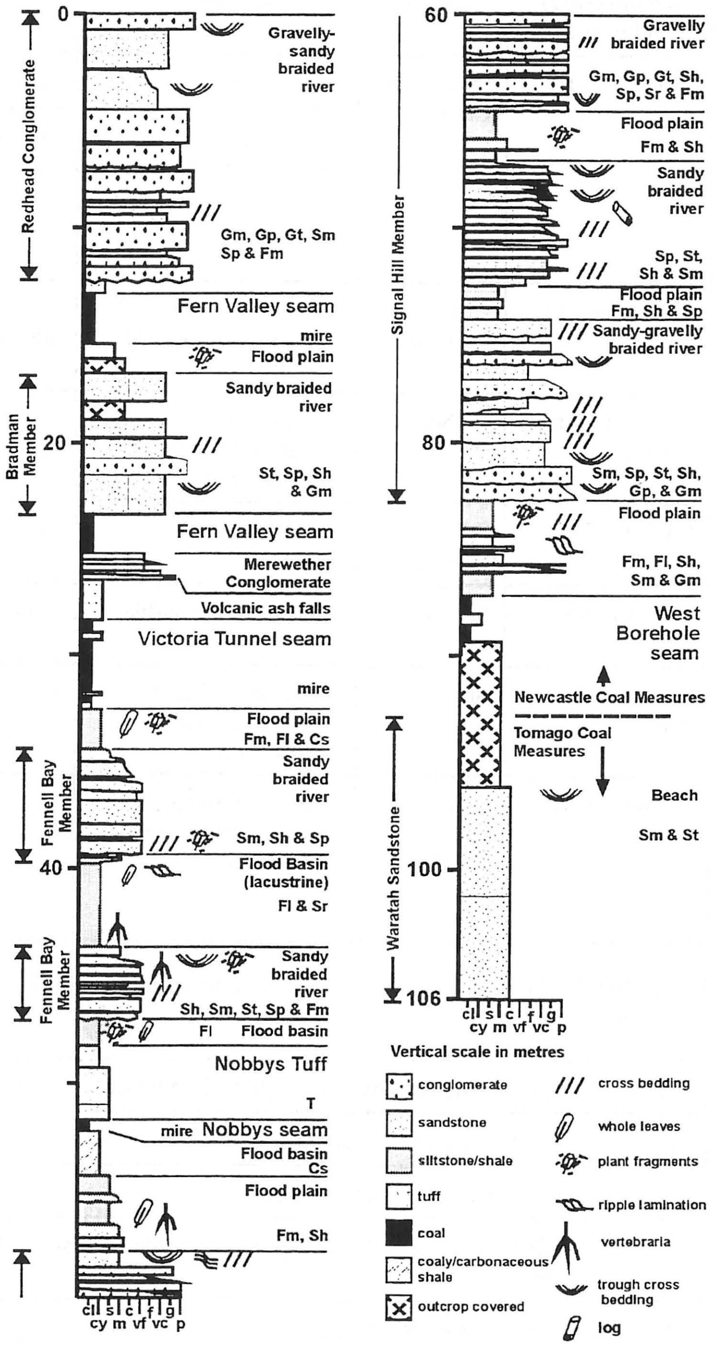


Figure 23. Composite log of the geology exposed at Black Hill.

Architectural Element	Facies	Geometry	Comments	Interpretation
Channels (CH)	Facies from GB & SB	Full geometry not exposed in outcrop. Concave-up 5th order bases, internal 3rd & 4th order erosion surfaces	Full unit not exposed. Outcrop indicates channels up to 100's of metres wide, usually less than 10m thick. Channel bases cut into underlying floodplain deposits	Major channels of fluvial system
Gravel bars and bedforms (GB)	Gcm, Gh, Gt & Gp, Gci	Lenses, rectangles, and wedges with erosional tops and bases.	Common element. Often interbedded with SB	Channel fill.
Sandy bedforms (SB)	Ss, Sh, Sp, St, Sr	Lenses, rectangles, and wedges with erosional tops and bases.	Common element. Often interbedded with GB.	Channel fill.
LA/DA	Sp, Sm, Sr, Sh, Gm	Wedge shaped (?)	Few examples are present.	Lateral or downstream accretion macroform.
Crevasse splay (CS)	Sm, Sr	Rectangular, sheet-like geometry.	Typically less than 1m thick.	Deposits from crevasse channel into floodplain.
Crevasse channel (CR)	Sm, Gm	Concave-up channels, <1m thick, several metres wide.	Only a few example	Break in channel margins.
Floodplain fines (FF)	Mainly Fm, some Fl, Fr, Sr.	Sheets and wedges, at least 100m wide, up to 4m thick.	no bioturbation	Mainly deposits of overbank sheet flow, some thin, laterally restricted floodbasin lakes

Figure 24 (above). Architectural elements and facies of the Signal Hill Member fluvial system at Black Hill (see Figure 25 for facies codes).

