ENGINEERING GEOLOGICAL FACTORS AFFECTING SLOPE STABILITY IN SOFT BROWN COAL DEPOSITS - A SOUTH AUSTRALIAN EXAMPLE

(VOLUME 1)

BY

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STATEMENT OF ORIGINALITY

This thesis contains no material which has been accepted for the award or any other degree or diploma in any university and, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text.

Andrew Kremor.

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ABSTRACT

This geological study brings together the areas of geology and engineering as related to highwall slopes in soft brown coal mines. The approach centres on the role of the engineering geologist whose main objectives relate to the identification and prediction of the key geological factors affecting slope stability. The Lochiel Coal Deposit in South Australia is used as the example.

The Lochiel Coal Deposit is classified based on ;

- geological setting - Midplate continental position with depositional environments controlled by the interaction of movement about tectonic structures and by eustatic sea level changes. The depositional environments examined are those characteristic of continental shelves, including swamps, marshes, estuaries, deltas, lagoons, barrier bars and fluvial.
- engineering properties - fine grained, saturated soils and weak rock characterised by early deformational structures.

This study identified and analysed the key engineering geological factors characteristic of soft brown coal mining areas rather than those generic to other mines or excavations in weak rock and soil.

Three formations typical of coal bearing sequences were defined and analysed. The fluvio-deltaic Bumbunga Sand, the fan-delta and lagoonal Warrindi Silt and the estuarine Tarella Silt.

The key factors affecting slope stability for the study area were identified as the strength and geometry of near horizontal defects in the sediments. These defects are generally concordant with the bedding in the surrounding sediments and continuous over large areas. Where present their strength and geometry largely determine both the geometry of the slope as well as the direction of mining.

The location and formation of these defects is related to the boundaries of significant cyclic depositional events. The defects are located at the base of coarsening upward cycles in close stratigraphic location to the top of the previous cycle. The characteristics of the surrounding sediments suggested an aqueous depositional environment typical of lacustrine or estuarine basin infill sequences.

Detailed examination of the geological structures associated with the major overburden defect (the Tarella Silt Shear Zone) indicates that they are characteristic of shear defects. The stresses controlling their formation appear to be related to both compaction and the tectonic tilting of the deposit area. Typically the defects have residual friction angles as low as 7^{o}. Furthermore, given that cyclicity is characteristic of midplate continental margin

deposits, it is likely that such features are present in other similar areas.

These defects are also a key factor affecting the rate at which the fine grained sediments can be depressurised. There are two aspects involved. First, the shear plane itself acts as a relatively impermeable barrier to vertical drainage and, second, the structures associated with the shear zone act as vertical drains for the fine grained sediments. The result is that the fine grained silts above the shear zone behave as would a fractured rock mass but the drainage of porewater vertically is restricted by the shear zone.

- **The relationship between tectonics, eustacy and depositional processes and their effects on the key factors affecting slope stability**

The sequence in the study area encompasses two major episodes of transgression/highstand/regression.

The first episode is represented by the fluvio-deltaic Bumbunga Sand. Lithologically the sediments associated with this phase fine upwards from gravel and sand at the base to silt, clay and coal at the top. The accumulation of the coal was eustatically controlled and appears to coincide with a Highstand Systems Tract.

The second transgressive episode superimposed marginal marine conditions on the area and is represented by the fan-delta and lagoonal Warrindi Silt and the estuarine Tarella Silt Formations.

The sources of sediment and the sites of tectonic movement appear to be similar for both episodes. This provides the unique opportunity to contrast the effects of marine influence on the key factors of porewater movement and weak zones against a non-marine influence.

The basin infill processes which led to formation of the upward coarsening sequences containing weak zones were also similar for both episodes. Furthermore, there is no significant difference between the two episodes in terms of geometry, location and strength of the weak zones. The analysis also indicates that the location and characteristics of clean sand lithofacies are similar for both episodes.

The conclusion is that whilst eustacy controlled the regional depositional setting and the conditions necessary for coal formation, tectonics had the major control over the depositional processes and the segmentation and characteristics of lithofacies. The implication is that within the study area, tectonics rather than eustacy was the major geological control on engineering geological factors affecting the movement of porewater and the properties of weak zones.

CHAPTER 1.0 INTRODUCTION

This geological study brings together the areas of geology and engineering as related to highwall slopes in soft brown coal mines. The approach centres on the intermediate role of the engineering geologist whose main objectives relate to the provision of predictive information on the key geological factors affecting slope stability.

The specific objectives are specified as follows :

1. Develop models which characterise the key engineering geological factors in terms of depositional and tectonic processes.

2. Classify the study area in terms of its global tectonic and depositional setting thus providing a basis for translating the results to other soft brown coal mining sites.

3. Contribute to the understanding of the interaction of tectonics, eustacy and depositional processes in the St Vincent Basin.

In addition, there are a number of undeveloped soft brown coal deposits within the world. It is anticipated that the results of this study will illustrate the benefits of the application of detailed engineering geological interpretation to slope stability analysis and also provide a model for further research.

- Discussion of the objectives and of the approach used in this study

Many factors affect the stability of open cut mine highwall slopes including mining, geomechanical, hydrogeological and geological. Whilst recognising the importance of integrating each of these, this study approaches the identification and prediction of key factors from a geological perspective and focuses on characterising them from a geological rather than engineering viewpoint.

It is generally accepted that geological understanding can provide the basis for predicting key engineering geological factors ahead of mining. However, the application of this principle is restricted because few models exist which provide the basis for linking geological characteristics with engineering properties, especially for deposits of soft brown coal.

The models that do exist are generally based on geological description of the materials. This tends to make the models site specific and doesn't provide a good basis for applying them to other mining areas. To address this inadequacy the approach taken in this study is to first classify the deposit in terms of tectonic and depositional setting and, second, to identify and describe the particular geological **processes** which have controlled the development of the key factors.

1.1 Nature of engineering geological aspects of soft brown coal mining areas

Brown coal mining takes place in sedimentary geological environments and, generally, the overburden consists of saturated sediments with a strength between soil and weak rock. However, soft brown coal deposits cover large areas (the study area covers some 100 square kilometres) and often there is a significant variation in the engineering properties of these sediments. In the pre-mining stages the engineering geologist has two related objectives with respect to slope stability analysis. First, to identify the geologically related factors which affect slope stability and, second, to define and predict variations in the properties of these factors within the mining area. This study focuses on these objectives.

The geological factors affecting slope stability are the result of processes which first deposited the sediments and then modified them after deposition. This study analyses both types of processes in order to develop engineering geological models. Furthermore, as discussed earlier, the models are defined in a global context to provide a basis for translating the results of this study to other areas.

• The benefits of Engineering Geological Models to slope stability analysis

In recent years, slope stability studies have been increasingly focused on the integration of geological, geomechanical, hydrogeological and mining information (Mathews and Rosengren, 1986, Shields 1986, and Hawley and Stewart 1986). The development of engineering geological models is an important contribution to this trend with geological understanding providing the integrative mechanism. The benefits provided by effective engineering geological models include ;

- the early recognition of potential problem areas allowing timely development of cost effective solutions,
- the reduction of the economic and safety risk,
- more cost-effective data gathering in the pre-mining stages.

1.2 The Lochiel Coal Deposit - An example of a soft brown coal deposit

The Lochiel Coal Deposit is located 130 km north of Adelaide in the northern part of the Tertiary/Quaternary St. Vincent sedimentary basin, South Australia (Figure 1.1).

In the period between 1975 and 1989, the Electricity Trust of South Australia (ETSA) evaluated a number of soft brown coal deposits as possible sources of fuel for future electricity generation. The Lochiel Coal Deposit is one of these deposits and since discovery in 1982, has been the subject of a series of intensive geotechnical investigations. The Author has been largely responsible for the data collection and interpretation of the engineering geological aspects of these investigations.

The sediments in the deposit are essentially flat lying, undeformed and pre-consolidated. They were deposited in fault controlled depressions in deltaic, marginal marine environments, on a passive continental margin (Kremor, 1986). The coal is ranked as Soft Brown, Class 15 (ISO) or Lignite B (ATSM), (Kremor and Springbett, 1989).

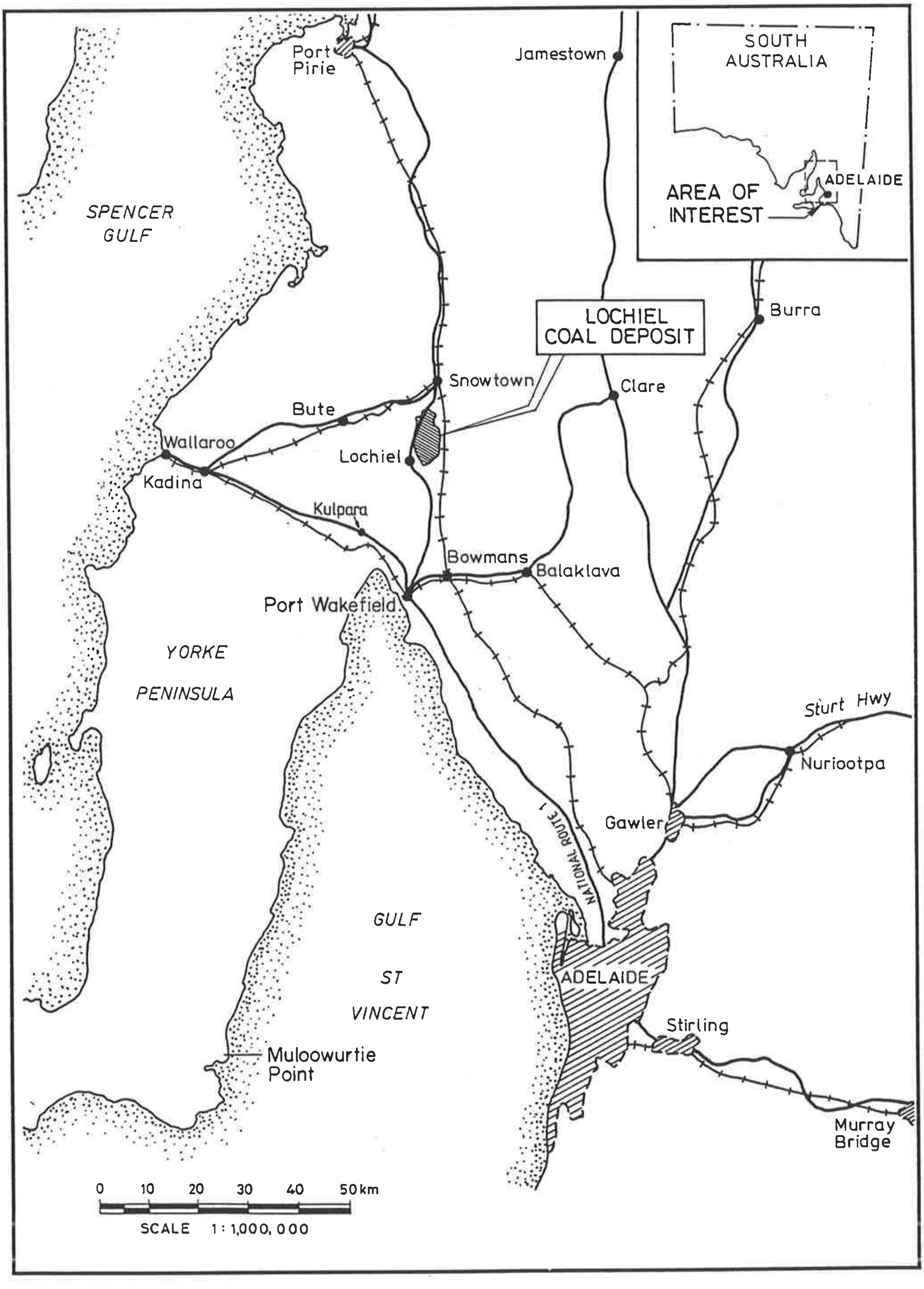


Figure 1.1 Locality plan of the study area

1.2.1 Previous investigations

At the time of its discovery, no specific information existed on the area although Stuart (1969, 1970), Alley (1969, 1973), Harris (1966, 1971, 1980) and Meakin (1985) had reported on the stratigraphy and structure of surrounding areas. Subsurface information on the stratigraphy south of the Lochiel area based on results of coal exploration drilling had been reported by Anderson (1950), Cooper (1976, 1977), Parkin (1952), Hillwood (1961), Johnson (1960, 1964), Meyer (1976, 1980) and Springbett (1980). A brief geological description of the geology of a trial excavation in the Bowmans coal deposit some 30 km south of Lochiel was also reported by Springbett (1981).

The formal stratigraphic nomenclature for the Lochiel area is defined by Kremor (in prep.) on the basis of this thesis.

The work carried out for the mining studies is summarised in ETSA (1989), and a summary of the integration of geological analyses is described by Kremor and Muir, (1987). A summary of the sequence and scope of investigations undertaken for the Lochiel Coal Deposit is provided on Figure 1.2.

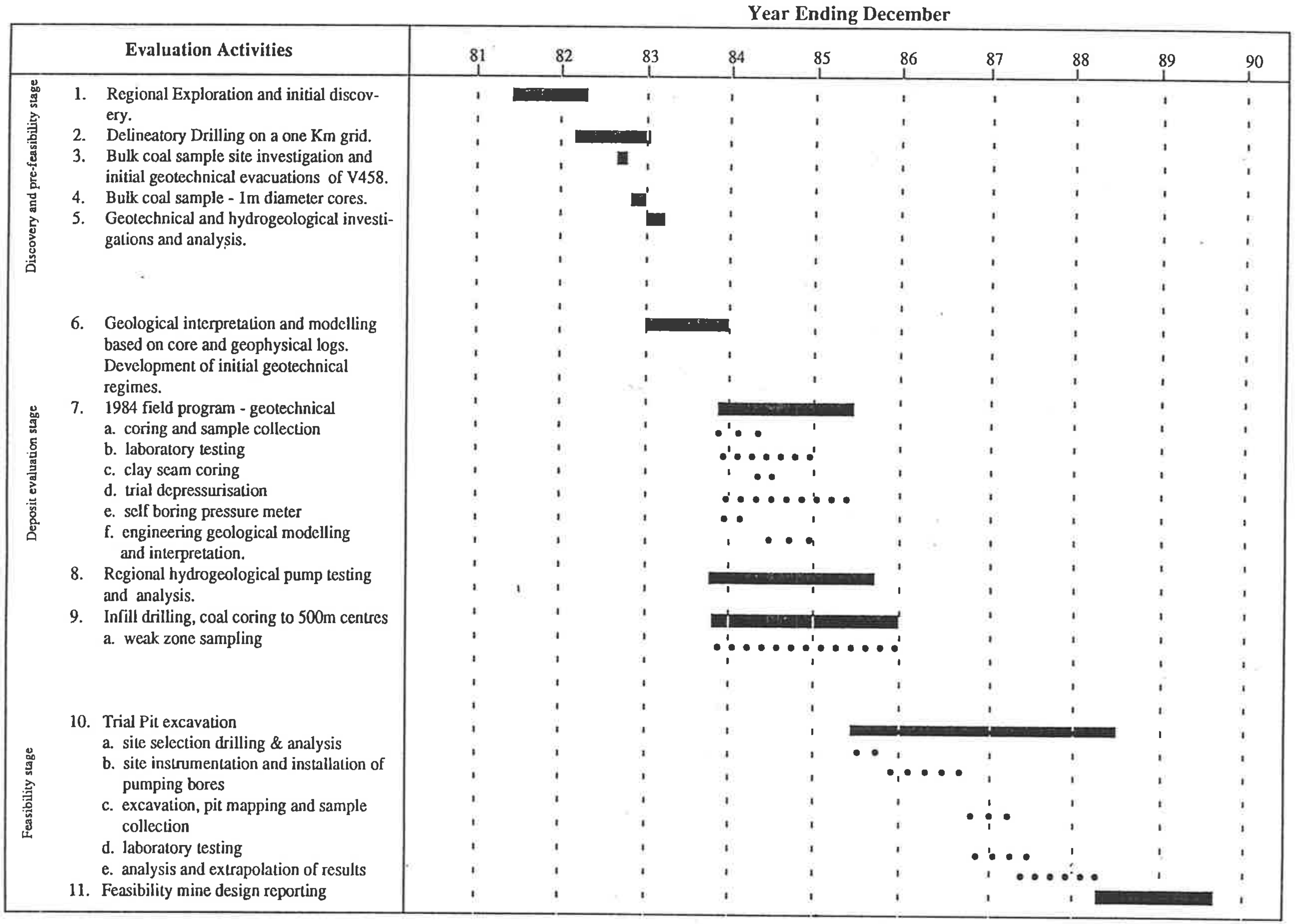


Figure 1.2 Summary of sequence of investigations

2.0 GEOLOGICAL SETTINGS OF SOFT BROWN COAL DEPOSITS - CLASSIFICATION OF THE ST VINCENT BASIN

Soft brown coals are defined by the ISO system as having a moisture content greater than 50 percent. Coals of this rank have been formed early in the coalification process with the fundamental coalification factors of heat and pressure having had only a limited impact. In addition, although the geological processes associated with the deposition of soft brown coal deposits are essentially the same as those for higher ranked coal deposits, the sediments surrounding the coal seams in soft brown coal deposits are likely to have been only marginally affected by diagenetic factors. As a result the sediments are generally classified in the engineering sense in the range of soils to weak rocks.

2.1 Geotectonic and depositional settings of soft brown coal deposits

Large scale coal formation can only occur in actively subsiding sedimentary basins with plate tectonics being the major factor causing basin formation. Curray (1975) provided a classification model for the major plate-tectonic settings and based on this model Diessel (1980) identified the sites containing major deposits of coal. This model is shown on Table 2.1. Three major categories of coal deposit are identified by Diessel (1980) as follows;

1. Midplate positions - Continental margin and interior
2. Rift zones - Divergent plate margins

3. Subduction zones - Convergence - continental collision
- oceanic subduction

Table 2.1 Plate-Tectonic subdivisions of the earth. Sites of major coalfields are emphasised by heavy ruling (after Diessel, 1980).

PLATE EDGE POSITION	**CONTINENTAL CRUST**		**OCEANIC CRUST**
MIDPLATE POSITION	CONTINENTAL	MIDPLATE CONTINENTAL MARGIN	OCEAN FLOOR
RIFT ZONE	RIFT VALLEY	NASCENT CONTINENTAL MARGIN	SPREADING RIDGE
SUBDUCTION ZONE	CONTINENTAL COLLISION MOUNTAIN RANGE	SUBDUCTION ZONE CONTINENTAL MARGIN	ISLAND ARC AND TRENCH COMPLEX
TRANSFORM FAULT ZONE	TRANSFORM FAULT CUTTING ACROSS CONTINENT	TRANSFORM FAULT TYPE CONTINENTAL MARGIN	ACTIVE PART OF FRACTURE ZONE

Sedimentation tends to be paralic in all but the Midplate continental interior settings which tend to be limnic.

Limnic deposits have no connection to the open sea and sedimentation is generally associated with lacustrine depositional processes. Falini (1965) has developed a number of models of depositional processes associated with this type of deposit. Although limnic deposits of coal are common the paralic deposits comprise a large majority of economic coal deposits. For this reason, this study focuses on paralic rather than limnic coal deposits.

Paralic deposits usually contain marine sequences within their stratigraphic column. In paralic deposits coal seams are associated with coastal environments such as marshes, coastal plains, deltas, lagoons and estuaries. Transgression/regression of the sea, whether caused by tectonics or eustacy, leads to migration of depositional environments producing sometimes complex vertical and lateral distribution of sediment types. A spatial relationship of the major depositional environments for coal bearing sediments associated with coastal settings is provided by Horne et al. (1978) and reproduced on Figure 2.1 (see Figure 2.7 for detailed depositional models).

2.2 Geotectonic setting of the Lochiel Coal Deposit

As shown on Figure 2.2, the Lochiel Coal Deposit occurs at the northern end of the St Vincent Basin and also correlates with sediments of the Pirie Basin to the north.

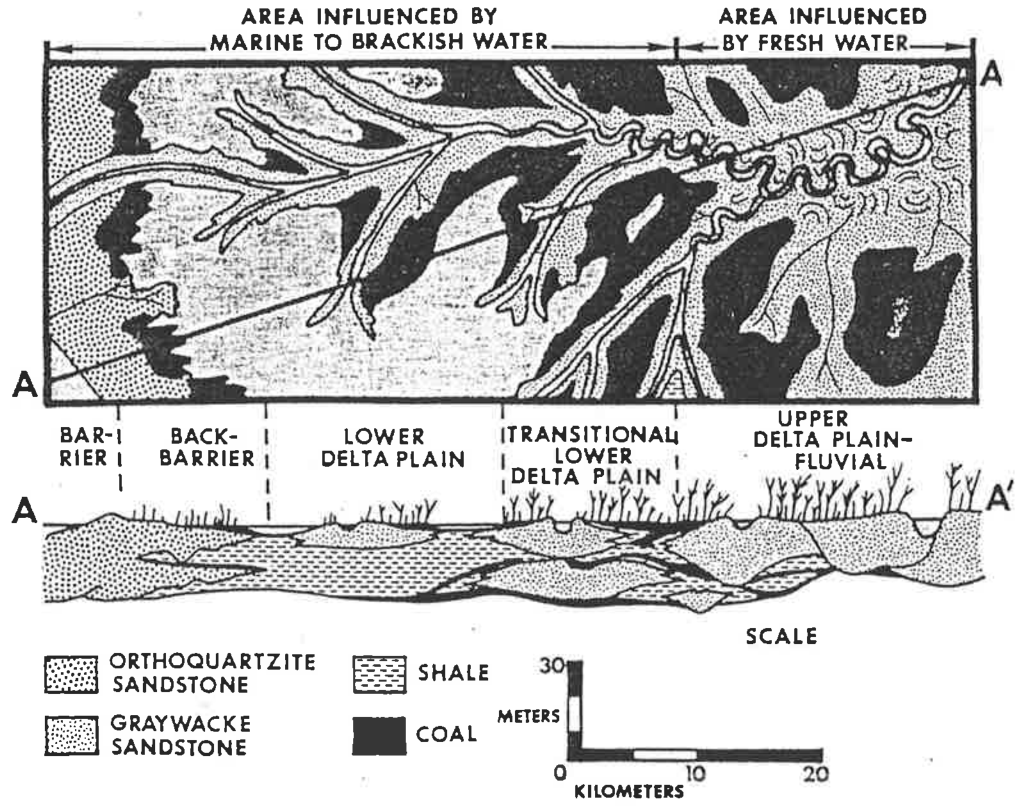


Figure 2.1 Spatial relationship of major depositional environments for coal bearing sediments associated with coastal settings (after Horne et al. 1978).

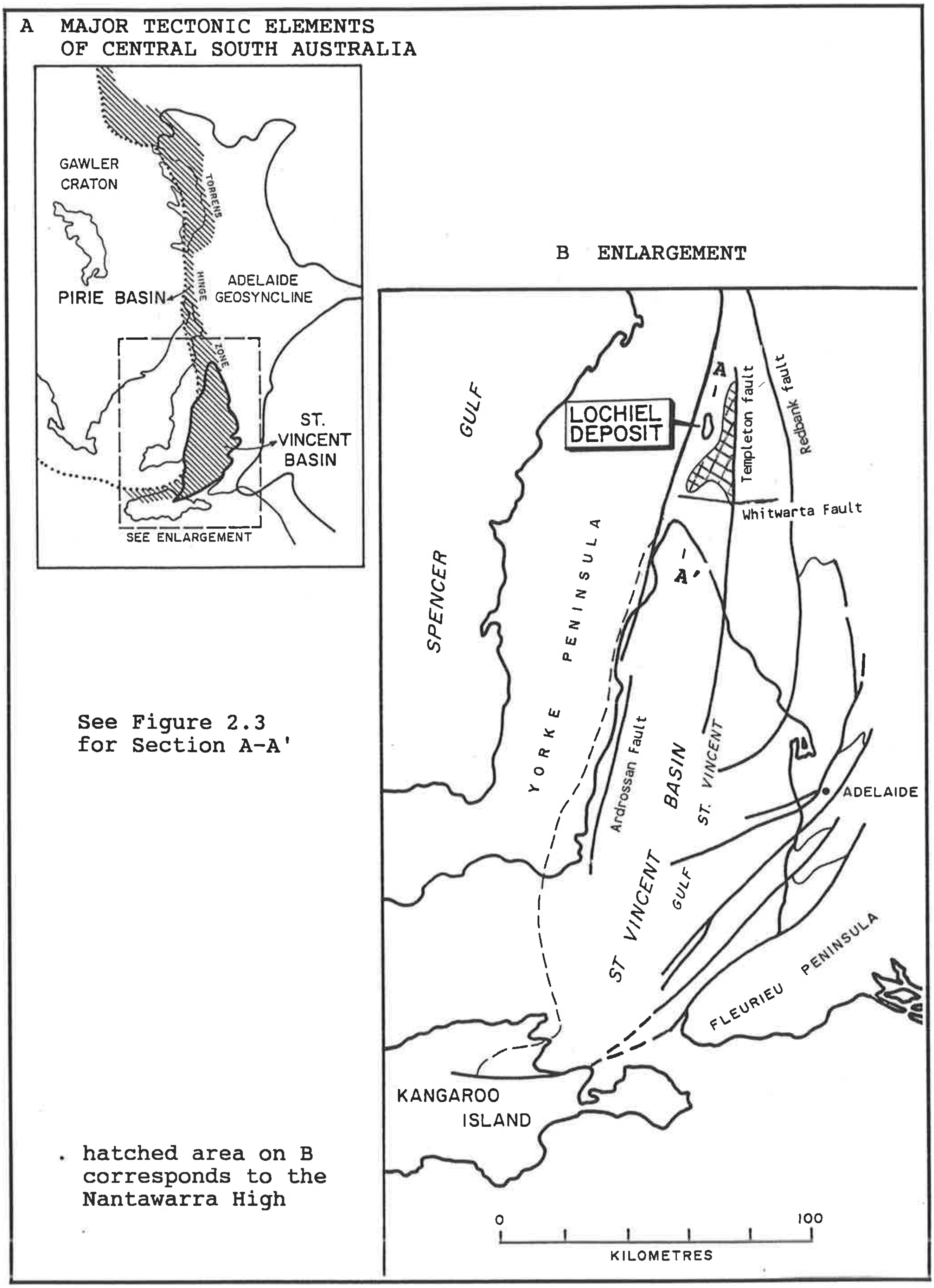
The St Vincent Basin has been defined by Glaessner and Wade (1958), Ludbrook (1980) and Parkin (1969) and the Pirie Basin by Lindsay (in press). These two basins were previously considered to be separate but, based on interpretation and correlation of drill cuttings and geophysical logs, it was concluded by Kremor (1986) that the two basins are contiguous.

As illustrated on Figure 2.2A, both the St Vincent and Pirie Basins overlie a structural boundary (Torrens Hinge Zone) which occurs between the stable Gawler Craton to the west and the mobile Adelaide Geosyncline/Delamerian Fold Belt (Preiss, 1987; Cooper, 1985) to the east and south.

2.2.1 Structure of the northern part of the St Vincent Basin

The present margins of the St Vincent Basin are bound by north-south trending and northerly converging faults (Figure 2.2B). To the north of Pt Wakefield, these are named the Ardrossan Fault (west) and the Redbank Fault (east).

A north-south elongate occurrence of ABC Range Quartzite, located between these marginal faults and known as the Nantawarra High, is bound to the east by the Templeton Fault and to the south by the east-west trending Whitwarta Fault. A detailed north-south cross-section shown in Figure 2.3 illustrates the relationship between the basement faults and the sedimentary sequences of the northern St Vincent Basin. The stratigraphic nomenclature used on Figure 2.3 is discussed later in section 2.5.



A MAJOR TECTONIC ELEMENTS OF CENTRAL SOUTH AUSTRALIA

B ENLARGEMENT

See Figure 2.3 for Section A-A'

- hatched area on B corresponds to the Nantawarra High

Figure 2.2 Geotectonic setting of the St Vincent Basin including location of major structural elements and of the study area.

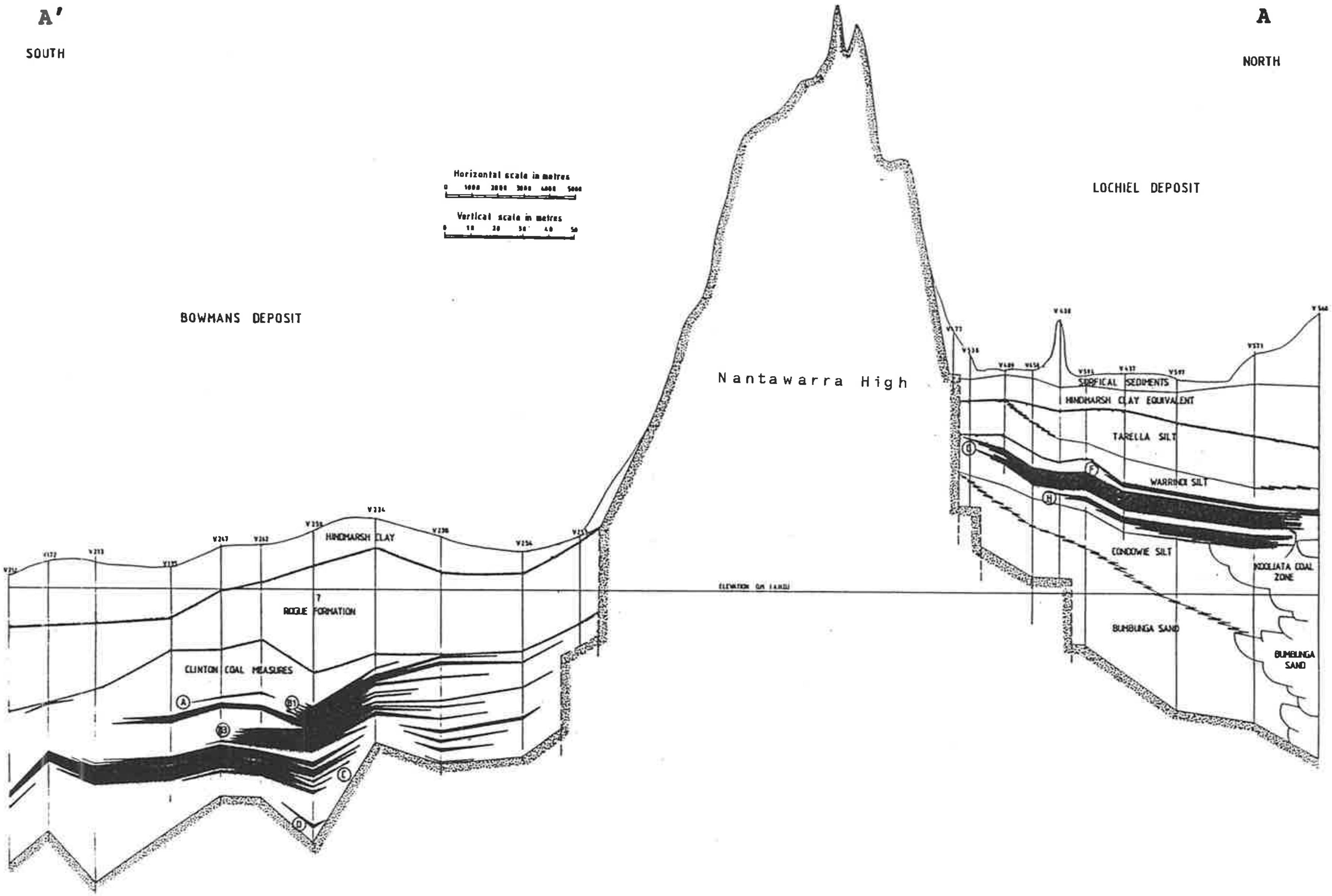


Figure 2.3 North-south section through the northern part of the St Vincent Basin illustrating the structural and stratigraphic relationships (Modified after Kremor and Springbett, 1989).

Figures 2.3 and 2.4 illustrate the major structural elements occurring within the Lochiel area. Two basement fault orientations are defined, northeast to southwest and east-northeast to west-southwest. Although no faults have been recognised within the sediments in the area, these basement faults appear to have acted as hinge zones about which very gentle monoclinal folding has occurred.

This is consistent with the findings of Stuart (1969). He concluded that within the Cainozoic sediments on the eastern side of the St Vincent basin, tectonically formed structures are confined to gentle monoclinal folds with more complex structures generally associated with basement faults.

Structure contours of the floor of the basin indicate a gentle ($<1^{\circ}$) slope towards the west and northwest reflecting a local basement tilting.

. Magnitude of fault movements

The Ardrossan Fault (previously called the Kulpara Fault by Crawford, 1965 and Alley, 1969) has displaced the Tertiary beds near Clinton by about 650 m (Horwitz, 1961). Near Lochiel this fault has a displacement of at least 500 m (the elevation difference between the base of the Tertiary sediments and the top of the South Hummocks ranges). Alley (1969) estimated a displacement of some 330 m at Snowtown to the north (see Figure 1.1, page 5 for location). The Whitwarta Fault has been traced south past the Bowmans coal

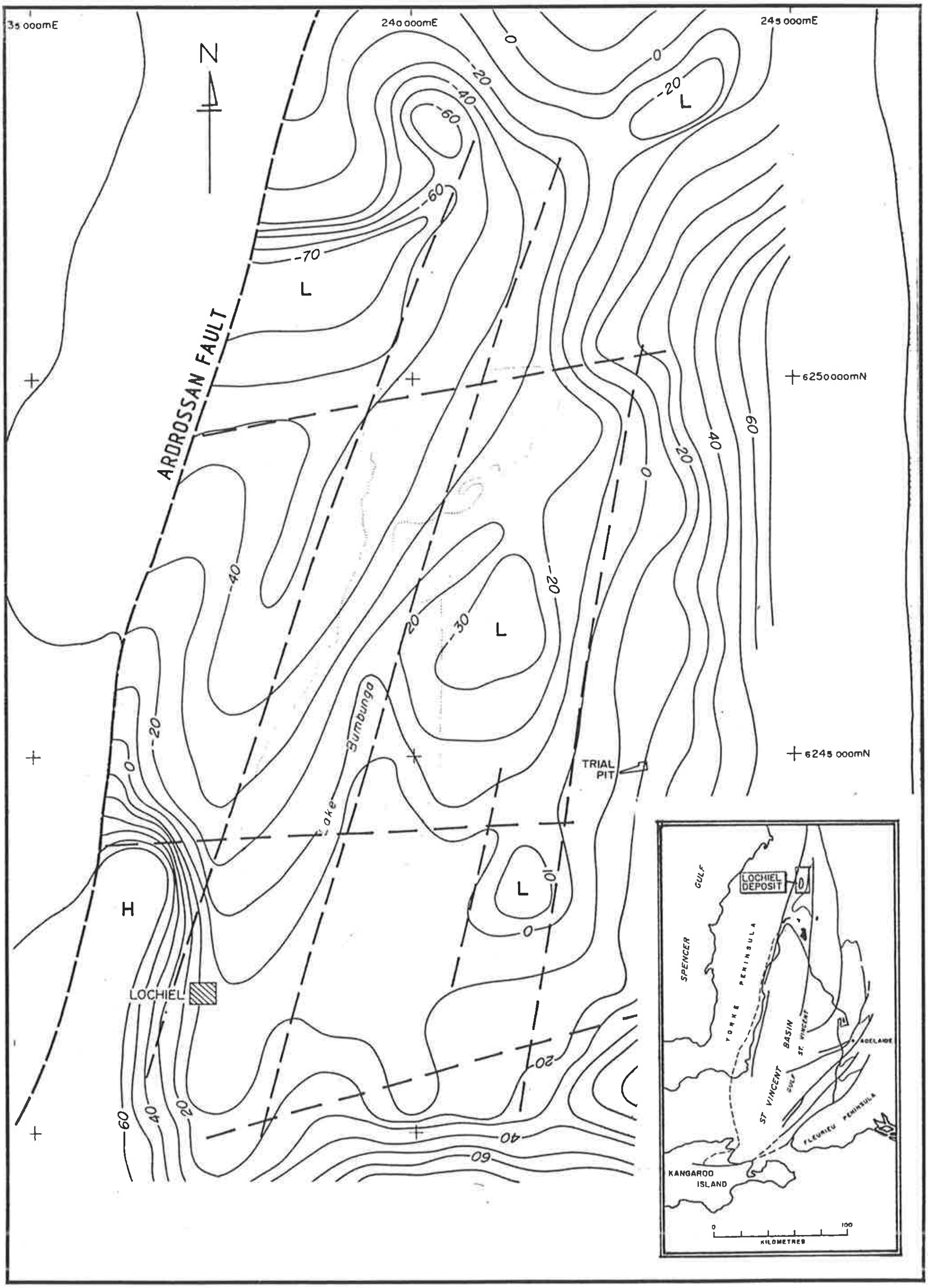


Figure 2.4 Structural setting and elements of the Lochiel Coal Deposit including structure contours of the basin floor.

deposit but is lost north of Snowtown (Figure 2.2). The magnitude and sense of movement along this fault appears to be related to the interaction of east-southeast trending faults which are located north of Pt Wakefield (Figures 2.2 and 2.3). To the south of these faults the down-thrown side is to the west whereas to the north, the eastern side is down.

In summary, there is evidence for considerable tectonic movement along the faults forming the margins of the northern St Vincent Basin and also along faults forming the margins of the study area. However, faults are confined to the basement and do not appear to displace sediments within the basin.

. Timing of fault movements

Cooper (1985), suggested that the most active period of faulting occurred during and immediately after basin initiation in the Middle Eocene with another distinct period in the Pleistocene. In addition, as reported by Selby and Lindsay 1982, and Stewart 1972, patterns of sedimentation and recent seismicity indicate that episodes of tectonic activity have occurred from the Middle Eocene to present.

2.2.2 Igneous activity

Stuart (1969) first recognised the zeolite clinoptilolite in the Blanche Point Formation. This mineral is often regarded as indirect evidence for volcanic input. Jones and Fitzgerald (1984, 1987), from chemical and mineralogical analyses of the formation regarded the non biogenic portion to be an accumulation of volcanic ash which settled through the water column. Furthermore, they found that passive continental margins world wide contain a common mineralogy typified by the presence of not only clinoptilolite but also smectite and opal CT and that explosive volcanic activity appears to have produced this mineralogy. Jones and Fitzgerald (1987) surmised that the preservation demands limited terrigenous input and a lack of strong sea currents.

As described by Cooper and Lindsay (1978) the St Vincent Basin had restricted marine access throughout its geological history. At the same time it can be surmised that the marginal peat swamps would have acted as filters of clastic sediments as indicated by the nature of the coal seams (see Chapter 5.4). It would appear that the depositional conditions in the St Vincent Basin were conducive to preserve such ash deposits.

Brown (1975) from analyses of samples from a borehole in the south part of the St Vincent Basin found clinoptilolite and smectite to be present in the South Maslin Sands, Blanche Point Formation, Chinaman Gully Formation and the Port Willunga Formation. If clinoptilolite and smectite do represent volcanic input then it is apparent that volcanic activity could have extended over a considerable time period encompassing several eustatic and tectonic events in the sedimentation history of the basin.

The possible presence of volcanic sediments in the sequence has significance. Weak seams of bentonitic clay formed from the chemical weathering of volcanic ash are common in mines from the western plains of North America, some of which are up to 1000 km away from the volcanic source (Wade, 1985). Furthermore, these weak seams can have residual angles of friction as low as 5° (Wade, 1985).

Volcanic activity is recorded in the Cainozoic in central and western Victoria. Although these are some 400 km away it is possible that they could have been a source of volcanic ash.

The evidence for volcanic input into the basin is inconclusive, however, it is possible that such sediments are present.

2.2.3 Geotectonic controls and basin formation

According to Cande and Mutter (1982) there was a rapid increase in the rate of separation of Australia and Antartica at about the Middle Eocene. Cooper (1985) considered that the commencement of basin formation is related to this separation.

Bott (1971) pointed out that the principle stress which acts on a divergent (passive) continental margin is tension initiated by the juxtaposition of thick continental crust against thin oceanic crust. The brittle continental crust responds to this tension by normal faulting.

Whereas these faults tend to align parallel to the continental edge if associated with the divergent continental margin, the faults in the area of the St Vincent Basin are aligned perpendicular to the edge. The conclusion is that whilst the separation of the two continents is coincident with basin formation in the study area, the stress regime which controlled the structure cannot be directly related to the separation.

. Basin formation

On the south-eastern margin there are a number of smaller fault bounded basins which, on their southern ends, open into the St Vincent Basin (Figure 2.2). By contrast, the only such basin occurring on the western margin is the Lochiel Basin. These smaller basins are bound by almost vertical normal faults, concordant with the trends in the underlying basement.

It was considered by Campana (1954), Forbes (1966), and Cooper (1985) that these bounding faults formed along pre-existing lines of weakness in the underlying Precambrian/Cambrian basement rocks. Moreover, the tensional stress field required to form these faults was considered by Cooper (1985) to be related to the relative difference in mobility between the Gawler Craton and the Adelaide Geosyncline (refer to Figure 2.2A).

The stresses produced from this relative difference in mobility appear to offer a plausible geotectonic mechanism for basin formation. It also explains the prevalence of the smaller basins along the margin of the more mobile Adelaide Geosyncline.

2.2.4 Summary

Tectonic controls leading to the formation of the St Vincent Basin are best related to tension developed between two cratonised areas on a continental plate. It is also recognised that the basin was in relatively close proximity to the divergent continental margin formed by the separation of Australia and Antartica (which could explain the presence of sediments of possible volcanic origin in the sequence).

The Lochiel Coal Deposit therefore appears to have formed on a **midplate continental margin** position in the sense of the classification model used by Diessel (1980) and illustrated on Table 2.1.

2.3 Depositional characteristics of coal deposits on midplate continental margins

Diessel (1980) provided a summary of the major depositional characteristics of coal deposits formed on midplate continental margin positions. Of significance is that such deposits are ;

> "..invariably paralic with intercalations of marine sediments. They belong to a group of depositional sites near the edge of a craton which are part of the continental shelf environment."

Furthermore, Diessel pointed out that ;

> "Such regions often have a setting intermediate between the craton and other geotectonic domains, for instance, geosynclines."

In the case of the St Vincent Basin these relate to the Gawler Craton and the Adelaide Geosyncline respectively.

As a result of the interaction of tectonic movement of faults and eustatic movement of sea levels, midplate continental margin settings could be expected to oscillate between the depositional environments typical of marginal marine settings discussed in section 2.3.2.

2.3.1 Eustacy and sedimentary sequences

The concepts of sequence stratigraphy in relation to eustatic changes in sea level were first described Vail et al. (1977a,b) and Micthum et al. (1977). These concepts are used to assist with the interpretation and characterisation of the vertical and lateral distribution of the major formations in the St Vincent Basin.

Sangree and Sneider (1987) described three basic types of eustatically controlled sequences (refer to Figure 2.5) :

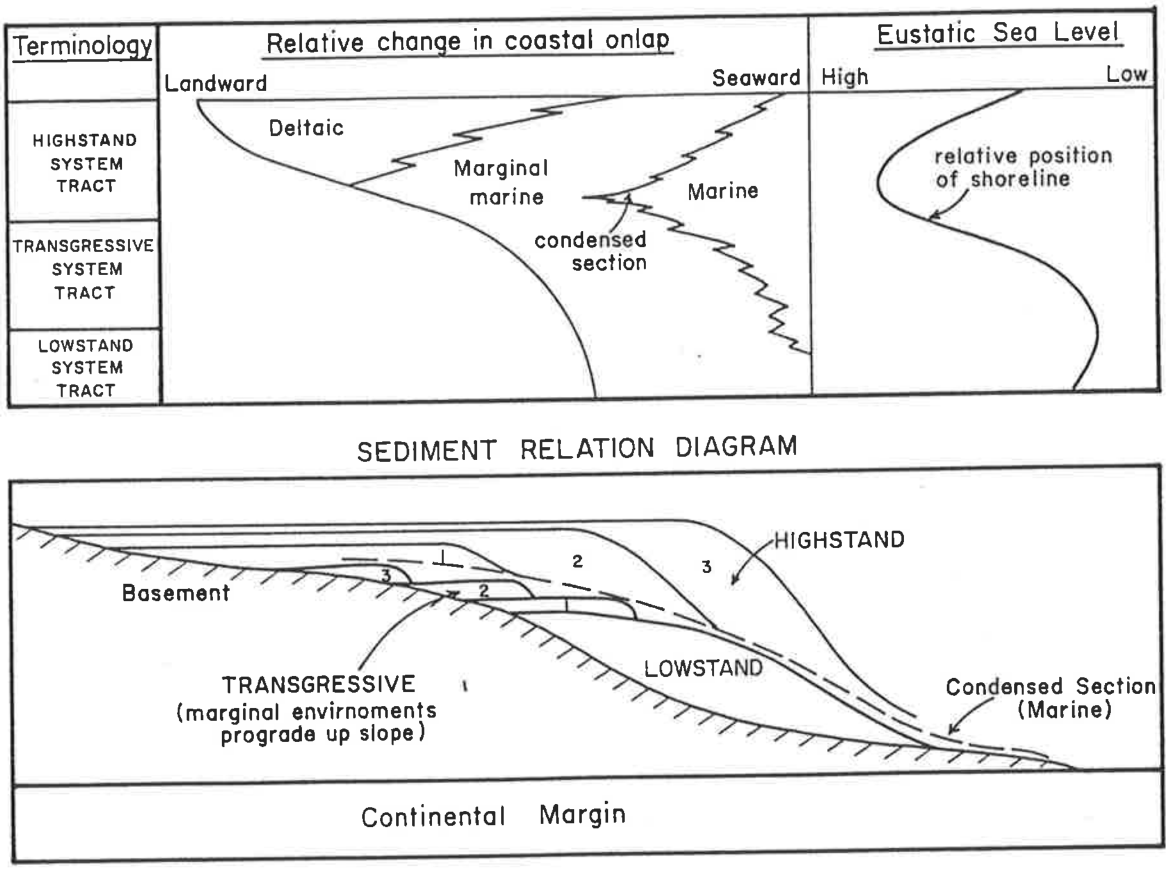
.Transgressive Systems Tract (TST) - sedimentation associated with eustatic sea level rises. During this period shoreline positions transgress landward.

.Highstand Systems Tract (HST) - As the eustatic rise slows, regression begins as the sediments entering the basin prograde back across the shelf.

.Lowstand Systems Tract (LST) - sediments related to low points in sea level. Sedimentation is similar to HST.

- Condensed Section (CS) - thin accumulations of marine sediments relating to the peak of the transgression.

Figure 2.5 Illustration of the concepts and terminology of sequence stratigraphy (modified after Vail, Hardenbol and Todd, 1984).



In addition to providing the conceptual framework to interpret eustatically controlled sequences, Vail and Hardenbol (1979) and Vail and Mitchum (1979) developed a model of actual eustatic sea levels for the Cenozoic and this is reproduced on Figure 2.6. Of significance are the multiple transgressive/regressive episodes which occurred during the Eocene and Oligocene.

2.3.2 Sedimentary environments

Typical depositional environments for midplate continental margin settings include coastal plains and marshes, lagoons, deltas, back swamps, estuaries and peat swamps. Schematic models of these depositional environments are reproduced on Figure 2.7.

Two basic sequences are developed through the interaction of eustacy and tectonics; regressive and transgressive.

During regressive eustatic phases (represented by Highstand Systems tract sediments) laterally coexisting sequences prograde down the palaeoslope, with the coal seams covering the sediments occurring closer to the sea. This results in a broad sequence comprising basal marine sediments overlain by coal bearing, deltaic and lacustrine sediments. For basins on midplate continental margins, Diessel (1980) considers this process to be analogous to the gradual silting up of a lake.

The opposite is the case for transgressive eustatic phases (TST) where coals seams are overlain by the marine sequences.

(It must, however, be recognised that the actual stratigraphic sequence is modified by the rate at which sediments enter the basin and the discussion above relates to a constant rate of sediment input.)

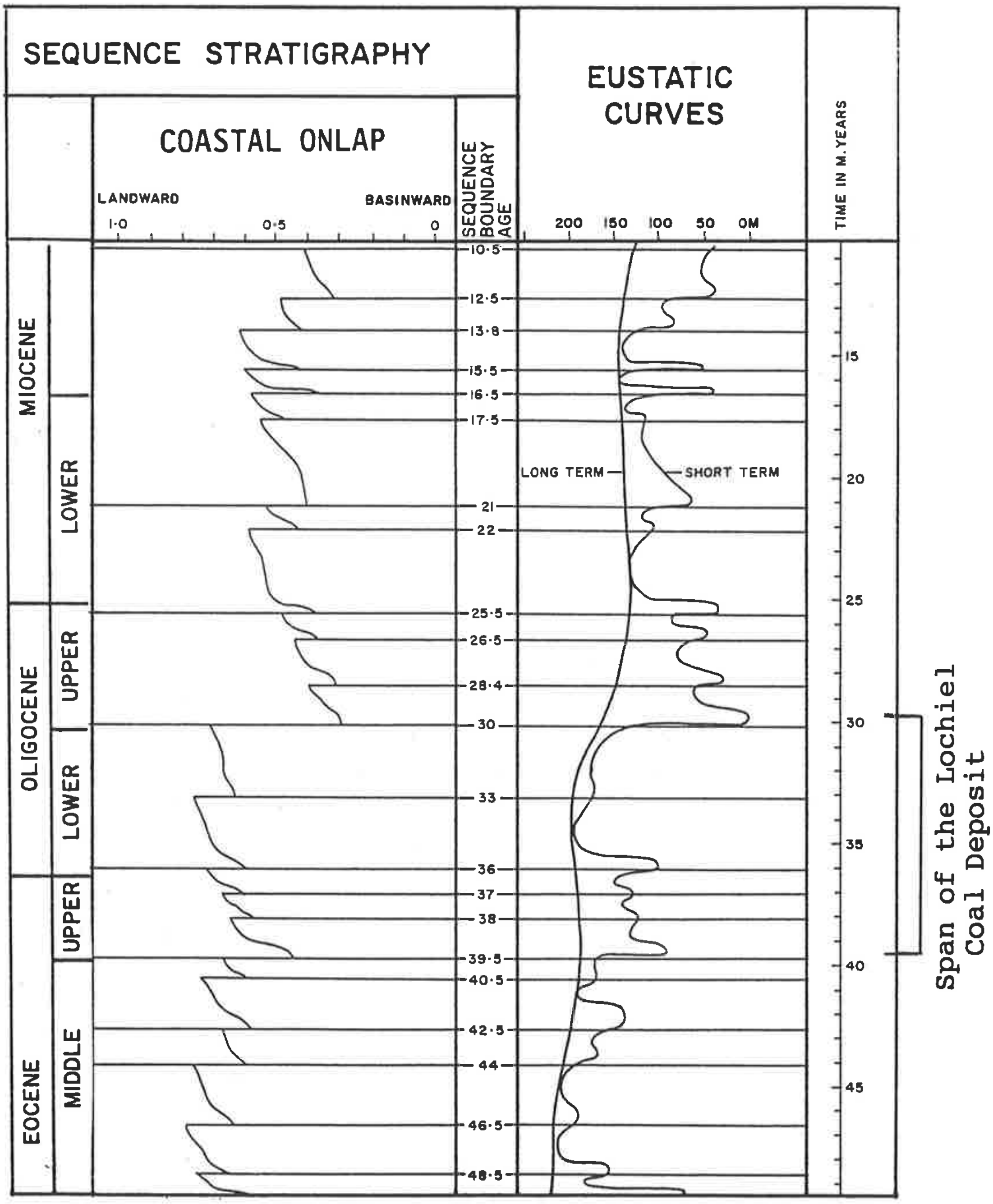


Figure 2.6 Eustatic sea level curves and relative change in coastal onlap for the Middle Eocene to Late Oligocene. (Modified after Haq et al. 1987)

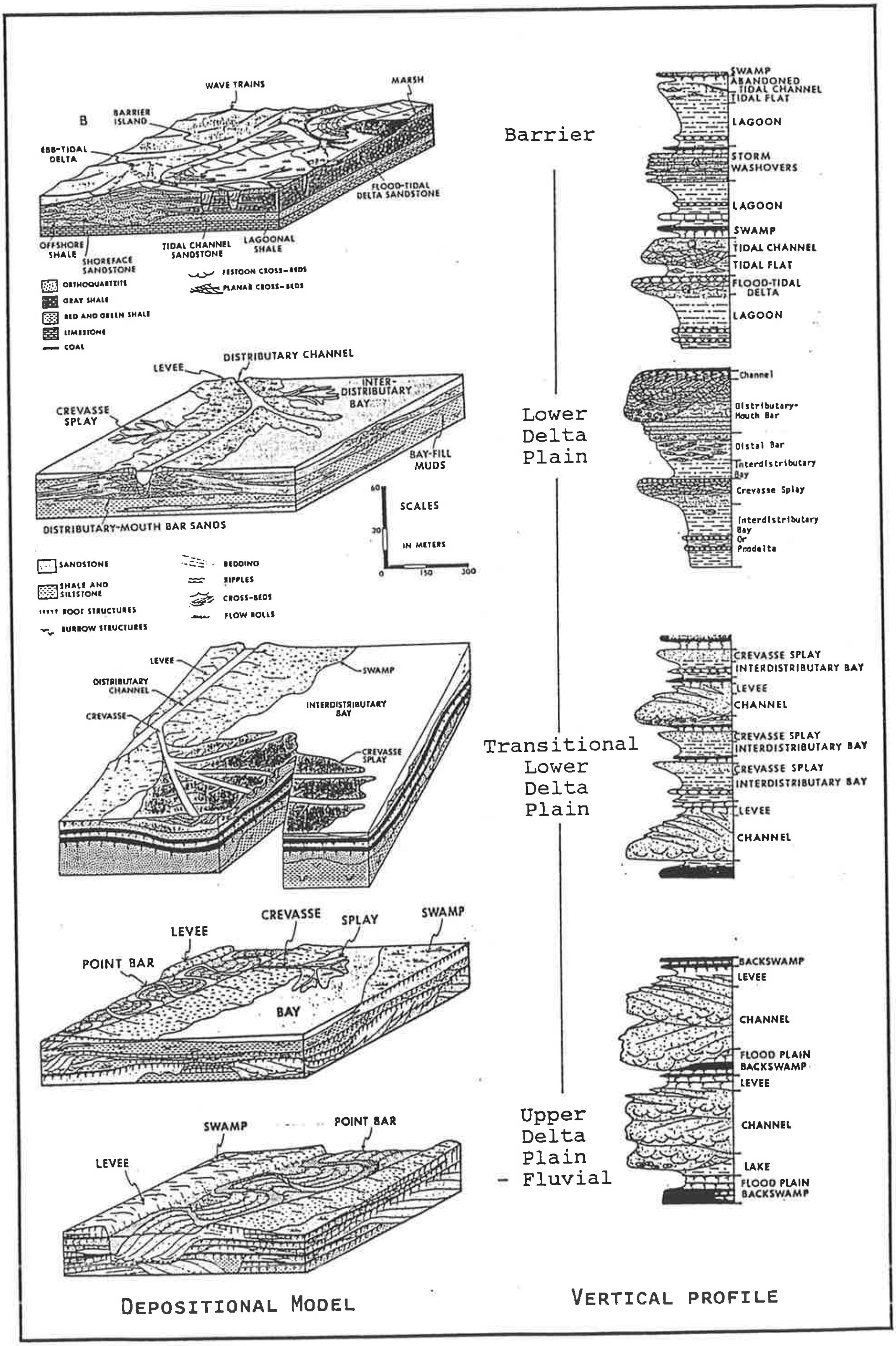


Figure 2.7 Depositional environments and vertical profiles for midplate continental margin settings (diagrams taken from Horne et al. 1978, Horne 1979a,b,c,d, Ferm and Horne 1979).

The implication for sedimentation and, therefore, the characteristics of the overburden, is that the stratigraphic profile will be determined largely by which of the transgressive or regressive regimes was present during deposition. Sequences related to predominantly regressive phases (HST) are likely to have deltaic and lacustrine sediments in the overburden whereas transgressive sequences (TST) are likely to be dominated by finer grained shallow marine sequences.

2.4 **Palaeogeographical setting of the northern St Vincent Basin**

From palynological evidence both Ludbrook (1980) and Cooper (1985) considered that sedimentation in the St Vincent Basin commenced in the Middle Eocene. Daily et al. (1976) concluded that prior to the commencement of sedimentation the area now covered by the basin was undergoing weathering and erosion.

2.4.1 Sources of sediment

The geographical studies by Alley (1969) are most informative as to the nature of the drainage system operating within the northern part of the basin and also to hiatuses in deposition in this area.

A major conclusion of the work of Alley (1969) is that the Broughton River, which enters the area from the east, has maintained its middle and upper courses for most of the period between the Eocene to the present day. Furthermore, it was also concluded in subsequent studies (Alley, 1973) that for this period of time the ancient Broughton River ran down the eastern side of the Templeton Fault (i.e. to the east of the Lochiel area, refer to Figure 2.2). Alley (1973) defined these fluvial sediments as the Snowtown Sands.

The Snowtown Sands have been correlated stratigraphically by the author with the Tarella Silt and Warrindi Silt in the Lochiel area. More recent palynological analyses by Alley (pers. comm., 1990) also support this conclusion.

The implication is that the ancient Broughton River drained through the Lochiel area at least during parts of the Oligocene. In addition, the conclusions reached in Chapter 6.0 suggest that prior to this time it is likely that drainage of the ancient Broughton River was into the Pirie Basin to the north, the southern path being blocked by an uplifted Nantawarra High.

Palaeocurrent analyses by Stuart (1970) on Middle to Late Eocene fluviatile sediments occurring in the south of the study area indicate sources also originated from the west at that time. This is consistent with the findings of this thesis (Chapter 6.0) which indicate that a major fluvial source entered from the west (at the northern end of the Lochiel area) during the Late Eocene and appears to have drained to the north, probably coalescing with the ancient Broughton River.

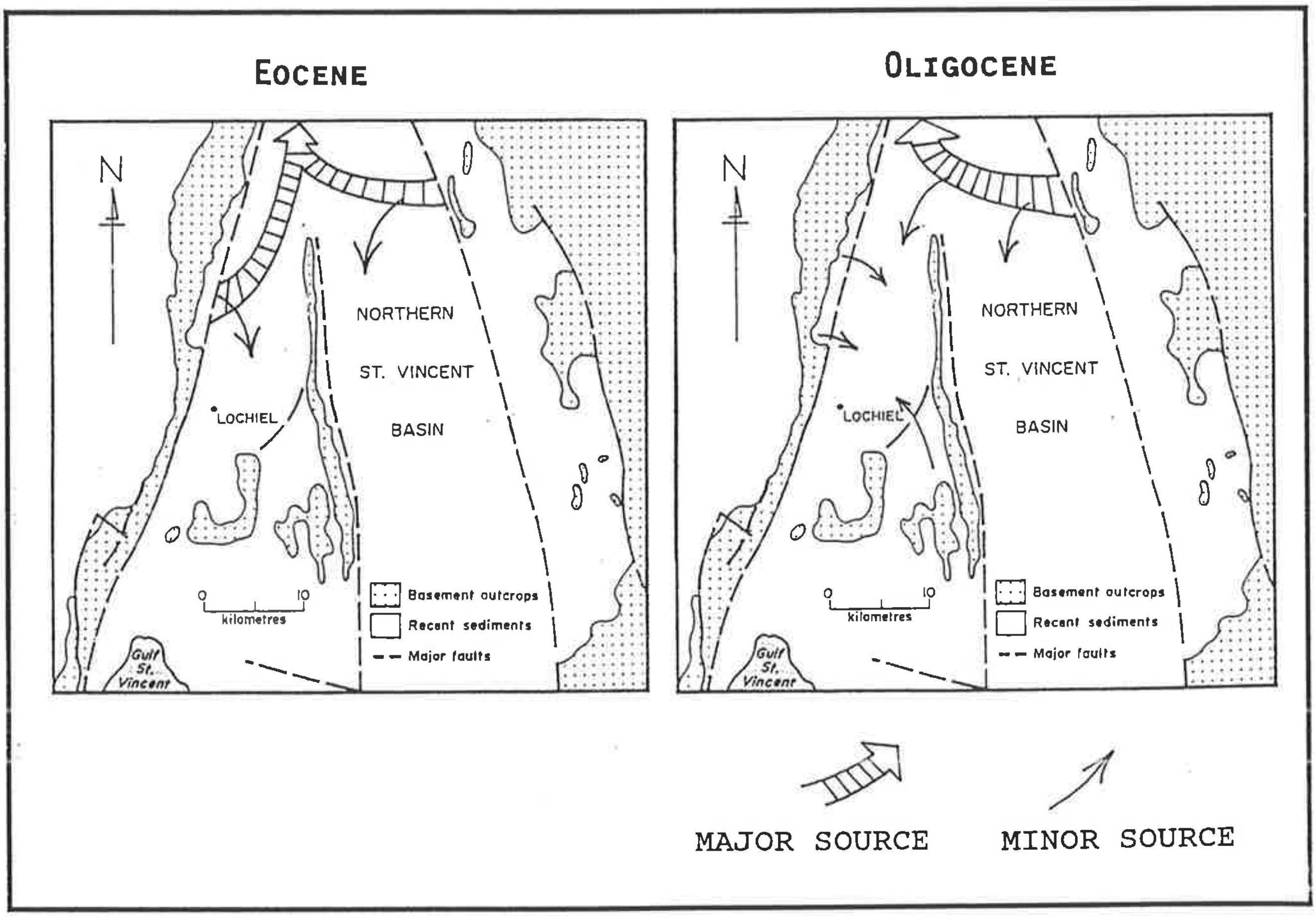
Based on the discussion above, a palaeogeographical model for the area for the Late Eocene to Miocene is presented on Figure 2.8.

2.4.2 Cainozoic hiatuses

Alley (1969) defined three major erosional episodes based on a study of erosional surfaces at the northern end of the St Vincent Basin.

The oldest of these he named the Mt Herbert surface which was characterised by heavily ferruginised and weathered basement.

Figure 2.8 Palaeogeographical reconstruction of the northern St Vincent Basin for the Oligocene and Eocene.



This surface was eroded to form the Moorundie etch surface. Both these surfaces predate Tertiary deposition and equate to the paleocene planation surface defined by Daily et al. (1976).

The second episode called the Huddleston surface with its related etch, the Yacka Moorundie surface, was considered to separate the Oligocene/Eocene sediments from the Miocene sediments in the Snowtown area. The Huddleston surface was considered to be a prolonged or intensive period of weathering and erosion. It developed on a fairly level surface with the base levels of erosion being dictated by the level of the groundwater table. This surface is characterised by the formation of a thin silcrete capping which covers highly kaolinised bedrock.

Hard, silcrete bands have also been intersected in boreholes in the Merriton and Crystal Brook areas at a stratigraphic location coinciding with the top of the Tertiary sediments, ETSA (1987).

According to Alley (1969) the third episode corresponds to the present land surface and is called the Condowie surface.

From a review of Alley (1969, 1973) it is not possible to distinguish any erosional/weathering periods in the Eocene/Oligocene.

2.4.3 Palaeoclimate

According to Cooper (1985), Cainozoic sedimentation in the St Vincent Basin reflects deposition under temperate climatic conditions although the appearance of large foraminifera amongst the Late Eocene, Late Oligocene/Early Miocene and Middle Miocene faunas (Lindsay, 1969; McGowran, 1979) is indicative of increased tropical influence.

A tropical climate for the Late Eocene is also supported by palaeobotanical studies by Christophel and Blackburn (1978), Kemp (1978), and by the presence of widespread coal formation.

2.5 Stratigraphic succession

The study area is located between the St Vincent Basin to the south and the Pirie Basin to the north. The stratigraphy of the northern part of the St Vincent Basin has been described previously by Johnson (1960), Hillwood (1961), Harris (1971), Meyer (1976), Cooper (1976, 1977) and Stuart (1969, 1970). The stratigraphy of the Pirie basin is described by Lindsay (in press).

A summary of the current stratigraphic nomenclature for the Bowmans - Clinton, and Snowtown areas is presented on Figure 2.9 and includes a correlation with eustatic sea level curves of Haq et al. (1987) and with erosion surfaces defined by Alley (1969, 1973). In addition, Figure 2.3 on page 13 shows the relationship between sediments occurring at the northern end of the St Vincent Basin.

