REGIONAL STRATIGRAPHIC ANALYSIS OF THE GIDGEALPA GROUP, SOUTHERN COOPER BASIN, AUSTRALIA

R. C. N. THORNTON

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Cover: Stage 3' isopach map

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Minister of Mines and Energy

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Minute of Transmittal

Geological Survey of South Australia,
Department of Mines and Energy,
191 Greenhill Road, Parkside 5063.

17th July 1979

To the Honourable the Minister of Mines and Energy,

I submit for publication a report by R. C. N. Thornton on the Regional Stratigraphic Analysis of the Gidgealpa Group of the Cooper Basin.

The Gidealpa Group, of Permian age, is the source and host rock for hydrocarbons in the Cooper Basin. The group does not outcrop, so that our knowledge of it is derived solely from drilling data.

A detailed evaluation of the electric logs has led to a better understanding of the palaeogeography and sedimentation history of the Cooper Basin. This is of particular value in the search for stratigraphic hydrocarbon trapping mechanisms.

Approval is sought to publish this report as a Bulletin of the Geological Survey.

16th July 1979

B. P. Webb, Director-General
Department of Mines and Energy

Approved,
H. R. Hudson, Minister of Mines and Energy

Regional Stratigraphic Analysis of the Gidgealpa Group, Southern Cooper Basin, Australia

Summary

A regional stratigraphic analysis, using mainly quantitative data derived from wireline logs, has led to the reconstruction of the palaeogeography and depositional history of the Permian Gidgealpa Group within the Southern Cooper Basin. The Southern Cooper Basin is an infrabasin, containing up to 1 600 m of Gidgealpa Group sediments, which covers an area of 60 000 km^2 near the centre of Australia. It contains major reserves of gas and minor amounts of oil in fluvial to marginal marine sandstone reservoirs within coal measures.

Lithofacies analysis of a sequential set of palynologically defined time-rock units through the Gidgealpa Group has clarified depositional trends, identified regions of optimum channel locations, located positions of shorelines, and shown directions of marine transgressions and regressions. Detailed core study, investigation of the cyclic nature of sedimentation, and linear regression analysis have helped to elucidate depositional environments.

Gidgealpa Group deposits were laid down from rivers, lakes, coal swamps, and large inland 'seas', during a period when the geomorphic relief diminished with time. As a result, the earliest fluvial deposition was from braided streams, whereas subsequent periods experienced mainly meandering rivers in a floodplain environment. Braided streams deposited Tirrawarra Sandstone on a possibly glacially scoured land surface.

As topographic gradients declined, rivers began to meander, and sandstones, shales and coal deposits of the Patchawarra Formation encroached over Tirrawarra Sandstone. Northwards flowing rivers entered the basin at its southern extremity where valleys were gradually filled by sediment. Few major rivers reached the northern part of the basin, which received mainly overbank deposits.

During uppermost Patchawarra Formation deposition, the Cooper Basin was invaded from the east by an inland 'sea', which deposited the Murteree Shale. As this 'sea' retreated, shoreline sediments of the Epsilon Formation built out towards the east. During a second transgressive pulse the land was once more inundated, and the Roseneath Shale was deposited. Finally, deltas of the Daralingie Beds prograded eastwards, in the wake of the retreating sea.

A long period of uplift and erosion followed, during which time, the present structural grain was imposed on the basin. By the time deposition commenced once more, the land surface was flat, except for a few hills rising above the plain, and meandering rivers entering the basin from the west, deposited sandstones, shales and coal of the Toolachee Formation, as they flowed eastwards. Accumulation of the Gidgealpa Group ended when the climate, perhaps, became unsuitable for continued deposition of the Toolachee Formation coal measures.

On a continental scale, Cooper Basin palaeogeography is related to that of the Permian basins to the east, all of which ultimately had access to the open sea somewhere in the vicinity of the present day coastline.

The Cooper Basin holds considerable scope for future petroleum discoveries in anticlines and fault traps. In addition, stratigraphic traps hold great potential, especially valley traps resulting from onlap, as well as shoreline and channel sandstones enclosed in shales.

Introduction

The primary purpose of this work is to study the depositional history and palaeogeography of the Southern Cooper Basin on a regional scale, using mainly quantitative data derived from wireline logs. The ultimate aim is to help in directing the focus of future petroleum exploration to the most prospective areas. The secondary purpose is to assess how helpful the methods used in this basin analysis may be in aiding palaeogeographic reconstruction, and to suggest further possible lines of research. Well data are the only source of sedimentologic information because the Permo-Triassic rocks of the Cooper Basin are not exposed.

The Southern Cooper Basin is situated near the centre of Australia (Fig. 1). It covers an area of about 60 000 km^2 and its prospective section has a maximum sediment thickness of 1 600 m. The basin is overlain by up to 3 000 m of Mesozoic and Cainozoic sediments.

Exploration in the Cooper Basin commenced with the drilling of Innamincka 1 in 1959. Gas was discovered first at Gidgealpa in 1963. Since then, over 150 exploration and development wells have been drilled in and around the basin.

Total proven and probable reserves amount to $184 \times 10^9 m^3$ ($6{\cdot}5 \times 10^{12} ft^3$) of raw gas in place (Devine, 1975). Twenty-three gas fields have been located so far (Battersby, 1976), but only minor amounts of oil have been discovered. Exploration has so far very successfully concentrated on drilling anticlinal structures, however it is now at a stage where significant new gas or oil discoveries may be made through the definition of new plays, most likely with a stratigraphic component (Jeffries, 1975). As yet, only two wells have been drilled specifically on stratigraphic targets, and both were unsuccessful.

This study attempts to provide the framework of a regional geologic history within which can be developed depositional models of localised areas. Accurate, detailed models will be essential in order to locate successfully wells drilled for stratigraphic traps.

Four methods are incorporated in this study: compilation of isopach, lithofacies, and derived palaeogeographic maps, examination of core material, study of cyclic sedimentation, and bivariate correlation analysis. The Gidgealpa Group sedimentary section has been divided into time-rock units. The name 'time-rock' unit is used in this thesis in the sense that *tabular slices of sedimentary rocks bounded by planes of synchroneity ('time planes')* have been studied. The time boundaries are based on the palynologic Stages defined by extensive microfloral studies (Evans, 1967; Paten, 1969; Price, 1973, and many well completion reports). Extrapolation and interpolation have extended the boundaries where palynologic data are not available. These time-rock units are the bases for the isopach, lithofacies and palaeogeographic analyses. With the exception of cores from Gidgealpa 6, which have been examined in detail, all lithologic interpretation is derived from wireline logs, mostly gamma-ray and sonic. Cyclic sedimentation and the relationship between certain stratigraphic variables such as cycle number and thickness, have been studied in order to understand better the processes that controlled deposition in the Cooper Basin.

The lithostratigraphy of the Cooper Basin has been adequately defined (Kapel, 1966, 1972; Martin, 1967b; Papalia, 1969; Gatehouse, 1972), and the stratigraphic scheme of Gatehouse (1972) is followed in this study (Table 1). Five sandstone units produce gas (Devine 1975, fig. 6). The Toolachee and Patchawarra Formations are the major reservoirs, while the Daralingie Beds, Epsilon Formation and Tirrawarra Sandstone have lesser amounts proven. The Tirrawarra Sandstone also contains oil.

Biostratigraphic units (Table 1) are defined solely by microfloral assemblages. The development of the palynologic concepts that led to the definition of five time zones, Stages 1-5, and the subsequent subdivision of Stages 4 and 5 into lower and upper parts, is documented by Paten (1969) and Price (1973), and is discussed briefly in Appendix 1. The correlation between absolute ages and biostratigraphy in Table 1 is very tentative, and based primarily on the work of Dickins (1976). The dates show the approximate time taken to deposit the various units.

RELATIONSHIP TO PREVIOUS WORK

This study has used methods for the examination of the Cooper Basin, which have not been published previously. Sprigg (1958) originally promoted the prospectivity of the region, where surface anticlines (Senior, 1968; Townsend and Thornton, 1975) had been recognised first by Jack (1930). Once exploration began, knowledge of the Cooper Basin geometry, sediments, and Mesozoic cover, increased rapidly as evidenced by Freeman (1963), Canaple and Smith (1965), Grund (1966), Laing (1969), Devine and Youngs (1975), Stuart (1976) and Nugent (1969). This study investigates more fully than earlier publications the regional distribution and lithofacies variation of the rocks in the basin, the processes which formed them, and the manner in which the basin has evolved.

Reports on the major gas fields have been published as they were discovered (Greer, 1965; Wopfner, 1966; Martin, 1967a; Pyecroft, 1973;

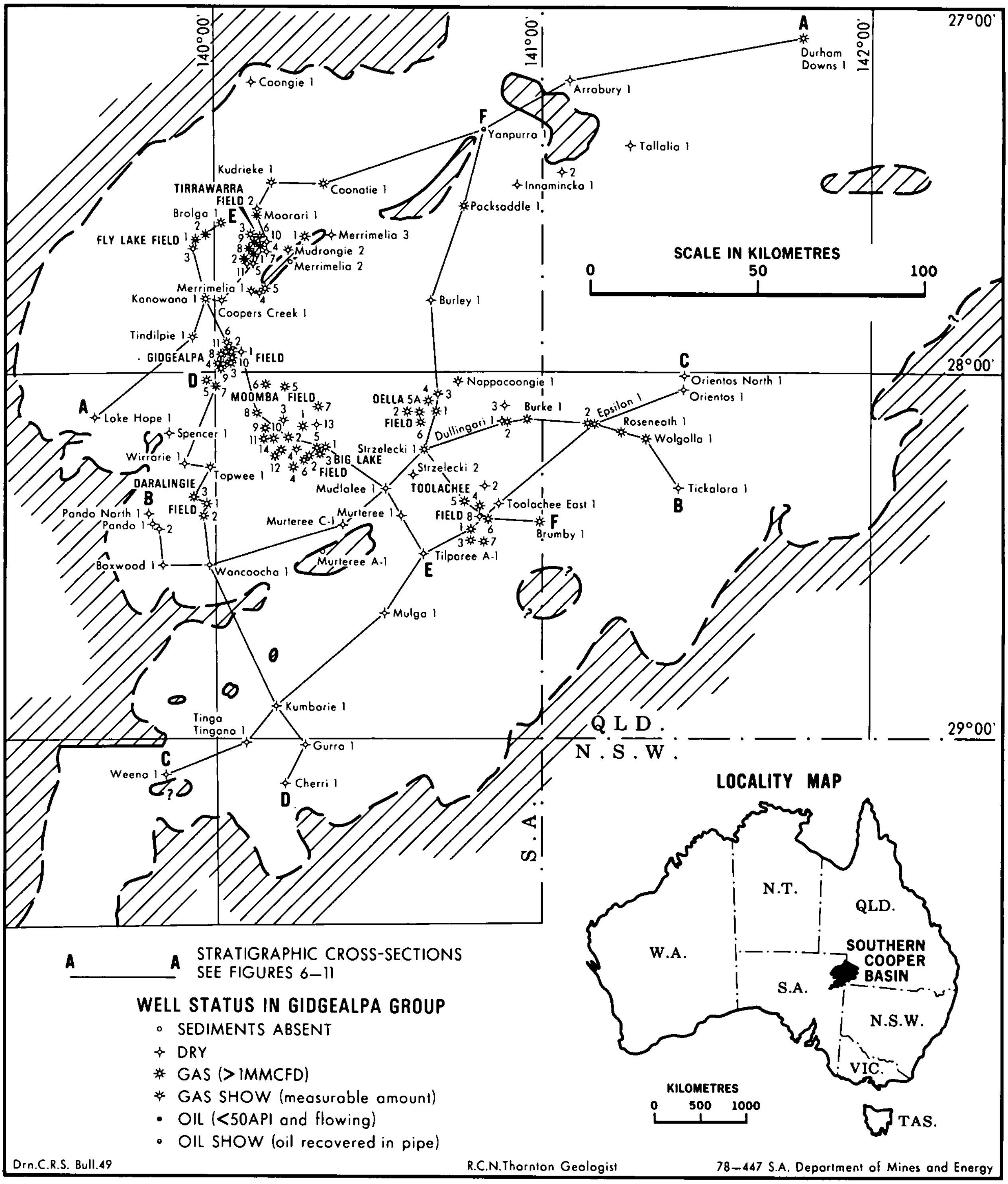
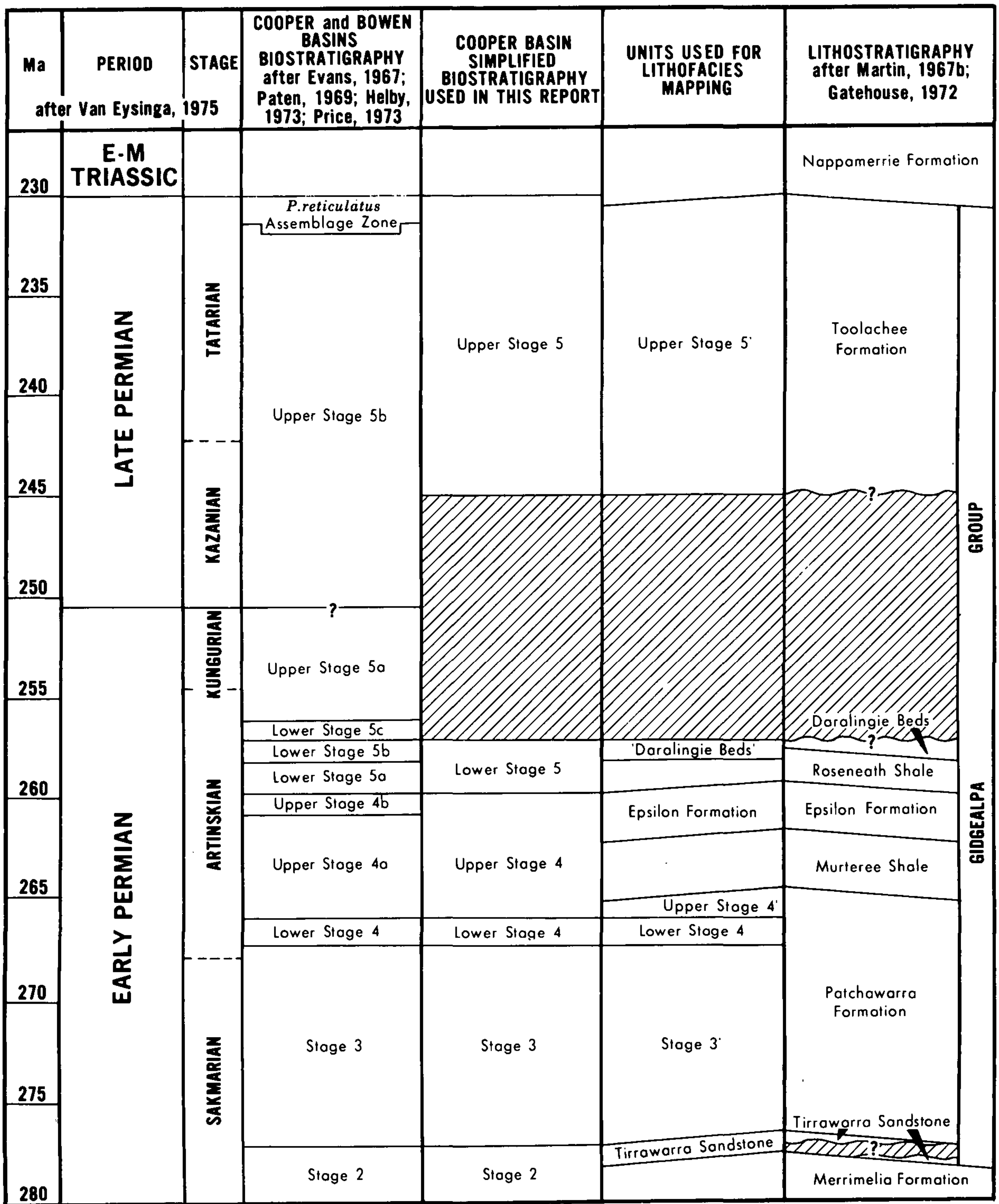


Fig. 1. Plan of Southern Cooper Basin showing locations of cross-sections

Battersby, 1976), and studies on the petrography of the reservoirs (Smale and Trueman, 1965; Steveson and Spry, 1973), and origin of the hydrocarbons (Brooks *et al.*, 1971; Shibaoka *et al.*, 1973) have helped to clarify the diagenetic history of the sediments. Geophysical (Hosking, 1966; Shetrone, 1972), petrophysical (Porter and Crocker, 1972; Porter, 1976), hydrological (Youngs, 1975) and geochemical (Devine and Sears, 1975, 1977) research has also been carried out. The Markov analysis of cyclic sedimentation and regression analysis used in this study are avenues of research not previously applied to the Cooper Basin. Reports of lithofacies mapping are not numerous, and studies by Demaison, *et al.*, (1969) and Battersby (1972) suffered from using purely rock units. Thornton (1973) first published a lithofacies analysis of time units, but mapped only a small area of the basin.

Table 1. *Cooper Basin stratigraphic table.*



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Knowledge of the depositional history of the central portion of the Southern Cooper Basin was enhanced considerably by Stuart (1976) who conducted an extensive study using core, cuttings and wireline log data. Stuart subdivided each well section into genetic units of different depositional environment, such as lake, delta distributary or plain, channel-point bar or floodplain, on the basis of lithology and log character. He then mapped the variations in the amount of these environments for a series of 'time slice' maps. The time slice boundaries were picked primarily on the basis of log correlation, using marker horizons such as 'lake' beds. These were co-ordinated with palynologic findings.

In this study, time-rock units have been mapped basin wide, with the result that depositional trends have been determined over wider areas than before. In addition, these trends have been correlated with depositional patterns in other nearby Permian basins.

Well Correlation, Lithologic Interpretation and Map Preparation—Methods

Isopach and lithofacies maps have been prepared of Gidgealpa Group time-rock units, the lithologies of which have been interpreted at each of 122 wells (Fig. 1) from wireline logs; almost invariably the sonic and gamma-ray logs. A total of 38 183 m was logged. On every map prepared, the symbol indicating the well status (sediment present or not) applies to the particular unit being mapped.

WELL CORRELATION

The time-rock units, which have been mapped, are bounded by palynologic Stage boundaries (Table 1), and all available palynologic data have been used to correlate these Stages throughout the basin. Palynologic control varies from excellent to non-existent, and therefore, basinwide correlation had to rely partly on lithologic comparison in those wells where microfloral evidence was insufficient.

In the correlation of the time-rock units, 24 wells with good palynologic data throughout the Gidgealpa Group succession were used as the primary control points (Table 2). Where microfloral evidence was not adequate in a well, lithologic comparison was made with the nearest control well, and time boundaries pushed through in a very similar manner to that described by Weimer (1966), as a subsurface equivalent of 'walking the outcrop'.

The wells with good palynologic control are distributed fairly widely throughout the basin. Significant exceptions are Gidgealpa, Moomba, Big Lake, Della, Burley and Innamincka, where a large degree of subjective interpretation was necessary to correlate the units.

Table 2 *Cooper Basin wells with good palynologic control*

Brolga 1	Fly Lake 3	Murteree 1
Brumby 1	Kanowana 1	Murteree C 1
Burke 1	Kudrieke 1	Tindilpie 1
Coopers Creek 1	Kumbarie 1	Tinga Tingana 1
Daralingie 3	Lake Hope 1	Tirrawarra 5
Epsilon 1	Mudlalee 1	Toolachee 1
Fly Lake 1	Moorari 2	Toolachee 6
Fly Lake 2	Mulga 1	Toolachee East 1

The 24 wells listed in Table 2 have been the most notable in their yield of abundant biostratigraphic information. In addition, these are in many cases the wells where palynologic boundaries are the most accurately defined.

Virtually every well in the Cooper Basin has been examined for microfloral content, but due to carbonisation, many have proved to be barren (Appendix 1; Paten, 1969).

A few palynologic determinations were discounted from wells in two areas, where they conflicted with other evidence.

LITHOLOGIC INTERPRETATION

In the lithologic interpretations, specific criteria have been used rigidly to define the rock types in order to attain uniformity of interpretation. Sandstone, shale, and coal bands, 0·3 m (1 ft) or greater in thickness, were identified, and lithologic interpretation was made from 1:240 (5 in = 100 ft) scale sonic and gamma-ray logs. Siltstones do occur in the Cooper Basin sediments. However, it was felt that the range of error in interpretation of the logs was too great to identify accurately a clastic lithology intermediate between sandstone and shale. A critical value of 100 API (American Petroleum Institute arbitrary scale) on the gamma-ray log was used to differentiate between sandstone and shale. Coals were interpreted uniformly against peaks on the sonic log with a value of at least 100 microsecs/ft.

The lithology-defining criteria are operational definitions in the sense of Krumbein (1958), because they (a) have geologic meaning; (b) are obtained by an objective process; and (c) are expressed in a form convenient for mathematical and statistical analysis.

On the gamma-ray log, shales record a relatively high counting rate, whereas clean sandstones and coals record very low rates. The gamma-ray log is thus a measurement of the natural radioactivity of the formations, and it normally reflects the shale content in a sedimentary unit, because the radioactive elements, potassium 40 in particular, tend to concentrate in clay minerals in shales. Natural gamma-rays are bursts of high-energy electro-magnetic radiation, which are continually emitted as a result of the decay of the naturally radioactive materials. The energy emitted is sporadic in nature, and so statistical averaging circuits (called time constants) are used to convert the random signals into a useable form (Allen, 1975, p. 358).

In the interpretation of gamma-ray logs, bed boundaries should be picked at a point half-way between the maximum and minimum deflections of the anomaly (Schlumberger, 1972, p. 58). In this study, a uniform figure of 100 API units was chosen as the critical value between shale and either sandstone or coal, and applied wherever possible. In the majority of wells, the critical value of 100 API is the midpoint between maximum and minimum levels of radioactivity.

In 24 anomalous wells, however, the midpoint and hence critical value is not 100 API, but generally 80-90 API.

Reasons for the anomalous well logs are many, ranging from less sophisticated equipment used in older wells (such as Innamincka 1 and 2), to a different logging company, or to very high formation temperatures (such as in Burley 1). However, some recently logged wells, also have low sandstone-shale critical values, e.g. Fly Lake 1 and 3, and Della 1 and 3. Perhaps this is related to variations in formation density, which affects the reading on a gamma-ray log (Schlumberger, 1972, p. 58).

Dullingari 1 provides a good example of the large differences in sandstone-shale ratio, which result from altering the critical value. This well was logged first with a critical value of 100 API, but the resultant sandstone-shale ratios were so different from Dullingari 2 (which is located 1·3 km from the first well) that the log for Dullingari 1 was reinterpreted using 80 API as the critical value. As a result of this reappraisal, the sandstone-shale ratios for the two wells became concordant. For the time-rock unit Upper Stage 5', the sandstone-shale ratio for Dullingari 1 is 0·47 when a critical value of 80 API is used, compared with 1·0 using 100 API.

On sonic logs, coals have a high interval transit time primarily because of their low density. In this study, they were recognised against peaks with a value of at least 100 microsecs/ft. The sonic log is a recording, versus depth, of the time required for a compressional sound wave to traverse one foot of formation. This time, known as the interval transit time, is the reciprocal of the velocity of the compressional sound wave (Schlumberger, 1972, p. 37).

The interval transit time is a function of matrix composition, porosity, type and amounts of pore fluids, and the degree of compaction and cementation (Allen, 1975, p. 363). It is recorded in microsecs/ft, over a range from about 44 microsecs/ft for zero porosity dense dolomite, to about 190 microsecs/ft, for water (Schlumberger, 1972, p. 38).

MAP PREPARATION

Four types of maps; structure contour, isopach, lithofacies, and 'D'-function maps, provide the basis for the interpretation of the geologic history and palaeogeography of the Cooper Basin. One structure contour map shows the present day structure near the top of the Permian, 'P' Horizon. The twelve isopach maps in the study comprise a composite isopach map of the Gidgealpa Group, plus eleven isopach maps of subdivisions within the Gidgealpa Group. Likewise, a lithofacies map and 'D'-function map have been prepared for each of five of the subdivisions, and a sandstone-shale ratio map and coal percentage map for a sixth.

Structure and Isopach Maps

The 'P' Horizon structure contour map (Fig. 3) and Gidgealpa Group isopach map (Fig. 4) were compiled from original maps prepared by Delhi International Oil Corporation from recent seismic surveys, together with a compilation map produced by Delhi International in 1970. The seismic reflector mapped as the 'P' Horizon has its origins in the uppermost Permian coal, which occurs very close to, or at the top of the Gidgealpa Group (Thiele, *et al.*, 1973). The areal extent of, and reliability of data from the seismic surveys used are shown by information source diagrams on Figures 3 and 4. Data reliability is reduced considerably on the isopach map because of the poor quality of seismic horizons beneath the 'P' Horizon (discussed further in Appendix 2A).

Eleven isopach maps have been drawn of subdivisions within the Gidgealpa Group with five of these encompassing virtually the complete period of Gidgealpa Group Formation. They are Stage 3', Lower Stage 4, Upper Stage 4, Lower Stage 5, and Upper Stage 5' (Table 1; Figs. 21, 26, 30, 41 and 49). Consequently, the thickness of the five subdivisions summed together should equal that of the Gidgealpa Group. This was achieved by first compiling eleven structural cross sections, drawn across the Cooper Basin through as many wells as possible. In areas of poor well control, the base of Gidgealpa Group on the sections was derived from the Gidgealpa Group isopach map. These sections thus provided additional control between wells. (See Appendix 2B for further details.)

Each of the other six subdivisions for which isopach maps have been drawn represents only part of one of the main five subdivisions. Isopach maps of these units were prepared using the maps of the appropriate main subdivision as control.

Lithofacies Maps

Seven different types of lithofacies map have been used. The simplest of these (see Krumbein, 1948) are the maps of sandstone percentage, shale percentage, coal percentage, sandstone-shale ratio (thickness of sandstone/thickness of shale), and clastic ratio (thickness of sandstone plus shale/thickness of coal). The sandstone-shale and clastic ratio maps were combined to make 'standard' triangle lithofacies maps (Krumbein and Sloss, 1963, p. 462). The seventh type of map is the

'D'-function lithofacies map (Pelto, 1954), in which lithologic percentages are plotted on triangular graph paper and the 'D'-function read using a transparent overlay. For reasons given below, facies maps were contoured using all data points, and without using structural control in areas without wells.

All the lithofacies maps were contoured in an unbiased manner using only well control and the zero edge from the isopach map. Structural maps were ignored in preparing these plans, primarily because it has not been proved that the structures seen today controlled deposition. Depending on well control, the actual contouring process varied between 'equal spacing' and 'interpretive', as discussed by Bishop (1960, p. 46-48).

Data from all wells drilled to the end of 1973 were used in the map preparation, even though this led to relatively tight well control over some fields. This conflicts with Krumbein (1952) who advocates open control point spacing of about 20-50 mm between points. He also suggests that in regions of high well density representative wells be chosen and others left out, so as to avoid complexities brought in by local anomalies. The Cooper Basin well control however is so unevenly distributed, that spacing would vary widely no matter how the wells to be included in the study were chosen.

The major differences between the triangle facies and 'D'-function maps (Table 3) originate from the fact that the triangle facies map is formed by superimposing two ratio maps, whereas only one variable is shown on the 'D'-function map. The resulting facies triangles are different, and are shown on the appropriate maps.

In compiling the standard triangle lithofacies map, sandstone-shale ratios of 8, 1 and $^1/_8$ and clastic ratios of 8, 1 and $^1/_4$ have been used. These are the limiting ratios advocated by Krumbein and Sloss (1963, p. 462) because universal use of the standard triangle will facilitate comparison between different units in different areas.

Pelto (1954) designed a triangle for a three component system which divides the system into seven classes. 'Three of these (classes) are characterised by mixtures in which one of the components is prominent and the other two subordinate; three contain mixtures in which two components are prominent; and one contains mixtures in which all three components are approximately equally prominent'. Any proportion of the three end members is defined by the distance (thus D) from an end member. Thus a value of 0 indicates a homogeneous lithology, whereas 100 (the value of the bounding lines between the seven classes) implies a composition which is not more like one end-mixture than the other. The minimum 'D'-function value for the three two-component classes is 50, and for the one three-component system is $66^2/_3$.

Table 3 *Comparison between triangle facies and 'D'-Function lithofacies maps*

Triangle Facies Map	'D'-Function Map
• Derived by superposition of two sets of contours: sandstone-shale and clastic ratios.	• Only one variable mapped.
• Sandstone-shale and clastic ratios are contoured geometrically.	• Contoured arithmetically.
• Ratio maps have no more than 12 contour values. Contour lines tend to be smooth and well spaced apart. Small scale variations are lost on the lithofacies map because not all ratio contours are shown.	• Small-scale variations mapped. Strict rules regarding class boundaries (e.g. one-component systems must be separated by a two component system).
• Map shows only that a data point has a value somewhere between four contour values.	• Provides information on the relative proportion of a specific end member within its class (Forgotson, 1960).
• Map primarily differentiates between areas with more or less sand than shale.	• Shows central regions of mixing.
• Shows area of virtually homogeneous sand and shale.	• End members are less homogeneous than for triangle facies map.
• Sandstone-shale and clastic ratio contours bear obvious relationship to variations in lithologic composition (Forgotson, 1960). Therefore environmental significance is shown by parallelism or discordance between facies strike and isopach or structural strike (Krumbein, 1952).	• Variations of contour lines with lithology not so clear as for triangle facies map.

Cooper Basin Structure

The Cooper Basin is an infrabasin beneath the Great Artesian Basin, and therefore knowledge of its structure has been derived entirely from subsurface data. The basin can be divided into six major structural zones (Fig. 2) on the basis of structure contours on a horizon near the top of the Permian succession ('P' Horizon, Fig. 3) and an isopach map of the Gidgealpa Group (Fig. 4). These zones are the Gidgealpa-Merrimelia-Innamincka and Murteree-Nappacoongee anticlinal trends, the Patchawarra, Nappamerrie and Tennapera Troughs, and the area to the northeast of the Karmona anticlinal trends.

The high degree of parallelism between the structure contours and the isopachs is interpreted as resulting from 'structural growth' during deposition, by diastrophism (faulting and folding), and by differential compaction.

The Cooper Basin is covered everywhere by a thick Mesozoic to Tertiary section. Its shallowest depth is 600 m below sea level in the south, whilst it is deepest (−3 200 m at the level of the 'P' Horizon) in the north, near Yanpurra. The northern margin of the basin occurs at a depth of −2 300 to −2 700 m. Thus, the Cooper Basin plunges strongly towards the north.

Of the six major structural zones (Fig. 2), the dominant features are two sinuous, narrow, northeasterly trending anticlinal zones. These are the Gidgealpa-Merrimelia-Innamincka and Murteree-Nappacoongee anticlinal trends. Most of the individual anticlines along these trends are associated with large high-angle faults, many of which do not cut the 'P' Horizon. At the northeastern end of both these features are west-northwesterly pointing anticlinal trends; the Karmona trend, and the Wolgolla and Tickalara trends.

These major anticlinal trends subdivide the Cooper Basin into four other structural zones; two of these are deep synclinal features, the Patchawarra Trough and the Nappamerrie Trough, the latter encompassing the central part of the Cooper Basin. Northeast of the Karmona anticlinal trend is a little understood region (due to poor seismic coverage), containing a series of structural lows and highs extending from the Arrabury Trough eastwards across the Durham Downs anticlinal trend. The fourth region, which has relatively little structural relief, and lies in the southern part of the basin, is a zone, which deepens from the southeastern margin into the Tennapera Trough.

Most, if not all, of the anticlinal structures are associated with major faults. In many cases, the faults do not intersect the 'P' Horizon (Fig. 3), although they are important features on the Gidgealpa Group isopach map (Fig. 4). The throw on some of the major faults appears not to have been consistently in one direction, as shown by the Big Lake Fault, which separates the Big Lake and Moomba structures. At the level of the 'P' Horizon, the Big Lake structure is about 100 m shallower than Moomba, but as Big Lake contains 200 m more sediment than Moomba, this means that although the Big Lake area is on the upthrown side of the fault now, during much of the Permian it must have been down-thrown to receive thicker sediments.

Recent seismic mapping in the Cooper Basin (Hollingsworth, *et al.*, 1976) indicates that some of the faults, including the Big Lake Fault, have very high angles of throw, and both normal and reverse faults occur. Further study may show that the dominant structural style in the basin was one of wrench faulting, as discussed by Harding (1976).

Further evidence for the inconsistency of directions of structural development, in some local areas, is given by the non-parallelism between top and bottom Permian surfaces. This is shown by detailed seismic maps over areas where record quality is good throughout the Permian section, such as in the vicinity of Burke-Dullingari (Thiele, *et al.*, 1973). Some of this local discrepancy between the seismic reflectors equated with the top and bottom surfaces can be attributed in part to a combination of a rugged basal depositional surface with perhaps diminishing structural activity over time.

On a regional scale, however, isopachs of the Gidgealpa Group largely parallel the contours of the 'P' Horizon, because the sedimentary sequence is thickest in the structural lows and thinnest over anticlinal trends. The basin in most parts thins gently towards the margin, which is not noticeably fault controlled. The high degree of parallelism between contours on the Gidgealpa Group isopach map and the 'P' structure contour map can mean only that there was structural growth during Gidgealpa Group deposition. This could have been due to two factors, structural movements and differential compaction.

Differential compaction of sediment deposited over an irregular, resistant surface may lead to the formation of anticlines (Weller, 1960, p. 303). The Gidgealpa Group consists of high proportions of shale and coal, which are particularly prone to compaction, and loss of porosity could result in shale reducing to 45-20 per cent of its original volume, coal 14-5 per cent, and sandstone 85-75 per cent (Weller, 1960; Perrier and Quiblier, 1974). Thus, syndepositional compaction must have been an important factor in the development of the Cooper Basin.

Each of the six major structural zones, already referred to, are composed of smaller structural

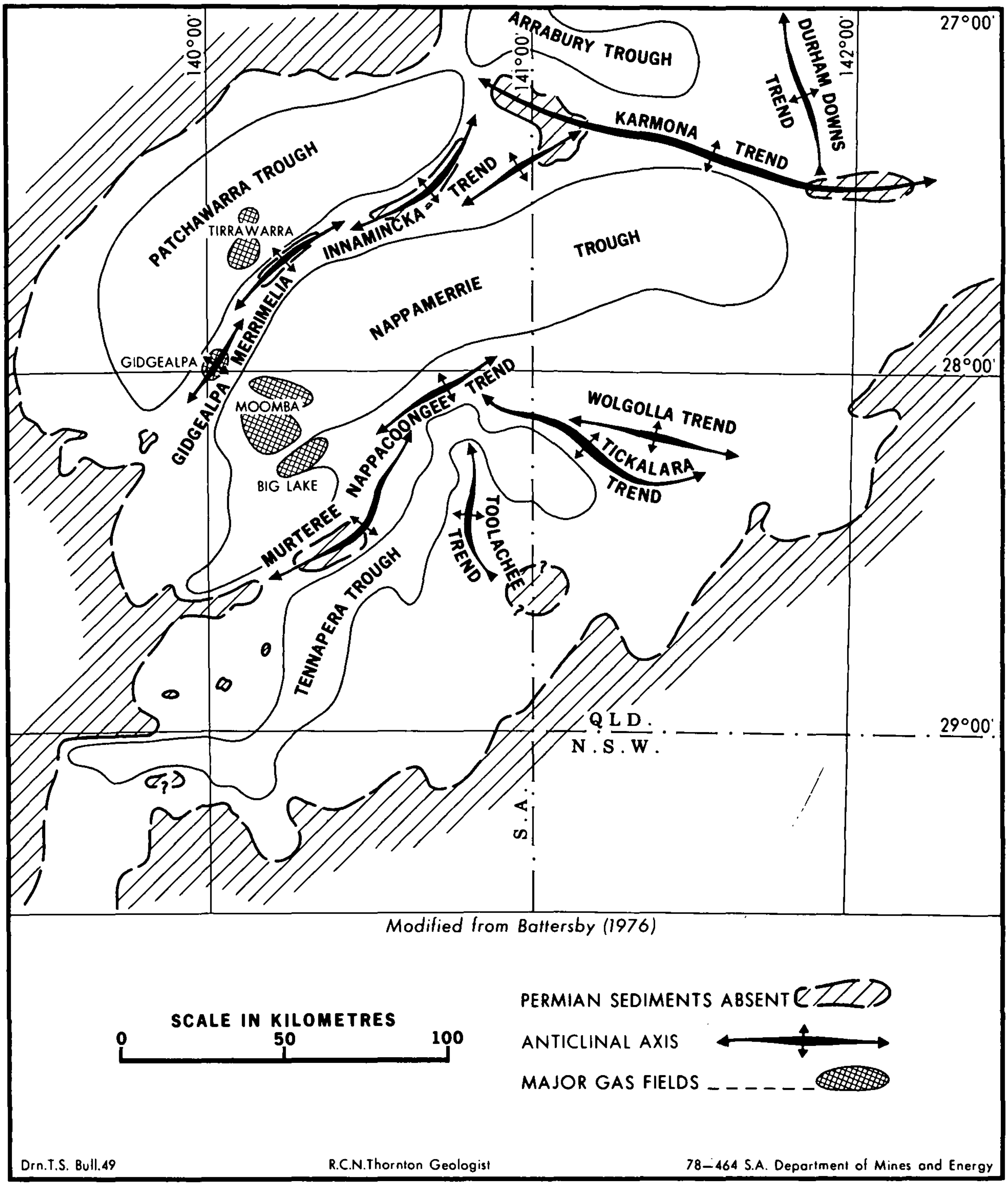


Fig. 2. Cooper Basin—Major structural elements

elements, and in the brief following description of these zones and their component parts, all depths relate to the 'P' Horizon map.

The *Gidgealpa-Merrimelia-Innamincka (GMI) anticlinal trend* is the most prominent anticlinal feature in the basin, and extends for a distance of 150 km in an arc from the very edge of the basin in the southwest, to abut the Karmona Trend in the northeast. It comprises four major structural culminations, namely Gidgealpa, Merrimelia, Packsaddle and Innamincka. The GMI Trend is a very steep sided feature, largely fault controlled, with a maximum relief of 1 000 m. It is baldheaded of Gidgealpa Group sediments on three of the four culminations, viz. Merrimelia, Packsaddle and Innamincka.