Gmm	Conglomerate, matrix supported, massive	Weak grading
Gci	Conglomerate, clast supported	Normal grading
Gcm	Conglomerate, clast supported	-
Gh	Conglomerate, clast supported crudely bedded gravel	Horizontal bedding, imbrication
Gt	Conglomerate, stratified	Trough cross-beds
Gp	Conglomerate	Planar cross-beds
St	Sandstone,	Solitary or grouped trough cross-beds
Sp	Sandstone, fine to very coarse, may be pebbly	Solitary or grouped planar cross-beds
Sr	Sandstone, very fine to coarse	Ripple cross-lamination
Sh	Sandstone, very fine to coarse, may be pebbly	Horizontal lamination parting or streaming lineation
Ss	Sandstone, fine to coarse may be pebbly	Broad shallow scours
Sm	Sandstone, fine to coarse	Massive or faint lamination

Fl	Sandstone, siltstone, shale	Fine lamination
Fr	Siltstone, sandstone	Small ripples
Fm	Siltstone, shale	Massive
T	tuff, tuffite	Massive, laminated, ripple cross-lamination or cross-bedded.
C	coal	-

Figure 25. Lithofacies used in this study (after Miall 1996)

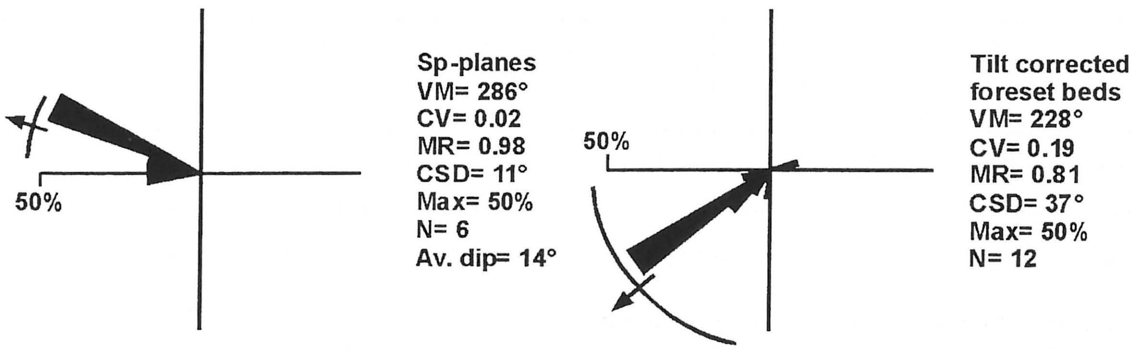


Figure 26. Dip direction of Sp surfaces (left) compared to palaeoflow direction of tilt corrected foreset beds. Note the 58° difference between vector means of the Sp surfaces and tilt corrected foreset beds.

Principle bedding surfaces (Sp-planes) display enhanced dip in some of the lowermost channels of the Signal Hill Member (average dip of 14°, maximum dip of 20°). There is a 58° difference between the mean azimuth of dip of Sp-planes (286°) and mean azimuth of dip of foreset beds (Sf-planes, 228°, see Figure 26). The mean dip direction of the Sp-planes indicates direction of lateral channel migration towards the peat mire, while the mean dip direction of the tilt corrected beds roughly indicates palaeoflow direction of the channel . The over-steepened Sp-planes are interpreted to be the result of differential compaction due to fluvial system migration onto the relatively uncompacted peat. This model of deposition is the similar to that proposed by Diessel (1992) for the Redhead Conglomerate. The maximum dip of Sp-planes of 20° is shallow when compared to the dips Sp-planes of up to 55° in the Redhead Conglomerate recorded by Diessel (1992). The lower maximum dips may be related to the presence of floodplain siltstones and sandstones, up to several metres thick, overlying the West Borehole coal seam at Black Hill. The Redhead Conglomerate example directly overlies coal (Diessel 1992). The floodplain units may have already partially compacted the underlying peat, since the peat has been partially compacted there is a lower amount of compaction that can result from the migration of channel sands and gravel over the underlying peat and floodplain units. In the channels higher above the West Borehole coal seam Sp-planes appear to display a decrease in enhanced dip due to differential compaction. The uppermost channels of the Signal Hill Member appear to display no over-steepening of Sp-planes. By the time the uppermost channels were deposited the underlying West Borehole peat had been significantly compacted by the previously deposited lowermost channel sediment, therefore permitting no further differential compaction. These dipping Sp-planes are not the classic lateral accretion surfaces presented in Miall (1996), such as point bar lateral accretion surfaces, as they contain small scale channels that are also tilted in the same direction as the bedding surface.

Facies of the floodplain include siltstones and fine sandstones (Fm, Fr, Fl, Sm, Sr). Floodplain architectural elements are dominated by overbank fines, crevasse splays and less commonly crevasse channels. Floodplain deposits are often partially or completely eroded by overlying channel bases.

The Signal Hill Member at Black Hill appears to display characteristics of a braided river fluvial style, as indicated by abrupt and erosive lateral facies changes, and abundant internal erosional boundaries. When compared to the sixteen different fluvial styles of Miall's (1996) classification of fluvial systems, the Signal Hill Member appears to have the closest similarities to the deep gravel-bed braided "Donjeck type" and wandering river styles (see Figure 27 for characteristics, compare vertical profiles in Figure 28 and 23). The deep gravel-bed braided "Donjeck type" is the only style that is dominated by elements GB and SB, therefore the Signal Hill Member is quite similar as it dominated by architectural elements

Style name	Sinuosity	Braiding parameter	Sediment type	Characteristic elements
Deep gravel-bed braided "Donjeck type"	Low to intermediate	Intermediate to high	Gravel, minor sand, fines	GB, SB, DA (FF)
Gravel wandering	Intermediate to high	Intermediate	Gravel, minor sand, fines	GB, DA, LA (SB, FF)

Figure 27. Characteristics of the Gravel Wandering and Deep gravel braided "Donjeck type" fluvial styles (Miall 1996).