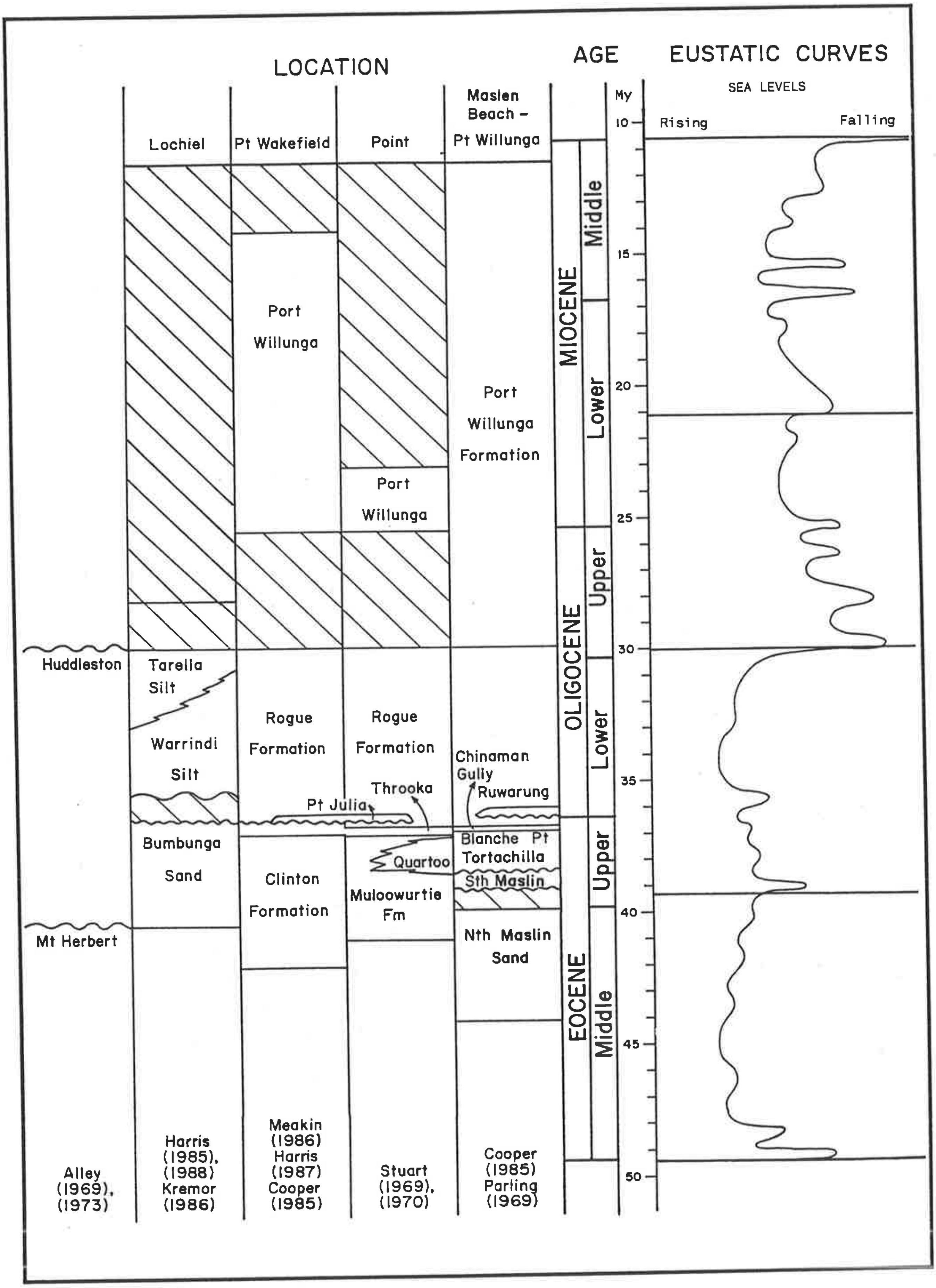


Figure 2.9 Stratigraphic nomenclature and correlation of formations in the northern St Vincent Basin.

2.5.1 Tertiary - St Vincent Basin

- Clinton Formation (formerly referred to as Clinton Coal Measures)

Palynological studies by Harris (1966) assigned the fluvio-deltaic brown coal bearing sand and clay in the Bowmans area south of Lochiel to the Middle to Upper Eocene Clinton Coal Measures.

Meakin (1985) and Harris (1987) divided the Clinton Coal Measures in this area into upper and lower sequences (spanning late Middle Eocene to Early Oligocene) based on the stratigraphic distribution of index palynomorphs. Meakin (1985) inferred a hiatus of short duration and correlated the upper sequence with the Chinaman Gully Formation and the lower to the Blanche Point Formation.

More recent studies by Alley (pers.comm. 1990) also suggest that the Clinton Formation in the Bowmans area is Late Eocene to Early Oligocene.

Alley (1969) and Harris (1970, 1985) both considered that the Clinton Coal Measures become progressively younger towards the north. This trend is consistent as far south as the Willunga embayment where Middle Eocene coal bearing sediments are present (South Maslin and North Maslin Sand).

Harris (1980) recognised the close correlation of sea level cycles in the Eocene to the depositional architecture of the basin and the occurrence of coal. Based on palynological evidence Harris suggested that the lateral distribution of coal deposits was related to the position of the shoreline which in turn was controlled by eustatic sea level changes.

A similar relationship is also envisaged by Holgate (1985) for the extremely thick deposits of Tertiary age brown coal in the Latrobe Valley. Holgate (1985) suggested that these accumulated behind a sequence of barrier bars.

Although the formation of coal seams and major facies in the St Vincent Basin appear to be related to eustatic sea level changes, as discussed later in Chapter 6.0, it is considered that the thickness and local facies relationships are more influenced by the local tectonic structure.

Also significant is that these deposits are both overlain by marginal marine sequences (the Clinton Coal Measures in the Bowmans area is overlain by the marginal marine Rogue Formation). This is also true of the Muloowurtie Formation, a correlative of the Clinton Coal Measures occurring on the Yorke Peninsula, which is overlain by the marginal marine Throoka Silts and in turn by the marine Rogue Formation (Stuart 1969, 1970).

Based on the concepts of sequence stratigraphy it is evident that the Clinton Formation and its correlatives are representative of a Transgressive Systems Tract.

. Rogue Formation

Stuart (1970) defined the Rogue Formation as being a mainly marine sequence consisting of quartz sand, sandstones and siliceous sandstones, siliceous and arenaceous limestones, mudstones and clays. He assigned the Rogue Formation an Late Eocene to Oligocene age based on palynological dating of samples from the east coast of Yorke Peninsula. The formation is characterised by numerous facies changes and erosion has limited its distribution.

From the descriptions provided by Stuart (1969, 1970) it is likely that the Rogue Formation represents marginal marine and deltaic sedimentation. Furthermore, the Rogue in the Bowmans area is represented by fine to medium grained sand with thinner intercalations of silty and carbonaceous sand.

It is considered that these represent barrier bar and shoreface deposits. This is consistent with the barrier bar depositional environment attributed by Stuart (1970) to the laterally equivalent Quartoo Sand Member occurring at the top of the Muloowurtie Formation farther to the south.

Stuart (1970) also recognised that the Quartoo Member was laterally equivalent to the marine Port Vincent Limestone (includes parts of the Willunga Formation and the Blanche Point Marls) farther south. Stuart (1970) hypothesised that the relationship between the Muloowurtie-Quartoo Sand-Port Willunga represented a regression, standstill and then a northerly transgression respectively. He hypothesised that these lateral facies relationships were tectonically controlled.

In addition, Harris (1985) on the basis of palynological evidence concluded that the Rogue and Port Willunga Formations were also lateral equivalents.

Stuart (1970) reported that clay minerals occurring in the formation are mainly montmorillonites, mixed montmorillonites and glauconite with variable amounts of illite. The zeolite clinoptilolite is also common.

The Rogue Formation includes the Port Julia Greensands Member, a thin green glauconitic quartz sandstone and arenaceous glauconitic mudstone (Stuart, 1970) which contains occasional opaque minerals and chert nodules. Cooper (1977, 1985) correlated this member to similar biostratigraphic levels farther south in the basin and it is considered to represent an erosional, transgressive phase of marginal marine sedimentation.

Hillwood (1961) also identified similar sediments in the Bowmans area and although Stuart (1969) proposed that there was probably not a direct correlation with those described on the Yorke Peninsula, it is possible that these sediments represent an equivalent transgressive phase of sedimentation.

. Snowtown Sands

To the north and northeast of the Lochiel area, and on the basis of palynological interpretation by Harris (1969,1970), Alley (1973) assigned the name Snowtown Sands to an interbedded sequence of Miocene fluvio-lacustrine sands, clays and brown coals which overlay the Clinton Formation. However, subsequent analysis by Alley (pers comm. 1990) suggest that these sediments are Oligocene in age, correlating "largely with the Oligocene _Proteadidites tuberculatus_ Zone."

Furthermore, lithological and geophysical log correlation, suggests that the Snowtown Sands are laterally equivalent to the Warrindi and Tarella Silts in the Lochiel area.

From vertical profile analysis of geophysical logs and interpretation of drill cuttings and cores it appears that the Snowtown Sands represent a mainly fluvial depositional environment. The common occurrence of thin coal seams and upward coarsening cycles of silt and fine sand also indicate the lateral co-existence of peatswamp and lacustrine and crevasse splay environments.

. Port Willunga Formation

The Port Willunga Formation was defined by Lindsay (1967, 1969) and is equivalent to the Port Vincent Limestone described by Stuart (1969, 1970). It is a bryozoal limestone of Late Eocene to Middle Miocene age and the distribution of the formation at the northern end of the basin coincides with and appears to be limited by major structural features.

In general, the Port Willunga Formation thins towards the north. Stuart (1970) suggested that this thinning can be explained by the interaction of three controlling mechanisms; angular unconformity at the top of the formation, lateral gradation down to the Rogue Formation and minor diastems within the formation.

Near Muloowurtie Point, Stuart (1969) described a transgressive and erosional quartz sand only 1.2 m thick directly overlying the Rogue Formation.

The occurrence of the erosional sands is common in transgressive marine sequences and the base is defined by Swift (1968) as the ravinement surface. It may be related to the Ruwarung Member described elsewhere in the basin (Cooper, 1977, 1985; Lindsay, 1967, 1987; McGowran, 1978).

2.5.2 Tertiary - Pirie Basin

The Pirie Basin is defined by Lindsay (in press), and based on the interpretation of drillholes, Kremor (1986) has suggested a connection with the sequences in the Snowtown and Lochiel areas (Figure 2.2).

The Basin contains two major stratigraphic sequences, the Kanaka Beds and the Melton Limestone. The Kanaka Beds consist of carbonaceous siltstone, shale and sand, with minor lignite. The age of the Kanaka Beds has not been accurately determined, however, Lindsay (in press) suggests a possible range from latest Eocene to Early Oligocene. It is considered by the author that the the Kanaka Beds correlate with the Clinton Formation.

The contact between the Kanaka Beds and the Melton Limestone is characterised by the presence of a thin sand unit representing the marine transgression which preceded the deposition of the Melton Limestone (Lindsay, 1970).

The Melton Limestone represents marine deposition associated with five transgressive episodes between the Late Oligocene and the early Middle Miocene. The Melton Limestone is not present in the Condowie Basin, nor have any sediments of Miocene age have been identified. It is apparent that the for most of the Condowie Basin deposition ceased between the Late Oligocene and the Early Middle Miocene. However, it is considered that if some sedimentation did occur, it is most likely that it would have been against the Ardrossan and Templeton Faults.

2.5.3 Quaternary

Within the Lochiel deposit the Tertiary sequence is overlain unconformably by the Hindmarsh Clay and by the Gypsum Hill Beds. These sediments were described in detail by Kremor (1989) but as they were not part of the coal forming depositional environment detailed analysis is beyond the scope of this study.

2.6 Geotectonic and eustatic model for the stratigraphic sequence of the Northern St Vincent Basin

From the review of the sedimentary formations occurring within the basin it is possible to develop a broad model of the laterally coexisting environments of deposition within the northern St Vincent Basin. This model is shown on Figure 2.10. The major depositional environments are considered to be;

1. Fluvio-deltaic - Bumbunga Sand, Clinton Formation, Muloowurtie Formation, North Maslin Sand, Chinaman Gully Formation.

2. Marginal marine - Warrindi Silt, Tarella Silt, Throoka Silts, Quartoo Sands, South Maslin Sands.

3. Marine - Port Willunga Formation, Blanche Point Marls.

4. Transgressive destructional units - Pt Julia Greensands, Ruwarung Member of the Port Willunga Formation, Tortachilla Limestone.

Figure 2.6 on page 24 and Figure 2.9 on page 31 also provide an indication of the interaction of eustatic sea levels with sedimentation patterns. There is a general rise in sea level up to the Eocene/Oligocene boundary after which there is a general fall. Within these major trends there are a number of relatively minor transgressive/regressive episodes.

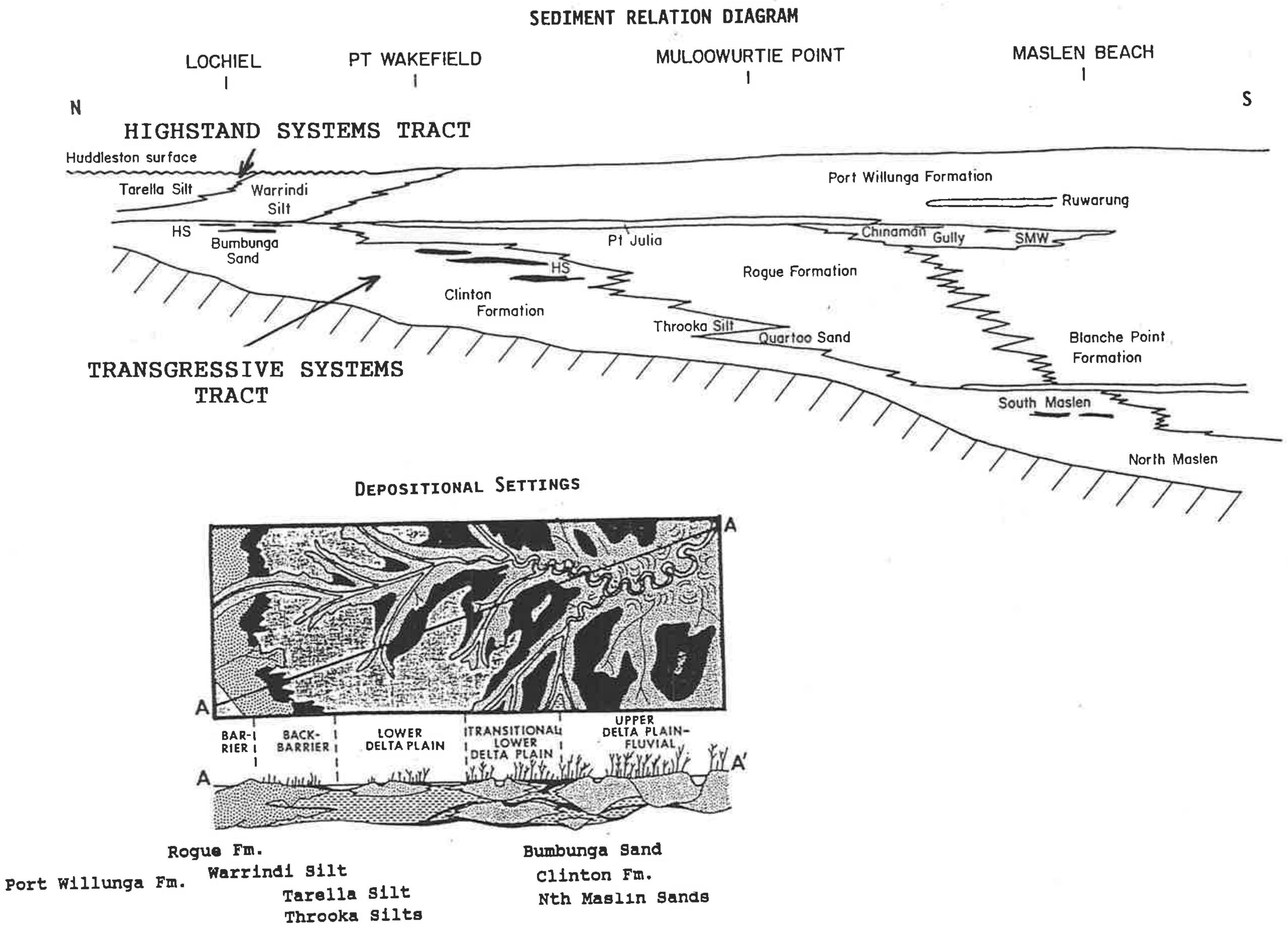


Figure 2.10 Sediment relation diagram and inferred depositional setting for the northern part of the St Vincent Basin.

A summary of the main features of the Late Eocene to Middle Oligocene depositional settings are discussed below.

a) A northerly migration of the fluvio-deltaic sequences culminating in the Late Eocene to earliest Oligocene.

These equate to Transgressive Systems Tract (TST) sequences.

It is evident that from the commencement of basin formation in the Middle Eocene to the Late Eocene/Early Oligocene, eustatic rise in sea-level (transgression) was the major controlling process. Notwithstanding this, a number of smaller scaled regressive (HST) episodes also occurred during this time. These HST episodes are characterised by containing accumulations of coal and discussed below.

b) A number of smaller scaled regressive episodes within the major transgressive episode often represented by accumulations of coal.

This characteristic has important implications for both the nature of basin subsidence and coal formation. As Diessel (1980) pointed out coal can only accumulate when the depth of water is within a range of no more than a few metres. Greater depths tend to drown the vegetation whilst lower depths lead to oxidation and hence destruction of the peat.

The presence of thick coal seams such as those found in the Bowmans and Lochiel deposits must, therefore, represent a balance of eustatic and tectonic controls. That is, the rate at which the sea level rises/falls is matched approximately by tectonic subsidence and peat accumulation. Theoretically this must occur at least at Highstand (HS) points in the eustatic cycles.

It is evident that Highstand points are a likely stratigraphic location for coal formation and coal seams. At this time coal accumulation can be terminated by either of two processes.

1. First, by a continued transgression in which case the coal seams are overlain by the marginal marine and marine sequences (as is the case for the Bowmans deposit). A variation of this process occurs when transgression is blocked by tectonic uplift along the shoreline. In this case the peatswamp is also drowned but a lagoonal/estuarine environment forms (as is the case at Lochiel, and for the Maslen Beach/Port Willunga sequences). Both of these variations equate to Highstand systems tract sequences.

2. Second, by progradation of the fluvio-deltaic environments over the peatswamps. Again Highstand systems tract sequences form, however, in contrast to the above there is little or no marine influence.

3. A hiatus and regression at the Late Eocene/Oligocene boundary followed by a transgressive destructional episode which reworked the underlying sediments.

This episode covered the area up to the Nantawarra High with sediments of the marine Port Willunga Formation. In this context the Port Julia Greensands and Chinaman Gully Formation are representative of a Condensed Section (CS). It is appears that this episode coincided with having the shoreline located in the Lochiel area.

2.7 Summary

The St Vincent Basin is classified on the basis of its plate tectonic setting as representative of a midplate continental margin position. The basin is bound by north-south trending and northerly converging normal faults. Within the basin a second set of faults with east-west trends are common. In the Cainozoic, the most likely cause of movement along these faults is related to differential movement between the stable Gawler Craton to the west and the more mobile Adelaide Geosyncline to the east.

The midplate continental margin setting is a common site of peat accumulation leading to coal seams. Typically, the associated depositional environments are marginal marine in character and include barrier bars, back-barrier environments, estuaries, lagoons and deltas.

Two major controls on sedimentation patterns and lateral facies distribution are identified; tectonic movement along basement faults and eustatic sea level changes. The major Cainozoic formations can be interpreted on the basis of these controls.

One major transgressive/regressive eustatic episode is recognised in the stratigraphic sequence in the northern St Vincent Basin. This eustatic episode resulted in deltaic and marginal marine sediments (Transgressive Systems Tract (TST) deposits) being overlain by marine sediments and culminated in the formation of coal seams at both the Lochiel and Bowmans deposits. A standstill (Condensed Section (CS)) and then regression (represented by Highstand System Tract (HST) sedimentation) appears to have followed the TST. The CS and HST phases led to the establishment of marginal marine depositional environments within the Lochiel area.

The controlling processes outlined above have led to the sedimentary sequence now present within the Lochiel Coal Deposit. In addition, the definition of these processes and the classification of the study area within them provides the basis for both translating the results of this study to other soft brown coal occurrences and for the detailed analysis of geological processes which follow in Chapters 5 and 6.

3.0 IDENTIFICATION OF ENGINEERING GEOLOGICAL FACTORS AFFECTING SLOPE STABILITY IN THE LOCHIEL COAL DEPOSIT

The purpose of this Chapter is to identify the key engineering geological features affecting slope stability in the Lochiel Coal Deposit.

The analysis of slope stability necessarily identifies which geological factors have the greatest impact on slope stability. Therefore, results of slope stability analysis underpin the approach used to identify the key factors to be analysed in this study.

Considering that the role of the engineering geologist centres on providing predictive information on the engineering geological properties and for the geotechnical engineer to analyse slope behaviour it is beyond the scope of this study to undertake such slope stability analyses.

A large amount of information is available on how slopes fail (the mode of failure) and on why they fail (mechanisms for failure). Based on a review of this existing information, the following section attempts to summarise the key engineering geological factors which contribute to the stability of an excavated slope.

The first step is to establish what are the key engineering geological features relating to the mode and mechanism of failures in generic terms.

The second step is to clarify the nature of these features for the Lochiel Coal Deposit. This will be accomplished using both interpretations made by the author as well as by reviewing published information on slope stability analyses for the deposit.

3.1 Generic Modes of slope failure in weak rock and soil.

Hoek and Bray (1977) and Ross-Brown (1979) provided descriptions of the major types of failure. The major types can be categorised into those with failure surfaces (plane, wedge, two-block and certain types of circular failures) and those without failure surfaces (toppling, ravelling and most circular failures). These modes of failure are illustrated on Figure 3.1.

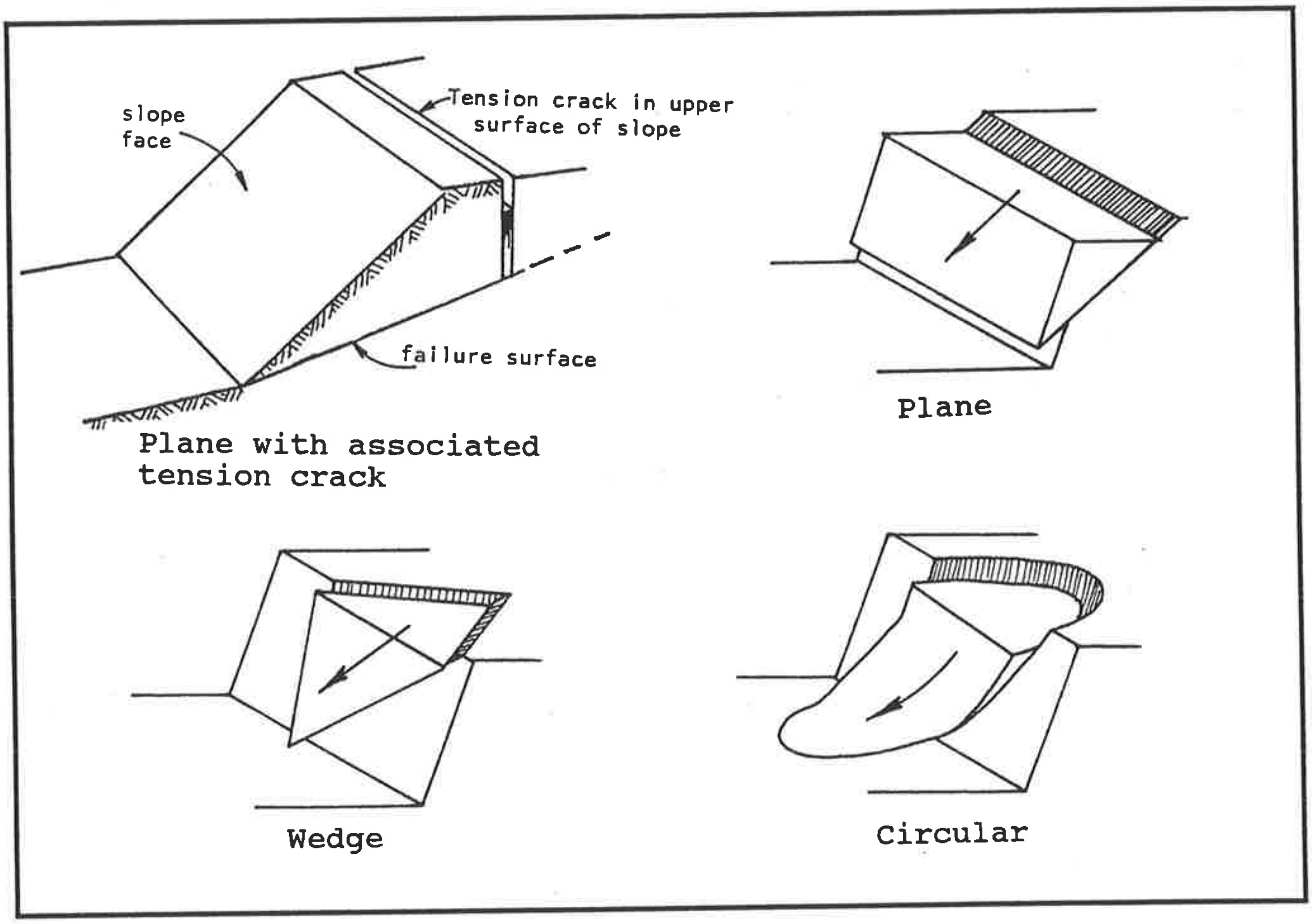
a) Plane Failure.

Failure occurs when a geological discontinuity strikes parallel to the slope face and into the excavation at an angle greater than the angle of friction. Variations to this occur when a tension crack forms, or when the mean sliding plane is a combination of two joint sets which form a stepped path.

b) Wedge Failure.

When two discontinuities strike obliquely across the slope face and their line of intersection daylights in the slope face, the wedge of rock resting on these discontinuities will slide down the line of intersection, provided that the inclination of this line is greater than the angle of friction.

Figure 3.1 Schematic representation of the characteristics of the modes of failure for weak rock and soil (modified after Hoek and Bray, 1977).



Plane with associated tension crack

Plane

Wedge

Circular

c) Circular Failure.

When material is very weak, as in a soil slope, the failure will be defined by a single discontinuity surface but will tend to follow a circular path. A variation of this type of failure is the non-circular failure, where the failure surface tends to run parallel to a set of weakness planes.

d) Two Block failure

Occurs when an unstable wedge produces an active force on a lower, second wedge which would otherwise be stable, resulting in failure of both wedges.

e) Toppling Failure.

When blocks rotate about their lowest contact edge. This mode of failure can occur when there is a vertical or near vertical joint set.

f) Ravelling Failure.

When materials deteriorate on exposure and break off in small blocks.

It is recognised that this summary of generic failure modes is not exhaustive and that many failures actually involve combinations of those listed above. However, it is considered that this summary reflects the current state of thinking for generic modes of slope failure.

Discontinuities in the sediments are crucial to all the generic modes of failure listed above (although to a lesser extent for circular failures). The conclusion is that **discontinuities** are a key geological factor affecting slope stability. Furthermore, the key engineering properties of discontinuities are location, geometry and strength.

3.2 Mechanisms causing failure of slopes in weak rock and soils

The science of predicting the behaviour of soils was founded by Terzaghi in about 1918 (Stapledon, 1982). In doing so Terzaghi provided a "...framework that helps engineers to organise, interpret and evaluate experience." (Peck, 1962). This soil mechanics framework will be used to develop a simplified description of the mechanisms causing slope failure. It is recognised that in practice the analysis of the causes of slope failure is a complex exercise requiring the consideration of such factors as time, slope geometry, movement of equipment, seismicity and climate, however, such detailed analyses are beyond the scope of this study.

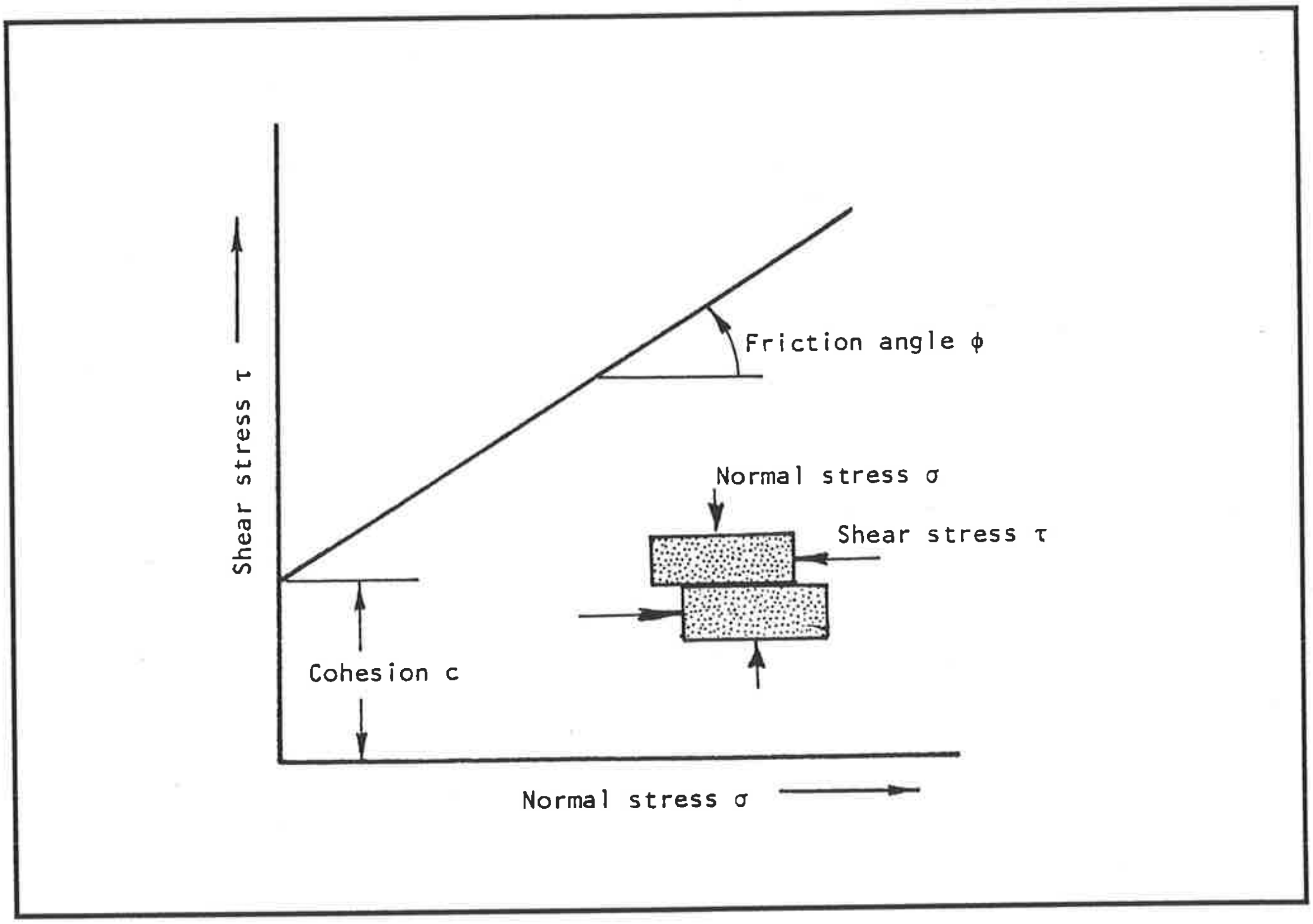
Failures occur when the available shear strength is less than the shear stress (mobilising force). The shear stress required to cause sliding can be calculated for a soil by using the following equation (Bolton, 1984) :-

$$\tau = c + \sigma' \mathrm{Tan}\ \phi$$

These components are illustrated on Figure 3.2.

It is apparent from this equation that for a particular soil or weak rock, the shear strength (residual friction angle and cohesion for intact materials and defects) and the normal effective stress are the key factors in determining the stability of a slope.

Figure 3.2 Relationship between the factors affecting failure along a discontinuity (modified after Hoek and Bray, 1977).



The normal effective stress (σ') is defined by the following equation ;

$$\sigma = \sigma' - u$$

where σ = normal stress and u = pore water pressure.

In soft brown coal mining areas the normal effective stress (and thus the shear stress) can be varied to reduce the probability of failure by reducing the porewater pressure through activities such as dewatering and depressurising.

Shear stresses can also be reduced by minimising any imbalance between horizontal and vertical loads. In practice, this can be achieved by excavating part of the overburden ahead of the highwall face (unloading or pre-stripping) or by the design of the slope geometry.

As described in Section 3.1, there are a number of modes of failure each of which is characterised by a particular failure plane. Essentially these failure planes can coincide with pre-existing geological features such as shear planes, or can develop within intact material.

Further analysis of these or other methods of varying the normal effective stress or shear stress is beyond the scope of this thesis. However, for the purposes of this study it can be concluded that slope failure is controlled by :

- the normal effective stress,
- cohesion,
- strength of the sediment or of geological structures (discontinuities) within the sediment.

In addition, it can be concluded that the methods available to influence these controlling factors are :

- the rate and extent to which the porewater pressure can be reduced,
- geometry and stratigraphic location of the geological structures.

3.3 Review of slope stability analyses for the Lochiel Coal Deposit

An extensive series of tests were undertaken to identify the key geological features affecting slope stability for the Lochiel Coal Deposit. The author was responsible for the engineering geological input into the planning and design of these tests and subsequently for the interpretation of the results from a geological viewpoint. A discussion on these tests and their limitations is provided in Chapter 4.

Specific slope stability analyses were undertaken by Coffey and Partners Pty Ltd (1988a).

3.3.1 Summary of stratigraphy

The stratigraphy and lateral continuity of sediments within the Lochiel Coal Deposit is summarised on Figure 3.3. Three Cainozoic formations are present, the Bumbunga Sand, Warrindi Silt and the Tarella Silt. Each of these formations is analysed in detail in Chapters 5 and 6 to identify and define the processes which led to their particular characteristics.

In addition, the deposit is overlain by the Pleistocene Hindmarsh Clay. However, because the Hindmarsh clay was not part of the depositional event associated with coal

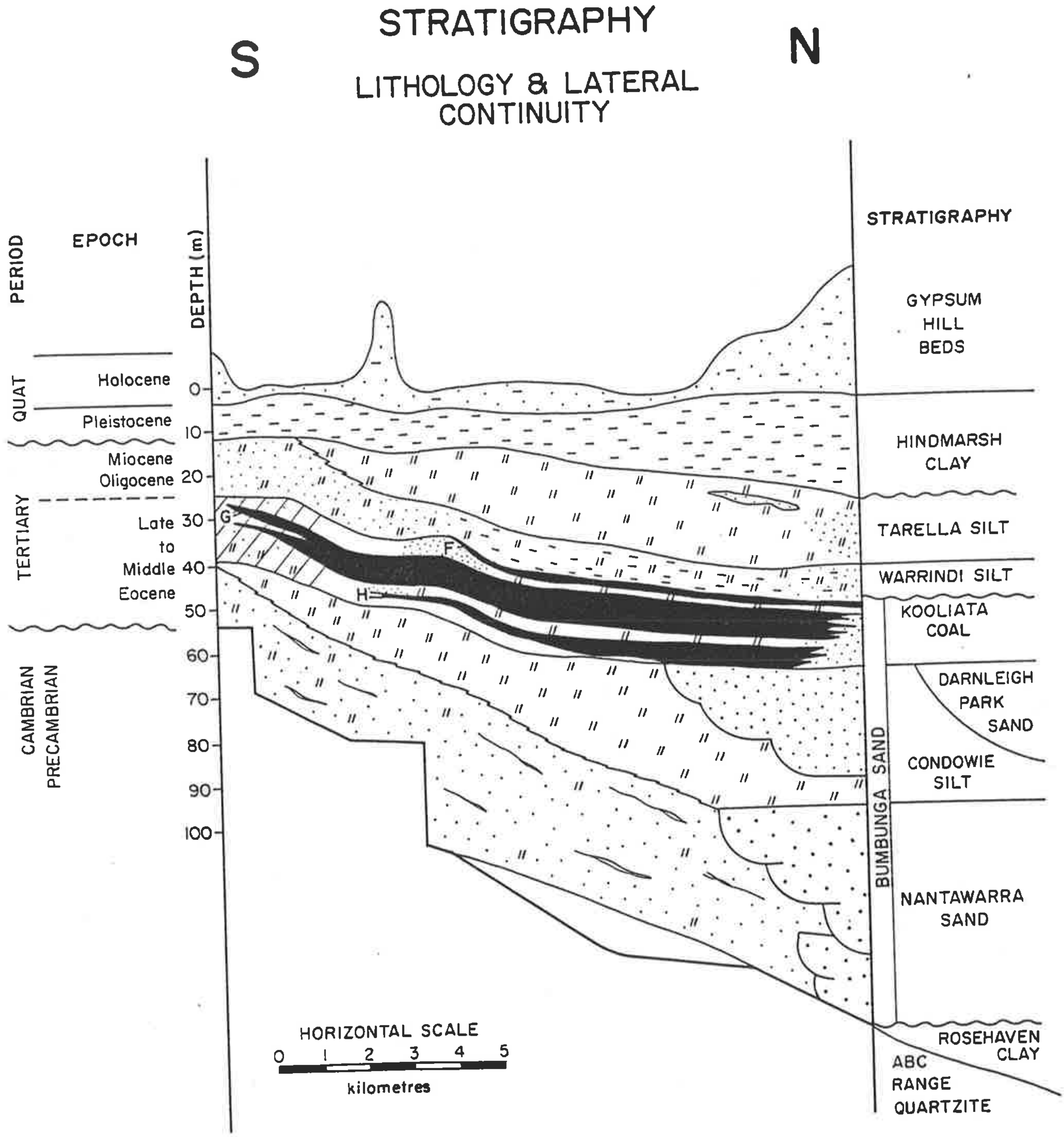


Figure 3.3 Stratigraphy and lateral lithological variation for the Lochiel Coal Deposit

formation, it is not appropriate to include analysis of this unit in this study.

3.3.2 Summary of engineering properties

The properties of materials present in the Lochiel Coal Deposit are summarised on Table 3.1.

The properties of the stratigraphic Formations can be stated as follows :

- Tarella Silt - Firm to hard, highly carbonaceous clayey silt of low to high liquid limit. Moisture content greater than plastic limit.

- Warrindi Silt - Firm to hard, clayey silt, sandy clayey silt of low to high liquid limit. Moisture content greater than plastic limit.

- Bumbunga Sand :
  - F Zone and H Zone - Stiff to hard carbonaceous sand.
  - Coal seams - Stiff to hard coal.
  - Condowie Silt - Firm to very stiff clayey silt and silty clay of low plasticity and high liquid limit.

Stratigraphy	Moisture Content % Mean (Range)	Dry Density % Mean (Range)	Unconfined Compressive Strength (kPa) Mean (Range)	Intact Shear Strengths Mean c'(kPa)	 O'(Deg)	 Lower Bound c'(kPa)	 O'(Deg
Tarella Silt	57 (12 - 156)	1.0 (0.4 - 1.9)	244 (65 - 448)	65	26	33	22
Warrindi Silt	30 (16 - 81)	1.6 (1.3 - 1.8)	255 (67 - 548)	48	31	7	31
F-Zone	51 (12 - 130)	1.1 (0.7 - 1.8)	240 (60 - 380)	-	-	-	-
GH Interseam	46 (2 - 153)	1.1 (0.5 - 1.4)	286 (165 - 400)	-	-	-	-
H-Zone	58 (29 - 88)	0.9 (0.7 - 1.2)	317 (198 - 513)	-	-	-	-
Coal	126 (21 - 186)	0.6 (0.4 - 1.7)	400 (134 - 675)	174	26	122	26
Condowie Silt	46 (24 - 103)	1.2 (0.8 - 1.4)	281 (104 - 375)	85	22	54	22

TABLE 3.1 Summary of engineering properties of sediments occurring in the Lochiel Coal Deposit (summarised from tests performed for ETSA by Coffey and Partners 1987).

3.3.3 Modes of failure

Two modes of failure were analysed for highwalls in the Lochiel Coal Deposit, circular and non-circular (plane failure). Non-circular failures were found to have the lowest factor of safety for a particular slope (Coffey and Partners Pty Ltd, 1988a) and, therefore, non-circular failures are the focus of this thesis.

The engineering geological factors affecting slope stability in the Lochiel Coal Deposit are illustrated on Figure 3.4. This model was developed from analysis of failures within the Trial Pit (Plates 3.1 and 3.2).

The key factors affecting the mode of non-circular failures were considered to be the ;

- shear strength and orientation of near horizontal weak zones,
- porewater pressure (effective stress)
- location and orientation of tensional joints.

- **Stratigraphic location of weak zones and porewater pressure**

Figure 3.5 summarises the stratigraphic location of the weak zones as well as the porewater pressure profile. Two types of weak zone were identified, both relating to sedimentary horizons and both being characterised by the presence of a shear zone.

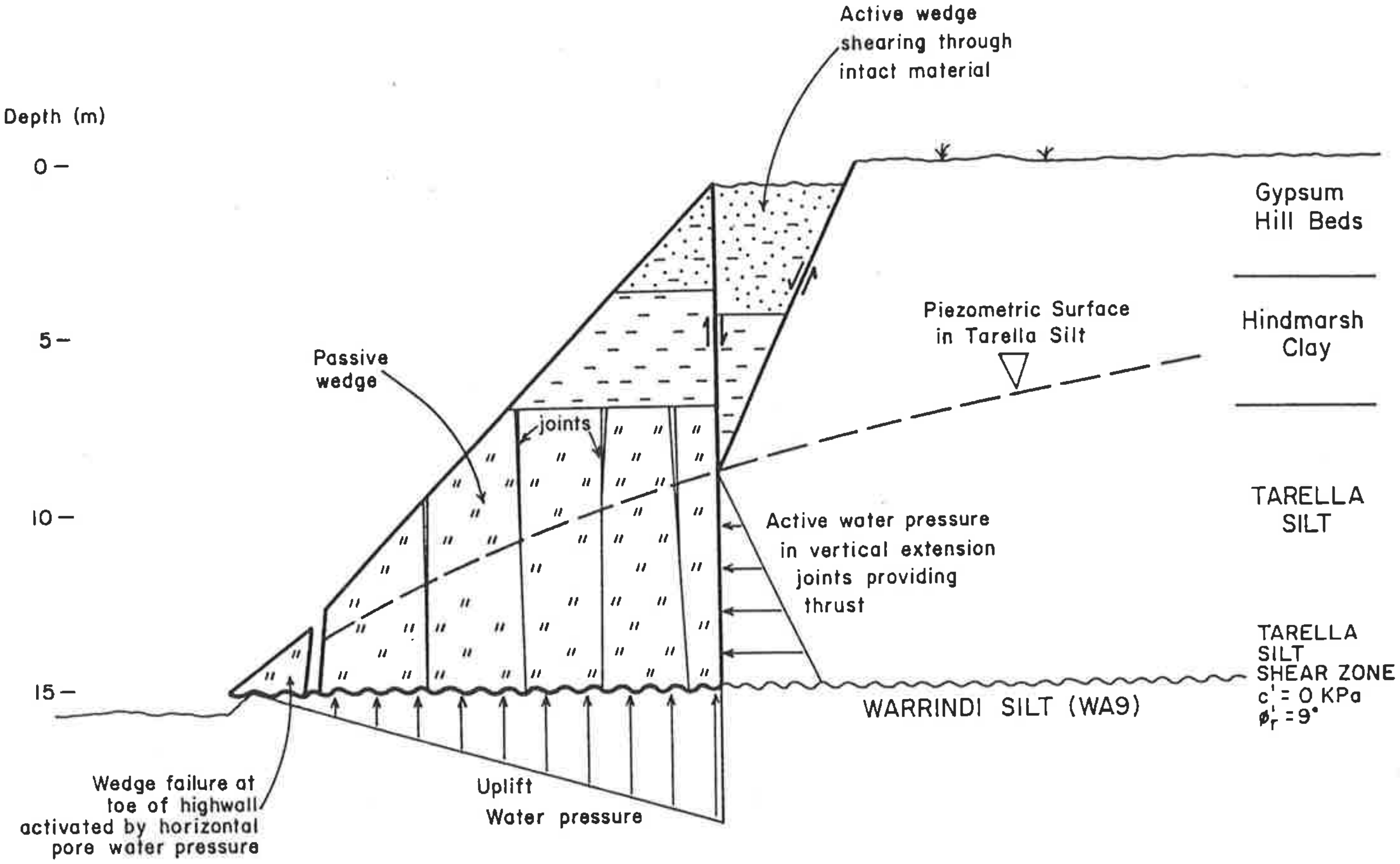


Figure 3.4 Relationships between the key factors affecting slope stability for the Lochiel Deposit Trial Pit site.

3.3.4 Mechanisms causing failure

The Lochiel Coal Deposit is subject to artesian groundwater pressures which tend to lower the effective stress, adversely affecting mine slope stability.

It is common practice in mines with high porewater pressure to increase effective stress by lowering the porewater pressure. The method which is used is to pump porewater from bores at a rate greater than it can be recharged. This reduces the porewater pressure of the sequence with the piezometric surface usually taken down to the level required to maintain a stable slope.

In the Lochiel Coal Deposit the high porewater pressure necessitates depressurisation of the fine grained sediments (silts and clayey silts) and dewatering/depressurisation of the coarser grained units (sands and gravels).

The geological factors affecting the dewatering/ depressurising of sands are relatively well understood. The geological factors relate mainly to grain size and soil structure.

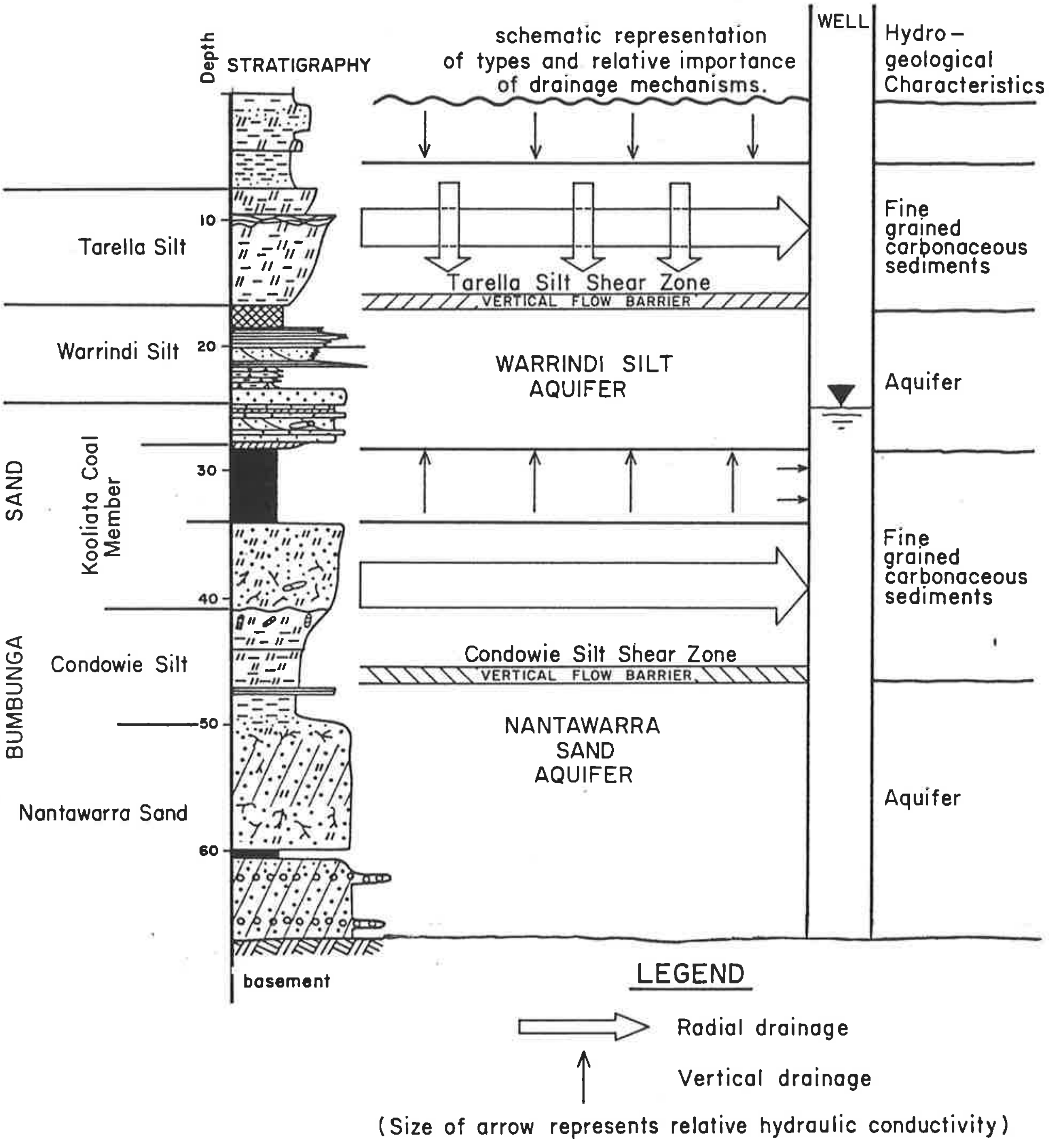
On the other hand, it is not common practice to attempt to depressurise fine grained sediments such as silts. In fact, conventional thinking at the time that the Lochiel Coal Deposit was being evaluated was that fine grained sediments, such as those occurring within the overburden at Lochiel, could not be economically depressurised within the time limits imposed by the mine's coal schedule.

As discussed by Coffey and Partners Pty Ltd (1988b) and illustrated on Figure 3.5, porewater pressure in fine grained sediments (silts) is controlled by two mechanisms;

1. Radial drainage towards the pump or drainage well through aquifers (zones of relatively high permeability such as sands);

2. Vertical drainage to an aquifer and then radial drainage towards the pump or drain.

Figure 3.5 Radial and vertical drainage mechanisms and their relationship with pumping bores.



A number of tests were undertaken within the Lochiel Coal Deposit to examine the response of the fine grained sediments to depressurisation through pumping from wells. The effect of pumping on the porewater pressures within the sediments is illustrated on Figure 3.6.

It became apparent from these tests that the porewater pressure of the majority of the fine grained sediments could be lowered within a reasonable timeframe. However, within the sequence there were several relatively impermeable zones which determined the rate at which the sediments could be depressurised. Of particular significance is that the impermeable zones are the weak zones described above. As further evidence of the affect of these weak zones on vertical drainage it was observed in the Trial Pit that water accumulated and run out from directly above these weak zones.

3.4 Review of engineering properties

3.4.1 Intact material strength

Shear strength is defined by the Mohr-Coulomb Law as described in Section 3.2, page 49. The fundamental components of shear strength are effective normal stress, cohesion and friction angle. As described on page 50, effective stress parameters are a function of both normal stress and porewater pressure. To evaluate what constitutes a significant effective stress parameter, shear strength may be viewed as related to two

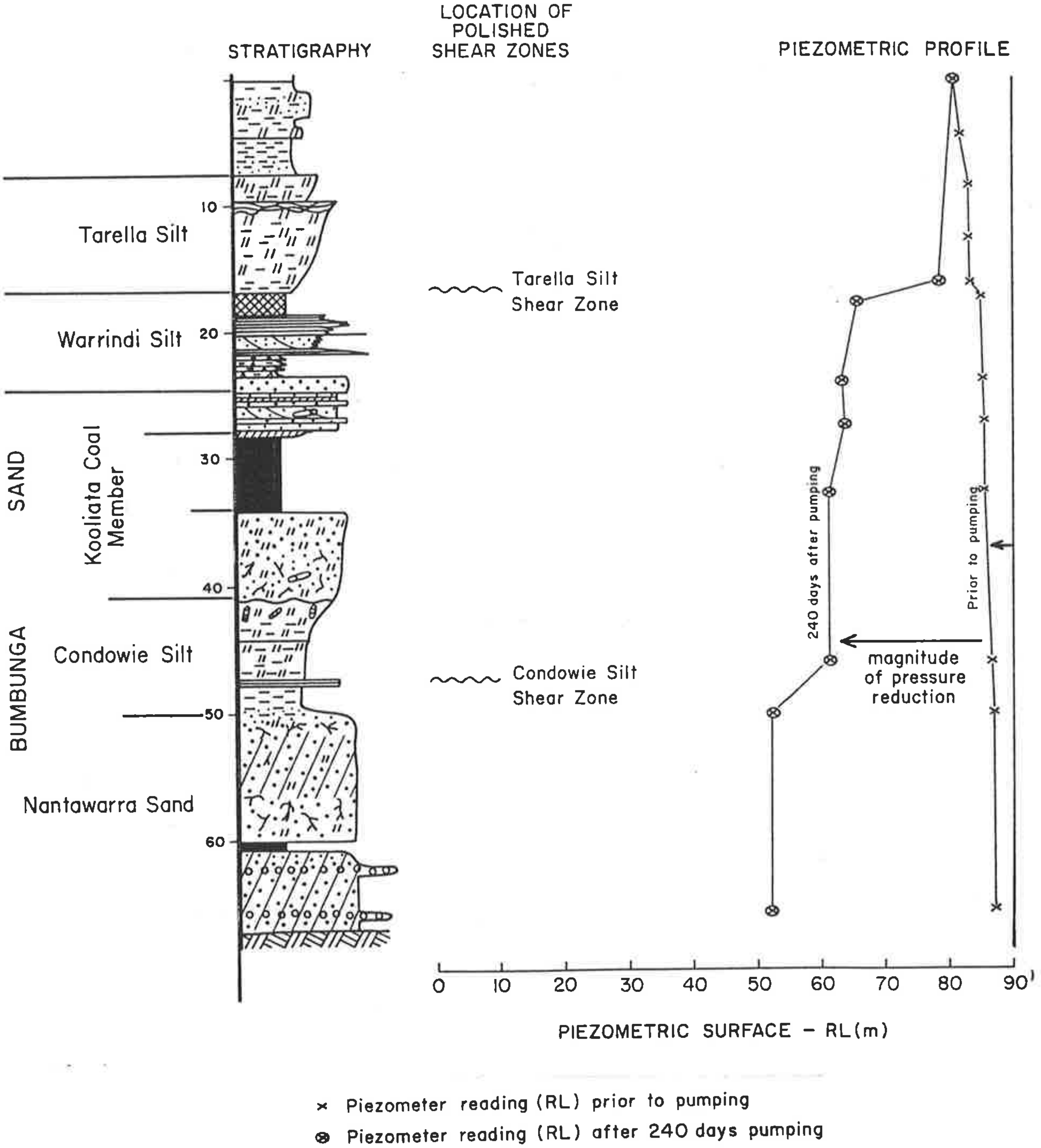


Figure 3.6 Stratigraphic location of weak zones and their relationship with rates of dewatering/ depressurisation.

basic components, physical and physio-chemical. For cohesive soils (such as most fine grained clayey soils) the physical components of shear strength arise primarily from the resistance to relative movement of sliding of one particle over another and, to interlocking between particles (Young and Warkentin, 1975). Rosenquist (1955) divided the interlocking phenomena into macroscopic and microscopic.

Macroscopic interlocking is important for granular (i.e. sandy) soils where appreciable movement of granular particles normal to the failure plane is required.

Microscopic interlocking is crucial for fine grained (clay) soils where small movements can result in alignment of particles parallel to the failure plane. This study is concerned mainly with the shear strength of fine grained soils and the following section concentrates on the aspects related to shear failure of these.

3.4.2 Physical components of shear strength in fine grained soils

For the purposes of examining the major factors affecting shear strength, fine grained soils can be viewed as consisting of two types of particles; discrete minerals and bonded sets of discrete minerals. Conceptually, shear strength of fine grained soils is comprised of an interaction of particles through an absorbed particle layer (cohesion or physio-chemical interaction) and also the interaction directly between particles (physical interaction).

- Cohesion

When two particles are brought into contact under stress, the close proximity of contacting areas results in adhesive or frictional resistance due to the electrical forces of attraction. However, in a clay-water system the interaction of clay particles and fabric units with water is such that there may be little actual particle-particle contact. In these soils, cohesion is a component of shear strength which arises mainly from the interaction of clay particles through the layer of absorbed water and through diffuse layers of exchangeable cations.

- Direct particle contact

During shear, particles and fabric units in the failure plane become oriented parallel to each other. At shear, the soil particles are arranged to give a minimum particle interference and this is best accomplished by a parallel arrangement at or near the failure plane.

This concept is reinforced by stress-strain relationships developed after failure. Typically, the stress-strain relationship is characterised by a peak stress required to cause failure and then once failure has occurred a lesser stress is required to cause movement along the failure surface. The latter state is referred to as the residual shear strength (Skempton, 1964).

In cases where the soil has previously been sheared the stress-deformation curve may not exhibit a peak. This is the case for the shear zones occurring in the Lochiel Deposit.

3.4.3 Residual angle of friction vs mineralogy and grain shape

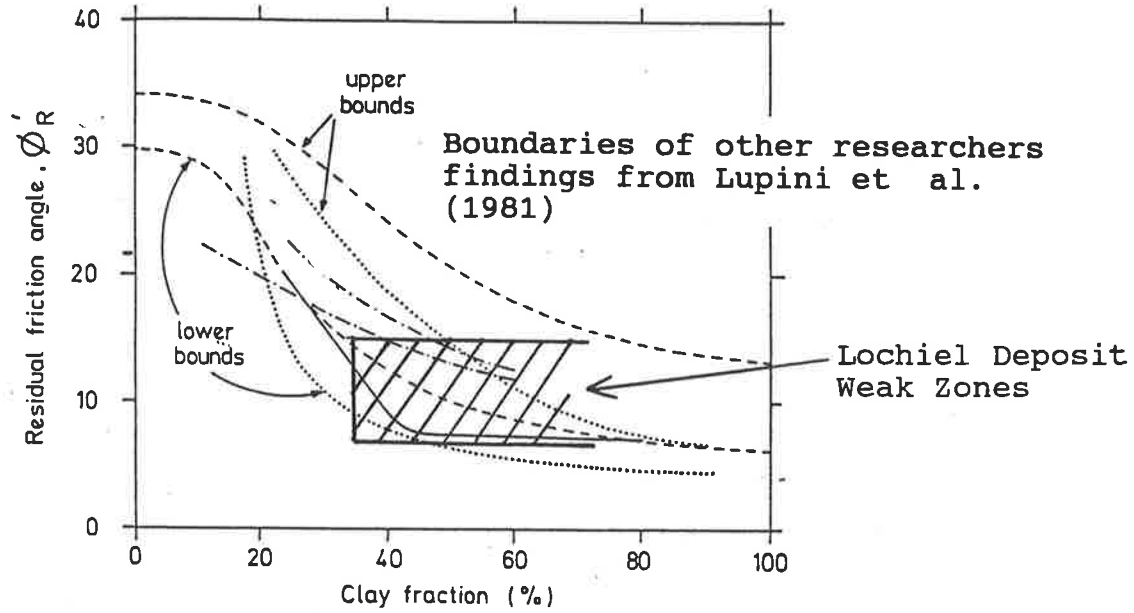
Mitchell (1975) found from tests relating residual strength to particle shape that low residual friction angles were associated with platy particles (clays), with angular and rod-shaped particles giving higher residual friction angles.

Lupini et al. (1981) investigated residual shear behaviour using thin section and electron microscope techniques and recognised three modes; turbulent, transition and sliding, depending mainly on the dominant particle shape and on the mineralogy (coefficient of interparticle friction).

Turbulent shear occurs with essentially granular soils and is characterised by relatively high residual strength. The sliding mode is typical of clay soils and is characterised by low residual shear strength. The transitional mode occurs in mixtures of clay and granular particles.

Skempton (1964) first suggested that there was a general relationship between clay content and the residual angle of friction. This relationship is presented on Figure 3.7 and illustrates a gradual increase in residual strength with decreasing clay content.

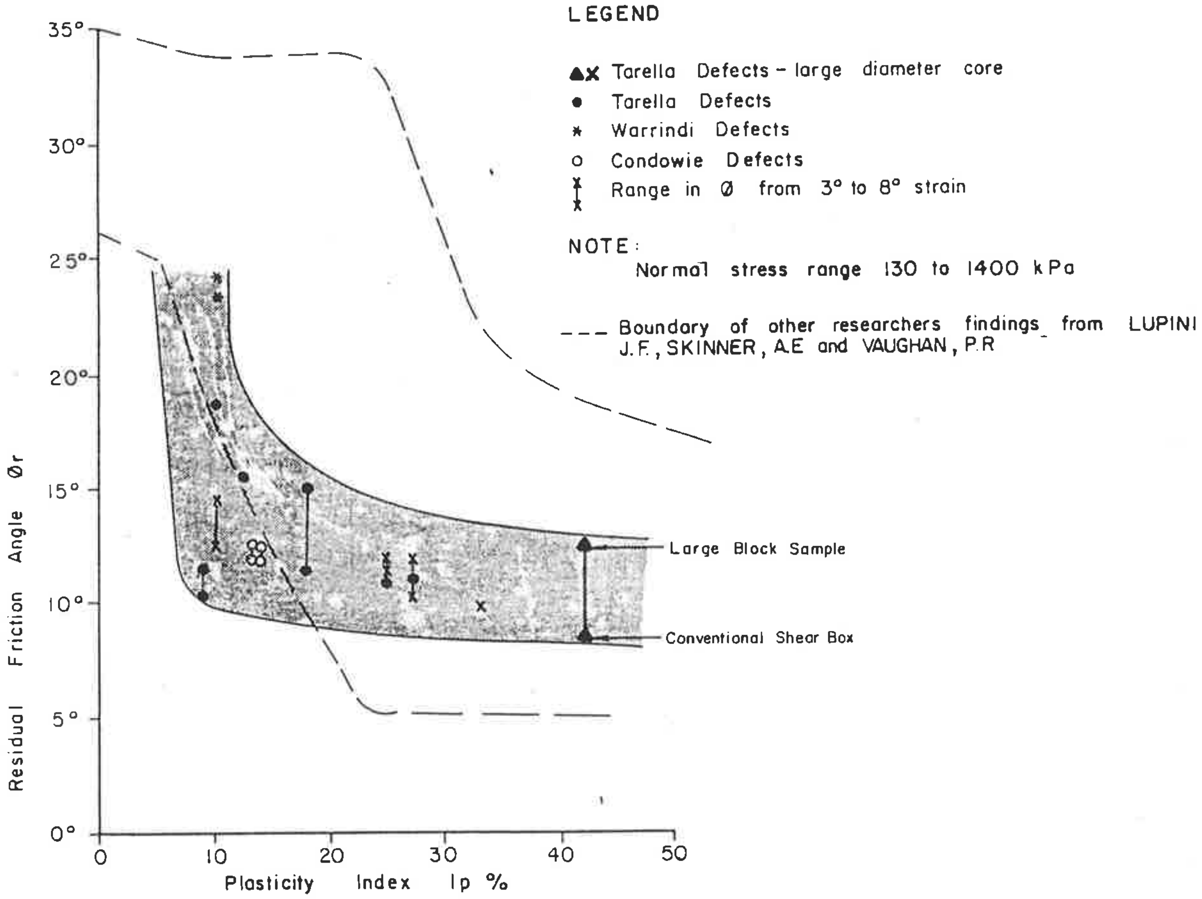
Figure 3.7 Relationship between residual friction angle and clay fraction (modified after Lupini et al. 1981).



Vaughan and Walbanke (1975), as reported in Lupini et al. (1981), postulated a discontinuous relationship between residual friction angle and Plasticity Index (Ip) (Figure 3.8).

They postulated that the controlling factor was likely to be related to the proportion of platy clay minerals present and that this would correlate with Ip for clays of similar activity. Bucher (1975) also found a similar relationship between Ip and residual friction angle and Seycek (1978) after performing his own tests and summarising the work of others reported that there was a better correlation between residual friction angle and Ip than any other parameter.

Figure 3.8 Relationship between residual friction angle and plasticity index for the Lochiel Coal Deposit (modified after Coffey and Partners 1985).



In summary, the proportion of clay minerals and their mineralogy have a major affect on the residual shear strength and this relationship is likely to be reflected in the plasticity indices.

As illustrated on Figures 3.7 and 3.8 these relationships are found to hold for the weak zones occurring within the study area. A summary of results of Atterberg, total organic carbon, XRD and moisture content tests for the Tarella Silt is provided on Figure 3.9.

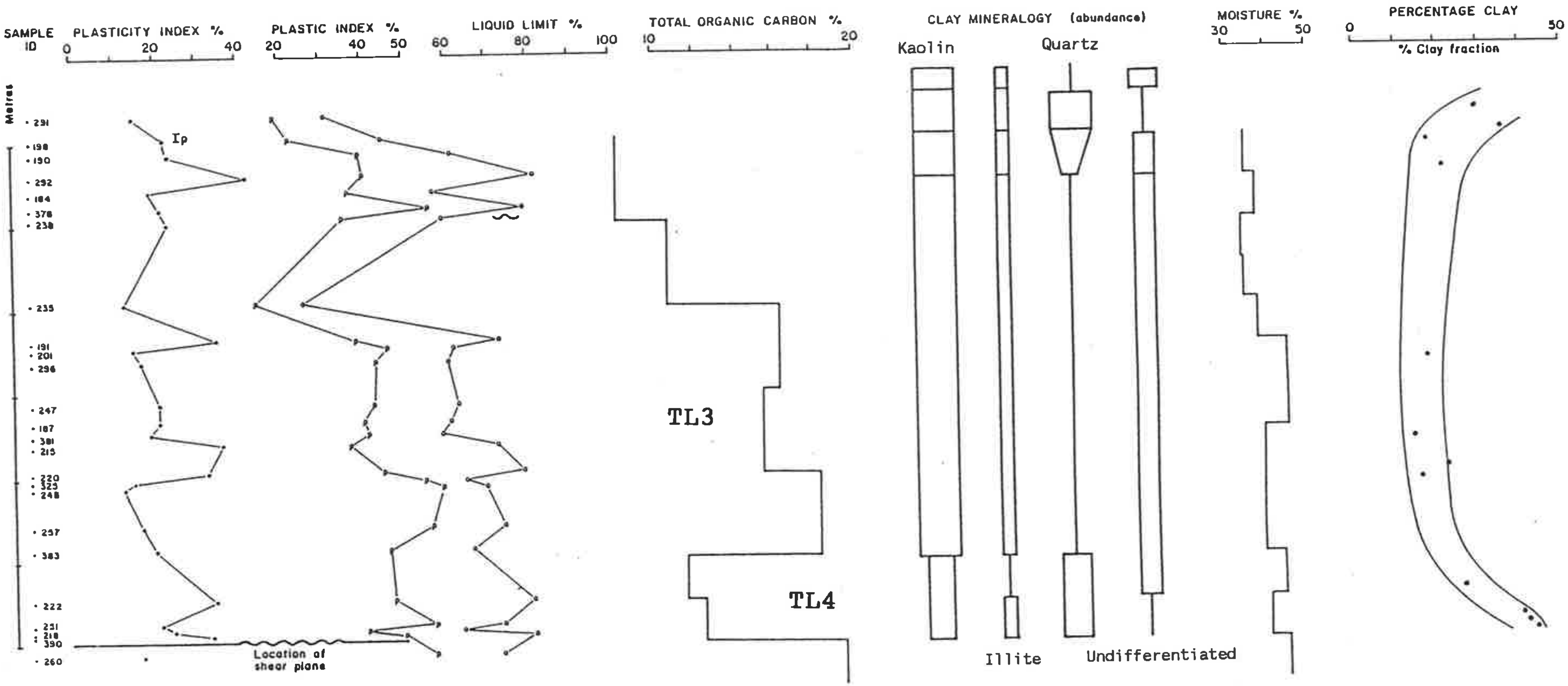


Figure 3.9 Summary of results of Atterberg, XRD, total organic carbon, clay mineralogy, moisture content and percentage clay fraction tests for the Tarella Silt.