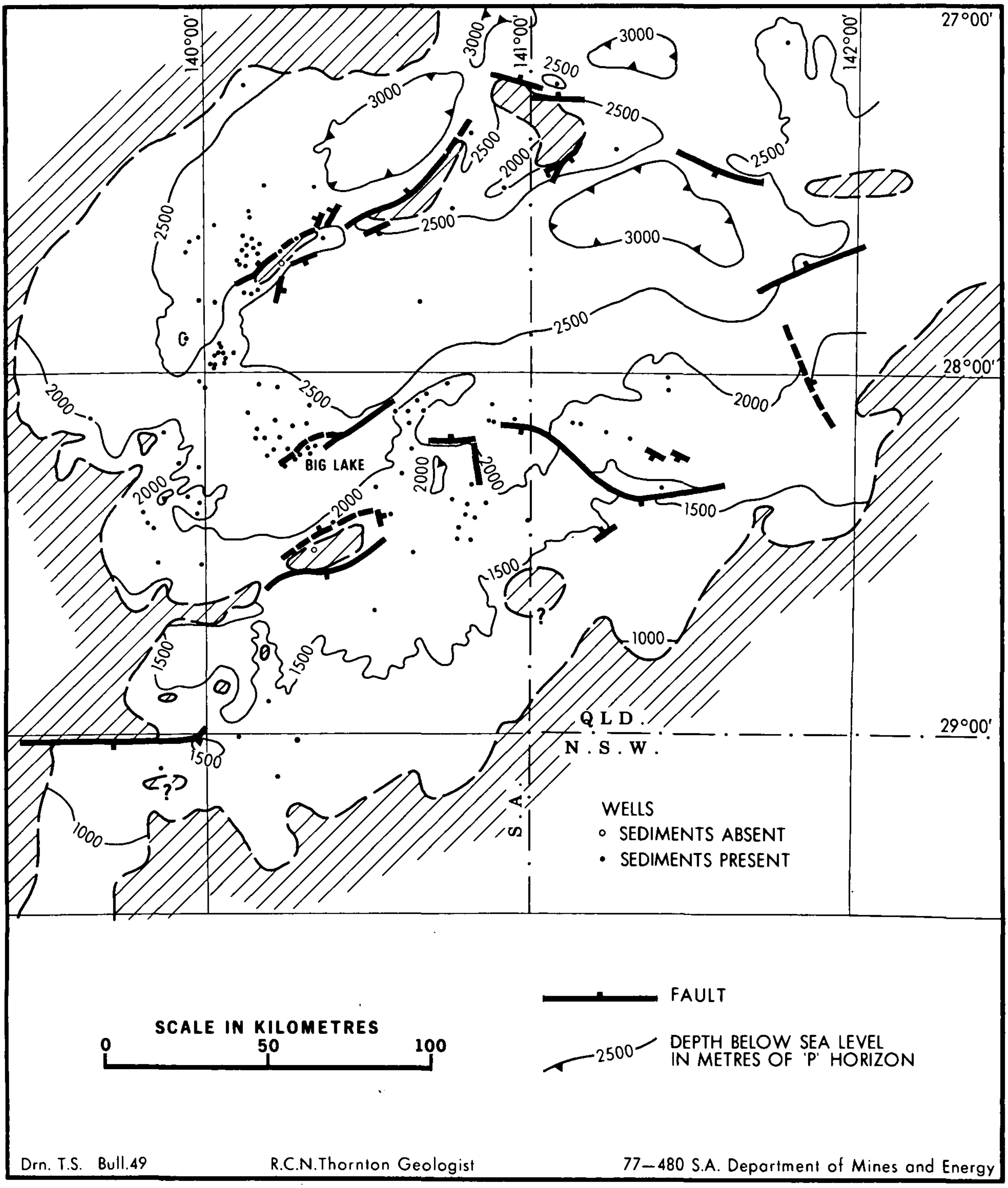


Fig. 3. 'P' Horizon structure contour map

The *Murteree-Nappacoongee (MN) anticlinal trend* is S-shaped and extends for 100 km in a northeasterly direction. It is neither as steepsided as the GMI trend, nor has as much structural relief (maximum of 800 m northwest of Della). It reaches its shallowest depth, 1 500 m below sea level, at Murteree, and plunges northeast and southwest from there. The Murteree structure is bald of Gidgealpa Group sediments, and in addition, the Patchawarra Formation is missing from the apex of the Della culmination.

The *Nappamerrie Trough* is a very long, doubly plunging feature that extends from the western edge, nearly through to the eastern edge of the basin. It is 310 km long, up to 100 km

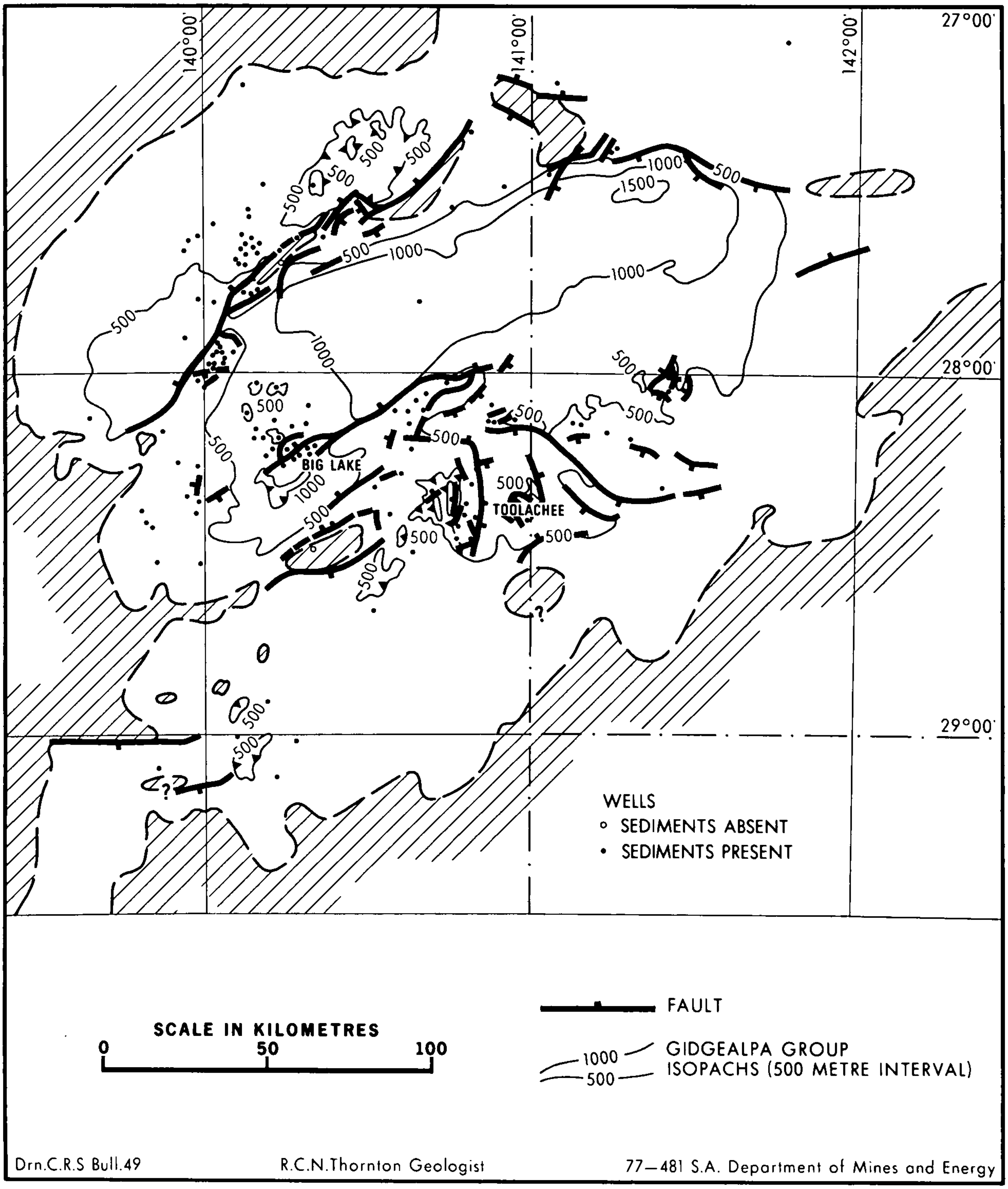


Fig. 4. Gidgealpa Group isopach map

wide, and at its deepest point, south of Tallalia, is 3 000 m below sea level. The Moomba gas field, the largest gas filled structure so far located, is situated on the flank of this trough.

Both the interpreted maximum thickness of the Gidgealpa Group, and the greatest thickness intersected by drilling, occur within the Nappamerrie Trough. South of Tallalia, as much as 1 600 m of sediments are thought to occur, while further to the southwest, Burley 1 encountered 991 m without reaching the base of the section. The Nappamerrie Trough is the only region where the sedimentary sequence is interpreted to be in excess of 1 000 m.

The *Patchawarra Trough* is an arcuate feature, running sub-parallel to the GMI anticlinal trend.

It is 140 km long, attains a maximum depth of 3 200 m below sea level at its northeastern end, and is as much as 40 km wide. Anticlinal structures, of which Tirrawarra is the largest known, occur near the axis of the trough. The sedimentary section is thickest (900 m) at its southwestern end, thins to about 400 m in the Tirrawarra region, but thickens again to 500 m in the northeast.

In the northeastern region, the *Karmona anticlinal trend* separates the northern and southern parts of the Cooper Basin. It plunges west-northwest, is 150 km long and at the eastern end reaches a minimum depth of 1 900 m below sea level. In part, its southern flank is defined by a fault with a maximum throw of 500 m at the level of the 'P' Horizon. On the surface, this structure is reflected in a major lineament which transects the Australian continent (E. S. O'Driscoll, Western Mining Corp., pers. comm., 1977).

In the northern Cooper Basin, the *Arrabury Trough* is parallel with, and north of, the Karmona Trend, and also plunges westwards. It is only 50 km long, by 25 km wide, but its deepest point is 3 000 m below sea level. Further to the east, the *Durham Downs Trend* is aligned slightly west of north, and is 40 km long. It is deeper than any of the other anticlinal features with a minimum depth of 2 300 m below sea level, and plunges northwards.

Along the southern flank of the Cooper Basin, the main synclinal feature is the *Tennapera Trough,* which is long and sinuous, and fairly indistinct south of Murteree. It is 220 km long, with a width up to 25 km, and a maximum depth of 2 200 m below sea level in the vicinity of Burke-Dullingari. The trough curves around the northern end of the *Toolachee anticlinal trend.*

At its northeastern end, the MN anticlinal trend bifurcates into the *Tickalara* and *Wolgolla anticlinal trends.* The Tickalara feature is the longer, and for virtually the whole of its 80 km length is bound by a fault on its southern side.

Cooper Basin Stratigraphy

Sediments preserved in the Cooper Basin record three very different phases of basin development, over a period of more than 50 million years. The rock units related to these phases are the Merrimelia Formation, which consists largely of glacially derived sediments, the Gidgealpa Group of mainly non-marine origin and the non-marine Nappamerrie Formation. These units are of (?) Late Carboniferous-Early Permian, Permian, and Triassic age respectively (Table 1).

The Patchawarra and Epsilon Formations, Daralingie Beds and Toolachee Formation of the Gidgealpa Group consist of varying proportions of sandstones, shales and coals. These are interbedded with the Tirrawarra Sandstone, Murteree Shale and Roseneath Shale.

Biostratigraphic units are defined solely by microfloral assemblages, on the basis of the first arrival of diagnostic forms. A total of nine subdivisions has been recognised in the Cooper Basin (Price, 1973). However, because the minor subdivisions have been recognised in only the most recently drilled wells, a simplified scheme has been used, which incorporates only the six major Stages in this study (Table1). The palynology of these Stages is discussed in Appendix 1.

In the Gidgealpa Group, Price (1973) has recognised unconformities within the Tirrawarra Sandstone, and at the base of the Toolachee Formation on the basis of a lack of certain palynologic associations recognised in the Bowen Basin (Price, 1976). Lithologic evidence does not support an unconformity within the Tirrawarra Sandstone although an angular unconformity beneath the Toolachee Formation has been observed from production drilling results (Wopfner, 1966; Pyecroft, 1973) and seismic records (Hollingsworth, *et al.*, 1976). These indications support the palynologic findings that there was a major break in the geologic record at the end of Early Permian.

The units of the Gidgealpa Group are diachronous, a feature documented by the relationship of the rock units to the palynologic Stages (Table 1), and illustrated by two diagrammatic sections (Fig. 5) and six stratigraphic cross-sections (Figs. 6-11). Each well on the stratigraphic cross-sections is represented by its gamma-ray and sonic logs, and the sites of palynologic determinations are marked (see Table 4 for a description of the palynologic symbols used). The cross-sections have been drawn using the base of the Toolachee Formation as a datum, and with a diagrammatic horizontal scale.

On the cross-sections, the wireline logs for each well have been juxtaposed with respect to normal practice, in order to save space. Thus, the sonic log is on the left, and the gamma-ray log on the right. The legend at the bottom of each section shows a key to aid lithologic interpretation of the logs. Virtually every well with some palynologic control is shown on the cross-sections. It can be seen that the exact depth of almost every time boundary is open to interpretation. Only in a few cases was the sampling interval small enough to locate the boundary within less than a few metres. However, some of the boundaries could be fixed reasonably accurately within a particular field by using a combination of the palynologic data for all the wells and lithologic comparison between them. Thus the cross-sections may not show completely the reason for the position of a time boundary.

Table 4 *Palynologic symbols used on stratigraphic cross-sections*

P. ret.	:	*P. reticulatus* Assemblage Zone
Para.	:	*Paravittatina* Assemblage
U5	:	Upper Stage 5
L5	:	Lower Stage 5
L5b	:	Lower Stage 5b
4	:	Stage 4
U4	:	Upper Stage 4
U4b	:	Upper Stage 4b
U4a	:	Upper Stage 4a
L4	:	Lower Stage 4
3	:	Stage 3
2	:	Stage 2
1	:	Stage 1
E.T.	:	Early Triassic
L.P.	:	Late Permian
E.P.	:	Early Permian
?	:	perhaps
N.Y.T.	:	no younger than
N.O.T.	:	no older than

LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS

Although this study deals only with the sediments of the Gidgealpa Group, the lithology and depositional environments of the Merrimelia and Nappamerrie Formations are discussed also, because they have some bearing on the depositional history of the Gidgealpa Group. The rock descriptions are based primarily on data from well completion reports, together with some personal observations made on cores from Gidgealpa 6.

The *Merrimelia Formation* comprises a succession of conglomeratic sandstones, which in some places are overlain by shales and siltstones. Thicknesses in excess of 350 m have been encountered by drilling. The sandstones are generally white to light grey in colour, quartzose and poorly sorted. They consist of fine, angular grains set in a clay-rich matrix with scattered pebbles and cobbles, up to 130 mm in diameter, of quartzite, chert, siltstone, shale and metamorphic and igneous fragments. In places, the pebbles dominate the lithology to form a conglomerate. The overlying shales and siltstones tend to be light to dark grey, hard and micaceous.

Grund (1966) described the Merrimelia Formation as comprising tillites, glacio-fluvial, glacio-lacustrine inter-glacial, and peri-glacial sediments. Subsequent investigations have supported the theory of a glacial origin (Battersby, 1976).

Unconformities form both the base and top of the Merrimelia Formation.

The *Tirrawarra Sandstone* is brown to white in colour and is composed of well-sorted, subrounded quartz grains, set in a clay matrix. Grain size ranges from fine to medium grained, and occasionally conglomeratic. Interbedded with the sandstones are very minor amounts of carbonaceous siltstone, shale and very thin coals.

Kapel (1972) suggested a fluvial origin for the formation, and considered that it might have been partly derived from reworked Merrimelia Formation. Gostin (1973) in his study of the basal sediments in the Tirrawarra field recognised three units of fluvial channel and braided stream origin.

The *Patchawarra Formation* is the thickest of the formations within the Gidgealpa Group, and exceeds 300 m in thickness in the deeper parts of the basin. At the base of this formation, Kapel (1972) has recognised a 25 m thick suite of 'distributary sandstones', which he called the Moorari Beds. They are limited in geographical extent to the Patchawarra Trough, and may be equivalent to Gostin's (1973) upper Tirrawarra Sandstone unit (Battersby, 1976).

The remainder of the Patchawarra Formation is composed of a rhythmic succession of sandstones, siltstones, shales and coals. Depositional environments ranging from floodplain, through deltaic to offshore, were recognised by Stuart (1976), and are confirmed by results in this report. The sandstones are predominantly quartzose, with some lithics, fine to medium grained and occasionally conglomeratic, and set in a kaolinitic matrix. Often they grade up into interbedded sandstone, siltstone, and shale units showing small-scale current, slump and load structures. The shales are dark grey to black, micaceous and carbonaceous, and in some places grade directly into coal. Coal seams are up to 25 m in thickness. The Patchawarra Formation is areally extensive; and covers a wide timespan. As a result, considerable facies variation occurs. For example, three lithologic units are recognisable in the Patchawarra Trough (Kapel, 1972, and cross-section A-A, Fig. 6), which cannot be correlated elsewhere in the basin.

Murteree Shale generally conformably overlies the Patchawarra Formation, although in a few wells there is evidence for a minor niatus between the two (Battersby, 1976). Lithologically, the unit comprises almost completely light to dark grey shales, which are micaceous and partly carbonaceous. There are minor thin interbeds of brown, micaceous siltstone. Battersby (1976) suggested that the Murteree Shale was deposited in a series of lakes, although the interpretation proposed in this study is that there was virtually complete submergence of the basin under a single shallow body of water.

The *Epsilon Formation* conformably overlies and interfingers with the Murteree Shale, and consists of shales and silts with thinly interbedded sandstone and coal. Sandstones are fine grained and clay cemented and were laid down in floodplain to shoreline environments. The rock types and environments of the *Roseneath Shale* are essentially the same as those of the Murteree Shale.

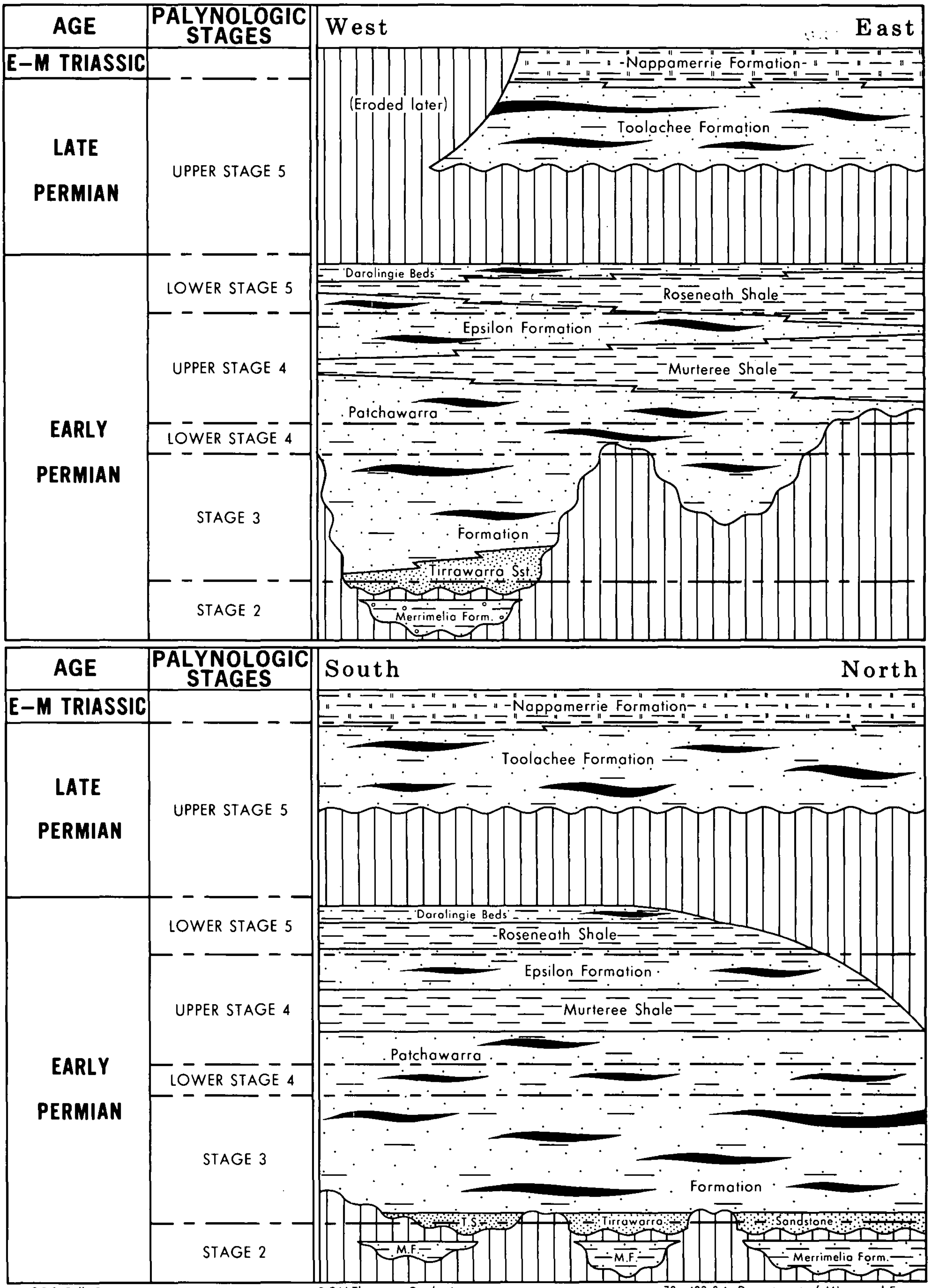
The *Daralingie Beds* comprise a succession of thin sandstones, siltstones, shales and coals similar to the lower part of the Epsilon Formation, and reflect a similar regressive environment. In the upper part of the succession, thicker sands and coals apparently were deposited in lower deltaic to floodplain environments (Battersby, 1976).

The *Toolachee Formation* comprises freshwater sandstones, siltstones, shales and coals. The sandstones are predominantly quartzose with various amounts of lithic fragments. Mica and carbonaceous wisps are common. The sandstones are often medium to coarse grained, and where they overlie coals, are regularly, but not invariably, conglomeratic. Upwards fining graded bedding and medium-scale (Conybeare and Crook, 1968) cross-bedding are common.

In many cases sandstones are finely interlaminated with siltstones, and shales, and are then normally rather finer grained. Small-scale current structures are abundent. Shales regularly grade upwards from silty to coaly; are often micromicaceous, and almost invariably carbonaceous, containing abundant carbonised plant fragments.

The final phase of sedimentation within the Cooper Basin resulted in the accumulation of the *Nappamerrie Formation*, which is thought to be over 750 m thick in the deeper parts of the basin.

The Nappamerrie Formation consists dominantly of interbedded shales, siltstones and sandstones. Papalia (1969) recognised four members within the formation, numbered I to IV from the base upwards. Members I and III essentially consist of shales and siltstones, which exhibit red bed characteristics. The presence of pelletoid siderite, abundant carbonaceous material and the crustacean *Cyzicus (Estheria)*, were considered by Papalia (1969) to be indicative of a fresh, to brackish water lake environment. Members II and IV



Drn.C.R.S. Bull.49 R.C.N.Thornton Geologist 78—483 S.A. Department of Mines and Energy

Fig. 5. East-west and north-south diagrammatic sections across the Cooper Basin

mainly comprise grey to brown sandstones, with minor interbedded siltstones and shales. It has been suggested that they are continental-fluvial in origin.

FACIES RELATIONSHIPS

The rock units in the Cooper Basin are separated by unconformities or conformable, but diachronous, boundaries. These relationships, and the different histories of subsidence, deposition and erosion of different areas in the basin, are illustrated by diagrammatic sections (Fig. 5), and the six stratigraphic cross-sections encompassing 59 of the Cooper Basin wells (Figs. 6-11—at rear). The stratigraphic sections also show lateral facies changes within the rock units. Three of them approximately parallel the dominant northeasterly structural trend, and three cross it at right angles (Fig. 2).

The significance and interpretation of the time-rock and facies relationships are elaborated in the Regional Facies Distribution and Palaeogeography section. Supporting evidence comes from studies of Gidgealpa core material, analysis of cyclic sedimentation, and regression analysis.

Major unconformities in the Cooper Basin succession occur at the base and top of the Merrimelia Formation and at the base of the Toolachee Formation. Erosion prior to Toolachee Formation deposition removed a considerable thickness of, and in some cases all, the Early Permian deposits from structural highs. Nonetheless, the Early Permian section which is preserved provides visible evidence of the diachronous nature of some of the conformable boundaries. Major directions of facies change are from east to west, or vice versa (Fig. 5).

Different parts of the Cooper Basin have experienced very different depositional histories with the maximum difference existing between the Patchawarra Trough and the rest of the basin. In the Patchawarra Trough (Sects. A-A and E-E, Figs. 6 and 10) deposition commenced on an essentially level surface and the lowermost units, the Merrimelia Formation and Tirrawarra Sandstone, were evenly distributed throughout the area. A very thick section of Stage 3 age was deposited and stable conditions are exemplified by very thick coal seams. From then on, however, the Patchawarra Trough was a stable area, where only minor deposition occurred. On the other hand, south of the GMI anticlinal trend deposition commenced on a more rugged basal surface, with the result that Merrimelia Formation, Tirrawarra Sandstone and the oldest parts of the Patchawarra Formation were deposited only in areas of low relief. Onlap up the flanks of pre-existing structures accompanied deposition of successively younger units, which are much thicker than in the Patchawarra Trough (Sects. B-B and E-E, Figs. 7 and 10).

The present northeasterly structural grain of the Cooper Basin was imposed after the deposition of the earliest Permian units. Merrimelia Formation is very thick along parts of the GMI trend (Fig. 2), and is the only Permian rock unit preserved on the Murteree structure. Tirrawarra Sandstone is well developed in the Gidgealpa and Big Lake anticlinal features, but absent from Moomba and troughs to the east. The lack of these units in the southeast of the Cooper Basin suggests that this may have been an 'upland' area during earliest Permian.

Rock units within the Gidgealpa Group show lateral facies changes, which can be seen on the cross-sections. For example, the Toolachee Formation, which ranges from very coal rich on the western flank of the basin, through interbedded sandstones, shales and coals in the centre, to coal poor and shale rich in the northeast at Durham Downs (Sects. A-A and B-B, Figs. 6 and 7; Fig 5).

The relatively level basal depositional surface of the Patchawarra Trough is indicated by the continuity and uniform thickness of the Merrimelia Formation and the Tirrawarra Sandstone (Sect. A-A, Fig. 6): the Tirrawarra Sandstone being thickest in Tindilpie 1, at the southwestern end of the basin. In direct contrast to this, the uneven depositional surface of the southern part of the basin is shown by the intermittent distribution of the oldest Permian formations which occur only in the west of the southern part of the basin (Sects. B-B and C-C, Figs. 7 and 8; Fig. 5).

Merrimelia Formation occurs along the length of the GMI trend, but its presence within the deepest part of the Nappamerrie Trough can only be surmised, because even the well drilled in the deepest part (Burley 1), did not intersect the complete Permian section (Sect. F-F, Fig. 11). Further to the south (Sect. C-C, Fig. 8), the formation is very thin at Tilparee A-1 and Toolachee 1, and is absent from Toolachee East 1, suggesting perhaps that this location marks the eastern margin of Merrimelia Formation deposition in the region. The alternative is that near the end of Stage 2 time, the region around Toolachee East was uplifted and eroded. In the southern part of the basin, Tirrawarra Sandstone distribution is similar to, but slightly more restricted than that of the Merrimelia Formation (Sects.B-B and C-C, Figs. 7 and 8). The absence of these units at Durham Downs 1 (Sect. A-A, Fig. 6), suggests that they may not exist in the Northern Cooper Basin.

The top surface of the Merrimelia Formation is unconformable, but that of the Tirrawarra Sandstone is diachronous (Fig. 5). Synchronous deposition of uppermost Tirrawarra Sandstone and lowermost Patchawarra Formation is indicated in the vicinity of Murteree C1 and

Dullingari 2 (Sect. B-B, Fig. 7), and Tinga Tingana 1 and Kumbarie 1 (Sect. C-C, Fig. 8). For example, in Murteree C1 the rocks of Stage 3 age are almost all Tirrawarra Sandstone, with only a thin Patchawarra section, however, at Dullingari 2, the section consists totally of Patchawarra Formation. Therefore, assuming approximately equal sedimentation rates, and no major diastem in the section, deposition of Patchawarra Formation must have commenced before completion of Tirrawarra Sandstone deposition.

The thickness of the Patchawarra Formation of Stage 3 age varies throughout the Cooper Basin more than any other unit (Sect. E-E, Fig. 10). The formation is uniformly thick in the Patchawarra Trough (Sect. A-A, Fig. 6), but varies considerably in thickness elsewhere, particularly where it onlaps onto previously existing basement highs, and is very thick over part of the GMI anticlinal trend. Onlap is clearly exhibited on cross-section B-B (Fig. 7), where the oldest Patchawarra Formation sediments occur only in the wells drilled in the structural lows. Thus, a considerable thickness of sediments was deposited at Dullingari 2 before deposition commenced at Burke 1. By the end of Stage 3, the 'valleys' were partly filled, and the surface upon which rocks of Lower Stage 4 age were deposited was relatively flat (Fig. 5).

By Upper Stage 4 time, deposition of the Patchawarra Formation had almost extended throughout the basin, and onlap was complete by the middle of Upper Stage 4. The western flank of the southern part of the basin (Sect. D-D, Fig. 9) experienced continuous onlap as deposition occurred progressively further towards the west.

The great thickness of Stage 3 sediments in Packsaddle 1, on the GMI anticlinal trend, indicates that during this period part of the GMI trend was sinking rapidly to allow for the accumulation of such a sequence. By Lower Stage 4, however, the region was relatively uplifted, as shown by the very thin section in Packsaddle 1 and Yanpurra 1.

During Stage 4 and Lower Stage 5, the major area of deposition changed from the Patchawarra Trough to south of the GMI anticlinal trend, as shown by increased formation thickness (Sect. E-E, Fig. 10). For example, the progressive northerly decrease in thickness of the Murteree Shale on moving into the Patchawarra Trough is the result of diminishing subsidence in that area. It cannot be due to later erosion, because the Murteree Shale is everywhere overlain by Epsilon Formation. This interpretation points to a stabilising of the Patchawarra Trough during late Early Permian, rather than deposition during Upper Stage 4 and Lower Stage 5, followed by erosion.

Diachroneity of rock unit boundaries is documented most clearly by the top of the Epsilon Formation (Fig. 5). This boundary is seen to be diachronous because it transgresses the Upper Stage 4/Lower Stage 5 boundary (Sect. B-B, Fig. 7). In the east, at Wolgolla 1, the time boundary is within the Roseneath Shale. However, it approaches the top of the Epsilon Formation in each successively more western well, until at Murteree C1, time and rock boundaries coincide. In the four most westerly wells, the top of the Epsilon Formation is Lower Stage 5 in age. This diachroneity shows that the change from Epsilon Formation to Roseneath Shale occurred first in the east.

On the northwest-southeast cross-section E-E (Fig. 10), time and rock boundaries parallel one another. This means that in the central part of the basin, the major diachronous facies changes must have occurred approximately normal to the section.

Diachroneity at the base of the Daralingie Beds (Fig. 5) is indicated southwest of Toolachee 1 (Sect. C-C, Fig. 8) where Roseneath Shale thins and Daralingie Beds thicken. This implies perhaps, that in the Mulga and Tilparee region, the Daralingie Beds environment replaced Roseneath Shale deposition earlier than at Toolachee. In other words, the change occurred towards the northeast.

Controls on sediment accumulation were different during Early Permian compared with Late Permian, and as a result, thickness variations of the Toolachee Formation bear very little relationship to differences in the Early Permian sections (Sects. A-A, B-B and C-C, Figs. 6-8). Overall, Toolachee Formation thickness varies very little, indicating deposition on a relatively flat surface, and continuous sedimentation in a gradually subsiding basin, with very little tectonic activity. The Patchawarra Trough was an area of uniformly thin development, whereas maximum deposition occurred in the southeast, around Wolgolla 1. Absence of Toolachee Formation from the western flank of the basin is probably due to subsequent erosion, following deposition of the Nappamerrie Formation. This interpretation is due to the fact that in the southwest of the basin (Sect. C-C, Fig. 8) offlapping Early Permian deposits are directly overlain by post-Triassic sediments.

Lithostratigraphic Interpretation of Cores from Gidgealpa 6

The cores from Gidgealpa 6 provide continuous lithologic information over a large part of the Gidgealpa Group interval, which is relatively thin in this well. As such, they provide excellent data for a comparison of core lithology and interpretation with wireline-log responses. A detailed description and sedimentologic analysis of the cores was undertaken, therefore, and compared with the gamma-ray and sonic logs.

Eight cores were cut in the Gidgealpa Group at Gidgealpa 6 (Fig. 12). Cores 1 and 2 intersected an 18·3 m section near the middle of the Toolachee Formation. Cores 3-8 intersected a major proportion of the Patchawarra Formation, over a time interval interpreted to have covered the latter part of Stage 3, Lower Stage 4, and the earliest part of Upper Stage 4. Therefore, the cores are suitable for studying the depositional history of a long period of time in a relatively condensed section. This is especially true because nearly 100 per cent recovery was obtained of the 81·7 m of core.

The 8 cores are pictorially displayed in Figs. 13-17 in a manner suggested by Selley (1968), and are described in three groups; namely core 8, cores 3-7 and cores 1-2. The discussion of the depositional environments deals with each of the same three groups in order to trace their chronologic change.

Because the regional facies analysis of the Cooper Basin in this report is based on gamma-ray and sonic logs, it is instructive to compare the interpretation from such logs with the core interpretation from Gidgealpa 6. This has been done, and the differences between core description and log interpretation, and their implications, are described.

DESCRIPTION

Core 8

In Core 8, Patchawarra Formation conglomerates, shales, and siltstones, overlie tuffs of presumed Proterozoic age (Wopfner, 1966). Both the volcanic material and the lowermost sediments are altered almost totally to pale green clay (Steveson, 1972). As a result, the exact unconformable surface is very hard to recognise.

Much of the conglomerate consists of volcanic pebbles (Plate 1, 7565') and although extensively altered, porphyritic volcanic fragments

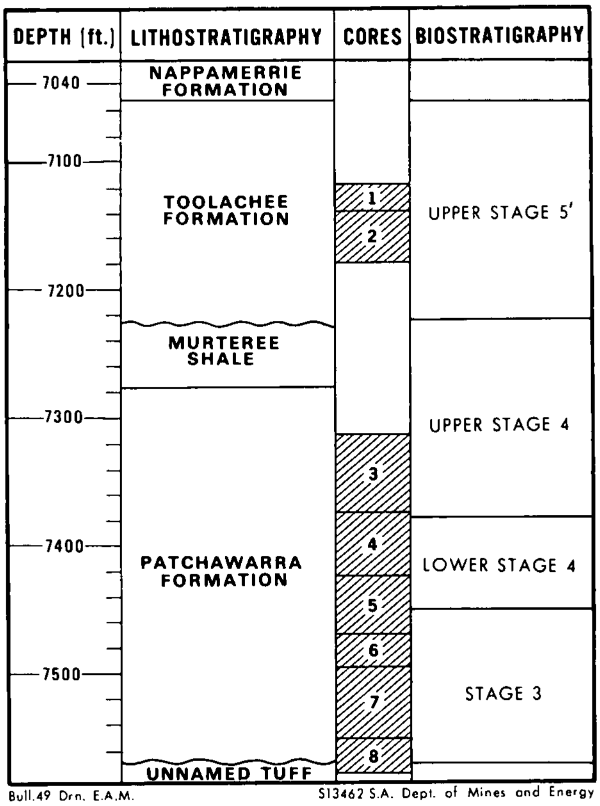


Fig. 12. Gidgealpa 6—stratigraphic position of Cores 1-8

containing pseudomorphs after plagioclase can be recognised (Steveson, 1972). Most pebbles are subrounded to round, and vary in size from a usual 2-5 mm up to flattened blocks 50 x 30 mm. The conglomerate bands vary from less than 50 mm thick within sandstone or shale sequences, to massive, poorly-sorted units up to 1 m in thickness.

Shales vary in colour from pale-brown, through green to grey. At the top of the core there is a 1·2 m thick siltstone unit, which is off-white, massive and hard.

Cores 3-7

Cores 3-7 cover most of the Patchawarra Formation (Fig. 12). Half this interval consists of units of interbedded sandstone and shale while the rest comprises approximately equal proportions of fine-grained, pale-grey, quartz sandstones, dark grey shales, and coal. Sedimentary structures range from cross stratification and ripples, to convolute bedding, pillars, burrows and roots. Microfaulting, both syndepositional and post-lithification, is common.

Most sandstone beds are thin (0·3-1·2 m thick) and comprise about 90 per cent uniformly fine-grained quartz, plus altered argillaceous lithic fragments, now deformed illite (Steveson, 1972). In a few cases, sands are slightly coarser at the base. In one 4·5 m thick sandbed there are overall slight variations in grain size, but generally individual sets are well sorted.