SB and GB. But noticeable differences between the Black Hill example and these ideal models include the lack of architectural element LA in the Signal Hill Member (which typifies the wandering river style). In addition the Signal Hill Member contains a larger proportion of sandstone facies when compared to the wandering river and deep gravel-bed braided "Donjeck type" styles. The abundance of erosional bases on elements GB and SB indicate that the Signal Hill Member is closer to a braided river style rather than the composite braided/meandering wandering river style. The Signal Hill Member at Black Hill appears to be a sandier version of the deep gravel-bed braided "Donjeck type" style of Miall (1996).

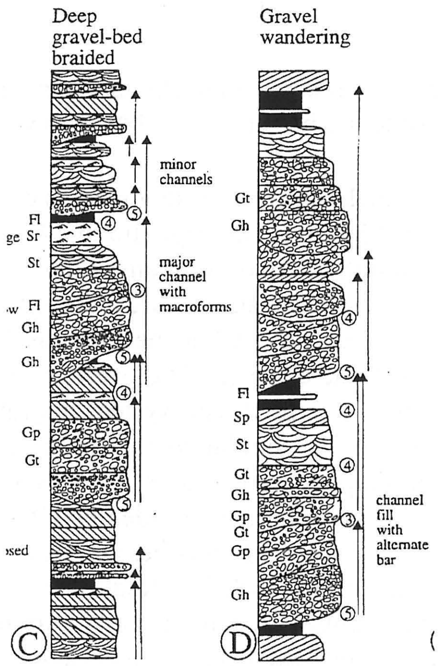
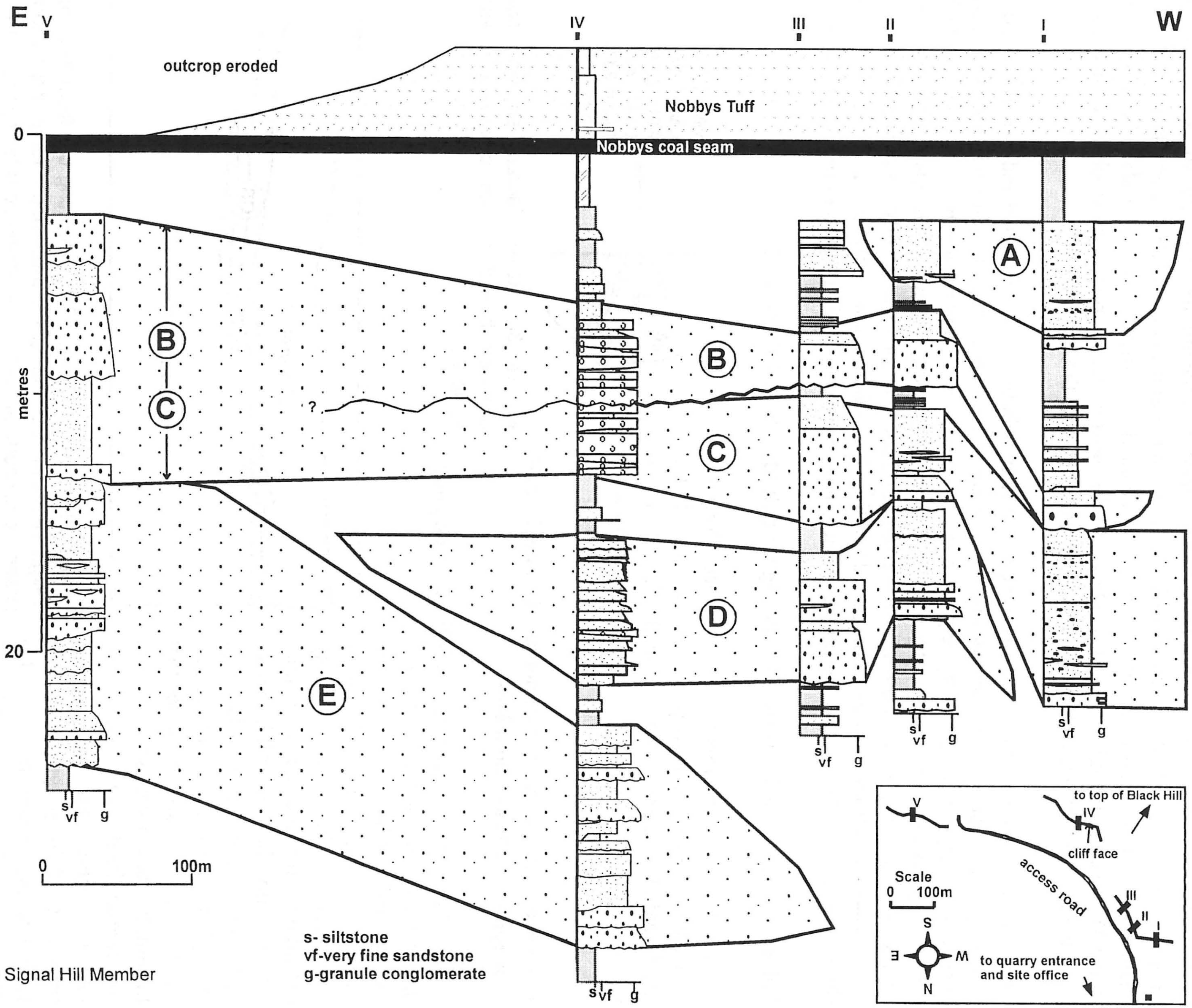


Figure 28. Vertical profiles of deep gravel-bed braided and gravel wandering fluvial styles (after Miall 1996).