- Directional properties

Bishop et al. (1966) from extensive tests on London clay concluded that both peak and residual strengths were approximately constant whether samples were cut across or parallel to bedding. However, Barden (1972) from microscopic examination of London Clay considered that there was only a tendency to horizontal orientation so Bishop's findings may not be applicable to clays with a strong tendency for preferred orientation.

It could be reasonably expected that the peak strength of clays may vary in strongly oriented samples, however, the residual strength is an intrinsic property and thus independent of directional properties. James (1971), however, tested samples of Oxford Clay and reported repeatedly higher residual strength for samples tested perpendicular to dip direction compared with those parallel. He suggested that particle orientation resulting from depositional characteristics or the consolidation of the formation has an important bearing on the path to the residual in any particular direction.

- Summary

The clay content, clay mineralogy and to a lesser extent directional properties have a significant impact on shear strength. The characteristics of each of these properties can be related to geological processes and are, thus, within the scope of this study. However, the primary objective of this thesis is relates to the modelling of the key factors affecting slope stability rather than the actual properties of these factors. In line with this the characterisation of these properties is considered to be a minor or supporting objective of this study.

3.5 Discontinuities and weak zones

Discontinuities and weak zones in soils can be related to two basic types of geological processes :-

- Tectonic,
- Sedimentary.

3.5.1 Tectonic discontinuities

Tectonic discontinuities are those produced by the progressive deformation of the intact soil when subjected to external stresses.

Specific studies on tectonic processes forming soil structures are limited. Based on analysis of the geometry and type of defects in a stiff, overconsolidated Siwalik Clay, Fookes (1965) and Fookes and Wilson (1966) postulated that their formation was controlled by folding due to basin subsidence, leading to the development of shear stresses in the more competent beds.

Similarly, Sullivan (1982) in his study on the origin of defects in heavily overconsolidated clays and oil shales, concluded that soil macro-structure is related to basin folding.

. Characteristics of tectonic discontinuities

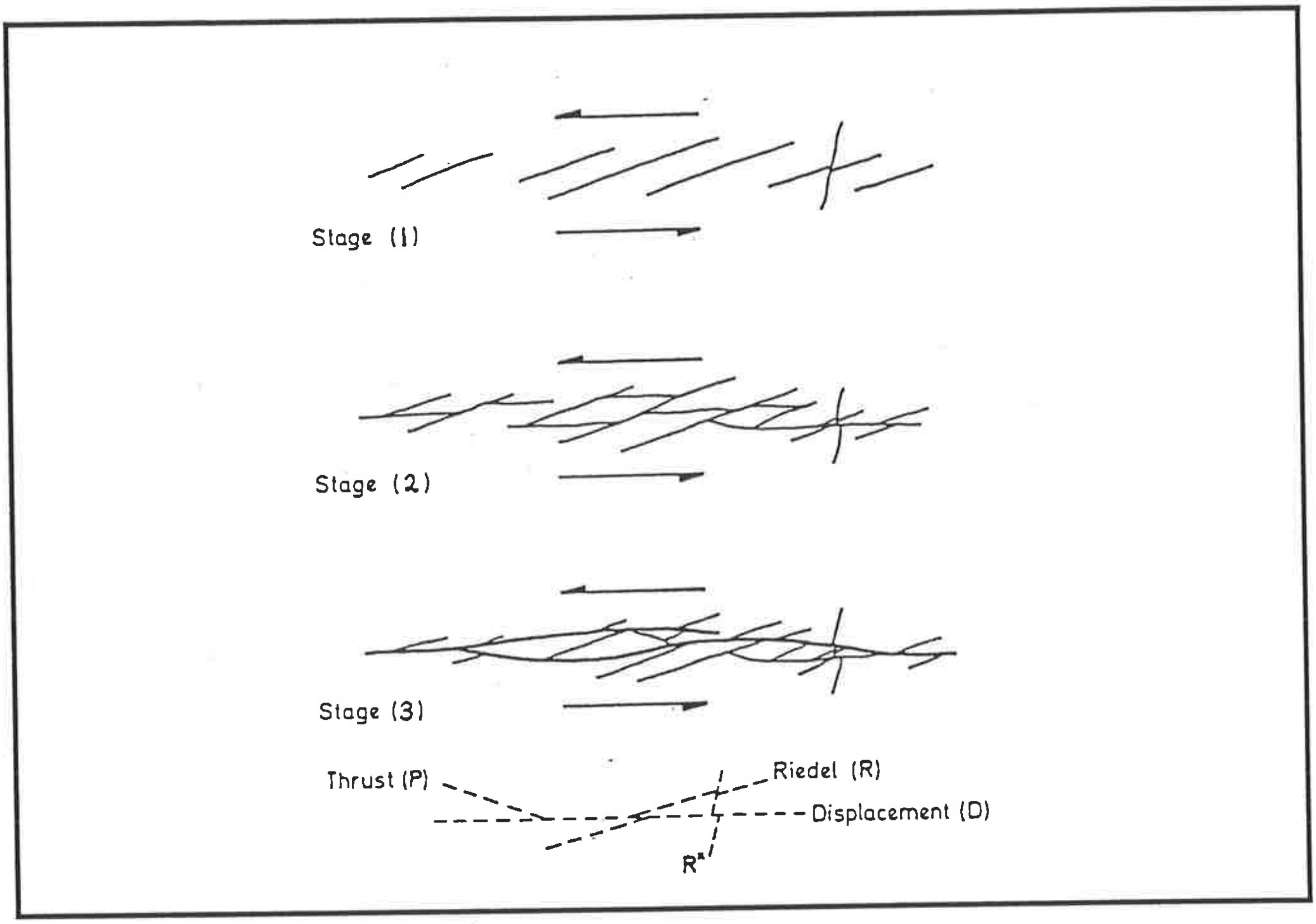
Skempton (1966) defined a shear zone as consisting of single or multiple discontinuities along which a finite shearing has taken place. Tchalenko (1970) compared the morphology of different magnitudes of shear zones and Morgenstern and Tchalenko (1967a,b) compared shear features of experimentally deformed kaolin with regard to the primary fabric. Each of these studies found that both the same types of defects and similar geometric relationships existed.

The development of shear stresses leads to the progressive development of shear defects in the soil. Based on direct shear and microscopic test observations, Morgenstern and Tchalenko (1976) described three stages of formation of shear zones as shown on Figure 3.10.

3.5.2 Sedimentary weak zones

Weak zones are characterised by having a relatively high clay content in contrast with the surrounding sediments. These clay-rich zones form from clay settling from suspension in standing bodies of water. Furthermore, it has been shown by Staub and Cohen (1978) that clays flocculate rapidly when they come into contact with high acidity waters which are characteristic of coal forming depositional environments.

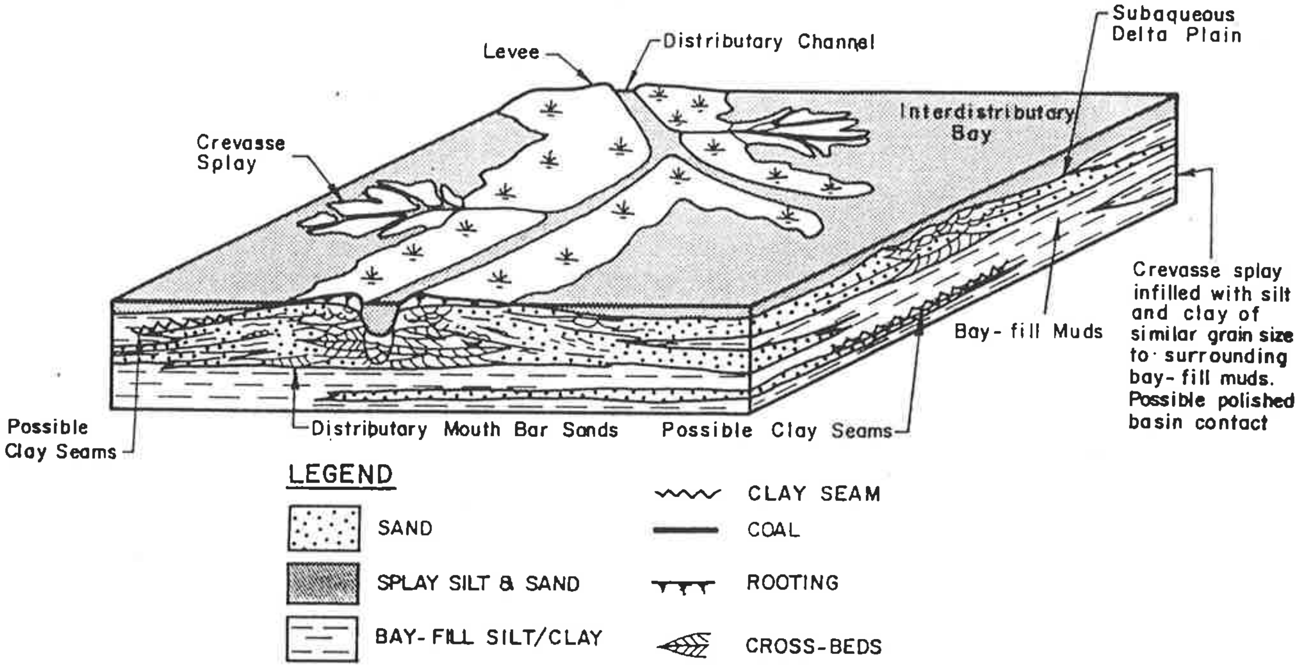
Figure 3.10 Discontinuities associated with tectonically formed shear zones (after Skempton,1966).



The geometry of the clay seams is related to the geometry of the surface on which they were deposited and on the effects of differential compaction.

Clay seams can theoretically form as conformable beds within both progradational and aggradational sequences or as disconformable beds draped over erosional surfaces. These depositional locations are illustrated on Figure 3.11.

A PROGRADATIONAL ENVIRONMENT



B AGGRADATIONAL ENVIRONMENT

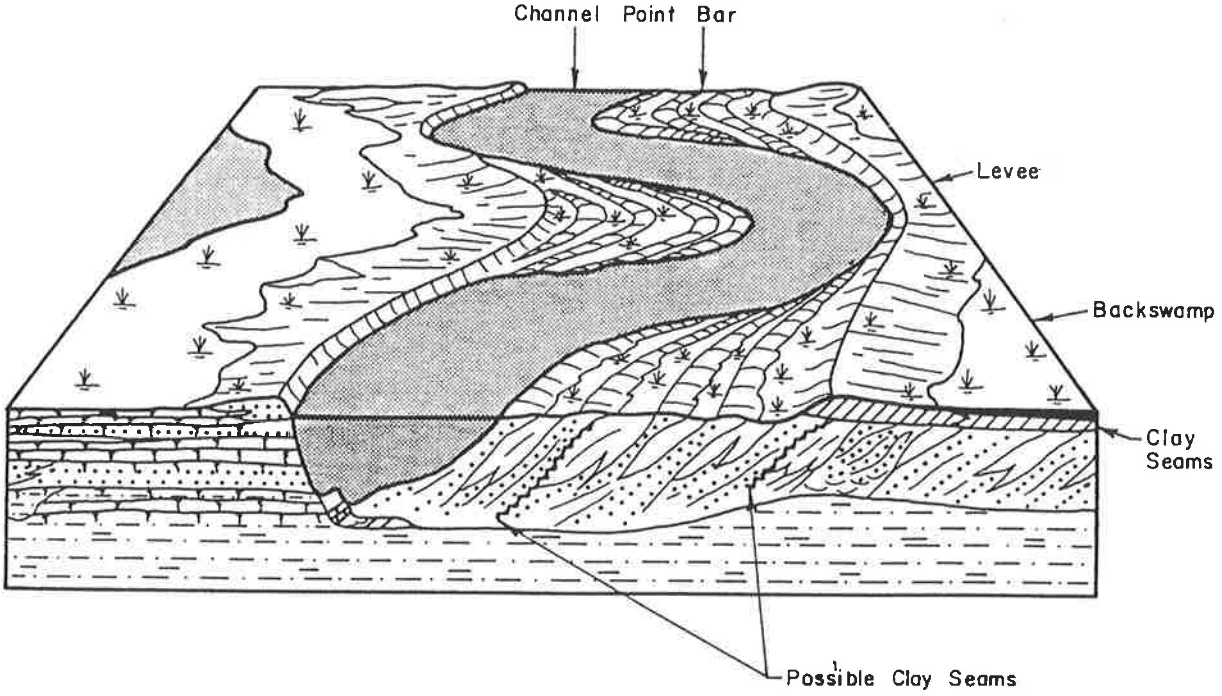


Figure 3.11 Locations of weak zones in progradational and aggradational sequences (modified after Ferm and Horne, 1979).

- Progradational clay seams

For progradational sequences such as crevasse splays and fan deltas or tidal deltas, clay deposition is most likely to occur either at the waning stages of particular depositional episodes (i.e. at the top of a sedimentary cycle) or at locations distal from the sediment source, refer to Figure 3.11A. These two processes have implications for the location and geometry of the clay seams with two types of clay seam being possible.

First, thin beds of clay deposited between two sedimentary cycles. The lateral continuity would be largely determined by the presence and location of the lake/swamp/marsh which covers the area.

Second, clay-rich sediments deposited at distal locations within the basin. Because these form as part of an actively prograding sequence, the location, thickness and extent are largely determined by the nature of the sediment source. When the sediment supply is constant in volume and mineralogy, then the prograding sequence would form a zone of clay-rich sediments at its base and this zone is likely to be both laterally continuous and extensive.

- Aggradational weak zones (refer to Figure 3.11B)

Because deposition of clay relies on still or almost still water, clay seams in aggradational sequences such as those deposited by fluvial processes rely on a mechanism which produces episodic or cyclic water movements. The most striking example of this are sequences formed within the tidal range.

Clay seams are deposited on point bars during high and low tide and characteristically form "bundles" of clay seams separated by sand. A variation to these occurs when a meander channel is cut off and is filled with fine grained sediments. Both of these types of sequence are common to the sequence occurring in the Athabasca Tarsands in Canada (MacCallum et al., 1979).

For the purposes of this study the conclusion is that the geometry and lateral continuity of clay seams are controlled by the depositional environment.

3.6 Porewater movement

The key information required on the hydrogeology is on the hydraulic properties of the sediments and their variation within the deposit. For soils, the hydraulic properties are controlled by grain size and soil structure/soil fabric. For soil stability analysis, particle size distributions are used to given indications of permeability, capillarity and likely material behaviour.

A summary of the grain size analysis and well test results for the Lochiel Coal Deposit are provided on Figures 3.12 and 3.13. For sand and gravel soils, the shape of the grading curve can be useful to determine some aspects of engineering behaviour. A smooth curve indicates a well graded soil in engineering terms (poorly sorted in geological terms) and hence unlikely to be subject to reduction in volume due to vibration or washing out of the finest fraction. If the soil is to be used as a drainage layer then a uniform particle size distribution (well sorted) would indicate highest porosity and permeability.

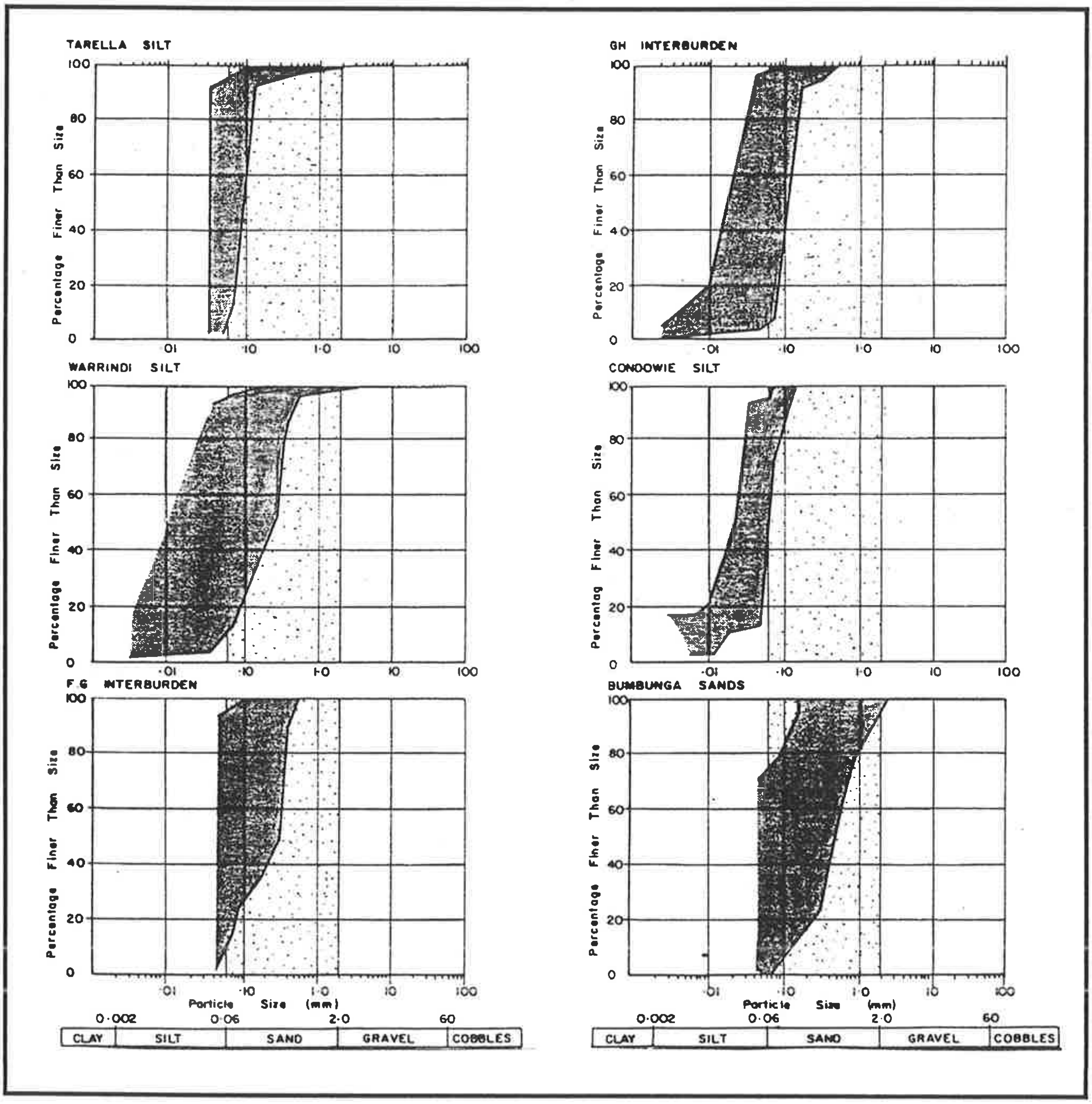
Sedimentary soil deposits are likely, however, to show marked variation between horizontal and vertical permeability due to stratification and grain fabric. Lambe and Whitman (1969) and Bolton (1984) considered that the use of particle size distribution for fine grained soils is questionable because the chemical and mechanical treatment given for the analysis usually results in effective particle sizes which are quite different to those of natural soils.

Rowe (1972) demonstrated by tests on silty clays that soil structure can give in situ permeabilities 100 - 1 000 times higher than remoulded samples. He emphasised that gradings and index tests alone are not indicative of engineering performance.

As discussed by Pettijohn et al. (1987), there is nearly always a good correlation between effective porosity and permeability within a facies but not between facies. This is because permeability is related to specific surface area so that two facies of differing grain size may have equivalent effective porosity but the finer facies will have a lower permeability.

With respect to porewater movement the conclusion is that it is essential to first understand the facies characteristics and relationships before interpreting the results of grain size analysis.

Figure 3.12 Summary of grain size analyses for sandy sediments occurring within the Lochiel Coal Deposit. (GH and FG interburden are discussed in section 5.4 and represent intercalations between the coal seams).



Hole No.	Stratigraphy	Aquifer Thickness (m)	Hydraulic Conductivity ($m^3/day/m^2$)	Transmissivity ($m^3/day/m$)
V 572	Tarella Silt - TL1	3.3	2.1	7.0
V 611	Tarella Silt - TL1	2.1	6.7	14.0
V 533	Warrindi Silt - WA2	3.3	2.1	7.0
V 623	Warrindi Silt - WA10	2.3	32.0	73.0
V 437	Warrindi Silt - WA4	2.5	3.0	7.5
V 627	Kooliata Coal - FG	0.7	7.1	5.0
V 620	Bumbumga Sand - NS2	13.5	2.3	31.0
V 629	Bumbunga Sand - NS2	6.8	2.9	20.0
V 614	Bumbunga Sand - NS1	15.8	3.9	61.0
V 613	Bumbunga Sand - NS3	3.0	2.3	7.0
V 611	Darnleigh Park Sand	4.0	40.0	160.0
V 640	Bumbunga Sand - NS1	30.0	13.0	400.0
V 630	Bumbunga Sand - NS1	20.0	8.0	160.0

Figure 3.13 Summary of well test results (see Appendix 6 for location of test sites.)

CHAPTER 4.0 METHODOLOGY AND DATA AVAILABILITY

The methodology applied to the analysis of the Lochiel Coal Deposit relies on the integration of geological and engineering interpretation techniques. The interpretation is based on a number of differing data types and the limitations on these need to be reviewed prior to detailed analysis.

The analysis to follow is supported by a series of Tables and Figures. These are included in the text when they are considered to be of direct support to the analysis.

There are, however, a number of figures which either provide more detail on the figures included in the text or provide indirect support to the analysis. These figures are set out in a series of appendices in Volume II. These include;

Appendix 1	Photographs referred to in Volume I.
Appendix 2	Geophysical log response models for the Bumbunga Sand Formation.
Appendix 3	Geophysical and lithological correlation sections for the Bumbunga Sand Formation.
Appendix 4	Geophysical and lithological correlation sections for the Warrindi and Tarella Silts.
Appendix 5	Structural analyses for the Tarella Silt.
Appendix 6	Borehole location plan.

4.1 Data availability and limitations

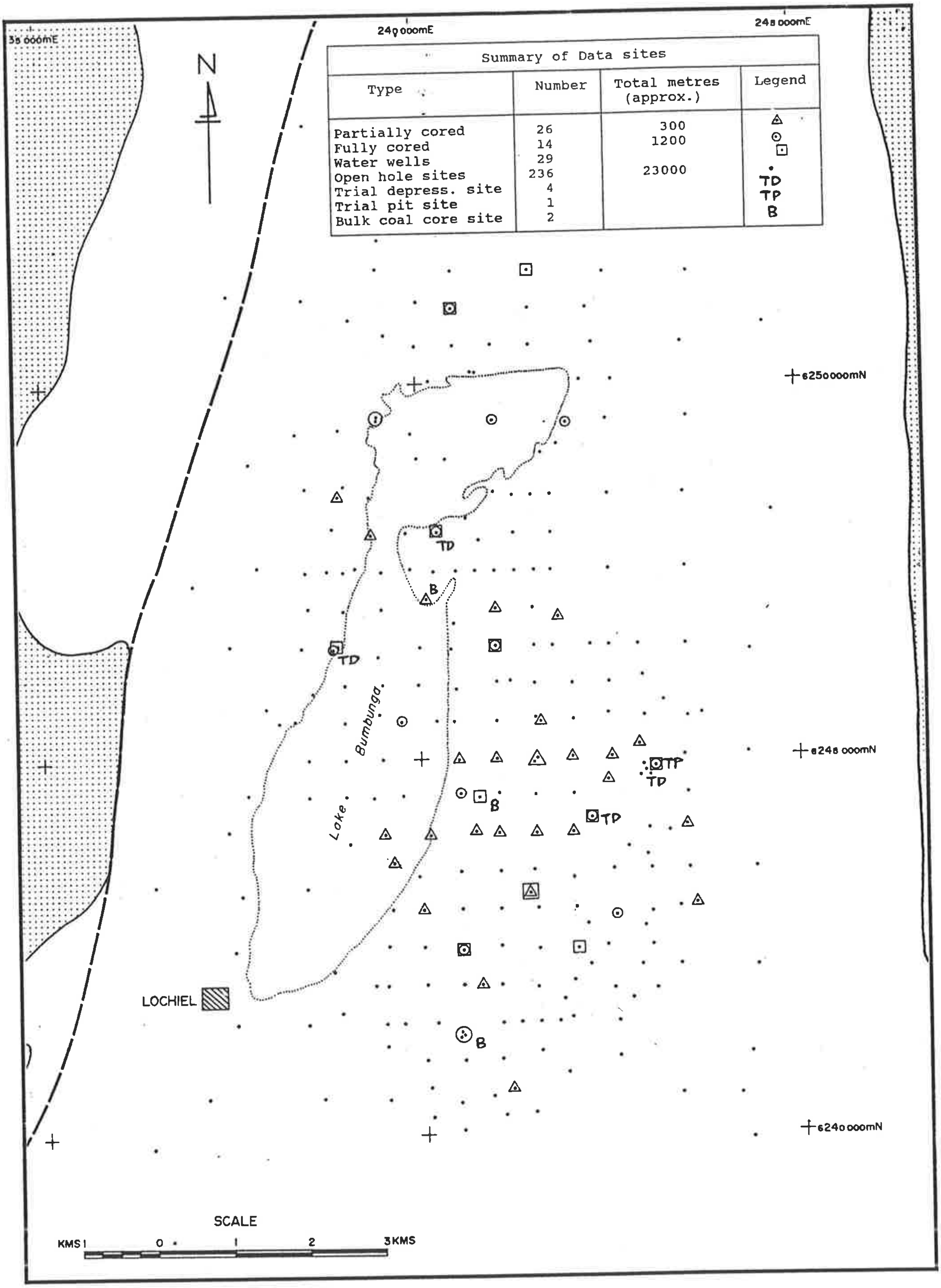
Unconsolidated sedimentary deposits, such as Lochiel, are generally flat lying with few or no surface exposures. In these settings subsurface methods of obtaining data are used. Four types of data are available for the study of the Lochiel Coal Deposit :-

- Drillholes - cuttings and core,
- Geophysical downhole logs,
- Hydrogeological test sites,
- Trial excavations.

A summary of both the number and types of data collection sites used in this study is presented on Figure 4.1 with a detailed borehole location plan available in Appendix 6.

These data types are the fundamental source of all information on the geological and engineering characteristics of the sediments. Furthermore, these types of information are also generic to other soft brown coal deposits.

However, it is important to realise that even in the design stage, the spacing of data points in the deposit will be relatively broad, especially when compared to the geometry of the operating pits and of significant engineering geological features. To compound this limitation, the engineering and hydrogeological test sites make up only a small percentage of the total number of data points (for



Summary of Data sites			
Type	Number	Total metres (approx.)	Legend
Partially cored	26	300	△
Fully cored	14	1200	⊙
Water wells	29		⊡
Open hole sites	236	23000	•
Trial depress. site	4		TD
Trial pit site	1		TP
Bulk coal core site	2		B

Figure 4.1 Summary of number and types of data collection sites

Lochiel, fully cored geotechnical holes make up less than 5% of the total number of holes drilled).

- Drillholes

Apart from when a trial excavation is undertaken, drillholes are the only means of obtaining subsurface material for engineering testing. Drillcores of diameter up to 0.9 metres can be obtained but generally diameters of 0.063 and 0.100 metres are recovered.

Apart from the limitations concerning the spacing of data points, a significant limitation with having to rely on drillcores for samples in unconsolidated sediments is that parts of the sequence are often missed due to core losses. This factor can have an significant impact especially if the lost section contains a significant feature such as a weak zone.

Almost all of the holes drilled are vertical thus limiting the effectiveness of obtaining data on steeply dipping tectonic defects. A possible solution to this is to drill inclined holes, however, as the tectonic structures in soft sedimentary environments are difficult to distinguish even in exposed faces, angle holes will provide little additional data, especially if they are not oriented.

- Geophysical borehole logs

Geophysical borehole logs are used extensively in the petroleum industry for the quantitative analysis of material properties. Some geophysical logs are also used to characterise physical rock properties (Mathewson and Cato, 1986). However, the application of quantitative interpretation techniques to engineering geological aspects of soils is largely impractical because :-

- of the nature of the properties being measured. Most defects cannot be detected from the tools currently available. In ideal conditions (where there is a contrast in material types) the tools currently available can detect features down to 50 mm thick. In the Lochiel deposit, the sub-horizontal defects are mostly less than 10 mm thick, with little contrast in material type.

- of the strength of both the intact soils and the defects are in general so low as to be out of the normal operating range of the sonic tools.

- drilling in unconsolidated sediments is normally done by rotary mud techniques. The technique cuts and flushes the soils often resulting in holes of uneven diameter and mudcake thickness. This effect is further compounded when drilling takes place in areas of high artesian pressure, such as at Lochiel, because the additives which are included to control the flow of water can invade the formation to give inaccurate tool responses.

> These problems can be overcome by modifying the drilling technique and enhancing the capabilities of the logging tools and their processing. However, these solutions are relatively expensive and rarely employed.

Notwithstanding these limitations, and because geophysical logs are normally available for every drillhole, the geophysical logs can be a prime source of data for geological stratigraphic interpretation.

To minimise the limitations described above, a suite of logs have been used as the basis for interpretation.

A set of typical log signatures are defined for the various sedimentary facies. These signatures are based primarily on the responses of the gamma-gamma density, neutron and natural gamma tools and were derived from detailed correlation of geophysical log responses to 8 fully cored drillholes (approximately 700 metres of core). Detailed core to geophysical log correlation sheets are not included in this thesis but are stored by Coal Resources Department, ETSA.

The geophysical signatures provide the means to interpret geophysically logged open drillholes. This interpretation forms the primary basis for correlating and mapping the sedimentary sequence around the deposit.

- Hydrogeological test sites

Four detailed tests were undertaken (including the trial excavation site) to obtain data on the rate and extent to which the porewater pressure could be reduced. These tests involved a pumping bore and a number of piezometers set in each of the major stratigraphic units.

Sites must be selected so as to be representative of the total deposit. This can be difficult to achieve especially early in the exploration and investigation programme because of the lack of information available for interpretation.

- Trial excavation (refer to Plate 4.1)

The Lochiel Trial Pit provided the opportunity for a 3-dimensional view of the relationship between sedimentary and structural features.

A trial excavation also has the advantages of being able to demonstrate the actual behaviour of the slope and allows for detailed analysis of the failure mechanism.

The major limitation of a trial excavation is that it provides data on only one site. Other limitations concern the geometry and timing of the excavation.

4.2 Methodology

The purpose of interpreting data is to produce predictive geological models which describe the key factors affecting slope stability. These models are then used by the geotechnical engineer to analyse the behaviour of the key factors when subjected to mining induced stresses. The purpose of this section is to :

- describe the interpretive methods in current use,
- describe the types of models produced,
- define the limitations of the methods and models.

For the interpretation to be effective, the elements of the model must have significance to the context of the objectives of the study. The key factors for the geological, geomechanical and hydrogeological aspects have been described previously and the following discussion will examine how well the methods of interpretation and the models address these factors.

4.2.1 Principles of geological interpretation and modelling

Geological interpretation relies on an understanding of geological processes and the outcomes of these processes, or in the words of Stapledon (1979) "finding out what's down there by understanding how it got there". Further, he stated that "without (an) understanding of the geological environment we are unlikely to ask the right geological questions, that is the geological questions which are relevant to the geological environment and the proposed operation."

It is considered that these views capture the essence of geological interpretation. In sedimentary deposits, such as Lochiel, the processes are broadly controlled by the depositional environments present at the time of sedimentation and by the processes which deform the sediments subsequent to deposition.

A principle around which this thesis is developed is that an understanding of these processes will facilitate the prediction of the key factors affecting slope stability.

- Key aspects of the geological interpretation process

The geological interpretation process involves a sequence of iterative steps during which the level of detail in understanding is progressively enhanced. The recognition of depositional facies relies on the experience of the analyst and in particular his or her knowledge of precedents. Numerous accounts of sedimentary facies in coal bearing environments currently exist and these can be used to provide additional detail.

However, because of the variations in the controls affecting the sedimentary processes, these precedents can only act as a guide to the detailed nature of the sediments.

When examining a deposit from an engineering viewpoint, and particularly for slope stability studies, it is common for these detailed features to be the key aspects. Hence, although the traditional methods employed by the environmental analyst can provide valuable information, it is unlikely to provide the key information unless the site specific controls on the process forming the features are understood.

a) Facies classification

The design of the facies classification system is critical for successful interpretation, and was stated by Lindholm (1987) as "one of the most difficult aspects of facies analysis...".

Lindholm (1987) and Walker (1984) emphasised that both the degree and scale of subdivision is governed by the objectives of the study. Further, the classification system should also be simple enough to allow easy understanding and use. In practical terms Anderton (1985) considered this to mean that the number facies be kept to a minimum. The only caveat is that the facies defined adequately encompass all rock types present in the study area (Miall, 1984).

Anderton (1985) and Lindholm (1987) considered that the classification system be designed in a hierarchial manner. Furthermore, the classification criteria selected should allow objective description and measurement to enable use by successive workers.

b) Cyclic sedimentation - Classification

Sedimentation within the overall vertical sequence at Lochiel is characterised by cyclic sequences with both rapid and gradational changes between cycles.

Clastic cycles may be divided into three types on the basis of grain size. These are upward fining, upward coarsening and homogeneous cycles. As described by Miall (1984), these can be caused by a variety of sedimentary, climatic and tectonic mechanisms.

As discussed by Beerbower (1964), these mechanisms may be divided into two types, those related to :

1. the depositional system, autocyclic,
2. an external cause, allocyclic.

Generally, the autocyclic mechanisms are related to sedimentation mechanisms such as channel switching, the building and breaking of bars and banks, shoreline migration, channel avulsion and delta building.

Allocyclic mechanisms include tectonics, sediment supply, palaeoslope, sea level changes and climate, and are large scale controls which effect the whole of the basin at one time.

Thus a sedimentary sequence may be divided into two scales of cycles. First the large scale cycles which were initiated and terminated by allocyclic mechanisms and second, smaller scale cycles which are related to autocyclic mechanisms.

Miall (1984) related these mechanisms to depositional systems analysis and facies analysis respectively. Each allocycle is made up of one or many autocycles and in terms of depositional environment, the allocycle represents a sedimentary system while the autocycle represents the numerous subenvironments making up that system.

These concepts are a useful adjunct to the concepts discussed in Chapter 3 and together will be applied to the interpretation of the Lochiel sequence.

c) Stratigraphic correlation

Generally, two processes are involved in building sedimentary sequences, vertical accretion and lateral aggradation.

Vertical accretion occurs in static systems where sedimentation is uniform, developing stratigraphic zones with homogeneous properties and a tabular geometry. Correlation of these zones is relatively easy (the G seam of the Lochiel Coal Deposit is an example).

Lateral aggradation occurs where deposition is related to migrating environments which may build up or out or both. The distribution of environments is controlled by internal or external (autocyclic or allocyclic) mechanisms leading to variable geometry and rapid lateral changes of facies. Detailed correlation in migrating systems is thus more difficult than for aggradational systems.

Within both of these types of sequences lithological boundaries correspond to time horizons. Where both processes are acting at the same time in laterally equivalent depositional environments, such as fluvial systems and lakes, distinct lateral facies changes occur. Correlation across these boundaries is difficult because of marked lithological changes but equivalent facies can be confidently correlated if contained between known time horizons.

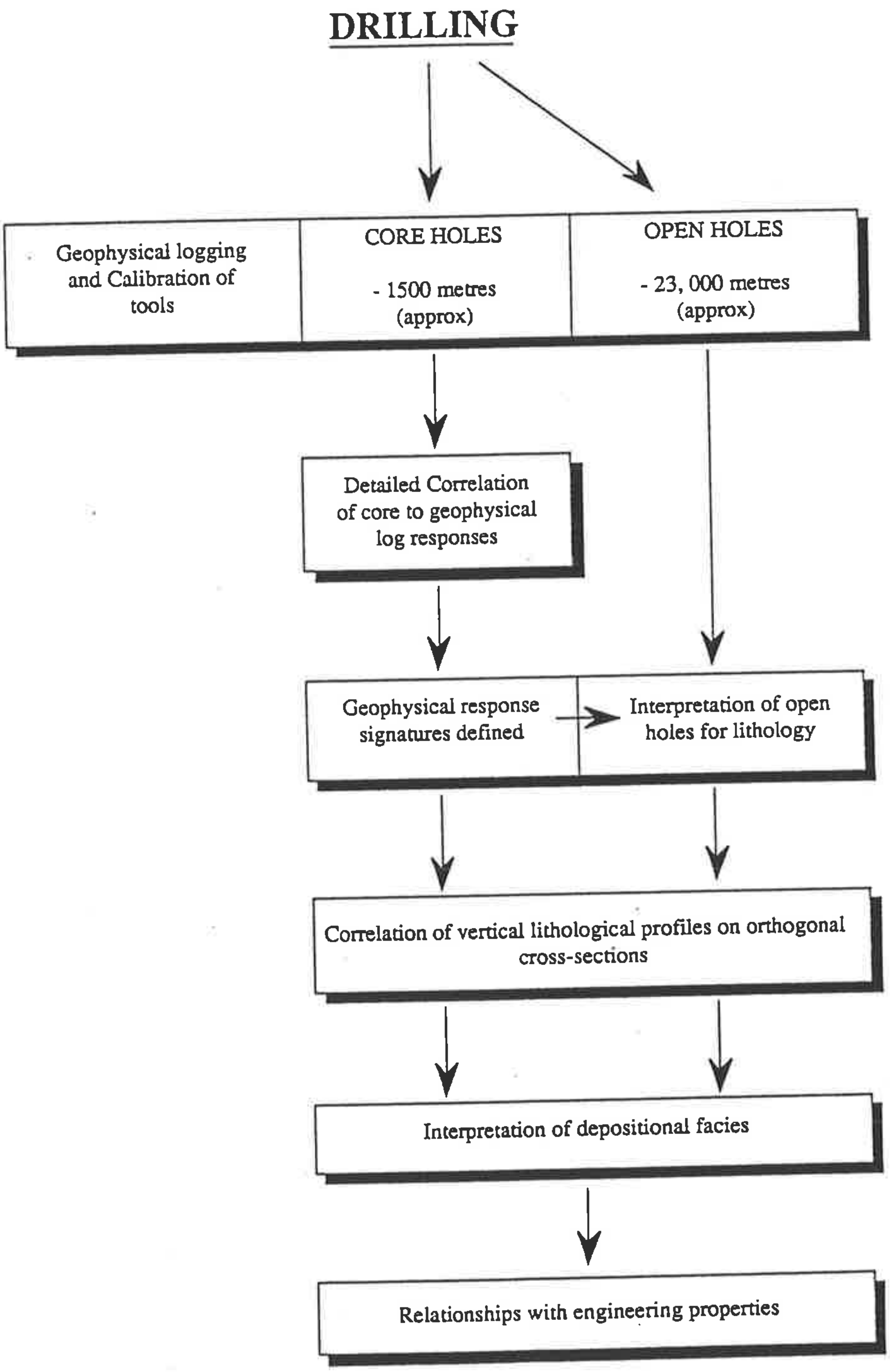
In the Lochiel area such time horizons may be identified at the top or base of vertical accretion deposits such as coal seams. This provides a means of correlating and interpreting complex facies associations.

d) Correlation procedures

Correlation of sediments was based on geophysical log responses. The interpretation flow path as shown in Figure 4.2 consists of an initial calibration phase in which geophysical responses were matched with drillcore to obtain a set of geophysical signatures for the sediments.

Using these signatures as a basis, all open holes were then interpreted manually for lithology and depositional facies. Lithological columns were then placed on orthogonal cross-sections encompassing all holes in the area and the lithology/geophysical log responses representing major changes correlated. At that stage, the sequence was divided into members which were then analysed in detail in terms of depositional system and facies.

Figure 4.2 Core and geophysical log response interpretation flow path.



e) Geological description and representation

Sediments are generally described under the following general headings of sedimentary structures, grain fabric, trace fossils, particle morphology, mineralogy, grain size, colour, fossils.

The description and representation of sediments under these headings serves two purposes :

- It documents in detail sediments at a particular site, thus providing a basis for reinterpretation or comparison with engineering test data.

- Provides a basis for environmental interpretation to allow prediction of geological properties elsewhere.

Interpretation is based on the way in which various facies are associated and on the geometry and internal characteristics of the sediments.

Analysis of the depositional environment is done by comparison with modern and ancient models.

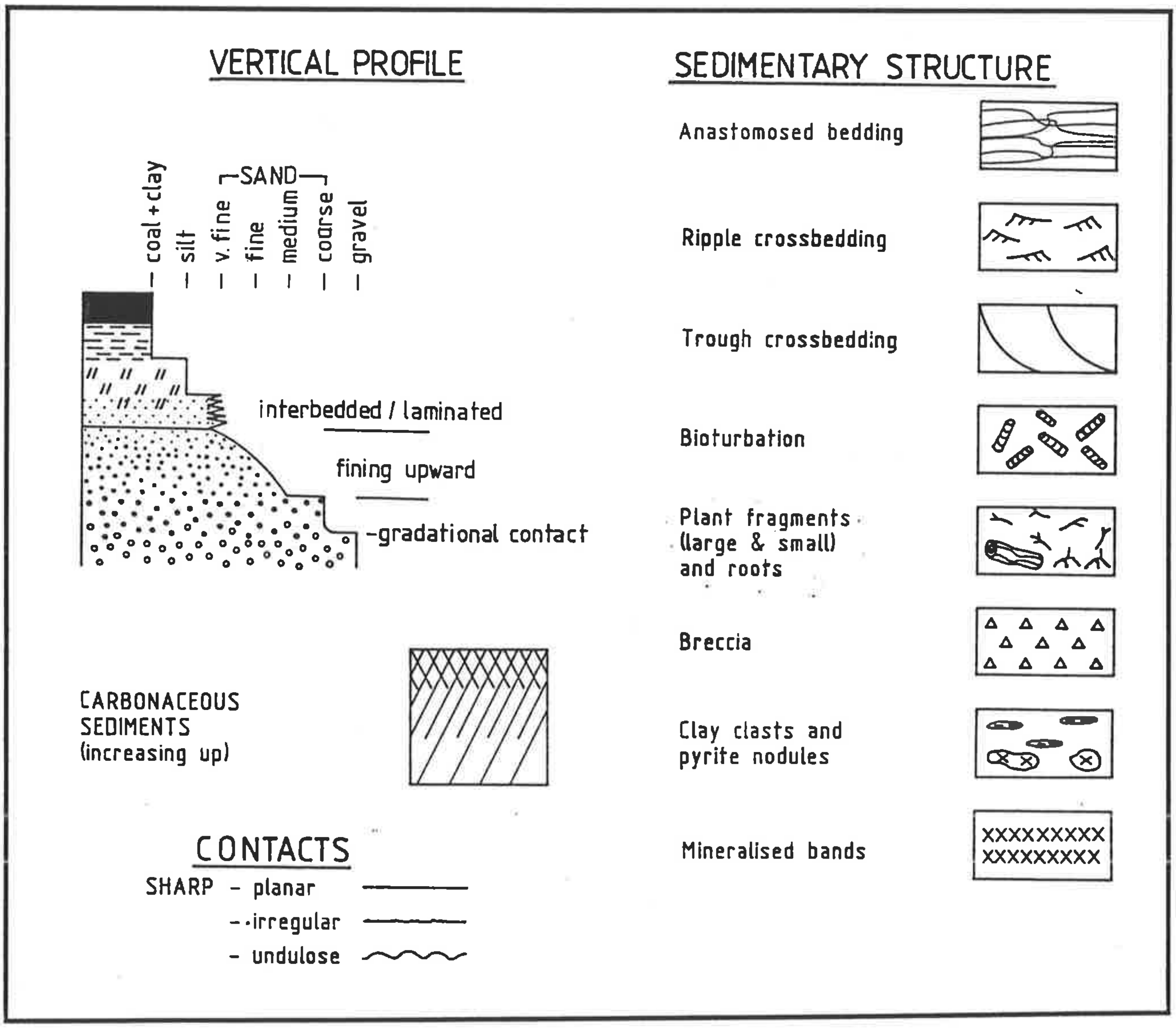
Isopach, structure contour and ratio maps adequately define the geometry and orientation of facies while also enabling easy comparison with other modern or ancient models.

For comparison of internal characteristics, graphic logs are used. The most commonly used columns are those which graphically represent sedimentary structures and variation in grain size with one of more other features (Miall, 1984; Collinson, 1978; Lindholm, 1987).

Anderton (1985) discussed the use of graphic logs for presenting geological information and suggested that the use of standardised symbols tended to "result in only a small part of the available sedimentological detail being recorded on the log". He went on to suggest that "logs should be as detailed and realistic as the ability of the drawer will allow" and that this could be accomplished by using symbols which accurately depict the relevant features.

In this study, standardised symbols are used but these symbols are designed in such a way so as not to lose detail. This type of approach is required in this study to allow detailed correlation of engineering test data and facies. The legend is presented on Figure 4.3.

Figure 4.3 Legend for stratigraphic symbols



4.2.2 Principles of engineering geological interpretation and modelling

Geotechnical interpretation aims to assign values of engineering properties to the geological models.

The traditional practice is to divide the deposit into sectors or regimes in which similar geotechnical conditions exist (Wade, 1985; Kremor, 1988). The definition of the regimes is based solely on the results of analyses directed toward specific questions. These commonly relate to slope stability, dewatering/depressurisation and spoilpile stability (Kremor, 1988).

This approach can be deficient if it presents only the average conditions for each regime without giving any indication of the relationship between regimes. This study addresses this issue by providing a detailed basis for understanding the relationship between each regime based on geological understanding.

4.3 Stratigraphic nomenclature for the Lochiel Coal Deposit

The sediments which comprise the Bumbunga Sand Formation correlate with the Clinton Formation described by Harris (1966, 1971) in the St Vincent Basin to the south and also to the informally named Kanaka Beds of the Pirie Basin to the north (Lindsay, in press).

The Bumbunga Sand represents the initial phase of basin infilling in the Lochiel area. The sediments were derived from surrounding uplifted basement and transported to the depositional site by fluvial channels originating from the northwest.

The character of sedimentation farther north indicates that several fans were present during that time with the channels coalescing to form a longitudinal system.

Regional correlation of the channel facies suggests that the flow was south to north, with the thickest accumulation of fluvial channel sediments occurring in the narrow neck of the basin near Crystal Brook. Channel facies sediments in the Bumbunga Sand are confined to the north and central areas and do not extend south. This is also true for the area to the east of the Nantawarra High where borehole information indicate the existence of a basement high overlain only by Hindmarsh Clay.

The implication is that the sediments north of the Nantawarra High block were deposited in a basin which was separate from the St Vincent Basin.

The alternative is that there was a continuity at the time of deposition but subsequent uplift of the Nantawarra High has led to erosion. Uplift is known to have occurred because the elevation difference between the coal seams in the Bowmans deposit and those in Lochiel is in the order of about 100 metres (Kremor and Springbett, 1989). Any sediments which may have overlain the Nantawarra High could have been eroded. However, the interpreted limits of successive units (from the base of the sequence upwards) lie progressively further to the south, overlying the Nantawarra High.

In addition, the Nantawarra High in known to be a source of sediment throughout the Late Eocene-Oligocene. The conclusion is that uplift and erosion are not the cause of the present distribution.

To the north, there appears to be a connection with the Pirie Basin (Kremor, 1986). Although this Basin is not well defined, Lindsay (in press) considers the sandy, carbonaceous and coal bearing Kanaka Beds to be Late Eocene to Early Oligocene in age and can be correlated with the Bumbunga Sand in the Lochiel area.

There is strong evidence to suggest that the sediments north of the Nantawarra High were deposited in a discrete basin, separate from the St Vincent Basin to the south.

The channel facies can be correlated north past Crystal Brook and it is considered that it is likely that the basal sediments are continuous with the Kanaka Beds in the Pirie Basin to the north.

There are, however, other considerations relating to the definition of the stratigraphic nomenclature. There is evidence which indicates that during the deposition of the sediments of the Warrindi and Tarella Silt Formations there was a connection with the St Vincent Basin to the south. However, as discussed in Chapter 5.0, these differ in lithology from their stratigraphic equivalents in the St Vincent basin.

Staines (1985) suggested the establishment of new stratigraphic nomenclature only where it will aid the geological interpretation of the area.

To promote a clearer understanding of the stratigraphy and sedimentology it is proposed that the Tertiary sequences occurring between the Nantawarra High and Crystal Brook and between the Ardrossan Fault and the Redbank Fault be assigned to a separate basin, the Snowtown Basin. Accordingly, the basal, Late Eocene sediments are to be assigned to the Bumbunga Sand Formation which contains the Nantawarra Sand, Condowie Silt, Darnleigh Sand and Kooliata Coal Members (Figure 3.3).

CHAPTER 5.0 ANALYSIS OF SEDIMENTS OCCURRING BELOW THE OVERBURDEN

The aim of this Section is to analyse the Bumbunga Sand Formation to;

- describe the lithology and lateral variation of the sediments,
- identify the major factors controlling sedimentation and develop a model which will assist in interpreting these controls,
- define the relationship between the key geological features affecting slope stability and characterise these features in terms of their engineering properties.

The stratigraphy is summarised on Figure 3.3 (page 53).

5.1 Bumbunga Sand Formation - Nantawarra Sand Member

The Nantawarra Sand Member unconformably overlies both the Rosehaven Clay and the ABC Range Quartzite. The member ranges in thickness up to 65 m in the northwest and laps out to the south and east (Figure 5.1). To the west it abuts the Ardrossan Fault and is laterally continuous with fluvial and lacustrine sequences of similar character to the north.

Lithologically the formation exhibits a gradational lateral change from fining upward and stacked cycles of clean quartz sand (NS1 Braided Stream Facies) in the northwest

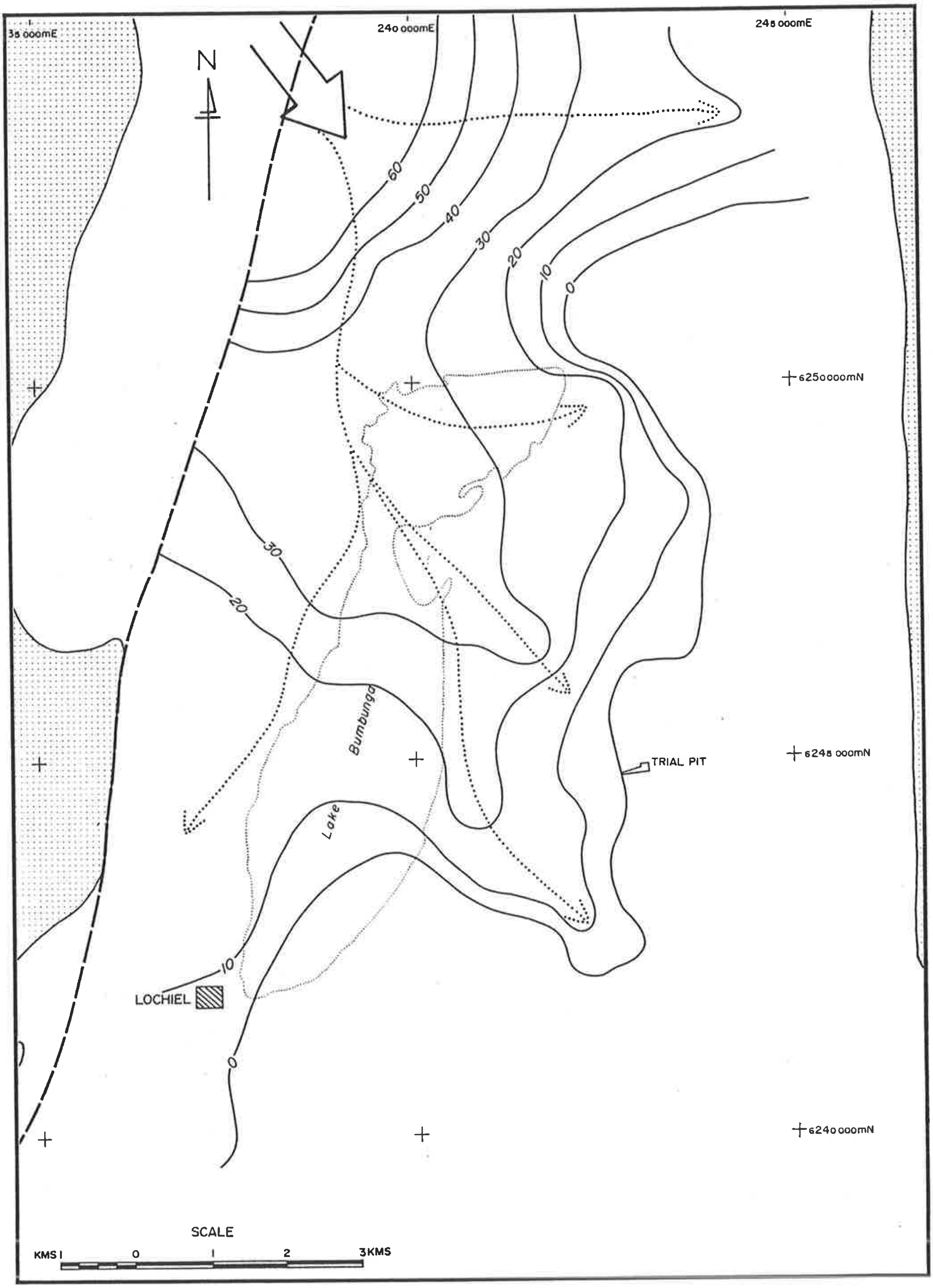
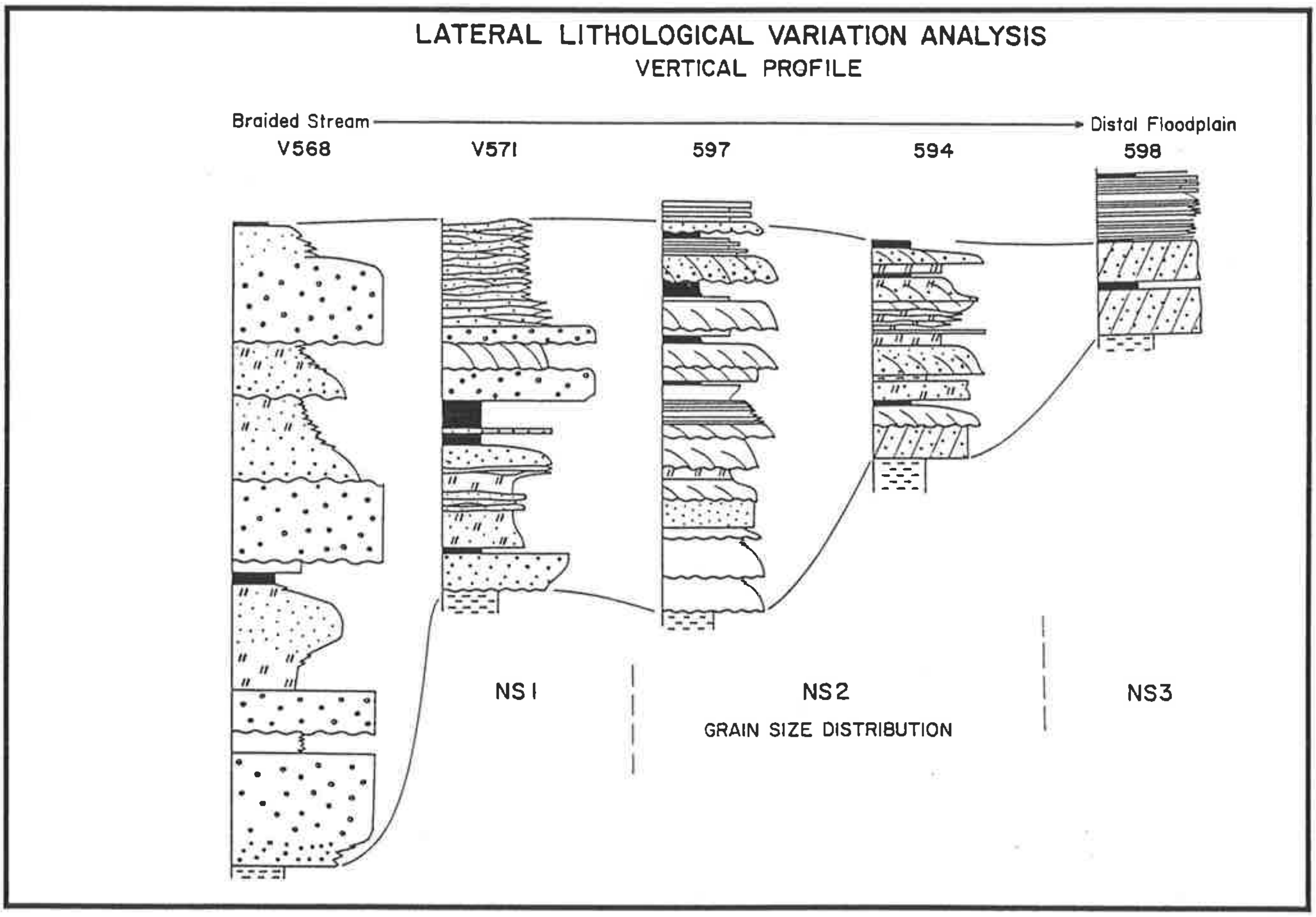


Figure 5.1 Thickness and lateral distribution of the Nantawarra Sand Member

through interbedded clean sand (NS2, Floodplain Channel Facies) and carbonaceous sand (NS3, Distal Floodplain Facies) in the central areas and carbonaceous silty sand in the south and southeast (Figure 5.2 and Appendix 2 for detailed geophysical log response models).

Figure 5.2 Nantawarra Sand Member - Lateral variation in lithology and vertical sequence.



5.1.1 Lithology and lateral variation

- Northwestern area (NS1 facies)

To the northwest of the area, the Nantawarra Sand Member comprises a relatively thick sequence of stacked and truncated fining upward, coarse to fine grained clean sand

and gravel cycles interbedded with fine sand, carbonaceous sand and sandy coal. The clean sand within this facies is generally poorly sorted and subangular, ranging in grain size from medium sand to fine gravel.

Individual sand zones range up to 10 m in thickness and are composed of cycles up to 2 m thick. Bedding within the sand and gravel zones is indistinct, probably due to the homogeneous nature of the sediments being deposited, but occasionally individual beds are outlined by fine carbonaceous matter. Crossbedding with dips of up to 35° have been observed within the zones.

Both the individual cycles and the sand zones tend to fine upwards in grain size and characteristically have sharp, irregular and erosional lower contacts with large clay galls and wood pieces lying on the boundary (Plate 5.1).

As shown by Plate 5.2, the fining upward cycles are often truncated at the tops of the cycles by overlying cycles to form stacked sequences of clean sand. Where the top of the cycles are not truncated, they continue to grade upward into a sequence of interbedded fine clean sand, carbonaceous silt and dirty coal.

The carbonaceous zones are up to 18 metres thick and often distinct coarsening upward cycles up to a metre thick are present within the sequence. These comprise silty coal or clayey, highly carbonaceous silt at the base and become less carbonaceous and more sandy upward. Towards the top, the cycles are characterised by indistinct parallel laminations of fine to very fine, clean white sand (refer to Plate 5.3) with an occasional thin bed of fine sand at the top. Generally these coarsening up cycles are bioturbated and rooted and characteristically have sharp, planar upper and lower boundaries.

There is a strong trend characterised by a rapid increase in grain size towards the west corresponding to the location of the Ardrossan Fault. Drillholes located close to this fault intersect a sequence dominated by cobble sized particles.

The characteristics of NS1 appear to correlate with those described by Coleman and Prior (1982) as being typical of braided stream deposits.

The trend towards a rapid increase in grainsize towards the west indicates a change in gradient towards the Ardrossan Fault. It is common for braided stream deposits to be laterally equivalent to alluvial fans with the extent of the latter being controlled largely by the gradient.

It is considered that NS1 represents an alluvial fan/braided stream depositional environment.

- Central area (NS2 facies)

In the central part of the area, the fining upward cycles grade laterally into a sequence of interbedded clean sand and silty carbonaceous sand.

The clean sand present in this interbedded zone is usually less than 2 metres thick and rarely do individual cycles stack to form thicker units. The sand is fine grained, moderately well sorted and generally fines upward into carbonaceous sand comprising an abundance of wood fragments in a slightly carbonaceous, silty sand matrix.

Bedding is rarely observed, being destroyed by intensive bioturbation and rooting. Occasionally, the carbonaceous sands grade into dirty, woody coal seams up to 1.0 metres thick.

The features described for the NS2 facies are characteristic of lacustrine fill environments as described by Coleman and Prior (1982) and Horne et al. (1978) or as fan deltas (alluvial fans entering bodies of water) as described by Wescott and Etheridge (1980). The clean sands are considered to represent distributary channels entering a swamp environment.

- Southeastern area (NS3 facies)

Farther to the southeast, the Nantawarra Sand Member grades into a carbonaceous sand facies. A number of carbonaceous sand lithologies are present. Many of these lithologies are present in other parts of the sequence and an abbreviated nomenclature is developed to assist with the description of these other parts.

a) Inferior coal facies (SA5)

A large proportion of the Nantawarra Sand Member in the southeastern part of the area consists of an abundance of wood fragments of varying size in a slightly carbonaceous, silty sand matrix. This is equivalent to the SA5 lithology present in many of the overlying members as well as being common in the Nantawarra Sand Member. Bedding is rarely observed in these beds, being disrupted by intensive burrowing and root systems. Depending on the amounts of plant fragments, the material may grade into coal but only thin seams have been observed.

b) Sand with a fine grained carbonaceous matrix (SA3) (refer to Plate 5.4)

This type of sand is often present both within the Nantawarra Sand Member and in overlying members. Within the former it consists of indistinctly bedded sand with a fine to very fine carbonaceous matrix. The carbonaceous matrix forms a cement for the sand grains and depending on the proportion of carbonaceous matrix, the sands vary from uncemented (designated SA2 type sand) to weakly cemented (SA3). The sand comprises very well rounded, poorly to moderately well sorted quartz varying from fine to coarse grained.

c) Bioturbated fine sand facies (SA6)

Occasionally, thin beds of fine to very fine grained, clean, white sand occur within the carbonaceous sequence. These zones are usually strongly bioturbated and indistinctly laminated with light brown silt or silty sands. The laminations often become more obvious towards the base of the zone and dips range up to 30°. Characteristically the upper contact is sharp and irregular while the lower contact is gradational, usually with a clean sand zone.

d) Non-carbonaceous silt

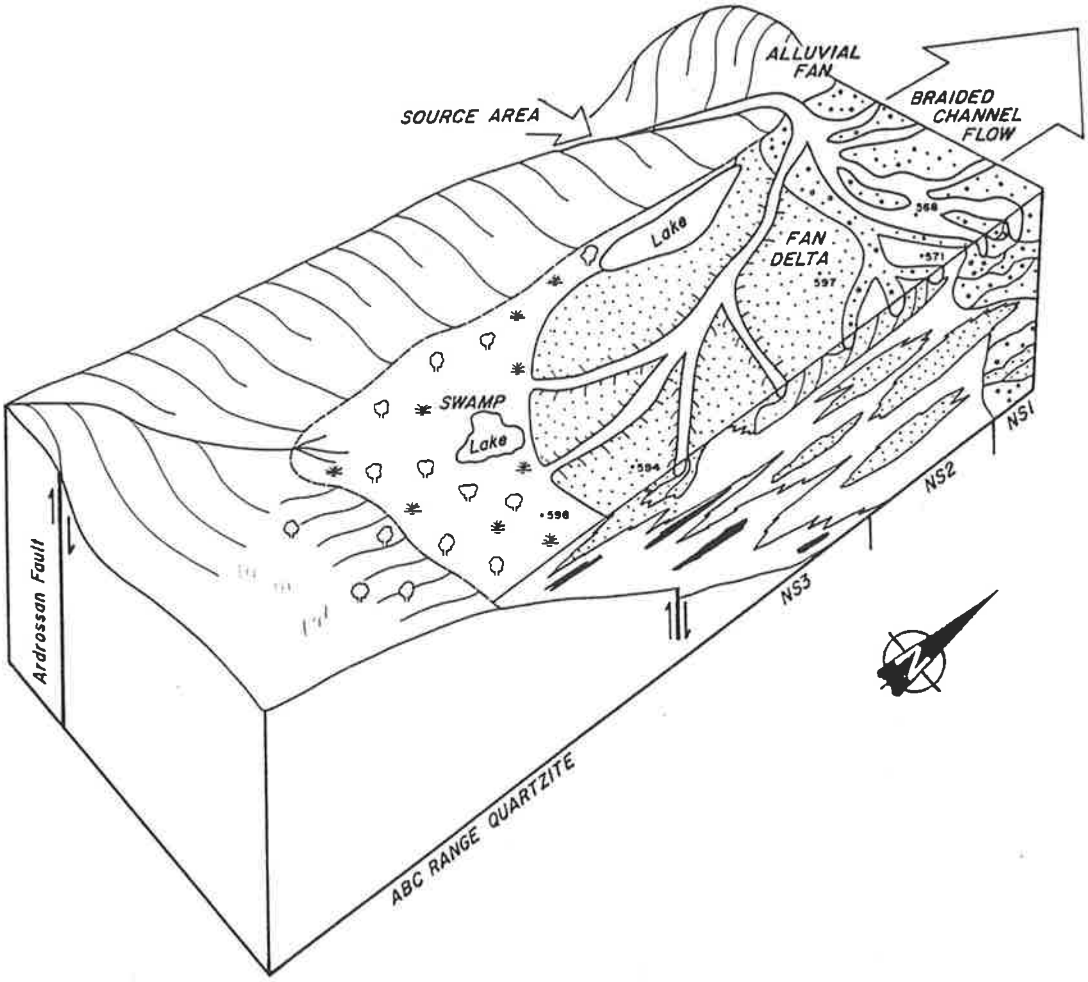
Occasionally thin zones of partially indurated non-carbonaceous, light-brown to cream silt and sandy silt occur as interbeds within the carbonaceous sequence. These zones are structureless apart from being extensively rooted. Generally these zones have sharp, irregular upper boundaries and gradational basal contacts. They appear to represent soil horizons.