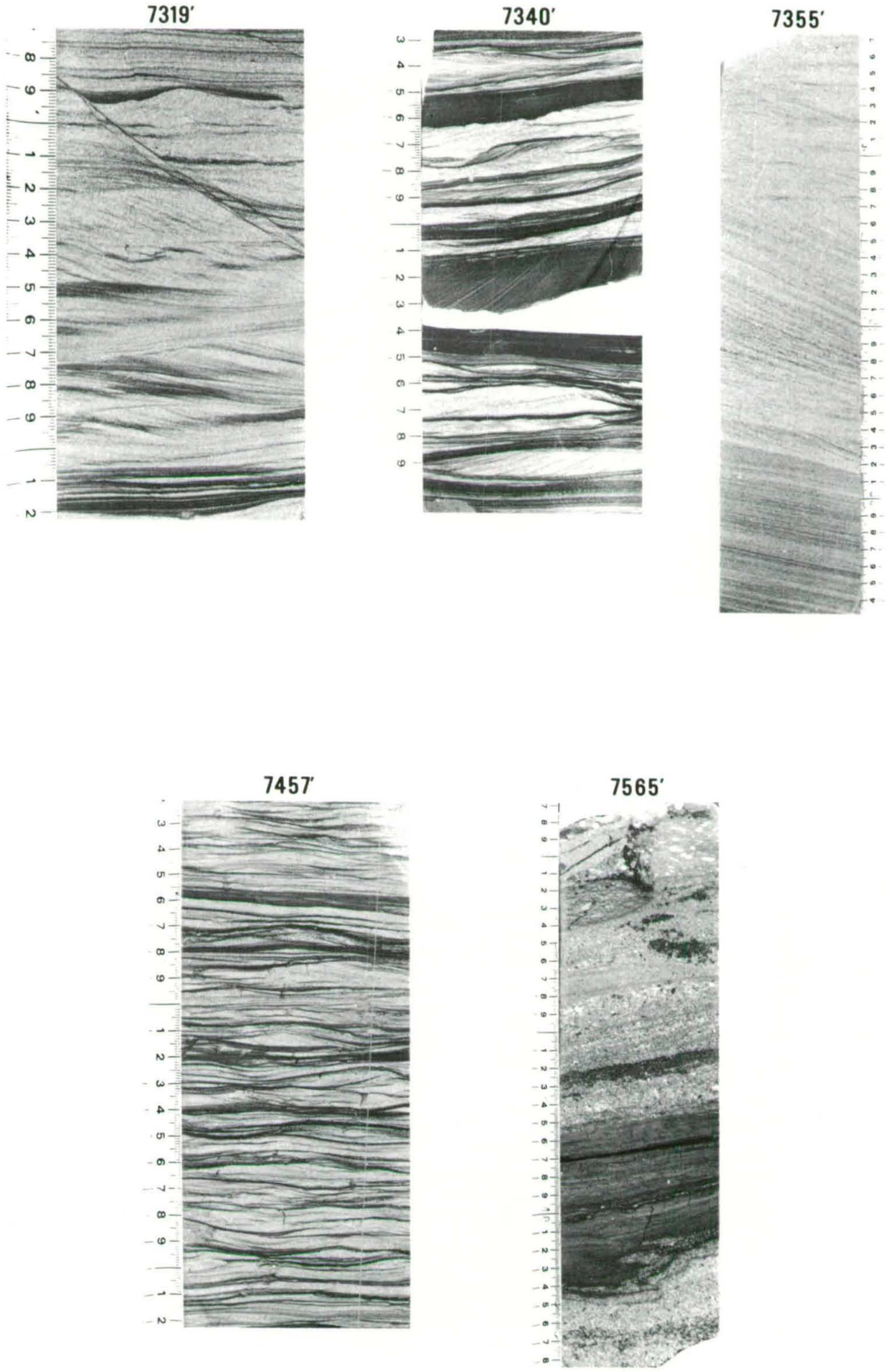


Plate 1. Gidgealpa 6: Core material from Cores 3-8 *(see p.30)*.

Two-thirds of the sands overlie coals or coaly shales, with, in some instances, intervening very thin conglomerate bands. Broken coal or shale fragments are commonly incorporated within the basal sands, while elsewhere in the unit thin coal laminae and shale bands occur delineating bedding planes. Medium-scale cross stratification (Conybeare and Crook, 1968) is common, with cosets 100-200 mm thick (Plate 1, 7355'). Foresets are planar to concave upwards, the latter sometimes being truncated on top.

The shales are dark grey to black, micaceous and highly carbonaceous. Thickness varies from generally less than 1 m to 3 m. Slickensides are common. Gradational contacts occur both above and below coals. Most coals are less than 3 m thick.

The interbedded units are generally less than 3 m thick and range up to a maximum of 4·5 m. Within them, fine to very fine-grained sandstone and shale laminae vary in thickness up to about 50 mm, but most are in the range of 2-5 mm (Plate 1, 7319', 7340', 7457'). Bedding forms range from flaser through to lenticular (Reineck and Sing, 1975, p. 98). Some sandstone beds grade upwards into shales, others have sharp contacts. Interbedded units contain all proportions of sandstone and shale from 100 per cent sandstone to 100 per cent shale. In many of these units the lithologic proportions change with depth. When this happens, both the abundance and lamina thickness decrease together. The proportion of sandstone has been observed to increase upwards in twice as many interbedded units as it decreases.

The internal structures of the sandstone and siltstone laminae and beds are well preserved. Bedding is delineated by very thin clay layers and small-scale planar and trough bedding are common. Current ripples are abundant, while climbing ripples although difficult to see, do occur, some with stoss side eroded (type A of Jopling and Walker, 1968). Within some shales there are starved ripples. Erosional surfaces between laminae are regular features, and the infilling material of small scours varies from sand to shale. In some cases, shale overlies an eroded sandstone surface. Mudcracks have been observed on one shale surface.

The beds have been disturbed in a number of ways and features such as flame structures at the boundaries between sands and shales, deformed sand lenses, convolute bedding, rolled up laminae, roots and burrows do occur. Finally, some features commonly observed, especially in Core 3, are interpreted to be pillar structures (Lowe and LoPiccolo, 1974; Lowe, 1975).

The pillars, consisting of sandstone, are streamlined, vertical to very high angled, about 5 mm in cross-section, and vary in length from 10-250 mm (Plate 2, 7329; 7364'). They occur in both massive sandstones, and interbedded sands and shales. Within sandstones, the pillars are visible because the sands within them are unlaminated (Plate 2, 7329'). In some cases they have a 'skin' of clay or clay-rich sand. Within interbedded units, the pillars have disrupted the shale bands and deflected them upwards. Dish structures were not observed, and therefore the pillars are type B of Lowe (1975). Lowe and LoPiccolo (1974) consider that pillars are formed by upward flow of water as it escapes from rapidly deposited sands.

Roots and burrows were observed only very infrequently and the undisturbed nature of the laminae shows that bioturbation was not an important process in the formation of these sediments. This could be due either to a lack of burrowing organisms, or else be the result of rapid burial (Reineck, 1972). Observed roots (Plate 2, 7352') are less than 1 mm in diameter, up to 40 mm long, and exhibit a branching pattern. The burrow mottled interval (Plate 2, 7423') contains 1 mm diameter spots which are interpreted as being formed by a horizontally burrowing organism.

In summary, the internal structures of the interbedded sandstone and shale laminae have been identified as small-scale cross-bedding, ripples, erosional surfaces, deformation structures, roots, burrows, and pillars. As well as these features, there are structures of unknown origin, such as the very small wisps and craters disrupting the ripple bedding (Plate 1, 7457') which may be due to either fluid escape or biologic activity.

Plate 1. Gidgealpa 6: Core material from Cores 3-8.
Patchawarra Formation: bedding features.
7319' Flaser bedding in fine-grained sandstone.
7340' Wavy bedding between fine-grained sandstone and shale laminae.
7355' Planar cross stratification in medium-grained sandstone.
7457' Wavy and flaser bedding between very fine-grained sandstone and shale laminae.
7565' Volcanic pebbles in coarse-grained sandstone.

Plate 2. Gidgealpa 6: Core material from Cores 3-5.
Patchawarra Formation: deformation features.
7329' Pillars transecting interlaminated sandstone and shale.
7352' Roots in very fine-grained sandstone.
7364' Pillars transecting interlaminated sandstone and shale.
7393' Microfaults in interlaminated fine-grained sandstone and shale.
7423' Burrow mottling in shale.

Plate 3. Gidgealpa 6: Core material from Cores 1-2.
Toolachee Formation.
7127' Sandstone pebble in coarse-grained sandstone.
7133' Quartzite pebbles and coal fragments in coarse-grained sandstone.
7141' Wavy bedding with oscillation ripples between fine-grained sandstone and shale.
7161' Flaser bedding in fine-grained sandstone.
7168' Cross stratification in coarse-grained sandstone etched out by shale partings.

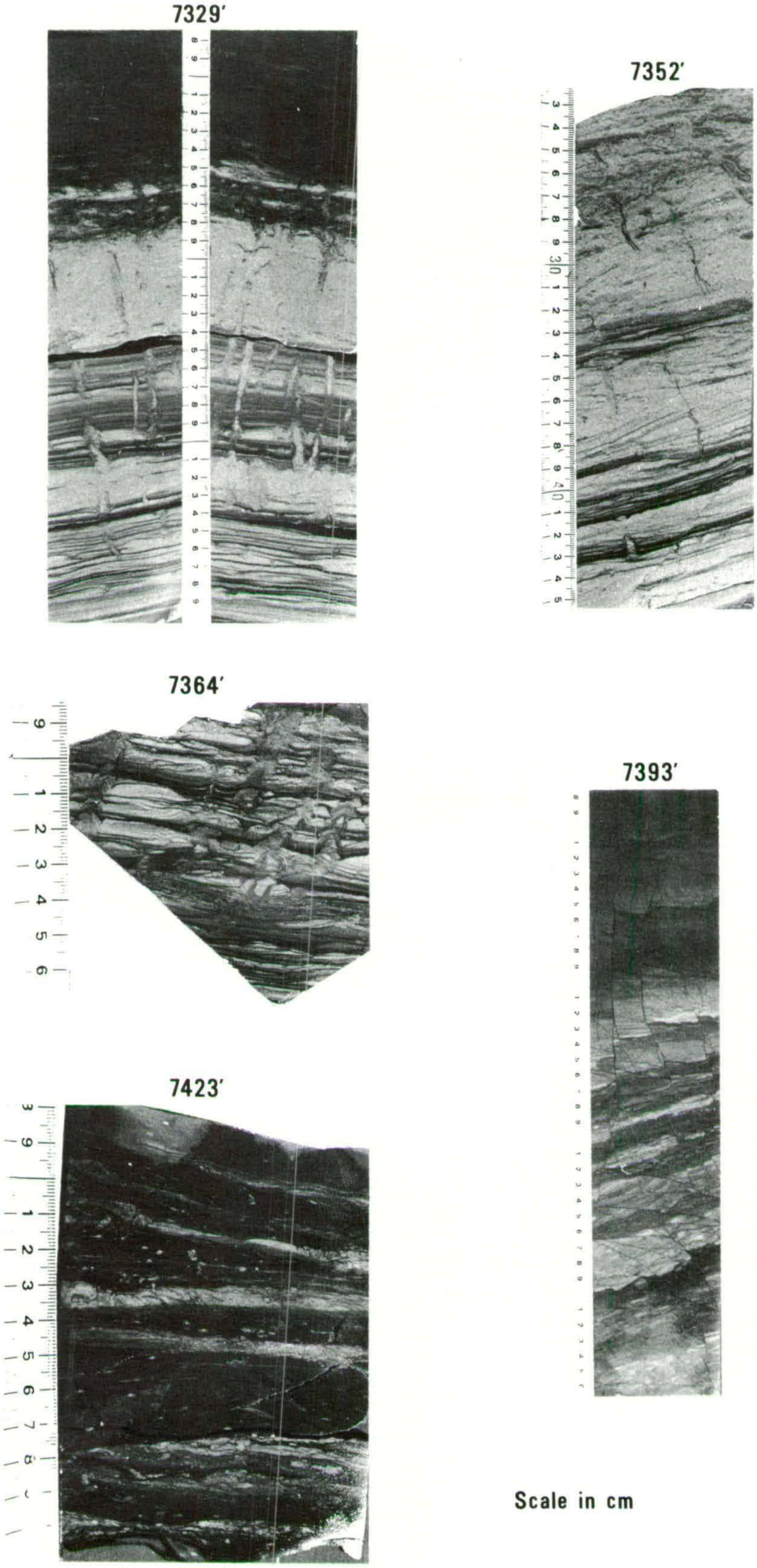


Plate 2. Gidgealpa 6: Core material from Cores 3-5 *(see p. 30).*

Microfaults occur throughout the section, as either high or low-angle, normal or reverse faults (Plate 2, 7393'). The vertical microfaults are probably the result of late structural deformation, while some of the low-angle faults appear to be associated with slump structures, and are therefore presumably syndepositional features. McKee, *et al.* (1962), produced experimental evidence to support the possibility of such syndepositional microfaulting. They found that in alternating layers of saturated mud and sand, convolute bedding could be formed by differential loading of the unconsolidated sediment, and that intraformational thrust structures were created by horizontal flowage as a result of progressive loading in one direction.

Cores 1-2

The Toolachee Formation lithology comprises sandstones, interbedded sandstones and shales, and coals. The sandstones are mature, containing 85-90 per cent clear quartz, and have undergone considerable compaction with resultant deformation and authigenic recrystallisation of quartz. Argillaceous lithic fragments constitute about 5 per cent and have been deformed and altered to illite. Detrital mica is a common accessory, together with traces of opaques, rutile, tourmaline, zircon, staurolite, and garnet. Regularly included in grey sandstones are wisps and fragments of coal.

Grain size of the sandstone ranges from conglomeratic to fine-grained. Pebbles and cobbles which range from angular to well rounded (Plate 3, 7127', 7133'), consist of quartzite, fine-grained sandstone, shale, and perhaps igneous material. Upwards graded bedding is normal. High-angle, apparently planar cross-bedding is visible because sets are etched out by fine clay partings or thin coal laminae (Plate 3, 7168'). In some cases, each 10 mm set exhibits upward graded bedding.

Where sandstones are interlaminated with shales and siltstones, they tend to be very fine to fine grained and consist of thin beds up to 100 mm. Flaser, lenticular, and wavy bedding (Reineck and Singh, 1975, p. 98) occur, with ripples (some of them oscillation ripples) and trough bedding (Plate 3, 7141', 7161').

Shales are dark grey and micaceous, and vary from fine discontinuous laminae interbedded with sands to beds of almost 100 per cent fissile shale. The shales are very carbonaceous, containing abundant carbonised plant fragments along partings, and in places grades upwards into coal. Lenses and laminae, 1-2 mm thick, of silt occur within the shales and exhibit micro-crossbedding. The dominant clay is kaolinite (Steveson, 1972).

Coal, black and bituminous, varies from dull to shiny, and normally has a blocky fracture. Especially within the coals, but also in some of the shales, are lenses and bands of hard, smooth, brown siderite. The carbonate has replaced much of the original rock, forming radial arrays of acicular crystals, normally with a diameter of 0·4 mm (Steveson, 1972).

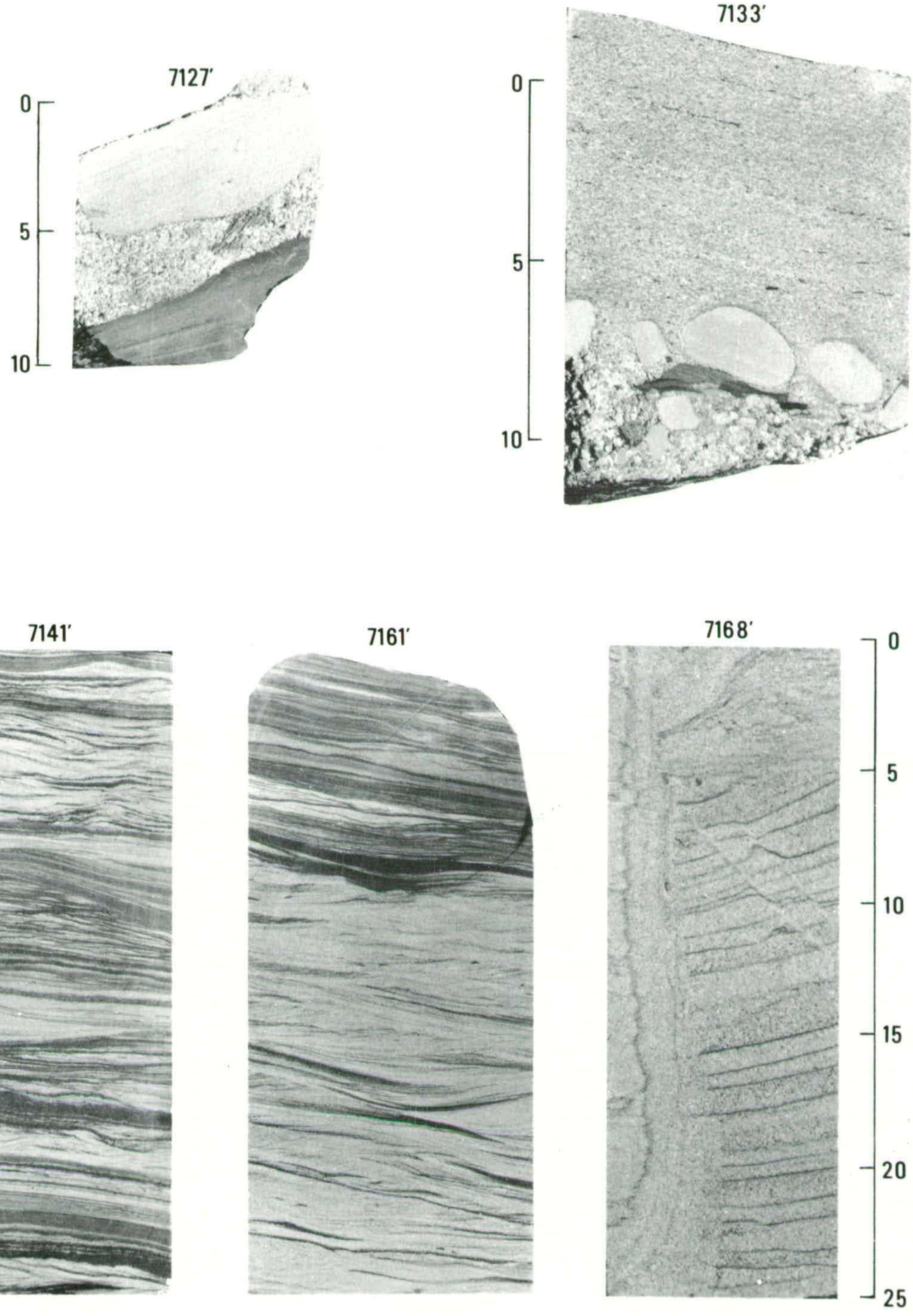
ENVIRONMENTAL INTERPRETATION

Interpretation of depositional environments on the basis of core from one well is difficult, and in many cases cannot be definitive, largely because only one dimension of the section is being observed. However, some vertical successions are diagnostic of particular environments. Thus, fining upwards sequences generally indicate floodplain deposition. On the other hand, coarsening upwards sequences can be deposited in fluvial, interdistributary bay, shoreline, and offshore environments. In addition, few sedimentary structures are unique to a particular environment. Nonetheless, tentative interpretations can be made from a combination of all the information.

In the last few years, many environmental studies, such as Visher (1965) have concentrated on the vertical ordering of successions. However, the early optimism embodied by the belief of Masters (1967), that 'depositional environments can be recognised by the analysis of vertical sequences of stratification types', has been replaced by the more reasonable approach of Visher, *et al.* (1971). These latter authors maintain that the primary basis of environmental reconstruction is the vertical sequence of depositional units, and that this should be used in conjunction with studies of sand body geometry, palaeocurrents, sedimentary structures, mineralogy, textures and petrography.

Direct application of Walther's Law (Middleton, 1973) on a 'complete section' without any breaks in the record can lead to the recognition of some environments. The best example of this is probably the relationship of the fining upwards sequence to modern alluvial floodplains (Allen, 1964). However, it is precisely the difficulty of determining the 'complete section' that has led to the cyclicity study in this bulletin.

Fining upwards sequences are usually diagnostic of fluvial deposition, and such sequences occurring in most of the Gidgealpa 6 cores are therefore interpreted as resulting from deposition in a floodplain environment. Each fining upwards cycle records the establishment of a channel system, its abandonment by the stream, and burial beneath a floodplain (Allen, 1965, 1970b). The upwards grading sequence from a basal scoured surface of conglomerate, medium-scale cross-bedded sandstone, ripple cross-bedded sandstone, alternating sandstone, siltstone and shale, to coal observed in Gidgealpa 6 cores compares very closely with



Scale in cm

Plate 3. Gidgealpa 6: Core material from Cores 1-2 *(see p. 30)*.

observations made on modern streams and floodplains, such as described by Harms and Fahnestock (1965). The chief morphologic elements that make up a floodplain are point bars, channel bars and alluvial islands, cut-off channels and channel fills, levees, crevasse splays, and floodbasins (Allen, 1965). These elements, and the deposits they form fall into two distinct groups. The conglomerate to ripple-bedded part of the sequence is laid down by lateral accretion in a channel as a result of the upwards decline in flow velocity. On the other hand, the interbedded sands, silts and clays are vertical accretion deposits laid down during repeated emergence and submergence during overbank flooding.

Features observed in Gidgealpa 6 cores, other than fining upwards sequences may also be combined to indicate a meandering river regime. For example, angular shale blocks in sandstone could not have been transported and the most likely interpretation is that they fell into the river due to bank erosion, and were buried almost immediately. Again, the presence of abundant coal fragments lying along the bedding planes of cross-bedded sandstones could be the result of rapid burial of river transported plant debris, on point bars.

The coarsening upwards sequences observed in Gidgealpa 6 cores cannot be interpreted with the same diagnostic precision as fining upwards sequences. Nevertheless, they may be compatible with the interpretation of a fluvial depositional regime. For example, Allen (1965a) showed that coarsening upwards sequences occur in the fluvial regime due to overbank sheet flooding from a river channel. Individual sheet floods deposit vertically graded units, which become thinner and finer further away from the channel into the adjacent floodplain. Thus, in natural levees, coarse beds increase in frequency upwards and become thicker upwards, because as levees develop vertically and laterally, 'distal' levee facies are progressively overlain by coarser 'proximal' levee facies (Elliott, 1976).

Although coarsening upwards sequences in some cases have a fluvial origin, they are more commonly associated with shorelines and shallow marine conditions, or interdistributary bays. Part of the Gidgealpa 6 section can be attributed to such environments. Gould (1970, fig. 13) shows pictorially sediments of the shallow water delta facies, which grade upwards from clay, through interlaminated sand and clay, to clean cross-bedded and laminated sands with thin layers of organic debris. The regressive marine model of Visher (1965) is very similar. Overlying the topmost well-sorted sand unit are either marine shales or lagoonal shales, silts and fine-grained sands. Le Blanc (1972) distinguishes delta front sands, barrier island sand bodies and chenier sands as deposits of the transitional environment with coarsening upwards sequences.

Elliott (1974) recognises eight predominant coarsening upwards sequence types related to different environments of interdistributary bays. These types fall into five categories, namely overbank flooding, crevasse splay, minor sand spit, minor mouth bar-crevasse channel, and bay mouth sequence. However, for reasons similar to those given above, Elliott (1974) emphasises that the presence or absence of gradational coarsening upwards sequences is not a reliable means of distinguishing between environments.

A similar problem applies to the interpretation of environments from the sedimentary structures observed, because few sedimentary structures are unique to a particular environment (Conybeare and Crook, 1968). The hydrodynamic conditions required for their formation can occur in different environments. Thus, taken singly, structures such as ripples, slumps and pillars observed in the cores are not environmentally diagnostic.

Flaser, lenticular and other types of bedding observed in the cores are also not unique to any single depositional environment. Flaser bedding, for example, occurs on tidal flats (Reineck and Singh, 1973) and as vertical accretion deposits in the alluvial environment (Potter, 1967). Another example is thinly interlaminated, very fine-grained sand and shale, which Allen (1970a) shows can occur both at the foot of a delta front platform and as a levee deposit on the floodplain.

The sediments have undergone considerable soft sediment deformation, microfaulting, and compaction. As a result, some environmentally significant structures will have been obliterated. For example, even minor deformation could make both current and oscillation ripples look the same.

The small size of sample provided by a core can cause problems in interpretation, particularly with medium and large-scale cross-bedding. A vertical core cut through large sinusoidal foreset beds will look like planar foreset bedding. Planar foreset bedding is common in braided, but rare in meandering streams (Smith, 1970; Cant and Walker, 1976), so there is a possibility of environmental misinterpretation.

DEPOSITIONAL ENVIRONMENTS

The depositional environments that have been interpreted for the Gidgealpa 6 cores are shown beside the core descriptions (Figs. 13-17). From the above discussion, it should be clear that much of the interpretation is tentative, because on the evidence available more than one interpretation is possible. More precise definition requires a three-dimensional study of the geometry of the lithologic units.

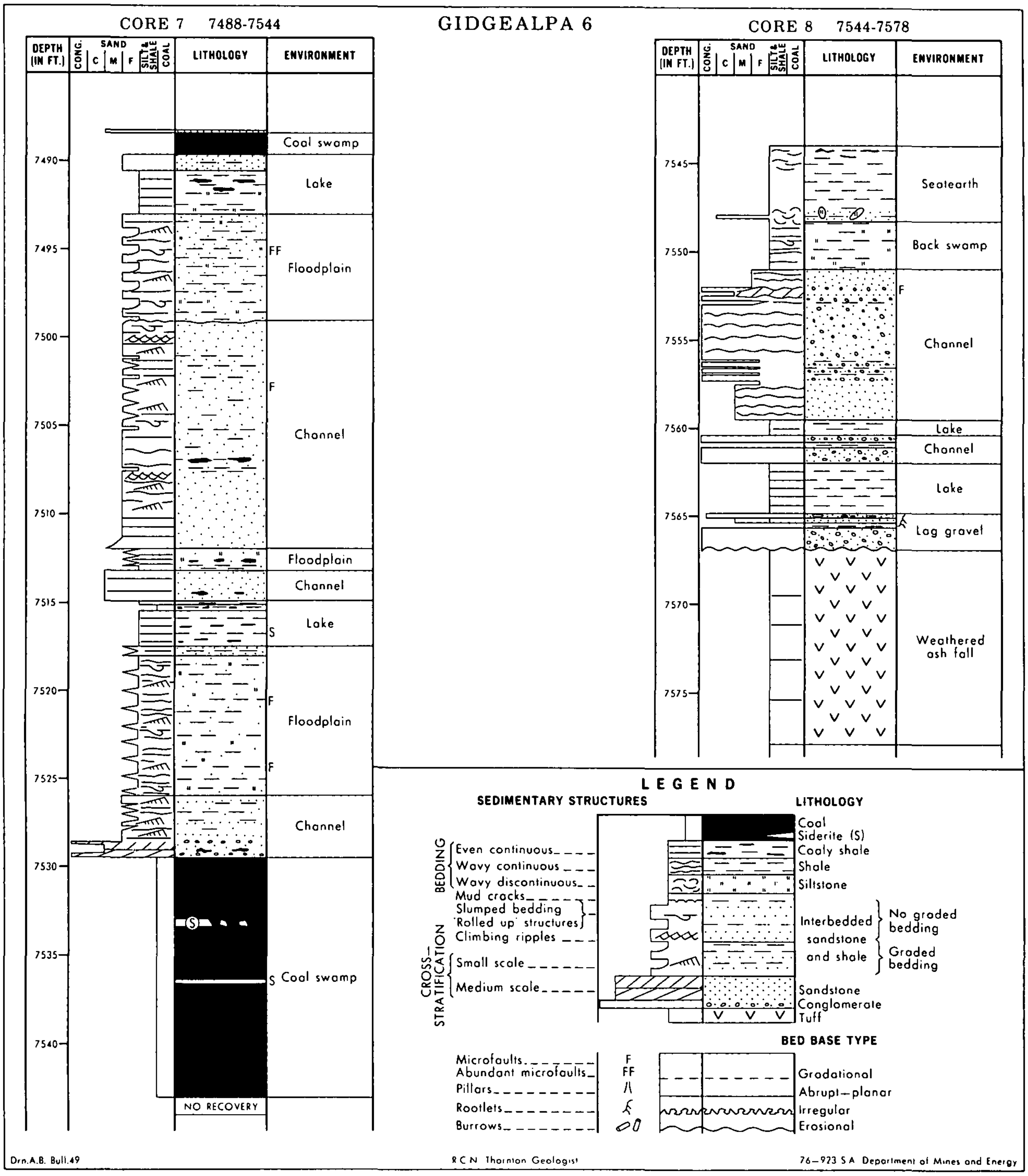


Fig. 13. Gidgealpa 6, Cores 7 and 8. Lithology and depositional environment

Core 8

The conglomerates are thought to be either talus or river deposits. The lowermost ones are probably talus, and originated, at least in part, from lag gravel derived by erosion of the underlying tuffs. A long period of subaerial erosion is indicated by the extremely weathered nature of the volcanic clasts. Following basal Permian deposition, the weathering products, both from the volcanic pebbles as well as the host rock, have percolated through the sediments, staining them green. In contrast the uppermost conglomerates are thought to be the result of river deposition as the preponderance of very coarse clastics indicates high flow gradients in a juvenile landscape.

The siltstone at the top of the core (Fig. 13) is probably a seatearth. It contains broken up coal bands in its upper part, and underlies a 4·6 m thick coal. Its average grain size is 0·01 mm, with a maximum of 0·02 mm, and it is composed of at least 70 per cent quartz. Rootlet horizons have

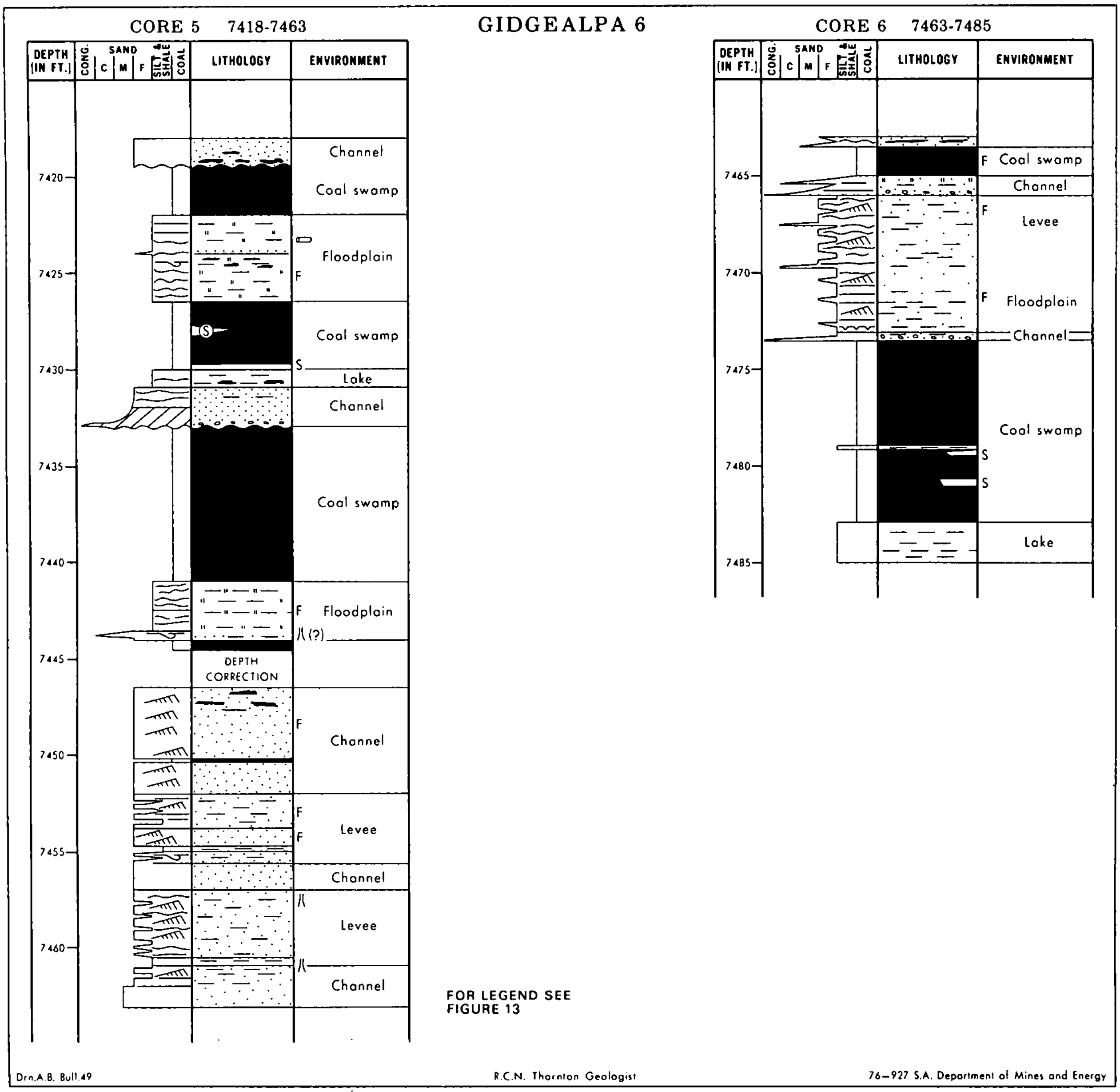


Fig. 14. Gidgealpa 6, Cores 5 and 6. Lithology and depositional environment

not been observed, but the presence of coal fragments and the very high quartz percentage for a rock of this grain size, suggests that it was formed by leaching during coal formation (Murchison and Westall, 1968, p. 120).

Cores 3-7

Deposition took place on an alluvial floodplain, although no major river sand deposit is preserved. The environment did not remain exactly the same during the period represented by these cores, as with time the depositional site on the floodplain became situated increasingly closer to a shoreline. Some of the sediments in Core 3 were deposited offshore, or at least in interdistributary bays. This is shown by major changes in the proportions of rock types up the core, the most obvious being the upwards decrease in amounts of coal, and the increase in amount of interbedded units.

The section in *Core 7* records the change from a long lived coal swamp, to river channel deposition, interspersed with periods when floodplain conditions prevailed. The sandstones are predominantly fine grained, and, apart from in the basal sands, medium cross-stratification was not observed. The presence of type A climbing ripples implies that fall out from suspension was not rapid enough to bury the grains moving on the bed, and therefore not rapid enough to preserve stoss side lamination (Jopling and Walker, 1968). The sands were not deposited as the result of lateral migration of a meandering river, instead, the main depositional process was vertical accretion on a floodplain, with minor in-channel sand deposition. Perhaps,

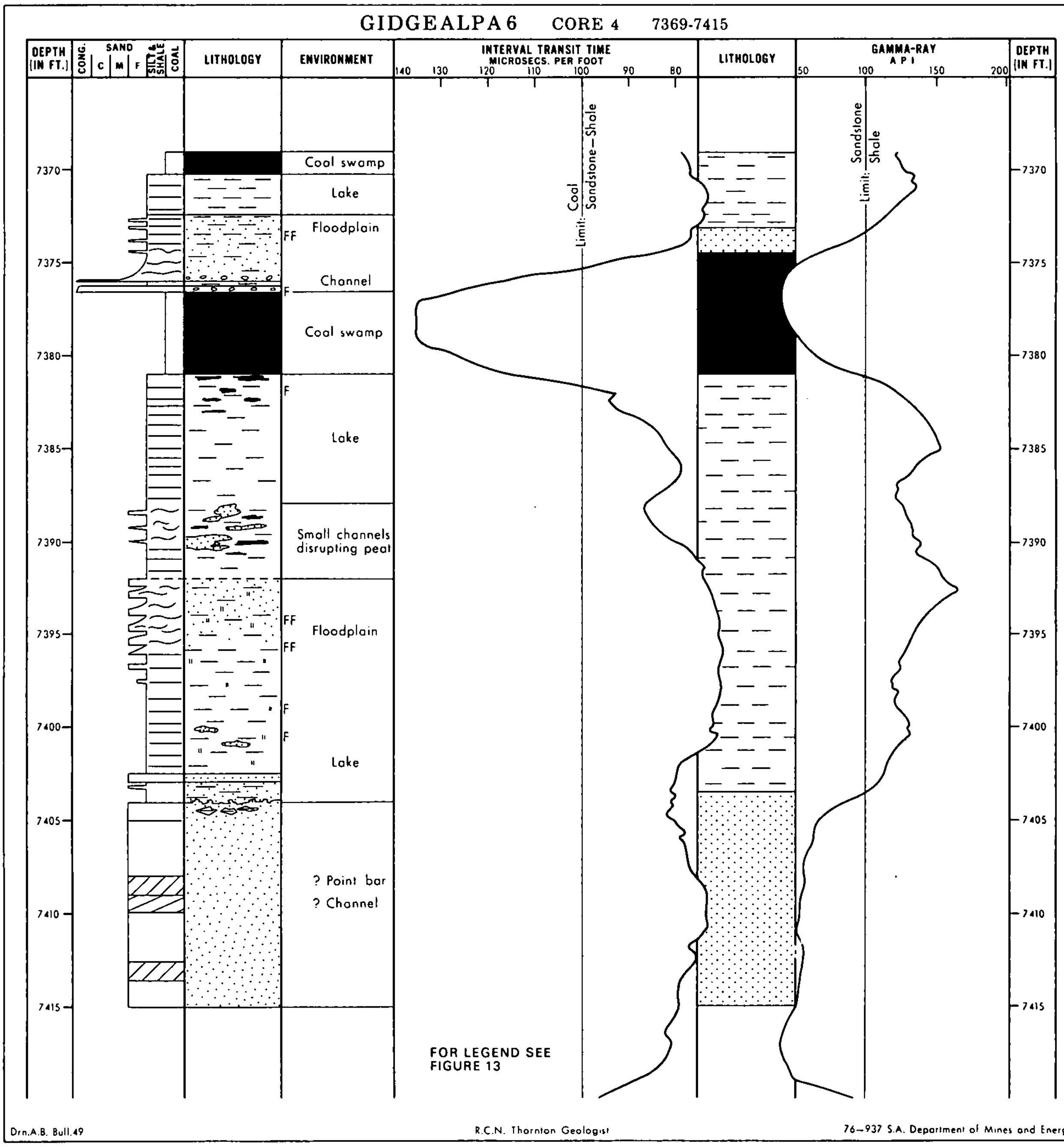


Fig. 15. Gidgealpa 6, Core 4. Lithology, depositional environment and wireline log derived lithology

the sands were deposited in small channel bars, or dunes and ripples, which migrated downstream.

Core 6 reflects coal swamp deposition, interrupted by a period of floodplain, levee and minor channel development. Much the same conditions applied with the *Core 5* section (Fig. 14).

In *Core 4* (Fig. 15), sands at the base give way to thick lake and floodplain deposits, which in turn are overlain by a second fluvial fining upwards cycle. The blocky gamma-ray log pattern recorded against the lower sands reflects the very homogeneous nature of the sediments. It is very similar in shape to the log pattern for channel-fill deposits shown by Allen (1975, p. 382), and corresponds to the type B sands of Porter and Crocker (1972).