Distribution of Channels at Black Hill

Three outcrop locations at the Black Hill quarry display vertically stacked channels. Figure 29 illustrates the correlations of channels using vertical profiles and also shows the position of these outcrop locations. The most western exposure reveals four channels (A-D) that are mainly separated by fine-grained floodplain units. Logs I-III illustrate the



s- siltstone
vf-very fine sandstone
g-granule conglomerate

Figure 29. Correlation of the Signal Hill Member fluvial channels at Black Hill.

channels at this section. Note that Channel B erodes directly into the top of channel C. Channel A is only present at the most western exposure where its concave-up channel margins can be seen. The middle cliff exposure is located some 200m to the east of the logs I-III. Log IV illustrates the degree of channel stacking at this location. Channel B erodes into the top of channel C at this location. Channel D appears to lens out at this middle exposure. The Channel E appears at the middle cliff exposure. This channel has the enhanced dip (11-18°) resulting from differential compaction of the underlying peat mire. If the entire channel was exposed it is likely that the margin of channel may display the "sigmoidal" geometry similar to the Merewether Conglomerate at Dudley. At the most eastern exposure channels B, C and E stack directly onto each other, and no floodplain deposits separate these channels.

The vertical stacking and lateral arrangement of channels indicates an aggrading and laterally migrating fluvial system existed. The examples of concave-up channels margins indicates that not every fluvial channel has a sigmoidal geometry (e.g. with at least one concave-down margin), as implied by Herbert (1997). Sigmoidal channel geometry is likely to be mainly associated with channels that closely overlie coal seams where the greatest potential for differential compaction exists. Only the lowermost channels (E & D) at Black Hill display over-steepened bedding due to differential compaction. The upper channels show little, if any effect, of differential compaction on principle bedding surfaces (e.g. channel A).

Palaeocurrent Flow Directions of the Signal Hill Member at Black Hill

Twenty-five measurements of crossbed foresets, indicate a mean palaeoflow direction towards 251° for the Signal Hill Member channels at Black Hill. These measurements are plotted on a rose diagram in Figure 30.

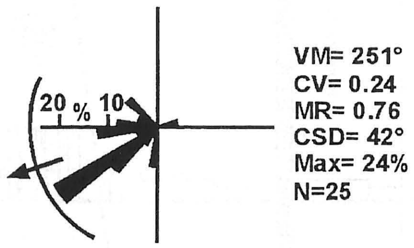


Figure 30. Rose diagram showing flow direction based on 25 crossbed foreset surfaces.

Evidence for Contemporaneous Channel and Floodplain Units at Black Hill

Figure 31 displays a crevasse splay (CS) extending from the uppermost section of channel C into floodplain siltstones, shales and fine sandstones. Channel B erodes the splay. The crevasse splay extending from the upper channel margin into the floodplain facies indicates that channels and floodplain units deposited at the same time. This also indicates that the thin flat-based sand sheets within the fine-grained facies are fluvial crevasse splays and are not the product of delta progradation into long standing water bodies. Also note the complete absence of in situ fossil tree stumps in the floodplain units interbedded with the Signal Hill Member.

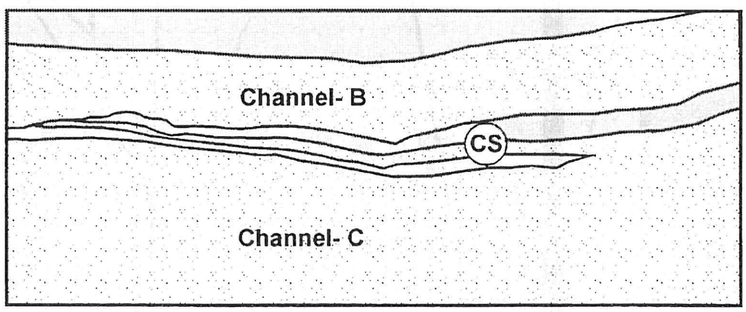


Figure 31. Crevasse splay (CS) extending out from the upper margin of channel C, indicating contemporaneous deposition of channel and floodplain units. The splay is eroded by the overlying Channel B. Grey fill= floodplain shales and fine sandstones.

CONCLUSION

The 400m thick NCM are an example of coal-bearing non-marine unit that contains no incised valleys or sequence boundaries. The NCM accumulated in an alluvial environment consisting of contemporaneously aggrading fluvial systems and peat mires. This interpretation is in marked contrast to that of Herbert (1994, 1995, 1997) who suggested that incised-valleys exist, and that fine-grained units are deltaic deposits rather than floodplain deposits associated with the conglomerate/sandstone fluvial systems.

There is no evidence to indicate that fine-grained units represent large scale deltaic systems as suggested by Herbert (1997). Investigation of geophysical logs and outcrops, indicate that fine-grained units are floodplain deposits. Correlation of geophysical logs indicates that overall coarsening upward signatures are in the minority and do not correlate from bore to bore.

The only regional interruptions to the deposition of contemporaneous fluvial systems and peat mires was from the brief episodes of volcanic activity that produced the regionally correlatable tuffs (up to 25m thick). Both local and regional scale correlations reveal stratigraphic relationships between coals, tuffs, conglomerate/sandstone units and fine-grained units that indicate contemporaneous deposition of fluvial systems and peat mires. At Black Hill quarry an outcrop example of contemporaneous deposition of fine-grained floodplain deposits and channel systems is indicated by a crevasse splay that extends from the top of a channel into adjacent floodplain units. Coal characteristics, such as seam thickness and ash values (CF1.60) typically change as the thick conglomerate/sandstone units are approached. Such changes in coal characteristics are interpreted to be the result of contemporaneous deposition of fluvial systems and peat mires.