The NS3 facies represents the distal equivalent to the fan delta environment (NS2).

5.1.2 Depositional environment - Nantawarra Sand Member

Based on the characteristics of the sediments described above a palaeogeographic reconstruction of the area is presented on Figure 5.3.

Figure 5.3 Schematic representation of the depositional setting for Nantawarra Sand Member



The drill hole locations for Figure 5.2 are indicated by the numbers.

The lateral lithological variations are considered to represent a depositional setting characterised by the lateral association of ;

SWAMP - NS3 facies
FAN DELTA - NS2 facies
BRAIDED STREAM - NS1 facies
ALLUVIAL FAN - NS1 facies

It is apparent from the thickness distribution, grain size and facies distribution that the source of sediments originated from an uplifted area to the northwest.

Regional correlation undertaken by Kremor (1986) also suggested that the braided streams coalesced and formed part of a major fluvial system which drained to the north into the Pirie Basin.

5.1.3 Engineering properties

The Nantawarra Sand Member is the major sub-coal aquifer in the area. Particle size analyses are presented on Figure 3.12, page 76.

The NS1 facies exhibit a significantly higher hydraulic conductivity than the NS2 and NS3 facies (Figure 3.13, page 77). This relates to the greater proportion of clean sand and also the trend of increasing grain size towards the source of the alluvial fan/fan delta.

5.2 Bumbunga Sand Formation - Darnleigh Park Sand Member

The Darnleigh Park Sand Member is present only at the northern end of Lake Bumbunga. It has an average thickness of about 13 metres, and attains a maximum thickness of 24 metres (Figure 5.4).

The lateral and vertical relationship between the Darnleigh Park Sand and the Nantawarra Sand Members is illustrated in Appendices 2 and 3.

The Darnleigh Park Sand Member is laterally equivalent to the Nantawarra Sand Member to the north and erodes into the upper parts of the Condowie Silt Member to the south.

The member is considered to represent continued alluvial/delta fan sedimentation but is assigned a separate formal name on the basis of its stratigraphic and areal location and because of its importance to the hydrogeological regime.

5.2.1 Lithology and lateral variation

The Darnleigh Park Sand Member is described from core from V571, (Appendix 3) and the vertical lithological profile and geophysical log response is summarised on Figure 5.5.

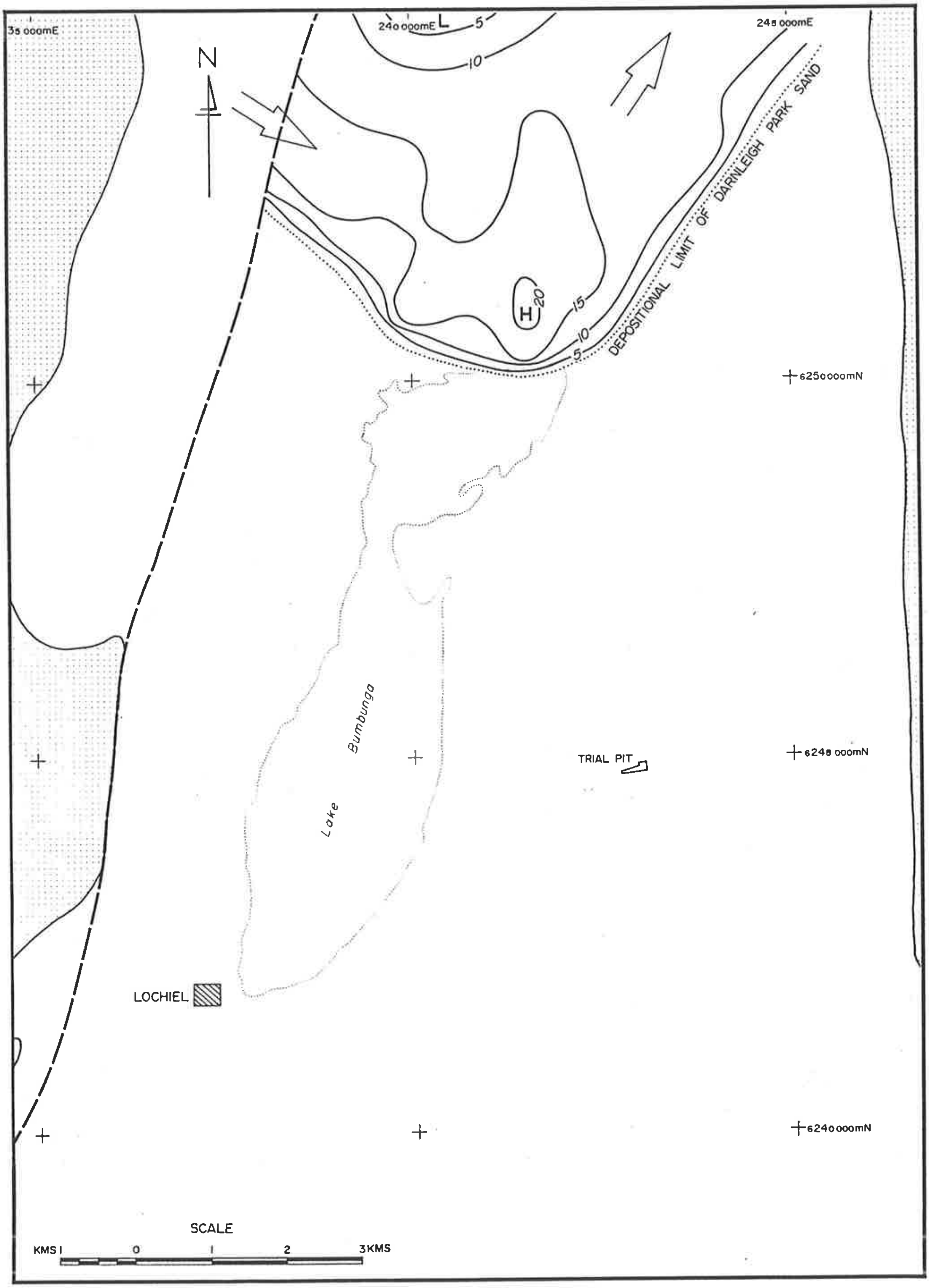
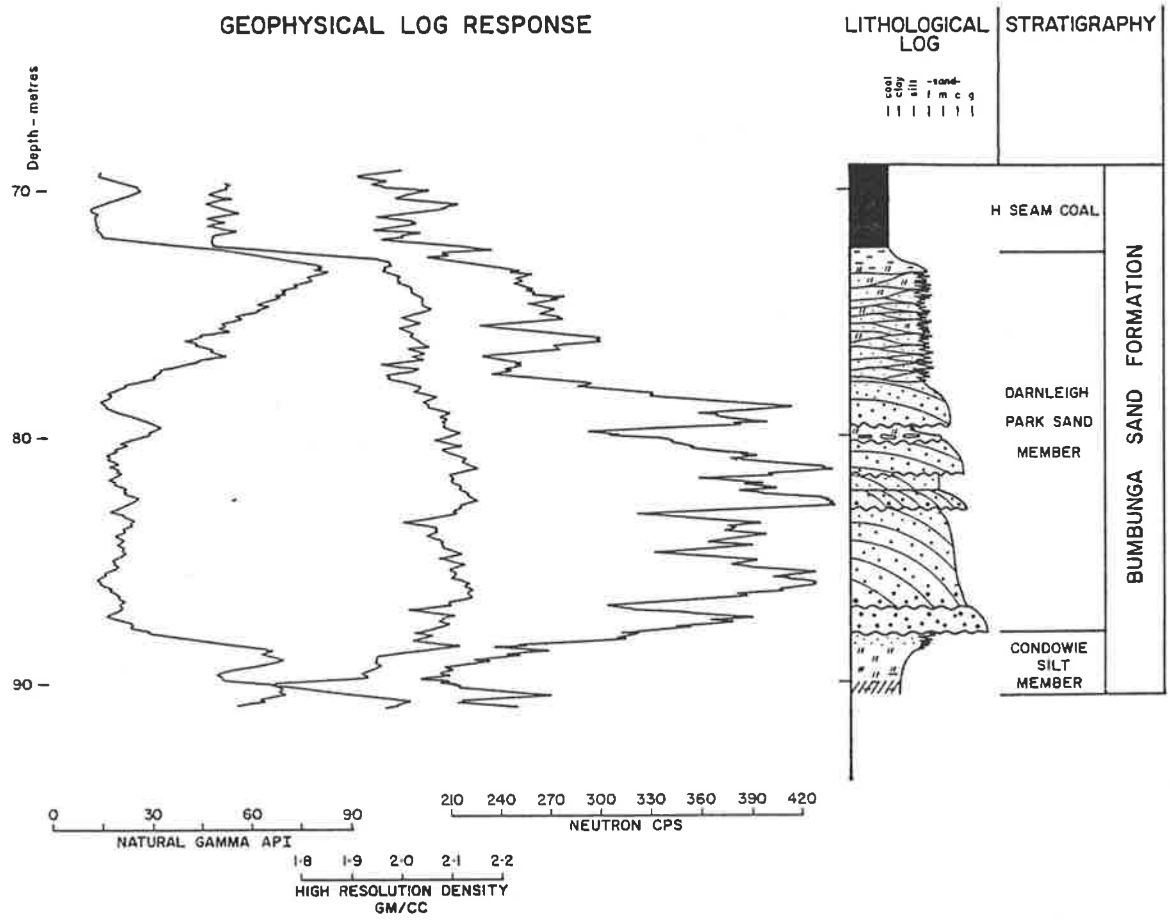


Figure 5.4 Thickness and lateral distribution of the Darnleigh Park Sand Member.

Figure 5.5 Darnleigh Park Sand Member Geophysical log response and vertical lithological profile.



Overall, the sequence is upward fining from poorly sorted, subangular, clean, coarse sand/fine gravel at the base to silt and clay at the top. Within the lower part of the sequence there exists a number of truncated/erosional upward fining cycles.

Trough crossbedding is indistinct due to the monomineralic nature but occasionally beds are outlined by fine detrital carbonaceous matter. Large (> 0.1 metre diameter) wood pieces are also present. A 0.5 metre thick bed of medium grained sand with 10% clay galls is present towards the top of the sequence. The galls are 5 mm in diameter, rounded, elongate (formed by compaction) are composed of cream and fawn silty clay.

The upper part of the sequence comprises interbedded dark grey-brown, bioturbated, fine to medium grained sand and moderately carbonaceous silt. The beds are generally discontinuous and partly anastomosing with crossbed dips up to 15°.

These beds grade from light brown to cream mottled clayey silt and a silty clay into the overlying the H zone. This contact is characterised by intensive bioturbation and rooting (Plate 5.5).

The Darnleigh Park Sand Member appears to have eroded laterally into the Condowie Silt Member, however, to the north it merges with the Nantawarra Sand Member where it becomes indistinguishable on geophysical log response (Appendix 2).

The characteristics of the Darnleigh Park Sand Memeber are similar to those of the Nantawarra Sand Member and it is considered that the two members are representative of a braided stream environment. However, because the Darnleigh Park Sand Member represents a single episode of deposition it is possible to analyse in greater detail the features of the braided stream system in the study area.

5.2.2 Depositional environments

The Darnleigh Park Sand Member has the following definitive characteristics :

1. Upward fining grain size and sedimentary features.
2. Lateral consistency of cyclic patterns.

3. Erosional, scoured base.
4. Cross bedded sands.
5. Intraclast, gravel and wood fragments at the base of cycles.
6. Sands represent 80% of the cycle.
7. Sharp lateral contact.

These characteristics are similar to the sequences described by Cant (1982) and Miall (1978) including :

A. Channel Floor - trough cross beds and intraclast strewn scour surfaces developed in coarse sandstone. Sediments are poorly sorted and internal stratification is poorly defined.

B. In channel - trough cross beds in slightly finer sandstone with intercalations of planar crossbedded sandstone.

C. Bar top - interbedded rippled sandstone, mudstone and low angle to horizontally laminated sandstone.

Interpretation of the vertical profile on the basis of these depositional sites is included on Figure 5.6

- Vertical and lateral depositional environment relationships

Braided rivers are laterally unstable and migrate leaving sheet or wedge shaped deposits of channel and bar complexes, preserving only minor amounts of flood plain material (Schoelle and Spearing, 1982). Characteristically braided stream deposits may be divided into two scales of sand bodies, the largest of these representing the migration of the river system itself and the smaller representing lateral migration of channels within the system.

Cant (1982) drew a hypothetical picture of stacking of fluvial facies sequences, with the major features being major erosional surfaces associated with migration of the entire river system and truncation surfaces associated with channel migration within the river system.

The geophysical lithofacies section (Appendix 3) illustrates these features within the Nantawarra Sand Member and the Darnleigh Park Sand Member. The section also indicates that the Darnleigh Park Sand Member represents an erosional phase of sedimentation.

5.3 Bumbunga Sand Formation - Condowie Silt Member

The Condowie Silt Member conformably overlies the Nantawarra Sand Member and is truncated to the north of the area by the erosional Darnleigh Park Sand Member. The Condowie Silt Member laps onto basement on the eastern and southern margins and terminates against the Ardrossan Fault on the western side.

Over most of the area the member has a thickness of approximately 22 metres and attains a maximum thickness of 30 metres in the south (Figure 5.6).

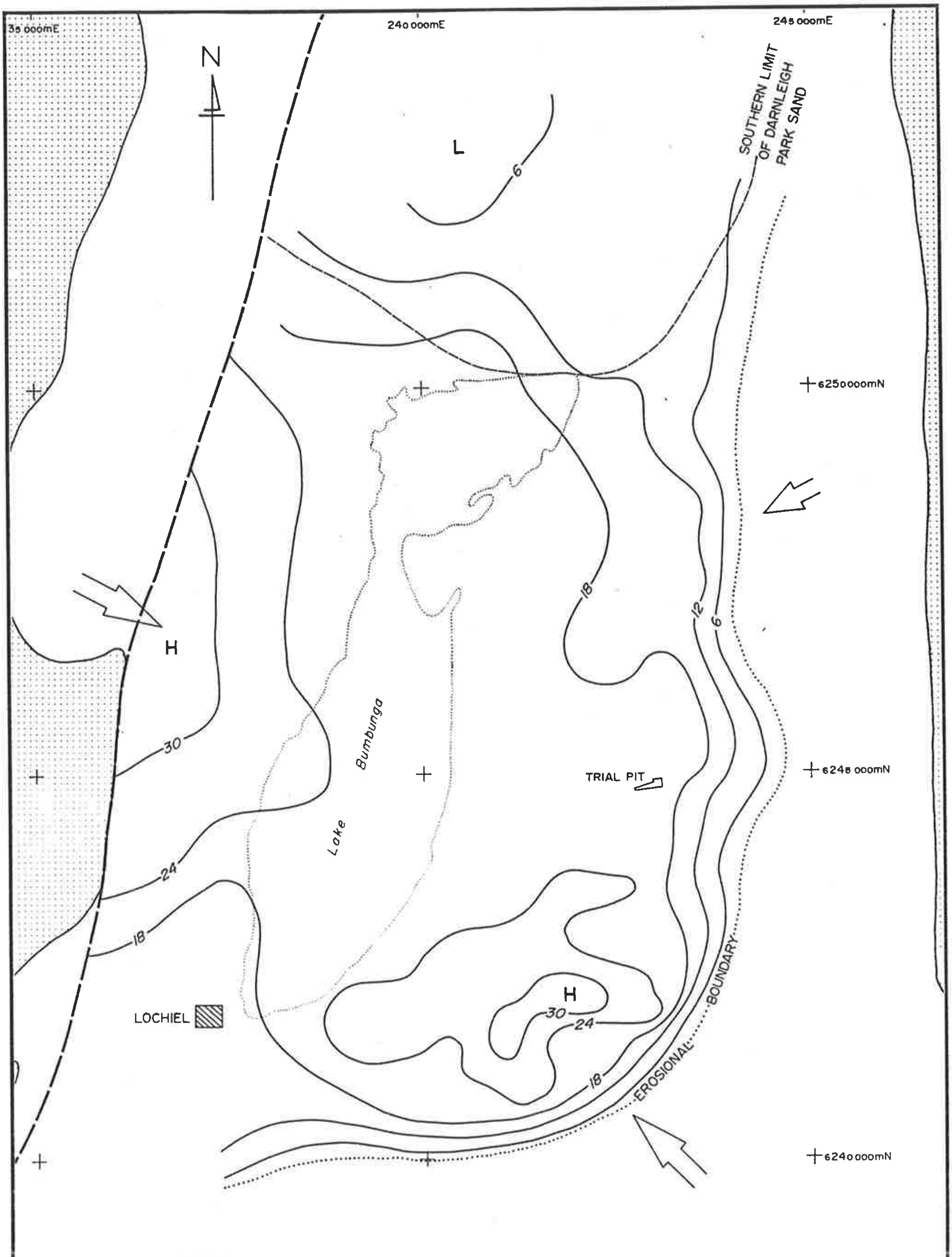
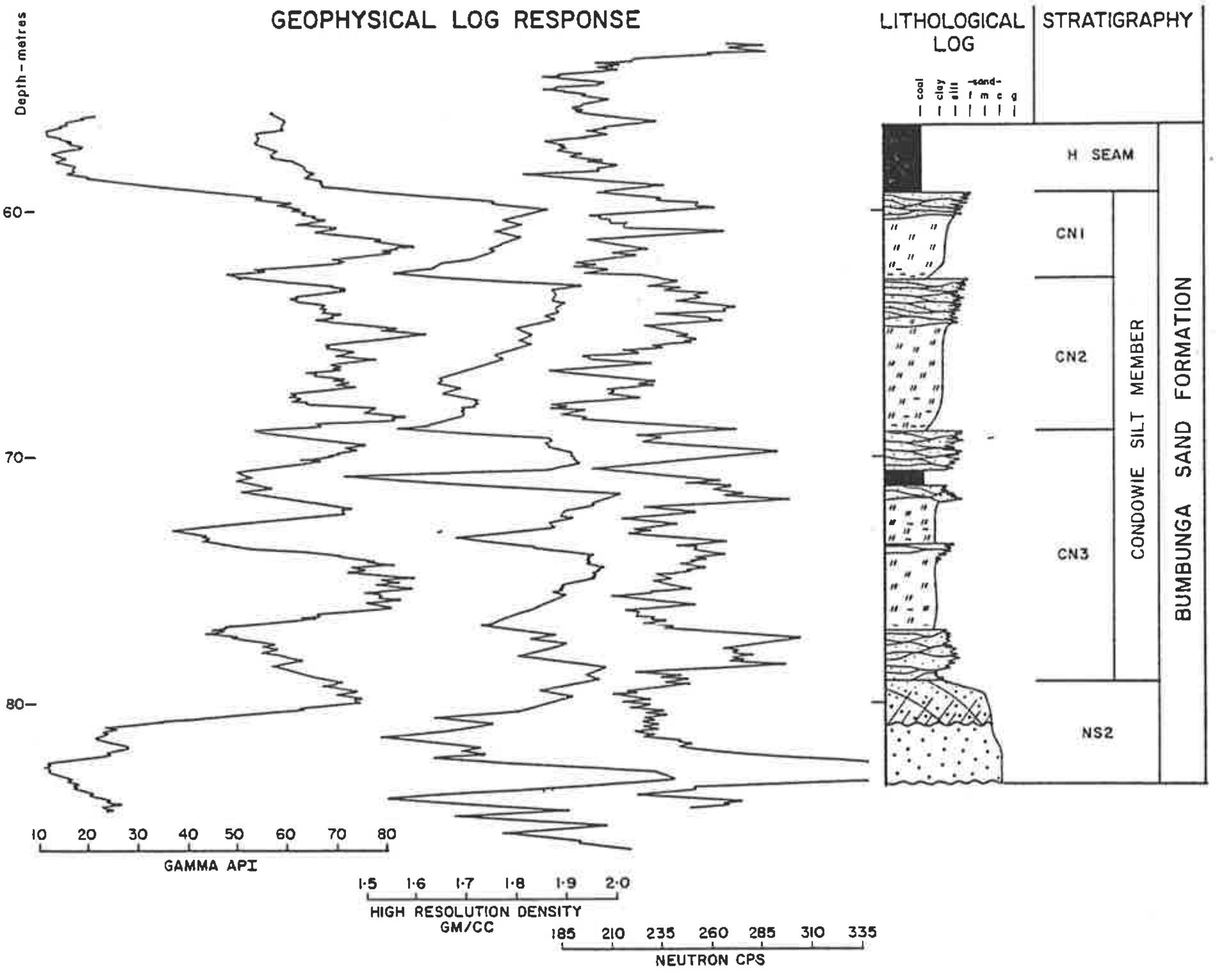


Figure 5.6 Thickness and lateral distribution of the Condowie Silt Member.

The Condowie Silt Member has been divided into three submembers named CN1, (top), CN2 and CN3. The definition of the these submembers is based on the lithological and geophysical log response changes which occur in the vertical sequence in the centre of the area (Figure 5.7).

Figure 5.7 Condowie Silt Member - Geophysical log response and vertical lithological profile



From the central area, the geophysical signatures have been correlated to the margins of the deposit utilising lithological descriptions from cored holes where available.

These correlations have attempted to follow entire depositional systems and as such transgress facies boundaries. This type of correlation procedure has inherent difficulties and relies on trend recognition and lithostratigraphic distinction between and within cycles.

In the centre of the deposit, very distinct cyclic sequences are developed, allowing for confident definition of submembers. At the southern end of the deposit the distinction between cycles is poor and a lower level of confidence should be placed on interpretations.

Lithofacies and geophysical log response models are presented in Appendix 2.

The CN1 and CN2 submembers each consist of a single cycle whereas CN3 consists of multiple cycles. All three submembers follow the same thickness trends of being thicker in the south and then thinning to the north (Figure 5.8a,b &c).

The CN3 submember also thickens again at the northern end of the deposit.

5.3.1 Lithology and lateral variation

Each of CN1,2 & 3 displays a similar lateral lithologic variation and each can be divided into either a silty or a sandy facies. The silty facies occur in the north and central areas while the laterally equivalent sandy facies are present in the south.

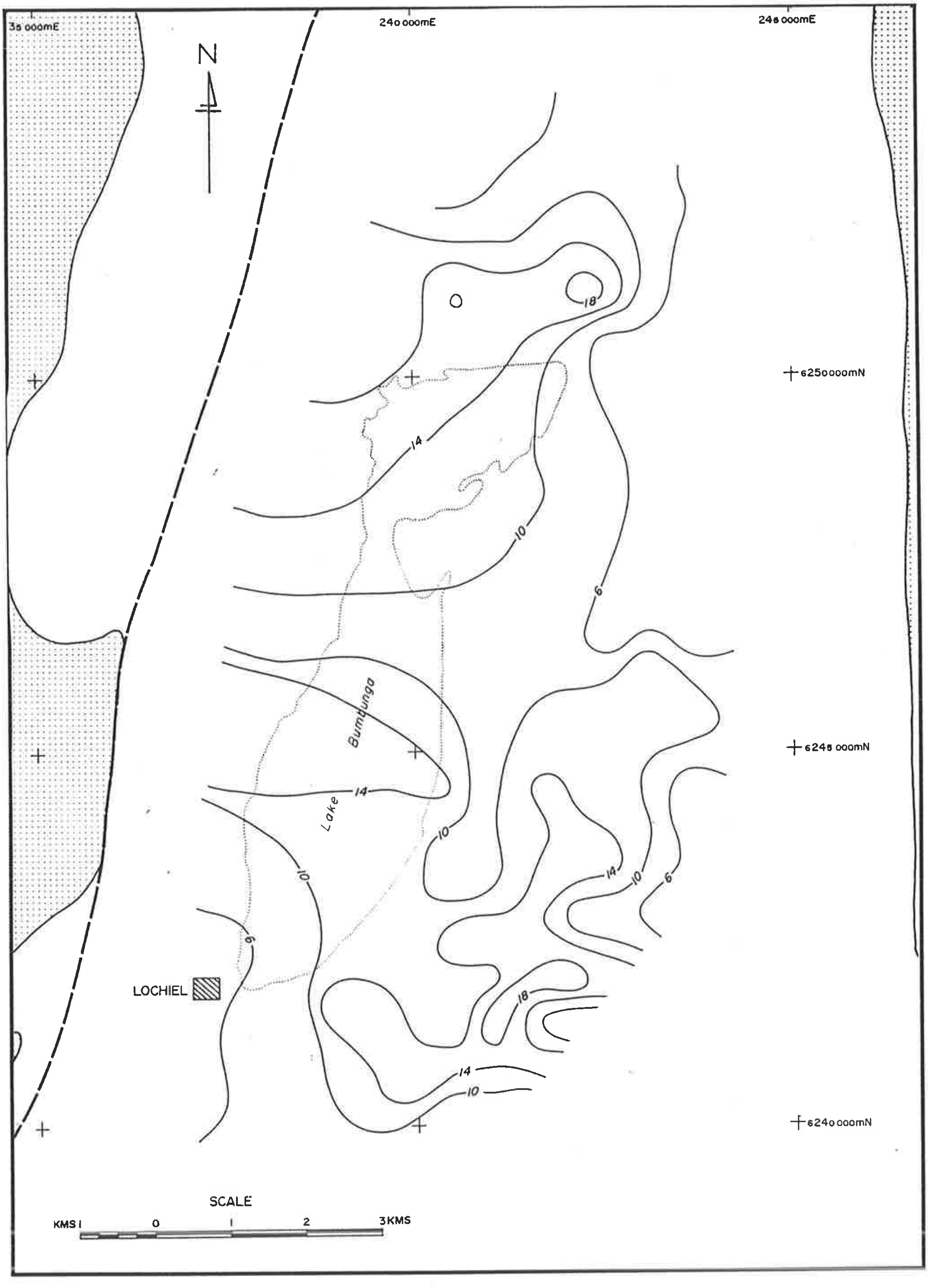


Figure 5.8a Thickness and lateral distribution of the CN3 unit - Condowie Silt Member.

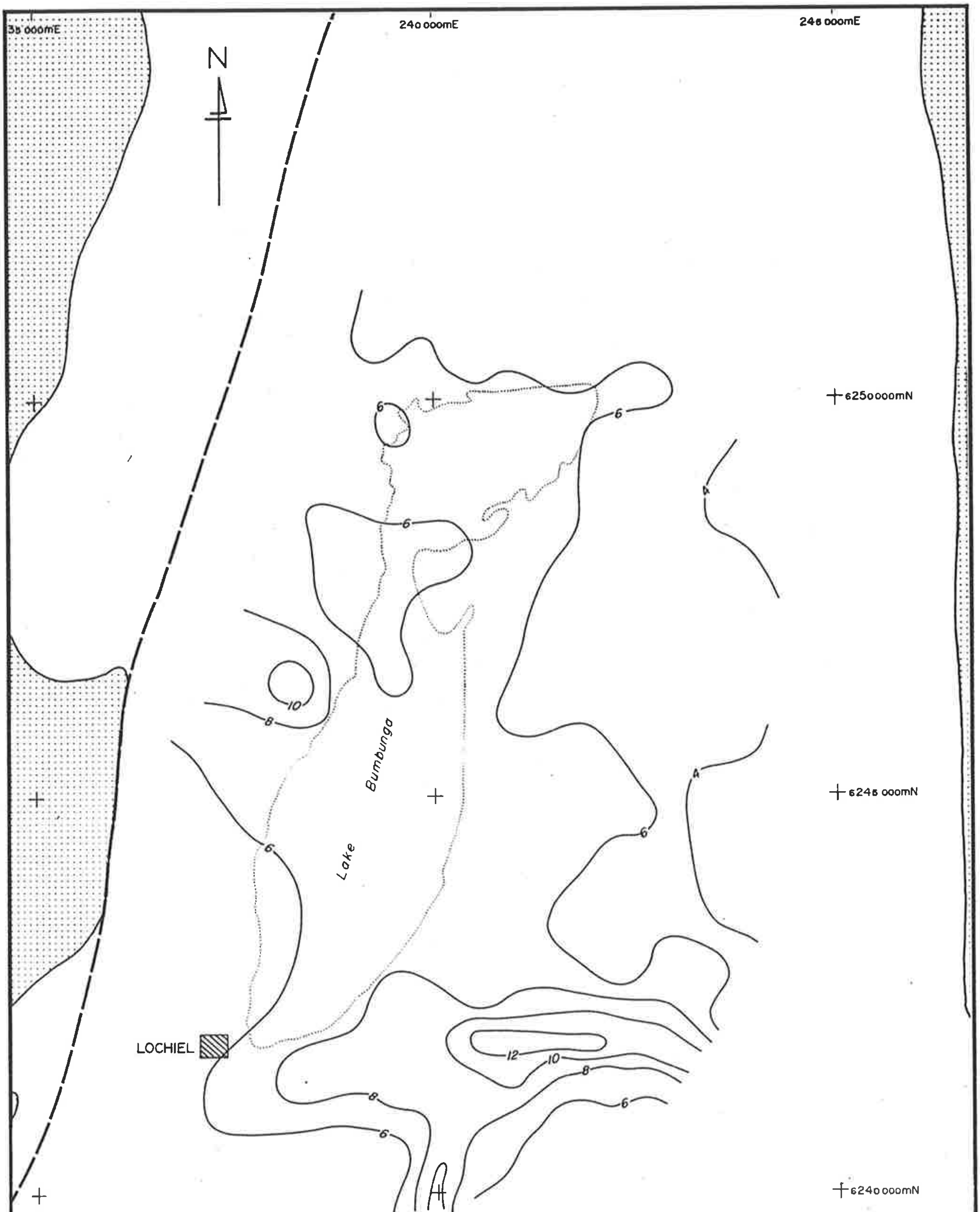


Figure 5.8b Thickness and lateral distribution of the CN2 unit - Condowie Silt Member.

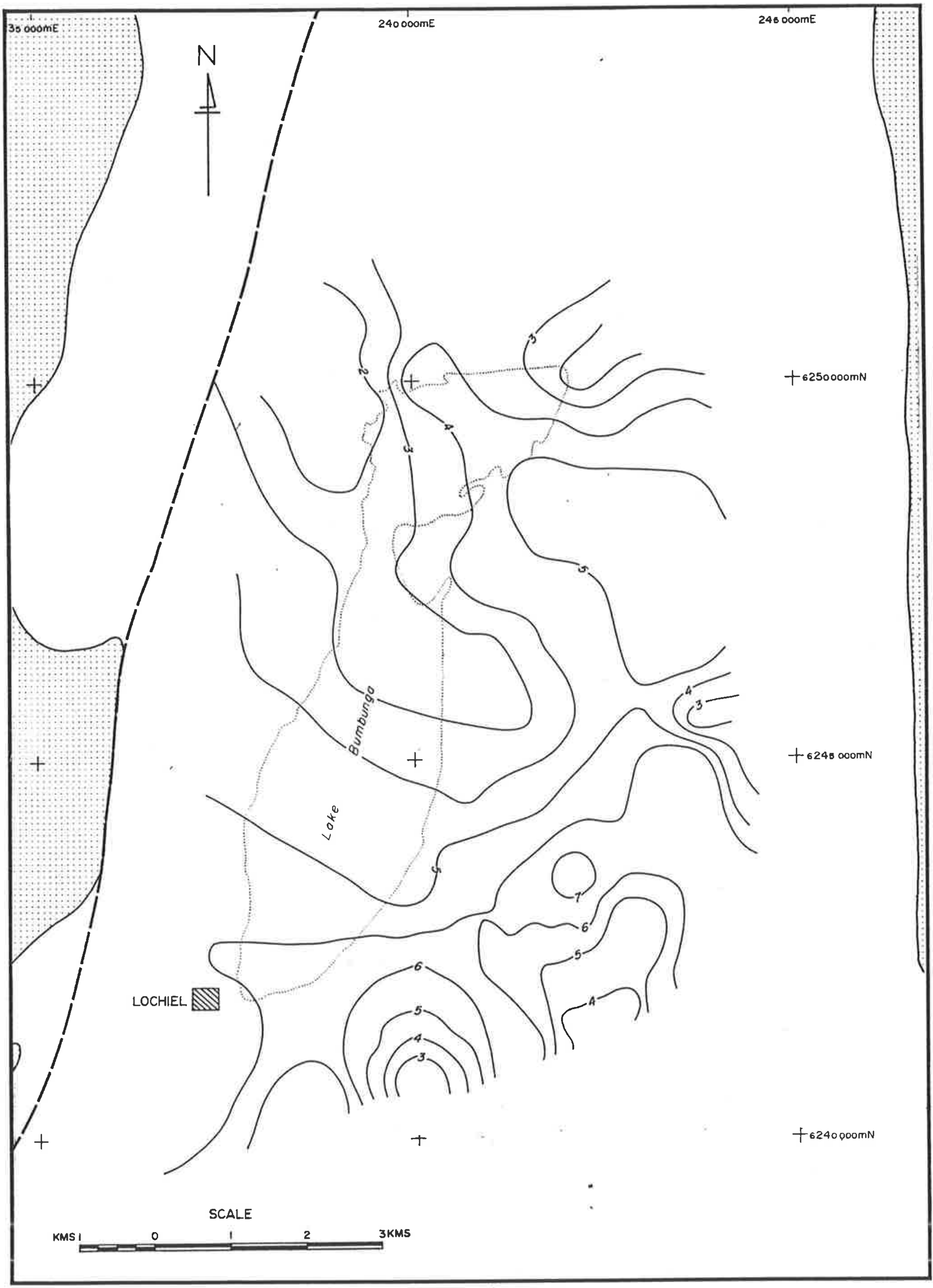


Figure 5.8c Thickness and lateral distribution of the CN1 unit - Condowie Silt Member.

In vertical profile CN1 and CN2 share similar lithologic characteristics. Both are single sedimentary cycles so will be described together whereas CN3 comprises multiple cycles and is described separately. In comparison with the CN2 and CN1 cycles, CN3 cycles are thinner, contain more sand and are laterally more variable.

- CN3 lithology and lateral variation

CN3 conformably overlies the Nantawarra Sand Member and consists of multiple coarsening upward sedimentary cycles. CN3 reaches a maximum thickness of about 16 metres in the south, and thins to less than 10 metres in the central area (Figure 5.8a).

Towards the north CN3 appears to grade laterally into the upper sections of the Nantawarra Sand Member (Appendix 2,)

In the central area, CN3 comprises upward coarsening cycles interbedded with clean sand, carbonaceous sand and coal. The coarsening upward cycles are up to four metres thick and consist of a basal clayey, carbonaceous silt which grades upwards into very fine grained and laminated silty sand or sandy silt.

Bedding within these cycles is often indistinct and rarely present in the lower portion of cycles, where present bedding is less than 10°. Interbedded with these coarsening upward cycles are zones, generally less than two metres thick, of fine grained clean sand, carbonaceous sand and coal.

These types of vertical profiles are common in alluvial/deltaic fan environments and can be attributed to either crevasses splays (Galloway and Hobday, 1983; Davies, 1980), or to lacustrine delta fills (Coleman and Prior, 1982).

Crevasse splay deposits are generally small in areal distribution (maximum of several square kilometres, Galloway and Hobday, 1983) and require a nearby fluvial source. This is inconsistent with the area covered by the CN3 silty facies and further, none of the drillholes in the area have intersected erosional channel sand in this facies.

However, the size and lateral continuity of beds is consistent with lacustrine delta fill deposits and this model is also supported by the radial location of marginal facies laterally equivalent to the carbonaceous sand swamp facies of CN3 and the braided stream facies of the Nantawarra Sand Member.

To the south and west CN3 grades into a carbonaceous sand facies (SA5 lithology). This facies thickens towards the margins and is considered to represent small deltas which were fed from small streams originating from tectonically uplifted basement. The high proportion of carbonaceous matter in the sediments indicates that these deltas were heavily vegetated.

. CN1, CN2 lithology and lateral variation

a) Silty facies - CN11, CN21 - lithological description

The silty facies are present over the central and northern parts of the area with the silty facies of CN1 extending further south than CN2 (Figures 5.8b & c).

The silty facies has a characteristic vertical lithological sequence which is easily distinguished from geophysical logs, in particular, the density response, (Figure 5.8, Appendix 1, Figure 3).

The sequence coarsens upwards and grades from a highly carbonaceous silt at the base to a fine to very fine grained laminated sand at the top. Where CN1 and CN2 are superimposed, they are in sharp contact (Plate 5.6).

The silt at the base of the cycles is commonly clayey and highly carbonaceous, brown to dark brown and often contains sub-horizontal, slickensided shear planes and striated subvertical joints. Thin, irregular horizontal clay seams are also present in this basal zone.

The highly carbonaceous silt zone is generally less than one metre thick and passes vertically into a gradational silt zone which is up to six metres thick.

The gradational silt zone is characterised by a decrease in clay and carbonaceous content and an increase in discontinuous fine to very fine grained sand laminations upwards. The sand laminations are usually bedded at less than 5°.

Near vertical joints are common in this zone and towards the top of the zone these are sometimes infilled with fine sand from overlying beds (Plate 5.7).

As the number of fine sand laminations increases, the sequence gradually passes into a thin zone of indistinctly laminated fine to very fine grained sand and silty sand. This zone is commonly rooted and bioturbated with bedding dips up to 10°.

The contact with the overlying H zone is gradational at the south end of the deposit and sharp in the central and northern parts.

b) Sand facies - CN12, CN22

Towards the south, the silt facies CN11 and CN21 grade laterally into sand facies. The lateral gradational zone is between 500 metres and 2 000 metres. Lithologically the lateral gradation is characterised by the basal part of the silt facies becoming progressively more sandy. This sand facies thickens in a southerly direction, gradually replacing the silt facies (Appendix 2.).

The sand facies is variable in grain size, consisting of fine grained, poorly sorted, subangular silty sand containing up to 50% plant fragments. The plant fragments consist of organic debris such as twigs and leaves, as well as large wood fragments (SA5).

The thickness of clean sand is shown on Figure 5.9 and indicates sediment input from sources to the north, south and west.

5.3.2 Depositional environments

The lateral and vertical variations and associations observed within the Condowie Silt Member may be summarised as consisting of:

1. vertical coarsening upward cycles,
2. lateral coarsening towards the margins,
3. lateral association with fluvial sediments.

The Condowie Silt Member is associated with the alluvial/delta fan sediments of the Nantawarra Sand Member and represents deposition in a lacustrine delta fill environment.

. Lacustrine depositional environments

Fouch and Dean (1982) considered that it is difficult and potentially misleading to propose a set of physical and biological criteria that uniquely identify specific lacustrine environments because of the dynamic nature of these depositional sites. They considered that tectonics, bathymetry and water chemistry to be the most important mechanisms controlling sedimentation.

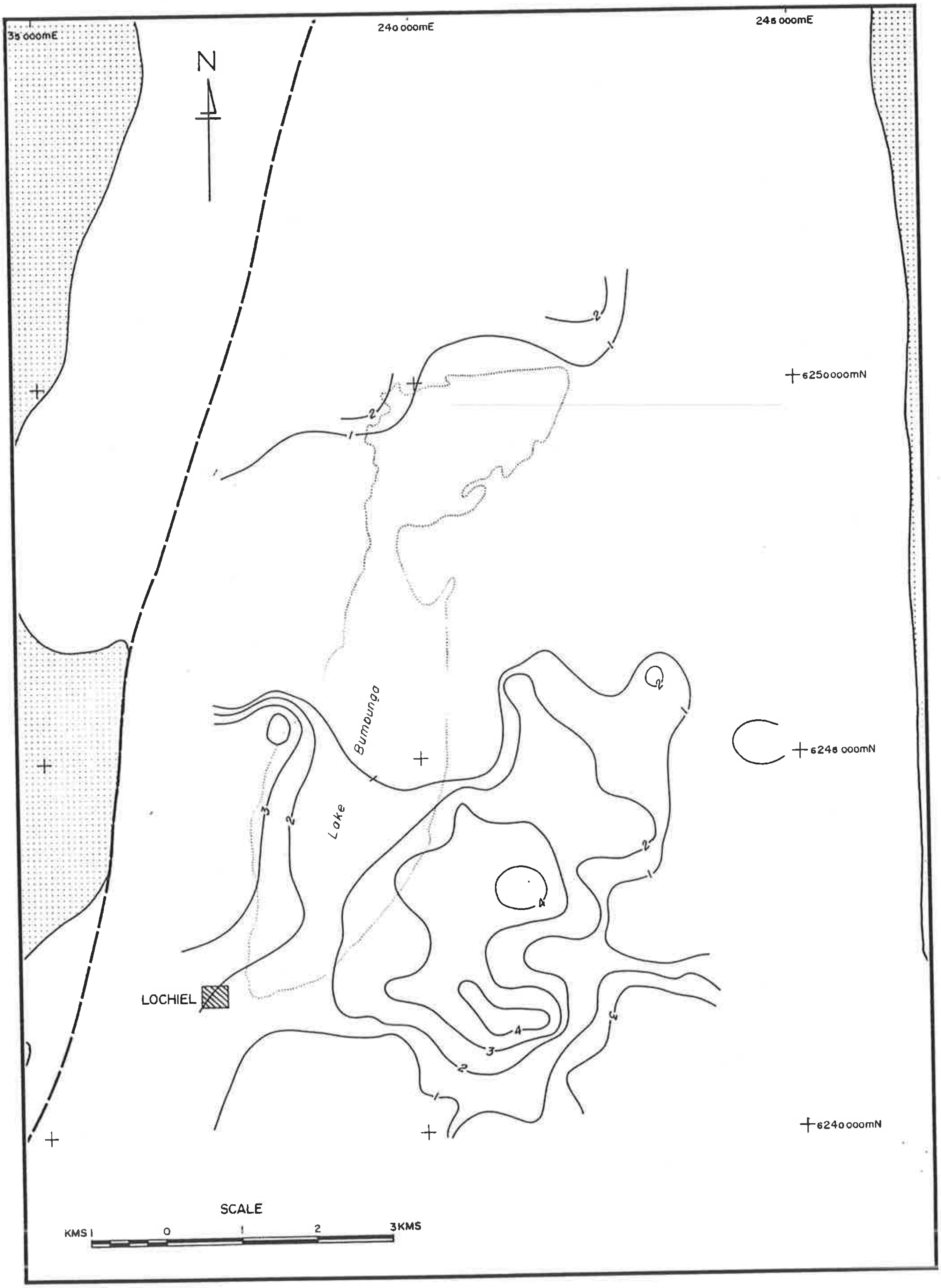


Figure 5.9 Condowie Silt - thickness and lateral distribution of clean sand.

Picard and High (1972a,b, 1981) also recognise the variability of lacustrine sediments and did not attempt to define a generalised model on the distribution and occurrence of sediment types. They also considered that climate was a major factor controlling sedimentation.

In the deeper parts of the lake basins, sedimentation is almost entirely from suspension and there is a distal fining of sediment away from the source. However, Picard and High (1981) noted that deposition in the centre of the lake :

- may not develop bedding,
- can be continuous and develop bedding,
- may develop bedding but bedding may be destroyed by organisms (Reading (1978) considered that because of this, bedding lamination will only be preserved in reducing conditions).

The result is that the sediments may be finely laminated or non-bedded.

Picard and High (1981) and Twenhofel (1932) considered the ideal lacustrine pattern to consist of an outer belt of relatively coarse grained shore deposits which gradationally become finer towards the centre.

This reflects the deltaic, progradational process which is common for lacustrine deposits as described by Reading (1978).

As lakes are ultimately filled, regressive processes dominate and the ideal lacustrine sequences grades upward from fine to coarse grained sediments. This corresponds to a lateral migration of environment from fine sediments occurring below wave base into coarser shore and on-shore sediments.

The transition from nearshore to offshore is generally abrupt and if wave action is limited, the nearshore to offshore phases can consist of organic, fine grained materials.

Visher (1965) suggested that lakes are filled by deposition of fine materials over the entire basin floor and thus extensive deposits of below wave base sediment will occur and shore environments will be restricted and irregular.

- Summary of depositional environments and controlling processes

CN3 represents a transitional phase of sedimentation in which the depositional environment changed from a floodplain distributory environment to an essentially lacustrine environment. As such CN3 consists of numerous interbeds of materials from each of these environments.

These have been categorised into three depositional facies, fan delta sand, lacustrine silt and marginal forest/swamp carbonaceous sand. A schematic representation of the depositional setting for the Condowie Silt Member is presented on Figure 5.10.

CN1 and CN2 represent deposition during a relatively stable tectonic period. This allowed for extensive areas of

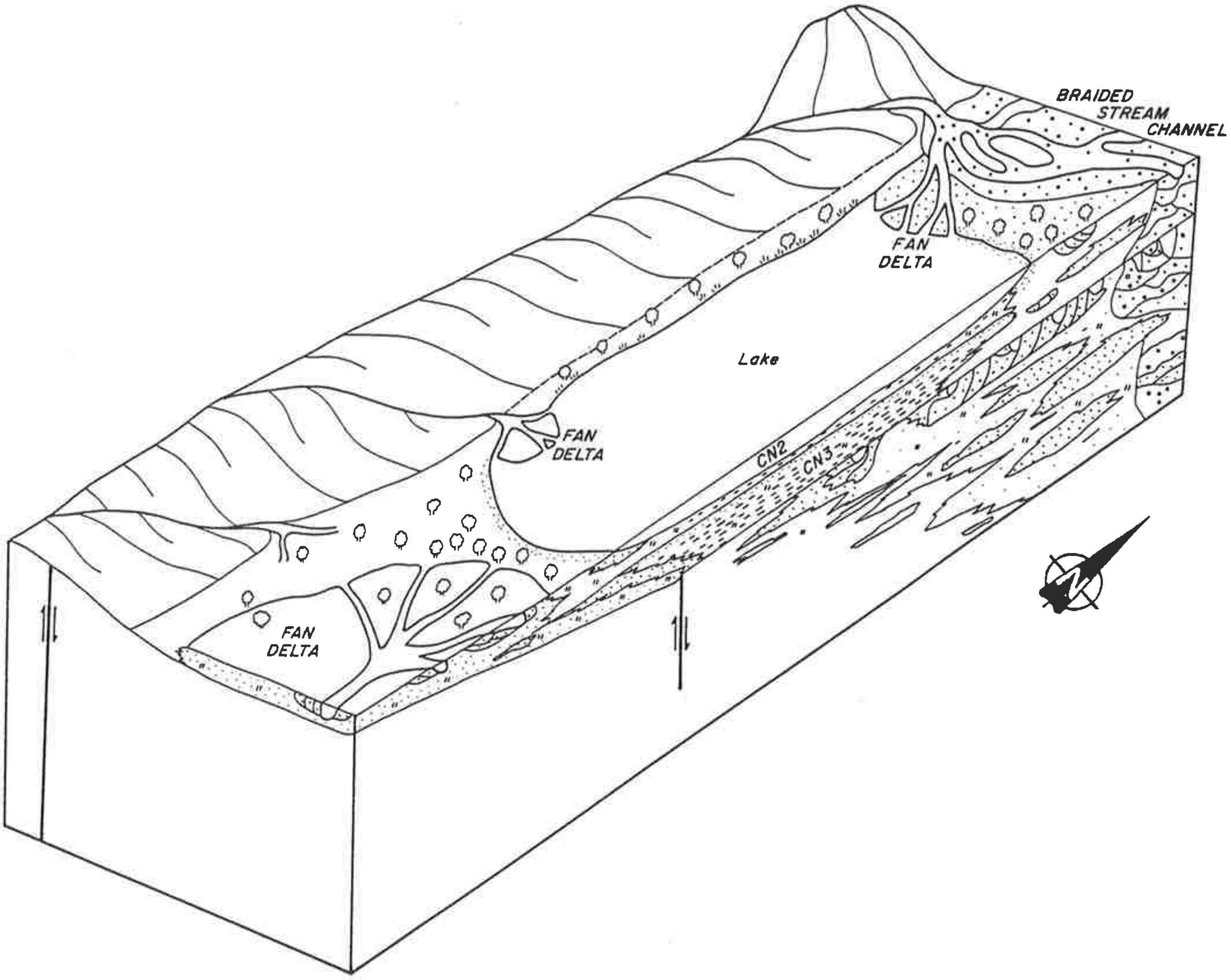


Figure 5.10 Depositional setting for the Condowie Silt Member

lacustrine sediments to be deposited over most of the area but with a marginal forest/swamp facies being present in the south.

These sediments represent cyclic phases of lacustrine delta fill. During this sedimentation episode, the northwestern source had little influence on the depositional patterns. The major source of sediment was from a fan delta to the south but with sediments also entering from the western margin.

The gradation between lacustrine and fan delta sediments is characterised in vertical profile by a gradual increase in sand from the base upwards. This trend is consistent with prograding sequences which typically coarsen upward, Galloway and Hobday (1983).

5.3.3 Properties of weak zones

The silty facies of the Condowie Silt Member is a firm to very stiff, clayey silt and silty clay of low plasticity and high liquid limit. A summary of the intact properties is presented on Table 3.1 (page 55) with the location of test sites and results of strength testing shown on Figure 5.11.

The weak zones are characterised by polished partings and are stratigraphically located at the base of coarsening upward lacustrine cycles. This stratigraphic location coincides with a relatively high clay content and is related to deposition in the distal part of the lake.

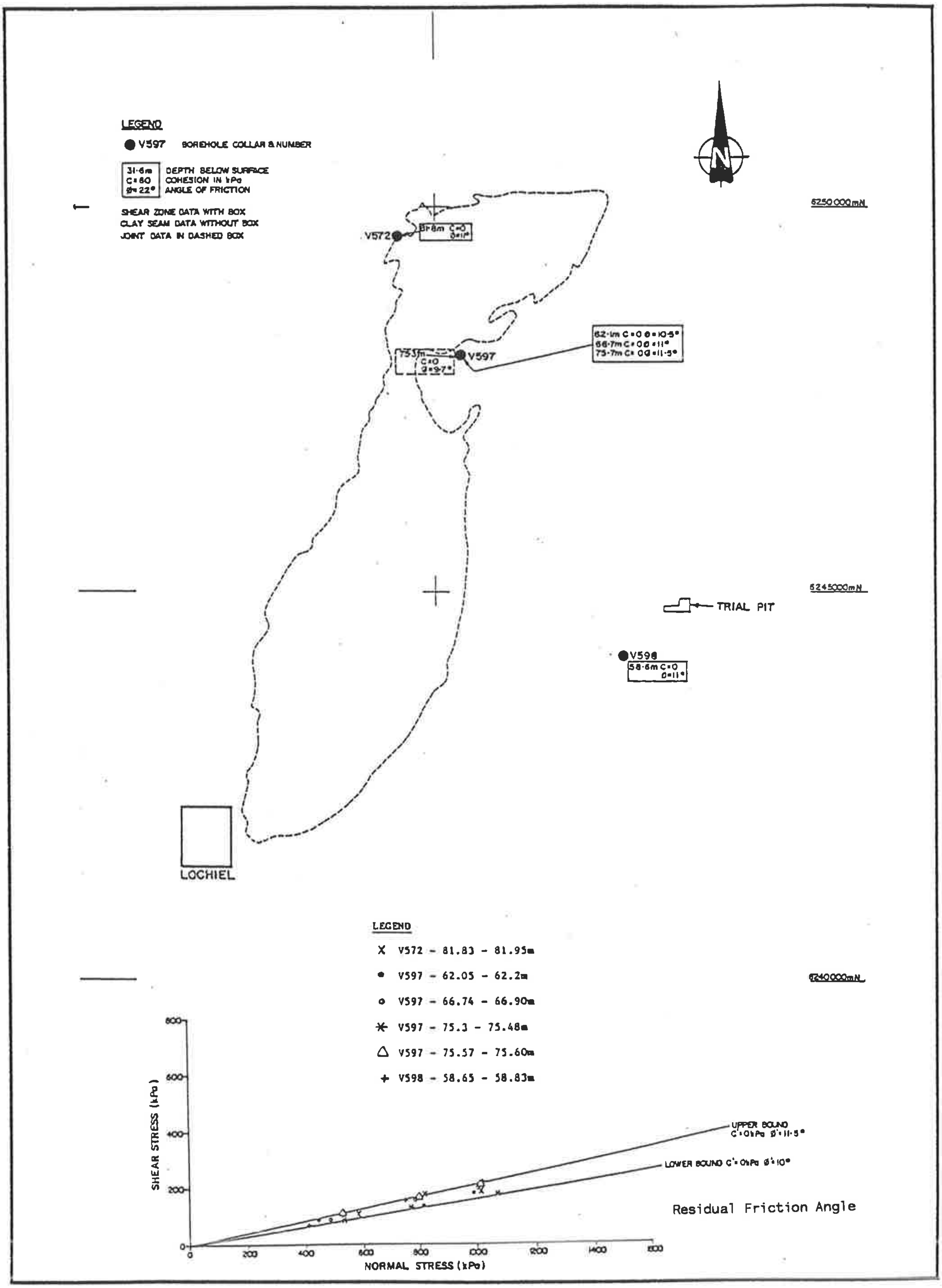


Figure 5.11 Condowie Silt Member weak zones - Location of test sites and summary of results of strength testing (testing performed by Coffey and Partners Pty Ltd, 1988).

This type of weak zone is of the progradational type discussed in section 3.5.2.

From drillcores alone it is not possible to conclude on the lateral continuity of these weak zones. However, their stratigraphic position and relationship with CN2 and CN2 implies that their distribution coincides with the silty lacustrine facies.

5.4 Bumbunga Sand Formation - Kooliata Coal Member

The Kooliata Coal Member conformably overlies both the Darnleigh Park Sand Member and the Condowie Silt Member. The coal zone has a cumulative thickness of about 15 metres over most of the area but the thickness increases towards the margins (Figure 5.12).

This trend reflects a change from silt and coal in the centre, to sand at the margins. Figure 5.13a, b, c, d and e show the lateral facies relationships and thickness for all units within the Kooliata Coal Member.

The coal zone laps onto basement on the southern and eastern margins, is continuous with Bumbunga Sand Formation equivalents to the north and in faulted contact with basement to the west.

The Kooliata Coal Member correlates with the coal bearing horizon in the Bowmans deposit although Harris (1987) concluded from palynological dating that the coals in the Bowmans and Clinton areas were slightly older. The Kooliata

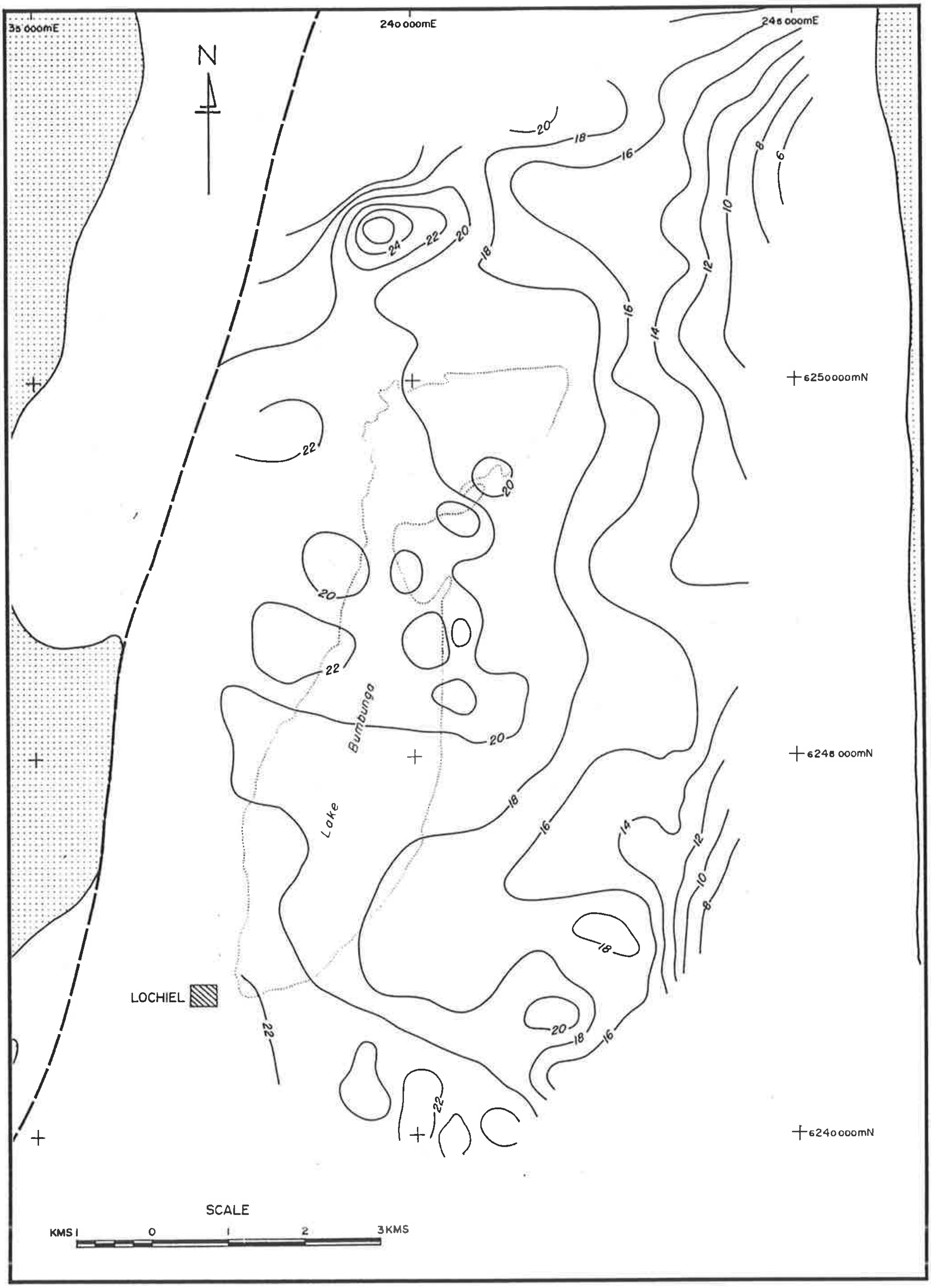


Figure 5.12 Thickness and lateral distribution of the Kooliata Coal Member.

Coal Member represents a major coal forming episode in the Lochiel area with coal formation being periodically interrupted by deltaic sedimentation entering the area from the west, northwest and southeast.

Three correlatable coal bearing zones separated by well defined interbeds of sand, silt and clay have been defined. The coal zones are named H, G, and F with the respective interseam sediments of GH and FG (refer to Figure 5.13f). Vertical and lateral lithological variations and geophysical log response models are presented in Appendix 2 and a geophysical correlation section in Appendix 3.

5.4.1 H Zone

The H zone conformably overlies the Condowie Silt Member in the south and the Darnleigh Park Sand Member to the north. It ranges up to 13.5 metres thick in the south where dominated by a sandy facies but over the majority of the area, it maintains an average thickness of about 6 metres (Figure 5.13a). The thickness distribution reflects the trends of CN1 and CN2.

- Lithology and lateral facies distribution

The H zone can be divided into a clean coal facies and a carbonaceous sand facies (SA5). These two facies are laterally gradational and the variation in vertical profile is represented in Appendix 3.

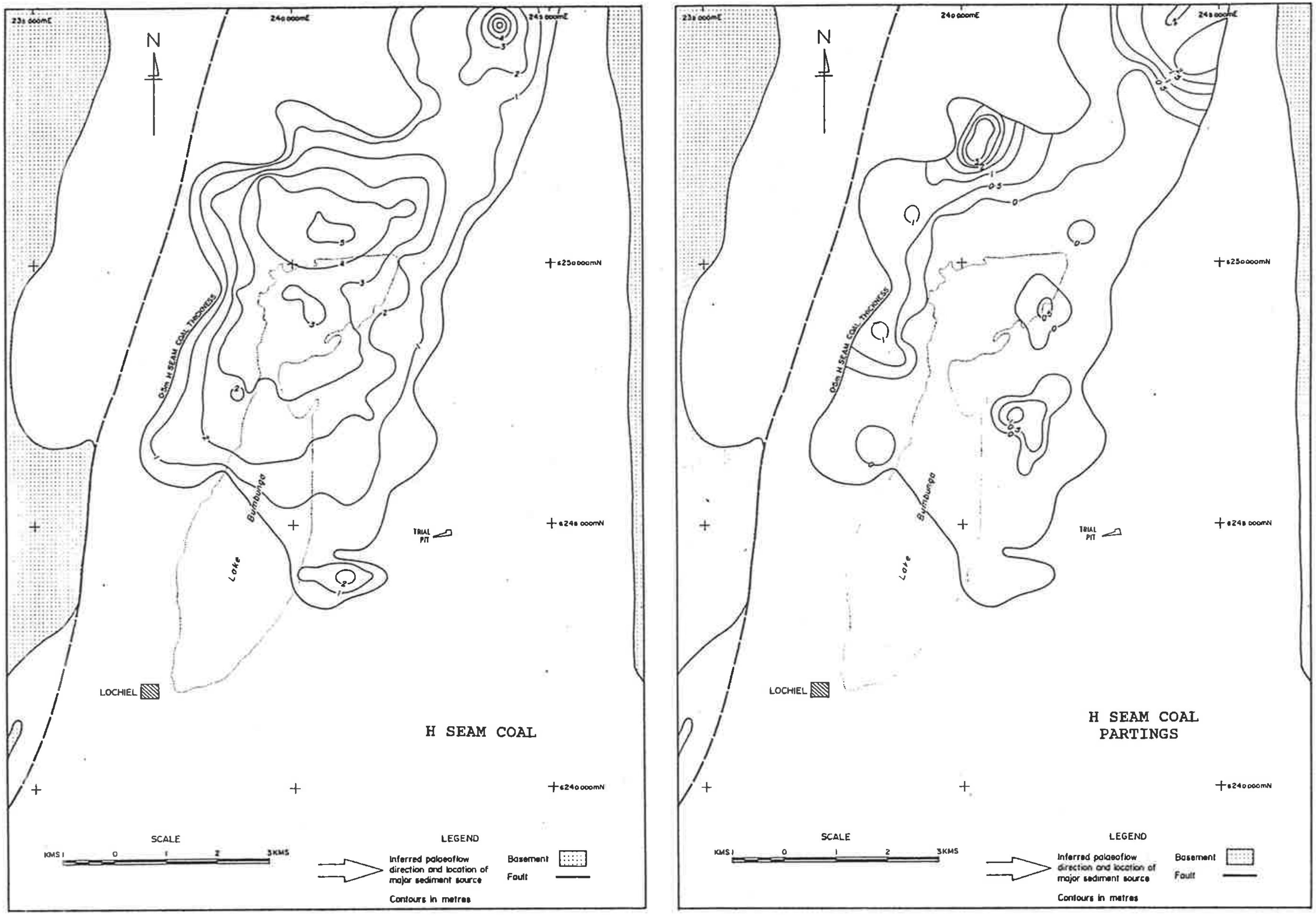


Figure 5.13a Kooliata Coal Member - thickness of H Zone coal and H Zone coal parting.

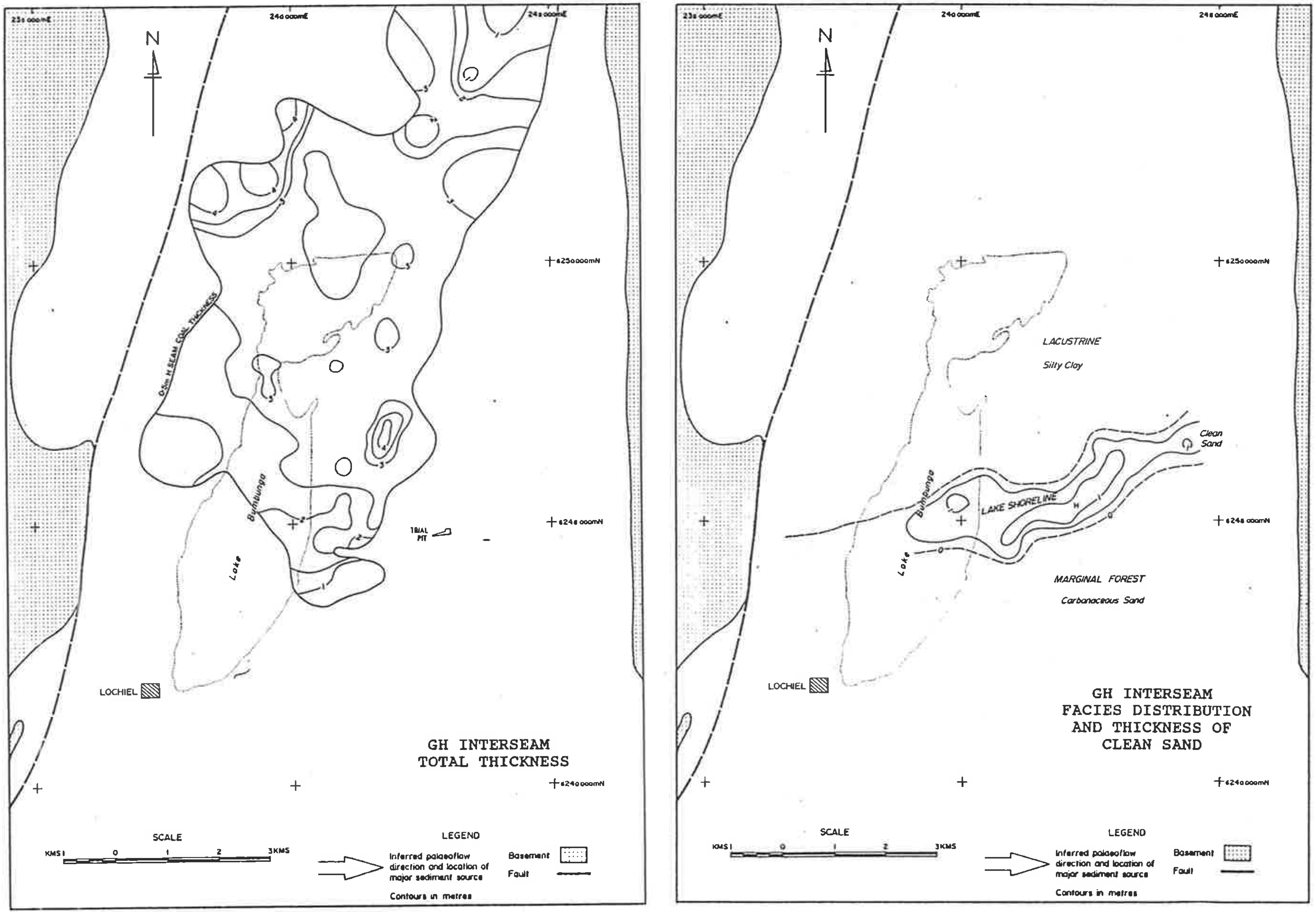


Figure 5.13b Kooliata Coal Member GH Interseam sediments - Total thickness and facies distribution and thickness of clean sand.