At one stage of the lake's history, a river approached close enough to inundate it with overbank sands and silts during flooding. Abundant plant material was carried into the lake, which eventually dried up enough for trees to develop and form a coal swamp.

Core 3 contains a column of sediments, which individually look virtually no different from some of the underlying rocks. However, when all the parameters, such as the proportions of the different rock types, the vertical sequences, and the internal structures are combined, a different

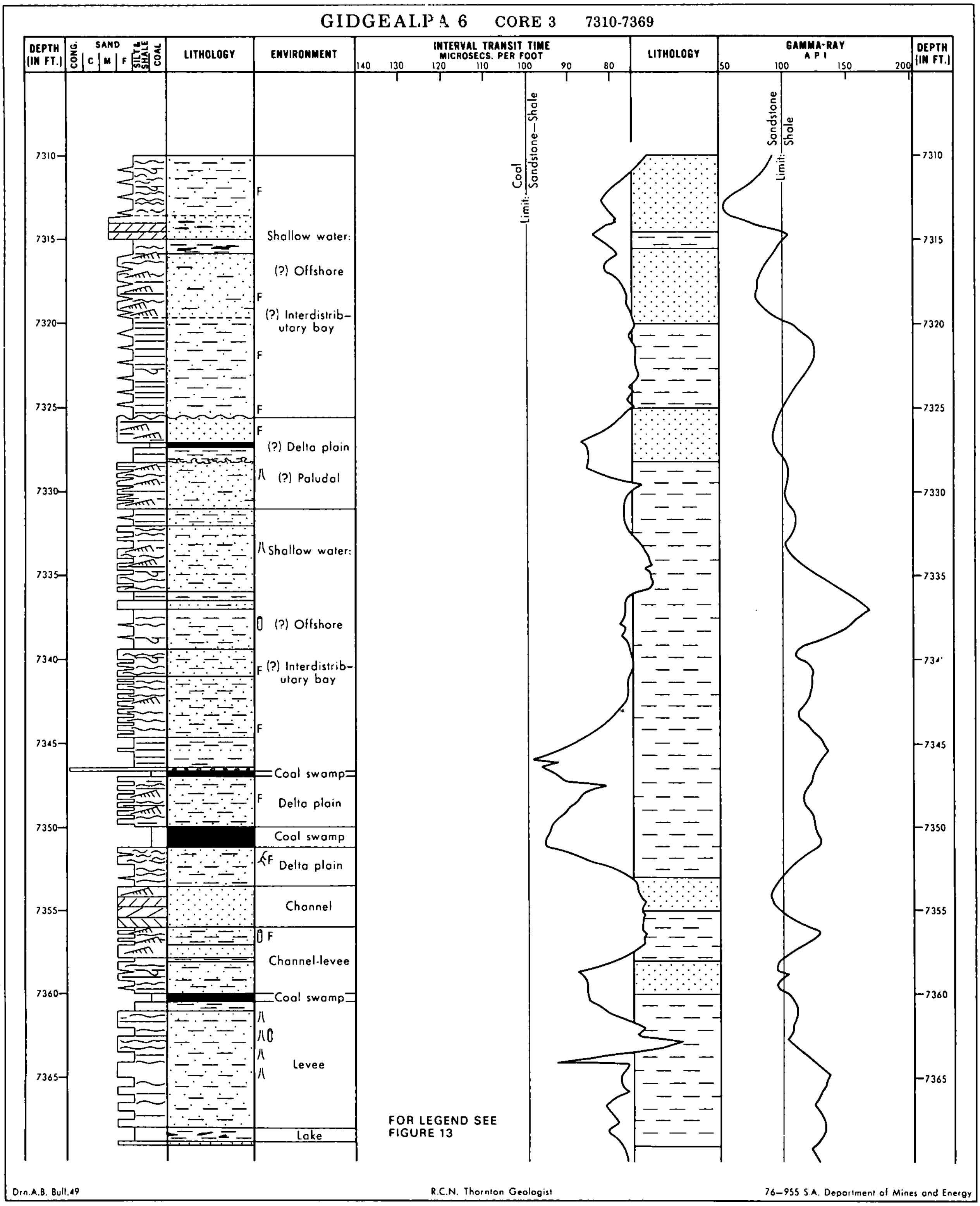


Fig. 16. Gidgealpa 6, Core 3. Lithology, depositional environment and wireline log derived lithology

picture emerges. It appears that the sediments of at least the upper part of Core 3 are more likely to have been deposited in a shallow water, offshore or interdistributary bay environment rather than under fluvial conditions.

A summary of diagnostic bedding features in Core 3 are as follows: coals are very thin, and virtually all the rest of the core comprises finely interbedded sandstones, siltstones, and shales; most of the interbedded units exhibit upwards increases in the amount of coarse clastics; there is no coarse-grained sand, and only one pebble band; the rocks are abundantly microfaulted, contain more pillar structures than elsewhere, are burrowed, and exhibit flame structures, along with numerous roll-overs and slumped

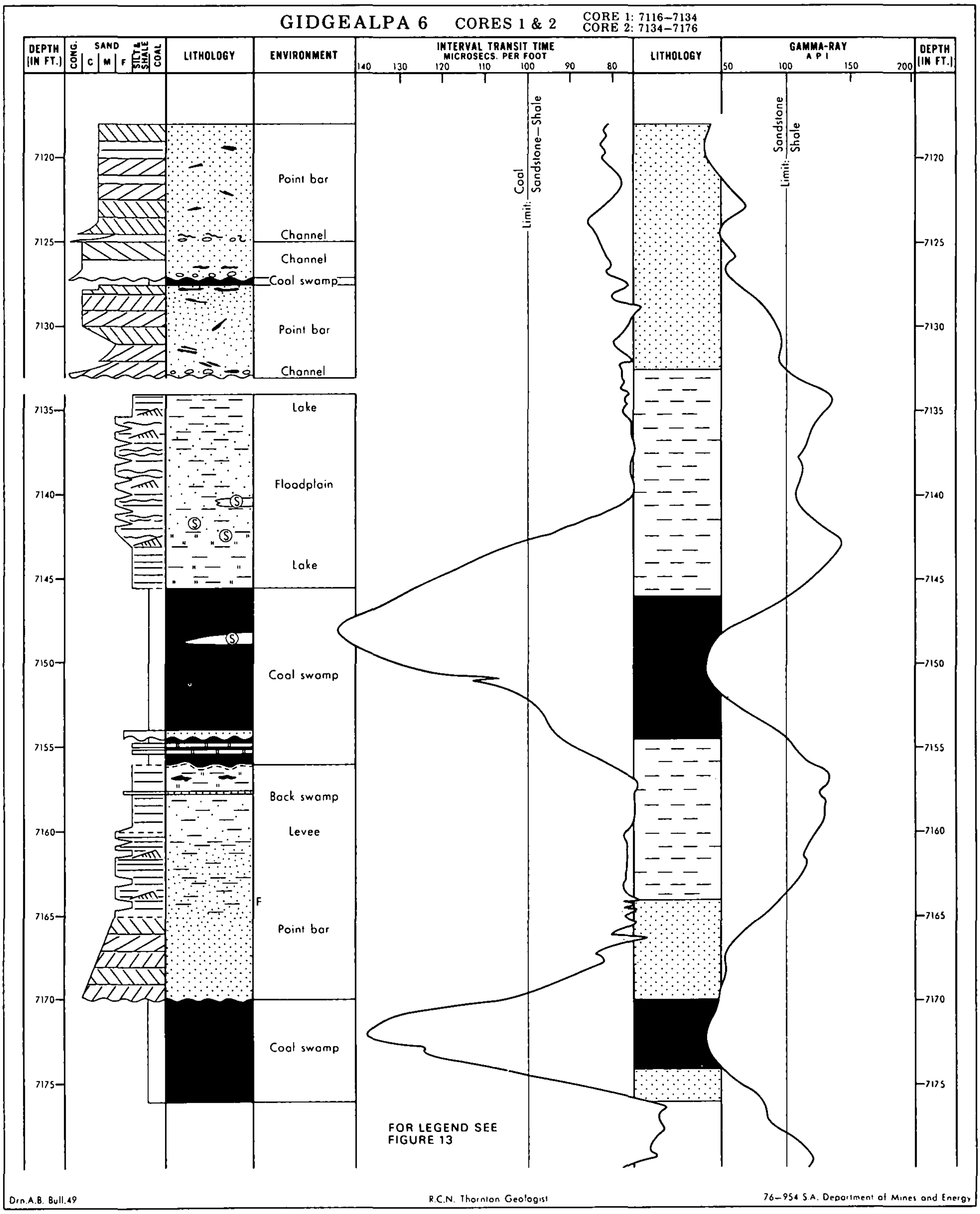


Fig. 17. Gidgealpa 6, Cores 1 and 2. Lithology, depositional environment and wireline log derived lithology

bedding. These features are all very common in deltaic to regressive marine deposits (Coleman and Gagliano, 1965; Allen, 1965b; Moore and Scrutton, 1957).

The pillar structures developed during compaction as a result of the explosive escape of water (Lowe and Lopiccolo, 1974). Lowe (1975) considers that the most favourable conditions for the development of water escape structures are episodic rapid deposition of fine to medium-grained sand, interbedded sand and shale, and overall high sedimentation rates. These conditions occur together both in shallow water prodelta environments and point bar, levee, and proximal overbank sands in the fluvial system. However, Lowe (1975) states that prodelta sediments exhibit pillar structures more frequently than fluvial sequences, because the latter tend to be coarser grained and show less regular alternation of sand and shale units.

Cores 1-2

Compared with the underlying rocks, the sandstones are much coarser and more abundant, and medium-scale cross-lamination is common. Deposition can be explained satisfactorily by lateral accretion of point bars, followed by vertical accretion on the floodplain and in coal swamps.

The fining upwards sequence from 7 170-7 150 ft (Fig. 17) is analogous in all respects to sections observed from modern alluvial floodplains (e.g. Allen, 1964).

In the section from 7 135-7 124 ft, at least three fluvial cycles occur, grading upwards from conglomerate to sandstone. Each cycle is interpreted mainly as being a fluvial channel to point-bar deposit, which has been truncated by the sudden transgression of another stream channel.

The two types of coal occurrence within the sandstones, namely thin bands and angular blocks, result from different processes. The wisps and fine laminae are the result of branches and other organic detritus being buried within channel and point-bar sands. The larger coal fragments occur within conglomerates and are the result of peat being ripped up by the river and dumped at the base of the channel as lag.

The formation of siderite in the sediments would seem to indicate undisturbed, static pond water conditions for considerable lengths of time. It is an early diagenetic mineral, formed a few centimetres beneath the sediment/water interface and requires a strongly reducing environment for its formation (Curtis, 1967). The fact that many of the shales are highly carbonaceous supports an interpretation of anaerobic depositional conditions. Also, siderite usually forms only in a non-marine environment, while at high salinities pyrite is formed instead (Curtis, 1967; Ferm, *et al.*, 1975).

COMPARISON BETWEEN CORES AND WIRELINE LOGS

The quantitative data used to prepare the lithofacies maps in this study have all been obtained from wireline logs. In this section, comparison is made between the lithologic interpretations of the cores, and logs from Gidgealpa 6, in order to assess the likely accuracy of log interpretation.

As would be expected, comparison shows that cores provide much more detail than the wireline logs. The logs satisfactorily identify single lithologic units greater than 0·6 m thick, but a much less precise definition is obtained for units which are finely interlaminated. However, it appears from the comparison in Gidgealpa 6, that such errors in interpretation of logs average out to the extent that lithologic percentages derived from cores and logs are very similar. Generally, any bias in interpreting the logs will diminish sandstone percentage, because interbedded units are interpreted as shales.

These relationships between core and log interpretations are illustrated with Cores 1-4 (Figs. 15-17). The gamma-ray and sonic logs, together with the lithologs interpreted from them, have been redrawn at the same vertical scale as the core descriptions and placed beside them. As discussed in the section on methods, coals have been identified where interval transit time exceeds 100 microsecs/ft, and sands where the gamma-ray count is less than 100 API units. These two limits are drawn on the log.

The gamma-ray and sonic logs do not record very thin lithologic units, due both to the speed at which the logs are run, and, in the case of the sonic log, the distance between the transmitters and receiver. The sonic log run on Gidgealpa 6 had a 0·9 m detector spacing, which means that it will not define accurately beds less than 0·9 m thick. The amount of gamma radiation reaching the detector fluctuates, and has to be averaged statistically (Schlumberger, 1972). Thus, for thin beds, the accurate API reading, either low or high, will not be obtained. Slowing the logging speed increases the accuracy of bed definition (Allen, 1975).

The result of these shortcomings is that some lithologic changes are missed. Coals need to be greater than 0·3 m thick, and sandstones greater than 0·6 m to be identified on the logs. In Cores 3 and 4, five coal beds, 0·3 m or less in thickness, were not recognised on the logs, although in most cases interval transit time did increase at the coal intervals.

Where units comprise a single lithology, and exceed 0·6 m in thickness, excellent correlation occurs. In Core 1, for example, bed boundaries have been picked on the logs at depths virtually identical with those in the core. However, in the deeper cores, especially Core 3, the dominant lithology is one of finely interlaminated sandstones, siltstones and shales in varying proportions. Across the interbedded intervals, the gamma radiation hovers around the arbitrary 100 API sandstone-shale critical value. Thus a very minor fluctuation in log scale is recorded as a significant lithologic change, while in fact the rock contains only a slightly greater or smaller percentage of shale laminae.

The sandstone percentage calculated from the logs will tend to reflect the amount of massive sandstone, and ignore the interlaminated sandstones. This is because the gramma-ray log essentially records the amount of potassium rich clay. Therefore fine-grained sandstones, which tend to be rich in potassium-bearing clays, have a higher API value than coarser grained, cleaner sands. Most of the sand laminae in interbedded successions are fine grained, and therefore the gamma-ray log across such interbedded intervals shows a bias towards shale.

The worst correlation between Gidgealpa 6 cores and logs occurred at the base of the Permian above the underlying highly weathered tuff. Conglomeratic sandstones were recorded on the gamma-ray log as shale, because of the presence of blocks and pebbles of volcanic debris, which have altered completely to clay.

The seatearth at the top of Core 8 records on the logs as coal, because of its lack of potassium-rich clay, together with its low density. This is good from the point of view of environmental interpretation, because a coal must have overlain the seatearth for the latter's formation.

Comparison of sandstone, shale and coal percentages between the core and log derived sections of Gidgealpa 6 shows some variation (Table 5). In the individual cores, the differences vary from insignificant to very large. Nonetheless, the average percentages for log and core derived data are very close (core: 42% sandstone, 37% shale, 21% coal; log: 36% sandstone, 44% shale, 21% coal).

Large variations in lithological percentage on some of the cores is due to a lack of absolute correlation between cores and wireline logs. Thus a unit, such as coal, at the base of one core may have been recorded on the log at a depth equivalent to the top of the underlying core.

Table 5 *Gidgealpa 6: comparison between core and wireline log derived lithologic percentages*

Core No.	Core			Wireline Log		
	Sandstone %	Shale %	Coal %	Sandstone %	Shale %	Coal %
1+2	50	22	28	39	40	21
3	49	48	3	27	73	0
4	36	53	11	28	58	14
5	40	26	34	38	29	33
6	20	31	49	23	27	50
7	39	33	28	63	12	25
8	54	46	0	24	62	14
Average	42	37	21	36	44	21
Sandstone/shale ratio		1·14			0·84	

The difference between the average percentages from cores and logs results in different sandstone/shale ratios (core: 1·14; log: 0·84). If this difference observed at Gidgealpa 6 is typical of all Cooper Basin wells, then the degree of error would be similar for all, and thus comparison of results valid. However, if this difference varies from well to well, then lithofacies maps which use a sandstone/shale ratio of 1 as a limiting parameter in the definition of facies, may not be as meaningful as one that emphasises the difference between end member lithologies and a central mixed zone.

Regional Facies Distribution and Palaeogeography

Gidgealpa Group deposits have been laid down in the Cooper Basin from rivers, lakes, coal swamps and large inland 'seas', during a period when the geomorphic relief and depositional gradient gradually declined with time. As a result, the earliest fluvial deposition was from braided streams, whereas subsequent periods experienced mainly meandering rivers in a floodplain environment. Floodplain deposition was terminated twice as a result of the transgression of large inland 'seas'. Deltaic successions built out into these 'seas' each time they retreated.

This depositional history of the Cooper Basin has been determined by studying the thickness and facies distributions of the palynologic Stages, and their component rock units. Isopach, lithofacies and palaeogeographic maps have provided most of the data but in addition, inferences have been drawn from petrological information, a study of cores from Gidgealpa 6, and the literature. The depositional history, and its attendant palaeogeography, fit acceptably into the regional Permian geologic history of central and northeastern Australia.

Wherever possible, two different types of lithofacies map have been used, triangle lithofacies (Krumbein and Sloss, 1963, p. 460) and 'D'-function (Pelto, 1954), in order to obtain the maximum stratigraphic interpretation. Palaeogeographic maps were drawn using the lithofacies maps as guides.

The rationale behind this approach, as stated by Weller (1960, p. 524), is that 'Comparison of a set of time-equivalent facies throughout a region provides the basis for the interpretation of static palaegeographic relations. The recognition of changes in lateral facies relations throughout time is necessary for the reconstruction of geologic history. This requires the consideration of facies with a three-dimensional framework and the comparison of successive sets of time equivalent facies.'

The term 'lithofacies' has caused considerable confusion in the literature, as exemplified by the two conflicting opinions of Weller (1958) and Teichert (1958). In this study it is used in the manner defined by Weller (1960, p. 521) as a rock body, which is 'a lateral subdivision of some stratigraphic unit that is differentiated from adjacent subdivisions by its lithologic character'.

TIRRAWARRA SANDSTONE

The Tirrawarra Sandstone has been proved in the western and northern half of the Cooper Basin (Fig. 18). Its distribution in relation to present-day structural features suggests that the structural grain of the Cooper Basin has been imposed since the time of Tirrawarra deposition. Its relationship to the Stage 2/Stage 3 palynologic boundary shows it to be diachronous, becoming younger from west to east (cross-section B-B, Fig. 7). The Tirrawarra Sandstone is a relatively clean, quartz sandstone, which is interpreted as having been deposited from a braided stream regime. It appears to dovetail well into a facies picture of a progression from the fluvio-glacial deposition of the Merrimelia Formation, through the Tirrawarra braided stream deposition, to a meandering stream deposition represented by the Patchawarra Formation.

Distribution of Sediments

Tirrawarra Sandstone occurs throughout the Patchawarra Trough and in parts of the Nappamerrie and Tennapera Troughs as far south as Cherri, and as far east as Innamincka (Fig. 18). The thickest accumulations are preserved in an almost linear, northerly trend of 'lows' with a maximum intersection of 156 m encountered in Murteree C-I. The formation remains now in two separate areas, but most probably its original extent was somewhat greater than today, with the two areas joined together to form one basin.

The distribution of the Tirrawarra Sandstone into two separate subcrop areas, and its thickness distribution in relation to present-day structure, suggests structural re-ordering within the basin after Tirrawarra deposition. Thick areas of Tirrawarra Sandstone occur on structurally high regions and the presence of (?)Late Carboniferous-Early Permian Merrimelia Formation, as well as Tirrawarra Sandstone, in wells drilled on the GMI anticlinal trend shows that it was not an anticlinal feature early in the development of the Cooper Basin. In fact, it may have been a zone of maximum sediment deposition, a supposition supported by the fact that all the Merrimelia wells contain thick sections of Merrimelia Formation (to a maximum of 363 m at Merrimelia 1), as do Lake Hope, Packsaddle and Innamincka 2 (Gidgealpa 3 and 5 contain rather thinner sections). In addition, the presence of Tirrawarra Sandstone in Murteree C-1 indicates that the development of the Murteree anticlinal trend postdates deposition of this unit.

The Big Lake area also contains thick Tirrawarra Sandstone, and therefore must also have been a depression. By contrast, no Moomba wells encountered Tirrawarra

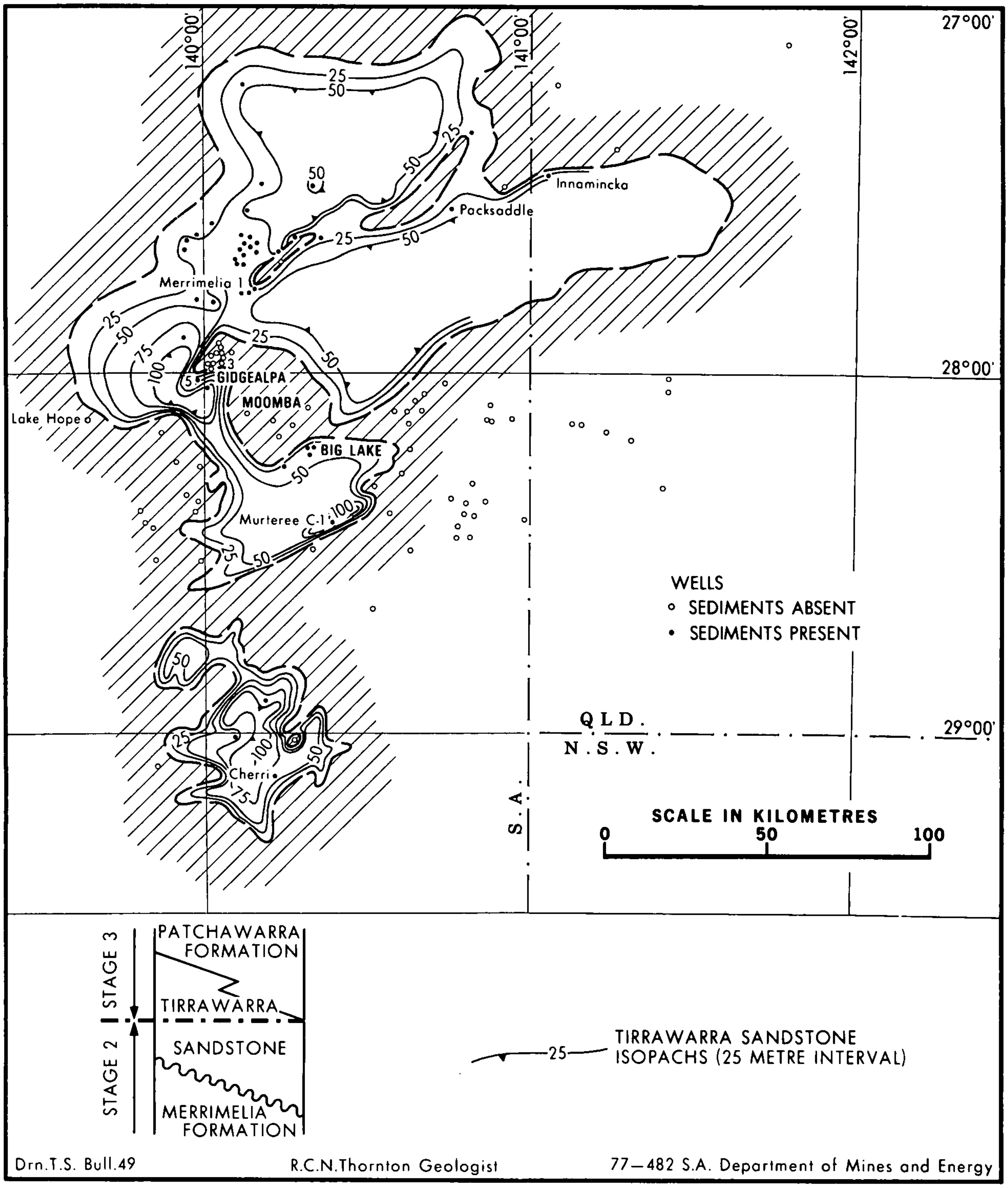


Fig. 18. Tirrawarra Sandstone isopach map

sediments and therefore this area must have had a relief too high for sedimentation. This high relief is shown by the very sharp thickness changes across the Moomba structure in the Stage 3' isopach map as a result of onlap (Fig. 21).

The structural interpretation of the Big Lake and Moomba areas is therefore opposite to the situation which exists today. Perhaps the Big Lake fault was active even then, with the downthrown side being the southeastern one.

Lithofacies

The rock boundary relationship with the palynologic Stage 2/Stage 3 boundary offers good evidence of the diachroneity of the unit. As discussed previously in the stratigraphy section, lithologic evidence does not support Price's (1973) suggestion of a time break during deposition of the Tirrawarra Sandstone. Instead, the results of this study indicate that the unit is diachronous upwards towards the east.

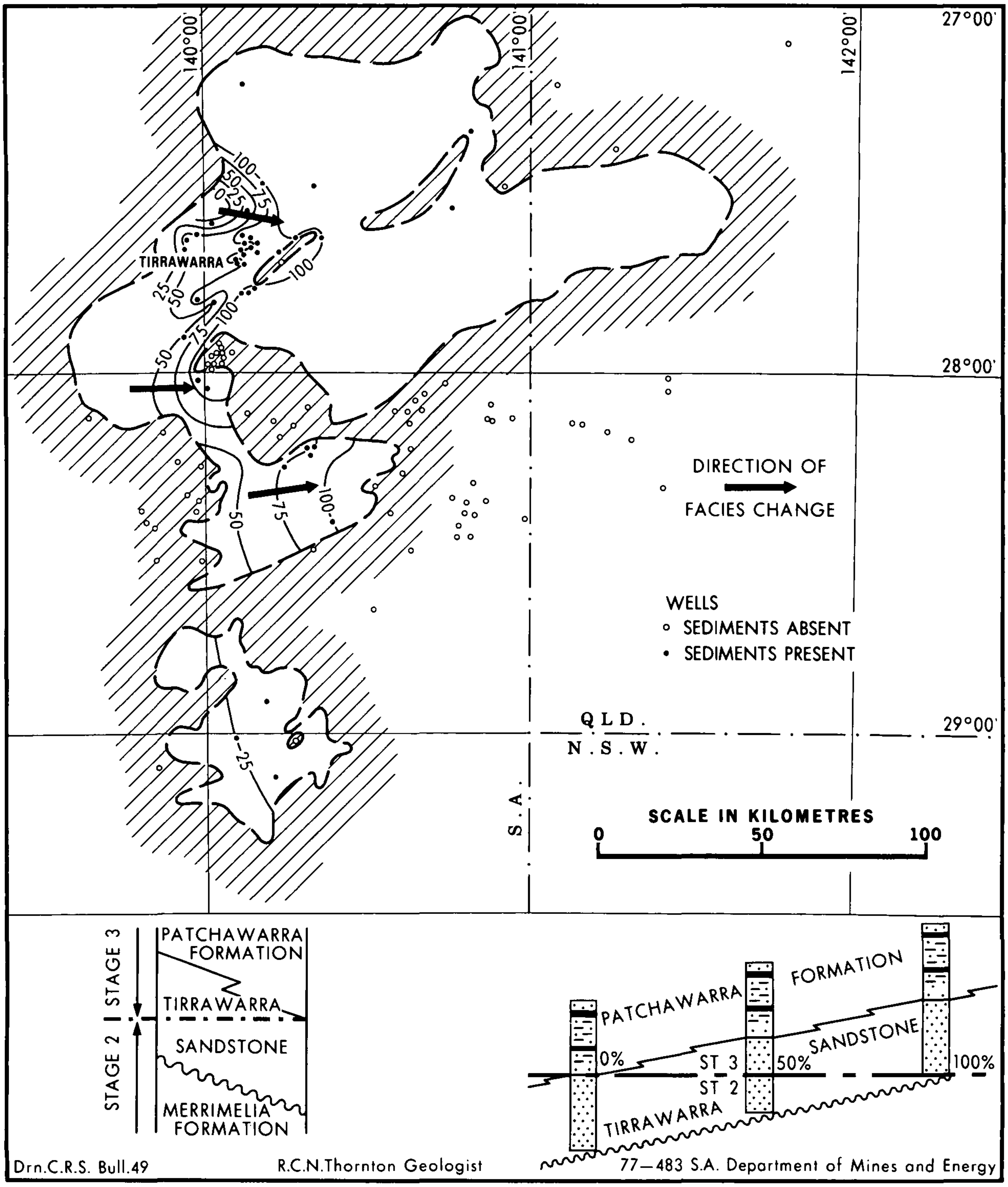


Fig. 19. Stage 2/Stage 3 facies change map

The upper part of the Tirrawarra Sandstone was deposited in the east synchronously with Patchawarra Formation in the west. This facies relationship is illustrated in Figure 19 by facies change isopleths, which are lines of equal percentage of Tirrawarra Sandstone to have been deposited during Stage 3 (see legend, Fig. 19). Where the total thickness of Tirrawarra Sandstone is Stage 2 age, its percentage after Stage 2 age is zero; where 50 per cent of the thickness of Tirrawarra Sandstone is Stage 2, and 50 per cent Stage 3 age, the isopleth value is 50 per cent; and so on. Thus the higher the isopleth value, the younger is the Tirrawarra Sandstone. The isopleth distribution on Figure 19 shows that the unit becomes younger towards the east.

The Tirrawarra Sandstone comprises almost entirely quartz sandstones, with only very minor intercalations of shale and coal, whereas the

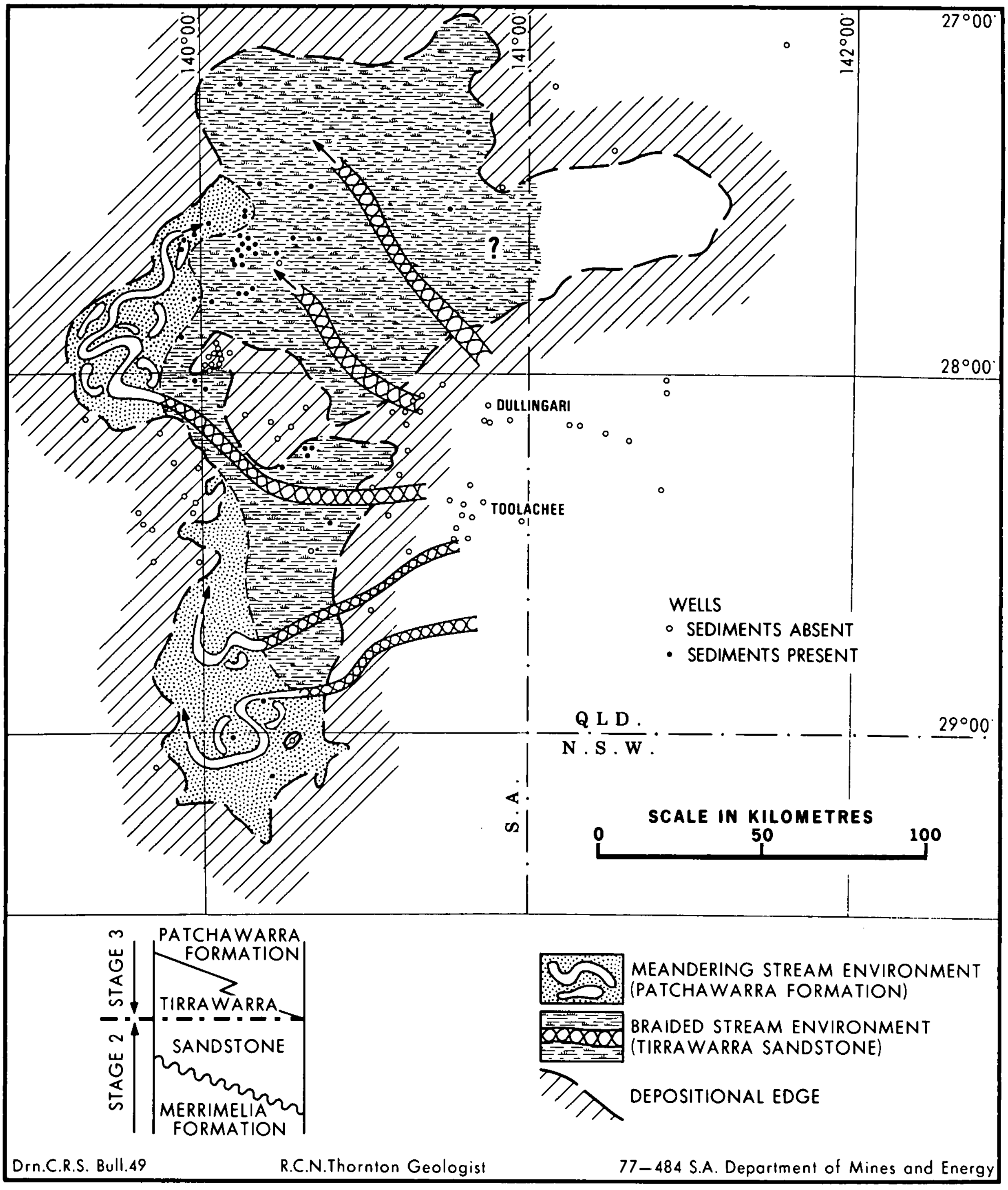


Fig. 20. Palaeogeography shortly after beginning of Stage 3

overlying Patchawarra Formation contains abundant shale and coal. The lithology of the Tirrawarra Sandstone is consistent with its interpretation as a braided stream deposit. Harms, *et al.* (1975), suggest that in braided streams, which are formed under a high-flow regime, in-channel deposits are laid down from laterally shifting medial bars between anastomosing channels. Such sediments are overlain by relatively thin, or absent, vertical accretion deposits. They point out that the braided stream is one end member of a gradational spectrum of fluvial environments, the other end member being the meandering stream, deposition from which is represented in the Cooper Basin by the Patchawarra Formation. In the meandering stream system, lateral accretion point-bar deposits are overlain by relatively thick vertical accretion deposits. For a given size of river (same discharge), braided channels develop in steeper slopes than meanders (Leopold, *et al.*, 1964, p. 292).

Gostin (1973) on the basis of lithologic interpretation from cores, considered the Tirrawarra Sandstone at Tirrawarra to be of fluvial origin, ranging upwards from channel conglomerates, to deposits from braided and then meandering streams. This upwards gradation is considered to reflect the facies change in the horizontal plane, which is shown on the facies change map (Fig. 19).

The braided stream hypothesis for the deposition of the Tirrawarra Sandstone, as stated earlier (p. 42), is consistent with the geomorphological evolution of the region. It must also be considered that as braided streams are often related to glacial conditions (Blatt, *et al.*, 1972), perhaps, therefore, the presence of Tirrawarra Sandstone indicates that glacial conditions in the provenance area persevered until early in Stage 3.

Palaeogeography and Geologic History

At the beginning of Tirrawarra deposition, the relief was greater, and the regional gradient steeper, than at any subsequent phase of Gidgealpa Group deposition. River transport occurred along braided streams, flowing from an uplifted region in the vicinity of Toolachee and Dullingari (Fig. 20). As the gradient diminished downslope from the intake area, rivers began to meander, with the consequent development of overbank deposits commencing along the western flank of the basin. Sediment intake is interpreted to have come from the eastern side of the basin because this is the area where the braided stream environment was replaced latest by a meandering stream one (Fig. 19).

STAGE 3′

The Stage 3′ unit (as defined below) is modified from the Stage 3 time-rock unit.

Stage 3 includes the upper part of the Tirrawarra Sandstone and the lower part of the Patchawarra Formation (Table 1). Therefore, in some wells where Patchawarra Formation is thin, Tirrawarra Sandstone has a disproportionately large effect on Stage 3 lithofacies ratios by greatly increasing the sandstone percentage. Consequently, the Tirrawarra Sandstone interferes in an areally non-uniform way with the sandstone-shale ratios in the Patchawarra Formation part of Stage 3. In fact it obscures lithofacies trends to an extent that a Stage 3 lithofacies map serves little purpose in the basin analysis. Therefore, a modified Stage 3 unit, here named Stage 3′ which eliminates the Tirrawarra Sandstone, has been mapped. Where Tirrawarra Sandstone is present, its upper boundary is taken as the lower boundary of the Stage 3′ interval.

The Gidgealpa 6 core examination indicates that during Stage 3′, deposition of sandstone, siltstones, shales and coal occurred within a non-marine, fluvial regime. The lithofacies and isopach patterns (Figs. 21-23) suggest that a major 'fairway' of channel sandstone predominance arose on the southern margin, bifurcated into a northerly and northeasterly trend, before being reunited in the Nappamerrie Trough through the central part of the basin (Fig. 24). The Patchawarra Trough was an area of mainly overbank and coal-swamp deposition.

Distribution of Sediments

Stage 3′ sediments extend virtually throughout the whole of the Cooper Basin, with the major exception of the southeastern flank (Fig. 21). On the basis of the isopach and lithofacies maps, the basin can be split into two major regions, separated by the GMI anticlinal trend. These are the southern area, and the Patchawarra Trough to the north.

South of the GMI anticlinal trend, the depositional surface had a very uneven topography as shown by the very close isopach spacing, especially around Moomba, by 'outcrop islands', and by onlap. The most obvious example of onlap is the southeastern region east of Burke. This area is devoid of rocks of Stage 3′, and Lower Stage 4 age, but does contain Upper Stage 4 sediments. The relationships shown in cross-section B-B (Fig. 7) suggest onlap rather than erosion on this flank, and around the 'islands'. Thus, the interpretation is that the area was outside the depositional basin during the first two Stages, and was inundated only in Upper Stage 4 time.

'Outcrop islands' occur along both the western and eastern flanks of the basin as demonstrated by the onlapping nature of the Patchawarra Formation. At Toolachee, at least four small 'islands' were not inundated during Stage 3′, and on the western flank, 'islands' existed at Pando, Wirrarie and Topwee.

Gidgealpa also may have been partly emergent, as onlap is indicated by the fact that Gidgealpa 2, 11 and 13 are devoid of Stage 3′ sediments, whereas Lower Stage 4 is missing from only Gidgealpa 2 and 11.

In the Patchawarra Trough, Stage 3′ sediments are more uniformly thick than in the southern part of the basin, with only the Coonatie structure outlined by closely spaced isopachs (Fig. 21), and are preserved over a greater area than those of any subsequent Stage. Thickness increases gradually southeastwards from the northwestern margin and decreases abruptly along the northwestern flank of the GMI anticlinal trend. The area is devoid of major faults.