The lack of sequence boundaries and incised-valley systems indicates that accommodation rates did not undergo cyclical changes and were relatively high throughout the entire deposition of the NCM. The were no periods when accommodation space was so low that sequence boundaries formed. As there are no sequence boundaries in the NCM sequence stratigraphy does not offer an alternative method of stratal correlation. The best method of stratal correlation in the NCM is provided by lithostratigraphic correlation of tuff markers.

ACKNOWLEDGEMENTS

The authors would like to thank the following companies and individuals who have provided invaluable assistance to this study. In particular we would like to thank Powercoal for permitting us to use the correlations of the Fassifern coal seam and Bolton Point Conglomerate, and coal characteristics of the Great Northern coal seam. Thanks also to the following coal mining companies for providing borehole data for our regional correlations and the assistance provided by their staff for accessing data: Powercoal (Malcolm Ives, Michael Creech), Newcastle Wallsend Coal Mining Company (Russel Rigby), Coal Operations Australia (John Edwards), Oceanic Coal (Chris Tobin). Thanks also to John Brunton of the Department of Mineral Resources for assistance with accessing data for the regional correlations. Thanks to Mark Woodbury for access to the Black Hill quarry.

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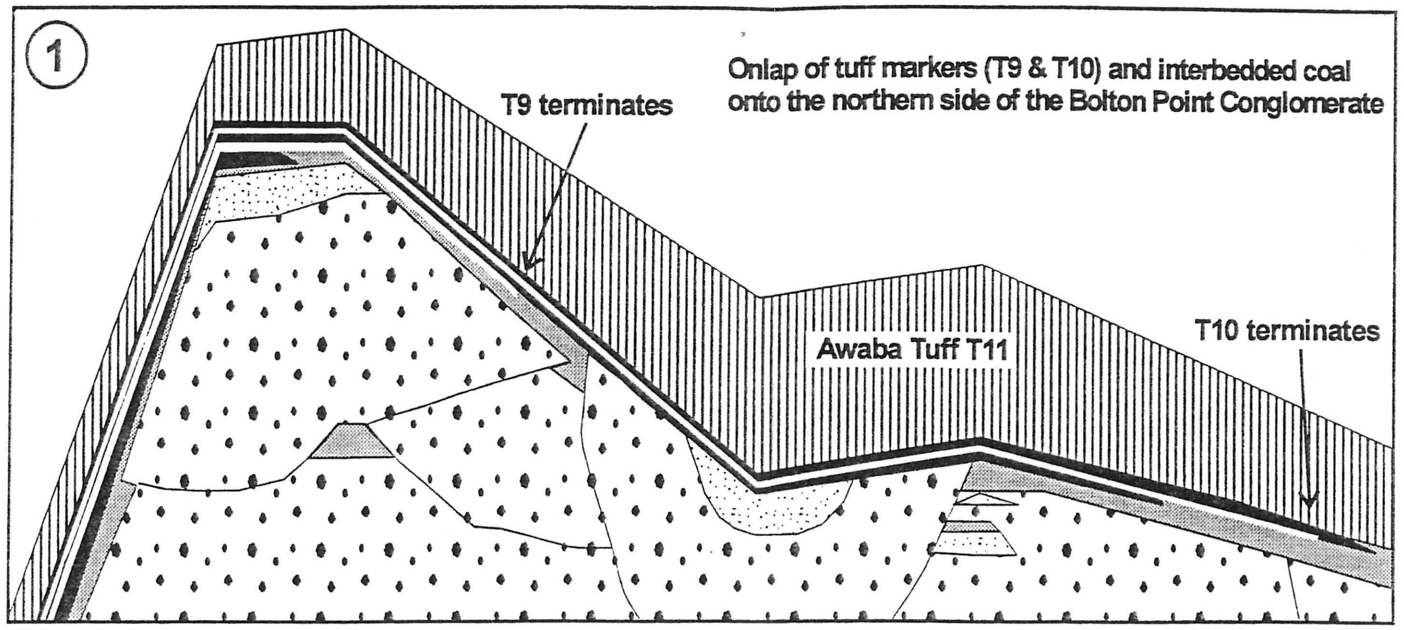
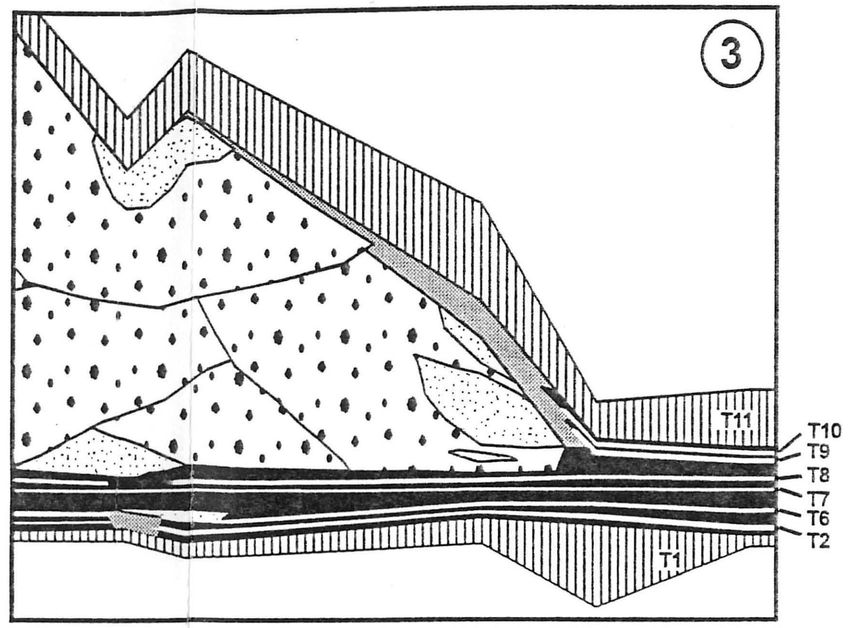
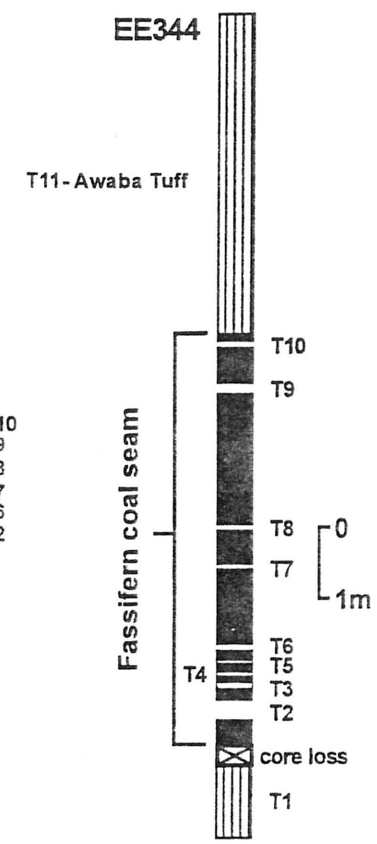