Figure 5.13c Kooliata Coal Member - thickness of G Zone coal and G Zone coal parting.

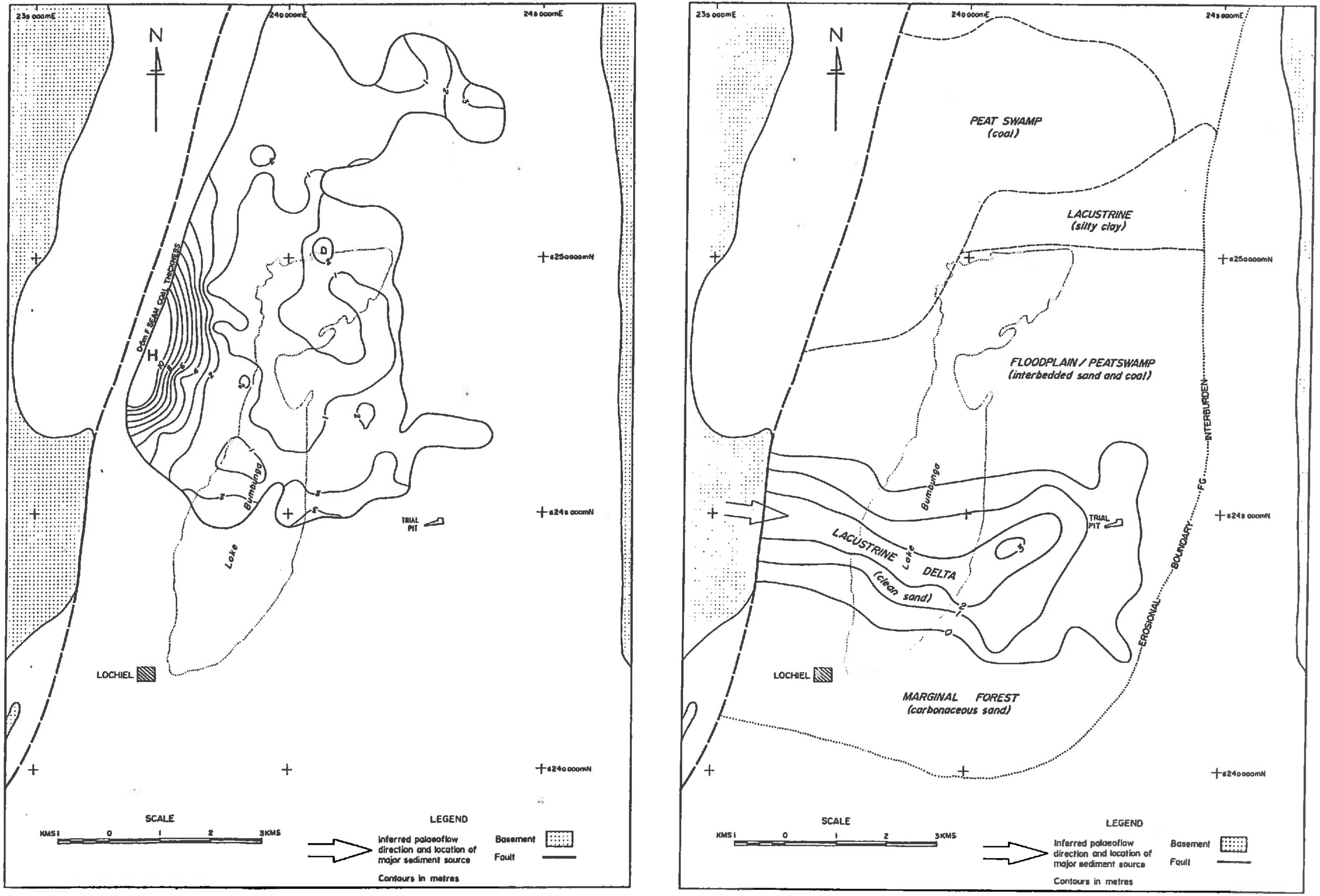


Figure 5.13d Kooliata Coal Member FG Interseam sediments - Total thickness and facies distribution and thickness of clean sand.

Figure 5.13e Kooliata Coal Member - thickness of F Zone coal (no partings occur in the F seam).

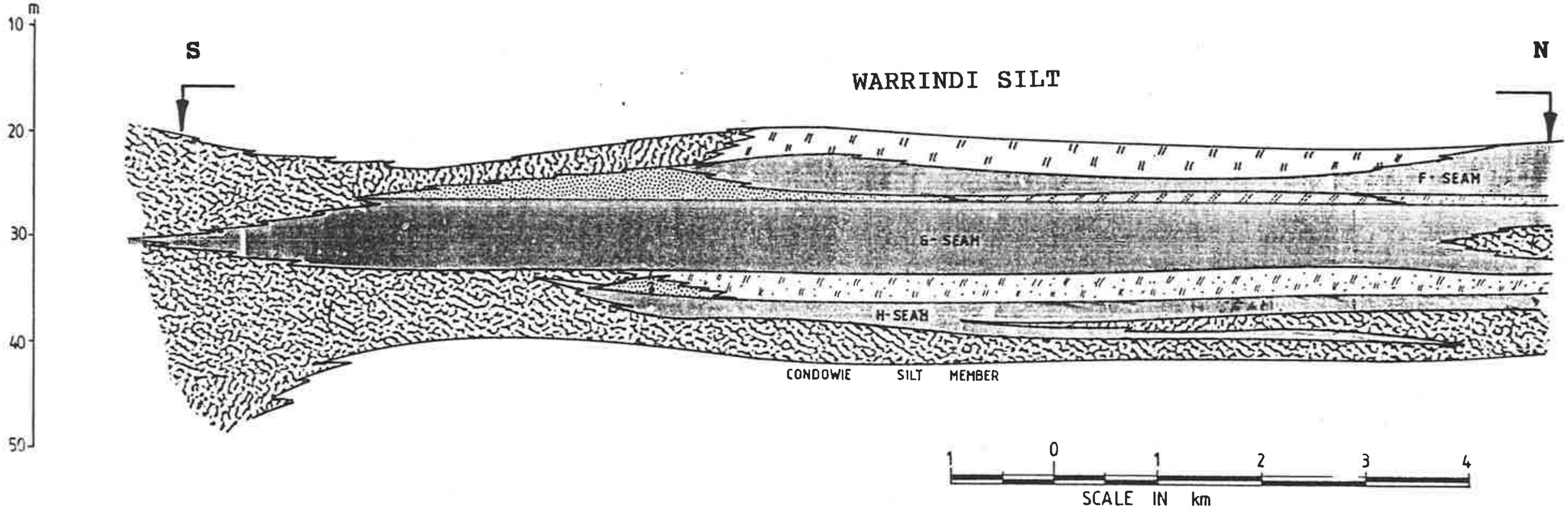


Figure 5.13f Detailed Stratigraphy and lateral relationships for the Kooliata Coal Member. Refer to Appendix 2 for legend.

a) Coal facies

The coal facies is composed of carbonaceous material with less than 30% ash on a dry basis. The coal attains a maximum thickness of 5.5 metres at the northern end of the lake. In this area the coal is in sharp contact with both the Condowie Silt Member and the Darnleigh Park Sand Member. Elsewhere, the coal grades down into a carbonaceous, silty sand (SA5) of the H zone. The upper contact of the H seam is generally sharp and the top 0.5 m of coal is often extensively burrowed with the burrows infilled with fine white sand (Plate 5.8).

The coal in the H seam consists of large woody fragments in a fine grained matrix and often vertical root structures are observed in the core.

Only minor partings of carbonaceous, sandy silt are present within the seam. The partings generally thicken towards the north and northwest and grade into fining upward cycles of delta fan channel sand. Partings of highly carbonaceous, fine grained sandy silt with thin discontinuous beds of silty clay also occur in the central areas. These appear to be isolated from the marginal sediments.

b) Sand facies

The coal seam grades laterally into a sandy coal facies (SA5), which is equivalent in lithology to the sand facies of the Condowie Silt Member and also the carbonaceous sand facies of the Nantawarra Sand Member. It consists of large plant fragments, including roots, in a fine to medium grained, poorly sorted sand matrix.

On the basis of trends in the vertical profile, the H zone may be divided into three laterally gradational areas, see Appendix 3. These trends correspond to changes in the relative proportions of sand and carbonaceous matter and have been identified from interpretation of the apparent density logs.

1. At the southern end the vertical profile becomes more carbonaceous downward and thin, dirty coal seams may be present. In the central and south-central area, the vertical sequence shows little or no variation in vertical profile and no coal occurs in this area.

2. Farther north, the vertical profile becomes more carbonaceous upward and grades into the H seam coal.

3. In a relatively small area at the northern end of the lake, the sequence consists almost entirely of H seam coal.

These variations are considered to be the result of the interaction of sediment sources, primarily from the south and west. The increase in carbonaceous content upward reflects a waning of the source whilst the decrease upwards indicates an increase in sediment input. Given that these two source areas are subject to the same climatic controls it can be concluded that the variations relate to variations in tectonic movement about the source areas.

5.4.2 GH interseam sediments

The GH interburden conformably overlies the H zone with a sharp conformable contact, the thickness distribution is presented on Figure 5.13b.

The unit reaches a maximum thickness of 6.3 metres to the northwest but averages about 2.5 metres elsewhere. The GH interseam sediments wedge out to the south, and are laterally equivalent to Bumbunga Sand Formation equivalents to the north.

. Lithology and lateral facies distribution

The lateral facies distribution and thickness of clean sand is presented on Figure 5.13b. Over most of the area the GH interseam sediments consist of a silty facies but a linear, east-west trending sand body is present in the centre of the area. South of this sand body the GH grades laterally into a SA5 facies which is indistinguishable from the H zone.

a) Silty facies

The vertical sequence of the silty facies is consistent over the area. It may be divided into two parts, a basal section of sandy silt and an upper section consisting of a coarsening upward cycle.

The basal section consists of about 0.8 metres of light grey to brown, very fine grained silty sand or sandy silt. It is intensely bioturbated with many of the burrows extending into the top of the H seam (Plates 5.8 and 5.9a,b).

Often roots are present within the zone and at V653 a large stump was intersected. The presence of these stumps and the bioturbation suggest a drowning of the peatswamp by relatively shallow water.

Overlying the basal section with a sharp contact are 2.5 metres of fine grained sediments forming a coarsening upward cycle.

This cycle begins with a dark brown, slightly carbonaceous silty clay and grades upwards to a laminated, fine to very fine grained, micaceous, silty, fawn sand and carbonaceous brown silt (Plate 5.10). Often a thin layer of fine grained, white sand is present at the top of the cycle. This sand layer is often penetrated by small rhizomes originating from the G seam coal above but no large roots are present.

Of particular interest is the presence of a polished shear zone at or near the contact between the two lithologies. This shear zone is discussed in section 5.4.7.

The characteristics of these sediments are consistent with the those of lacustrine environments as discussed previously.

b) Sandy facies

In the central part of the area the GH interseam consists of a basal section of light brown to fawn, fine to medium grained, moderately sorted, subangular sand with rare well rounded coarse grains. This sand grades upward into a laminated section consisting of light brown fine sand and medium brown, slightly carbonaceous silt. The contact with the overlying G seam is usually sharp. This sand body is elongate in an east-northeast direction and appears to originate from the western margin.

The lateral gradation between the clean sand facies and the silty facies is characterised by a progressively higher proportion of silt and clay towards the north.

5.4.3 G Zone

The G seam is present over most of the area and has an average thickness of about 6.5 metres (Figure 5.13c). The seam thins towards the margins and is split by a parting at the southern end. In this area the G seam is divided into the G (lower seam) and G1 (upper seam). As with the other seams it grades into carbonaceous silty sand (SA5) at the margins.

. Lithology and lateral facies variation

a) G Seam Coal

A number of coal lithotypes are present in the G seam with earthy, fibrous and woody types common. The vertical profile generally contains woody coals at the base with the fibrous and earthy types occurring higher in the sequence.

Christophel (1983) concluded from examination of a limited number of samples of plant macrofossils from the southern part of the area that the coal represents a swampy environment with few emergent trees.

From a microscopic examination of the coal, Springbett (pers. comm. 1989) found a high proportion of detrital plant matter and suggested that the seam is allochthonous.

This is supported by the absence of a well developed seat earth and large tree roots at the base of the coal. Springbett also mapped the distribution of coal lithotypes. In general he found a high degree of lateral consistency and was able to correlate specific lithotypes for several kilometres.

At both the southern and northern parts of the deposit the G seam is split by partings (Figure 5.14c). These partings thicken towards the margins of the area forming a wedge shape.

The partings to the south consists of carbonaceous sandy silt which gradationally becomes more sandy towards the margins.

b) G1 seam coal

The G1 seam is present at the southern end of the area. It has an ovoid shape with the coal gradually thickening to a maximum of 3.0 metres at the centre.

The coal is generally fibrous and woody with small fragments of charcoal common. Towards the margins of the seam, the coal appears to be fractured giving it a friable texture. The coal is also characterised by inclusions of fine sand and silt as pods or discontinuous beds near the contacts, especially towards the margins.

The upper contact is sharp and as with the F seam, a fusain-rich zone is present at the top of the G1 seam. The lower contact is also sharp and is sometimes inclined at up to 20°. A fusain-rich band is also often present directly below the G1 seam.

. Structure

A feature of the G Seam at the V653 bulk sample site is the presence of near vertical extension joints (Plates 5.11 and 5.12). These joints are planar with very irregular sides. Many extend through the entire thickness of the G seam.

The joints are infilled with either a very fine coal mass or a fine to medium grained light brown sand and appear to be parallel. However, is was not possible to orient the core samples so the orientation of these joints could not be determined.

No such extensional joints were present at the trial pit site.

5.4.4 FG Interseam sediments

The sediments between G zone and F zone have an average thickness of about 1.2 metres but thicken radially towards the margins (Figure 5.13d). These sediments were intersected in the Trial Pit.

. Lithology and lateral facies variation

The distribution of facies within the FG interseam is presented on Figure 5.14. Four facies are present, clean sand; anastomosing sand and coal; and two silty carbonaceous sands, one north and the other south of the clean sand facies.

a) Clean sand facies

The sand body is elongate in an east-west direction, thinning to the eastern, northern and southern margins and continuous to the Ardrossan Fault to the west.

Where the sequence is thickest, it comprises three parts.

1. The basal part consists of 0.35 metres of dark brown, moderately carbonaceous, medium grained sand equivalent to the SA3 type. This sand has a sharp, planar contact with the underlying G seam coal and is gradational upwards. Bedding in the basal part is indistinct or absent.
2. The basal zone is overlain by 2.5 metres of clean, white medium to coarse, moderately well sorted, rounded to subangular quartz sand which becomes finer grained upwards. The sand is bedded at 15^{o} in the lower section and 30^{o} towards the top. Bedding is characterised by variations in grain size between beds and rounded pyrite nodules up to 20 mm in diameter are common.
3. The clean sand facies grades into a transitional zone consisting of interbeds of silty, sandy coal and medium grained, ripple crossbedded sand with beds dipping at 30^{o}. In the trial pit, which is located on the margin of the sand body, the interseam sediments consist of 0.6 metres of SA2 type sand.

The association with the Ardrossan Fault, the geometry of the sand body and the lateral facies relationships suggest that the FG interseam represents a delta fan depositional environment. Furthermore, the controls discussed for the GH interseam sediments appear also to apply to FG.

b) Anastomosing sand and coal facies

The clean sand facies grades into a broad zone of anastomosing beds of clean medium grained sand and sandy coal (refer to Plate 5.13).

This zone averages 1.0 metre thick and thins and becomes less sandy towards the north. The anastomosing sand and coal facies grade vertically into the overlying F seam coal and is in sharp contact with the underlying G seam coal.

. Structure

At the V653 bulk sample site the anastomosing facies was intersected by near vertical extensional joints (Plate 5.14). These joints were infilled with a very fine grained coal and are continuous with similar joints in the G seam.

It is apparent that at least two tensional episodes caused the formation of these joints. The first being characterised by coal infilled joints and the second by sand infilled joints (Plate 5.12).

c) Silty facies - north

Farther to the north, the anastomosing facies becomes increasingly carbonaceous and silty and at the northern end of the area it consists of light brown, indistinctly laminated clayey silt with some charcoal fragments. In a small area to the northeast the FG interburden thickens and consists of laminated silt and fine grained sand.

d) Silty facies - south

To the south, the clean sand facies grades laterally into a silty carbonaceous sand facies. The FG interseam sediments in this area were also influenced by sources to the east and south. The sediments consist predominantly of fine grained, well sorted, silty, carbonaceous, quartz sand of the SA3 type.

Laterally the lithology grades through the SA6 type towards the Clean sand facies and into a SA3 to the south and east. The sediments generally contain some fusain fragments at the top of the sequence.

5.4.5 F Zone

The F zone averages about 5 metres in thickness over most of the area (Figure 5.13e). As with the H and G seams the F seam thins radially towards the margins where it grades into a SA5 facies.

. Lithology and distribution of sediment types

a) F seam

The F seam is present in the central and northern part of the area. The coal varies considerably in thickness with a 1.6 metre vertical change over a 4.0 metre horizontal distance being observed at the V634 large diameter site. The seam thickness averages 2.0 metres but ranges between 2.3 metres and 8.0 metres.

The coal is fine grained and earthy or fibrous with a layer of hard, black and brittle charred coal, (fusain), often present at the top of the seam. Fusain is formed from a number of processes but forest and peat fires are the most common mechanisms, ICCP (1971). It appears that this mechanism caused the considerable variation in the thickness of coal in seam F.

The upper contact with the overlying Warrindi Silt is usually sharp and in addition to the fusain zone it is also often lined with a thin band of fine grained clean sand.

5.4.6 Depositional environments

The Kooliata Coal Member is made up of two basic facies associations:

(1) Coal zone facies association

(2) Interseam sediment facies association

The depositional settings for each of these associations are illustrated on Figure 5.14. In addition a geophysical and lithological model for the Kooliata Coal Member is presented in Appendix 2.

The continuity of the coal zone has enabled the definition of the relatively thin interbeds which on the current drilling spacing would otherwise have been impossible. The definition of these interbeds has also enabled a reliable appraisal of the nature of lateral facies variations and trends for fan deltas in the Lochiel area and possibly also for the St Vincent Basin.

. Coal Facies

The controlling factor as to whether a backswamp area will become a peatswamp or an open lake depends on the position of the groundwater table (Diessel, 1980). Plant growth and peat accumulation can only occur in a limited range of water depths. A lack of water cover will enable aerobic decay processes to quickly disintegrate any plant debris, while deep water will not allow plant growth and only transported carbonaceous material will accumulate.

Once the peatswamp is established, the passage of sediments into the area is restricted by the sediment trap of vegetation.

All coal seams in the area have a characteristic facies association consisting of a coal and a carbonaceous sand facies. This association is indicative of a sediment trap mechanism as illustrated on Figure 5.15.

b) Interseam sediments

Both the GH and FG interseam sediments contain elongate, east-west trending bodies of clean sand. These lithologies are considered to represent a fan delta entering the area from an uplifted area to the west. Of particular note is the coincidence of the trend of the facies with an inferred basement structure. It is probable that movement along

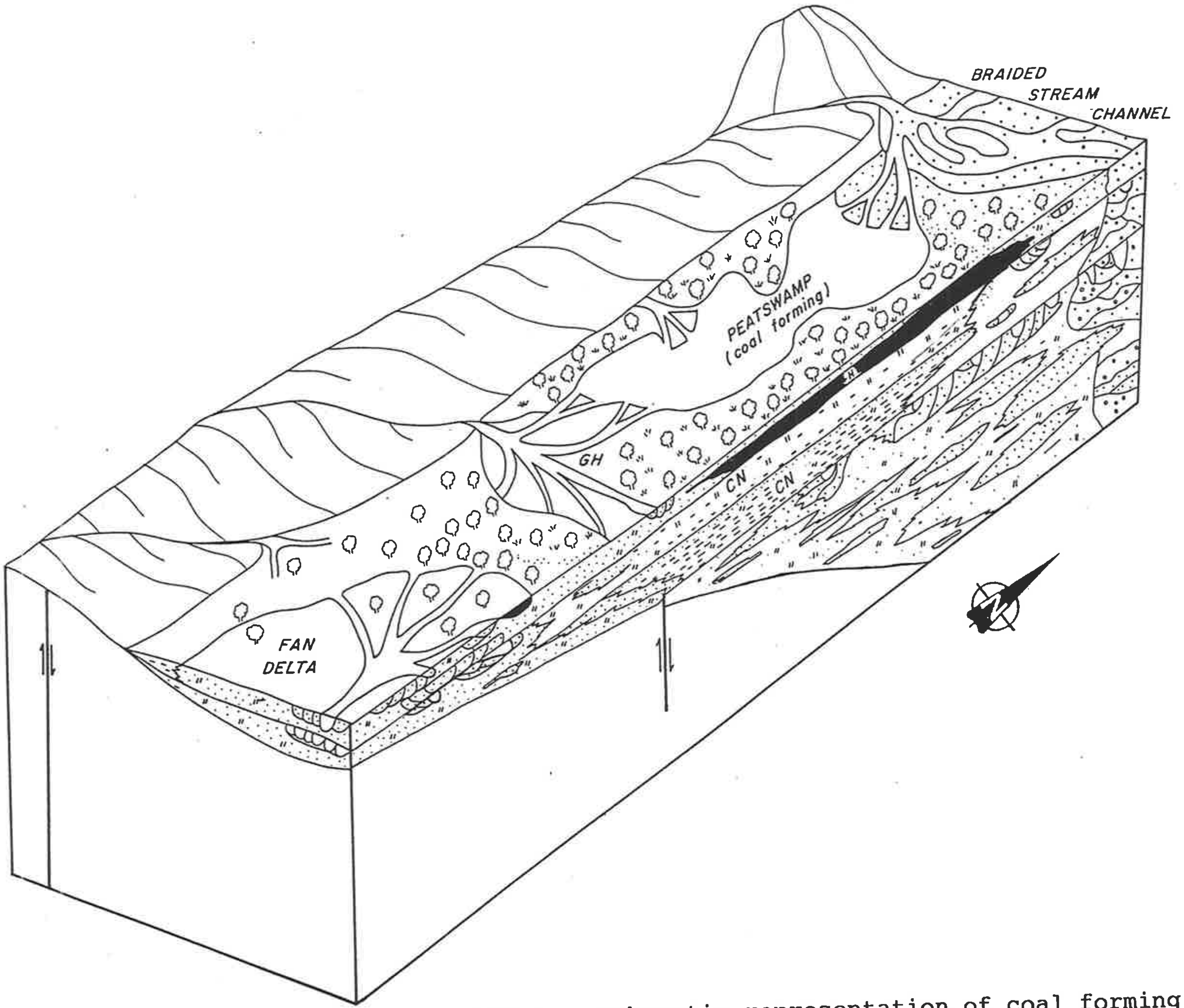
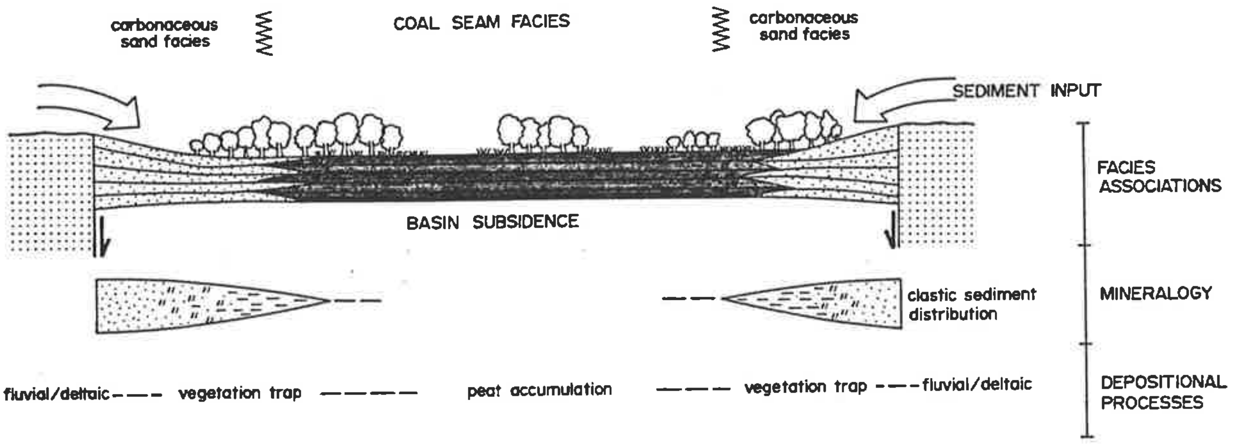


Figure 5.14 Kooliata Coal Member - Schematic representation of coal forming depositional environment.

Figure 5.15 Mechanism controlling peat accumulation



this fault (north side down) led to drowning of the peatswamp (H seam and G seam) and its replacement with a shallow lake.

The lateral and vertical facies distribution are consistent with the infilling of this lake. Two stages of infilling are recognised for the GH Interseam sediments. The first stage was associated with the fan delta to the west and the second stage with sources to the north and south. The progradation of the latter produced the characteristic upward coarsening sequence.

5.4.7 Synthesis of geological controls and engineering properties

- Factors affecting porewater movement

Transmissivity of the G sseam coal was 5 m^3/day/m with a relatively high hydraulic conductivity of 7.1 m^3/day/m^2, refer to Figure 3.13 (page 77). Based on the relatively the uniform grain size recorded from core logging it is expected that similar properties are likely where the clean sand facies is present. However, as only one pump test was completed it is not possible to draw direct conclusions as to the lateral variations in hydraulic properties.

- Properties of weak zones

A weak zone characterised by a polished shear plane was identified within the GH interseam sediments. The lateral and stratigraphic location together with a summary of the residual shear strength is presented on Figure 5.16.

As with the Condowie Silt Member weak zones, the GH weak zone occurs at the boundary of two distinct sedimentary cycles. In particular the weak zone occurs at the base of a coarsening upward cycle which was formed by lacustrine infill processes.

The higher shear strength results for V680 and V683 related to shear along intact material and the presence of surface irregularities respectively. Discounting these two results, the remaining shear plane results show :

- uniformly zero cohesion,
- friction angle increasing from west to east.

5.5 Bumbunga Sand Formation - Synthesis of geological processes controlling the properties of weak zones and porewater movement

In the Lochiel area, the vertical sequence consists of one fining upward allocycle (Figure 5.17). From the base, this cycle is comprised of braided stream-fan delta-lacustrine-peatswamp depositional environments.

Sediments for the Bumbunga Sand Formation were supplied from major sources of sediment which originated from the northwest, west and south.

For the Nantawarra Sand Member, the depositional axis runs parallel to the Ardrossan Fault with the depocentre located against this fault in the northwest of the area. This strongly suggests that the Ardrossan Fault had a major control on sedimentation and, in the sense of Beerbower (1964) and McLean and Jerzykiewicz (1978), controlled the allocyclicity of the Nantawarra Sand Member.

The Nantawarra Sand Member comprises three laterally equivalent and gradational facies. The gradation between each of these is across a northeast-southwest trending axis and these two axes coincide with two inferred fault lines. Furthermore, these inferred fault lines also coincide with major facies changes for both the Condowie Silt Member and the Kooliata Coal Member and mark the southern limit of the

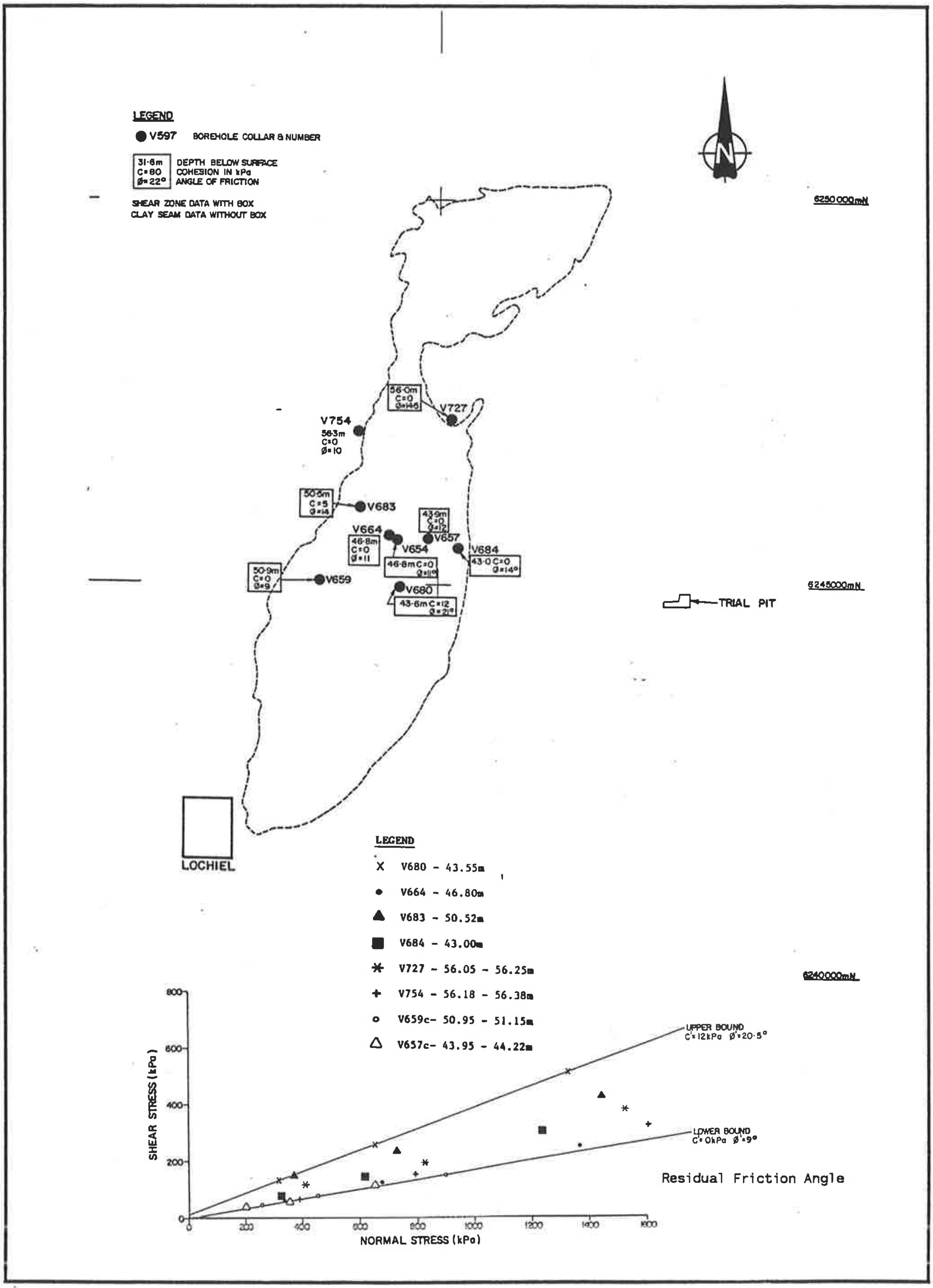


Figure 5.16 Kooliata Coal Member - Location of test sites and summary of results of strength testing (testing performed by Coffey and Partners Pty Ltd, Rept., 1988).

Darnleigh Park Sand Member. On this basis it is considered that these structures provided the major autocyclic controls for the Bumbunga Sand Formation.

- Effects of depositional controls on the properties of weak zones and porewater movement.

For the Bumbunga Sand Formation it is concluded that tectonics was the major geological control. Movement along the Ardrossan Fault controlled the timing, rate and location of sediment input whilst the east-west trending basement faults appear to have controlled the distribution of these sediments.

The depositional models presented on Figures 5.3, 5.10, 5.14 provide the basis for predicting the distribution of aquifer zones. In general they coincide with the braided stream and distributory part of the fan delta environments.

Weak zones occur at the boundaries between distinct depositional episodes. Lithologically they occur at the base of coarsening upward cycles and these cycles have been shown to represent lake infill processes and a lacustrine depositional environment. They are considered to represent progradational weak zones as discussed in section 3.5.2 (page 70).

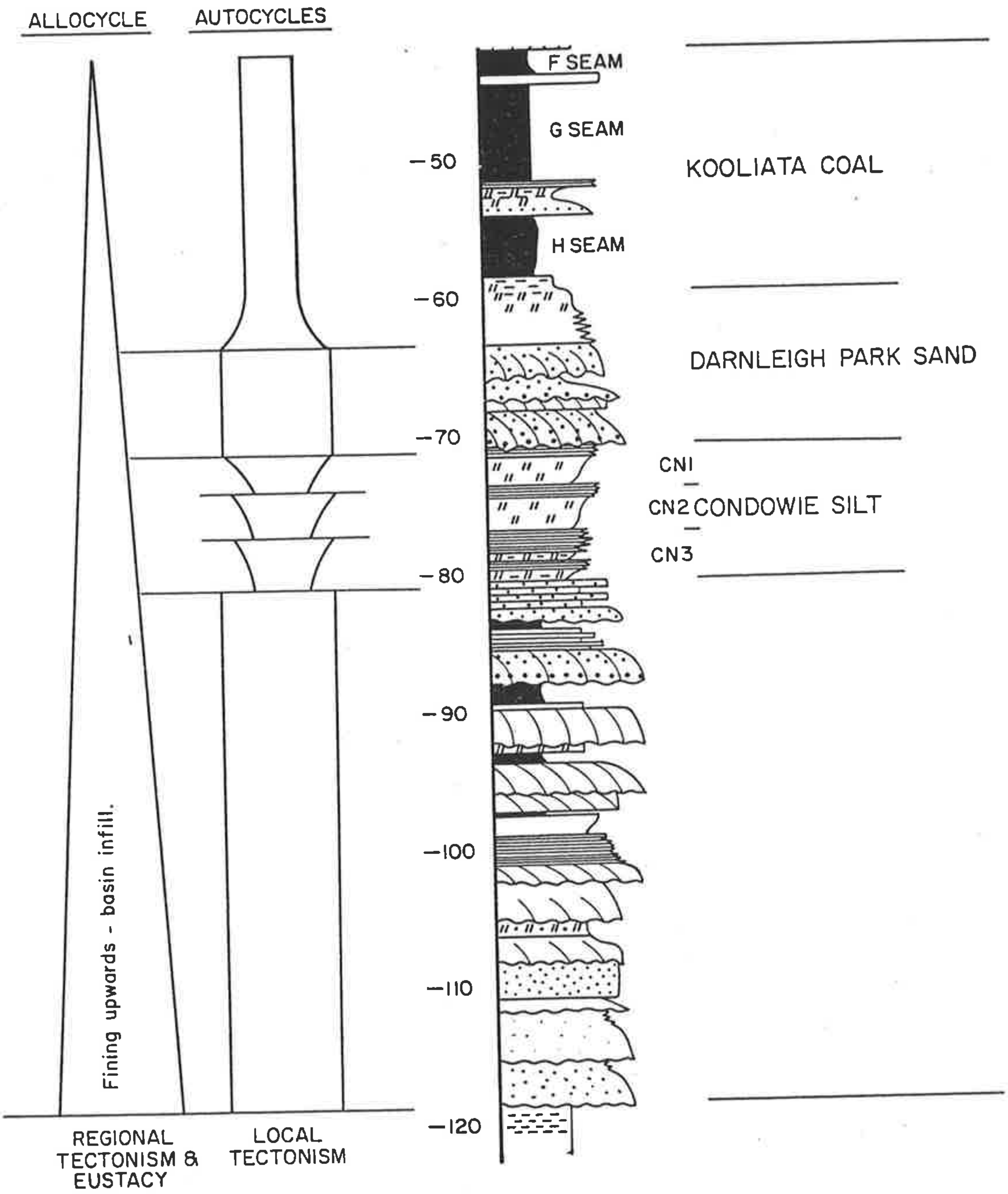


Figure 5.17 Bumbunga Sand Formation - Definition of allocycles and autocycles within the stratigraphic profile.

CHAPTER 6.0 ANALYSIS OF OVERBURDEN SEDIMENTS

The purpose of this Section is to analyse the overburden sediments, however, as discussed in Chapter 2 the analysis is confined to those formations which are associated with coal deposition. The aim is to :

- describe the lithology and lateral variation of the sediments,
- identify the major factors controlling sedimentation and develop models which assist in interpreting these controls,
- define the relationship between the key geological features (identified earlier as discontinuities and porewater movement) affecting slope stability and characterise these features in terms of their engineering properties.

The stratigraphy is summarised on Figure 3.3 (page 53). The overburden sequence comprises two formations, the Warrindi Silt Formation at the base overlain by the Tarella Silt Formation (Figure 6.1).

6.1 Stratigraphic nomenclature

Palynological analysis by Harris (1982, 1983, 1986) gives the Warrindi and Tarella Silt Formations an Oligocene-Miocene age. Formations which fall into this time range are the Rogue Formation (south, Stuart, 1970) and the Snowtown Sand (north, Alley, 1973). However, neither of these two provides a good lithological correlation.

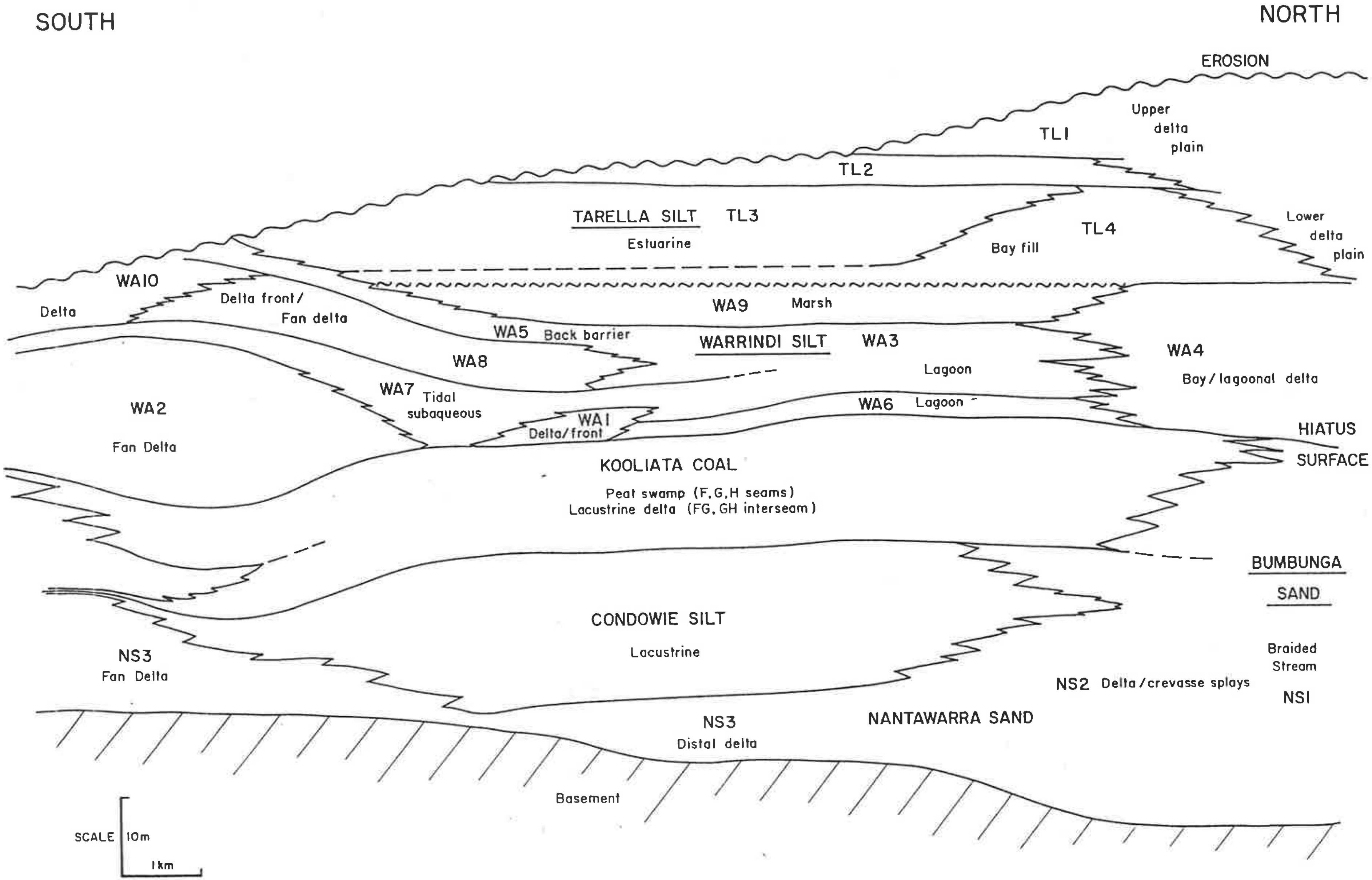


Figure 6.1 Detailed stratigraphy, lateral continuity and lithology for Warrindi Silt and Tarella Silt Formations.

The Rogue Formation contains a significant proportion of calcareous (biogenic) and glauconitic sediments; none of these are present in either the Tarella or Warrindi Silt Formations.

The Snowtown Sands appear to represent sandy and carbonaceous, fluvial delta plain sediments (Alley, 1973), however, more recent analysis by Alley (1990) suggested that there is also an estuarine influence. The Warrindi and Tarella Silt Formations represent predominantly fan delta, delta front and estuarine environments, but, while the estuarine influence tends to favour an association with the Snowtown Sands, lithologically they are quite distinct.

On the basis of the discussion above it is, therefore, appropriate to assign both the Warrindi and Tarella Silts formation status.

Before commencing the description of sediments it should be noted that sometime after the deposition of sediments of the Warrindi and Tarella Silt Formations, and prior to the deposition of the overlying Hindmarsh Clay, the area underwent a period of uplift, tilting and erosion. This erosion is thought to partially account for the thinning of the Warrindi Silt Formation on the southern and eastern margins and also the thinning of the upper part of the Tarella Silt Formation. (It should be noted that in attempting to clarify the stratigraphic nomenclature it was apparent that the available palynological evidence was insufficient to provide a reliable basis on which to base regional correlations.)

6.2 **Warrindi Silt Formation**

The Warrindi Silt Formation overlies the Kooliata Coal Member. It is the most complex formation in the area in terms of lithology and facies relationships and is been assigned an Oligocene to Miocene age by Harris, (1982, 1983 and 1986).

The nature of the contact between the Kooliata Coal Member and the Warrindi Silt Formation appears to be variable. The top of the Kooliata is characterised by the presence of a thin zone of fusain-rich sediments. However, the F seam has this fusain zone only at the very north of its occurrence, the remainder of the seam having a sharp, apparently conformable contact with the overlying Warrindi Silt.

The presence of this oxidised zone suggests that after the deposition of the Kooliata Coal Member there was a hiatus over most of the area, but to the south sedimentation appears to have been continuous.

Figure 2.9 (page 31) indicates a eustatic fall in sea level at the boundary between the Early and Late Oligocene. The hiatus described above may correlate with this sea level change.

Stratigraphic correlation by Kremor and Springbett (1989) also suggested a correlation with the Rogue Formation occurring to the south in the Bowmans area (refer to Figure 2.3 page 13).

It is probable that the Warrindi Silt Formation represents a period of sedimentation coinciding within the major eustatic transgression discussed in section 2.6 (page 39). Moreover, the Warrindi Silt Formation would appear to represent or be laterally equivalent to a transgressive systems tract in the sense of Sangree and Sneider (1987) (refer to Figure 2.5 and section 2.3.1 page 21).

Elsewhere in the St Vincent Basin the equivalent of the Bumbunga Sand Formation, the Clinton Formation is overlain by the glauconite-rich Pt Julia Greensand, which Harris (pers. comm. 1989) interpreted to be a condensed section in the sense of Sangree and Sneider (1987).

In general, the Warrindi Silt is about 4 metres thick in the centre of the area but thickens radially as the fine grained facies grade into more sandy facies towards the margins (Figure 6.2).

The Warrindi Silt Formation attains a maximum thickness of over 20 metres in the southern part but this area has been subject to erosion and the original thickness was greater. As with the underlying formations, the Warrindi Silt Formation laps onto basement in the southern and eastern margins, is laterally continuous to the north and truncated by the Ardrossan Fault to the west.

Figure 6.2 Thickness of the Warrindi Silt Formation.

6.2.1 Lithological description, facies relationships and depositional processes

The Warrindi Silt Formation has been divided into five gradational depositional phases based on a detailed correlation of all drillholes in the area (refer to Figure 6.3a,b and c).

Phases 2 and 4 represent active periods of sedimentation associated with local tectonic uplift of surrounding source areas whilst phases 1,3 and 5 represent relatively quiet depositional episodes between phases 2 and 4. Each depositional phase comprises a number of laterally equivalent facies. Figure 6.3a is a cross-section illustrating the vertical and lateral relationships between the depositional phases while Figure 6.4 summarises these relationships.

The lithofacies for each phase are defined on the basis of geophysical log response (refer to Figure 6.3b). The fine grained facies associated with phases 2 and 4 are characterised by a relatively high natural gamma log response reflecting the higher proportion of clay within the sediments.

The fine grained facies are WA6 for phase 1, WA7 for phase 3 and WA5 and WA9 for phase 5.

All facies grade laterally either directly or through other facies into the WA3 facies in the centre of the area.

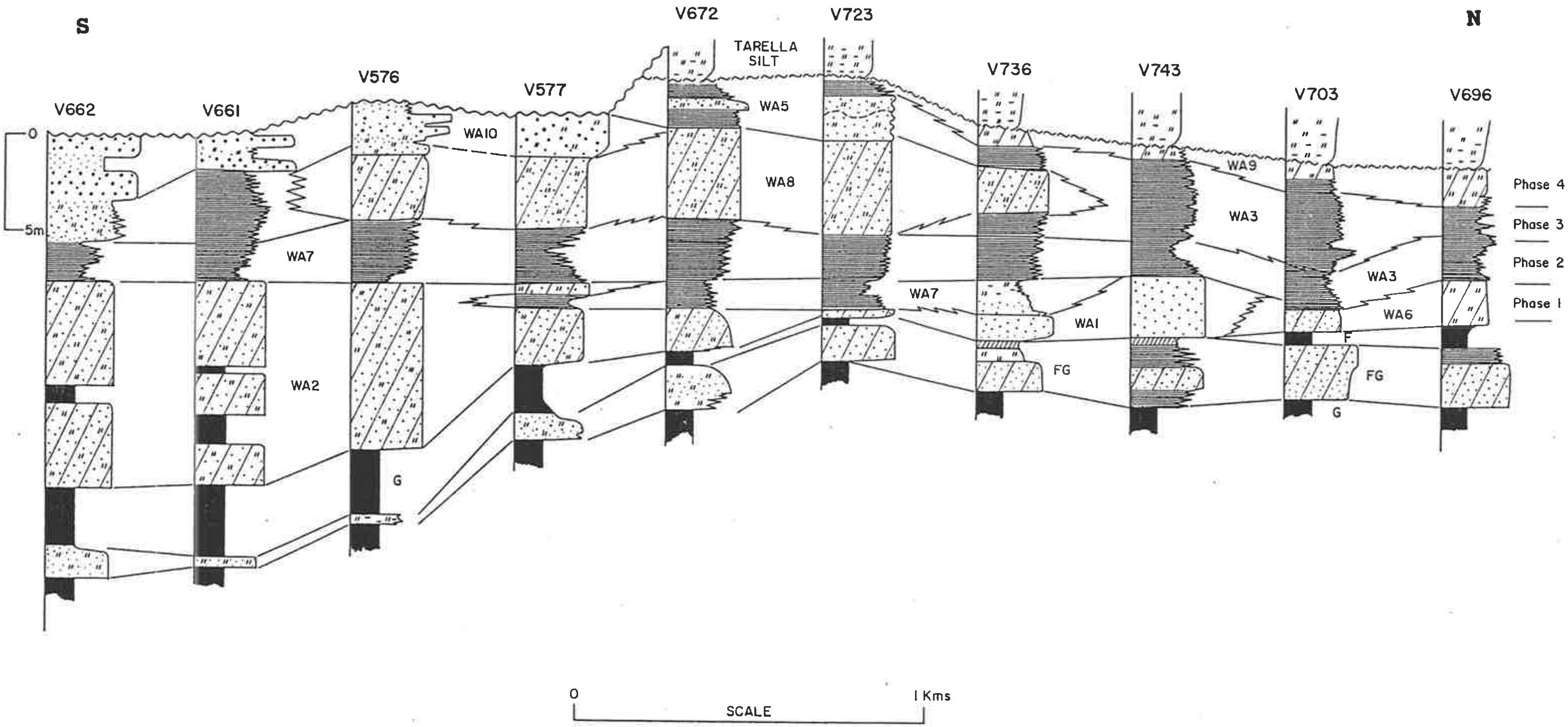


Figure 6.3a Summary of depositional phases and vertical and lateral lithological relationships for the Warrindi Silt. North-South section (refer to Appendix 6 for detailed location of this section).

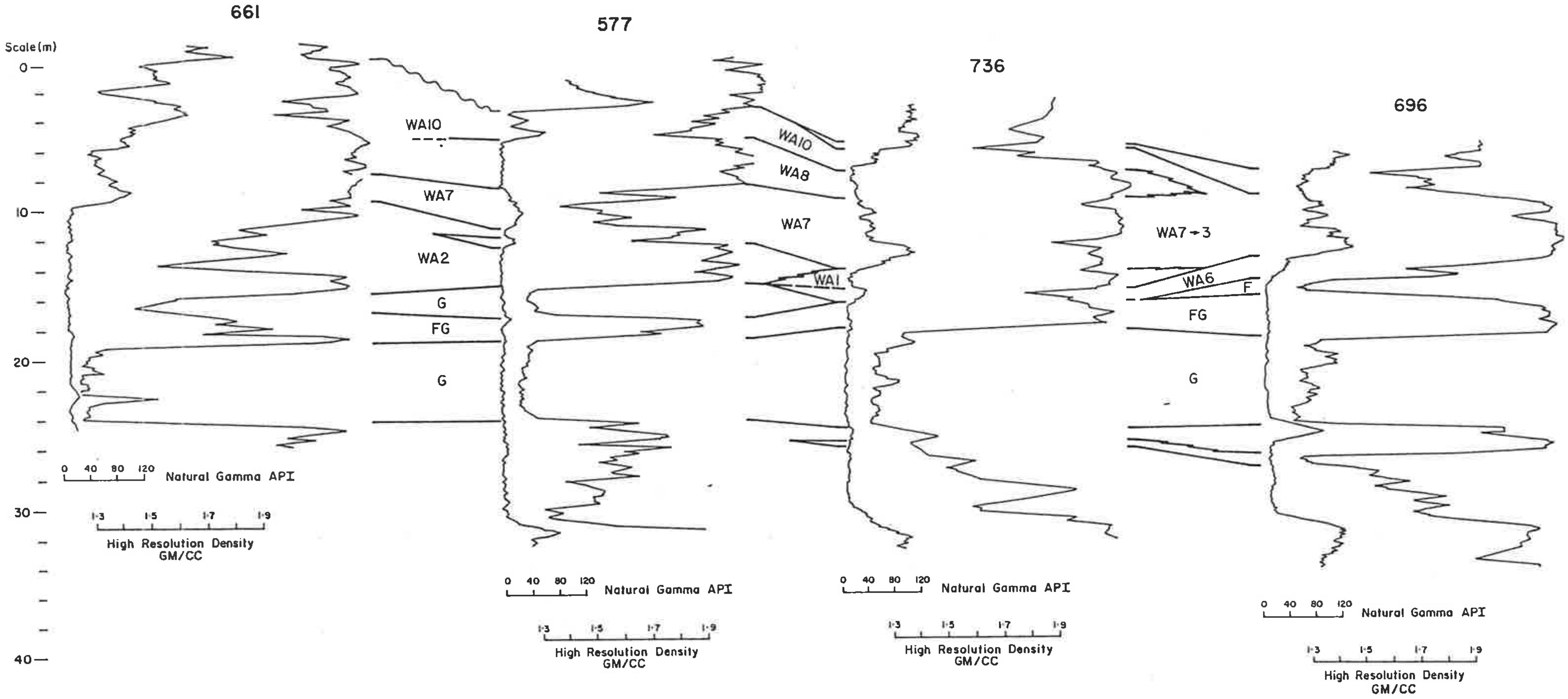


Figure 6.3b Geophysical log response for the Warrindi Silt. Refer to Figure 6.3a for lithological interpretation.

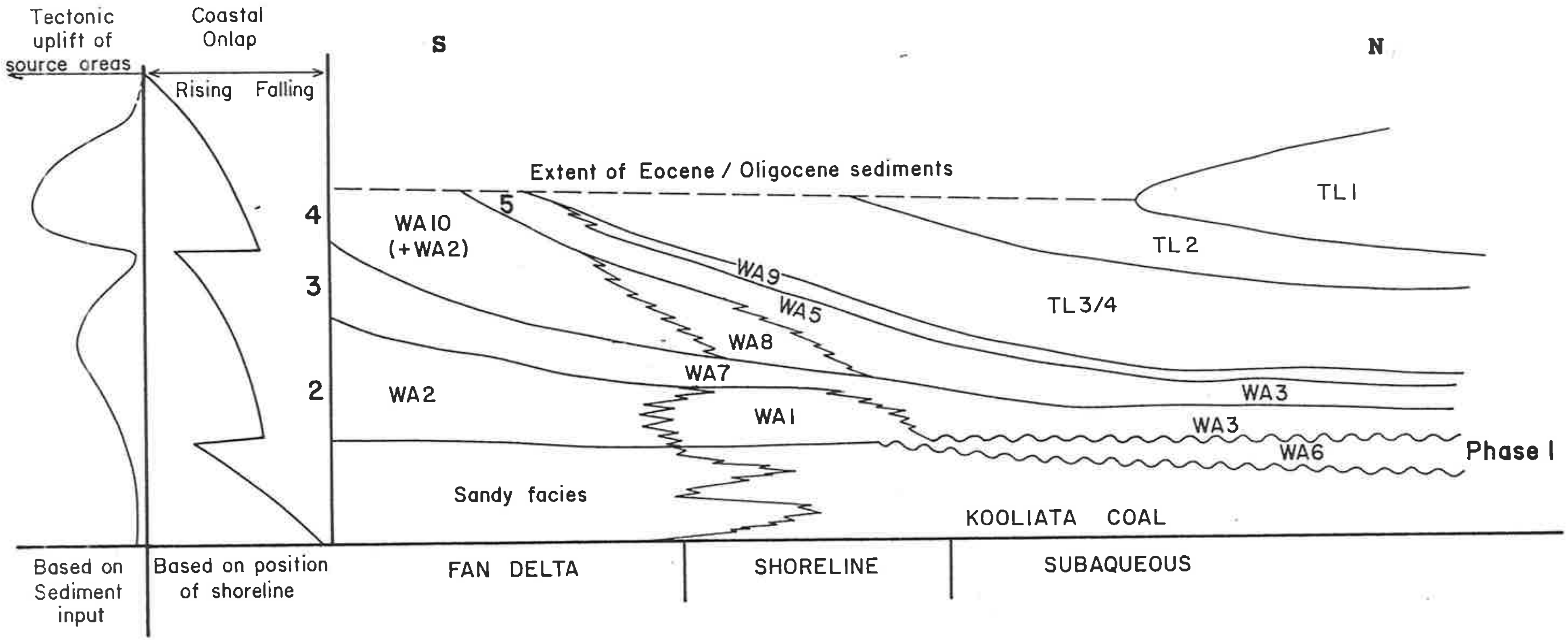


Figure 6.4 Synthesis of facies distribution, coastal onlap and tectonic movement associated with the southern source.

Three major source directions are recognised for the Warrindi Silt Formation, from the north and northwest, several points from the west and the third from the south and southeast (see Figure 2.8, page 28). As with the Bumbunga Sand Formation, the relative influence of each of these varied with time as did the specific entry point of the supply channels.

The sources to the northwest and west were associated with small streams originating from areas uplifted by the Ardrossan Fault. These sources, although intermittent, provided a supply of sediment throughout all depositional phases and are now represented by the WA4 facies (delta fans). The WA4 facies is hence laterally equivalent to and gradational with facies from each of the four depositional phases.

- Lithology and lateral variation

<u>Phase 1 sedimentation - WA6 lagoonal facies</u>

- WA6

WA6 occurs in a restricted area in the central part of the deposit. It overlies the F zone and F seam with a sharp contact which is commonly lined with fine grained light brown silty sand. WA6 averages 1.5 metres in thickness and its lateral distribution closely follows that of the F seam (refer to Figure 5.13e, page 138).

WA6 consists of moderately to highly carbonaceous (sometimes reaching coal quality), dark brown silt which has undergone extensive brecciation. Breccia blocks are generally less than 100 mm in width and fractures are commonly infilled with fine silty sand. As depicted on Figure 6.4, it is considered that phase 1 coincided with a eustatic rise in sea level which resulted in the formation of a lagoon. This rise in sea level would have also terminated peat formation by drowning the peatswamp (refer to the discussion in section 2.6 page 39). The brecciation represents a period of exposure and desiccation at the end of the phase 1 associated with a fall in the sea level. This event marked the commencement of phase 2.

Phase 2 sedimentation - WA1 and WA2 delta front and fan delta facies.

- WA1 delta front clean sand facies.

WA1 occurs as an elongate east-northeast trending body of clean sand reaching a maximum thickness of 3.5 m (Figure 6.5). In the Trial Pit the WA1 member averages 3.1 metres in thickness and the main lithology is well sorted, rounded, medium grained, light brown to white, bioturbated, quartz sand (Plate 6.1). A detailed vertical profile is presented on Figure 6.6. The basal part of WA1 is comprised of a 0.3 metre bed of fine to medium grained clean sand (Plate 6.2). Bedding in this sand is horizontal although some ripple crossbeds are present at the base. This bed overlies the F zone with a sharp irregular contact

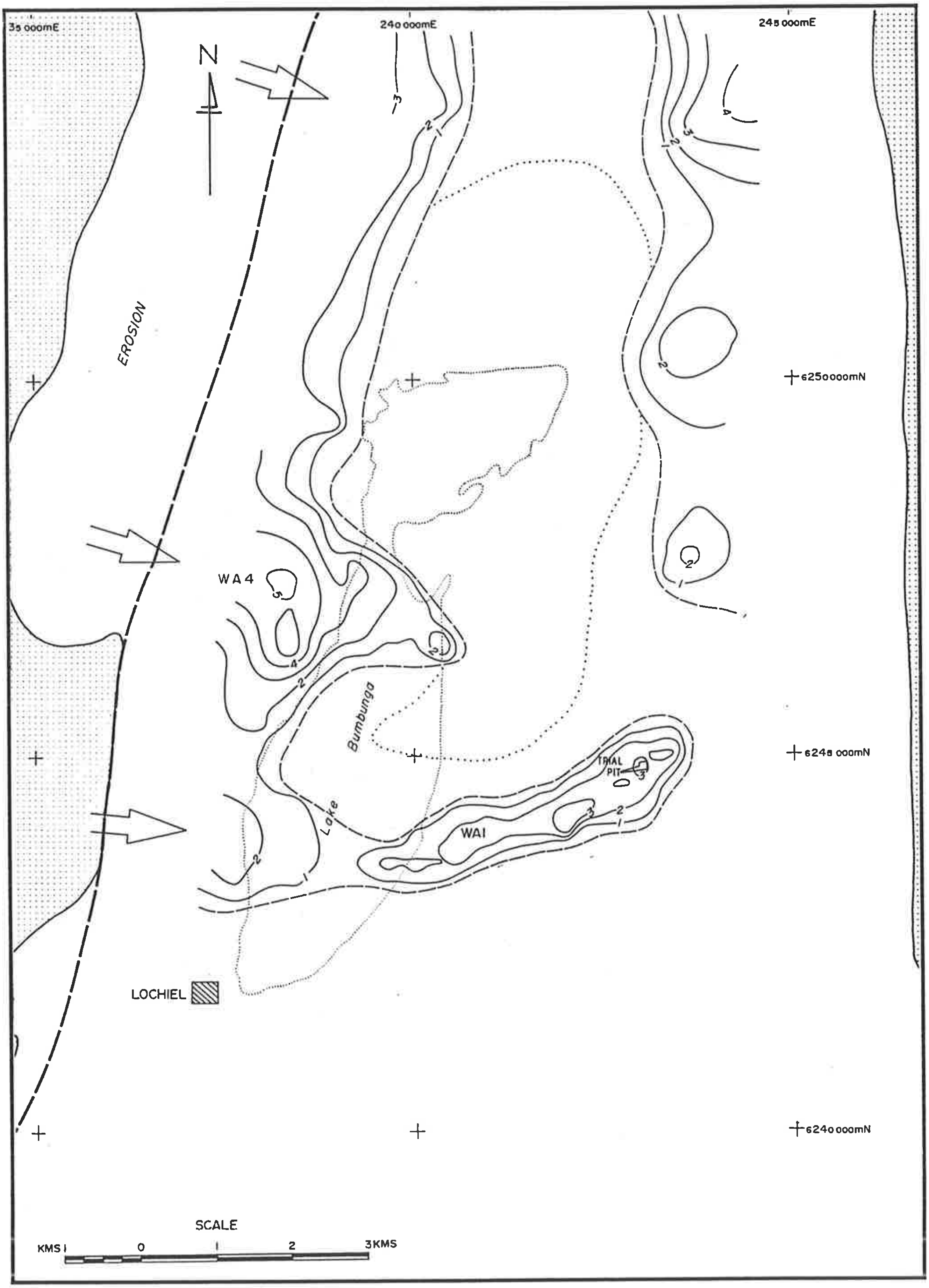


Figure 6.5 Warrindi Silt Formation - Thickness of WA1 and WA4 Members.

marked by a change in carbonaceous content (Plate 6.3). Beds equivalent in lithology, distribution and thickness also occur in the F zone and FG interburden in the Trial Pit. It is considered that all three are representative of the same depositional processes. A feature of these sediments in each of the FG, F zone and WA1 is that they each contain thin, laterally continuous carbonaceous sand beds within the clean sand (Plate 6.4). These carbonaceous beds are characterised by irregular, slumped lower contacts and sharp upper contacts. They are thought to represent quiet periods where sediments are deposited from suspension in a standing body of water. In the F zone and FG interseam, this facies is characterised by occasional logs along the base aligned in a northeast-southwest orientation and by small channel infill structures. No logs are present in the bed in WA1 in the Trial Pit.

The association of these clean sand beds with a major delta fan (WA2) (originating from the southeast as indicated by lateral lithological correlation and by the orientation of the logs in the F zone) and the presence of small channels indicate that these sediments represent deposition typical of sheet floods as described by Galloway and Hobday (1983) and Banerjee (1989). Furthermore, the presence and character of the carbonaceous beds indicates that the sheet floods entered a standing body of water (probably a lake for the F zone and FG interburden, and as discussed later, a lagoon for WA1).