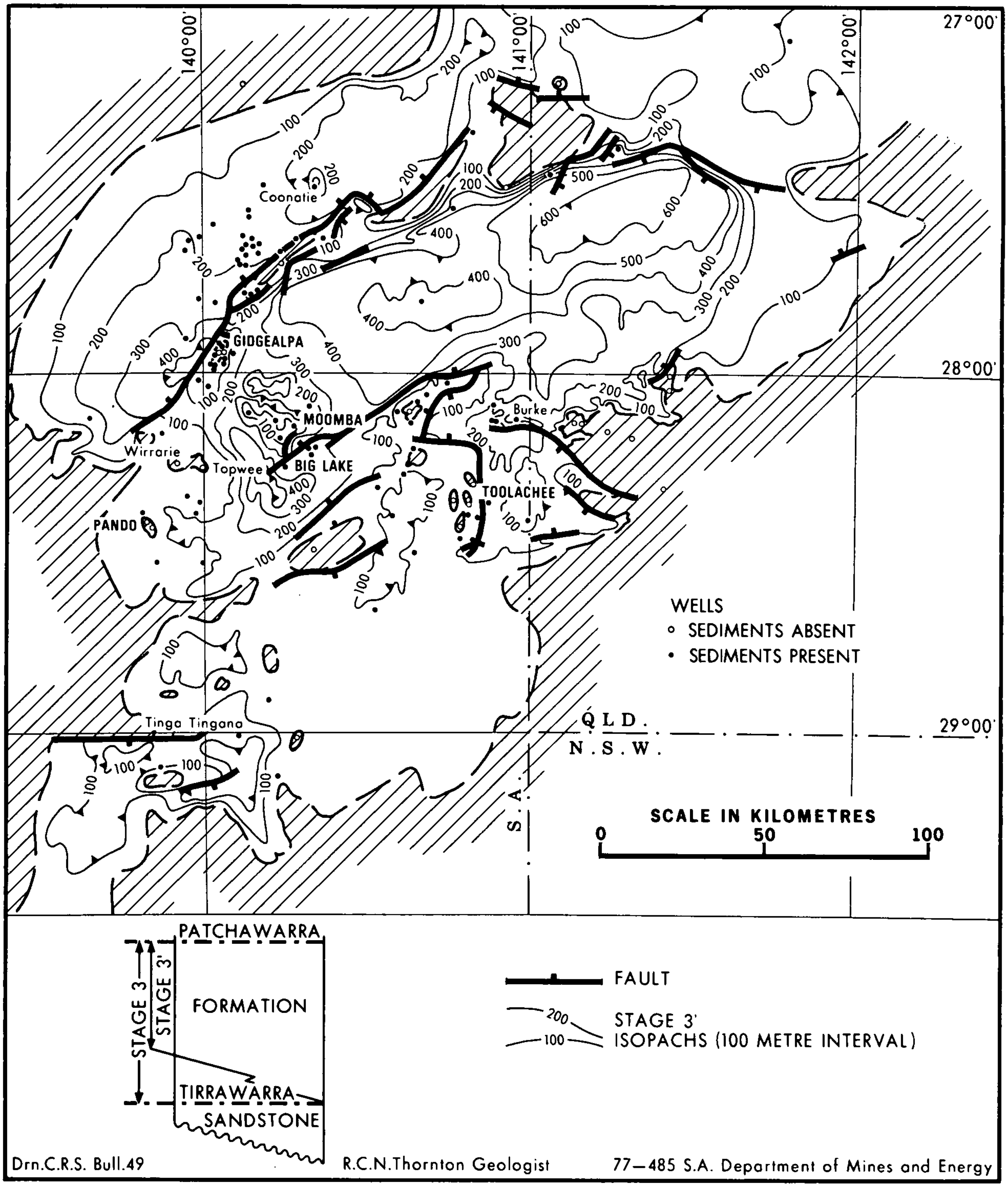


Fig. 21. Stage 3' isopach map

All these points indicate a relatively smooth original depositional surface, gradual and continuous subsidence along the GMI Trend, and continuous deposition in the Patchawarra Trough.

Lithofacies

As illustrated by the lithofacies maps (Figs. 22 and 23), the Cooper Basin can be split into five main areas on the basis of sandstone predominance. The highly sandy facies is restricted to the Cooper Basin south of the GMI anticlinal trend (Fig. 22), extending from the south, northwards around Moomba, into the Nappamerrie Trough, and in addition, covers the Strzelecki-Nappacoongee region. On the flanks of this sandy zone, the facies generally change laterally away from shale rich to shale and coal rich. The Patchawarra Trough is covered by the shale and coal-rich facies.

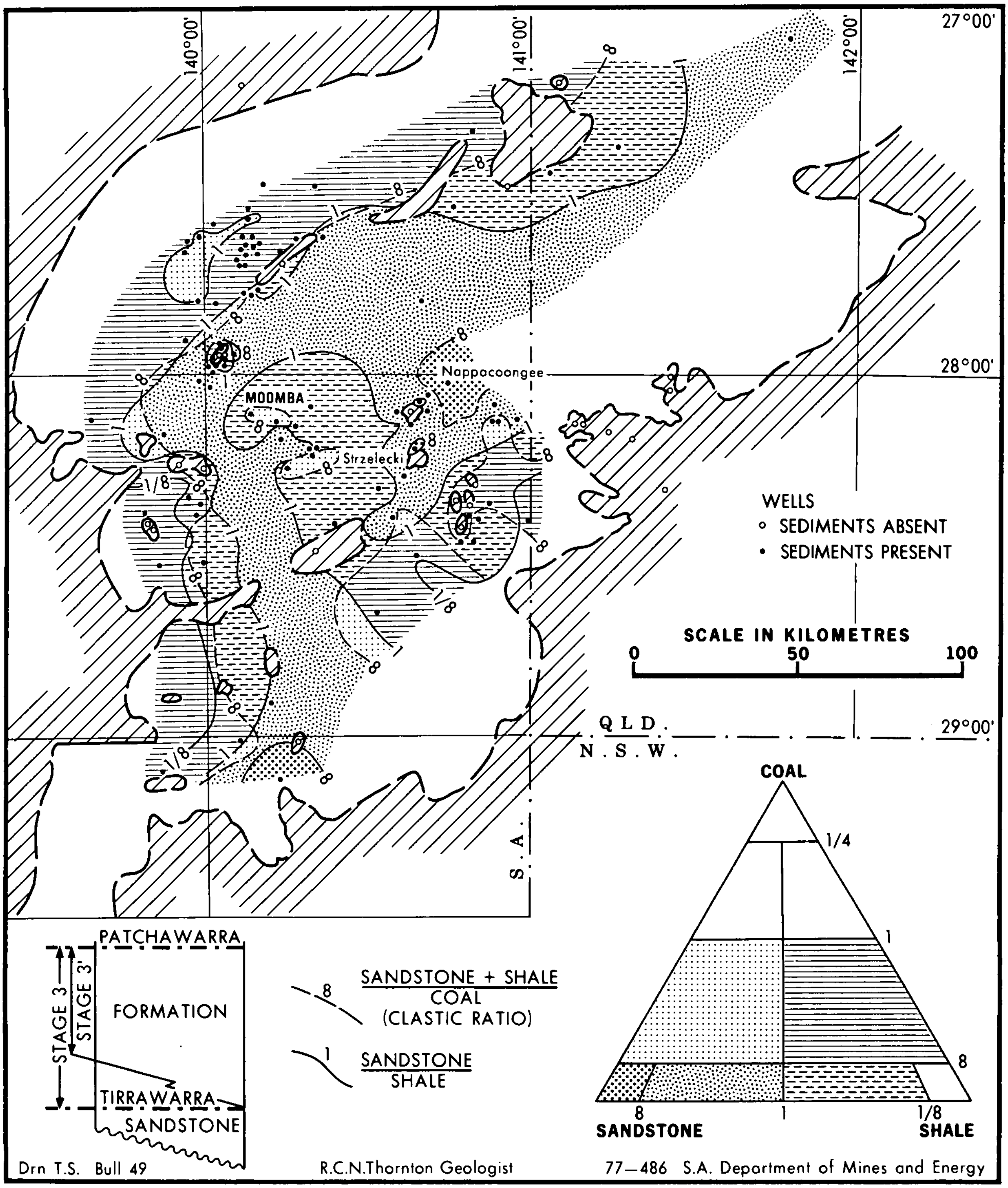


Fig. 22. Stage 3' lithofacies map

It is assumed that the areas with the highest sandstone content define the zone of major fluvial channel locations and sediment transport. This channel zone is shown approximately on the lithofacies map (Fig. 22) by the areas of sandstone-shale ratio greater than 1, and clastic ratio greater than 8. On the basis of high clastic and low sandstone-shale ratios, the areas to the west and east of the central channel region are interpreted as quiet, tectonically stable, basin marginal regions not cut by any major rivers. Thus, sand development was very minor, and conditions suitable for coal and shale deposition predominated.

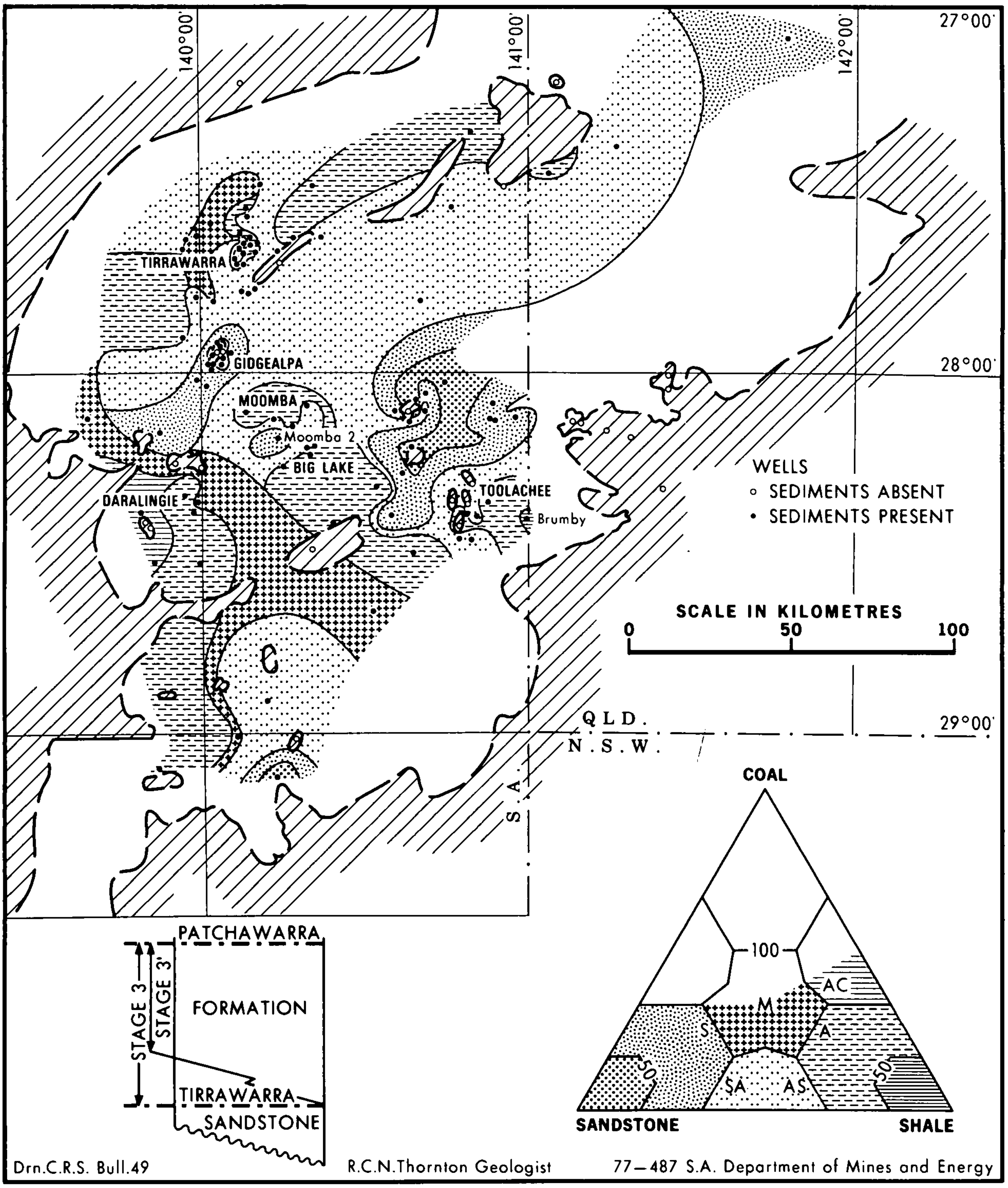


Fig. 23. Stage 3' 'D'-function map

Palaeogeography and Geologic History

Palaeogeographically the Cooper Basin can be divided into four major zones. These are a zone of channel development, marginal areas where backswamps predominated, a central region around Moomba and Big Lake, and the Patchawarra Trough (Fig. 24). South of the GMI anticlinical trend, deposition took place over hilly topography, in an area of active faults, some of which had a localising effect on channel systems. The Patchawarra Trough, on the other hand, was a gradually subsiding region where the floodplain was dominated by lakes and swamps. Neither the GMI nor MN anticlinal trends were anticlinal features during Stage 3', which implies that the present-day structural grain was imposed on the basin at a later date.

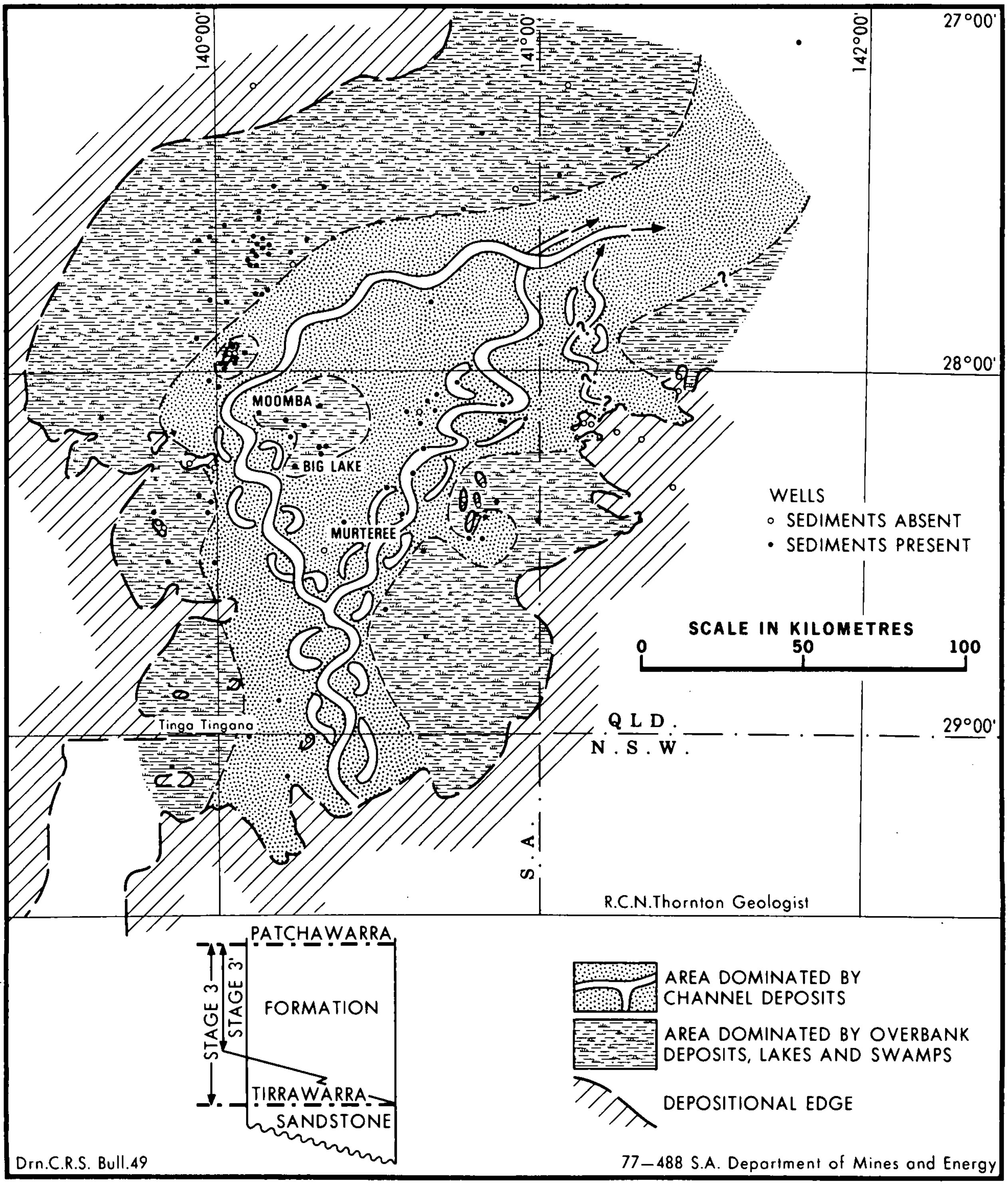


Fig. 24. Palaeogeography during Stage 3'

In the areas south of the GMI anticlinal trend, major rivers deposited sediments, and partially filled the valleys in a hilly topography, which perhaps had been shaped by earlier glacial activity (Fig. 24). Northwards trending river channels were restricted to the central part of the basin, while the western and southeastern flanks received mainly overbank and swamp deposits. The major rivers were mostly deflected around a central region of Moomba and Big Lake, part of which was a relict topographic high. A secondary zone of channels may have extended northwards into the Nappamerrie Trough region from the eastern flank of the basin.

By contrast, the Patchawarra Trough experienced deposition of a uniformly thick, and laterally extensive section of mainly overbank deposits in a depression largely unmarred by topographic highs. It was a floodplain environment dominated by lakes and coal swamps, as shown by the shale and coal rich lithofacies (Figs. 22 and 23). Continuity of deposition throughout the trough is shown by the lateral persistence of recognisable lithologic sub-units (Kapel, 1972 and Sect. A-A, Fig. 6). At this time, the GMI Trend in the main did not exist as a topographic divide to hinder transport of sediment from the south into the Patchawarra Trough.

South of the GMI Trend, well control on the distribution of the channel facies is very poor. Nonetheless, some corroboration is provided by isopach mapping, which shows that the postulated northerly fluvial zone coincides closely with a northerly trend of depositional 'sinks' around Tinga Tingana, and southwest of Big Lake.

The MN anticlinal trend cannot have been an emergent feature during deposition of Stage 3' sediments. Both arms of the bifurcating channel region cross the trend, which therefore must have been at the level of the alluvial plain during deposition. The Murteree structure is also thought to have been uplifted at a later date, with the consequent erosion of Gidgealpa Group sediments. That this structure was a depositional low, at least during the earliest Permian, is demonstrated by the presence of a relict veneer of Merrimelia Formation on the anticline.

Deposition of overbank deposits occurred on all sides of the channel zone with coal percentages especially high on the western flank. The dominance of coal swamps implies that the present-day western limit of Stage 3' sediments was the basin limit during Stage 3' and has not been seriously affected by erosion since then. Because onlap occurred in the western margin, the very coaly sediments at Pando North and Boxwood were deposited late in Stage 3'.

Onlap of sediments onto 'outcrop islands' along the flanks of the basin can be explained by the model of sediment transport in a northerly direction. The alluvial basin filled up from the centre outwards with sediment deposition gradually encroaching up both its western and eastern margins.

The shale rich lithofacies around many 'islands' show that overbank deposition prevailed in their vicinity, supporting the interpretation that they were emergent features, around which major channels were deflected. An increase in shale dominance up structure is shown on the 'D'-function map (Fig. 23) most clearly at Tirrawarra and Gidgealpa, but occurs also at Moomba, Big Lake, Daralingie, Toolachee, and perhaps Brumby (Moomba also shows the reverse trend around Moomba 2, although this is probably because of the thinness of section at that well). Thornton (1973) believed that this 'halo' effect was the result of the natural tendency for rivers to flow around the perimeter of an uplifted area, which thus received mainly the finer grained sediments of floodplain deposition.

The GMI anticlinal trend, for most of its length, probably did not act as a major barrier to the northwards transport of sediment into the Patchawarra Trough, even though the trend is clearly delineated on all the isopach and facies maps as a boundary between north and south, and syndepositional fault movements are indicated by the parallelism of facies, isopach and structural strike (Krumbein, 1952). However, there is doubt as to whether or not the GMI Trend was a topographic divide at this time.

Evidence either for or against the emergence of the GMI Trend is provided by the areal extent of the bald-headed features along the trend. These features progressively increase in areal extent from Stage 3', through Lower and Upper Stage 4, to Lower Stage 5. The inference that can be drawn from this is that the absence of sediments is due to one of three things. Firstly, deposition might have been continuous through Stages 3', 4 and Lower 5, and then uplift and erosion could have removed progressively less of each of the older units. Secondly, the GMI Trend could have been emergent throughout early Permian time, and during each successive Stage might have been more areally exposured than for the preceding one. Thirdly, and perhaps most likely, Gidgealpa at least might have been a 'high' during Stage 3' time only, because onlap of sediments occurs up the flank of the structure, so that deposition could have been continuous during the rest of the early Permian before a period of major erosion at the end of Lower Stage 5.

This third interpretation leads to the conclusion that the present northeasterly structural grain was imposed on the Cooper Basin by the uplift of both the GMI and MN anticlinal trends after Stage 3' time. This major uplift occurred at the end of Early Permian, and was accompanied by extensive erosion.

Earth movements synchronous with deposition during Stage 3' occurred in the form of growth faulting. Such faults had a localising effect on the position of individual fluvial channels, and generally caused formational thickness variations as illustrated on the Gidgealpa Group isopach map (Fig. 4). On some faults, such as that adjacent to Big Lake, continuous growth faulting had a pronounced effect on deposition. At Toolachee, the continuous movement on the large fault localised the paths of individual channel sandstone systems, the axes of which mostly parallel the northerly trend of the fault (Devine and Gatehouse, 1977). This parallelism of facies, isopach, and structural strike indicates that fault movements affected both thickness distribution and facies trends (Krumbein, 1952).

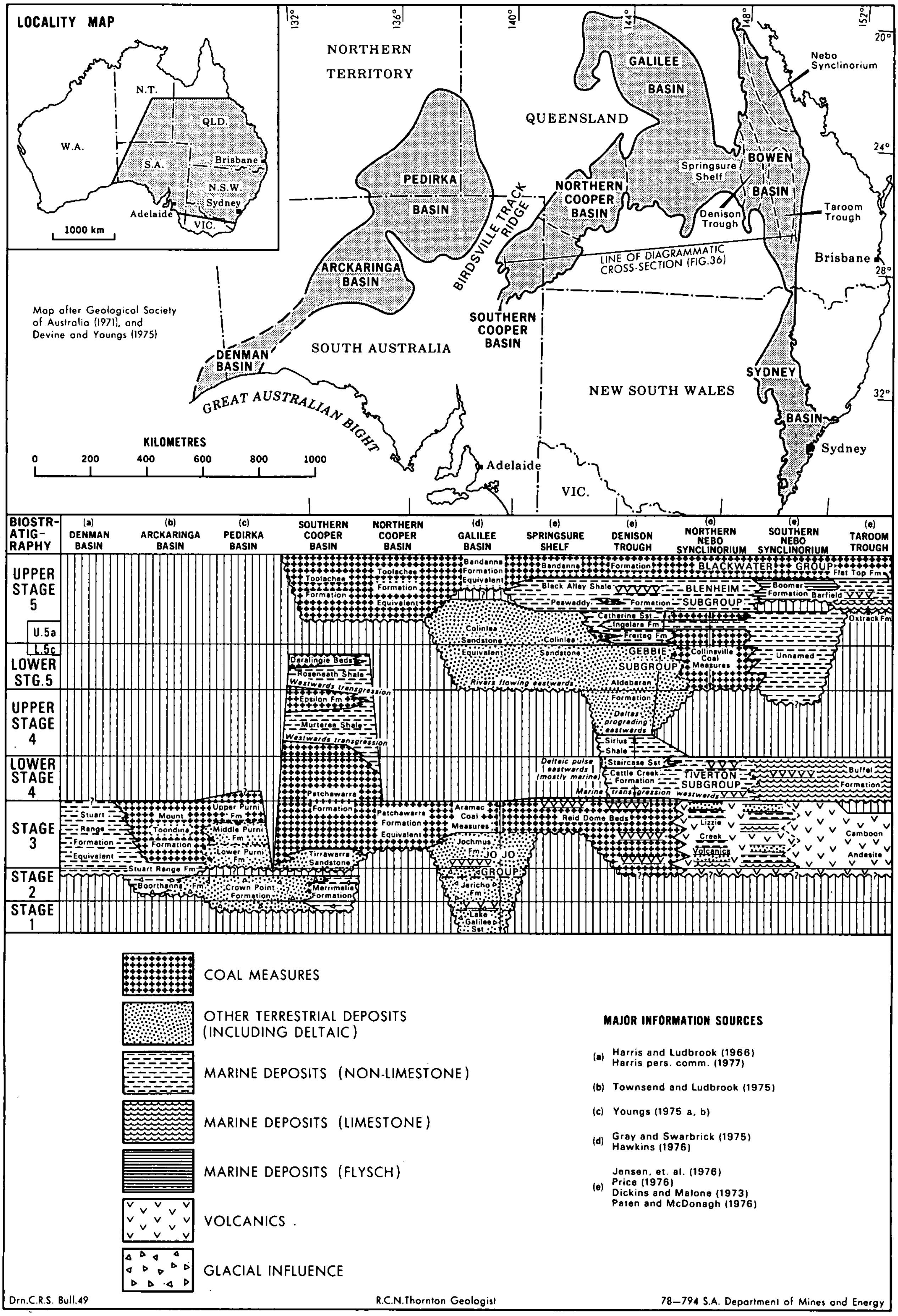


Fig. 25. Permian System of central and northeastern Australia—regional stratigraphic relationships

The palaeogeography of the Cooper Basin is related intimately to that of the surrounding basins (Fig. 25). The Cooper Basin lies in the centre of an arc of Permian basins, which extend from the Denman Basin in the west to the Sydney Basin in the east. This string of basins can be separated into two sets, one being related to marine access in the east, the other to marine access in the west. The Cooper Basin is the most westerly of the eastern group. The Pedirka Basin is the most easterly, and landward, of the western group of basins and was probably separated from the Cooper Basin during the Permian by the Birdsville Track Ridge, which acted as a continental divide (Devine and Youngs, 1975). The eastern basins can be related to a gradation towards the more central part of the continent from open marine, continental plate boundary near the present continental margin (Mayne, *et al.*, 1974), through the marginal marine Sydney and Bowen Basins, to the dominantly fluvial Galilee and Cooper Basins (Dickins and Malone, 1973; Jensen, *et al.*, 1976; Gray and Swarbrick, 1975; Hawkins, 1976).

Only rocks of Stage 3 age are known to be preserved in all the Permian basins (Fig. 25), therefore, Stage 3 may have been the only period when sediment deposition was ubiquitous. Coal measures predominate in the more centrally located basins, but change to restricted marine sediments in the Denman Basin to the west, and mixed volcanic and marine deposits in the Taroom Trough to the east. Thus, Stage 3 was a period of structural stability, and major terrestrial sediment accumulation, throughout the central part of the Australian continent.

LOWER STAGE 4

Lower Stage 4 is a narrow palynologic (time) zone, during which part of an upper section of the Patchawarra Formation only was deposited (Table 1). A depositional pattern basically similar to that of Stage 3′ prevailed.

Distribution of Sediments

The area of sedimentation increased slightly over Stage 3′ in the eastern part of the basin as onlap proceeded (Sect. C-C, Fig. 8). Present external limits probably equate broadly with original deposition limits (Fig. 26). The thickest zones of sediment form an arcuate trend from the south, through the Nappamerrie Trough. Lower Stage 4 sediments are absent from some areas within the basin, either due to incomplete onlap, as is the case along the western flank, or to erosion at the end of the early Permian, as on the anticlines along the GMI and MN anticlinal trends.

The Patchawarra Trough is covered by only a very thin Lower Stage 4 section; a feature not due to later erosion, because Lower Stage 4 rocks are conformably overlain by younger sediments (Sect. A-A, Fig. 6).

Lithofacies

The sand dominant areas exhibit basically the same pattern as on the Stage 3′ map, in particular the area which extends northwards from south of the basin (Figs. 27 and 28). The sand dominant zone arising in the east is south of Burke, rather than north, so that the size of the coal and shale dominant region around Toolachee is reduced. The Moomba-Big Lake area continues to be dominated by shale. An area of almost total shale on the lithofacies map (Fig. 27), which was not observed anywhere on the Stage 3′ map, occurs at Durham Downs in the northeast.

The lithofacies pattern around some wells is complicated by the fact that the section is very thin, as a result of either limited deposition or later erosion: the latter being indicated by the absence of younger Early Permian sediments. Those wells with only incomplete sections are marked by asterisks on the lithofacies maps. During mapping, these values were disregarded if they conflicted with data from surrounding wells, because as Krumbein (1952) points out, such control points are unreliable. The area most affected by erosion of Lower Stage 4 rocks is Gidgealpa. Its complex lithofacies pattern, compared with the rest of the basin, is probably largely due to the fact that the section is incomplete in seven wells.

Some widely spaced wells in the Patchawarra Trough, such as Coonatie and Kudrieke, contain very thin Lower Stage 4 sections, and therefore their lithofacies values must be open to question. Palynologic control in the wells is not so accurate that the time boundaries could not be moved up or down so as to include an additional thick unit of any lithology from the top or bottom of the section. The addition of any such unit in a thin section would seriously affect the 'D'-function value in particular. Weller (1960, p. 536) emphasises that the smaller the magnitude of a unit, the greater is the uncertainty concerning the correlation of its boundaries. He also points out the irony of the fact that detail and accuracy are incompatible because as standards in one respect are raised, their decline in the other is almost inevitable.

Palaeogeography and Geologic History

The palaeogeographic reconstruction (Fig. 29) which results from the lithofacies and isopach patterns is similar to that for Stage 3′. The Cooper Basin can be divided into firstly the

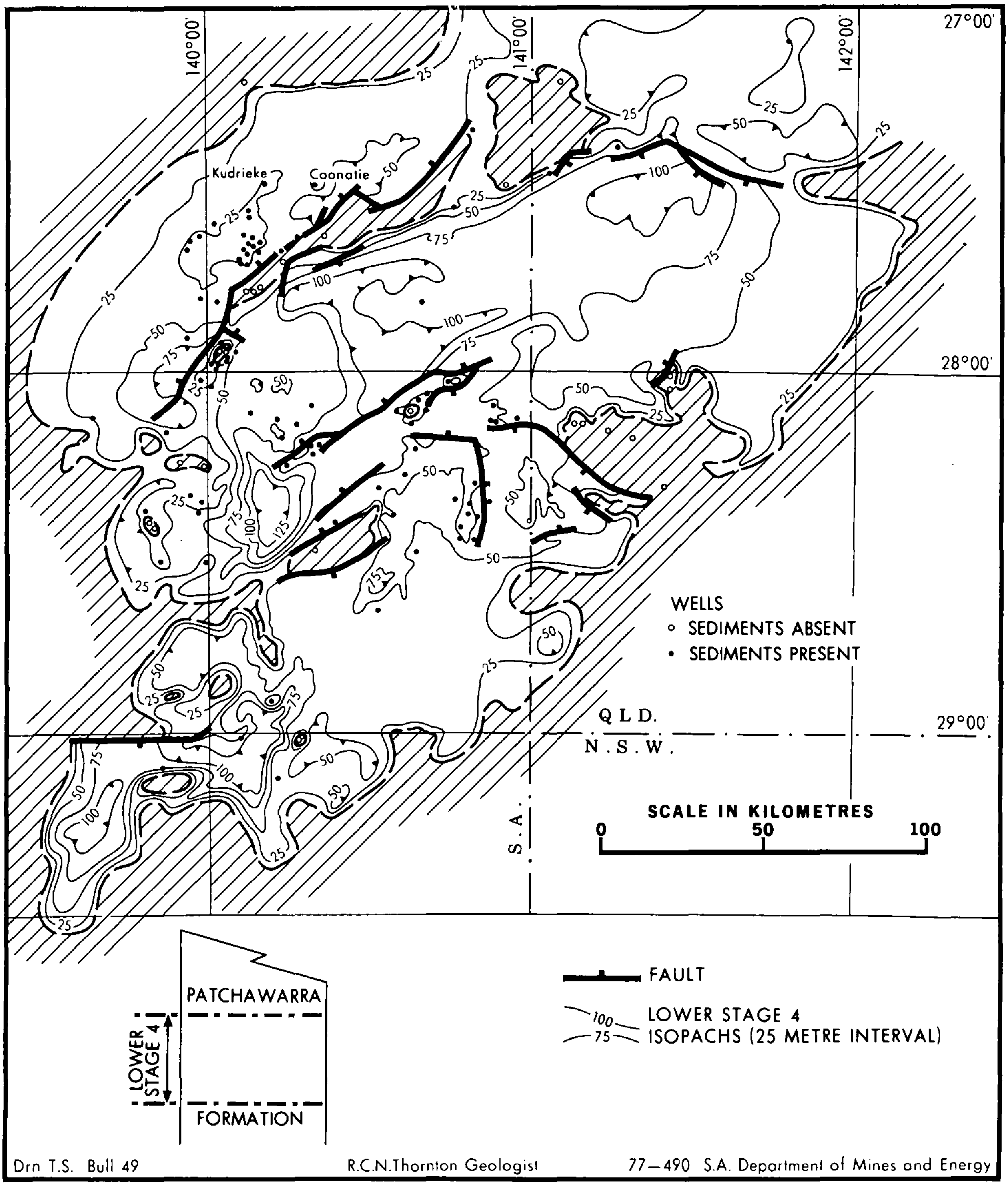


Fig. 26. Lower Stage 4 isopach map

'fairways' of major channel deposition and secondly those areas dominated by overbank deposits, namely the Moomba-Big Lake area, the southeastern and western flanks, and the Patchawarra Trough. In addition, a possible area of lacustrine deposition occurs to the northeast.

The distribution of sandy facies on both lithofacies maps indicates that sediment was brought into the Cooper Basin along two separate channel 'fairways', one from the south, the other from the southeast. Probably the major path was the one that extended northwards between Kumbarie and Spencer. This region is flanked on both sides by shaly areas, which become increasingly rich in coal towards the margins of the basin, and which therefore are interpreted as being the more favourable sites for lake and coal swamp development.

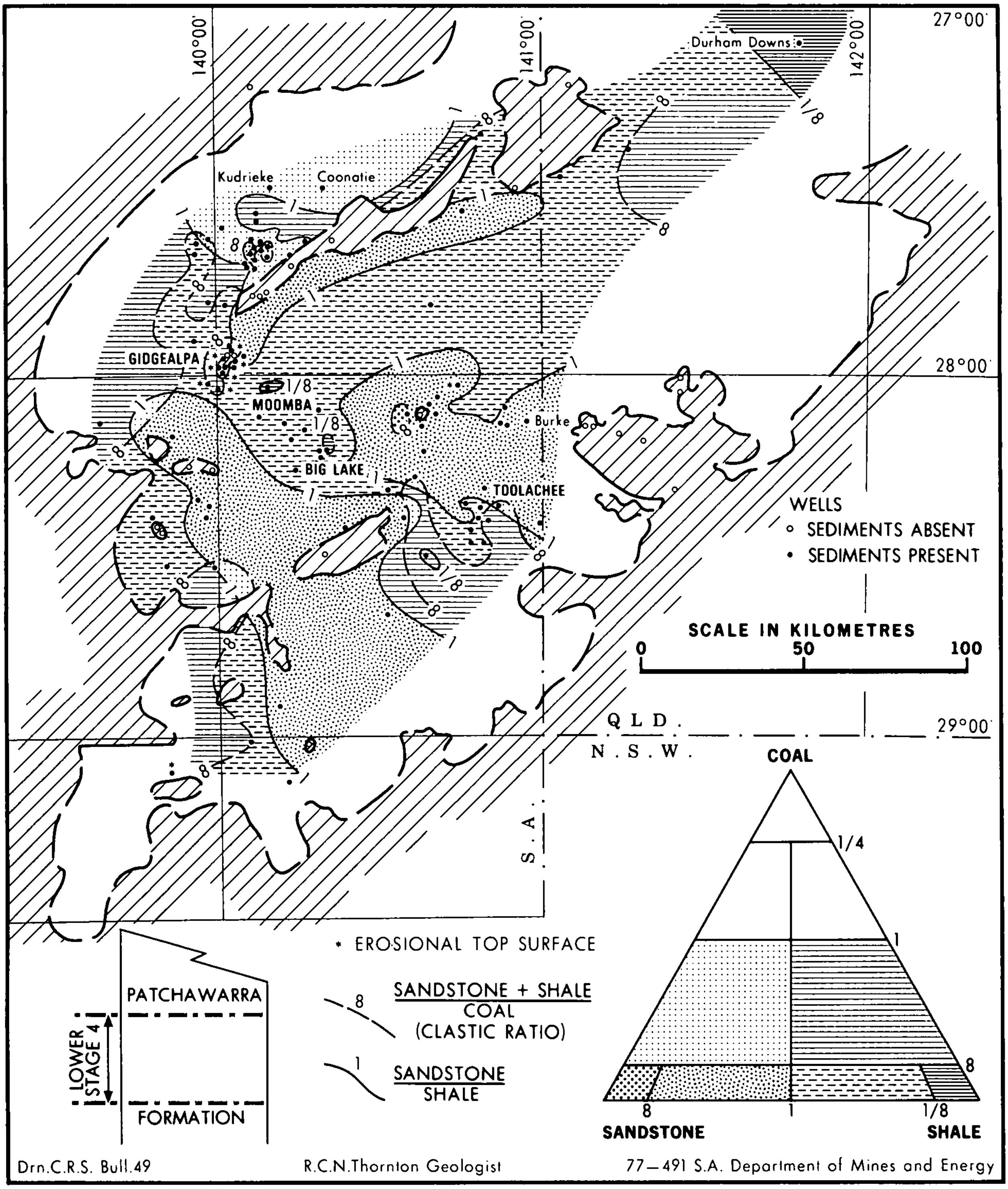


Fig. 27. Lower Stage 4 lithofacies map

The zone of sandy facies extending basinwards from the eastern margin is considered to reflect an optimum channel location for three reasons. Most importantly, the sandy facies does not change to shale near the basin margin: secondly, the area encompasses the whole or parts of six anticlinal structures, not all of which occur along the MN anticlinal trend, and therefore their sandiness cannot be related to structural movements along it, and thirdly, the facies grades at least on its southern side through a shale-rich region to an increasingly coaly region away from the 'fairway', consonant with the model of overbank deposits flanking the major river channels.