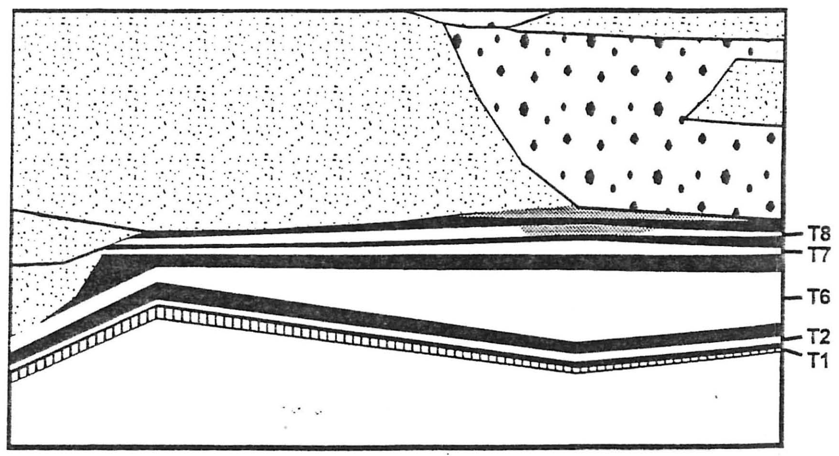


Position of tuff markers in the Fassifern coal seam (above).

KEY

	Tuff Markers		
Conglomerate	T11- Awaba Tuff	T5	Not used in correlation diagram
Sandstone	T10	T4	
	T9	T3	
Shale/siltstone/mudstone	T8	T2	
Coal/carbonaceous shale/ shaley coal/coaly shale	T7	T1	
	T6		

(2) Truncation/nondeposition of tuff markers T7 and T8 at the base of the Bolton Point Conglomerate.



Correlation of the Bolton Point Conglomerate, Fassifern coal seam and tuff markers along section 1 (below)