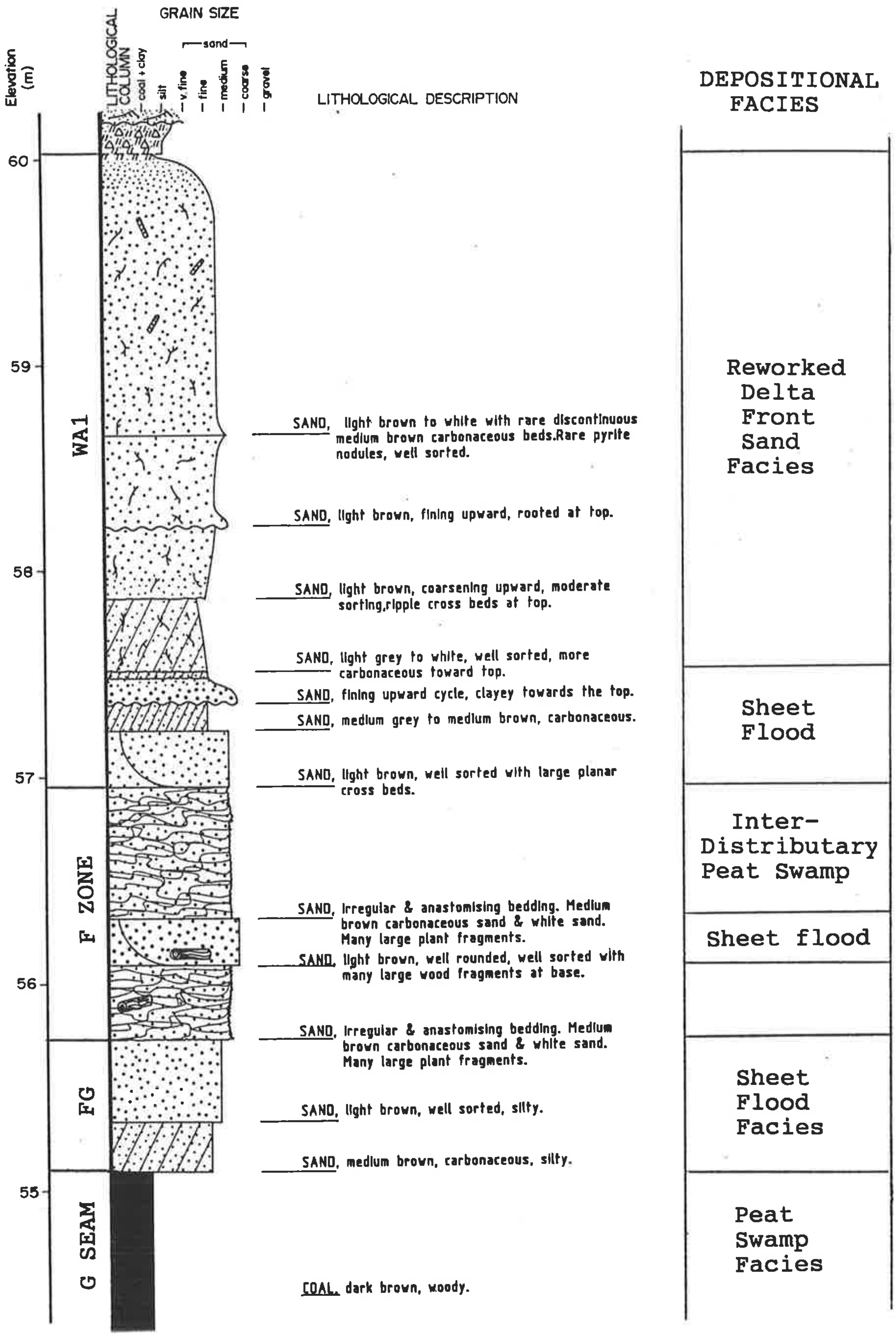


Figure 6.6 WA1 - detailed lithological description and vertical lithological profile for the Trial Pit site.

The basal section of the WA1 is characterised by a number of beds similar to the sheet flood beds discussed above. In addition, the beds in the basal section commonly contain small fining upward cycles (Plate 6.5) which Galloway and Hobday (1983) and Banerjee (1989) also considered characteristic of sheet flood processes. This conclusion is supported by the presence of mud chips and carbonaceous detrital matter within the sand beds (Plate 6.5). McGowen (1971), from a study of the Gum Hollow fan delta in Texas, observed that mud chips are a feature of sheet flood depositional processes.

In the middle and upper parts of WA1 both fining and coarsening upward cycles are present and carbonaceous sand beds are very rare. In order to identify the depositional setting of the middle and upper parts of WA1, it is useful to consider its location between delta fan (WA2) to the south and a lagoon (WA3) to the north. This location suggests a lagoonal shoreline environment.

In these settings, two processes control sedimentation. First, wave reworked delta front sands transgress the delta front and second, subsidence causes lagoonal development on the landward side. With continued subsidence, wave reworking of the delta front ceases, and the lagoon eventually extends over the abandoned delta and delta front sands. As muds and silts are deposited first, the result is a drape of mud and silt on the contact.

Galloway and Hobday (1983) considered that the geometries of river dominated lacustrine deltas are commonly elongate or lobate. However, the geometry of WA1 is arcuate suggesting that the delta was tide or wave dominated, or that it represents a modified distal delta, or a combination of both.

It is also important to recognise that the northeast-southwest trending structural feature described in Chapter 2 (refer to Figure 2.4 page 15) coincides in both location and orientation to that of the WA1 facies. As with the FG and GH clean sand facies it appears that this basement structure was a major factor controlling the lateral location of these sand facies.

WA7 overlies WA1 with a very sharp, planar contact lined by a thin, discontinuous clay drape (Plates 6.6 and 6.7). According to Galloway and Hobday (1983), Galloway (1986) and Penland and Suter (1982) such contacts typify abandoned deltas.

- WA2 fan delta silty carbonaceous sand and coal.

To the south WA1 grades into the WA2 facies. WA2 attains a maximum thickness of over 20 metres at the southern margin and thins to the north and west forming a wedge shaped body (Figures 6.3a,b, 6.4 and 6.7). WA2 consists of moderately to highly carbonaceous fine to medium grained, poorly sorted, silty sand (SA3,4,5) with thin interbeds of fine to medium grained clean sand and woody coal. The gradational zone between WA1 and WA2 was intersected in the Trial Pit.

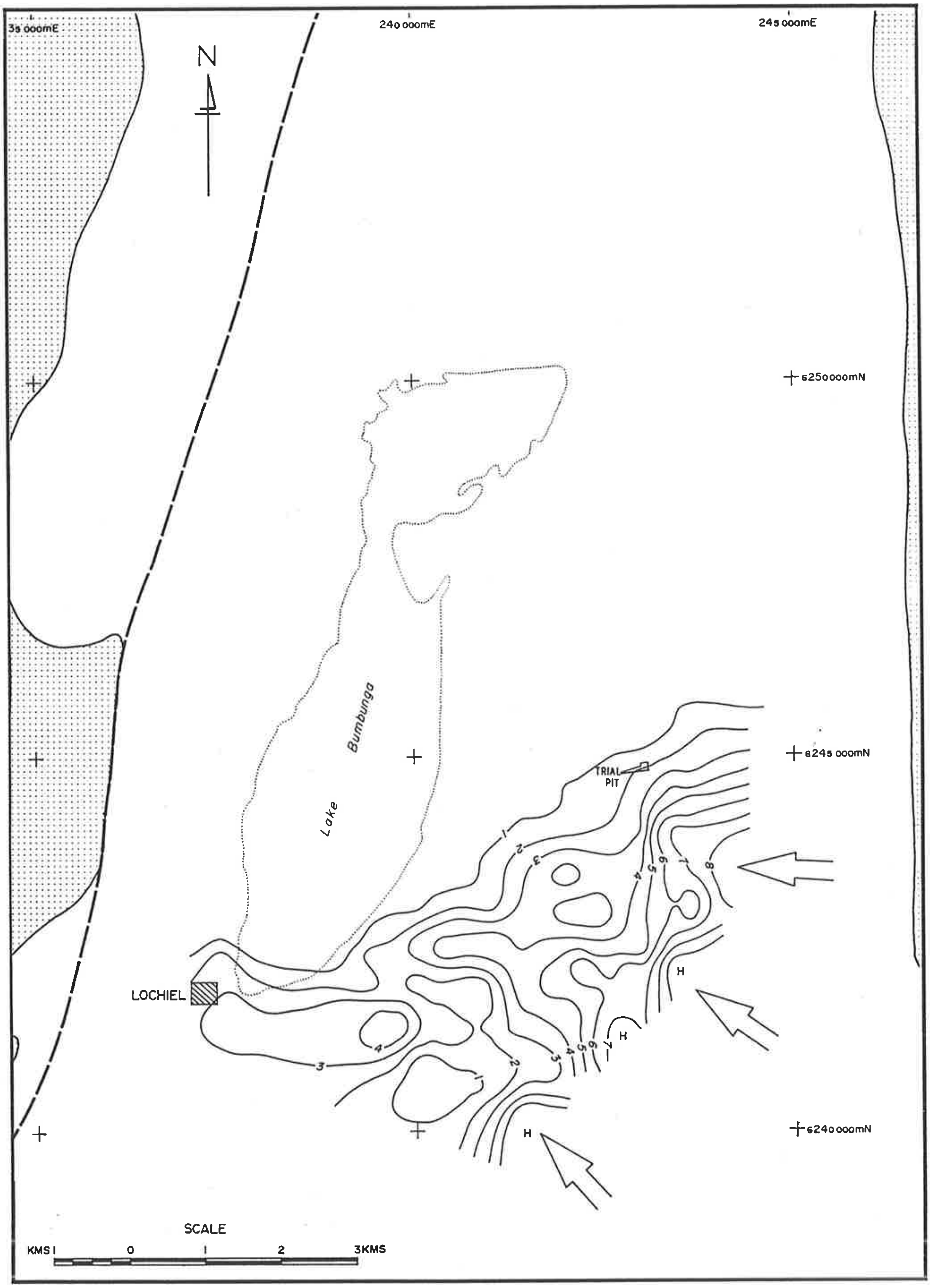


Figure 6.7 Warrindi Silt Formation - Thickness and distribution of the WA2 Member.

The carbonaceous material occurs as a fine grained matrix but many discontinuous and thin (< 10 mm) fibrous coal bands are also present. The fine carbonaceous matter appears to have partially cemented the sand. Bedding is often outlined by carbonaceous matter with dips of between 15^{o} - 20^{o} common and basal bedding contacts are generally sharp and irregular.

WA2 is considered to represent a fan delta which entered the area from the south. Fan deltas are defined by Wescott and Etheridge (1980), Holmes (1965) and Pettijohn et al. (1987) as alluvial fans that enter a standing body of water such as a lake or sea from an adjacent highland (in this case the Nantawarra High).

Although fan deltas have been recognised and documented for almost three decades, few attempts have been made at categorising them. Wescott and Etheridge (1980) provided a summary based on recent and ancient deposits on the basis of tectonic, geologic and geomorphic settings while Hayes and Michel (1982) examined fan deltas in a macrotidal setting and recognised five types based on sediment supply and the influence of waves. Of the examples discussed by Hayes and Michel (1982), the marginal coast of southwest Texas, and the Gulf of Arabia and Red Sea coasts appear to be analogous to the WA2 depositional environment.

The occurrence of fan deltas was considered by Pettijohn et al. (1987) to be an indicator of tectonic activity. This is consistent with the fan delta association at Lochiel as the alluvial fan must have originated from the Nantawarra

High which is known to be fault bounded and tectonically mobile.

Further, Alley (1969) recognised the presence of a well developed erosion surface cut across the sandstone and quartzite on the southern part of the Nantawarra High which would have provided a local source of sediment.

A characteristic feature of the WA2 sediments is the high carbonaceous content.

A clue to the origin of this carbonaceous matter is its fine grained nature. None of the core intersections of carbonaceous sand contain any large intact plant material even though such material is common in the coal. This suggests that the fine carbonaceous material is allochthonous.

The question arises as to the nature of the source of this carbonaceous material. There are two possibilities. First, it could be derived from vegetation growing higher on the delta or, second, it could be derived from reworking of peat which had accumulated prior to this phase of sedimentation.

If the material was derived from vegetation (and as indicated by the large wood pieces in the coal this vegetation would have included at least some large trees) then the minimum transport distance was probably less than 1 kilometre (the distance to vegetated parts of the delta).

It is considered most unlikely that complete disintegration of the plant matter could be achieved in that distance.

On the other hand, there must have been a ready source of peat and other carbonaceous lithologies derived from uplift of the Bumbunga Sand Formation along the structure(s) controlling the formation of the fan delta. Based on the discussion above it is considered that reworking of carbonaceous sediments is the most likely source of the detrital carbonaceous matter contained in the sediments of WA2.

As indicated on Figure 6.3b by the natural gamma log response (borehole 661) as well as from observations in the Trail Pit and from core, WA2 is in sharp contact with the overlying WA7 indicating a rapid change in the depositional regime. This characteristic is considered to reflect a change in the sedimentary environment, not greatly influenced by tectonism.

Phase 3 sedimentation - WA7 intertidal to subtidal facies.

- WA7 intertidal to subtidal sandy silty clay.

The WA7 lithofacies is laterally continuous with WA3 to the north and overlies both WA1 and WA2 to the south (Figure 6.3a). As shown on Figure 6.3b the geophysical log response of WA7 is characterised by a gamma peak of between 40 and 120 API units. This characteristic provides the basis for detailed correlation over a large area even though it is only between 1 to 3 metres thick.

At the Trial Pit site, WA7 is 1.7 metres thick and overlies WA1 with a very sharp, planar irregular contact which is lined by a thin, discontinuous clay drape (Plates 6.6 and 6.7).

As shown on Plates 6.6 and 6.7 and on Figure 6.8, WA7 comprises two intensely bioturbated types of sediments;

1. sandy fining upward cycles and
2. brecciated carbonaceous silts.

The fining upward sand beds are no more than 0.2 metres thick. They consist of fine sand at the base grading up into flaser bedded sand and clay (as described by Reineck and Wunderlich, 1968). Sometimes these beds also have a thin, brecciated carbonaceous silt at the top. According to Clifton (1982) flaser bedding constitutes one of the most characteristic features of tidally deposited sand.

The brecciated, carbonaceous silt beds are generally less than 0.20 metres thick (Plate 6.7). Lithologically they comprise brecciated, angular blocks of carbonaceous silt surrounded by fine grained sand. These beds probably represent mudcracks developed from periodic exposure of lagoonal silts.

The association of flaser bedded sand and desiccated lagoonal silts indicates an intertidal to subtidal depositional environment.

The upper half of WA7 has rare breccia layers and consists primarily of grey silty clay with gradational interbeds of

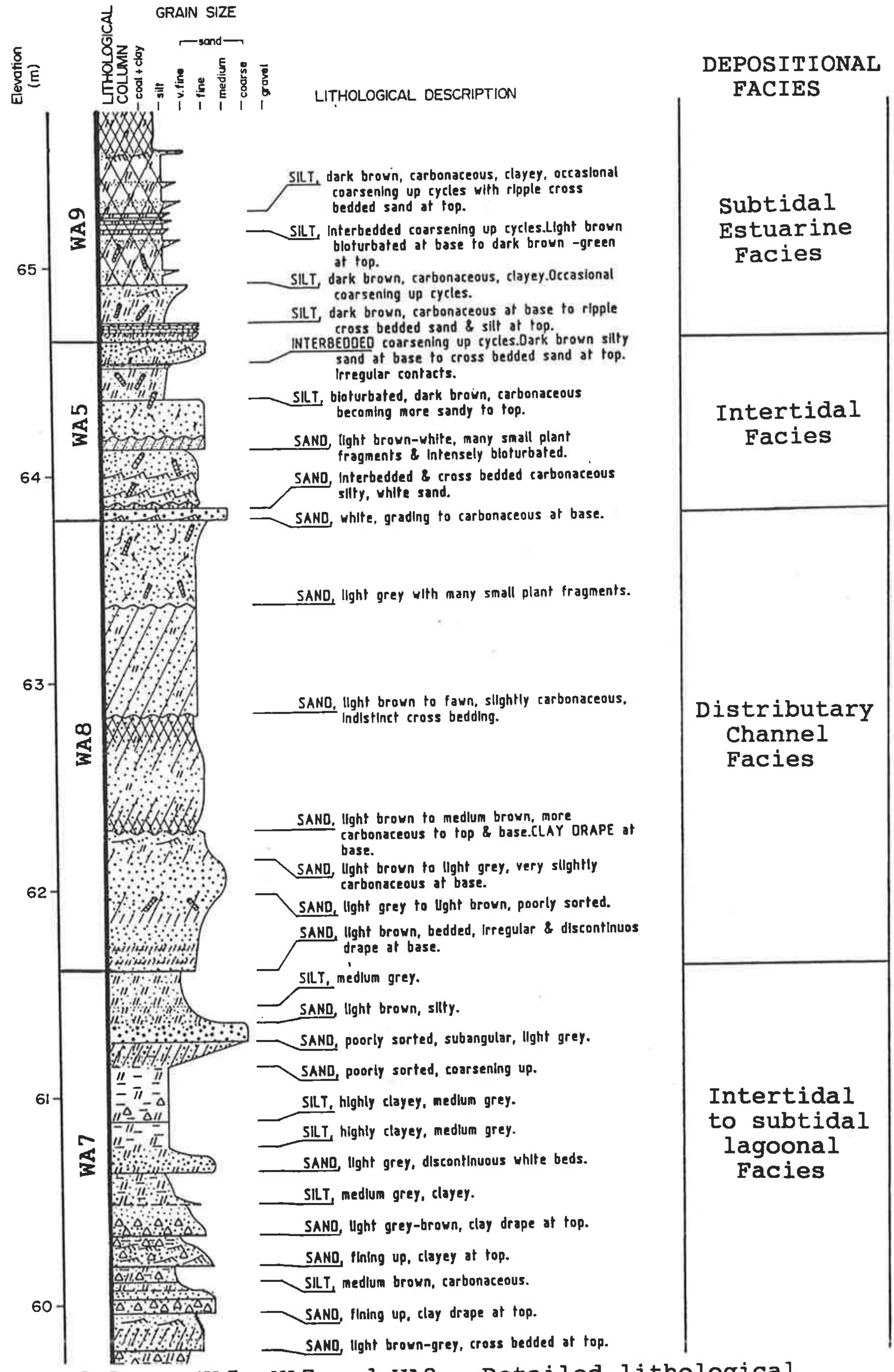


Figure 6.8 WA5, WA7 and WA8 - Detailed lithological description and vertical profile for the Trial Pit site.

poorly sorted, subangular, coarse grained sand and fine gravel. The rarity of brecciated beds and the generally finer and more homogeneous nature of the sediments indicates a progressive increase in the depth of water.

The coarse grained beds occur in thin upward fining cycles. Their presence in this part of the sequence raises the question as to the source of these coarse sediments. As described later, coarse grained, angular sediments occur in the sediments associated with Phase 4 sedimentation. It is considered that their appearance in WA7 marks the beginning on local tectonism which led to Phase 4. The fining upward nature indicates a sheet flood process of deposition.

WA7 grades into WA3 towards the north.

Phase 4 sedimentation - WA8 and WA10 distributary channel and fan delta.

- WA8 distributary channel silty carbonaceous sand.

WA8 is present in the south-central part of the area. It reaches a maximum thickness of 10 metres. The member thins to the west and north where it grades vertically and laterally into WA5. To the south and east it grades into WA10.

On the basis of lithology and sedimentary structure, WA8 in the trial excavation can be divided into two depositional facies :

1. Sheet flood sand,
2. Distributary channel sand,

1. Sheet flood sand facies (refer to Plate 6.8)

This facies is about 0.7 m thick and consists of interbedded fining upward cycles containing mottled, intensely bioturbated, light grey-brown well sorted fine sand at the base and grading to medium brown carbonaceous laminated silty sand at the top. An interbed of coarse, angular sand similar to those in the underlying WA7 is also present.

2. Fan delta distributary sand (refer to Plate 6.9)

This facies is about 1.1 metres thick and consists of fine grained, well sorted, slightly carbonaceous silty sand with interbeds of fine grained clean sand. Abandoned channel infills, trough crossbed sets and finer grained overbank deposits were also observed in the Trial Pit (see Plate 6.9). The contact between the sheet flood sand and the distributary sand is very sharp and irregular and lined with a very thin (1 to 2 millimetres) clay drape.

WA8 grades to the east and south into coarse sand and gravel of WA10. Elsewhere in the deposit, WA8 also consists of interbedded carbonaceous sand and clean sand, however, farther to the west and south it becomes considerably more carbonaceous.

This is a progressive change and reflects a decrease in the wave processes away from the shoreline. Thin horizons of well rounded quartzite pebbles and cobbles were intersected in core from V458 (refer to Appendix 6 for location) and these are considered to represent shoreline reworking of the delta fan sediments.

- WA10 fan delta clean sand and gravel.

WA10 is located on the southern and eastern margins of the study area. This lithofacies reaches a maximum thickness of 12 metres on the eastern margin and thins to the west and north. The top of WA10 is eroded on the margins and the thickness trend is partly in response to this. The description of this member is from cuttings descriptions and interpretation of geophysical logs.

From geophysical logs, WA10 has a distinct coarsening upward vertical profile. This coincides with carbonaceous silty sand at the base of the sequence and a gradation to interbedded gravels and pebbles and cobbles of quartzite and coarse sand at the top.

Based on the facies distribution and geometry, the source appears to have been from the east and to a lesser extent to the south.

Phase 5 sedimentation - WA5 and WA9 intertidal to subtidal facies

- WA5 intertidal flaser and lenticular bedded sand.

WA5 is 1.0 m thick and overlies WA8 with a sharp, erosional contact (Plates 6.10, 6.11 and 6.12). As indicated on Figure 6.4 it is considered that the change in depositional environment from WA8/WA10 to WA5/WA9 represents another period of sea level rise and/or decrease in tectonism.

The base of WA5 is marked by a thin (< 10 mm) bed of medium to coarse grained, sub-angular white and brown carbonaceous sand. This is followed by a sequence of silty carbonaceous sand and white fine grained well sorted sand which diplay flaser, lenticular and wavy bedding (Plate 6.12).

Small erosional channels were also observed within WA5. These were generally infilled with carbonaceous, fine grained sand and silt and often lined with a very thin silty clay drape (Plate 6.13).

It is apparent from these features, particularly the bioturbation, that this lithofacies represents an intertidal depositional environment which was cut by tidal channels.

It is considered that this sand unit formed when the shoreline began reworking the WA8/WA10 delta fan and marks the beginning of a major transgressive episode which led to the deposition of sediments of the Tarella Silt Formation.

Elsewhere in the deposit, equivalent sediments contain clay drapes.

In V723 (refer to Appendix 6 for location), the clay beds occurred as drapes on fine grained sand beds. One of these clay drapes was concordant with bedding while the other had a dip of 10°. The clay beds were up to 20 mm thick and the uppermost bed was observed to contain a polished shear plane. In V360, the clay bed also contained a shear plane but was parallel to the surrounding, horizontally bedded carbonaceous silt. These clay drapes are thought to represent the basal lining of channel infills.

The intertidal sand is overlain by 0.2 m of light brown, fine grained sand (Plates 6.14 and 6.15) in the Trial Pit area. A number of phases of sedimentation and erosion are recognised in this bed. One major phase is characterised by planar and shallow angle crossbedding consisting of alternating beds of carbonaceous and non-carbonaceous sand and by a thin zone of carbonaceous sand at the base. This thin carbonaceous sand at the base is considered to represent deposition into a tidal lagoon.

A number of subsequent depositional phases reworked the sediments in small erosional channels. The size of these is indicated by the channel infill structures which average about 0.15 m in depth and 0.4 m in width.

The lithology and geometry of these beds suggest a storm redeposited sand or a crevasse splay entering into a distributary bay.

- WA9 subtidal carbonaceous clayey silt.

WA9 attains a maximum thickness of 2.5 metres and attains a relatively constant thickness of about 2.0 metres (Figure 6.9). This facies occurs at the top of the Warrindi Silt Formation (Plate 6.16). The contact between the overlying Tarella Silt Formation is sharp and planar and coincides with the Tarella Silt Formation shear zone discussed later in section 6.4.3. Towards the south the

WA9 is composed of highly carbonaceous silts, interbedded with thin clay seams (Plate 6.17) and clay shear zones, non-carbonaceous silt beds, thin carbonaceous sand beds and flaser and lenticular bedded sand (Plate 6.18).

The carbonaceous material in the silt is very fine grained and dispersed evenly throughout. Petrographic analysis indicates that most of this material is fine grained and broken suggesting transportation and that a high proportion of the exine coal groups is present (see page 191).

Within this silt, thin seams of clay up to 40 mm thick occur and these generally dip at less than 5^{o} (Plate 6.17). The clay seams are of two types: as part of small scale coarsening upward cycles and as discrete beds with no apparent relationship with surrounding beds.

These two types of clay seams were present in a 900 mm diameter core taken at site V634 (refer to Appendix 6 for location). The discrete clay seam consisted of 3 mm of light brown clay, slickensided on one side and discontinuous because of numerous intersecting sedimentary faults. Displacement in these faults was of the order of 50 mm. These thin clay seams characteristically have dips of less than 5^{o}.

The second type consists of a relatively thick zone (up to 100mm) of silty clay occurring at the base of a coarsening upwards cycle. It is common for the clay-rich base of these zones to be sheared.

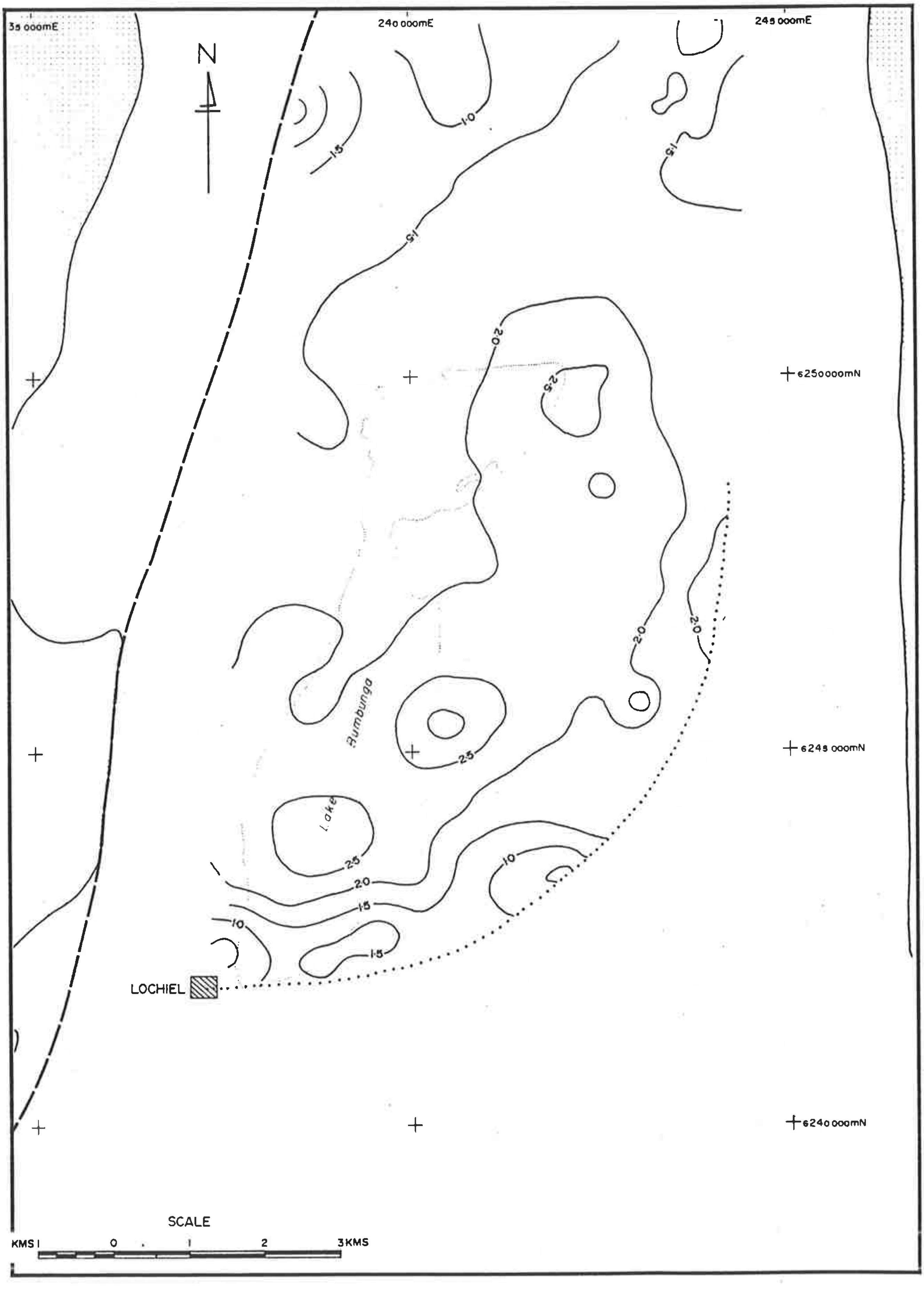


Figure 6.9 Warrindi Silt Formation - Thickness of WA9.

At the Trial Pit site, WA9 overlies WA5 with a sharp contact. At this location WA9 is about 1 metre thick and consists of interbedded coarsening upward cycles comprising highly carbonaceous silt at the base and grading to silty fine sand at the top. These sands are characterised by lenticular and flaser bedding (Plate 6.18).

Cycles vary from 10 mm to 20 mm in thickness. Occasional, small erosional distributary channels were also present.

In the Trial Pit area the upper 0.4 metres of WA9 is comprised of highly carbonaceous, black silt or coal. From the base upwards, this lithology gradually becomes less carbonaceous and more clayey and grades vertically into the overlying TL4. No bedding or lamination was visible but elongate intraformational clay pellets or clasts are present in the gradational zone (Plate 6.19). The Tarella Silt Formation shear zone is located on the boundary between the Warrindi Silt and the Tarella Silt Formations and is the subject of detailed analysis to follow in section 6.4.3.

The features of WA9 suggest that at least in the initial stages of sedimentation the depositional site was subject to tidal influence. However, the absence of sand at the top of the sequence indicates a cessation of input of sand to the depositional site. From the presence of allochthonous carbonaceous matter it is likely that the environment graded from intertidal to subtidal. The inclusion of clay pellets within the upper parts of WA9 indicate that there were erosional channels flowing through this subtidal environment.

- Petrology

The highly carbonaceous black silt or coal was examined to determine the nature of the organic constituents. A number of representative samples were examined using microscopic reflectance and fluorescent techniques (Plates 6.20a,b).

The samples contained a high proportion of liptodetrinite indicating that much of the organic matter was transported prior to deposition under anaerobic conditions.

The presence of Botryococcus related telalginite and phytoplankton indicate deposition in an estuarine environment.

Sedimentation in the centre and western margins of the area

- WA3 lagoonal clay and silty clay

In the central part of the area, the Warrindi Silt Formation consists of about 4 metres of slightly to non-carbonaceous silt (Figure 6.3). A laterally continuous band of interbedded highly carbonaceous silt and carbonaceous fine grained sand is present in the middle of the sequence. This sand is generally less than one metre thick and often contains coal breccias and thin clay beds. The silt above is generally slightly carbonaceous, brown and bioturbated and has a sharp contact with the overlying

The contact with the overlying WA9 is generally gradational but overlies WA6 with a sharp contact.

- WA4 fan delta distributary channel sand

This facies is present on the western margin of the deposit and from the thickness distribution appears to have been related to movements along the Ardrossan Fault (Figure 6.5).

WA4 is comprised of subrounded, moderately sorted, non-carbonaceous and medium grained sands. These occur in discrete cycles up to 2.5 metre thick. In the fully cored hole V582 (refer to Appendix 6 for location) only the basal section of these sand beds were recovered but from these and from interpretation of geophysical logs, it appears that they are part of upward coarsening cycles.

These cycles commence as a series of interbedded, carbonaceous, bioturbated, sandy and clayey silts usually with gradational boundaries followed by poorly sorted, subrounded, non-carbonaceous sands. The upper-most cycle in V582 was characterised by a carbonaceous and silty fine to medium grained sand.

The sand zones can be correlated over large distances and the cumulative thickness tends to increase towards the margins in response to an increase in the number of sand zones present in the sequence.

The limited amount of core available adds difficulty to the interpretation of the underlying members, the association of sandy units adjacent to faults in the Lochiel area is diagnostic of fan deltas.

To support this, the geophysical logs and limited core strongly suggest the sand occurs in upward coarsening cycles. These are widely accepted as one indicator of progradational environments typical of deltas.

6.2.2 Summary of depositional processes

The stratigraphic sequence in the Warrindi Silt Formation represents a complex interaction of both tectonic and eustatic controls and depositional processes. It is apparent that a sea level change at the end of the Late Eocene led to encroachment of the sea from the south. This produced a depositional setting characterised by marginal marine depositional environments (Figure 6.10).

The major characteristics of this setting include a lagoon/estuary in the central part of the area surrounded by fan deltas. The major source of sediment for these fan deltas was from the south and southeast, from the west and, to a lesser extent, from the north. The interaction of these depositional environments produced a complex vertical and lateral facies association.

- Depositional architecture

A synthesis of the facies distribution with the major depositional controls of tectonics and eustacy is provided

Five phases of sedimentation are recognised for the Warrindi Silt Formation. These phases resulted in a lateral shift of depositional environment and produced the facies distribution observed in the the study area.

The position of the shoreline can be interpreted from the location of the intertidal depositional environments and the tectonic movements for the southern source are interpreted from the stratigraphic distribution of fan delta sands and gravels.

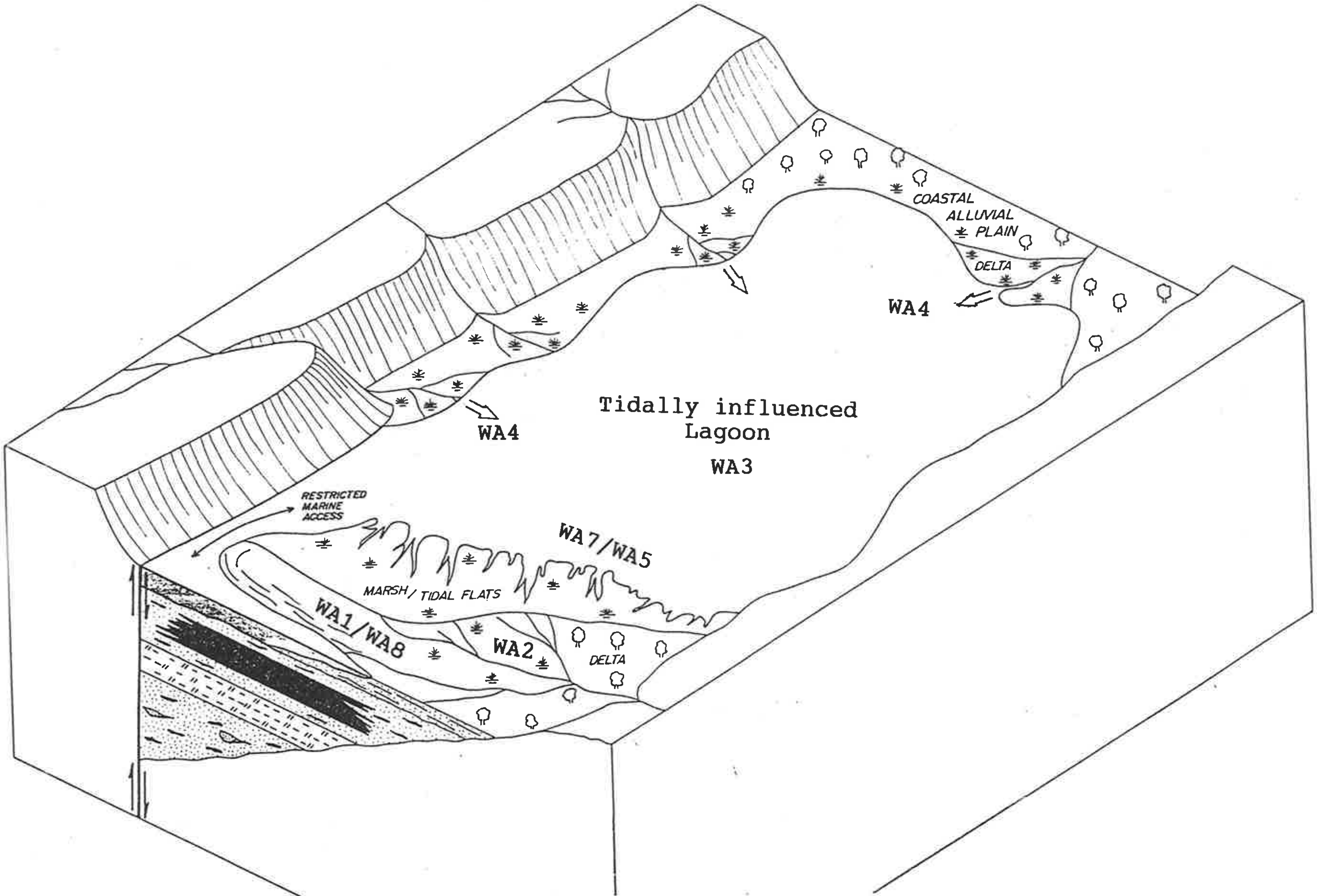


Figure 6.10 Schematic representation of the depositional setting for the Warrindi Silt Formation.

6.2.3 Engineering properties

A summary of the intact engineering properties of the Warrindi Silt Formation is presented on Table 3.1, page 55. These properties relate mainly to the WA3 and WA5 members. In general, it can be concluded from Table 3.1 that the properties of the Warrindi Silt Formation are similar to the Tarella Silt Formation.

. Geological factors affecting porewater movement

Hydraulic conductivities and grain size distribution for the Warrindi Silt Formation are presented on Figures 3.12 and 3.13 (pages 76 and 77 respectively).

The high hydraulic conductivity recorded for V623 is attributed to its location in the WA10 lithofacies. WA10 is characterised by an interbedded sequence of coarse grained sand and gravel and as such would be expected to have a relatively high hydraulic conductivity.

It is apparent that the location and properties of aquifers are primarily controlled by tectonics. Movement on faults at the margins of the area have produced several different sources of sediment which were active intermittently producing a series of stacked and laterally variable sand aquifers.

In contrast to the Bumbunga Sand Formation, the Warrindi Silt Formation represents deposition in a marginal marine depositional environment. Notwithstanding this, the essentially the same, fan deltas entering a central body of water, and it is apparent that the eustatic sea level rise had little effect on these processes.

The conclusion is that for the study area, tectonics was the major factor affecting the location, distribution and properties of the aquifers.

. Geological factors affecting Weak Zones

A number of weak zones characterised by thin seams of clay are present within the Warrindi Silt Formation and the depositional and stratigraphic association of these is shown on Figure 6.11.

These clay seams have been identified in association with;
a) Intertidal lithofacies (WA5, WA7)
b) Subaqueous lithofacies (WA3, WA9)

The clay seams present within the study area can be attributed to two geological processes;

1. Tidally influenced distributary channels

A model for the location of clay seams in tidally influenced channels is presented on Figure 3.11.

Clay drapes can form on the crossbed sets, being deposited at either high or ebb tide, or as linings of abandoned channels. Only the latter has been observed within the study area.

2. Onlap of aqueous depositional environments during regressive periods.

A prime site for the deposition of fine grained sediments and clay is at the distal end of distributary channels. The processes are similar to those described for the clay zone occurring within CN1 and CN2 (refer to Figure 3.11, page 72).

- Engineering properties

As presented on Figure 6.11, the test results for the few clay seams from the Warrindi Silt Formation indicated relatively high residual shear strength with a mean of 15°. and cohesion of 30 kPa. Only 5 samples were tested from a total of 4 sites and it is considered that it is not possible to draw any conclusions as to lateral variation.

- Petrology of clay seams

A sample of core taken from V723 (see Appendix 6 for location) and containing a sheared clay seam was examined using microscopic techniques (Plates 6.21a, b, c, d, e and f).

Some experimentation was required regarding impregnation techniques because the samples were very friable, wet and water sensitive. The samples were impregnated using "vapour exchange" techniques by the Waite Research Institute, Division of soils in Adelaide.

The sample examined has five distinct beds;

1. top bed of fine grained sand with distinctly angular detrital grains and intergranular carbonaceous material,
2. Thin (<1 mm) lamination of carbonaceous clay,
3. 30 mm bed of weakly carbonaceous silt,
4. 10 mm bed of highly carbonaceous clay which includes a polished shear plane,
5. fine grained angular sand with intergranular carbonaceous material as for bed (1.)

The top (1) and bottom (5) beds are of similar sediment and comprise a very loosely packed aggregate of angular sand grains moderately to well sorted with an average size of 0.15mm. Carbonaceous material is common as an intergranular matrix and in the thicker, lower bed is often more abundant than the quartz grains. Minor flakes of clay are also present in the lower bed and there is an apparent primary porosity forming up to 30% of this lithology.

A gently wavy lamination of highly carbonaceous clay (2) separates the upper most fine sand from the underlying middle silt bed (3).

The middle silt bed (3) is a fairly homogeneous massive sediment, composed of a random compact aggregate of angular quartz silt grains, and minor fine detrital muscovite, with a subordinate matrix of very slightly carbonaceous clay.

Minor extremely fine discrete grains of carbonaceous material and clay occur sporadically along the bedding. Small poorly defined mud clasts (carbonaceous clay mixed with silt) occur in the lower portion of this bed.

The highly carbonaceous clay bed (4) consists almost entirely of carbonaceous clay with a trace of dispersed silt material. Throughout most of bed 4 the clays have a common orientation probably reflecting their primary bedding orientation and compaction.

Two shear zones are contained in bed (4) and these appear to have the same mineralogy as that of the host bed. Within these zones the clays have a turbulent orientation. The shear zones are less than 1 mm thick and parallel to bedding.

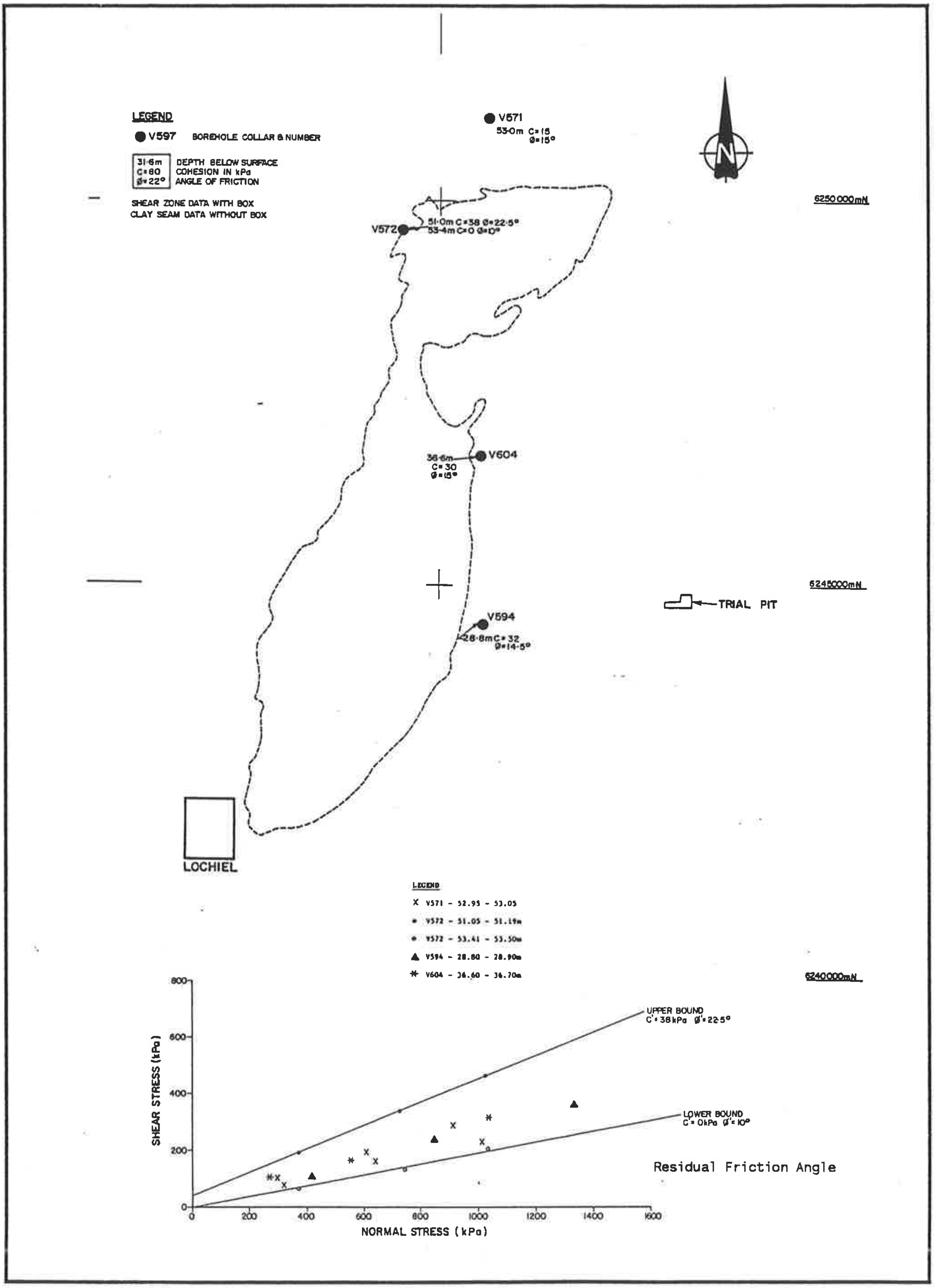


Figure 6.11 Warrindi Silt Formation - Location of test sites and summary of results of strength testing (testing performed by Coffey and Partners Pty Ltd, 1988).

6.3 Tarella Silt Formation

The Tarella Silt Formation overlies the Warrindi Silt Formation with a sharp contact. The formation attains a maximum thickness of 25 m in the north-central part of the area and overlaps on the southern and eastern margins (Figure 6.12).

The formation has been divided into four lithofacies based on lithology and geophysical log response. A typical vertical profile illustrating these subdivisions is presented in Figure 6.13. The top of the Tarella Silt Formation represents a surface of weathering and erosion (Plate 6.22).

6.3.1 Lithology and lateral variation

- TL4

TL4 overlies WA9 with a gradational contact. This contact coincides with the location of the Tarella Silt Formation Shear Zone discussed later in section 6.4.3. As shown on Figure 6.13 and Appendix 4, TL4 grades vertically into the overlying TL3. TL4 is distinguished from TL3 above and WA9 below by having a relatively low carbonaceous content (higher apparent density response) and relatively high clay content (higher natural gamma response).

The material consists of a medium brown, moderately carbonaceous silt with rare remains of arenaceous foraminifera dispersed throughout (Plate 6.23a and b).

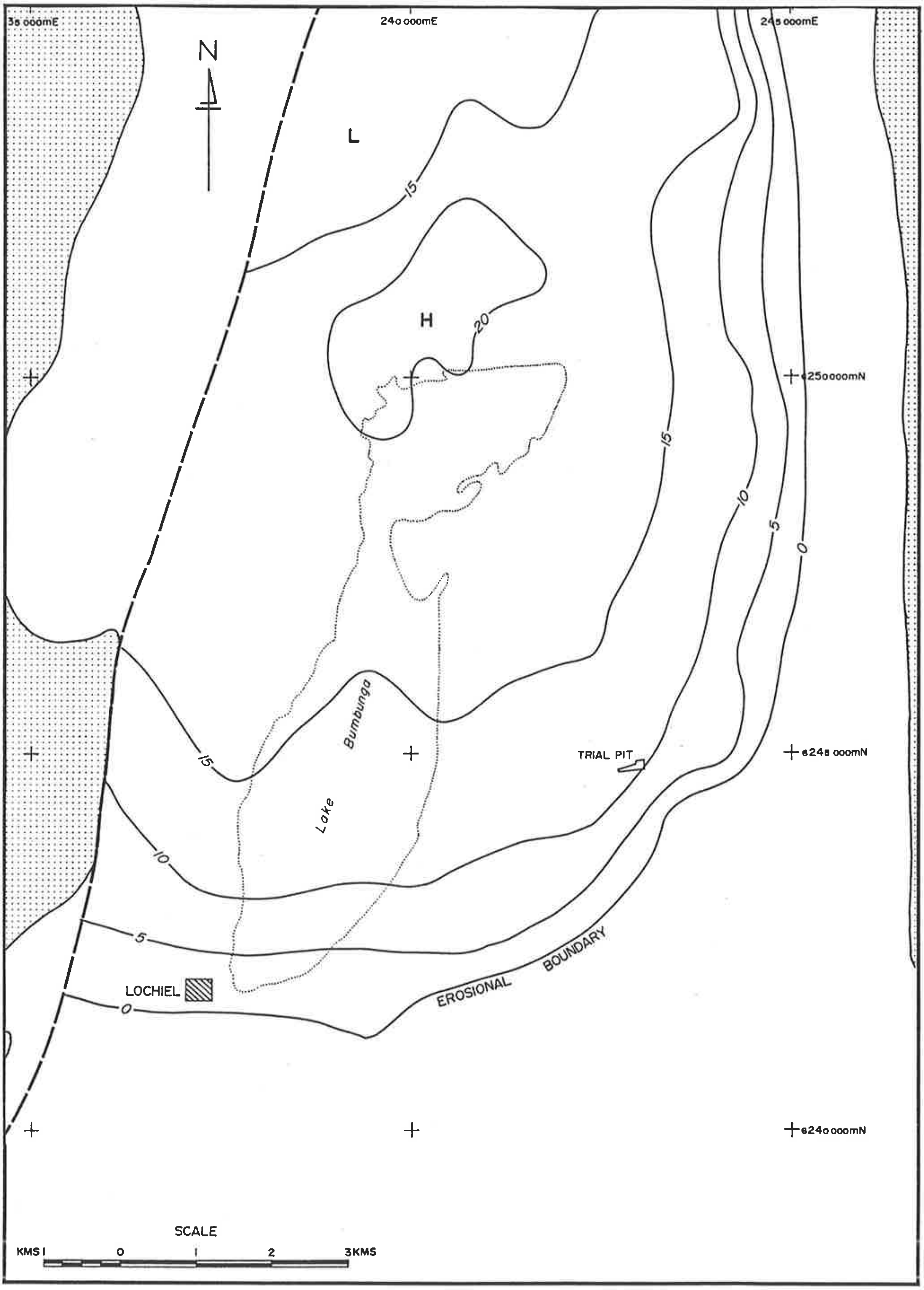
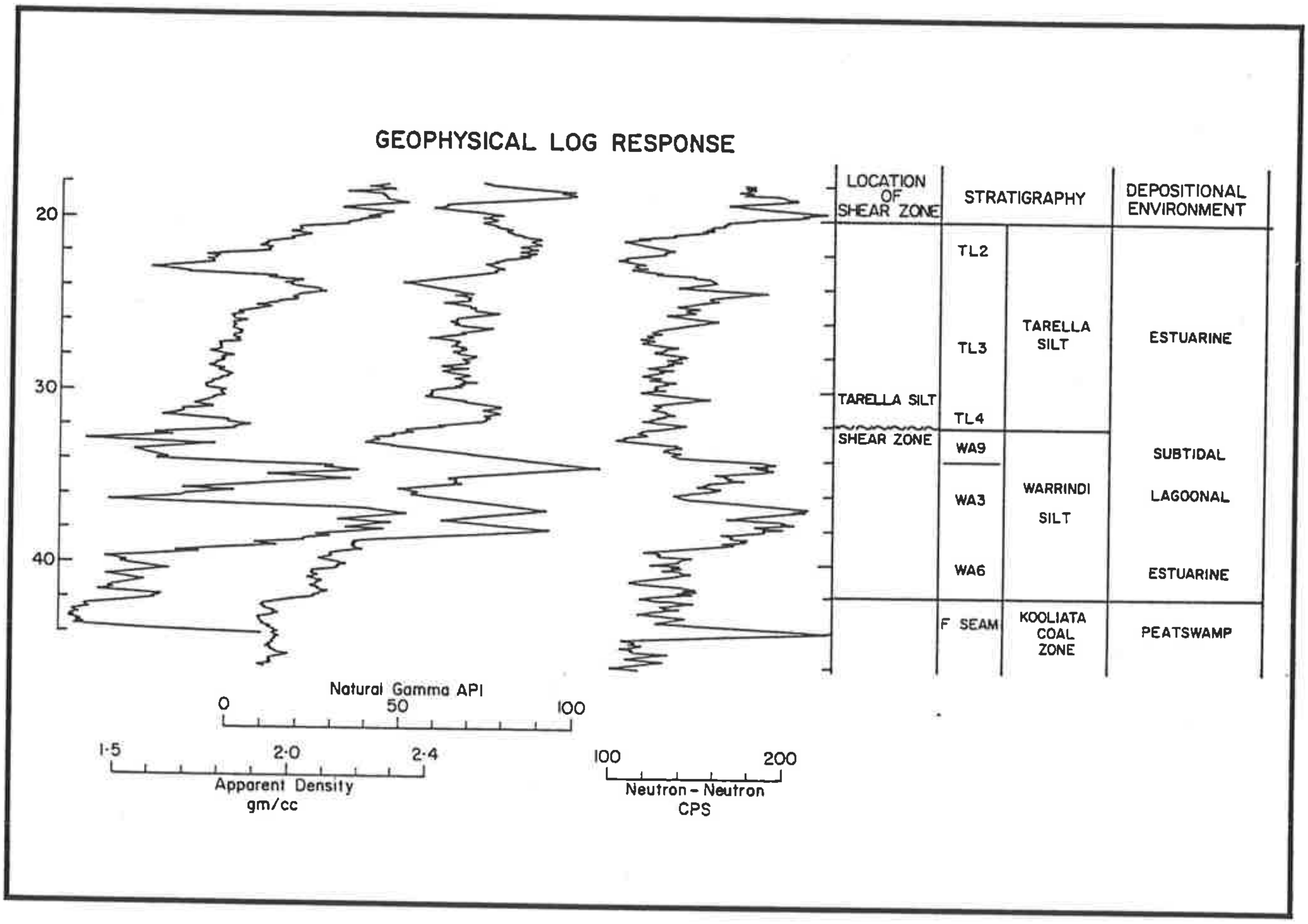


Figure 6.12 Tarella Silt Formation - Thickness and lateral distribution.

Figure 6.13 Tarella Silt Formation - geophysical log response, lithology and nomenclature.



Vague bedding is the only sedimentary structure in the sequence. TL4 varies from zero thickness in the south to a maximum of 6.5 m in the northwest. The thickness variations of this subunit are complementary to those of the overlying TL3 unit (Figures 6.14 and 6.15).

- TL3

TL3 varies in thickness from zero in the south and south-east up to 10.5 metres in the central area, thinning again farther north (Figure 6.15). It represents a gradational zone consisting of moderately carbonaceous,

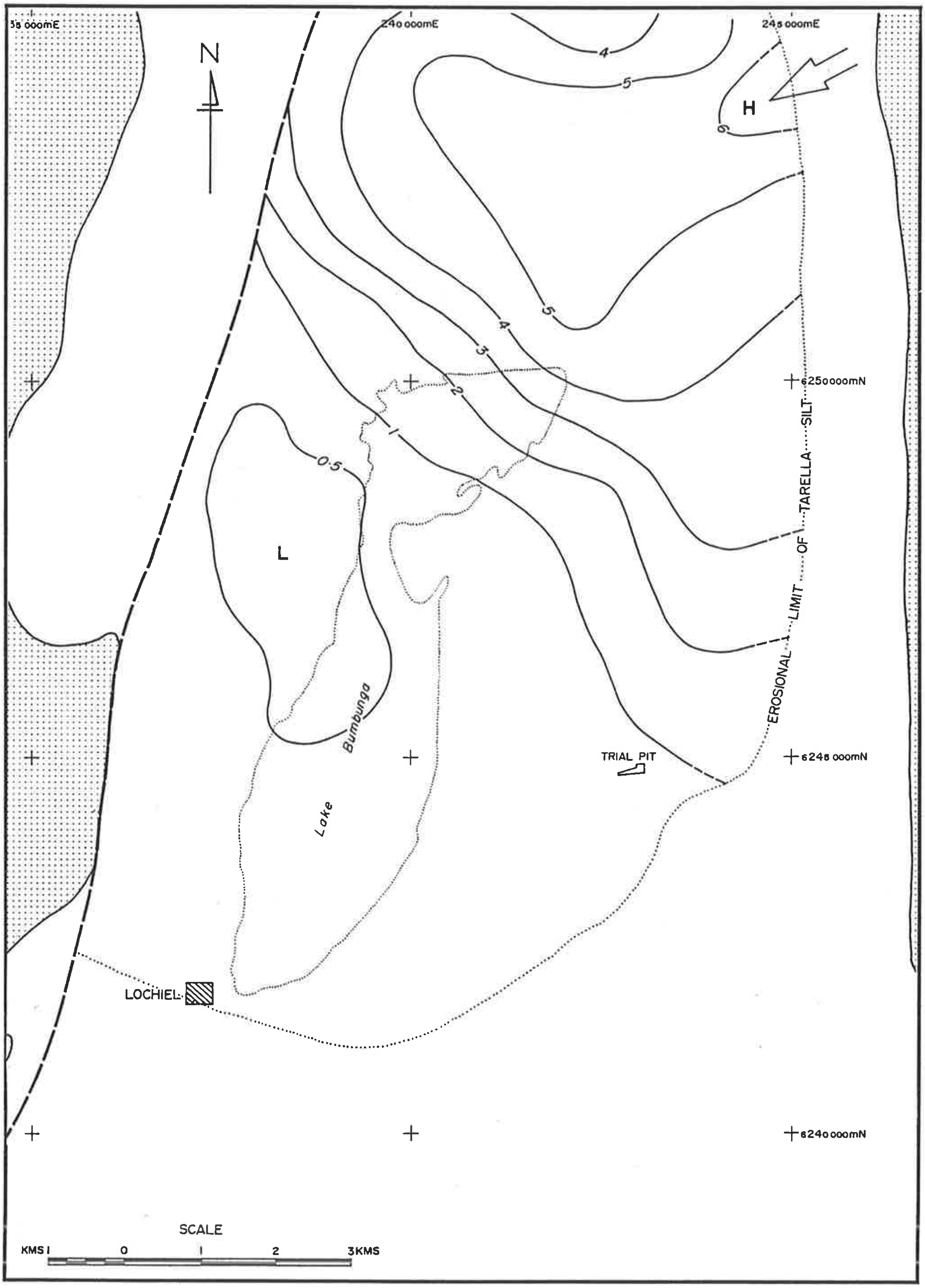


Figure 6.14 TL4 - Thickness and lateral distribution.

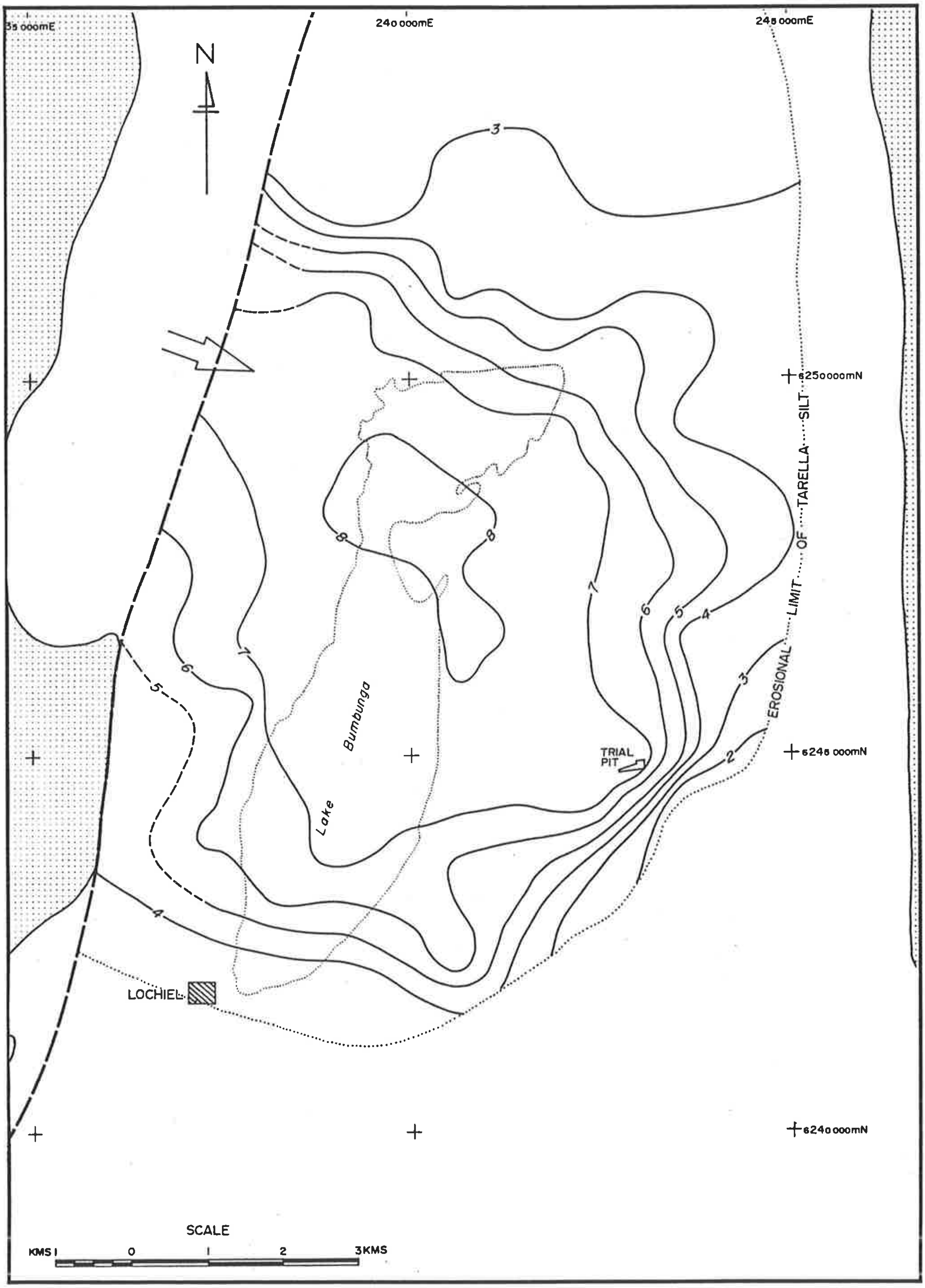


Figure 6.15 TL3 - Thickness and lateral distribution.

medium brown silt at the base to interbedded slightly carbonaceous silt and fine grained sand at the top. A characteristic feature is the presence of arenaceous foraminifera (Lindsay, pers. comm., 1987) which increase in number up the sequence.

The upper 2 metres characteristically comprises flaser and lenticular bedded fine grained sand and carbonaceous clayey silt.

- TL2

TL2 overlies TL3 with a sharp contact. TL2 consists of up to 4.7 metres of carbonaceous silt (Figure 6.16). It is similar in lithology and cycle type to the underlying TL3.

The base of the cycle consists of dark brown, highly carbonaceous silt. The silt becomes gradationally less carbonaceous towards the top until the upper 0.5 metres is essentially non-carbonaceous grey silt.

As the silt becomes less carbonaceous upwards, the proportion of fine to very fine grained white and light brown discontinuous sand interbeds increases. These beds are irregular both in thickness and geometry. Generally they are less than 5 mm and dip at 5° to 10° with maximum dips up to 15°. They are typical of the flaser and lenticular bedded sediments.

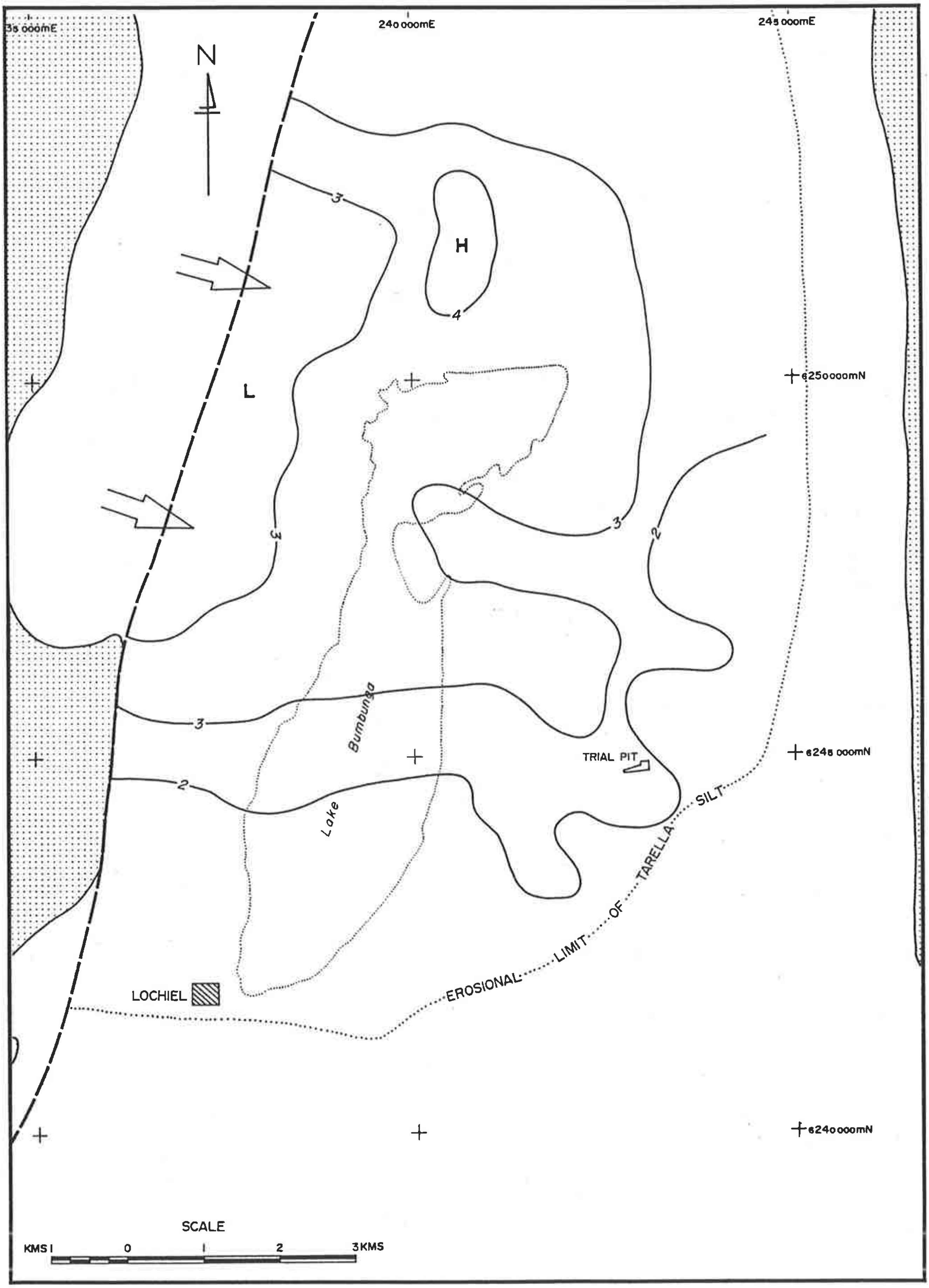


Figure 6.16 TL2 - Thickness and lateral distribution.

Some discontinuous medium brown silty clay seams up to 20 mm thick also occur within the flaser and lenticular bedded sediments. These clay seams generally occur as lenses but occasionally the lenses overlap to form contiguous beds.