The Moomba-Big Lake region is the only shale rich area (as defined on the 'D'-function map) south of the GMI anticlinal trend, which occurs

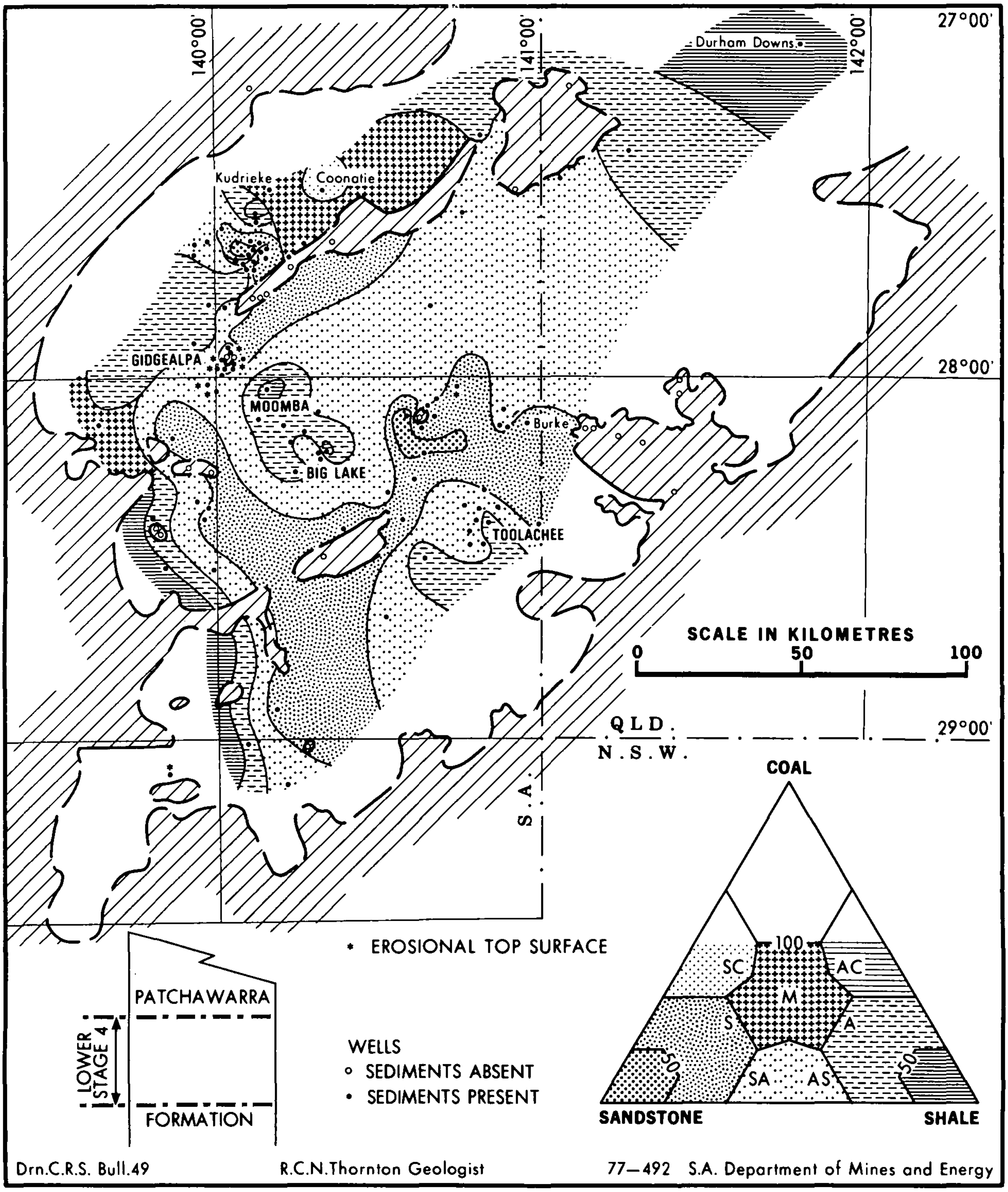


Fig. 28. Lower Stage 4 'D'-function map

away from the basin margin. Overbank deposits predominated on the basin flanks because they were on the margins of the major channels, and as the major channel 'fairways' bifurcate around Moomba-Big Lake, this area is placed in a similar depositional environment. The Moomba-Big Lake area is therefore interpreted as being a region which subsided less than the surrounding areas. As a result of this, it deflected most rivers around its flanks and thus accumulated mainly fine-grained deposits of the floodplain.

The coal rich nature of the Patchawarra Trough, especially in the north, together with the lack of sand rich facies, indicate that major river systems were absent from an area dominated by overbank deposits and coal swamps. The very thin section, and the dominance of backswamp deposits, suggests that the Patchawarra Trough

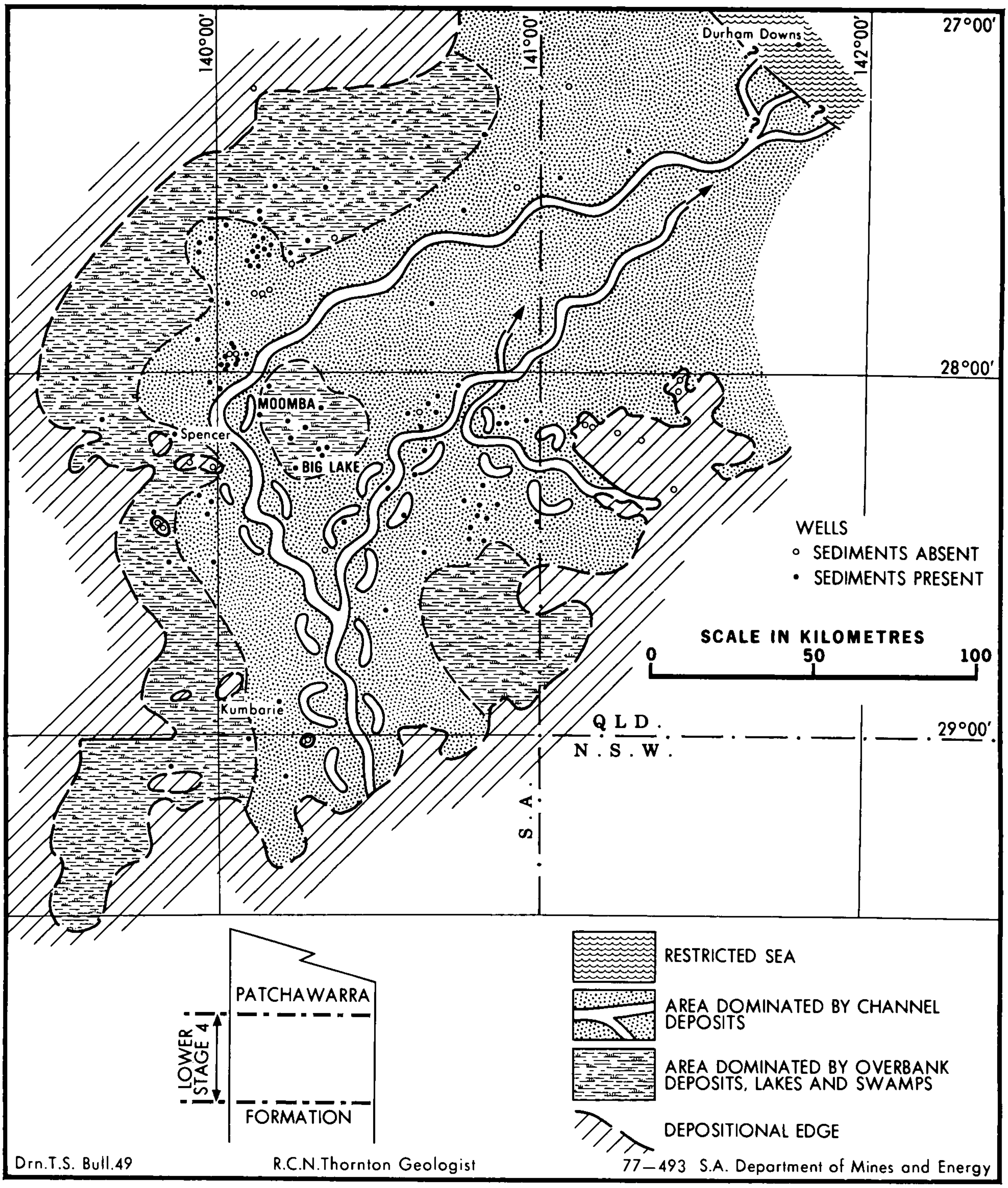


Fig. 29. Palaeogeography during Lower Stage 4

was very stable, and subsided only very gradually. As a consequence, major rivers may not have crossed into the Patchawarra Trough from areas to the south of the GMI anticlinal trend simply because the Patchawarra Trough was subsiding at a lesser rate.

The northeastern area of the Cooper Basin, in the vicinity of Durham Downs was possibly covered with lakes, or perhaps one single lake with a likely sediment source area from the south. Well control is very sparse in the northeast, but even so, the pattern on the 'D'-function map (Fig.28) of sandy in the southwest changing in turn to shaly, then very shaly, is a perfect decrease in sand with distance from source phenomenon. If this interpretation is correct, then the presence of the lake (or perhaps restricted sea) is the earliest evidence of the lacustrine transgression from the east, which was the dominant feature to affect Upper Stage 4 deposition.

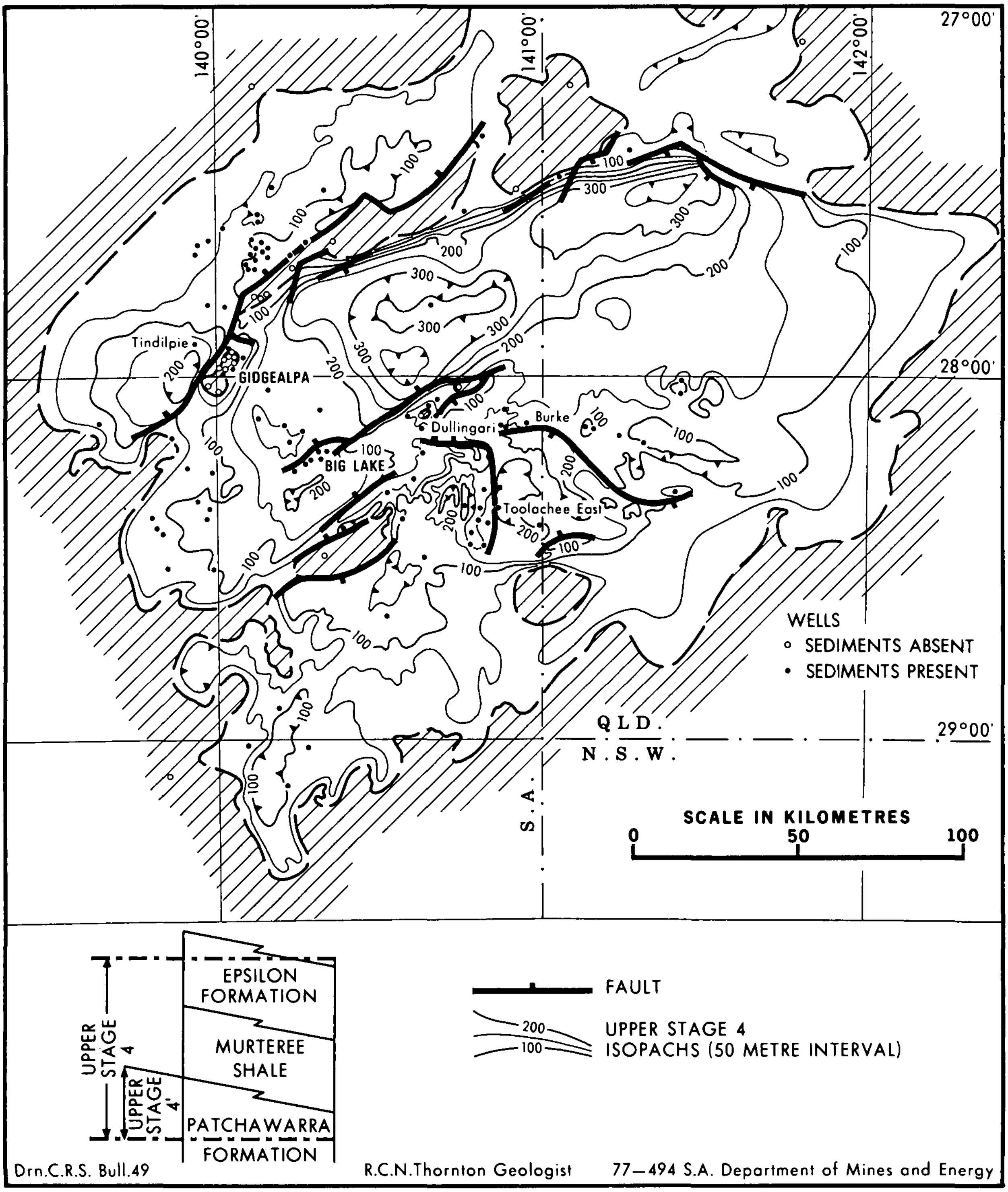


Fig. 30. Upper Stage 4 isopach map

UPPER STAGE 4

While Lower Stage 4 is a short time interval entirely contained within the Patchawarra Formation, and therefore mainly confirms or adds marginally to the depositional and palaeogeographic picture provided by the Stage 3' mapping, Upper Stage 4 suffers from the problem of being too wide a time interval. It was a period of major sediment accumulation south of the GMI anticlinal trend (Fig. 30). Upper Stage 4 incorporates the upper part of the Patchawarra Formation, the Murteree Shale, and most of the Epsilon Formation (Figs. 6-11).

In lithofacies maps of this total interval, the sandstone trends of the Patchawarra and Epsilon Formations interfere with one another.

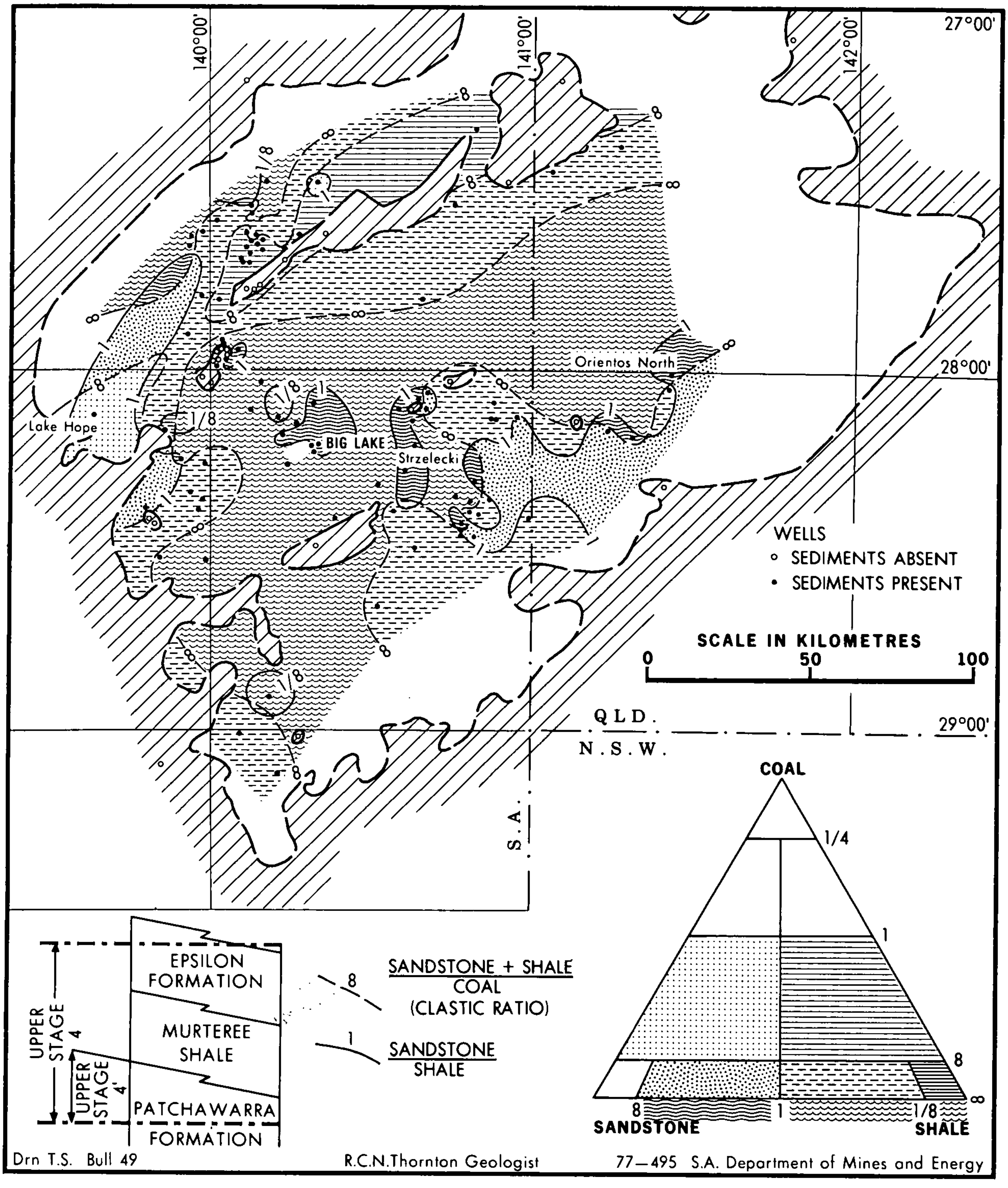


Fig. 31. Upper Stage 4' lithofacies map

In addition, such maps are complicated by the fact that many of the wells do not contain a complete lithologic section for this period due to onlap, erosion, or both. Because of these complicating factors, the Upper Stage 4 section has been studied by treating it in three separate parts. These are the top part of the Patchawarra Formation (Upper Stage 4'), Murteree Shale, and Epsilon Formation.

UPPER STAGE 4'

An interval, designated Upper Stage 4', has been mapped, which contains that part of the Patchawarra Formation which is of Upper Stage 4 age only. Ideally, a palynologic marker near the base of the Murteree Shale would have provided the most useful boundary for mapping the

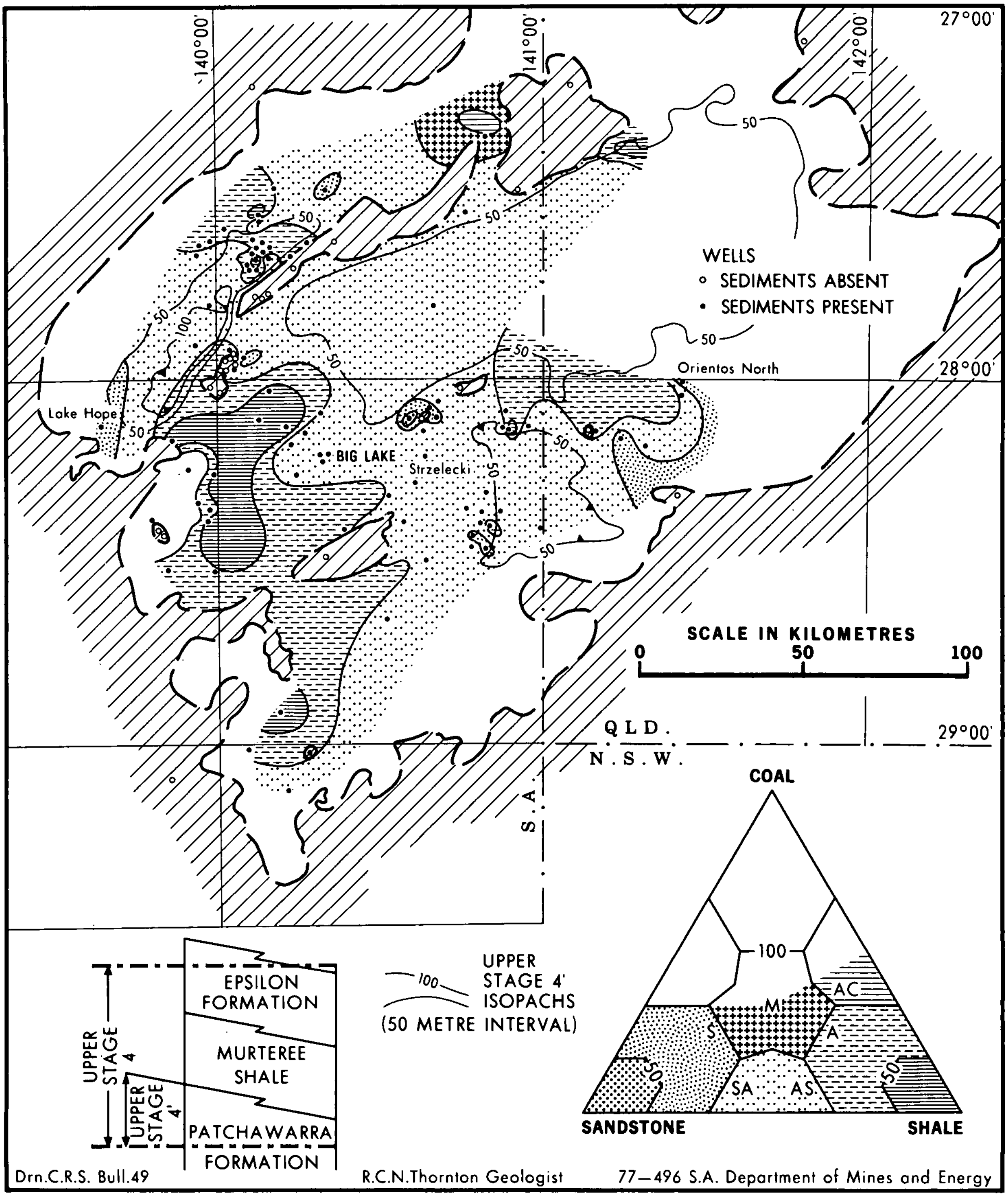


Fig. 32. Upper Stage 4' 'D'-function map

processes involved in the change from Patchawarra Formation to Murteree Shale deposition. Since such a marker is not available, and no thin lithologic marker in the Murteree Shale could be mapped with confidence, the rock boundary between the top of the Patchawarra Formation and the overlying Murteree Shale is used.

Mapping of this unit provides an analysis of the closing stages of the Patchawarra Formation deposition. Interpretation of the Gidgealpa 6 cores suggests that deposition occurred mainly in shallow water, either offshore, or in interdistributary bays.

Distribution of Sediments

Compared with earlier Stages, Upper Stage 4' rocks do not extend as far to the north or south of the basin, but do encroach much further to the southeast in an onlap relationship (Figs. 7 and 8). The unit is thin everywhere, and only exceeds 100 m at the southwestern end of the Patchawarra Trough (Figs. 31 and 32).

All the wells which intersect rocks of Upper Stage 4' age also intersect at least some of the overlying Murteree Shale. Therefore thinning is not due to later erosion, but instead to some contemporaneous depositional and/or structural factor. Because Upper Stage 4' is not a time-rock unit and is thin, thinning could be due to facies change from Patchawarra Formation to Murteree Shale. Nonetheless, the extremely thin section in the northeastern part of the Patchawarra Trough may indicate that conditions were unsuitable for sediment accumulation, probably because the area was subsiding only gradually, as a continuation of the process of 'drying up' which commenced during Lower Stage 4.

Evidence of thickness changes across some major faults leads to the interpretation that they were active during this period, and thus the considerable sediment thickness contrasts in the Tindilpie and Toolachee East areas suggests that the Gidgealpa, Toolachee and Burke-Dullingari faults were strongly active during earliest Upper Stage 4. There is no such great thickness change across the Big Lake Fault, which therefore, was probably not active at this time.

Lithofacies

The Upper Stage 4' lithofacies data indicate that most deposits are lacustrine or restricted marine. By far the largest part of the lithofacies map (Fig. 31) is represented by a high shale, zero coal (clastic ratio = infinity) facies. In addition, shale is twice as abundant as sandstone in those areas where coal is absent. The most likely depositional environment to fit these parameters is that of a permanent body of water in the shaly areas being fed by sediments from the onshore deltaic/alluvial plain.

Palaeogeography and Geologic History

A large area south of the GMI anticlinal trend and a small part of the Patchawarra Trough were covered by water: the infinite clastic ratio contour (Fig. 31) marking the furthest extent of the shoreline. (The question of whether this body of water was a lake or restricted sea, is discussed in the Murteree Shale section). The rocks deposited in these bodies of water mark the onset of lacustrine deposition, and are gradational with the shales of the overlying Murteree Shale. The GMI Trend and the southwestern part of the Patchawarra Trough were not submerged at this time, and provided a barrier between the two lakes.

Sediment was probably brought into the basin from the southeast and west, as shown by the very sandy areas on the lithofacies map (Fig. 31). In particular, the facies pattern in the east/central region is interpreted to indicate sediment transport northwards through Orientos North and westwards towards Strzelecki and Big Lake (Fig. 33). In a similar way Lake Hope was the site of sediment intake into the Patchawarra Trough.

On the 'D'-function map (Fig. 32), the very limited extent of sand-rich facies, and the dominance of admixed and shaly facies, fit the model of an encroaching lake shoreline. Great volumes of coarse clastics were not brought into the area, but instead, finer clastics dominated, both onshore and offshore. This implies that the rivers were sluggish, with a low bed load capacity, which in turn suggests they flowed through a senile topography; not enough sediment being delivered to the shoreline to prevent gradual inundation by the encroaching lake.

MURTEREE SHALE

The Murteree Shale lies wholly within Upper Stage 4: its distribution showing the maximum extent of the lake from which it was deposited. No interpretation of the direction of transgression can be obtained from the maps of this unit, because both its upper and lower surfaces are lithologic boundaries. Nevertheless, it is assumed from regional considerations to have transgressed from the east.

Lithologically, the Murteree Shale comprises a uniform suite of shales, with minor amounts of interbedded siltstone and fine-grained sandstone.

Distribution of Sediments

The Murteree Shale extends throughout the basin, with the exception of most of the GMI and MN anticlinal trends (Fig. 34). Its thickness distribution along these two structures has been affected by later erosion as illustrated by the fact that most of the wells on the GMI and MN Trends which contain Murteree Shale, have erosional upper contacts. Overall, the unit is thin, with a maximum drilled section of 88 m at Toolachee East (Fig. 34).

The depositional surface on which Murteree Shale was deposited was probably nearly flat, and with the exception of Epsilon 1, the Murteree Shale is underlain in all wells by the Patchawarra Formation, indicating that onlap

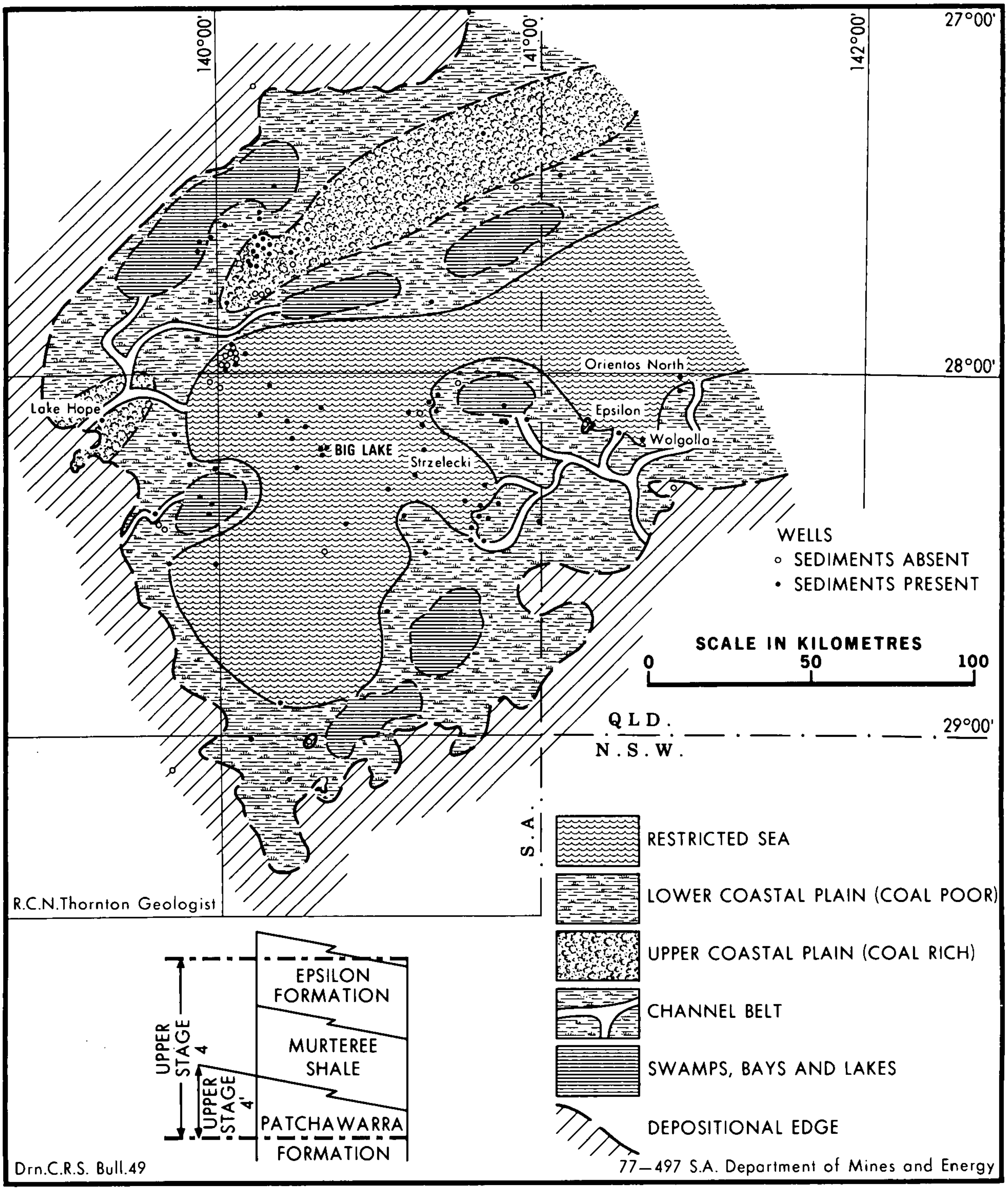


Fig. 33. Palaeogeography during Upper Stage 4'

was complete. The lack of relief on the depositional surface is also indicated by the fact that the youngest transgressed Patchawarra Formation rocks were deposited from sluggish streams, in a senile topography. Furthermore only slight variations in thickness of the Murteree Shale throughout the basin, other than in the vicinity of the major anticlinal trends, also points to a low relief depositional surface.

Palaeogeography and Geologic History

The Murteree Shale was deposited from one large lake with dimensions of about 250 x 150 km (Fig. 35). This lake marks the maximum extension of the lacustrine transgression, which interfaced with the end of Patchawarra Formation deposition. The lake submerged the whole Cooper Basin region, which by this time

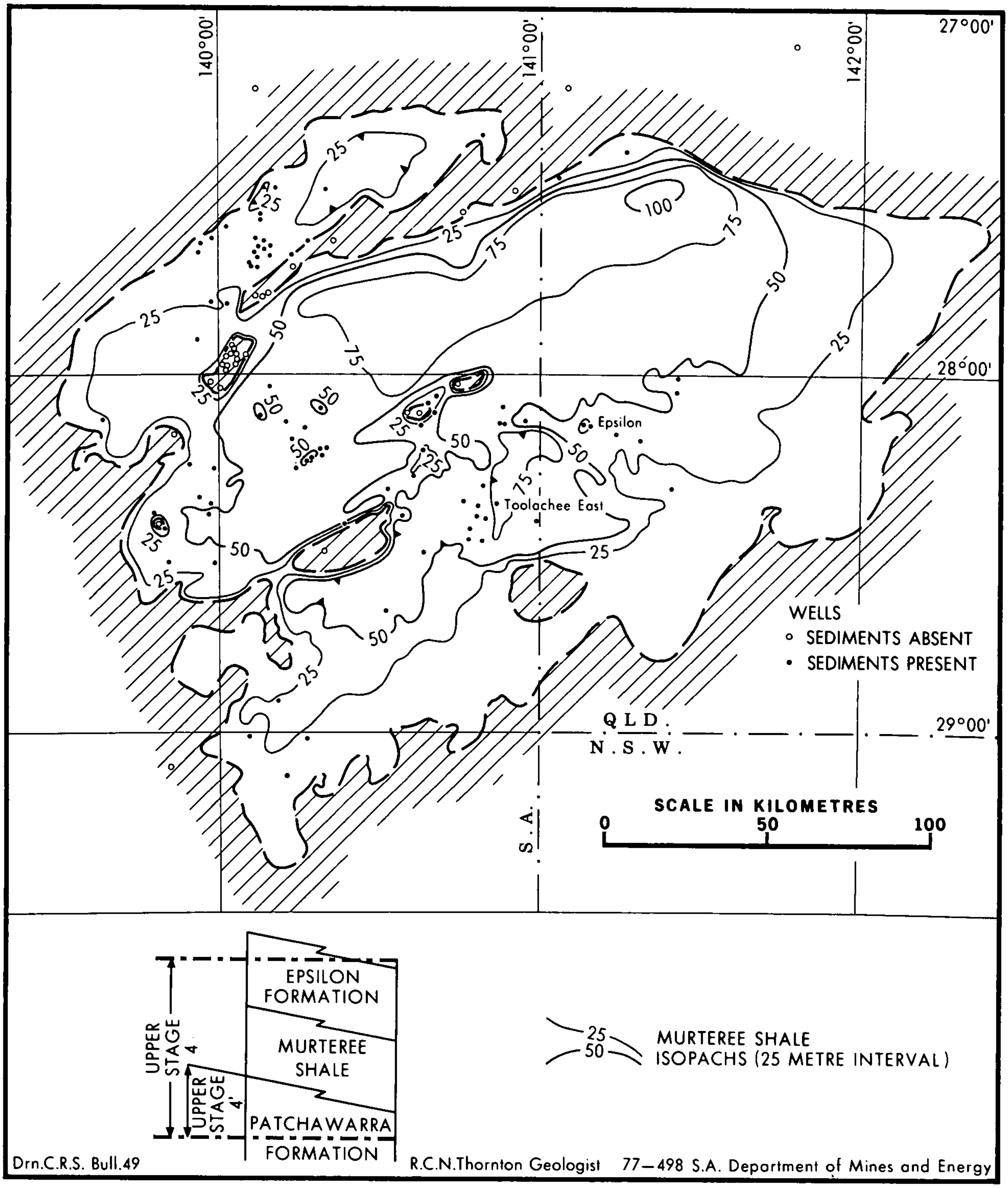


Fig. 34. Murteree Shale isopach map

was very flat. On the evidence of the palaeogeographic map during Upper Stage 4' (Fig. 33), the transgression came from the east or northeast.

Murteree Shale was deposited from either a fresh-water lake, or a restricted sea. Although no direct evidence of marine conditions has been discovered, the latter hypothesis is perhaps the more likely. Stuart (1976) indicated that if the body of water were a lake, then it formed as a result of the major rivers being blocked at the northeastern end of the basin, so that the lake then filled up towards the southwest. On the other hand, if it were a restricted sea, then the transgression occurred from the northeast. There are modern lakes of equivalent size to the Murteree lake, such as Lake Superior. Nevertheless support for the restricted sea

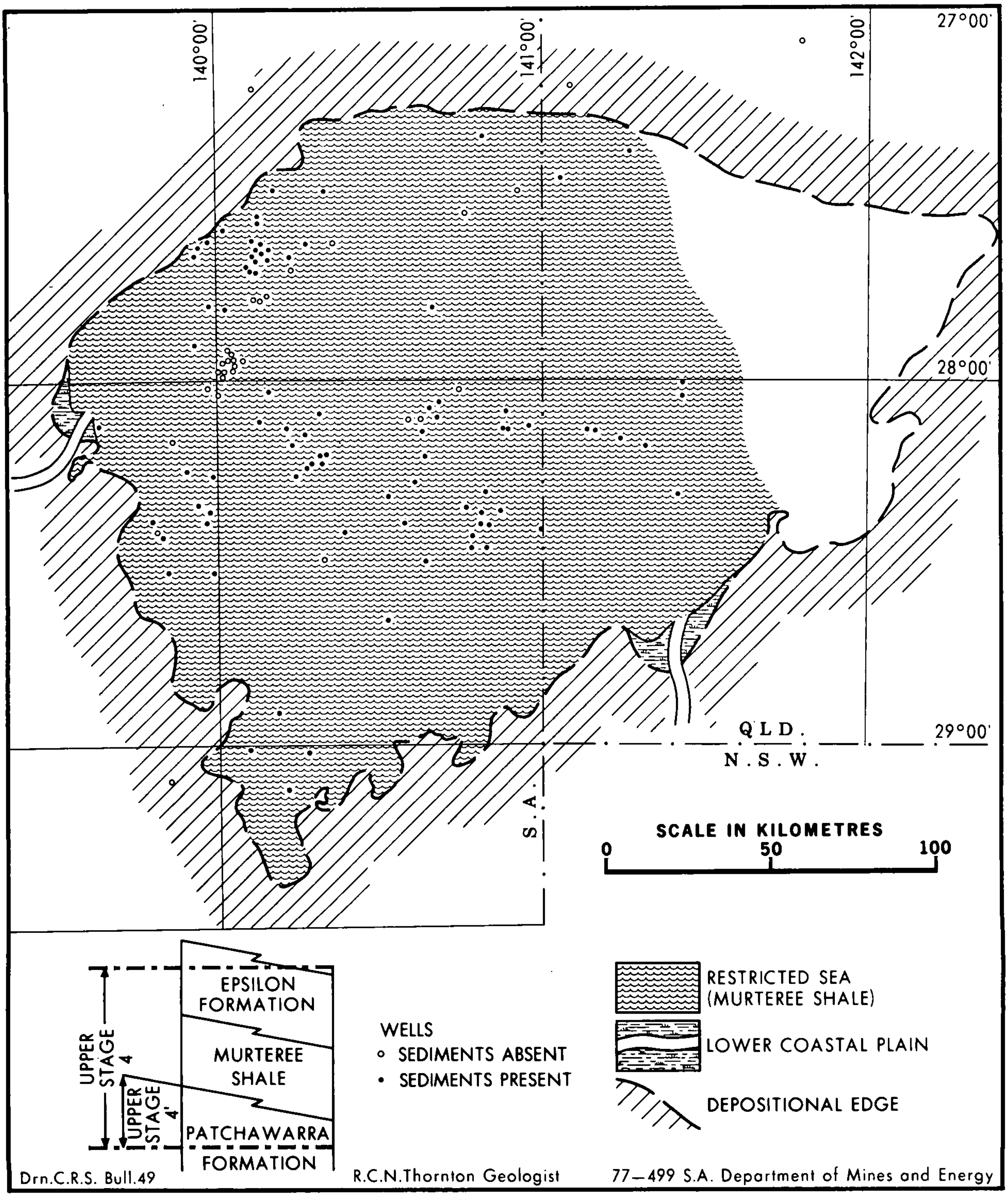


Fig. 35. Palaeogeography during middle Upper Stage 4

concept is provided by a combination of its size and the flat basal surface over which a sea could have transgressed with ease.