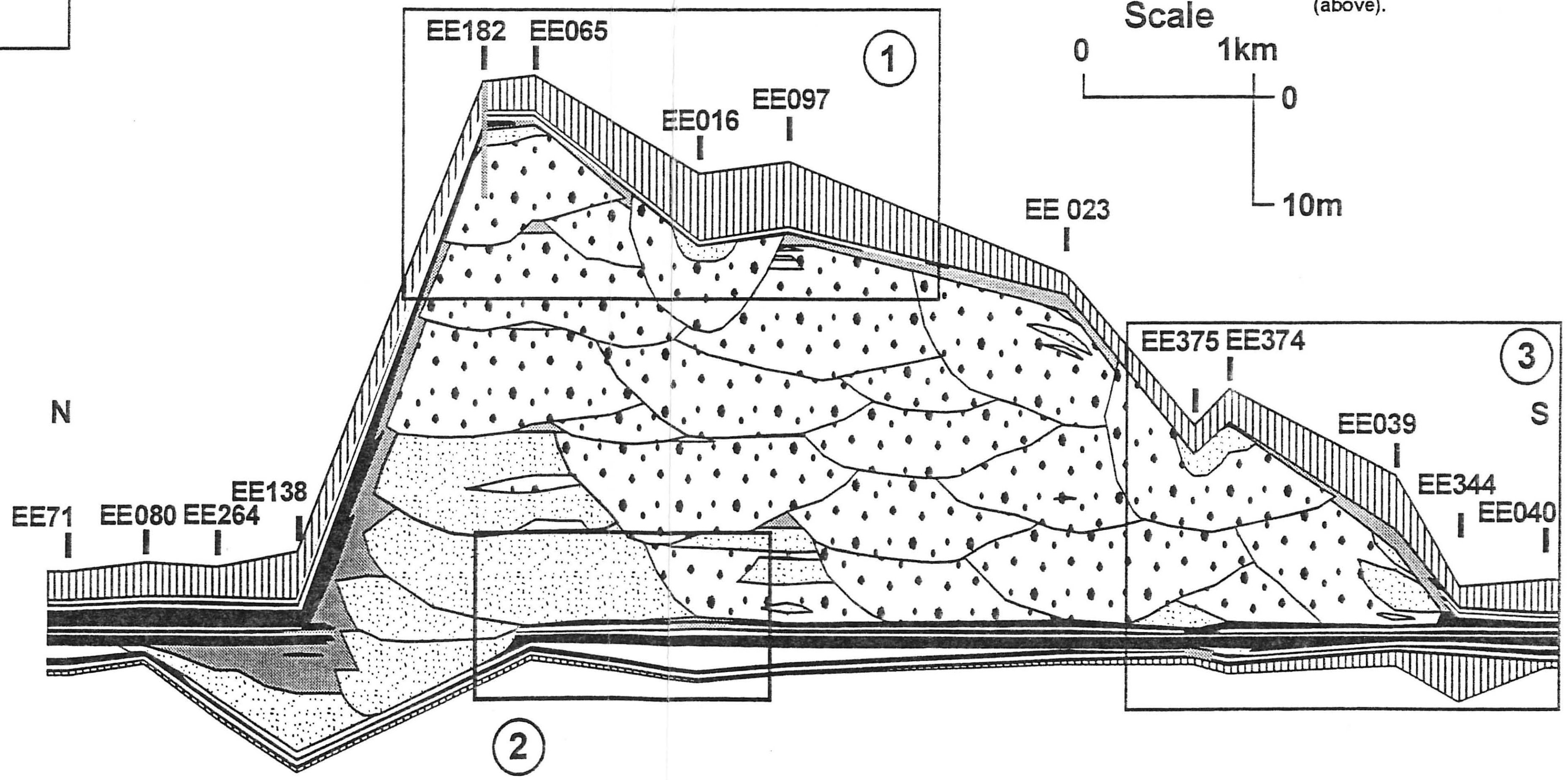
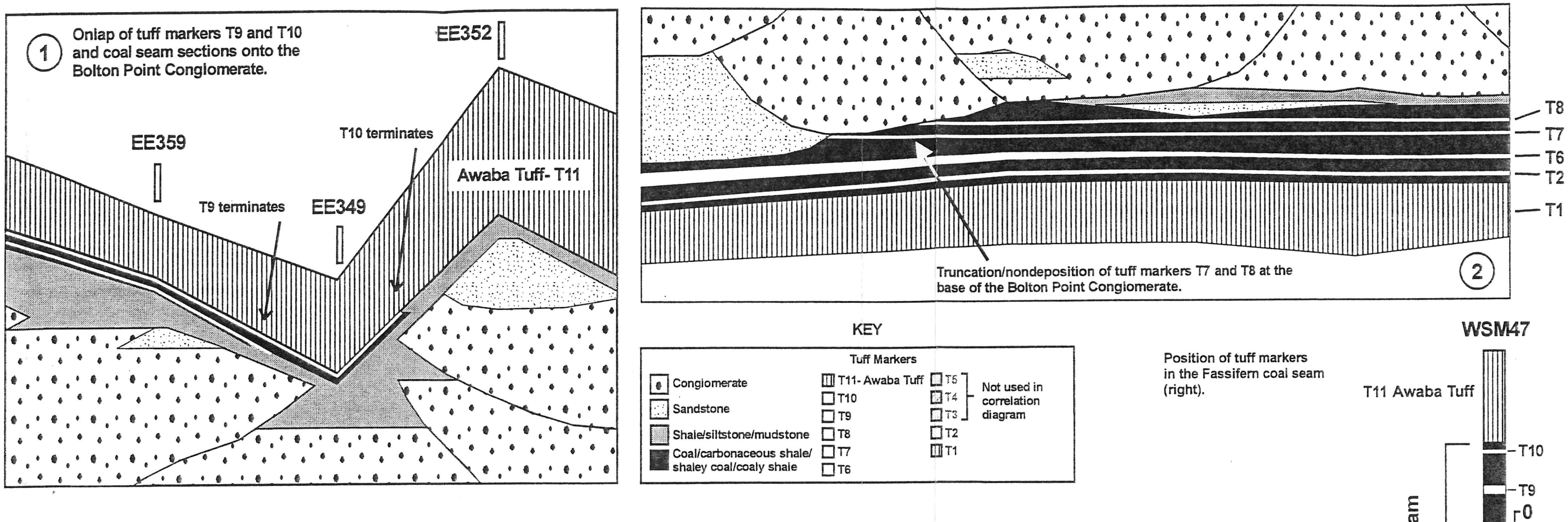
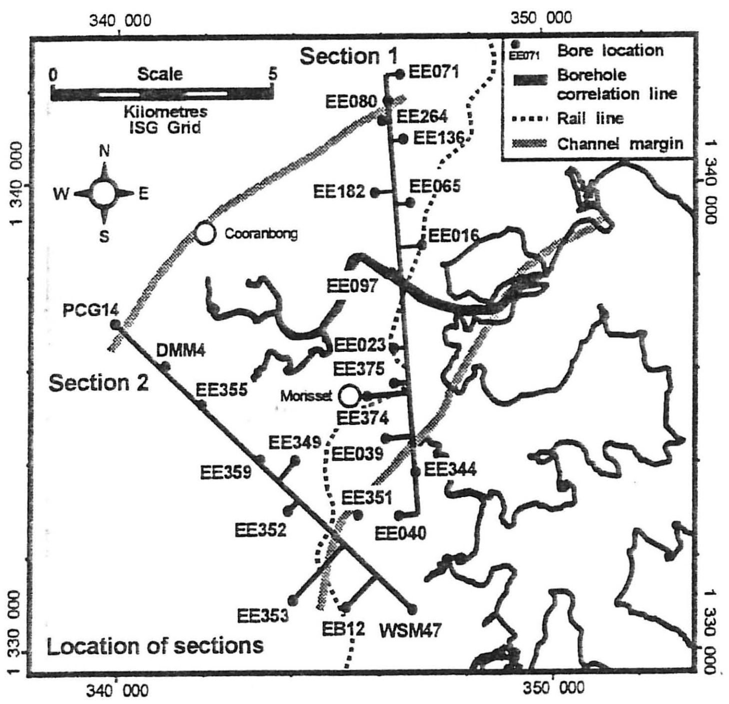