TL2 grades into the overlying TL1.

- TL1

TL1 is considered to represent the last phase of Tertiary sedimentation in the area and also to represent the same depositional environment as the underlying Tarella Silt members (section 6.3.2). The top of TL1 is weathered and eroded.

TL1 reaches a maximum thickness of 8.1 metres (Figure 6.17) on the northwestern side of the area and thins gradationally to the east and south. This thickness trend is thought to reflect both the weathering and erosion and a depositional trend.

TL1 is comprised of fluvial sand and overbank and lacustrine silt and clay (refer to Figure 3.11 page 72).

The fluvial sand is up to 5 metres thick (Figure 6.18) and comprises fining upward medium to fine grained, moderately well sorted, subrounded and non carbonaceous sand. The sequence becomes more silty towards the top and is occasionally overlain by thin (<0.3 m.) coal seams.

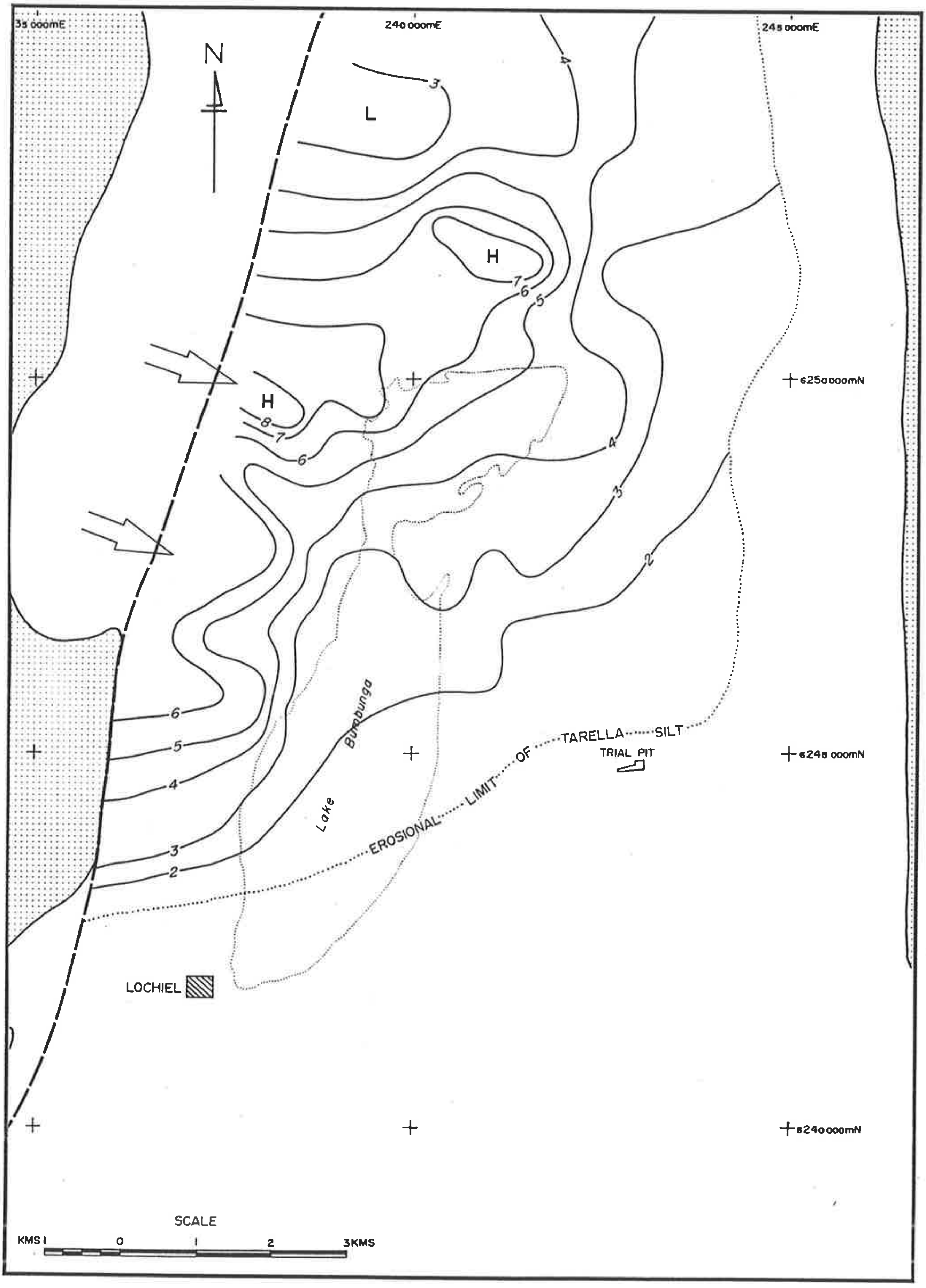


Figure 6.17 TL1 - Thickness and lateral distribution.

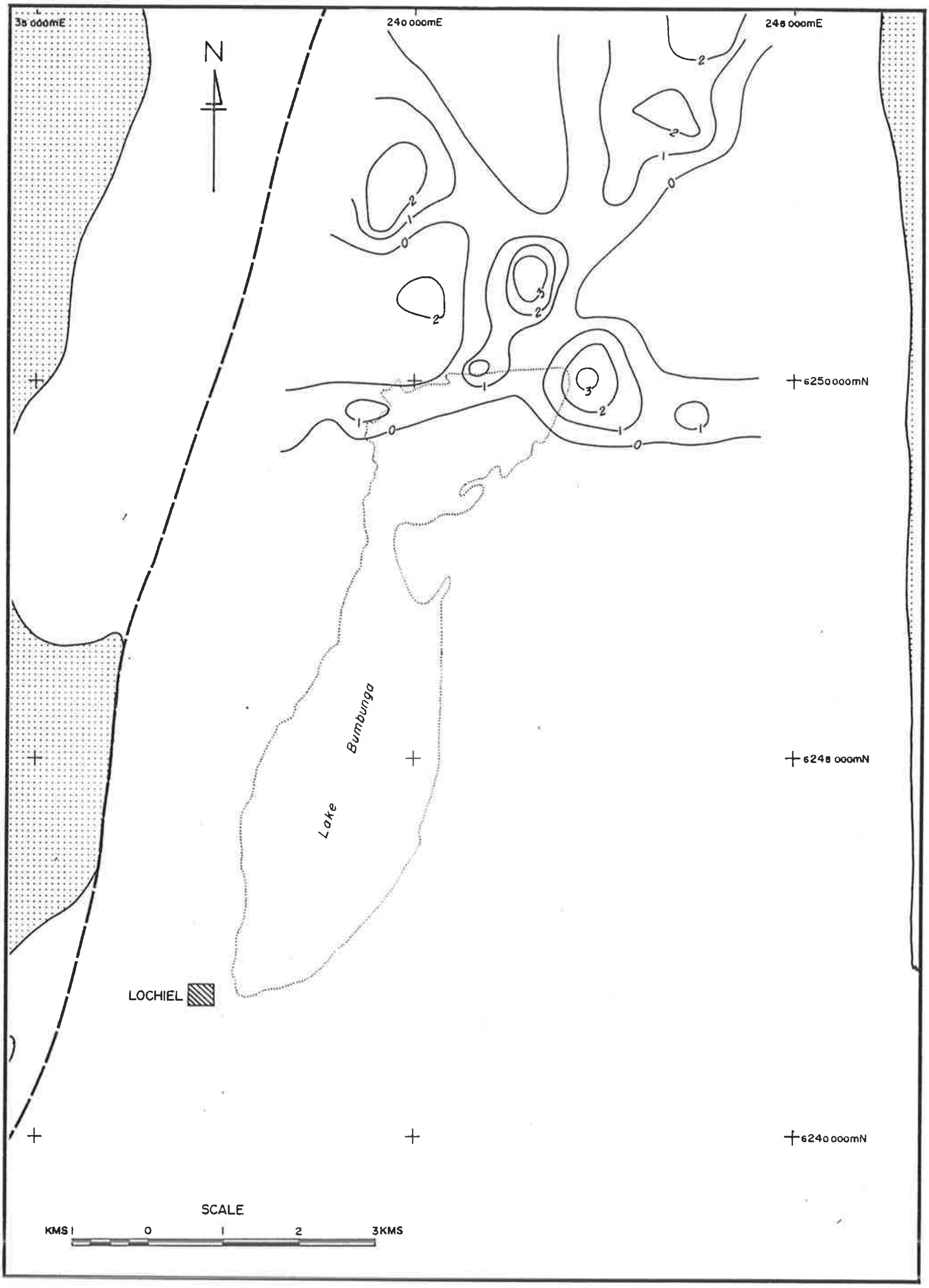


Figure 6.18 TL1 - Thickness and distribution of the clean sand facies.

bedded light grey or cream sandy and clayey silt representing crevasse splay and overbank sediments.

The fluvial and overbank and lacustrine facies are overlain by a zone of brecciated silty clay. This zone is up to 4 metres thick and comprises angular to subangular blocks of green, grey, yellow and brown clay in a light grey silty clay matrix (Plate 6.24). The blocks vary in size from 5 mm to greater than 100 mm and often appear to be weathered, having carbonaceous centres which gradually become less carbonaceous towards the edges. The breccia zone is associated with thin coal seams and where these are interbedded the breccia is extensively rooted. This breccia is considered to represent exposures and partial desiccation of lacustrine sediments.

6.3.2 Summary of facies relationships and depositional environments

The Tarella Silt Formation represents deposition in a mainly subaqueous, estuarine and back-barrier lagoon environment (Figure 6.19). Three distinct phases of sedimentation are recognised; TL3/4, TL2 and TL1.

TL3/4 and TL2 comprise coarsening upward sequences with highly clayey, carbonaceous sediments at the base grading to discontinuous interbeds of carbonaceous clayey silt and silty fine grained sand at the top. These sequences are considered to represent estuary/lagoon infills grading from aqueous at the base (carbonaceous silt) to subaqueous and intertidal at the top (flaser and lenticular bedded). The sediments exhibit a similar lateral distribution to the organic shales described by Piasecki et al. (1990). They found that hypolimnic sites were characterised by higher carbonaceous content (TL3) whilst the epilimnic sites were generally less carbonaceous (refer to Figure 3.9, page 67 for Total Organic Carbon (TOC) content of TL3 and TL4).

As discussed previously, TL1 represents fluvial and lacustrine depositional environments.

Of particular note is that the characteristics of the upward coarsening sequences in the Tarella Silt Formation are essentially the same as those for the Warrindi Silt Formation, GH interseam and Condowie Silt Member.

It is apparent that the depositional processes for each of these was equivalent, being controlled by tectonic movement along basement faults. However, the nature of the depositional environments changed from lacustrine for the GH intersem and Condowie Silt Member to marginal marine/estuarine for the Tarella Silt Formation reflecting the influence of eustacy.

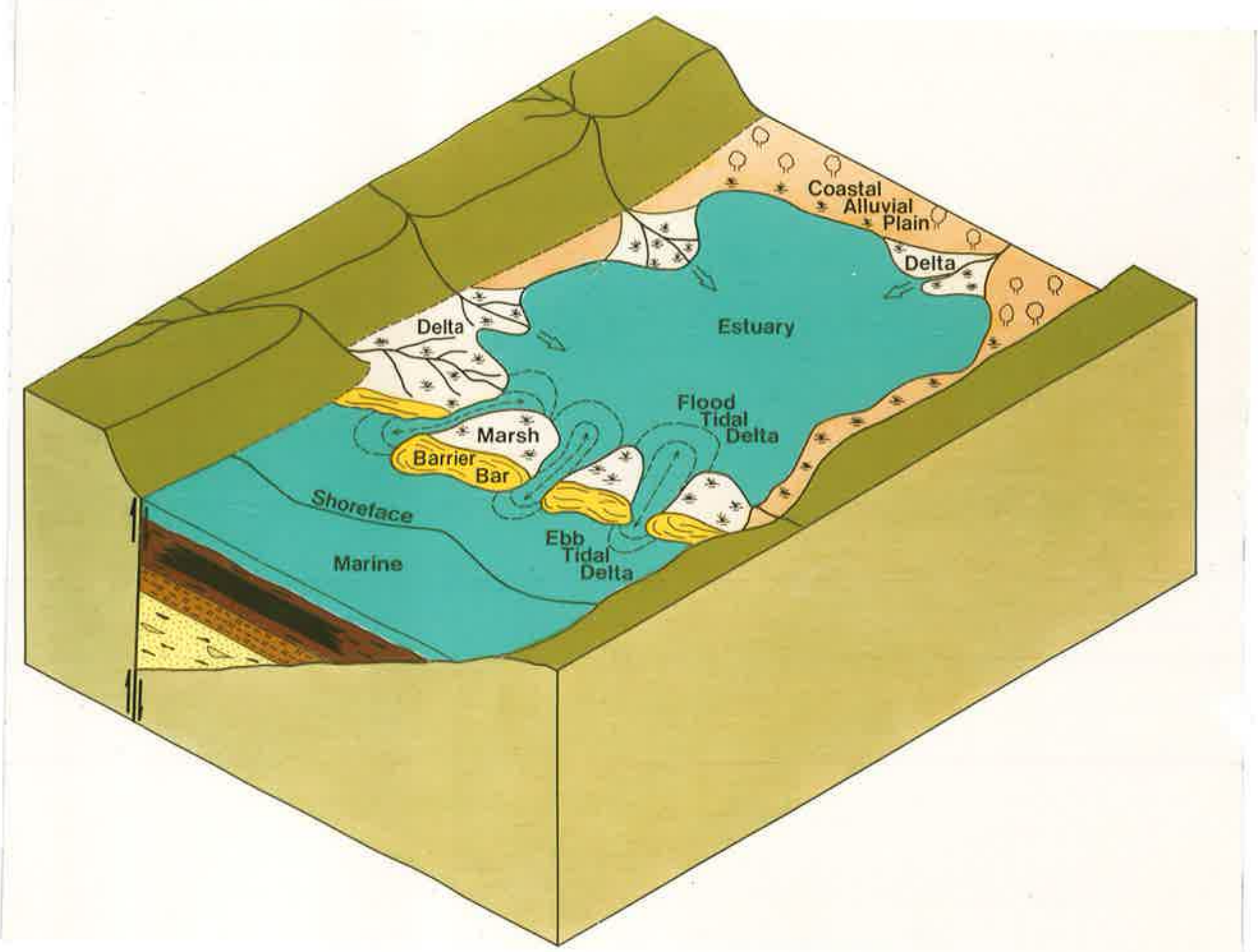


Figure 6.19 Schematic representation of the depositional setting of the Tarella Silt Formation.

6.4 Tectonic structures in the Tarella Silt Formation

In contrast to the underlying sediments, the Tarella Silt Formation is characterised by the presence of a number of tectonic structures. As discontinuities were identified in Chapter 4 as being a key factor affecting slope stability the purpose of this section is to :

- describe the tectonic structures and their interrelationships,
- define the geological factors which control their location, distribution, geometry and strength.

An understanding of the structural geology provides the basis for interpreting the properties of the defects present in the materials. However, before proceeding with the interpretation it is necessary to define the data available and the procedures best suited for analysis.

6.4.1 Data available

Data on tectonic structures is derived from two sources, core from drillholes and from the Trial Pit.

The core information was limited mainly to subhorizontal defects, whilst the trial excavation provided the opportunity to examine in detail the characteristics of all defects occurring at the Trial Pit site.

At the Trial Pit site, structural data was collected by three methods :

1. Line mapping of cut faces.

   A tape was run between two survey points and any structural feature which intersected the tape was measured and described on a structural logging form for inclusion into a computer data base. Orthogonal lines were used to eliminate geometric bias (Priest, 1985).

2. Floor mapping. Plans of joint geometry and type were prepared using tape and compass.

3. Detailed shear zone structural lines. Two orthogonal surveys of the surface structure of the Tarella Silt Formation Shear Zone were carried out. Measurements of all associated shear surfaces were surveyed at points with a spacing of about 0.5 metres.

. Tectonic structures in the Tarella Silt Formation

A number of types of structures were recognised in the Tarella Silt Formation. Characteristics of these are summarised on Table 6.1 and discussed in the following section. The structures have been classified into extensional and shear and each of these structures was further categorised on the basis of morphological characteristics and orientation.

Table 6.1 Structural features in the Tarella Silt

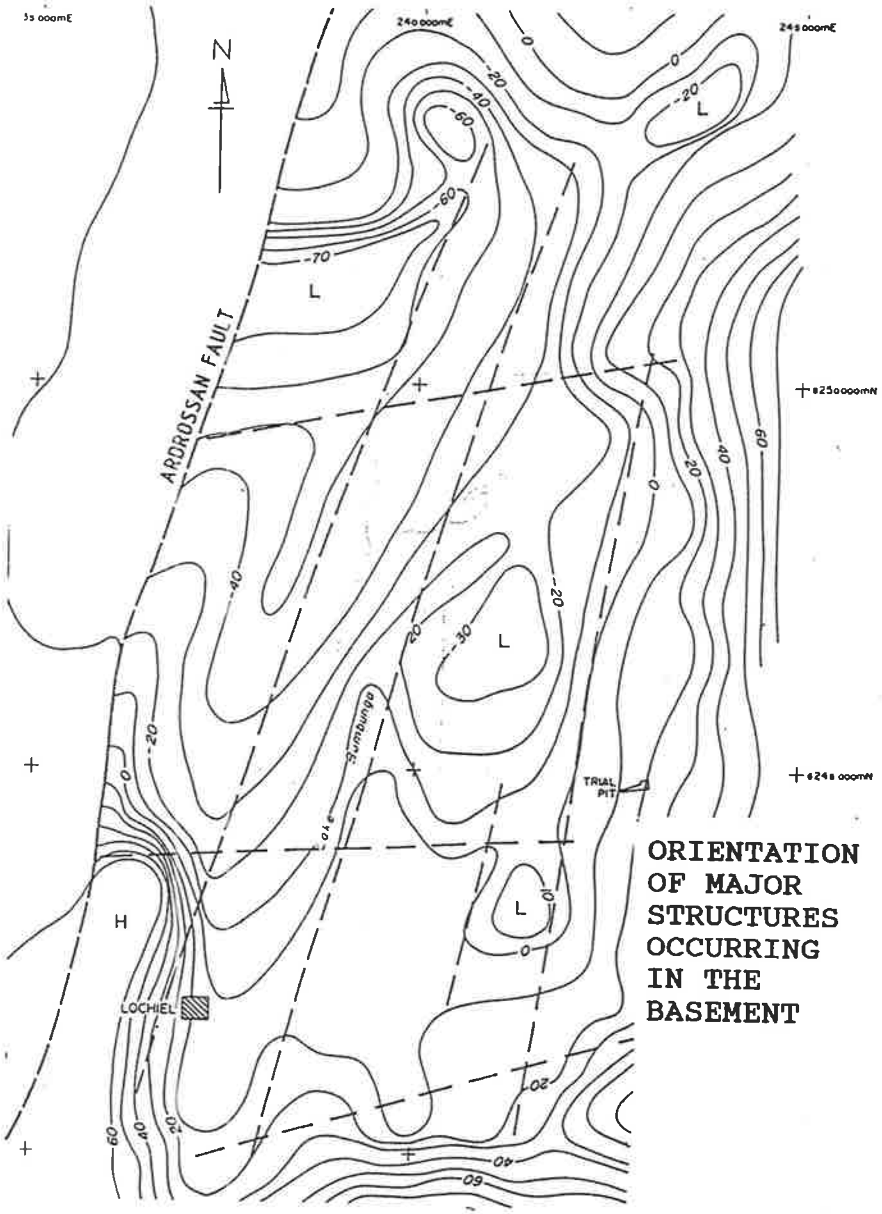
GENETIC TYPE	MORPHOLOGIC TYPE		ORIENTATION
Extension	. Mineralised	. Pyrite . Sand	Near vertical
	. Non mineralised		Near vertical
Shear	. Polished . Polished, slickensided, Ribbed . Polished, continuous		Near vertical Near vertical Near horizontal

6.4.2 Extensional structures

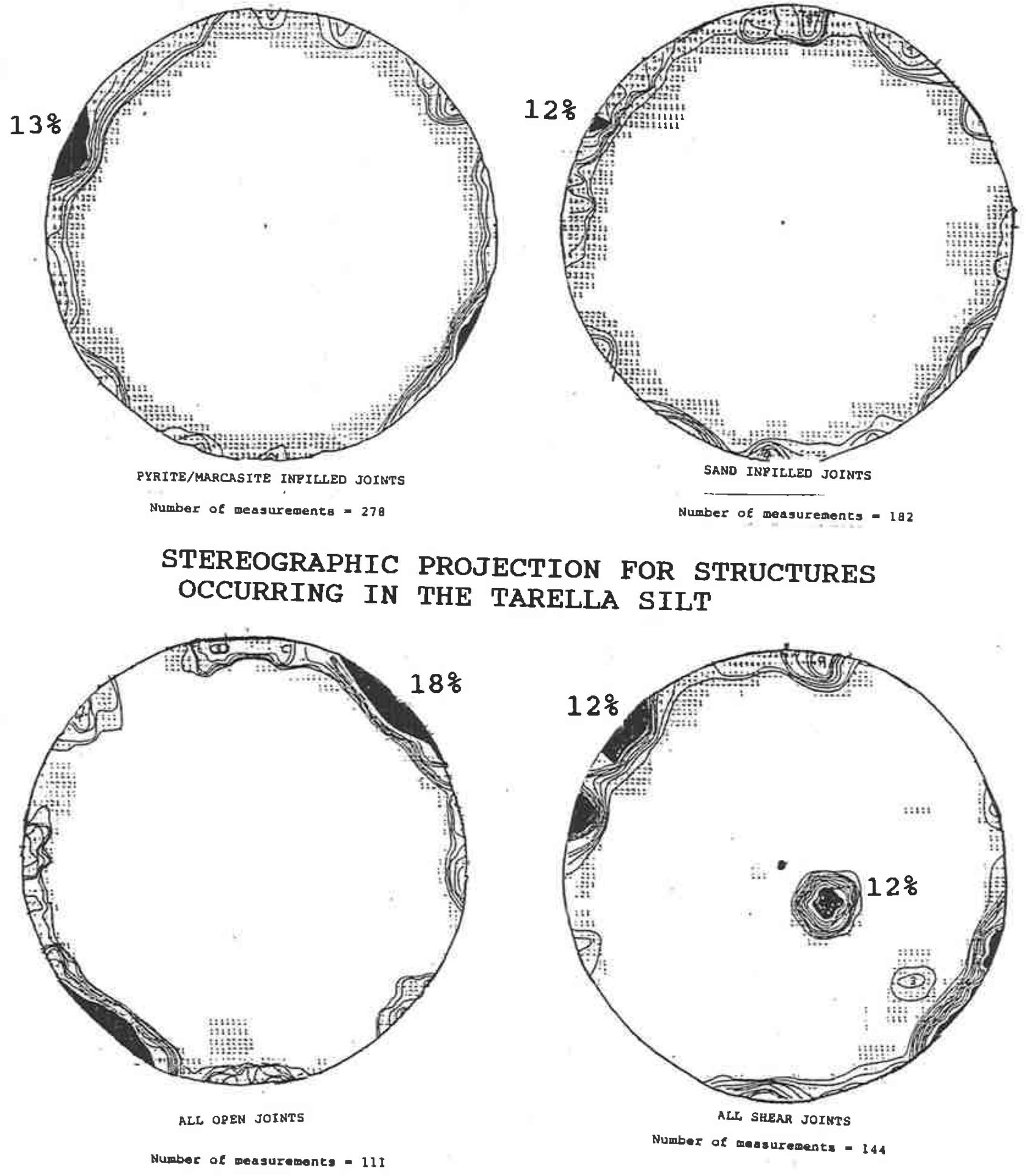
- Pyrite infilled joints

These occur as vertical to sub-vertical discontinuities infilled with pyrite/marcasite (Plates 6.25, 6.26 and 6.27). Pyrite is present as continuous and rough mineralisation ranging in thickness up to 10 mm and averaging 5 mm. Although there is considerable variation in the vertical extent of these joints they are commonly continuous from the top of TL3 to the shear zone at the base of TL4.

Stereographic projection of poles to these defects indicate a mean strike of 025° (Figure 6.20).



ORIENTATION OF MAJOR STRUCTURES OCCURRING IN THE BASEMENT



PYRITE/MARCASITE INFILLED JOINTS

Number of measurements = 278

SAND INFILLED JOINTS

Number of measurements = 182

STEREOGRAPHIC PROJECTION FOR STRUCTURES OCCURRING IN THE TARELLA SILT

ALL OPEN JOINTS

Number of measurements = 111

ALL SHEAR JOINTS

Number of measurements = 144

Figure 6.20 Summary of the geometric relationships between structural features in the Tarella Silt and their relationship with the regional structures.

Floor mapping shows that the joints are continuous and curved (Figure 6.21). It is this curvature which leads to the broad scatter exhibited by the stereographic projection.

Normalised spacings for large continuous joints were analysed with a lognormal distribution providing the best fit (Appendix 5). This analysis gave a mean spacing of 2.9 metres.

The pyrite infilled joints often grade upward into sand infilled joints and down into shear joints.

In the trial pit pyrite infilled joints also occur below the Tarella Silt Formation in WA9. These joints are small, grading upward into joints with shear features and terminate against the Tarella Silt Shear Zone. Towards the base, these joints terminate against WA5.

- Sand infilled joints

Stereographic projections of poles indicate a wide scatter of orientations with weak preferred orientation strike trends at 030°, 095° and 120° (Figure 6.20). The joints occur as continuous vertical to near vertical discontinuities infilled with fine to very fine grained silty sand (Plate 6.28 and 6.29). The infilling is thickest at the top of TL3 (maximum thickness 30 mm), wedging out downward.

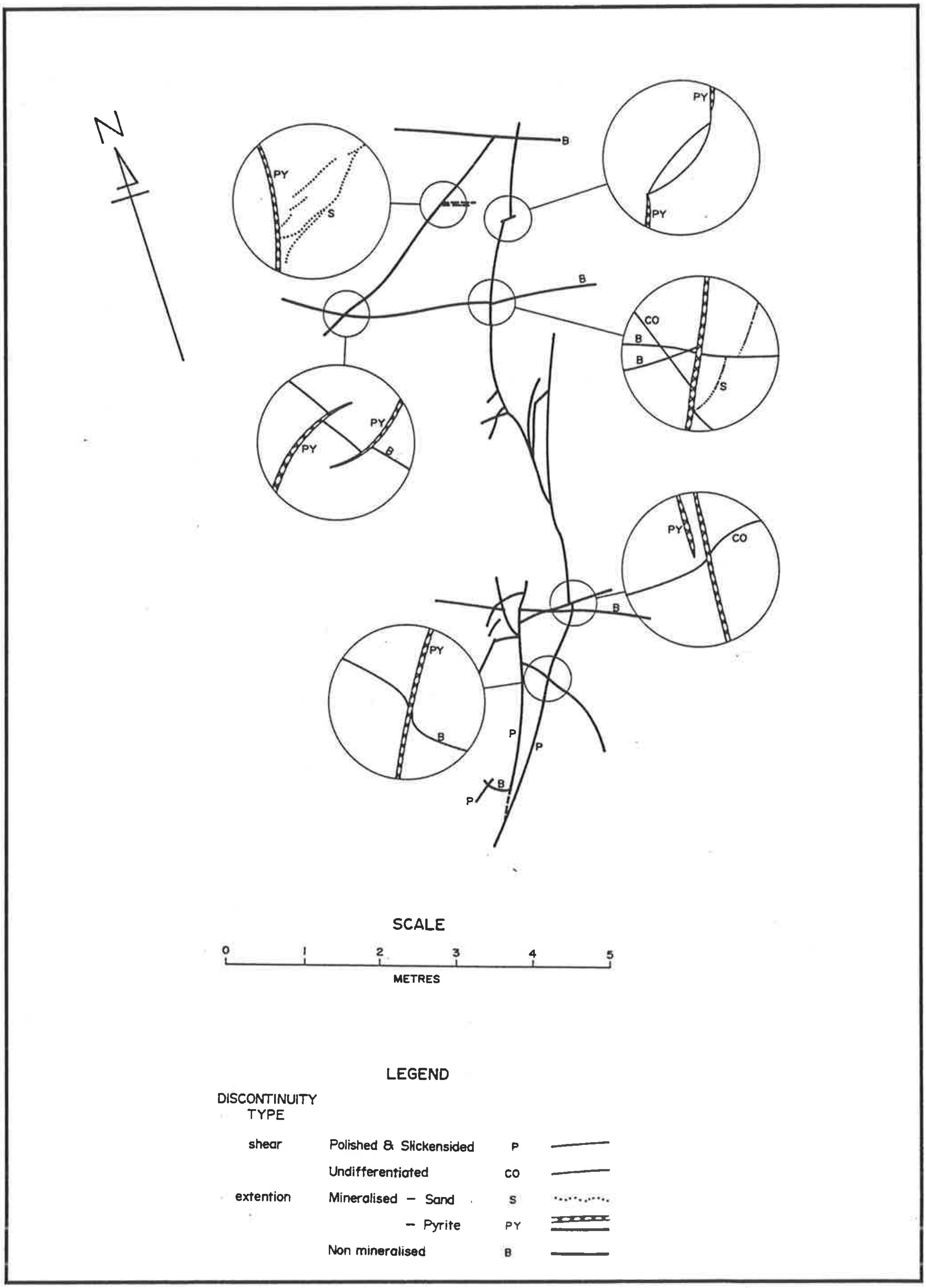


Figure 6.21 Relationships between tectonic structures in the Tarella Silt Formation from mapping of an intermediate floor of the Trial Pit.

The sand infilled joints have irregular, rough and curved surfaces at the top grading to planar at the base. The lower parts of the sand infilled joints commonly grade into pyritic joints. Less frequently, the sand infilling grades into silty clay.

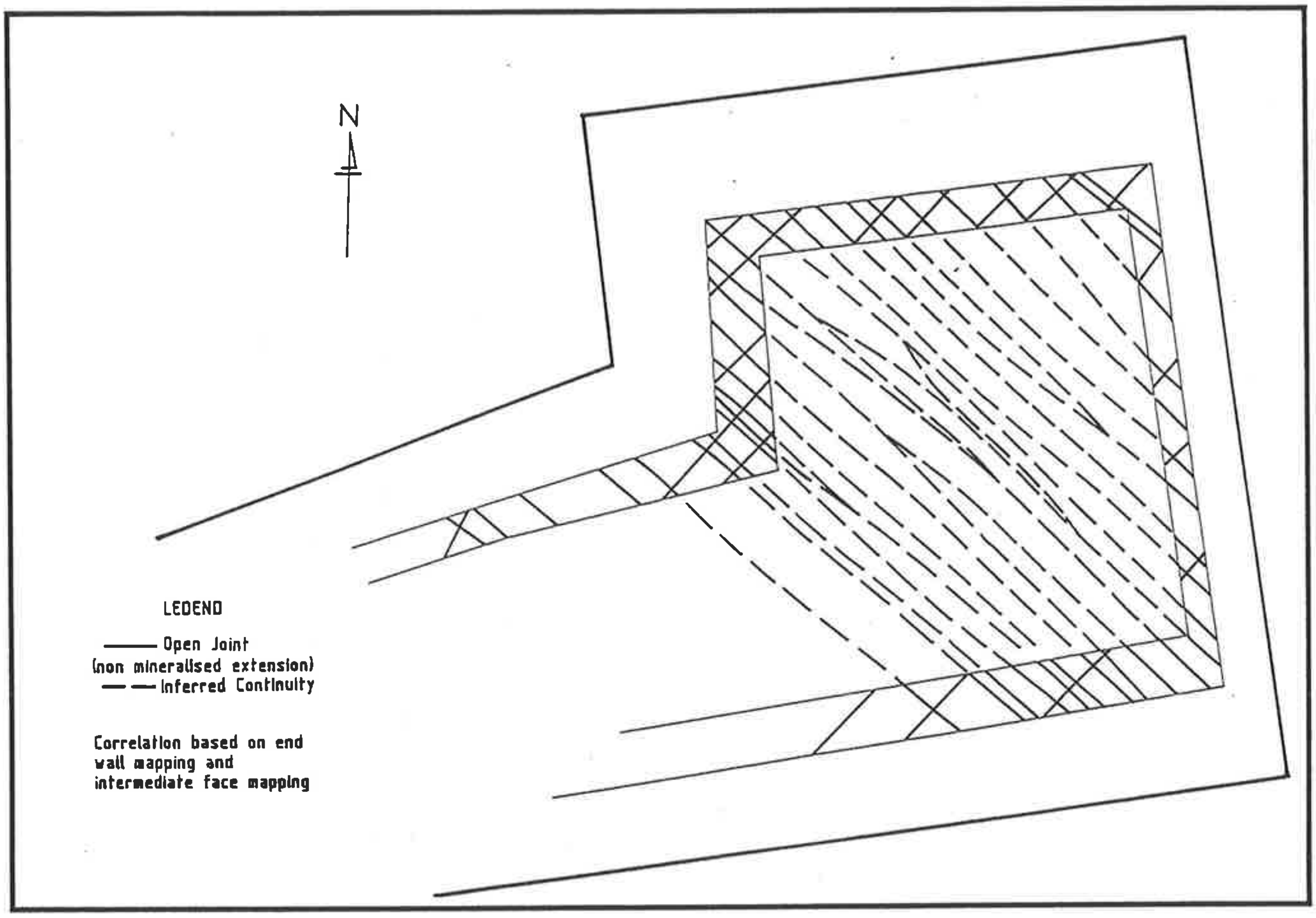
The sand infilled extensional joints are laterally continuous for up to 5 m, terminating against other sand infilled joints or wedging out into the formation. Rarely, the joints continue down to the Tarella Silt Shear Zone but in all cases terminate against this shear zone.

Analyses of spacings of sand infilled joints indicate a lognormal data distribution with a mean spacing of 2.7 metres (Appendix 5). Measurement and observations of these joints in the Pit indicates a bimodal spacing. The joints occur in sets with the sets having a mean spacing of 2.7 metres. These sets are about 1 metre wide and contain a number of closely spaced sand infilled joints.

- Non-mineralised, extensional joints

These joints occur as vertical to near vertical, open defects which are continuous vertically between the top of TL3 and the shear zone. Laterally these features have been mapped for distances of at least 30 metres and a diagrammatic representation of their occurrence is presented on Figure 6.22. The joints have curved to planar surfaces (Plate 6.30) and often have rib structures (as defined by Hodgson, 1961) near their termination against the Tarella Silt Shear Zone (Plates 6.31 and 6.32).

Figure 6.22 Lateral continuity and correlation of open joints in the Trial Pit



Stereographic projections of normals to these features indicate a strong alignment of strike trend at 310° with relatively minor sets occurring at 090° and 220° (Figures 6.20 and 6.22). These minor sets were not observed consistently over the trial pit area and are laterally discontinuous. Statistical analyses of the spacing between these joints indicates a lognormal distribution with a mean joint spacing of 2.4 metres (Appendix 5).

6.4.3 Shear structures

A summary of the types of shear joints occurring in the Trial Pit is presented on Table 6.2. The dipping joints generally terminate against the Tarella Silt Shear Zone though some continue through and are offset by this zone.

Table 6.2 Summary of the types of shear structures in the Tarella Silt Formation

Genetic Type	Range of Dip	Average Dip	Preferred Strike Trend	Morphology
Shear	Near 0°			Polished, striated slickensided
Shear	0° - 30°	15°	310°	Polished, slickensided
	60° - 80°	70°	310°	Polished, ribbed, slickensided
	80° - 90°		310°	Polished, slickensided

Terminology used is according to Skempton (1966), Morgenstern and Tchalenko (1967) and Tchalenko (1970).

- Tarella Silt Shear Zone (Dip near 0°)

The Tarella Silt Shear Zone has been studied to define the nature of the:

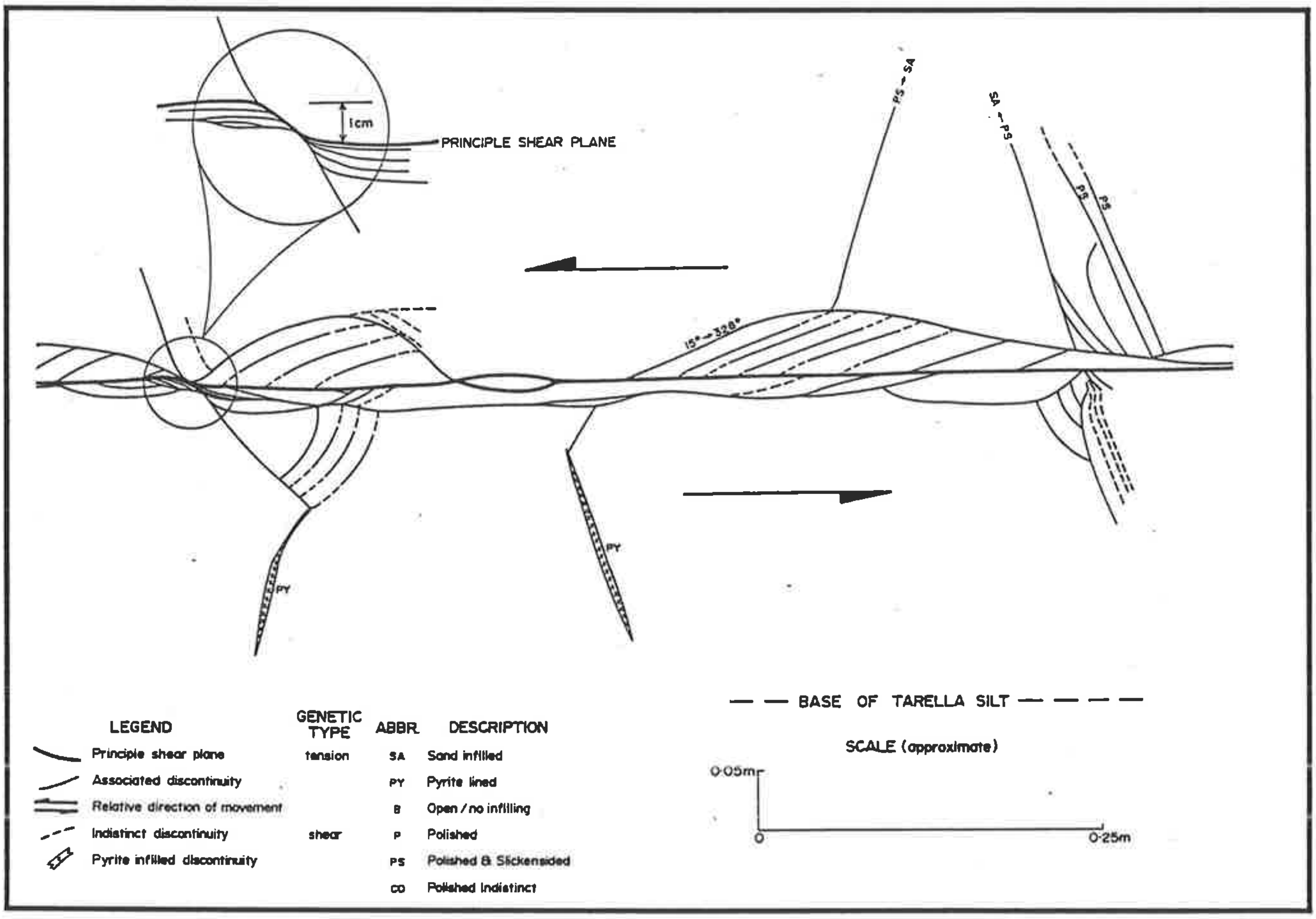
- stratigraphic location
- regional and local structural dip
- surface features
- relationships with other structural discontinuities
- sense of movement.

a) Stratigraphic location and description

The shear zone is stratigraphically located at the base of the Tarella Silt Formation and coincides with the clay-rich base of a coarsening up cycle as indicated by the natural gamma geophysical response (Figure 6.13).

The morphology of the Shear Zone appears to be typical of those described elsewhere, consisting of a continuous principal shear plane surrounded by a number of smaller, discontinuous shear slices (Plates 6.33-6.35 and Figure 6.23).

Figure 6.23 Tarella Silt Shear Zone - types and geometric relationships of associated structures



The thickness of the shear zone (principal shear plus slices) in the deposit area ranges between a few millimetres where only the principal shear surface is present up to 50 mm where several shear slices are present.

The lateral extent of the Tarella Silt Shear Zone is shown on Figure 6.24. This interpretation is based on the stratigraphic location and intersections in cored holes.

In the Trial Pit area, and from the interpretation of core, there was a gradation in the thickness of the shear zone from the northwestern side of the pit to the eastern and southern sides.

On the western side of the Trial Pit the shear zone consisted of three shear planes with the shear zone being 40 mm thick whereas on the eastern and southern sides the Shear Zone contains only a single shear plane (equivalent to the principal shear plane) less than 1 mm in thickness. For V709, the shear plane was indistinct. Observations on the shear zone within the Trial Pit confirm this trend though the minimum thickness of the shear zone was 10 mm and consisted of two shear planes (principal plus one slice).

These observations and measurements suggest that the shear zone is gradationally thinner to the south and east. This corresponds to a decrease in the shear character of the zone (fewer slices, indistinct principal shear plane) and is possibly related to the marginal location of the pit with respect to TL4.

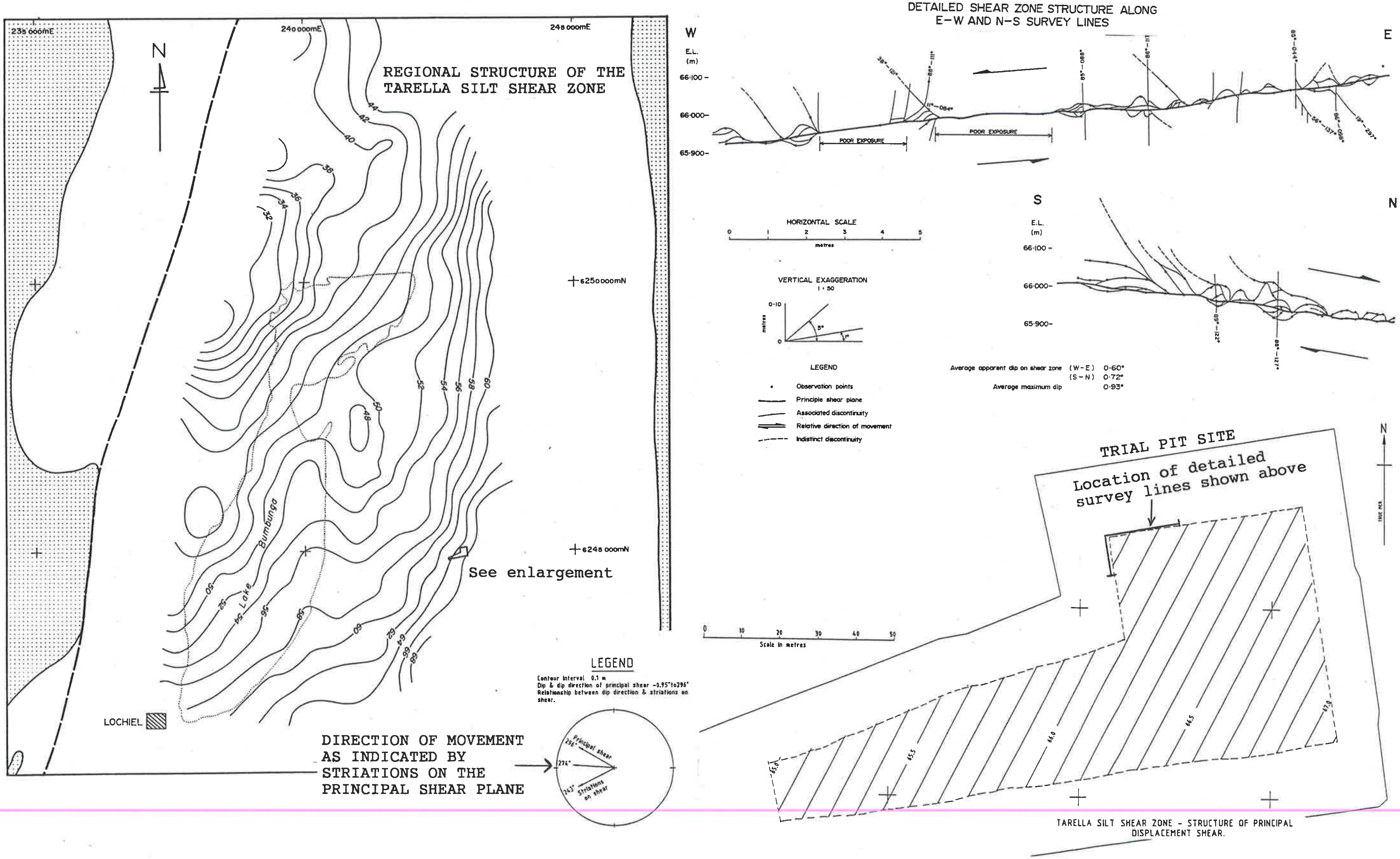


Figure 6.24 Tarella Silt Shear Zone - summary of structural characteristics.

b) Structural dip

As measured by detailed survey, the structure of the Tarella Silt Shear Zone in the Trial Pit area is shown on Figure 6.24. The maximum dip is .93° and this is confirmed from two detailed section lines. This dip is consistent with the regional dip derived from interpretation and surveying of all drillholes.

c) Surface features

The shear planes are highly polished with only indistinct striations. In order to determine the nature of undulation and asperities, measurements were taken at a spacing of about 0.5 m along orthogonal lines. These lines are plotted and presented on Figure 6.24.

The average maximum dip of the principal shear zone is 0.60° and 0.72° to the west and north respectively. From the line mapping it was found that the principal shear plane of the Tarella Silt Shear Zone exhibited an undulation with average variation in dip angle for the south-north line being 0.3° using a 0.5 m sample interval.

d) Relationships with other structural discontinuities

The other discontinuities which are present in the Tarella Silt Formation are considered to be directly related to the shear stresses and strains leading to the formation of the shear zone. All the extensional joints (pyritic, sand, open) terminate against this zone, though some shear joints were observed to displace the principal shear plane by up to 10 mm, within the shear zone.

The shear zone forms a continuous, clay-rich layer within the stratigraphic sequence. Groundwater has been observed to accumulate above this layer in the end walls of the pit indicating that the shear zone acts as a relatively impermeable layer between the overlying jointed carbonaceous silt and the underlying sandy silt.

e) Sense of movement

In order to evaluate the direction of movement, measurements were made on striations occurring on the principal shear plane at a number of locations in the pit. Two distinct and consistent orientations were present towards 274° and 243° as shown on Figure 6.24. The 274° set is the better developed.

- Tarella Silt Formation - slickensided and polished shear joints (Reidel shears dipping at between 0° and 30°)

These joints originate on the principal shear zone and are continuous upward for up to 4 metres. They become progressively less distinct upward and generally terminate on vertical or near vertical shear joints.

Laterally they are disrupted by intersecting open joints but individual shear joints were observed to continue for at least 5 metres.

These joints are considered to be equivalent to the Riedel shears of Skempton (1966). They have a strong preferential orientation with an average dip and dip direction of 15° towards 310° (Figure 6.20).

- Tarella Silt Formation - slickensided and polished shear joints dipping between 60° and 80°

Shear joints of this geometry occur in two stratigraphic horizons, at the top of TL3 and at the base of TL3.

a) Top of TL3

Shear joints of this orientation are rare. They occur as striated and slickensided planes continuous for less than 2 m vertically and less than 4 m laterally (Plate 6.36).

b) Base of TL3

These joints occur as ribbed and slickensided planar features which have been observed to continue for up to 10 metres laterally.

Vertically they are discontinuous, terminating against the Tarella Silt Shear Zone at the base and against other steeply dipping shear joints upward. Rib features on the surface of these joints (Plate 6.37) are indicative of lateral movement along these planes, probably in association with movements across the Tarella Silt Shear Zone.

As indicated on Figure 6.20(d) these shear defects have a preferential dip and dip direction of 70° toward 310°. However, striations on the principal shear plane indicate a direction of movement towards 274°. It is likely that this was probably the latest of a number of movements along the principal shear plane with the changes in stress directions resulting in the formation of the rib structures.

- Tarella Silt Formation - polished and slickensided shear joints dipping at between 80°and 90°

These are the most common types of shear joint in the Tarella Silt Formation. They are laterally continuous and grade vertically upward for up to 4 metres. Often the upper part of these joints are infilled with pyrite.

These joints have been observed to intersect and offset the Tarella Silt Shear Zone by up to 10 mm (Figures 6.23 and 6.24). Joints of this type are considered to be equivalent to the conjugate Riedels of Skempton (1966).

6.4.4 Origins of tectonic structures

The tectonic features observed in the Tarella Silt Formation can be divided into those associated with extensional stresses and those associated with shear stresses.

It is apparent from the facies distribution in the study area and from observations by Stuart (1969) that the sediments in the St Vincent Basin drape over normal faults in the underlying basement (Figure 6.25). It is generally accepted that these normal faults have been active intermittently since basin formation in the Middle Eocene to present.

Extension along the major principal stress axis would be conducive to the presence of these normal faults. This tension is considered to be related to the relative movement of the more mobile Adelaide Geosyncline in relation to the stable Gawler Craton.

At least three sets of extensional joints are identified based on the type of infilling material (sand, pyrite and open).

Gramberg (1966) developed a joint classification model and proposed that when "brittle" materials are subject to low confining pressures axial fractures are developed parallel to the compressive stress direction. The general character of the extensional joint sets suggests that they were formed under direct tensile stress at low confining pressure.

Two major orientations are identified for the extensional joints in the trial pit area. First, a NNE-SSW trending set of pyrite infilled joints (Figure 6.20(a)) and, second, a NNW-SSE set of open joints (Figure 6.20(c)). The open joints are observed to intersect the pyrite infilled joints and on this basis are considered to be younger. The sand infilled joints appear to be related to the pyrite infilled joints.

It is apparent from both the orientation of the two sets of extensional joints and the relationship with each other that there have been two different compressive episodes.

The first of these compressive episodes had the major stress axis aligned NNE-SSW and the second episode a NNW-SSE axis. These two trends parallel the strike of major basement structures in the study area. In addition, from the orientation of the shear features in the area it is apparent that shear stresses were related primarily to the first compressive episode. There is also a secondary set of shear features parallel to the extension features associated with the second episode (refer to Figure 6.20(d)).

This is supported by measurement of striations on the principal shear plane in the Tarella Silt Shear Zone which indicate two directions of movement on the shear plane.

Figure 6.25 presents a possible model for the formation of structural features present in the Lochiel area. This model is based on the first of the compressive episodes.

Notwithstanding the affects of tectonic movement on the formation of structures, there was also likely to be a secondary stress field associated with drainage and compaction of the sediments.

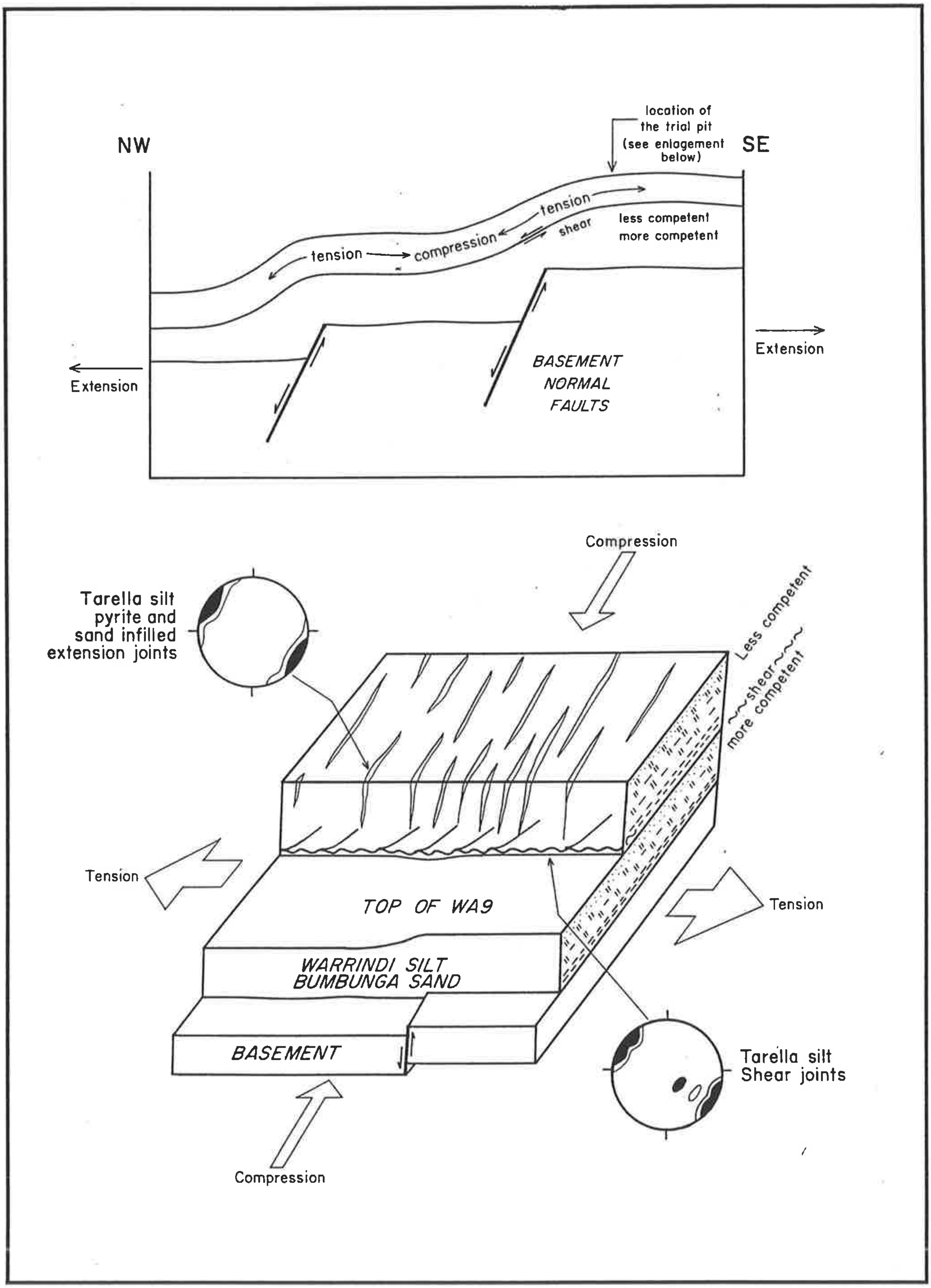


Figure 6.25 Model of stresses and the resultant structures present at the Trial Pit site

6.5 Synthesis of geological processes and engineering properties for the Tarella Silt Formation

6.5.1 Strength of the Tarella Silt Shear Zone

For the purposes of determining the properties of the Tarella Silt Shear Zone, a major program of sampling and geotechnical laboratory testing was undertaken. Most samples were recovered from drillcores taken in the study area but some samples were also collected within the Trial Pit.

- Testing procedure and limitations

The tests associated with the Tarella Silt Shear Zone were carried out by Coffey and Partners Pty Ltd. Strength testing of the shear zone was by the direct shear method and the testing procedure is detailed in Coffey and Partners Pty Ltd (1988).

A number of aspects influence the accuracy of results obtained from direct shear tests including;

- size of the test sample. A number of different sizes of samples were tested including 100mm, 900mm and 500mm.
- accuracy of the test procedure. From detailed mapping of the trial pit exposures it was concluded that the Tarella Silt Shear Zone contained a principal shear plane surrounded by a number of other associated shears. It is anticipated that the peak strength results are affected by the alignment of this principal shear plane within the shear apparatus.

(Refer to Plate 6.38 for example of how 500mm samples were collected in the Trial Pit.)

- orientation of the shear plane. As discussed in Section 3.4.3 page 64 there is likely to be a difference in shear strength based on whether the shear test is performed across the dip direction or along the dip direction. An attempt was made to assess the significance of this aspect on samples taken in the trial excavation however results were inconclusive.

- Test results

A summary of the location and results of the direct shear tests undertaken on the Tarella Silt Shear Zone is presented on Figure 6.26.

No lateral trends in strength variation are recognised and it is considered that any small variation which may be present is clouded by the accuracy of the test results.

6.5.2 Porewater movement

A synthesis of the effects of pumping on the piezometric profile for the trial pit area and the major geological features is presented on Figure 3.5 (page 59). A number of lithofacies within the sequence at the trial pit site developed near vertical porewater pressure profiles indicating a relatively high vertical permeability. Within the coal bearing sequence these included the :

- Tarella Silt Formation above the shear zone - probably due to the presence of vertical open joints and vertical sand infilled joints

- Warrindi Silt Formation, F zone and FG interseam sediments - these are mostly sand and are therefore likely to be free draining. The exception is WA7 which is silty but this lithofacies is characterised by intensive bioturbation which would provide drainage paths.

Also of significance are the relatively impermeable zones coinciding with the :

- Tarella Silt Shear Zone - The shear zone truncates the vertical extension structures above it and in the pit free water ran out from this zone down the face (note the significant step in piezometric profile across the shear zone illustrated on Figure 3.5).
- G seam coal - In the trial pit area the G seam is relatively structureless unlike in other areas of the deposit where the joints indicate that there has been at least 2 periods of extensional deformation.
- Boundary between the Condowie Silt Member units CN1 and CN2 - This is the site of a clay-rich shear zone.

As indicated on Table 6.3, vertical permeabilities for the Tarella Silt Shear Zone (TLSZ) are extremely low. This is probably due to the alignment of platy minerals along the shear plane.

Table 6.3 Summary of estimates of vertical permeabilities and coefficient of consolidation (after Coffey and Partners Pty Ltd in ETSA 88/13).

Stratigraphy	Vertical Permeability cm/sec x 10-8	Vertical Coefficient of Consolidation m2/year
CN1/CN2	3	135
G seam coal	5	90
TL Shear Zone	0.25	8
TL above shear	2000	950

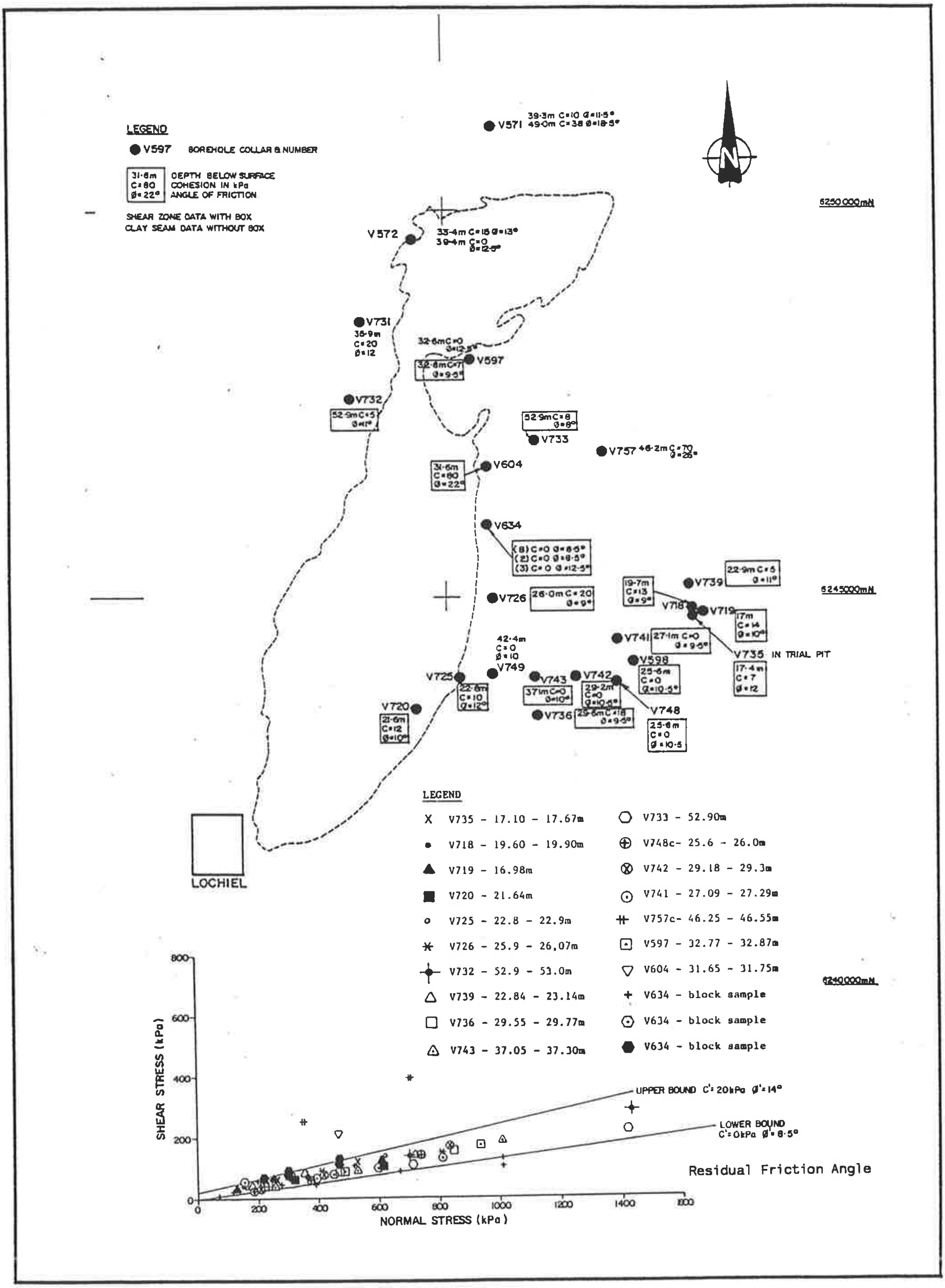


Figure 6.26 Tarella Silt Formation - Location of test sites and summary of results of strength testing (testing performed by Coffey and Partners Pty Ltd, 1988).

CHAPTER 7.0 SUMMARY OF ENGINEERING GEOLOGY OF THE LOCHIEL COAL DEPOSIT

This section summarises the engineering geological characteristics of the Lochiel Coal Deposit.

The aim is to categorise the deposit into discrete regimes which could provide the basis for slope stability analyses. A flowpath for defining regimes is provided on Figure 7.1. The regimes are defined based on differences in the following:

1. Intact material characteristics.
   These are primarily the thickness of the various sediment types (see Chapter 5.0) and the thickness of overburden (Figure 7.2).
2. Hydrogeological characteristics.
   The criteria used are the percentage and characteristics of clean sand facies in the overburden (Figure 7.3a and b) and the thickness of the Tarella Silt Formation (Figure 6.12). These criteria are appropriate because together they control the rate at which the sediments can be dewatered/depressurised. For the Tarella Silt Formation an arbitrary thickness cut-off of 5 metres is used.
3. Near horizontal weak zone characteristics.
   In the overburden these occur in the Tarella Silt Formation and GH interseam whilst below the coal seam(s) they are present within the Condowie Silt Member (Figure 7.4).

The regimes are confined to the area within the 6:1 strip ratio (cubic metres of overburden per tonne of coal).

7.1 Description of regimes

The locations of the Regimes are defined on Figure 7.5. Figure 7.6 also shows the lateral stratigraphic relationships between the Regimes.

- Regime 1

  Located at the northern end of the deposit. The depth to the base of coal averages 70m, with the sediments comprising predominantly silty facies of the Warrindi Silt and Tarella Silt Formations.

  The Tarella Silt Formation contains the shear zone and also the TL1 aquifer.

- Regime 2

  Occurs in the north-central and eastern sections of the deposit. The overburden comprises mainly silt and clay and has the lowest percentage of sand within the deposit. The boundaries are defined approximately by the 0.5m clean sand isopach but also by the 70m overburden thickness isopach to the north. Depth to the base of coal averages 60 metres.

  The Tarella Silt Shear Zone is present within this regime.

- Regime 3
  Is located in the central-western area of the deposit. Its boundaries are defined on the basis of a marked increase in depth to the base of coal. This increase in depth is associated with the regional tilting of the basin. The sediments are mainly silts and clays and include aquifers in the Warrindi Silt Formation and Kooliata Coal Member. The depth to the base of coal averages about 65 metres.

  The Tarella Silt Shear Zone is present within this regime as is the weak zone in the GH interseam.

  The WA4 aquifer is also present with the thickness of clean sand increasing to the west. In addition, the TL1 aquifer is present.

- Regime 4
  Occurs in the central and southeastern sections of the deposit. It is an area with a relatively uniform depth to coal and the southern boundary is defined by the lateral contact between the Tarella Silt Formation and the sandy facies of the Warrindi Silt Formation. The depth to the base of coal is about 50 metres and the overburden contains a mixture of sandy and silty facies of the Warrindi Silt Formation and the silty Tarella Silt Formation. The Trial Pit is located in this regime.

  This Regime contains the Tarella Silt Shear Zone.

Within this Regime aquifers include GH, FG, WA1, WA4 and WA2.

Regime 5

Is located in the south of the deposit. It is the only regime which contains no Tarella Silt Formation. The overburden comprises mainly silt and sand. The depth to the base of coal is of the order of 35 metres.