Stuart (1976) believes that the shale was deposited in an open basin with restricted access to the sea and doubts that the absence of fossils indicates freshwater conditions, because of the presence of trace fossils, which indicate biogenic activity. He suggests that the lack of fossils is due to diagenetic dissolution.

A possible modern analogue to the depositional basin for Upper Stage 4' and Murteree Shale is provided by Po Hai, a restricted sea, 500 x 150 km in size, adjoining the Yellow Sea in northeastern China (Heckel, 1972). Water depth is mostly less than 25 m. Immense amounts of mud and sand are supplied to Po Hai by the Hwang Ho River. The influx of fresh water reduces the salinity to about 25 per cent, and as a result the diversity and size of biota is reduced.

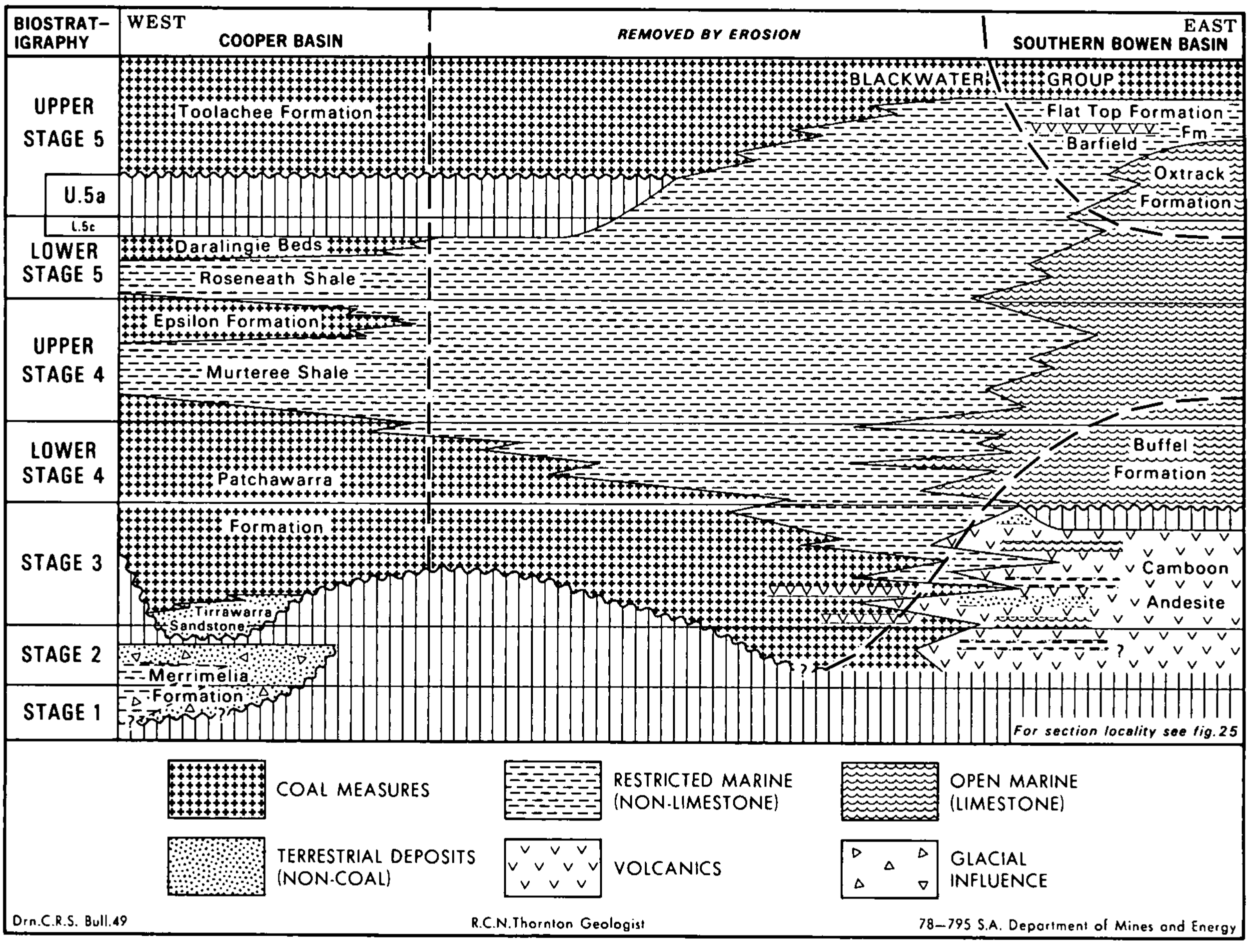


Fig. 36. Possible palaeogeographic relationship between the Cooper Basin and the eastern continental margin during the Permian

In the case of the Cooper Basin, as long as enough fresh water was brought into the basin, faunal development could have been kept to a minimum.

The interpretation of a restricted sea, for the deposition of the Murteree Shale and the Roseneath Shale, is justified by its regional relationship with facies in the eastern Permian basins of Australia (Fig. 25). It is seen as the most westerly extent of the marine environment, which encroached across the continent from the east. In a schematic time-depositional environment section (Fig. 36), the restricted sea interpretation fits into a scheme where a marine transgression began during Lower Stage 4, reached its furthest extent during deposition of Murteree Shale, retreated, transgressed again (Roseneath Shale), and then finally withdrew completely from the continent during Upper Stage 5.

Marine deposition became widespread in the Bowen Basin during Lower Stage 4, with limestone (Buffel Formation) being deposited on a wide shallow shelf in the southeast, and marginal marine deposits transgressing westwards over the Denison Trough (Cattle Creek Formation). In the Denison Trough (Fig. 25), there was a westerly provenance, as exemplified by the eastwards deltaic pulse of the Staircase Sandstone (Dickins and Malone, 1973; Power, 1967). At this time, the Patchawarra Formation was still being deposited in the Cooper Basin and in fact, Patchawarra Formation deposits were transgressed from the east at the same time as the westerly transgression through the Denison Trough ceased, to be replaced by an easterly prograding deltaic succesion. Therefore, Cooper Basin palaeogeography cannot be related solely to the present areal extent of Permian basins.

At the time of Murteree Shale deposition, Cooper Basin access to the sea was probably by way of a region to the south of the Galilee Basin. Upper Stage 4 rocks of the Denison Trough, in the Bowen Basin (Fig. 25), comprise marine Sirius Shale, overlain by deltaic Aldebaran Formation (Price, 1976). At the same time as the Murteree lake was transgressing westwards, the Aldebaran delta was prograding eastwards, over the Springsure Shelf (Dickins and Malone, 1973; Jensen, *et al.*, 1976). Therefore the connection between the Cooper Basin and the coastline could not have been through the Galilee Basin. Instead, the most likely area appears to be to the south, which has since been denuded of Permian sediments.

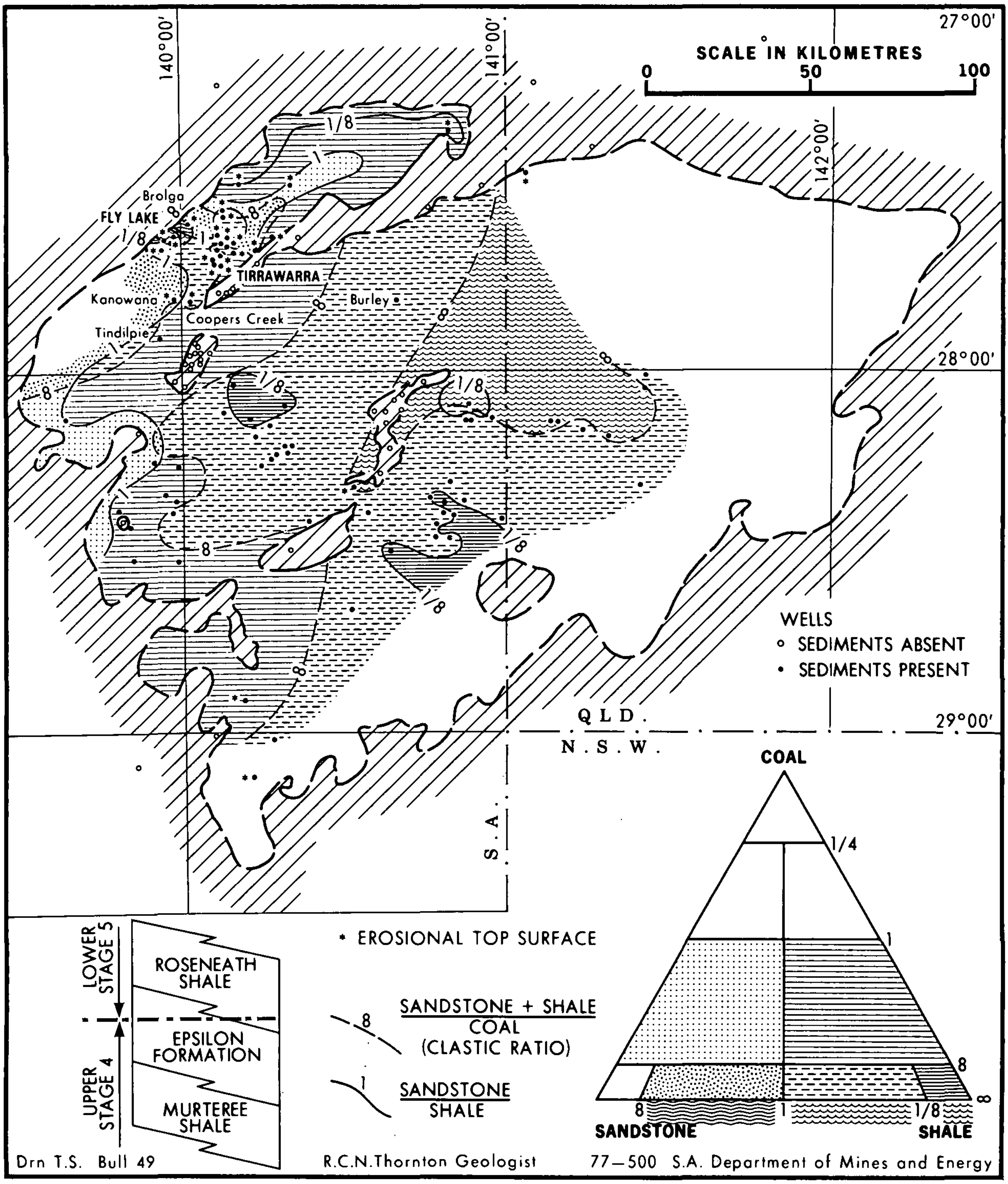


Fig. 37. Epsilon Formation lithofacies map

The possible palaeogeographic relationship between the Cooper Basin and the eastern margin of the Australian continent is shown by the diagrammatic section in Figure 36 (see Fig. 25 for location of section line). The section implies that the area to the south of the Galilee Basin was submerged throughout most of Permian time and erosion has subsequently removed the evidence for this connecting link between the Cooper Basin and the east.

EPSILON FORMATION

Deposition of the Epsilon Formation occurred during uppermost Upper Stage 4, and in the western half of the basin continued into Lower Stage 5 (Fig. 7). The Epsilon Formation conformably overlies the Murteree Shale, and in turn is overlain conformably by the Roseneath Shale. Thus it is the rock record of a

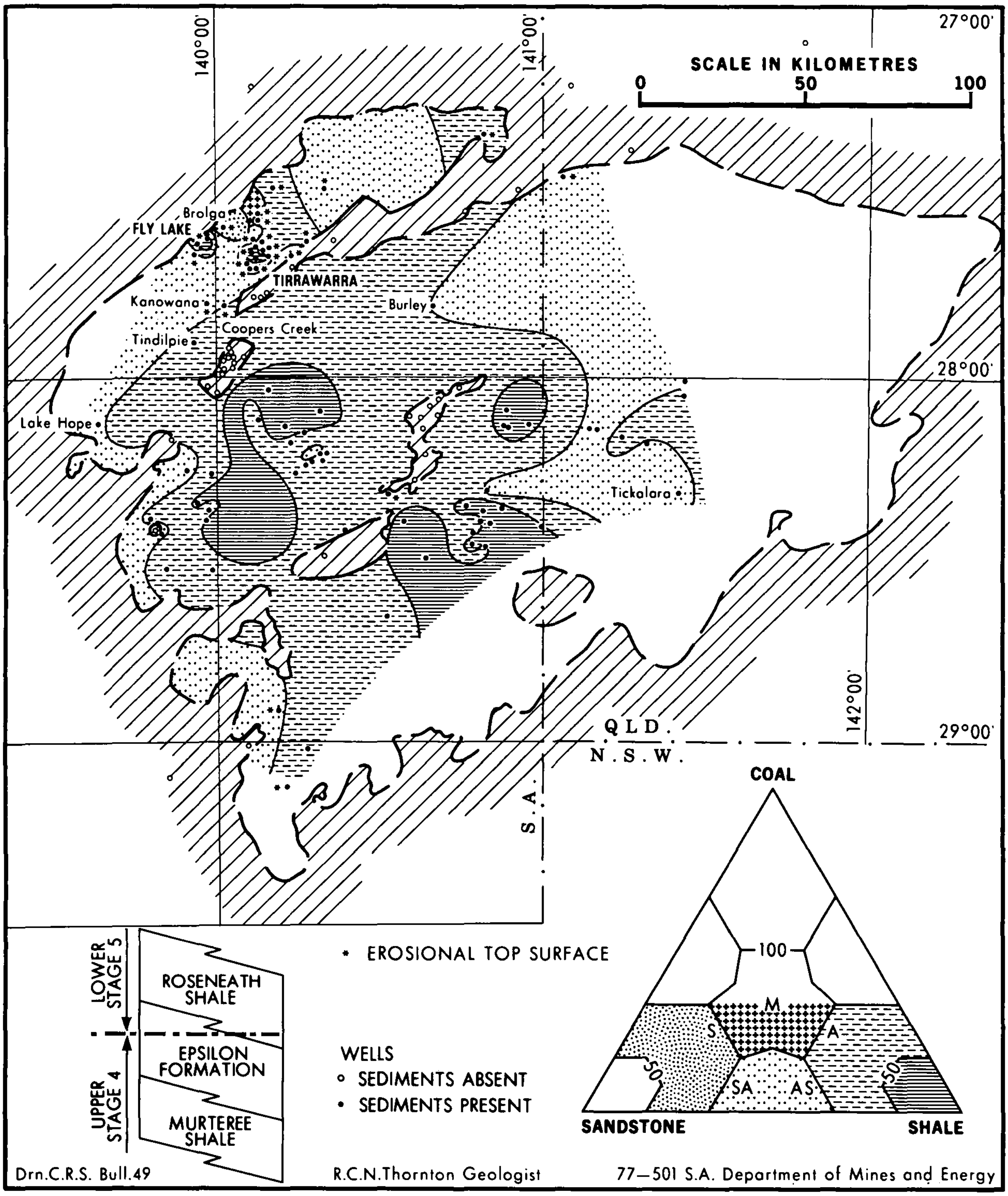


Fig. 38. Epsilon Formation 'D'-function map

lacustrine/marine regression, followed by a lacustrine/marine transgression. That this transgression occurred in a westerly direction has been shown by mapping the diachronous trend of the top boundary of the Epsilon Formation.

The Epsilon Formation comprises shales, sandstones and minor coals. From a study of core material, Stuart (1976) considered that the lower part of the unit comprised shoreline and delta-plain deposits, overlain by ingressive-regressive sandstones and offshore fine clastics.

Distribution of Sediments

The thickness and areal distribution of the Epsilon Formation is essentially the same as that of the Murteree Shale, except that the Epsilon

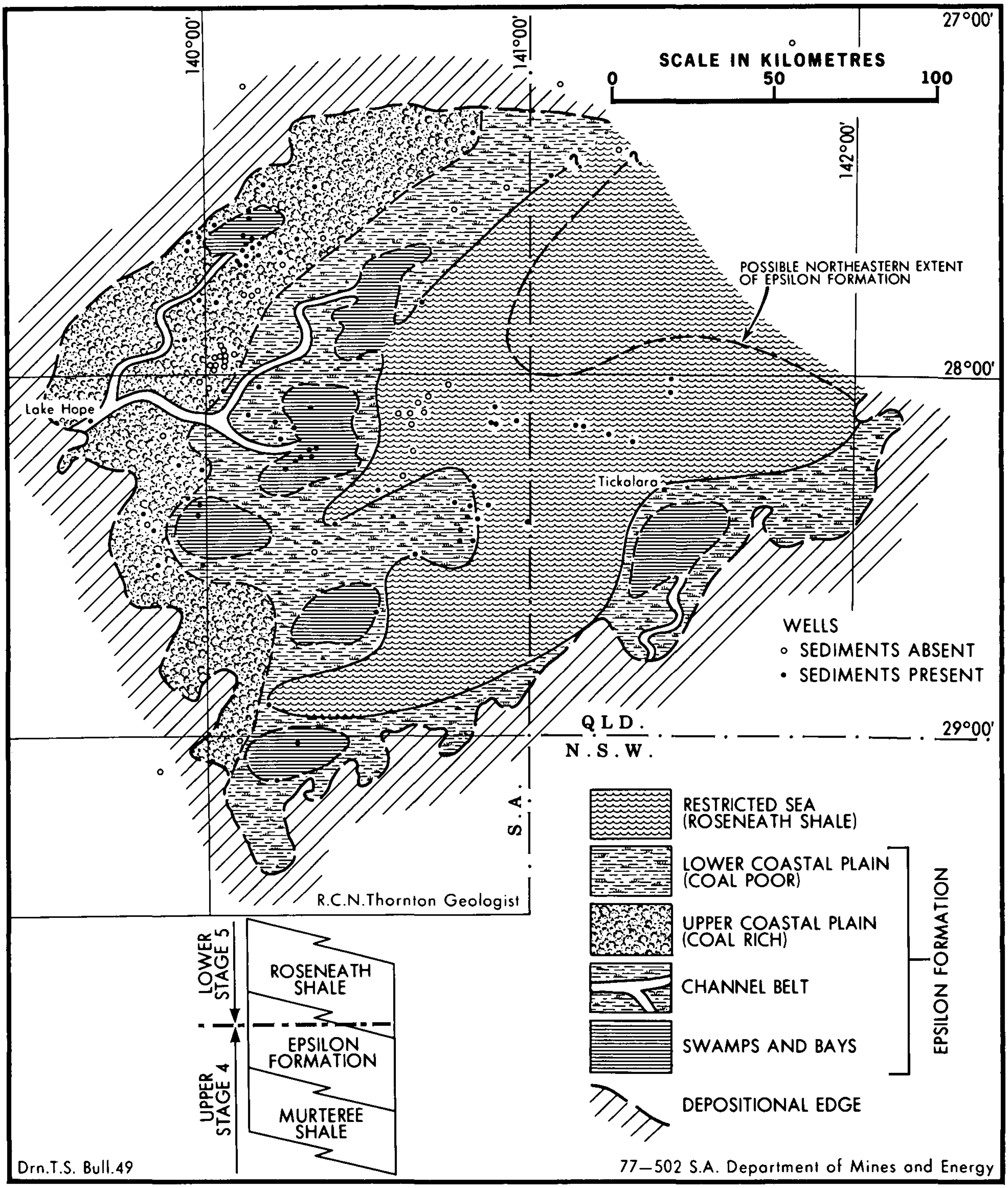


Fig. 39. Palaeogeography at end of Upper Stage 4

Formation is considerably thicker in the Nappamerrie Trough. Burley 1 intersected a maximum thickness of 138 m. No Epsilon Formation is thought to exist north of the Karmona Trend, perhaps due to non-deposition (Figs. 37 and 38).

Some Epsilon Formation may be missing from those wells marked by an asterisk, especially in the northeastern Patchawarra Trough, where Epsilon Formation is directly overlain by Toolachee Formation. At the southwestern end of the Patchawarra Trough, erosion probably did not remove great thicknesses. This is shown by the fact that the section at Cooper's Creek and Kanowana (both with erosional top contacts) is only marginally thinner than at Tindilpie, where Epsilon Formation is overlain by Roseneath Shale. However, towards the northeastern end of the Patchawarra Trough, erosion must have been more significant. This is shown by both the very thin section, and the large variations in lithofacies value of closely spaced wells.

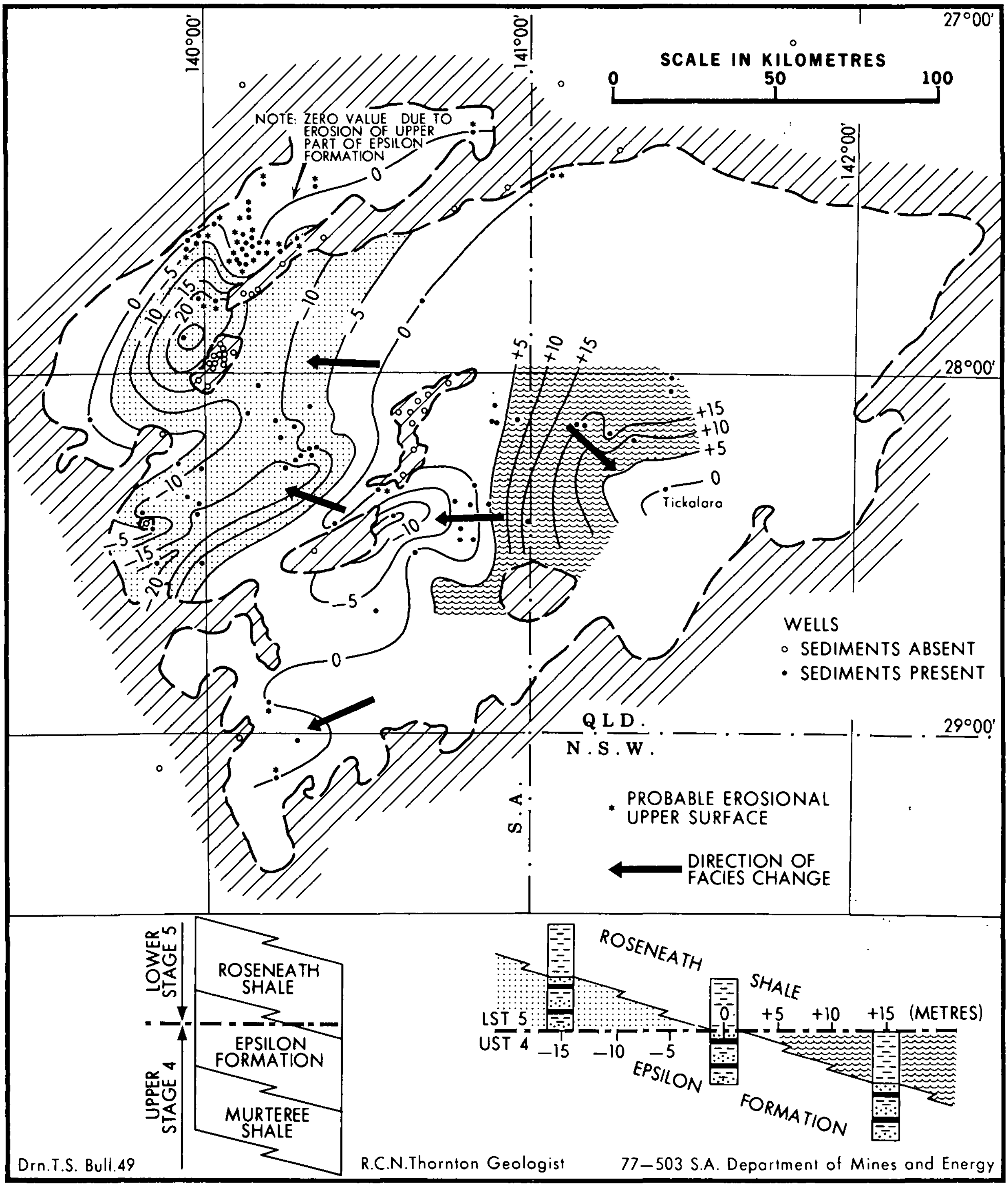


Fig. 40. Upper Stage 4/Lower Stage 5 facies change map

Lithofacies

The Epsilon Formation lithofacies map (Fig. 37) is dominated by shaly facies, which show an eastwards change from coal rich on the western flank to zero coal (clastic ratio = infinity) in the east. On the 'D'-function map (Fig. 38) there is an almost total lack of sandy facies.

In the Patchawarra Trough to the northeast of Kanowana, later erosion has had a serious effect on lithofacies values. For example, in the Tirrawarra Field, sandstone-shale ratios vary from 0·04 to 1·1, and in the Fly Lake Field, the variation is from 0 to 0·81. At Fly Lake, the sections in two wells are only 3 and 5 m thick and contain no sand. The very sandy nature of the Brolga section is also probably unrepresentative due to later erosion.

Palaeogeography and Geologic History

During deposition of the Epsilon Formation, the eastern part of the basin was submerged for longer than the west. Deltaic deposition of the lower part of the Epsilon Formation followed the easterly retreat of the Murteree Lake and thus the eastern part was the last to be subaerially exposed, and then was the first to be drowned again at the onset of the next marine transgression (Fig. 39), which reached its peak during deposition of the Roseneath Shale. The possible most easterly extent of Epsilon Formation progradation is marked on Figure 39.

Indication of longer submergence in the east is provided by the easterly decrease in coal (Fig. 37). As discussed for Upper Stage 4', infinite clastic ratio indicates that coal-forming conditions were never attained, and that the most likely depositional environment is a permanent body of water, if shales predominate.

River development during Epsilon Formation deposition was very minor compared with other periods, as shown by the lack of sandy facies. However, the admixed facies on the 'D'-function map (Fig. 38) in the region of Tickalara may indicate a sediment intake area, feeding much of the basin south of the GMI Trend. The Patchawarra Trough and some of the western part of the basin were perhaps supplied with sediments from the west, near Lake Hope.

The westerly direction of marine transgression is shown by the Upper Stage 4/Lower Stage 5 facies change map (Fig. 40), which shows the depth of the Upper Stage 4/Lower Stage 5 time boundary above or below the top of the Epsilon Formation. The map shows that Roseneath Shale was deposited earlier in those regions where the lithologic boundary is below the time boundary than it was in those regions where it is above. Roseneath Shale is Upper Stage 4 in age only in the eastern part of the basin. In the centre, the top of the time and rock units coincide, while in the west, the base of the Roseneath Shale is Lower Stage 5 in age. Therefore, the lake encroached from the east, and swept westward, except near Tickalara where it inundated the basin flank in a southeasterly direction.

LOWER STAGE 5

Deposition during Lower Stage 5 is represented in the stratigraphic record by the uppermost Epsilon Formation, the Roseneath Shale and the Daralingie Beds (Table 1). The Lower Stage 5 time unit is not an ideal mapping unit for the accurate determination of palaeogeographic trends. Therefore, separate isopach and lithofacies maps have been prepared for the Roseneath Shale, and a unit modified from the Daralingie Beds and designated by quotation marks 'Daralingie Beds'. The 'Daralingie Beds' vary from the Daralingie Beds in having their lower boundary as a time plane.

Lower Stage 5 is unsuitable for lithofacies analysis because it incorporates only parts of two separate sandstone-shale-coal units. In addition, the shale section which separates these two units is much thicker than they are, so that shale forms the greatest lithologic percentage. As a result, the lithofacies classes used are too broad to differentiate trends. Finally, post-depositional erosion has removed much of the Lower Stage 5 section, which consequently is complete only in the more synclinal regions of the basin.

The Roseneath Shale conformably overlies the Epsilon Formation and has a lithology and interpreted depositional environment similar to those of the Murteree Shale. The retreat of the Roseneath lake/sea is documented by regressive sandstones of the lowermost Daralingie Beds (Stuart, 1976). The Daralingie Beds were deposited from two northeasterly prograding delta systems.

Distribution of Sediments

Lower Stage 5 rocks are more limited in extent than those of any other stage, largely as a result of post-depositional erosion. They occur to the south of the GMI and Karmona anticlinal trends, and at the southwestern end of the Patchawarra Trough. The sediments are thick only in the Nappamerrie Trough, where a maximum of 156 m was encountered at Burley, and near Toolachee East (Fig. 41). Lower Stage 5 sediments may never have been deposited at the northeastern end of the Patchawarra Trough, or north of the Karmona Trend.

The distribution of Lower Stage 5 rocks is the result of two periods of erosion, and also perhaps to some degree of depositional basin shrinkage. The distribution of the three rock units deposited during Lower Stage 5 varies widely, as shown on the subcrop map (Fig. 42). On this map Epsilon Formation directly underlies the Early/Late Permian unconformity in the area marked '1'. The subcrop of the lower half of the Roseneath Shale is shown by the area marked '2', the upper half by '3', and Daralingie Beds by '4'. The full stratigraphic record occurs only in the synclinal areas, and everywhere the section becomes less complete towards the margin of the basin.

The first phase of erosion, which affected Lower Stage 5 distribution, occurred at the end of Early Permian, and had a major influence in the southern half of the basin. The western part of the basin was affected by a second period of erosion at the end of Triassic deposition.

The first period of erosion accompanied a major tectonic readjustment of the basin, which included uplift of the GMI and MN anticlinal

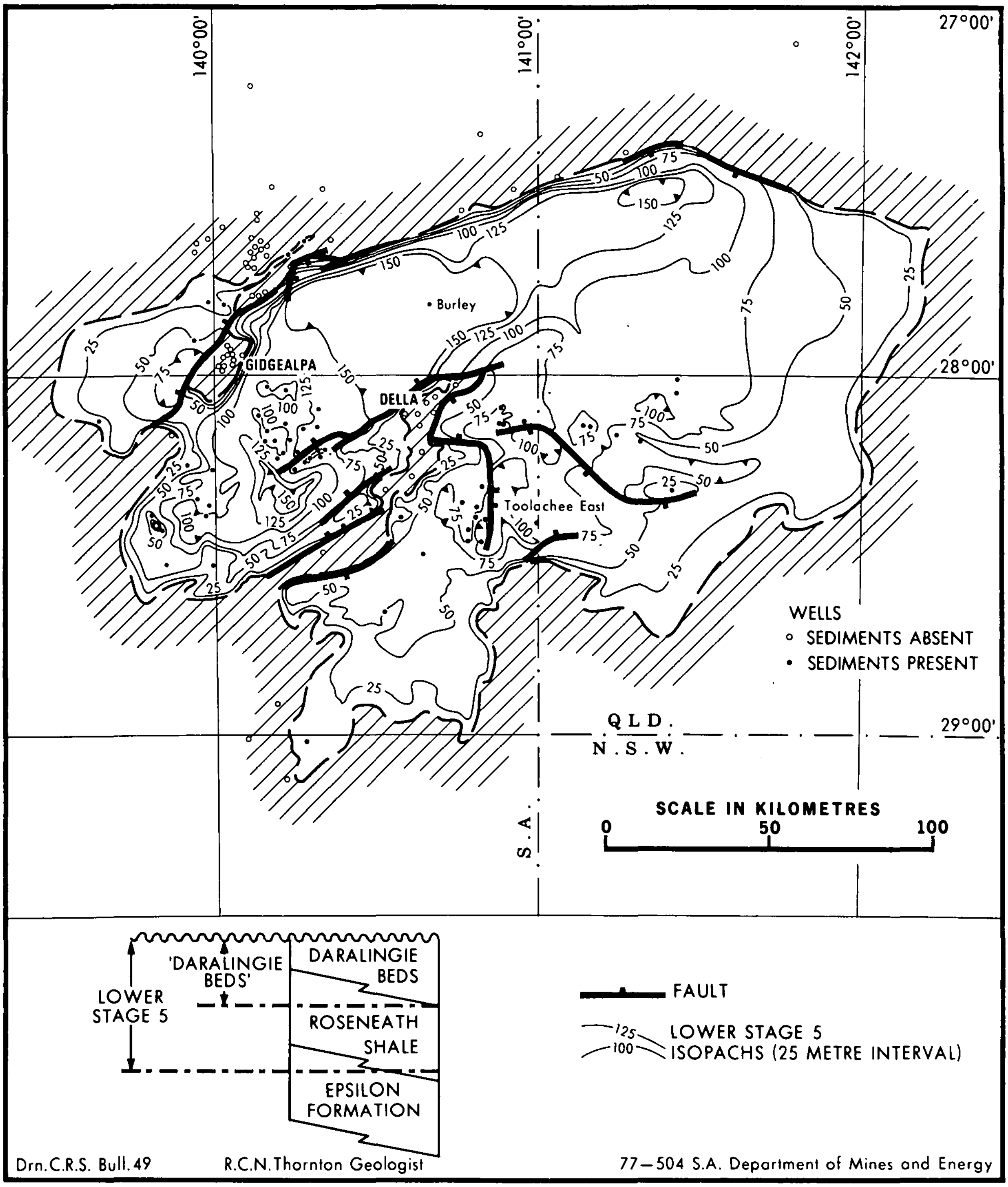


Fig. 41. Lower Stage 5 isopach map

trends. Erosion occurred throughout the basin, affecting not only the anticlines along the major trends but also those within the Nappamerrie Trough. Basin-wide, the total thickness removed is hard to judge, especially in the synclines, where there is virtually no angular unconformity between the Early and Late Permian sediments.

Evidence for this erosion at the end of Lower Stage 5 is provided in several areas in which detailed studies have been made. In the Della Field, detailed cross-sections show that progressively older rocks have been removed up the flanks of the structure to the crest (Pyecroft, 1973, figs. 6 and 7). Here, at Della 5A sediments of Upper Stage 5' age directly overlie pre-Permian rocks. A very similar picture can be seen at Gidgealpa (Wopfner, 1966). In a third area, the Nappamerrie Trough, erosion is interpreted from seismic section JBI, Tooroopie Seismic Survey, which indicates loss of section

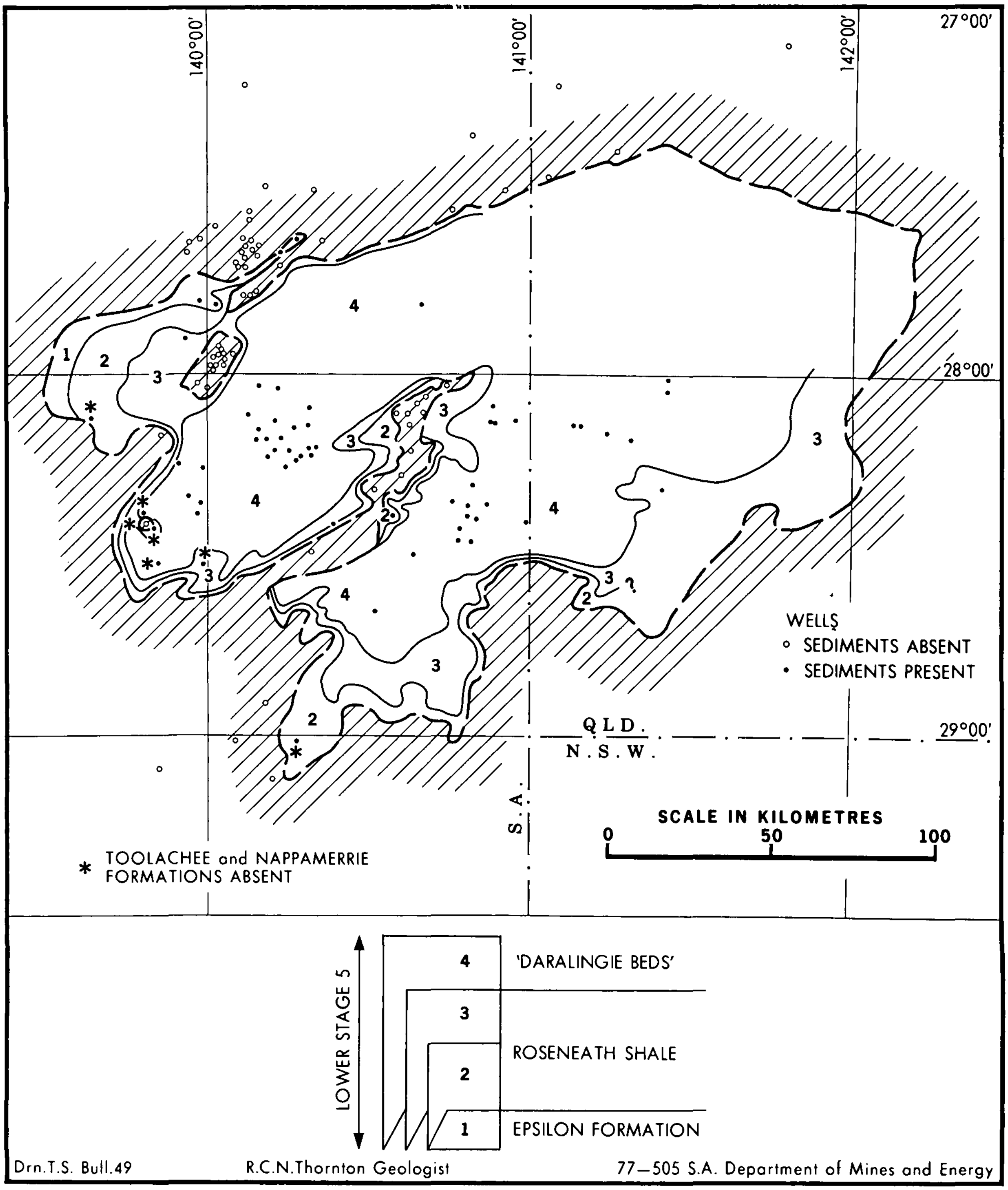


Fig. 42. Subcrop map of rock units beneath mid-Permian unconformity

beneath the pre-Toolachee Formation unconformity over the Kirby anticlinal prospect (Hollingsworth, *et al.*, 1976) at the northern part of the Nappamerrie Trough, north of Burley 1.