Figure 32. Correlation of the Bolton Point Conglomerate, Fassifern coal seam and tuff markers along section 1. Note the onlap of tuff markers T9 and T10, and Fassifern coal seam sections onto the northern side of the Bolton Point Conglomerate (enlarged in box 1). Tuff markers T7 and T8, and Fassifern seam sections terminate against the southern underside of the Bolton Point Conglomerate. See Figure 33 for section location.





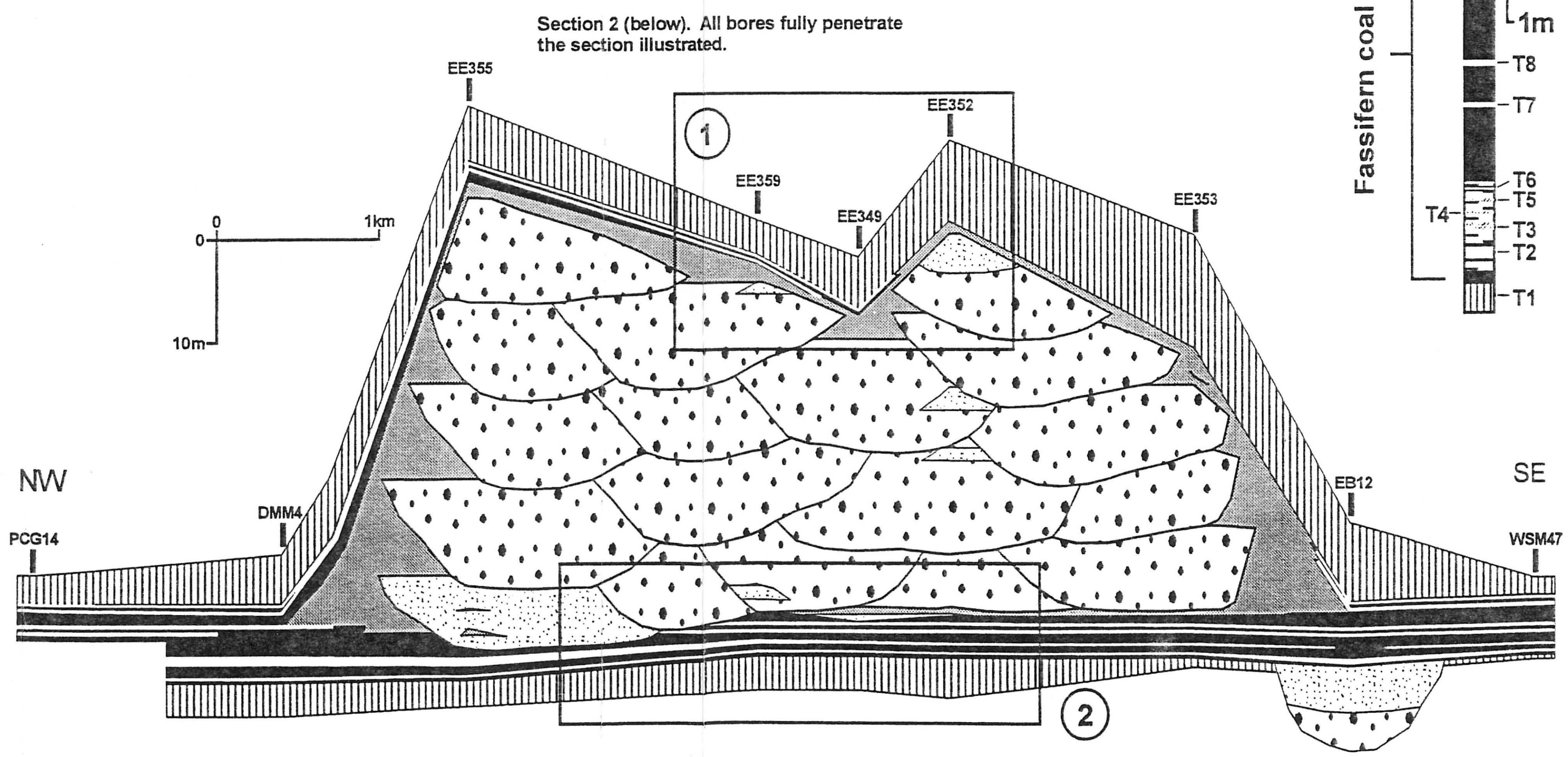


Figure 33. Correlation of the Bolton Point Conglomerate, Fassifern coal seam and tuff markers. Note the onlap of tuff markers T9 and T10, and Fassifern seam sections onto the northwestern margin of the Bolton Point Conglomerate (enlarged in box 1). Tuff markers and sections of the Fassifern coal seam terminate against the southeastern base of the Bolton Point Conglomerate (enlarged in box 2).