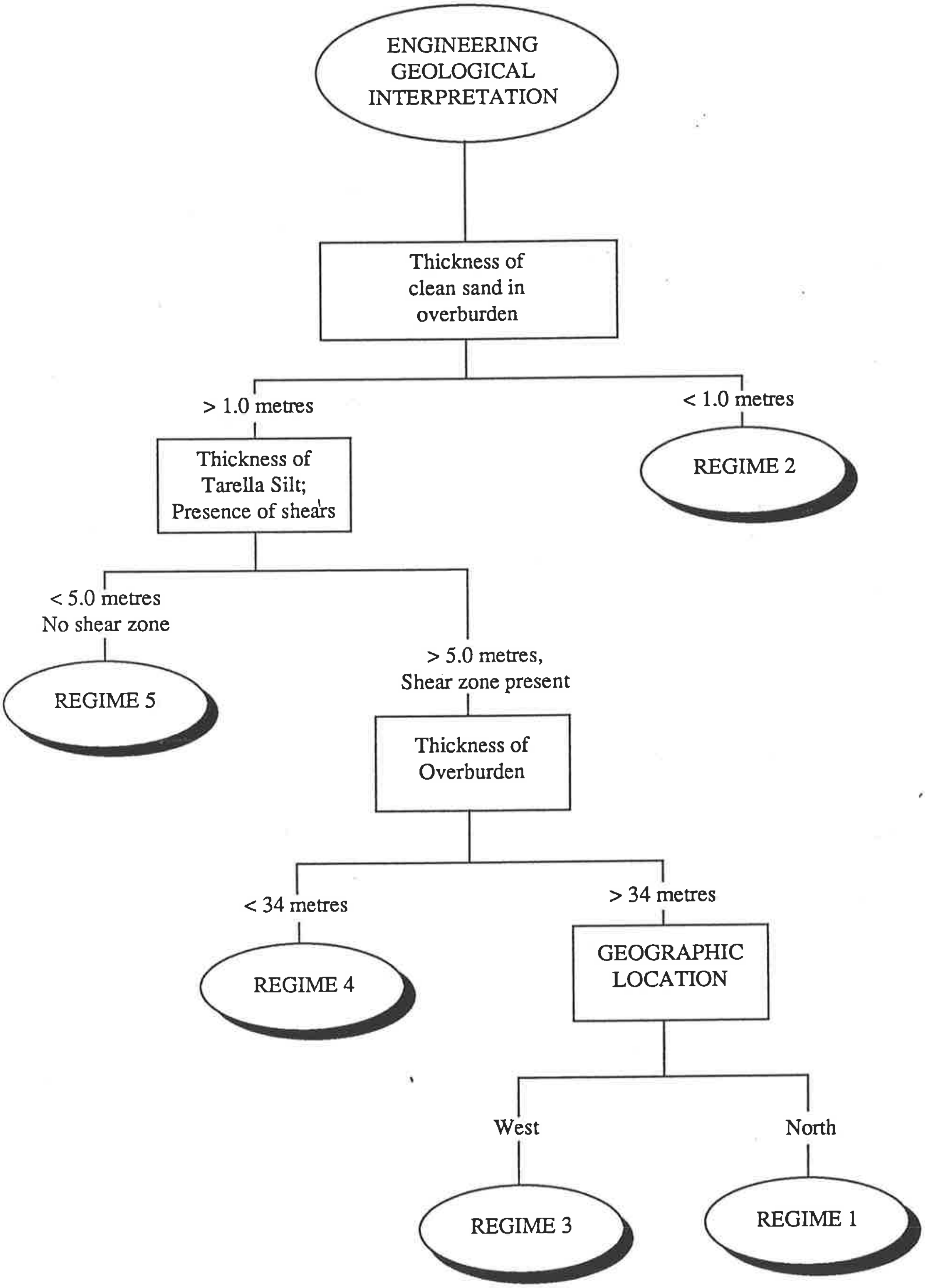


Figure 7.1 Flowpath for defining highwall stability design regimes.

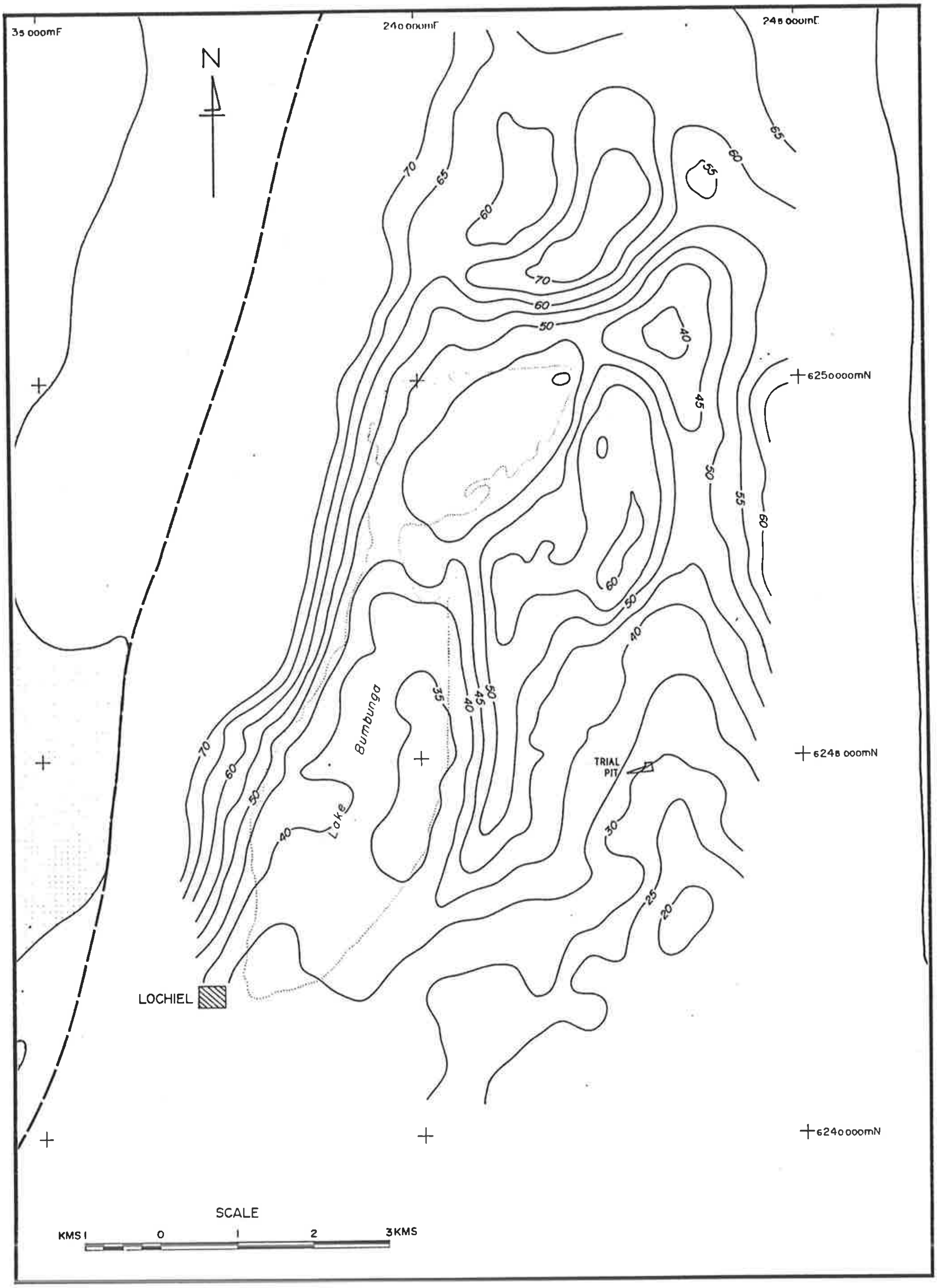


Figure 7.2 Thickness of overburden

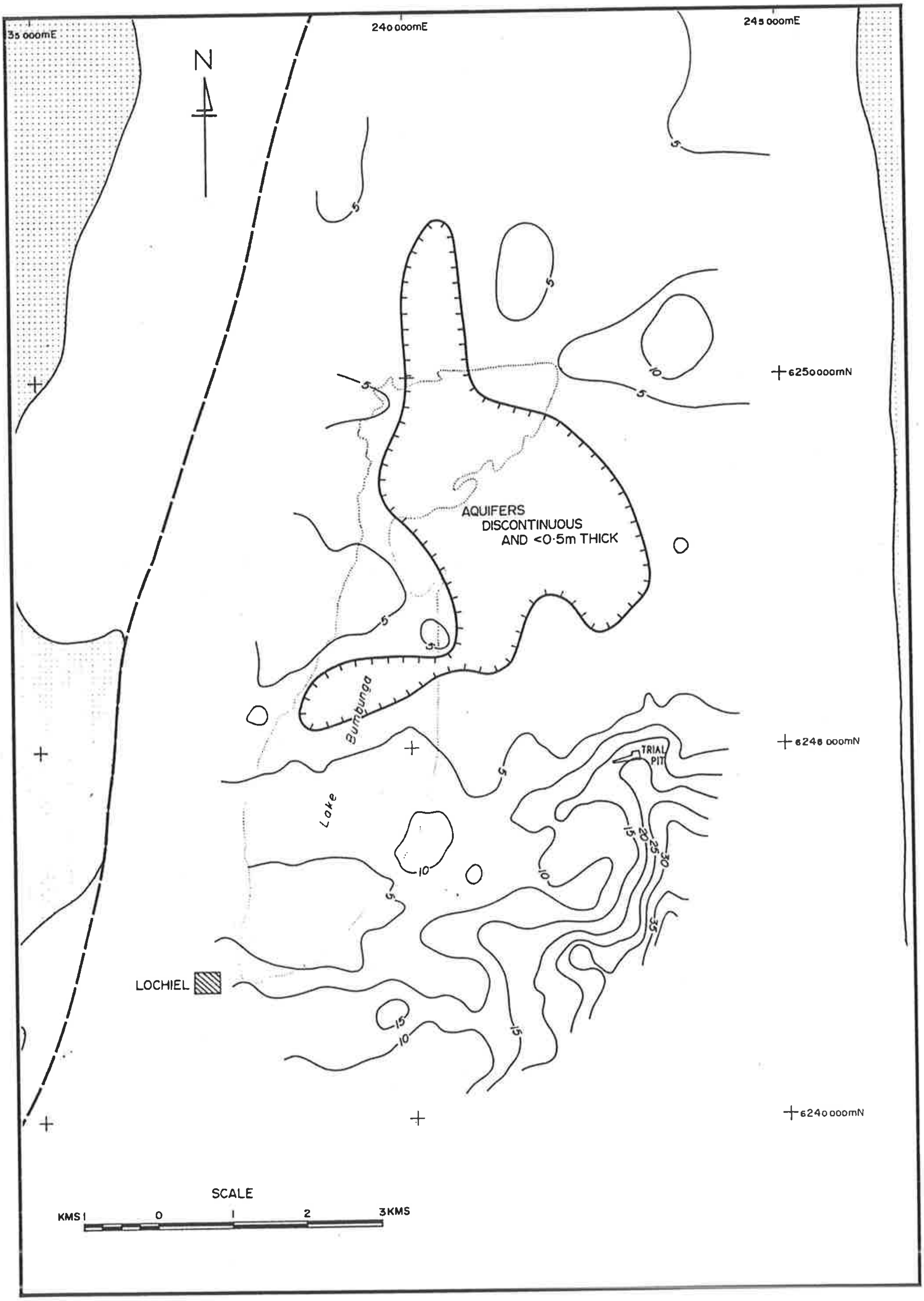


Figure 7.3a Percentage of clean sand in the overburden

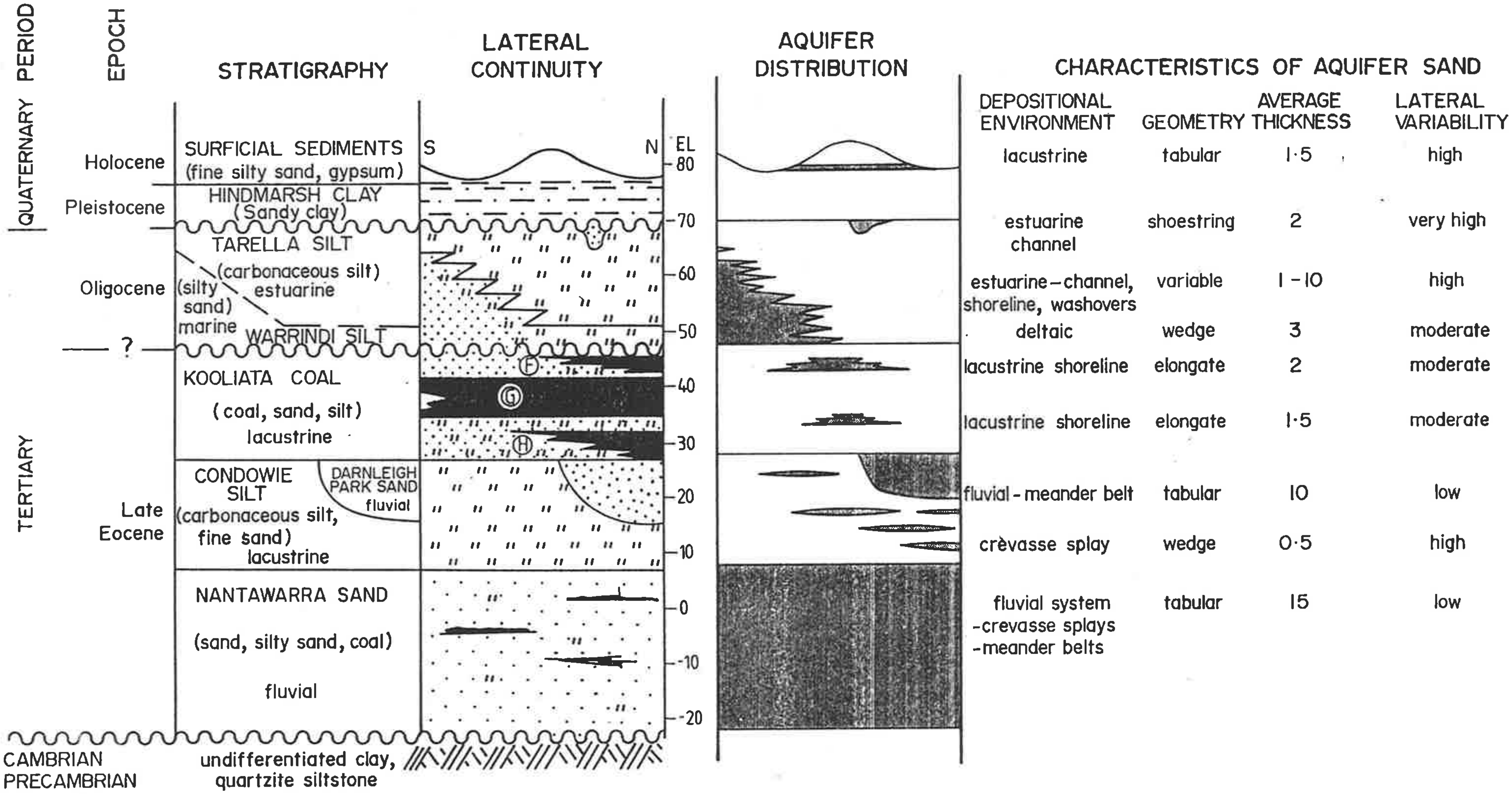


Figure 7.3b Summary of characteristics and distribution of clean sand facies occurring in the Lochiel Coal Deposit.

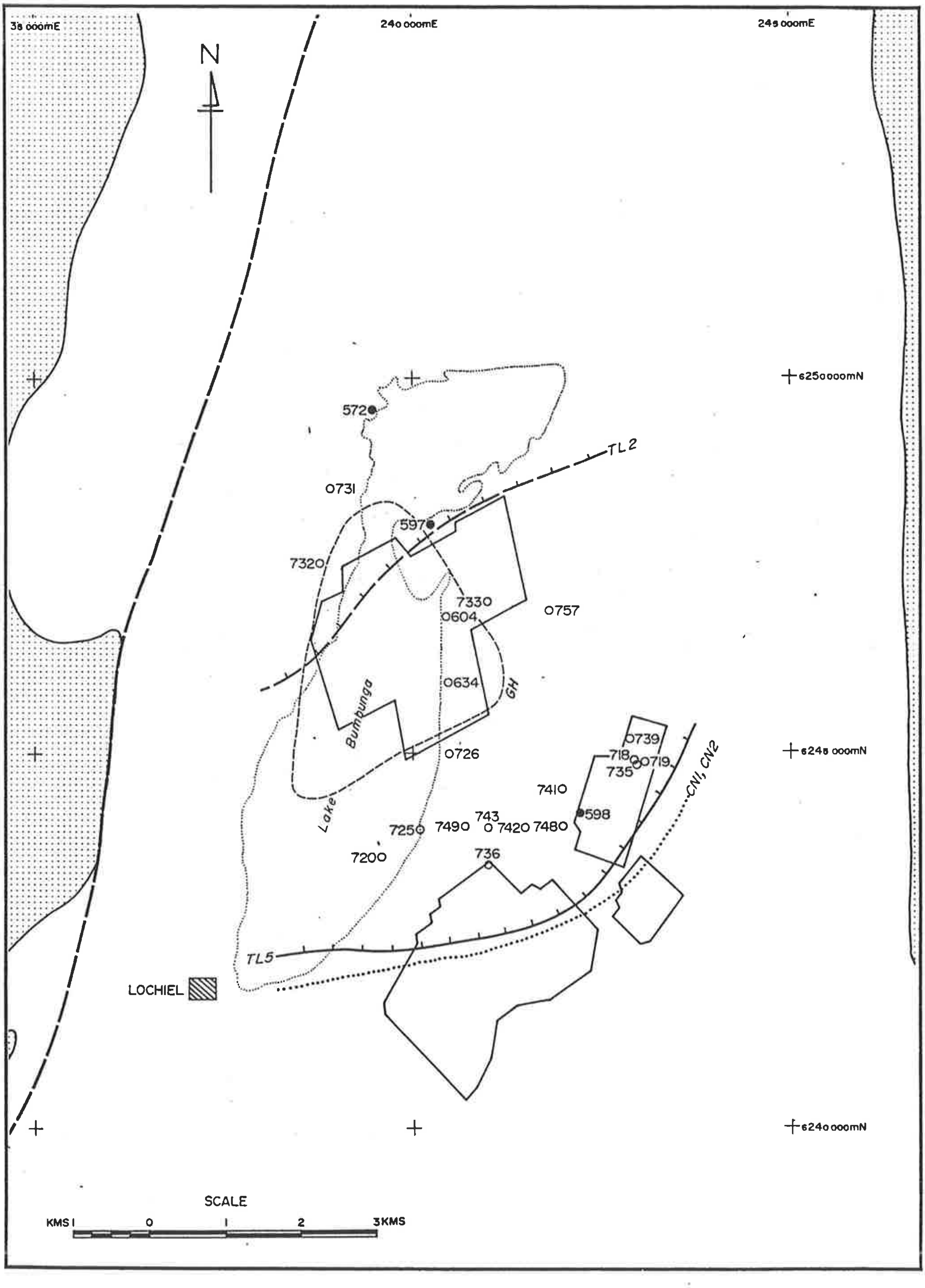


Figure 7.4 Location of near horizontal weak zones

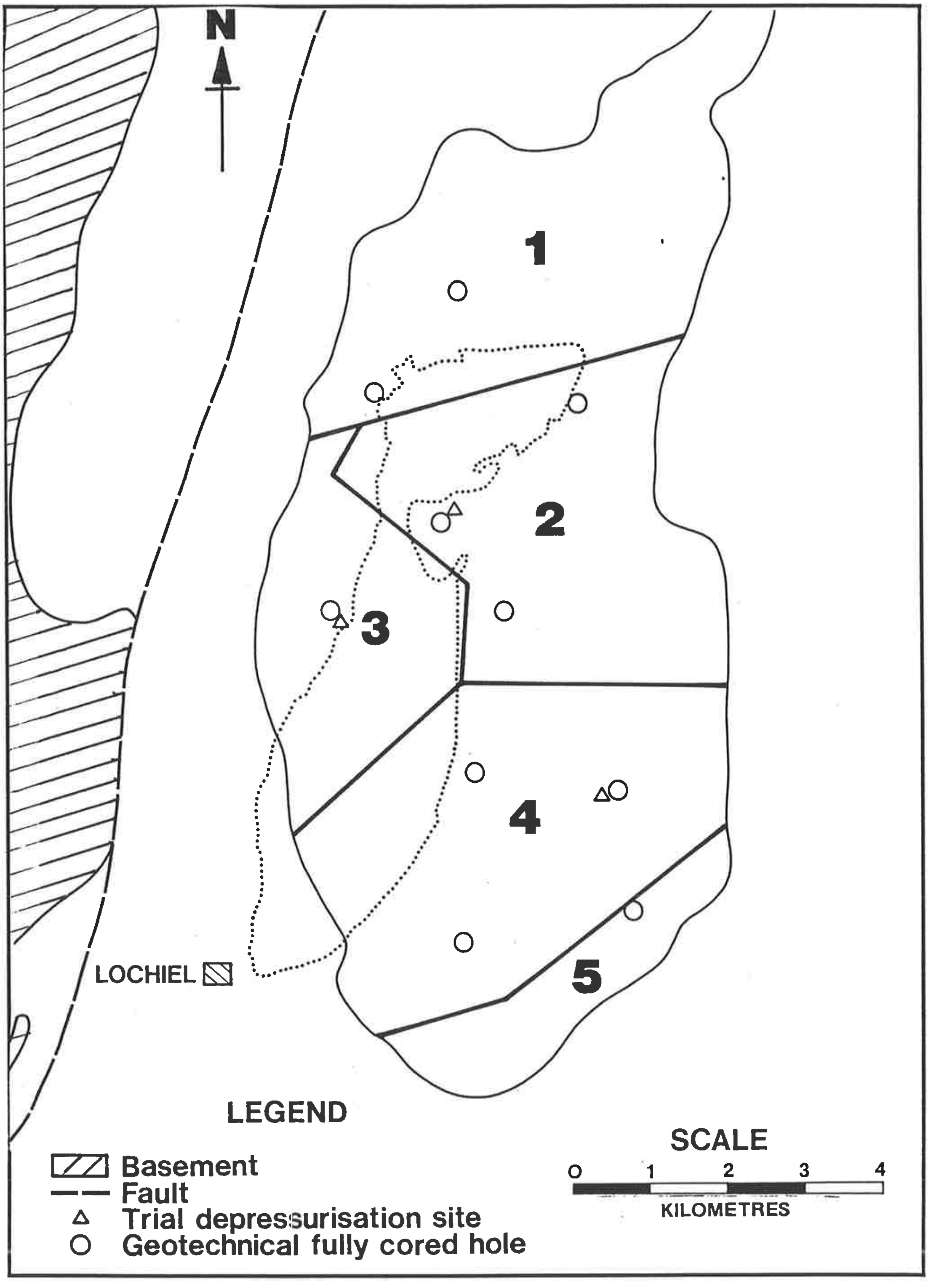


Figure 7.5 Location of highwall stability design regimes.

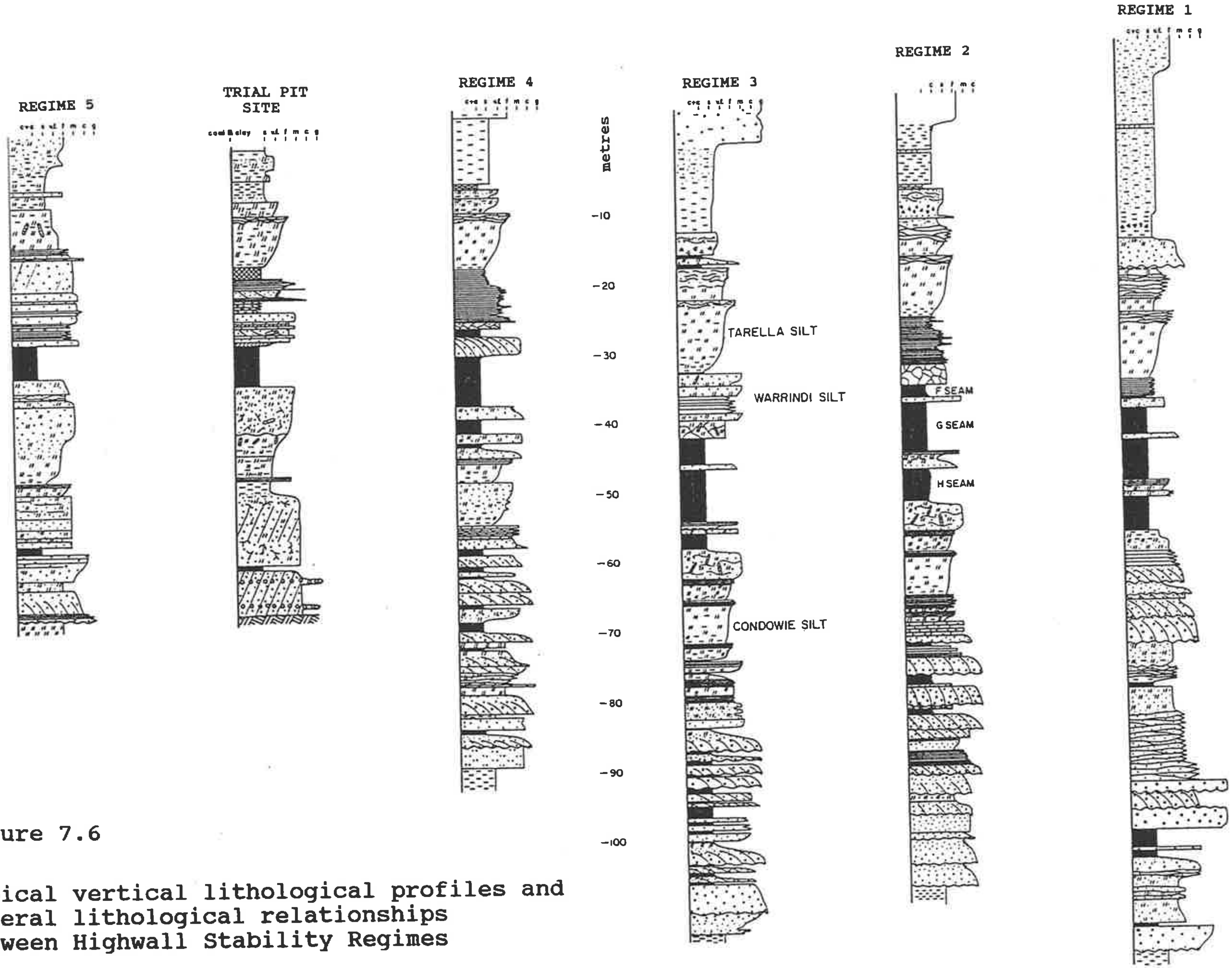


Figure 7.6

Typical vertical lithological profiles and lateral lithological relationships between Highwall Stability Regimes

CHAPTER 8.0 SUMMARY AND CONCLUSIONS

As stated in the Introduction (Section 1.0, page 1) the primary aim of this thesis is to bring together the related areas of geology and engineering within the context of highwall slope stability analysis for soft brown coal mines. The approach has centred on the intermediate role of the engineering geologist whose main objectives relate to the provision of predictive information on the key factors affecting slope stability.

The specific objectives were specified on page 1 as follows :

1. Develop models which characterise the key engineering geological factors in terms of depositional and tectonic processes.

2. Classify the study area in terms of its global tectonic and depositional setting thus providing a basis for translating the results to other soft brown coal mining sites.

3. Contribute to the understanding of the interaction of tectonics, eustacy and depositional processes in the St Vincent Basin.

The Lochiel Coal Deposit, which was used as the example, can be classified in geological and engineering terms as follows :

- geological setting - midplate continental position with depositional environments controlled by the interaction of movement about tectonic structures and by eustatic sea level changes. The depositional environments examined are those characteristic of continental shelves, including swamps, marshes, estuaries, deltas, lagoons, barrier bars and fluvial.

- engineering properties - fine grained, saturated soils and weak rock characterised by early deformational structures.

This classification provides the basis for translating the results obtained to similar mining areas elsewhere in the world.

The intention of the study was to analyse in detail key factors which are characteristic of soft brown coal mining areas rather than those generic to other mines or excavations in weak rock and soil. The study focused on analysing and modelling the geological processes controlling the key engineering geological factors of **defect strength and geometry** and **porewater movement**.

The approach taken to analyse these factors was to examine the relationship between the key engineering properties relating to these factors and the geological properties of the sediments. Data included drillholes, geophysical borehole logs, core, and Trial Pit mapping for the geological data and tests on core and Pit samples for the engineering data.

8.1 Geological processes

The sedimentary sequence in soft brown coal mines on midplate continental margins is controlled by an interaction between the affects of eustacy and tectonics.

Tectonic movement largely controls the amount of sediment input into the area whilst eustacy controls the position of the shore face and therefore the specific depositional environment. The Lochiel Coal Deposit is an example of this type of interaction.

8.1.1 Bumbunga Sand Formation

Initial basin formation commenced in the Middle Eocene after a period of weathering and erosion. The major controlling structures were two north-south trending normal faults, the Ardrossan to the west and the Whitwarta to the east. These formed a half graben whose floor was tilted to the northwest.

Initial sedimentation was fluvial with the major source of sediment being from the west. Regional correlation of this fluvial system indicates that the palaeoslope was inclined towards the north, flowing into the Pirie Basin. These fluvial sediments graded into lacustrine silts and clays to the south.

These silts and clays are assigned to the Condowie Silt Member of the Bumbunga Sand Formation. A characteristic feature of these sediments is the strongly cyclic, upward coarsening nature. This is considered to represent a sedimentation response to intermittent tectonic movements along the major faults. No evidence of marine influence has been distinguished for these sediments.

Towards the end of this basal depositional episode there is strong evidence that several other sources of sediment became active. These emanated from the Ardrossan Fault to the west and also from the Nantawwarra High to the south.

In addition, towards the end of this depositional episode peatswamps formed and lead to the accumulation of the three major coal seams. These seams are separated by interseam sediments originating from small deltas which entered the area from the west.

The Bumbunga Sand Formation represents a typical basin fill sequence culminating in the formation of thick coal seams, the Kooliata Coal Member.

8.2 Warrindi Silt and Tarella Silt Formations

The Bumbunga Sand Formation is overlain by a paralic sequence of carbonaceous silts and fine sands with fewer interbeds of non-carbonaceous sediments. Deposition spans the Late Eocene to the Early Oligocene and is characterised by a series of major transgressive/regressive episodes. In broad terms the depositional controls included :

- major sources of sediment from the north, southeast and to a lesser extent the west,
- Continued tectonic movement on the north-south trending faults but with significant influence from movement about east-west trending faults,
- a migrating shoreline characterised by micro tidal ranges,
- a largely stationary body of water in the centre of the area but whose depth varied over time.

Sediments are typical for continental margin coal settings and relate to shoreface, barrier bar, lagoonal, estuarine and deltaic environments subject to tidal influence.

8.3 Key engineering geological features affecting slope stability

The key features affecting slope stability in soft brown coal mines on midplate continental margins have been identified as:

- Defect strength and geometry,
- factors affecting porewater movement.

The analysis has demonstrated that whilst each of these factors is of importance to slope stability in the study area, it is the near horizontal shear zones which are the single most important feature.

These defects are generally concordant with the bedding in the surrounding sediments and continuous over large areas. Where present their strength and geometry are likely influence significantly the design of the highwall and the direction of mining.

As shown in this study and illustrated on Figure 8.1, the location and formation of these defects is related to the boundaries of significant cyclic depositional events. The defects are located at the base of coarsening upward cycles in close stratigraphic location to the top of the previous cycle. In particular the nature of the surrounding sediments suggests an aqueous depositional environment typical of a lacustrine or estuarine basin infill sequence.

Detailed examination of the defects associated with the Tarella Silt shear Zone indicates that they are characteristic of shear defects. The stresses controlling their formation appear to be related to both compaction and the tectonic tilting of the deposit area. Typically the defects have residual friction angles as low as 7^{o}.

Furthermore, given that cyclicity is characteristic of midplate continental margin deposits, it is likely that such features are present elsewhere in similar areas.

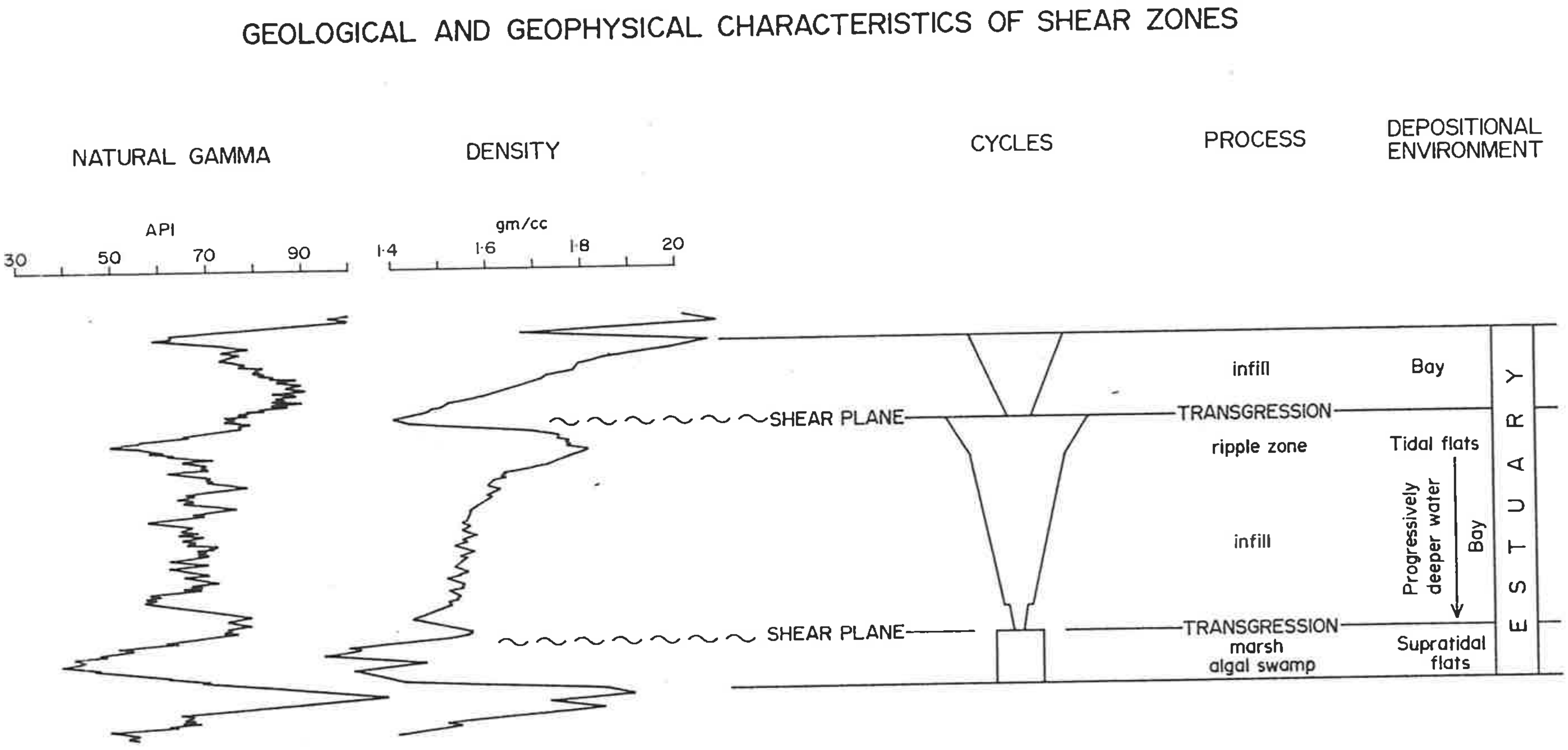


Figure 8.1 Summary of geological factors controlling the location and engineering properties of near horizontal shear zones.

These defects are also a major factor determining the rate at which the fine grained sediments can be depressurised. There are two aspects involved. First, the sheared material acts as a relatively impermeable barrier to vertical drainage and, second, some of the extension structures associated with the shear zone act as vertical drains for the fine grained sediments. The result is that the fine grained silts above the shear zone behave like a fractured rock mass but the drainage of porewater vertically is restricted by the shear zone.

8.4 The relationship between tectonics, eustacy and depositional processes and engineering geological factors affecting slope stability

In essence the sequence in the study area encompass two major phases of transgression/highstand/regression.

The first phase produced an allocycle equating to a TST (Nantawarra Sand , Darnleigh Park Sand and Condowie Silt Members) and HST (Kooliata Coal Member) sedimentary sequence. Lithologically the sediments associated with this phase fine upwards from gravel and sand at the base to silt, clay and coal at the top.

The formation of the coal was eustatically controlled and equivalent to a highstand with the depositional setting characterised by a barrier bar system located to the south of the study area.

Within the overall system, tectonics was the main factor controlling the segmentation of lithofacies and in particular the clean sand lithofacies. Tectonic episodes also produced the fine grained coarsening upward cycles which contain weak zones.

The second transgressive episode superimposed marginal marine conditions on the area. During this time, the sources of sediment and the sites of tectonic movement appear to be similar to the first episode. This provides the unique opportunity to contrast the effects of marine influence on the key factors of porewater movement and weak zones against a non-marine influence.

The results of the analysis indicate that the autocyclic depositional processes for the second episode remained essentially the same as those of the previous episode. In particular, the location and characteristics of clean sand lithofacies and the coarsening upwards cycles containing weak zones are similar for both episodes.

The conclusion is that whilst eustacy controls the regional depositional setting and the conditions necessary for coal formation, tectonics is the major control over the depositional processes and the segmentation and characteristics of lithofacies. The implication is that within the study area, tectonics rather than eustacy was the major geological factor affecting the subsequent movement of porewater and the properties of weak zones.

REFERENCES

Alley, N.F., 1969. The Cainozoic history of the mid north of South Australia. M.A. thesis, Uni. of Adelaide, (Unpublished).

Alley, N.F., 1973. Landsurface development in the mid north of South Australia. Trans. Roy. Soc. S. Aust., Vol. 97, p. 1-17.

Alley, N.F., 1990. Personal communication. Senior Geologist, South Australian Dept. of Mines and Energy.

Anderson, E., 1950. Whitwarta coal occurrence. South Australian Dept. of Mines and Energy Min. Rev., Adelaide, No. 90, p. 147-151.

Anderton, R., 1985. Clastic facies models and facies analysis. In Brenchley, P.J. and Williams, B.P.J., (eds.) Sedimentology. Blackwell Scientific Publications, p. 31-47.

Banerjee, I., 1989. Tidal sheet origin of the transgressive Basal Colorado Sandstone (Albian): a subsurface study of the Cessford Field, South Alberta. Bull. Canadian Petroleum Geol., Vol. 37, No. 1, p. 1-17.

Barden, L., 1972. The relation of soil structure to engineering geology of clay soil. Jour. Eng. Geol. Vol. 5, p. 85-102.

Beerbower, J.R., 1964. Cyclothems and cyclic depositional mechanisms in alluvial plain sedimentation. In Merriam, D.F., (ed.) Symposium on cyclic sedimentation, Kansas Geol. Surv. Bull., Vol. 169, No. 1, p. 31-42.

Bishop, A.W., Webb, D.L. and Lewin, P.I., 1966. Undisturbed samples of London Clay from the ashford common shaft: Strength and effective stress relationship. Geotechnique, Vol. 15, p. 1-31.

Bolton, M., 1984. A Guide to Soil Mechanics. MacMillan Publishers Ltd. London.

Bott, M.H.P., 1971. Evolution of young continental margins and formation of shelf basins. Tectonophysics, Vol. 11, p. 319-329.

Brown, R.N., 1975. Mineralogical and Chemical analysis of 71 borehole samples. AMDEL Rept., MP 1/10/0.

Campana, B., 1954. The structure of the eastern South Australian Ranges: the Mt Lofty-Olary Arc. Jour. Geol. Soc. Aust., Vol. 2, p. 47-61.

Cande, S.C. and Mutter, J.C., 1982. A revised identification of the oldest seafloor spreading anomalies between Australia and Antarctica. Earth and Planetary Science Letters, Vol. 58, p. 151-160.

Cant, D.J., 1982. Fluvial facies models and their application. In Scholle, P.A. and Spearing, D.,(eds.) Sandstone Depositional Environments. Am. Assoc. Petroleum Geol., Memoir 31, p. 115-137.

Christophel, D.C. and Blackburn, D.T., 1978. Tertiary mega-fossil flora of Maslin Bay, South Australia: a preliminary report. Alcheringa, Vol. 2, p. 311-319.

Christophel, D.C., 1983. Preliminary report on macrofossils in coal samples from the Lochiel Coal Deposit. Senior Lecturer, Dept. of Botany, Uni. of Adelaide, South Australia.

Clifton, H.E., 1982. Estuarine Deposits. In Scholle, P.A. and Spearing, D.,(eds.) Sandstone Depositional Environments. Am. Assoc. Petroleum Geol., Memoir 31, p. 179-189.

Coffey and Partners Pty Ltd, 1986. Lochiel Coal Deposit - Preliminary design of the Trial Pit. Internal report prepared for ETSA Coal resources Dept., Rept. 23/18, (Unpublished).

Coffey and Partners Pty Ltd, 1987. Lochiel Trial Pit Project - Laboratory testing results. Internal report prepared for ETSA Coal resources Dept., Rept. 87/35, (Unpublished).

Coffey and Partners Pty Ltd., 1988a. Lochiel Coal Deposit - Trial Pit project, Pit slope stability and failure analysis. Internal report prepared for ETSA Coal Resources Dept., Rept 88/18, (Unpublished).

Coffey and Partners Pty Ltd., 1988b. Lochiel Coal Deposit - Trial Pit project, Discussion of the application of depressurisation studies to the general mining areas. Internal report prepared for ETSA Coal Resources Dept., Rept 88/11, (Unpublished).

Coffey and Partners Pty Ltd, 1988c. Lochiel Coal Deposit: Regional direct shear laboratory testing. Internal report prepared for ETSA Coal Resources Dept., Rept. 88/12, (Unpublished).

Coleman, J.M. and Prior, D.B., 1982. Deltaic environments of deposition. In Scholle, P.A. and Spearing, D.,(eds.) Sandstone Depositional Environments. Am. Assoc. Petroleum Geol., Memoir 31, p. 139-178.

Collinson, J.D.,1978. Vertical sequence and sand body shape in alluvial sequences. In Miall, A.D., (ed.) Fluvial Sedimentology, Canadian Soc. Petroleum Geol., Memoir 5, p. 577-586.

Cooper, B.J., 1976. Tertiary Stratigraphic Nomenclature of a new bore in the Inkerman-Balaklava Coalfield. South Australian Dept. of Mines, Rept. 76/123.

Cooper, B.J., 1977. Tertiary Stratigraphic nomenclature in the Inkerman-Balaklava Coalfield. Quat. Geol. Notes, Geol. Surv. South Australia, Vol. 64, p. 2-5.

Cooper, B.J., 1985. The Cainozoic St Vincent Basin-tectonics, structure, stratigraphy. Spec. Publ., South Australian Dept. Mines and Energy, No. 5, p. 35-49.

Cooper, B.J. and Lindsay, J.M., 1978. Marine entrance to the Cainozoic St Vincent Basin. Quat. Geol. Notes, Geol. Surv. South Australia, Vol. 67, p. 4-6.

Crawford, A.R., 1965. The Geology of Yorke Peninsula. Bull. Geol. Surv. South Australia, No. 39.

Curray, J.R., 1975. Marine sediments, geosynclines and orogeny. In: Fischer, A.G. and Judson, S., (eds.) Petroleum and Global Tectonics. Princeton University Press, Princeton and London, p. 157-222.

Daily,B., Firman, J.B., Forbes, B.G. and Lindsay, J.M., 1976. Geology. In Twidale, C.R., Tyler, M.J. and Webb, B.P., (eds.) Natural History of the Adelaide Region. Royal Soc. South Australia, Adelaide, p. 5-52.

Davies, D.K., 1980. Sandstone reservoirs - Their genesis, diagenesis and diagnosis for successful exploration and development. PESA Distinguished lecturer series course notes.

Diessel, D.F.K., 1980. Coal Geology. AMF workshop course notes 137/80.

ETSA, 1987. Merriton Exploration Area - Relinquishment Report. Unpublished internal ETSA Coal Resources Dept. Rept. 87/55.

ETSA, 1989a. Lochiel and Sedan coalfield evaluation for the Energy Planning Executive Vol. 4A. Internal ETSA Coal Resources Rept. 89/01, (Unpublished).

Falini, F., 1965. On the formation of coal deposits of lacustrine origin. Factors influencing the formation of lacustrine deposits. Geol. Soc. Am. Bull., Vol. 76, p. 1317-1346.

Ferm, J.C. and Horne, J.C., 1979. Carboniferous depositional environments in the Appalachian region. Collected papers of the Carolina Coal Group, Dept. Geol. Uni. Sth. Carolina, p. 1-619.

Fookes, P.G., 1965. Orientation of fissures in stiff overconsolidated clay in the Siwalik System. Geotechnique, Vol. 15, No. 2, p. 195-206.

Fookes, P.G. and Wilson, D.D., 1966. The geometry of discontinuities and slope failures in Siwalik Clay. Geotechnique, Vol. 17, No. 4, p. 305-320.

Forbes, B.G., 1966. Features of Palaeozoic tectonism in South Australia. Trans. Royal Soc. South Australia, Vol. 90, p. 45-52.

Fouch, T.D. and Dean, E.D., 1982. Lacustrine and associated Clastic Depositional Environments. In Scholle, P.A. and Spearing, D.,(eds..) Sandstone Depositional Environments, American Assoc. Petroleum Geol. Memoir 31, p. 87-114.

Galloway, W.E., 1986. Reservoir Facies Architecture of Microtidal Barrier Systems. Bull. Am. Assoc. Petroleum Geol., Vol. 70, No. 7, p. 787-808.

Galloway, W.E. and Hobday, D.K., 1983. Terrigenous clastic depositional systems; applications to petroleum, coal, and uranium exploration. Springer-Verlag, New York.

Glaessner, M.F. and Wade, M., 1958. The St Vincent Basin. In Glaessner, M.F. and Parkin, L.W., (eds.) The geology of South Australia. Jour. Geol. Soc. Aust., Vol. 5, p. 115-126.

Gramberg, J., 1966. A theory on the occurrence of various types of vertical and sub-vertical joints in the earth's crust. Proc. 1st Soc. Congr. Rock Mechanics, p. 443-450.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of Fluctuating Sea Levels Since the Triassic. Science. Vol. 135, p. 1156-1167.

Harris, W.K., 1966. New and redefined names in South Australian Lower Tertiary stratigraphy. Quat. Geol. Notes, Geol. Surv. South Australia, Vol. 20, p. 1-3.

Harris, W.K., 1970. Palynology of Lower Tertiary sediments, Southeastern Australia. MSc. thesis, Uni. of Adelaide, (Unpublished).

Harris, W.K., 1980. Eocene eustacy and the deposition of lignites in South Australia. In Truswell, E.M. and Abell, R.S. (compilers) The Cainozoic evolution of continental Southeast Australia. Abstracts of papers presented at a symposium held in Canberra, November, 1980. Rec. Bur. Miner. Resour. Geol. Geophys. Aust., 1980/67, p.33, (Unpublished).

Harris, W.K., 1982. Lochiel Coal Deposit South Australia - Palynological determination of age and depositional environment. Internal report prepared for ETSA Coal Resources Dept, Rept. 82/45, (Unpublished).

Harris, W.K., 1983. Lochiel Coal Deposit - Palynological analysis of selected samples. Report prepared for ETSA Coal Resources Dept., (Unpublished).

Harris, W.K., 1985. Middle to Late Eocene depositional cycles and dinoflagellate zones in southern Australia. Spec. Publ., South. Aust. Dept. Mines and Energy, Vol. 5, p. 133-144.

Harris, W.K., 1986. Palynological analysis of borehole V597. Internal report prepared for ETSA Coal Resources Dept., Rept. 86/32, (Unpublished).

Harris, W. K., 1987. Vegetation changes during the Eocene. Abstract of seminar presented at the University of Adelaide.

Harris, W.K., 1989. Personal communication. Regional exploration Manager - Petroleum. Western Mining Corporation Ltd.

Hawley,P.M., and Stewart, A.F., 1986. Design of open pit coal mine slopes: an integrated approach. In Singhal, R., (ed.) <u>Geotechnical Stability in Surface Mining.</u> Proc. Int. Symp. on geotechnical stability in surface mining, Calgary. Balkema press. p. 69-78.

Hayes, O.M., and Michel, J., 1982. Shoreline sedimentation within a forearc embayment, Lower Cook Inlet, Alaska. <u>Jour. Sed. Pet.</u>, Vol. 52, No. 1, p. 251-263.

Herget, G. and Garg, O., 1982. Research requirements in surface mine stability and planning. <u>In</u> Brawner, C.O., (ed.) <u>Stability in surface mining</u> Vol. 3, p. 311-332.

Hillwood, E.R., 1961. Inkerman-Balaklava coalfield. <u>South Australian Dept. of Mines, Min. Rev.</u>, Adelaide, Vol. 112, p. 24-26.

Hodgson, R.A., 1961. Classification of structures on joint surfaces. Am. Jour. Sci., Vol. 259, p. 493-502.

Hoek, E. and Bray, J.W., 1977. Rock Slope Engineering. 2nd edition. The Institute of Mining and Metallurgy, London.

Holdgate, G.R., 1985. Latrobe Valley brown coals - Their geometry and facies equivalents as a guide to depositional environment. Aust. Coal Geol., Vol. 5, p. 53-68.

Holmes, A., 1965. Principles of physical geology. New York, Ronald Press Co.

Horne, J.C., 1979a. Criteria for the recognition of depositional environments. In Ferm, J.C. and Horne, J.C., (eds.) Carboniferous depositional environments in the Appalachian Region. Collected papers of the Carolina Coal Group, Dept. Geol. Uni. Sth. Carolina, p. 295-300.

Horne, J.C., 1979b. Estuarine deposits in the carboniferous of the Pocahantas Basin. In Ferm, J.C. and Horne, J.C., (eds.) Carboniferous depositional environments in the Appalachian Region. Collected papers of the Carolina Coal Group, Dept. Geol. Uni. Sth. Carolina, p. 428-435.

Horne, J.C., 1979c. Shoreline Models. In Ferm, J.C. and Horne, J.C., (eds.) Carboniferous depositional environments in the Appalachian Region. Collected papers of the Carolina Coal Group, Dept. Geol. Uni. Sth. Carolina, p. 368-369.

Horne, J.C., 1979d. The effects of carboniferous shoreline geometry on palaeocurrent distribution. In Ferm, J.C. and Horne, J.C., (eds.) Carboniferous depositional environments in the Appalachian Region. Collected papers of the Carolina Coal Group, Dept. Geol. Uni. Sth. Carolina, p. 509-516.

Horne, J.C., Ferm, J.C., Caruccio,F.T. and Baganz, B.P., 1978. Depositional models in coal exploration and mine planning in the Appalachian Region. Bull. Am. Assoc. Petroleum Geol., Vol. 62, p. 2379-2411.

Horwitz, R.C., 1961. The geology of the Wakefield military sheet. Rep. Invest. Geol. Surv. South Australia, No. 18, p. 1-32.

ICCP. (International Committee for Coal Petrology), 1971. International Handbook of Coal Petrology Centre National de la Recherche Scientisique, Vadis. Supplement, second edition.

James, F.M., 1971. Some effects of structure on the behaviour of argillaceous sediments. Australia - New Zealand Conf. on Geomechanics, Vol. 1, No. 1, p. 154-159.

Johnson, W., 1960. Coal exploration, Northern end of the St Vincent Basin. South Australian Dept. of Mines, Min.Rev., Adelaide, Vol. 110, p. 134-144.

Johnson, W., 1964. Coal exploration - Clinton North Coalfield. South Australian Dept. of Mines, Min. Rev., Adelaide, Vol. 116. p. 28-29.

Jones, J.B. and Fitzgerald, M.J., 1984. Extensive volcanism associated with the separation of Australia and Antartica. Science, Vol 226. p. 246-347.

Jones, J.B. and Fitzgerald, M.J., 1987. An unusual and characteristic sedimentary mineral suite associated with the evolution of passive margins. Sedimentary Geology, Vol. 52, p. 45-63.

Kemp, E.M., 1978. Tertiary climatic evolution and vegetation history in the Southeast Indian Ocean region. Palaeogeogr. Palaeoclimatol. Palaeoecol., Vol. 24, p. 169-208.

Kremor, A.G., 1986. Depositional environments of the Lochiel Coal Deposit, South Australia. Proc. 8th Aust. Geol. Conf., Adelaide.

Kremor, A.G., 1988. Lochiel Coal Deposit Trial Pit engineering geology extrapolation report. Internal ETSA Coal Resources Dept., Rept. 88/23, (Unpublished).

Kremor, A.G.,(in prep.) Stratigraphic Nomenclature of the Northern St Vincent Basin in the Lochiel Area. Quat. Geol. Notes, Geol. Surv. South Australia.

Kremor, A.G., and Muir, A.H., 1987. Geology, a key to mine planning. A case history of the Lochiel Coal Deposit, South Australia. Proc. Geol. and Coal Mining Conf., Sydney, Geol. Soc. Aust., p. 75-84.

Kremor, A.G.,& Springbett, G.S., 1989. Coal deposits of the Northern St Vincent Basin. BMR Bicentennial Monograph COAL, (Unpublished).

Lambe, T.W. and Whitman, R.V., 1969. Soil Mechanics. 2nd edition, Wiley, New York.

Lindholm, R.C., 1987. A practical approach to sedimentology. Allen and Unwin, London, Boston.

Lindsay, J.M., 1967. Foraminifera and stratigraphy of the type section of Port Willunga Sub-Basin, South Australia. Bull. Geol. Surv. South Australia, Vol. 91, p. 93-109.

Lindsay, J.M., 1969. Cainozoic foraminifera and stratigraphy of the Adelaide Plains Sub-basin, South Australia. Bull. Geol. Surv. South Australia, Vol. 42. p. 1-69.

Lindsay, J.M., 1970. Melton Limestone: multiple mid-Tertiary transgressions, southeastern Gawler Platform. Quat. Geol. Notes, Geol, Surv. South Australia, Vol. 33, p. 2-10.

Lindsay, J.M., 1987. Personal communication. Senior geologist, South Aust. Dept. Mines and Energy.

Lindsay, J.M., (ed.)(in prep.) Revised Handbook of South Australian geology. Publication of the South Australian Dept. of Mines and Energy.

Ludbrook, N.H., 1980. A guide to the geology and mineral resources of South Australia. Gov. Printer, Adelaide.

Lupini, J.F., Skinner, A.E. and Vaughan, P.R., 1981. The drained residual strength of cohesive soil. Geotechnique, Vol. 31, No. 2, p. 181-213.

MacCallum, Stewart and Associates, 1979. Environments of deposition project, McMurray Formation - Syncrude Mine Site. Vol. 1. Prepared for Syncrude Canada Ltd., Edmonton, Alberta.

Mathews, K.E., and Rosengren, K.J., 1986. The integrated planning of geotechnical investigations for new mining projects. The AusIMM, second project development symposium, Sydney, series 47:43-54.

Mathewson, C.C. and Cato, K.D., 1986. Pre and Post mine geotechnical conditions for surface mines developed from the comprehensive exploration programme. In Singhal, Raj, K., (ed.) Geotechnical Stability in Surface Mining, Balkema Press.

Meakin, S., 1985. Palynological analysis of the Clinton Coal Measures, Northern St Vincent Basin, South Australia. B. Sc. Hons. thesis, Uni. of Adelaide, (Unpublished).

McGowen, J.H., 1971. Gum Hollow fan delta, Nueces Bay, Texas. Univ. Texas, Bur. Econ. Geology, Rept. Invest., No. 69.

McGowran, B., 1979. The Tertiary of South Australia: foraminiferal overview. Marine Micropalaeontology, Vol. 4, p. 235-264.

McLean, J.R. and Jerzykiewicz, T., 1978. Cyclicity, Tectonics and Coal: Some aspects of fluvial sedimentology in the Brazeau-paskaroo formations, Coal Valley Area, Alberta, Canada. In Miall, A.D., (ed.) Fluvial Sedimentology. Canadian Soc. Petrol. Geol., Memoir 5, p. 441-468.

Meyer, G.M., 1976. Tertiary brown coal deposits in the Northern St Vincent Basin. South Australian Dept. Mines, Rept. No. 796 (Unpublished).

Meyer, G.M., 1980. Geological results from the 1977/78 drilling programme, Wakefield and Clinton Coal Deposits. South Australian Dept. of Mines, Rept. No 842 (Unpublished).

Miall, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits. In Miall, A.D., (ed.) Fluvial Sedimentology. Canadian Soc. Petrol. Geol., Memoir 5, p. 547-637.

Miall, A.D., 1984. Principles of Sedimentary Basin Analysis. Springer-Verlag, New York.

Mitchell, J.K., 1976. Fundamentals of soil behaviour. New York, J. Wiley.

Mitchum Jr, R.M., Vail, P.R. and Thompson III, S., 1977. Seismic stratigraphy and global changes of sea level, Part 2: the depositional sequence as a basic unit for stratigraphic analysis. In Payton, C.E. (ed.) Seismic stratigraphy-applications to hydrocarbon exploration. Am. Assoc. Petroleum Geol., Memoir 26, p. 53-62.

Morgenstern, N.R. and Tchalenko, J.S., 1967a. Microscopic Structures in Kaolin Subjected to direct shear. Geotechnique, Vol. 17, p. 309-328.

Morgenstern, N.R. and Tchalenko, J.S., 1967b. Microstructural observations on shear zones from slip in natural clays. Geotechnical Conf., Oslo, Vol. 1, p. 147-152.

Parkin, L.W., 1952. Whitwarta brown coal investigation. South Australian Dept. of Mines, Min. Rev., Adelaide, No. 93, p. 85-87.

Parkin, L.W., 1969. Handbook of South Australian Geology. Geol. Surv. South Australia. Gov. Printer.

Peck, R.B., 1962. Art and Science in Subsurface engineering. Geotechnique, Vol. 12, p. 60-66.

Penland, S. and Suter, J. R., 1983. Transgressive coastal facies preserved in barrier island retreat paths in the Mississippi river delta plain. Gulf Coast Assoc. Geol. Soc., Transactions, Vol. 33, p. 367-382.

Pettijohn, F.J., Potter, P.E., and Siever, R., 1987. Sand and Sandstone. Springer-Verlag, New York.

Piasecki, S., Fleming, G. C., and Stemmerick, L., 1990. Depositional history of an Upper Carboniferous organic-rich lacustrine shale from East Greenland. Bull. Canadian Petroleum Geol., Vol. 38, No. 3, p. 273-287.

Picard, M.D. and High, J.R., 1972a. Paleoenvironmental reconstruction in an area of rapid facies change, Parachute Creek member of Green River formation (Eocene). Bull. Geol. Soc. of Am., Vol. 83, p. 2689-2707.

Picard, D.M. and High, L.R., 1972. Criteria for recognising Lacustrine Rocks. SEPM, Spec. Publ., Vol. 16, p. 108-145.

Picard, M.D. and High, L.R., 1981. Physical Stratigraphy of Ancient Lacustrine deposits. In Etheridge, F.G. and Flores, R.M., (eds.) Recent and ancient non marine depositional environments. Models for exploration. SEPM Spec. Publ., Vol. 31, p. 233-259.

Preiss, W.,(ed.), 1987. The Adelaide Geosyncline: late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. Adelaide, Govt. Printer, South Australia.

Priest, S.D., 1985. Hemispherical projection methods in rock mechanics. Allen and Unwin; London, Boston.

Reading, H.G. (ed.), 1978. Sedimentary environments and facies. Blackwell Scientific Publications, London, Chapter 4: Lakes. p. 61-79.

Reinick, H.E., and Wunderlich, R., 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, Vol. 11, p. 99-104.

Rosenquist, I, Th., 1955. Investigations in the clay-electrolyte-water system. Norwegian Geotechnical Institute, Oslo, Publication No. 9, 125p.

Ross-Brown, D.M., 1979. Analytical Design. In Crawford, J.T., and Hustrulid, W.A., (eds.) Open pit mine planning and design. Published by AIME, New York.

Rowe, P.W., 1972. The relevance of soil fabric to site investigation practice. Geotechnique, Vol. 22, No. 2, p. 195.

Sangree, J.B. and Sneider, R.M., 1987. Sequence Stratigraphy. Richardson, Sangree and Sneider, Houston, Texas.

Schoelle, D.A and Spearing, R., 1982. Sandstone depositional environments. Am. Assoc. Petroleum Geol., Memoir 31.

Selby, J. and Lindsay, J.M., 1982. Engineering Geology of the Adelaide City Area. Geol. Surv. South Australia, Bull. 51.

Seycek, J., 1978. Residual shear strength of soils. Bull. Int. Ass. Eng. Geol., Vol. 17, p. 73-75.

Shields, D.H., 1986. Preliminary design of a deep open pit mine (Bukit Asam). An exercise in engineering method. In Singhal, Raj, K., 1986. Geotechnical Stability in Surface Mining. Proc. Int. Symp. on geotechnical stability in surface mining, Calgary. Balkema press.

Skempton, A.W., 1964. Long-term stability of clay slopes. Geotechnique, Vol. 14, p. 77-102.

Skempton, A.W., 1966. Some observations on tectonic shear zones. Proceedings of First International Congress, Rock Mechanics, No. 1, p. 329-335.

Spaulding, T.D.,Thurmond,E.N., Mercier, J.M.,& Wright, R., 1982. Technology management for risk minimisation. 6th ICCR Conference, London, paper B6, p. 123-137.

Springbett, G.S., 1980. Northern St Vincent Basin Coalfield, South Australia, Geological report. Internal ETSA Coal Resources Dept. Rept. 81/30, (Unpublished).

Springbett, G.S., 1981. Geological investigations of the Bowmans Trial Pit. Unpublished internal ETSA Rept. 81/16.

Springbett, G.S., 1989. Personal communication. Principal Geologist, G&S Resources, Adelaide.

Staines, H.R.E., 1985. Field Geologists Guide to Lithostratigraphic Nomenclature in Australia. Aust. Jour. Earth Science, Vol. 32, p. 83-106.

Stapledon, D.H., 1979. Investigation and characterisation. Extension course on tunnelling design and practice. Aust. Geomech. Soc., Melbourne.

Stapledon, D.H., 1982. Subsurface Engineering - in search of a rational approach. Aust. Geomech. News, No. 4, p. 26-33.

Staub, J.R. and Cohen, A.D., 1978. The Snuggery Swamp of South Carolina. A back barrier estuarine coal forming environment. Jour. Sed. Pet., Vol. 48, p. 203-210.

Stewart, I.C.F., 1972. Seismic interpretation of crustal structure in the Flinders-Mt Lofty Ranges and Gulf regions, South Australia. J. geol. Soc. Aust., Vol. 19, p. 351-362.

Stuart, W.J., 1969. Stratigraphic and structural development of the St Vincent Tertiary Basin, South Australia. Ph.D. thesis, Uni. of Adelaide, (Unpublished).

Stuart, W.J., 1970. The Cainozoic stratigraphy of the eastern coastal area of the Yorke Peninsula, South Australia. Trans. Roy. Soc. South Australia. Vol. 94, p. 151-178.

Sullivan, T., 1982. The Origin and Characteristics of defects in Oil Shale. Aust. Coal Geol., Vol. 4, No.2, p. 31-43.

Swift, D.J.P., 1968. Coastal erosion and transgressive stratigraphy. Jour. Geology. Vol. 76, p. 445-456.

Tchalenko, J.S., 1970. Similarities between shear zones of different magnitudes. Geol.Soc. Am. Bull., Vol. 81, p. 1625-1640.

Twenhofel, W.H., 1932. Treatise on sedimentation, second edition. The Williams and Wilkins Co. Baltimore.

Vail, P.R. and Hardenbol, J., 1979. Sea-level changes during the Tertiary. Oceanus, Vol. 22, p. 71-79.

Vail, P.R., Hardenbol, J., and Todd, R.G., 1984. Jurassic unconformities, chrono-stratigraphy and sea-level changes from seismic stratigraphy. In Schlee, J.S., (ed.) Inter-regional unconformities and hydrocarbon accumulation. Am. Assoc. Petroleum Geol., Memoir 36, p. 129-144.

Vail, P.R., Mitchum Jr, R.M. and Thompson III, S., 1977a. Seismic stratigraphy and global changes of sea level, Part 3: relative changes of sea level from coastal onlap. In Payton, C.E., (ed.) Seismic stratigraphy-applications to hydrocarbon exploration. Am. Assoc. Petroleum Geol., Memoir 26, p. 63-81.

Vail, P.R., Mitchum Jr, R.M. and Thompson III, S., 1977a. Seismic stratigraphy and global changes of sea level, Part 4: global cycles of relative changes of sea level. In Payton, C.E.,(ed.) Seismic stratigraphy-applications to hydrocarbon exploration. Am. Assoc. Petroleum Geol., Memoir 26, p. 83-97.

Vail, P.R. and Mitchum Jr, R.M., 1979. Global cycles of relative sea level changes from seismic stratigraphy. In Watkins, J.S., Montadert, L. and Dickerson, P.W. (eds.) Geological and geophysical investigations of continental margins. Am. Assoc. Petroleum Geol., Memoir 29, p. 469-472.

Vaughan, P.R., Davachi, M.M., El Ghamrawy, M.K., Hamza, M.M. and Hight, D.W., 1976. Stability analysis of large gravity structures. Proc. 1st International Conference of the Behaviour of Off-Shore Structures, No. 1, p. 467-480.

Vaughan, P.R. and Walbancke, H.J., 1975. The stability of cut and fill slopes in Boulder Clay. Proc. of symposium on engineering behaviour of glacial materials, Midland Society Soil Mechanics, Birmingham. p. 209-219.

Visher, G.S., 1965. Use of vertical profile in environmental reconstruction. Bull. Am. Assoc. Petroleum. Geol., Vol. 49, No. 1, p. 41-61.

Wade, N.H., 1987. Geotechnical Data on Highvale and Whitewood Mines, Alberta, Canada. Letter sent to Manager Coal Resources, ETSA, (Unpublished).

Wescott, W.A. and Etheridge, F.G., 1980. Fan-delta sedimentology and tectonic setting - Yallahs Fan Delta, southeast Jamaica. Bull. Am. Ass. of Petroleum Geol., Vol. 64, p. 374-399.

Walker, R.G.,(ed.), 1984. Facies Models. Reprint series 1, Geoscience Canada, Geol. Assoc. Canada Publ.

Young, R.N. and Warkentin, B.P., 1975. Developments in Geotechnical Engineering.