Erosion at the end of Lower Stage 5 also appears to have caused the present sediment distribution in the Patchawarra Trough. Near Mudrangie, a thin pod of sediments is preserved in an area too narrow to have been the full width of the original depositional trough. It is most likely that Lower Stage 5 sediments were laid down throughout much of the southern Patchawarra Trough, with relative uplift decreasing from the northern part southwards, only in the thickest and deepest areas was any section preserved. Preservation occurred at Mudrangie because it was on the down-thrown side of an active fault.

Palynologic evidence for a time break at the end of Lower Stage 5 rests on the fact that certain microfloral assemblages have not been detected in the Cooper Basin. These assemblages, which have been found in the Bowen Basin to the east, are of Early to Late Permian age (Lower Stage 5c and Upper Stage 5a on Table 1, Price, 1973). The long time break indicated by the palynologic evidence would have allowed considerable erosion to take place.

The distribution of Lower Stage 5 sediments was probably influenced by a second period of erosion, during the Triassic, in the last phase of Cooper Basin development (Battersby, 1976). Erosion affected the western and southwestern flanks of the basin, and along this margin, seven wells (marked on the subcrop map with an asterisk, Fig. 42) contain neither Toolachee, nor Nappamerrie Formation above Early Permian rocks (see Sect. B-B, Fig. 7). The lack of Late Permian and Triassic sediments is thought to be due to the period of erosion which marks the end of the Cooper Basin as a structural entity. Therefore, it is to be expected that Early Permian sediments were eroded during this period also.

Although erosion had a major influence on the present distribution of Lower Stage 5 sediments, shrinkage of the depositional area of the Cooper Basin may have been a contributing factor. The reason for this interpretation lies in the absence of all sediments of this Stage from the northern part of the basin. However, this situation could also have been caused by erosion at the end of Lower Stage 5, especially since the area of the Cooper Basin was levelled to a surface of low relief (peneplain or pediplain) by the end of this erosional phase (discussed later).

ROSENEATH SHALE

The Roseneath Shale is a diachronous rock unit with its basal contact on the Epsilon Formation varying in age from uppermost Upper Stage 4 to Lower Stage 5. The upwards change to Daralingie Beds deposition took place during mid-Lower Stage 5. Its lithology and depositional environment are essentially the same as those of the Murteree Shale.

Distribution of Sediments

Except for a small area in the Patchawarra Trough, the Roseneath Shale covers as great an area as the complete Lower Stage 5 time unit (Fig. 43). It is thickest in the eastern half of the basin, where it attains a maximum thickness of 88 m at Toolachee East. On the whole, thickness variations are very slight, which suggests that the depositional surface was very flat and subsidence uniform.

Palaeogeography and Geologic History

The Roseneath Shale was deposited in one large lake, which transgressed from the east and began to inundate the basin before the end of the Upper Stage 4 (Fig. 39). When the transgression was complete, the whole of the Cooper Basin was covered. This lake was either a large inland body of fresh water, or had restricted access to the sea, for the same reasons as discussed for the Murteree lake.

On a continental scale, the palaeogeography of the Cooper Basin with respect to the coastline is similar to that during deposition in the Murteree lake, and connection between the basin and the sea could not have been by way of the Permian basins as they exist today. In the Galilee Basin (Fig. 25), equivalents of the fluvial Colinlea Sandstone were being deposited from rivers which moved south, and then eastwards over the Springsure Shelf to deposit the deltaic Aldebaran formation in the Denison Trough (Dickins and Malone, 1973; Jensen, *et al.*, 1976; Hawkins, 1976). It is most likely that any marine access to the Cooper Basin, if it existed, was to the south of the present day basin limits (Fig. 36).

'DARALINGIE BEDS'

The 'Daralingie Beds' grade from the uniform shale lithology of the Roseneath Shale to interbedded shales, sandstones and coal. They are very similar to the Daralingie Beds except that their lower boundary is a lithologic marker assumed to approximate a time plane. This lower boundary has been chosen in order that directions of the facies change will be apparent. The top of the beds is limited by an erosional surface. The interpretation of lithofacies and sediment thickness patterns is complicated by the erosional upper limit, but nevertheless a valid interpretation is possible. The 'Daralingie Beds' are interpreted to have been laid down as a regressive succession by two delta systems encroaching from the south into the retreating Roseneath lake.

The base of the 'Daralingie Beds' has been picked in each region of good well control as a siltstone time marker at, or near, the top of the Roseneath Shale. This counteracts the effect of the inevitable diachroneity of the bottom of the Daralingie Beds in the lithofacies interpretation. Gatehouse (1972) defined the base as the first arrival of sandstone above the Roseneath Shale. The use of a time-rock line for the base is necessary so that depositional trends would not be hidden because the Daralingie Beds are thin, and not areally very extensive.

The Toolachee 1, 3 and 7 wells show the divergence between the basal contacts of the

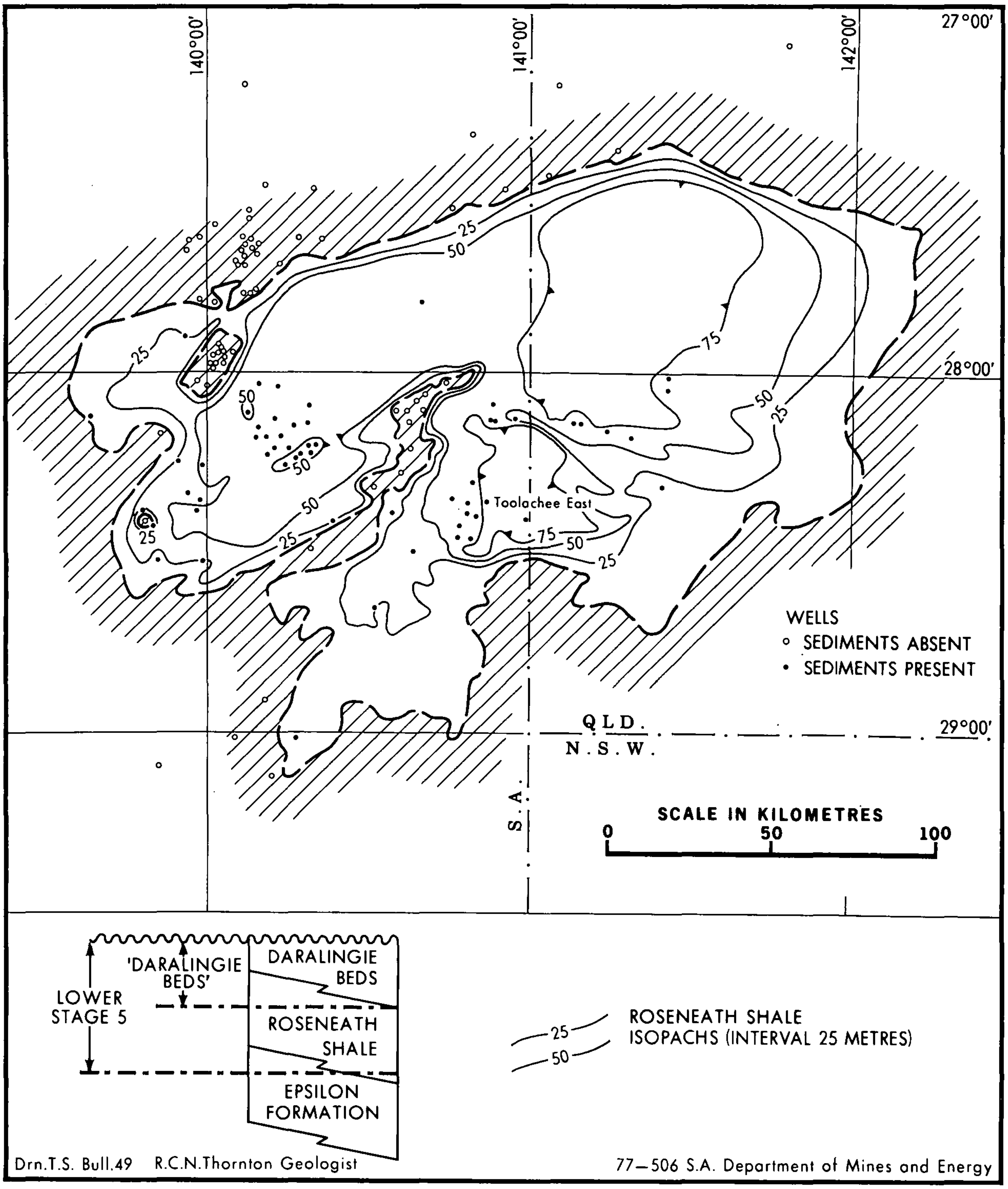


Fig. 43. Roseneath Shale isopach map

two units, and also the effect of erosion on the top surface (Fig. 44). The time lines which are marked on this diagram have been picked on the basis of gamma-ray and sonic-log character, and consist of thin silty bands and coals. The validity of these as time markers is discussed by Weimer (1966). By definition, the diachronous base of the Daralingie Beds occurs at the first point above the Roseneath Shale where the gamma-ray curve falls below the 100 API line. In the uppermost part of the Roseneath Shale, on moving up the log, the gamma-ray curve bends towards 100 API, because of the upwards decrease in shale associated with the gradual change from one sub-environment to another.

Different arbitrary time lines have been chosen as the base of the 'Daralingie Beds' in each area with high-well density, because of the

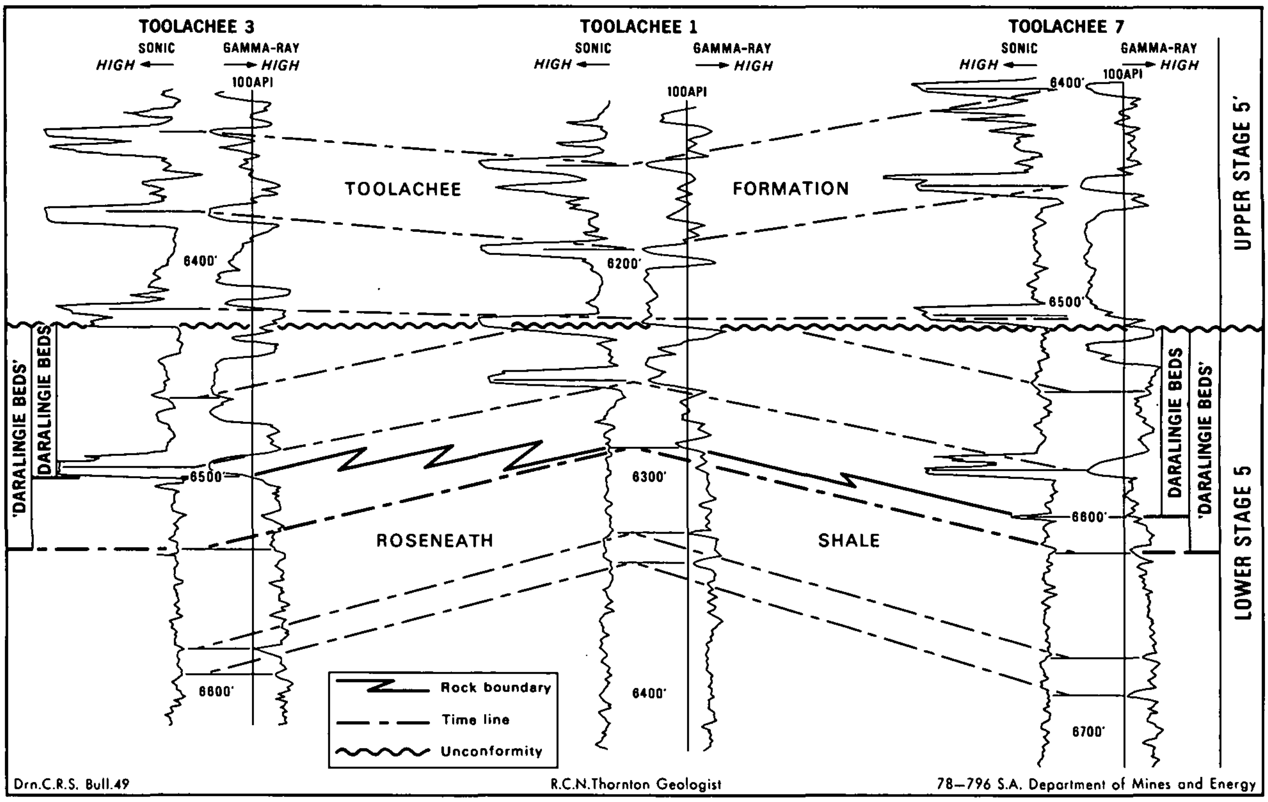


Fig. 44. Toolachee 1, 3 and 7. Relationship between rock boundaries and time lines

large distance between gas fields. Consequently, these lines are probably not exactly synchronous with one another. Therefore, between different areas, comparison should be made between general trends rather than values on the lithofacies maps.

Erosion has removed an unknown thickness of 'Daralingie Beds'; with increasing amounts taken from the top of anticlines (for example, Fig. 44). Nonetheless, the section which remains is the record of deposition throughout the basin during the early stages of the Roseneath lake regression. The facies maps (Figs. 45 and 46) are useful to indicate the directions of progradation.

Further weight is given to the regressive nature of 'Daralingie Beds' deposition by the gamma-ray log character of two sandstones, at the base of the 'Daralingie Beds', along the southwestern flank of Moomba. These sandstones have a distinctive funnel-shaped gamma-ray log character, which is due to an upwards graduation from shale, through siltstone, to sandstone. Conybeare (1976) considers the funnel-shaped log pattern to be indicative of regressive shoreline sand bodies, and Battersby (1976) interpreted the Moomba sandstones as such. The maximum thicknesses of the two sandstones are 3·6 m and 5·6 m (Fig. 47).

Distribution of Sediments

The 'Daralingie Beds' have a smaller areal distribution than the other rock units of Lower Stage 5 age (Figs. 45 and 46) largely due to later erosion, as has been discussed already. Sediments occur only in the Nappamerrie and Tennapera Troughs. The unit is very thin, except in the deeper parts of the Nappamerrie Trough, where Burley 1 intersected a maximum thickness of 96 m.

Lithofacies

The 'Daralingie Beds' are dominated by shales, with rather less sandstone, and very little coal. Consequently, the lithofacies distributions are portrayed more effectively with maps of sandstone-shale ratios (Fig. 45), and coal percentages (Fig. 46), than they would have been by the normal lithofacies and 'D'-function maps.

Both the Nappamerrie and Tennapera Troughs show very similar facies patterns of a central northeasterly trending region of high sandstone-shale ratios, flanked by increasingly

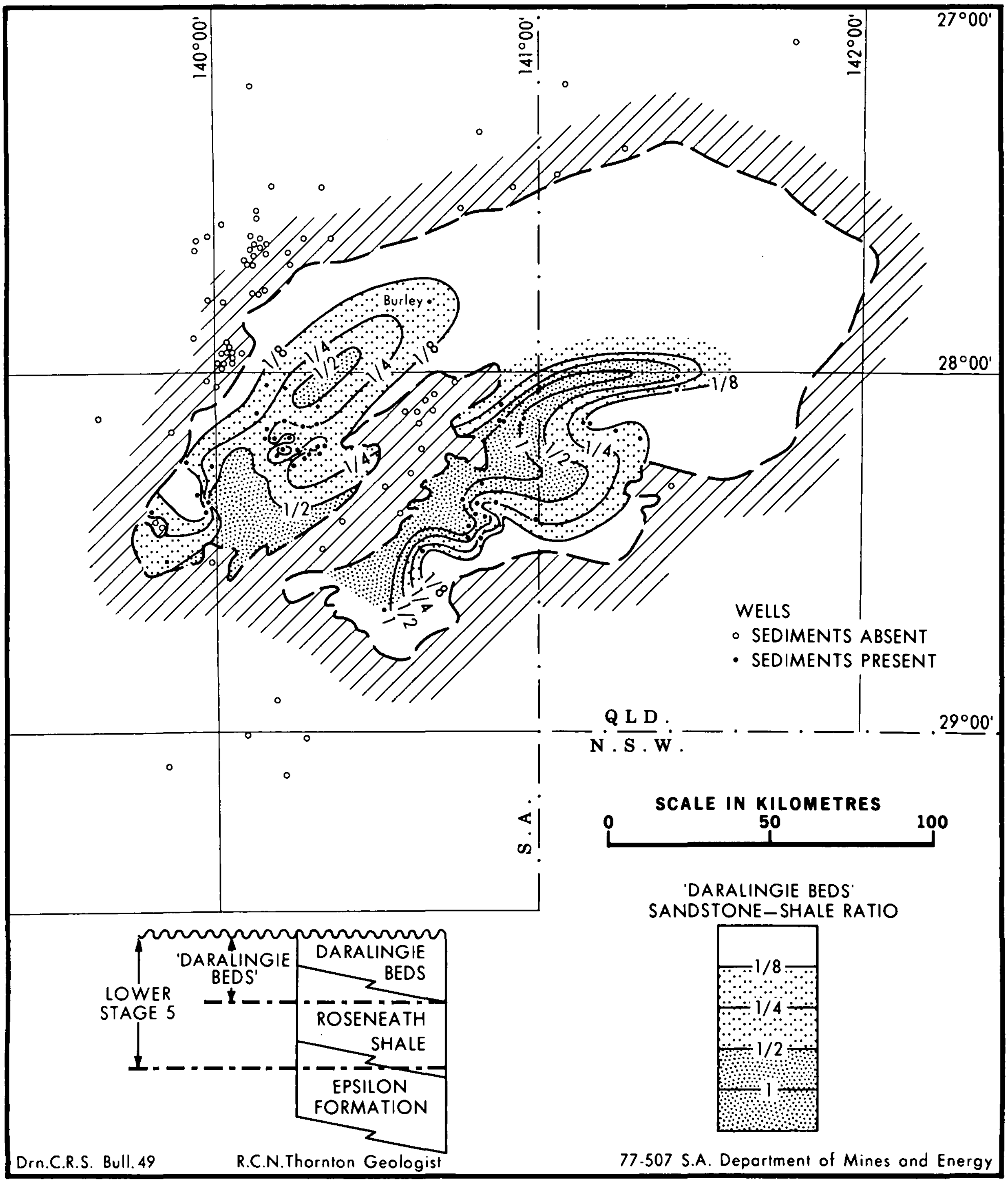


Fig. 45. 'Daralingie Beds' sandstone-shale ratio map

lower ratios (Fig. 45). Coal distribution is concentrated in four small areas (Fig. 46). These lithofacies patterns are interpreted to indicate the position of two deltas.

Evidence from a specific area in support of this regional lithofacies interpretation results from a detailed study of the two basal 'Daralingie Beds' sandstones at Moomba: these sandstones have the funnel-shaped log character (Fig. 47). They are interpreted as delta-front sheet sands on the basis of their internal grain size variations, sand body geometry, and distribution. Grain size variation is interpreted from log character.

Both sandstones occupy a similar position along the western flank of the Moomba anticline where they attain a maximum thickness of 3·6 m and 5·6 m. Their known areal extent is at least 10 × 25 km, although their western limit has not yet been determined by drilling. In each sandstone body, the succession consists of

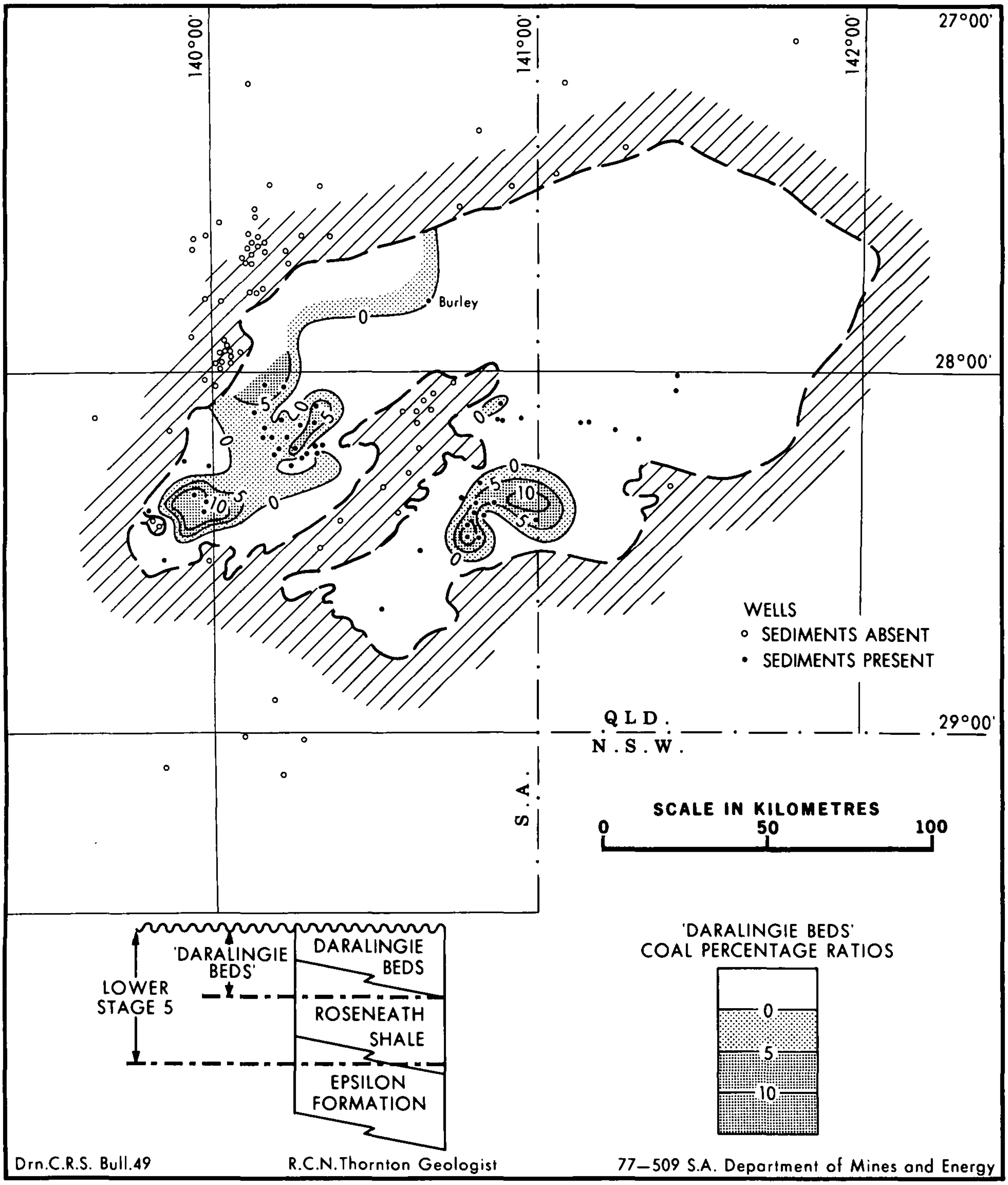


Fig. 46. 'Daralingie Beds' coal percentage map

lowermost siltstone, overlain by dirty sandstone, in turn overlain by clean, porous gas-bearing sandstone. In both sandstone bodies, the lowermost siltstone extends further to the east than the dirty sandstone, which in turn extends further than the uppermost, gas-bearing, clean sandstone.

The upwards increase in grainsize of these sandstone bodies is suggestive of a shoreline deposit, either a barrier-island sand body, chenier sand, or delta (LeBlanc, 1972). However, their sheet-like nature tends to rule out the first two of these alternatives, as sandstone bodies deposited in these environments tend to be long and narrow. Furthermore, the distribution of the rock types within each sandstone body leads to the interpretation that they were deposited at the front of the prograding delta, as it built out eastwards over a platform of shales and silts into the Roseneath lake. The abondoned Lafourche lobe of the Mississippi delta is a modern analogue (Gould, 1970, fig. 11).

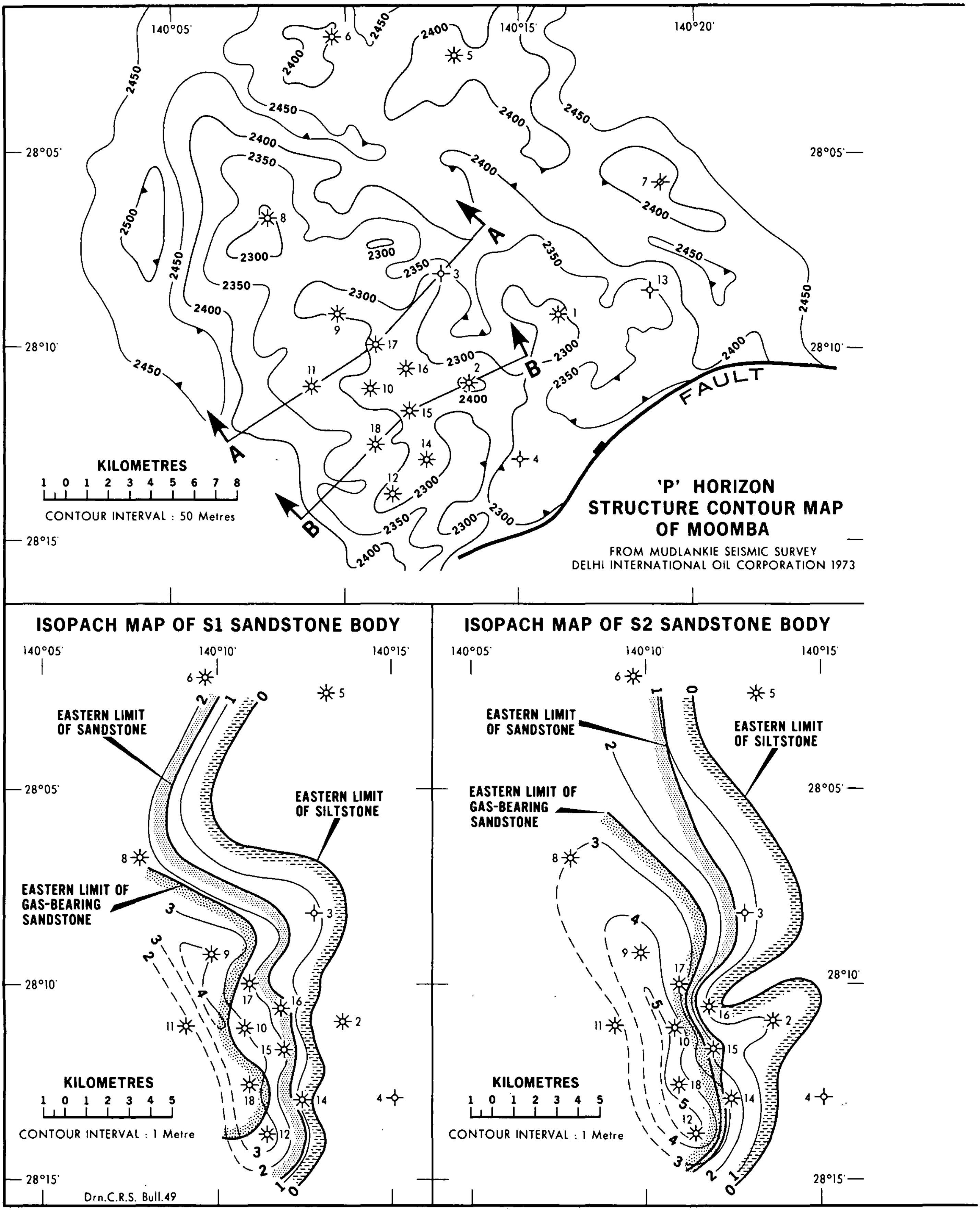
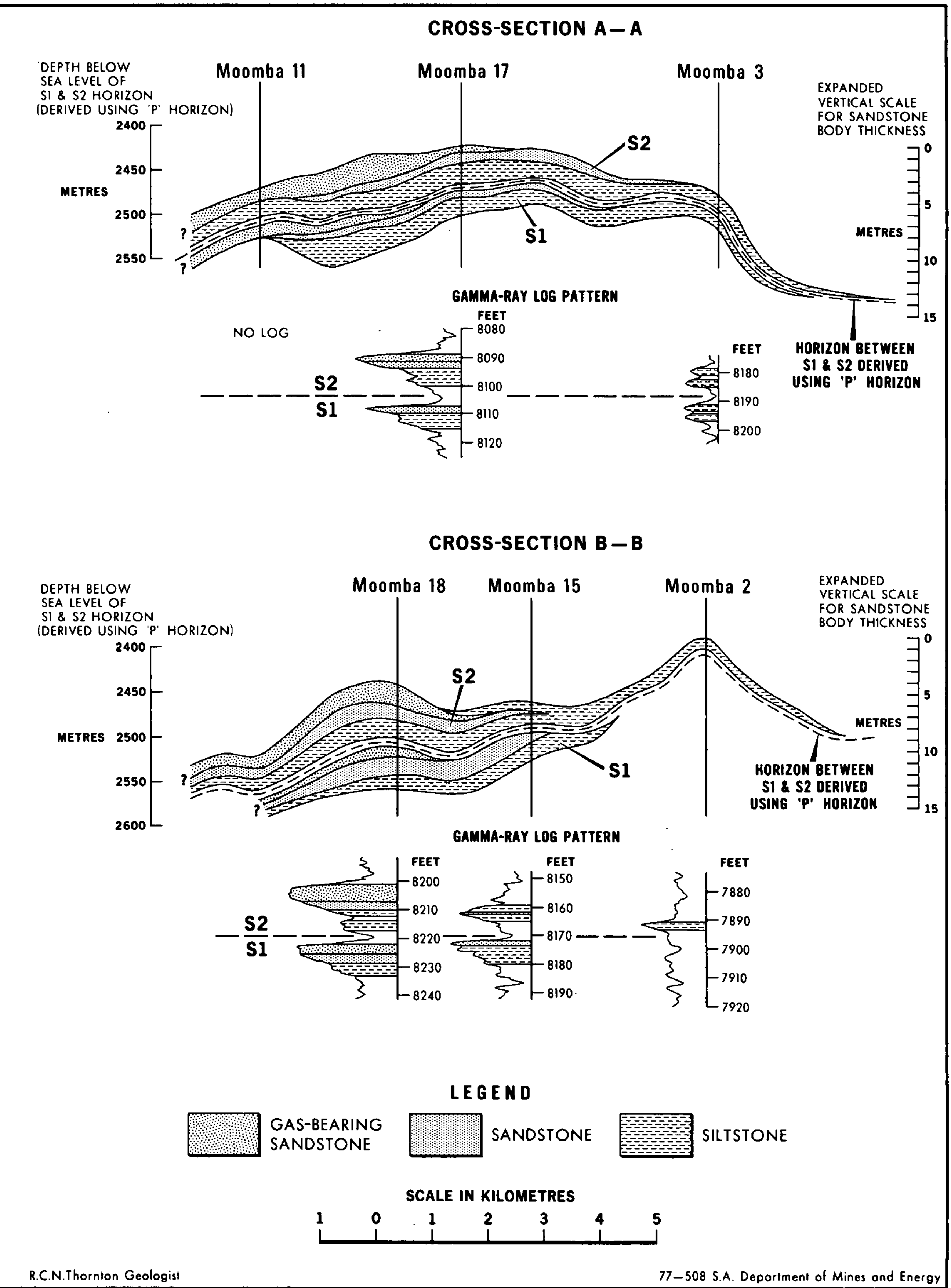


Fig. 47. 'Daralingie Beds' delta front sandstone bodies at Moomba


CROSS-SECTION A—A
DEPTH BELOW SEA LEVEL OF S1 & S2 HORIZON (DERIVED USING 'P' HORIZON)
METRES
2400
2450
2500
2550
Moomba 11
Moomba 17
Moomba 3
S2
S1
EXPANDED VERTICAL SCALE FOR SANDSTONE BODY THICKNESS
0
5
METRES
10
15
GAMMA-RAY LOG PATTERN
NO LOG
FEET
8080
8090
8100
8110
8120
FEET
8180
8190
8200
HORIZON BETWEEN S1 & S2 DERIVED USING 'P' HORIZON
CROSS-SECTION B—B
DEPTH BELOW SEA LEVEL OF S1 & S2 HORIZON (DERIVED USING 'P' HORIZON)
METRES
2400
2450
2500
2550
2600
Moomba 18
Moomba 15
Moomba 2
S2
S1
EXPANDED VERTICAL SCALE FOR SANDSTONE BODY THICKNESS
0
5
METRES
10
15
HORIZON BETWEEN S1 & S2 DERIVED USING 'P' HORIZON
GAMMA-RAY LOG PATTERN
FEET
8200
8210
8220
8230
8240
FEET
8150
8160
8170
8180
8190
FEET
7880
7890
7900
7910
7920
LEGEND
GAS-BEARING SANDSTONE
SANDSTONE
SILTSTONE
SCALE IN KILOMETRES
1 0 1 2 3 4 5
R.C.N.Thornton Geologist
77—508 S.A. Department of Mines and Energy

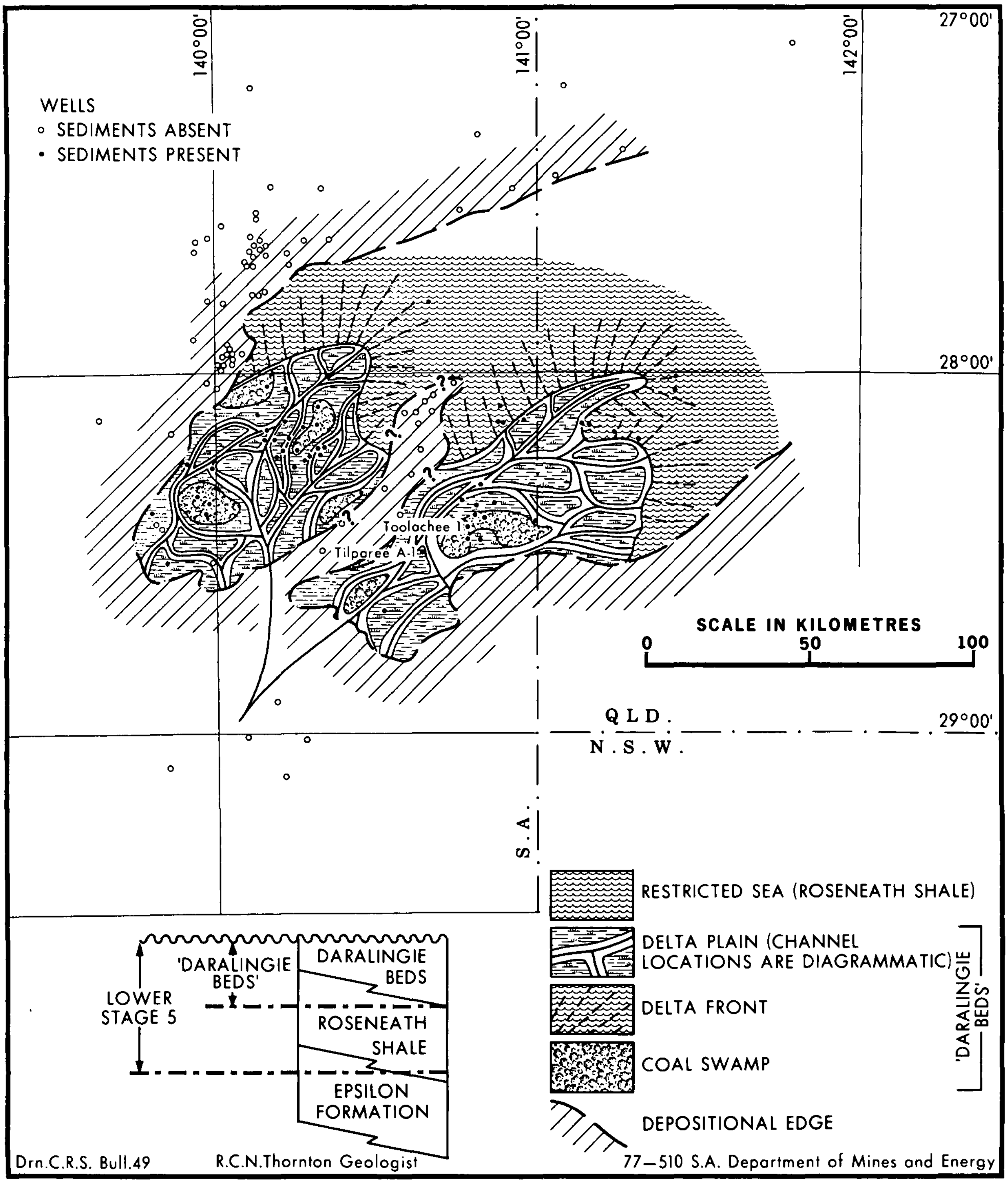


Fig. 48. Palaeogeography during late Lower Stage 5

Palaeogeography and Geologic History

The 'Daralingie Beds' were deposited in two northeasterly prograding delta systems, which were fed by a major river from the southwest (Fig. 48). The shape of the deltas is indicated from the sandstone-shale ratio map. At least four small, isolated coal swamps developed on the flanks of the delta channels.

Support for the interpretation of the northeasterly deltaic progradation in the Tennapera Trough is provided by the diachronous nature of the boundary between Roseneath Shale and Daralingie Beds, shown on cross section C-C (Fig. 8). The divergence of time and rock lines between Tilparee A-1 and Toolachee 1 suggests that the Daralingie Beds were deposited in the southwest first.

UPPER STAGE 5′

The section mapped as Upper Stage 5′ is identical to the Toolachee Formation (Table 1). It differs from Upper Stage 5 only in that it includes rocks of the *P. reticulatus* assemblage zone at the top. The basal surface of Upper Stage 5′ is an unconformity, and its top surface is gradational with the overlying Napamerrie Formation (Papalia, 1969; Battersby, 1976; Stuart, 1976). The *P. reticulatus* zone has been included because it is very thin, and while it has been recognised in the more recently drilled wells there is insufficient evidence for its presence in all wells. The top of the Toolachee Formation is a rather dubious time boundary, because sedimentation was continuous into the Nappamerrie Formation, and units with diachronous boundaries are not ideal for lithofacies analysis. However, the level of diachroneity is perhaps not very great, because the top of the Toolachee Formation is the same as the top of the *P. reticulatus* time zone, wherever that palynologic unit occurs. In fact, the boundary may be hardly diachronous at all if the transition from Toolachee to Nappamerrie Formation environments was the result of a change in climate, as suggested by Wopfner (1972).

The unconformable base of the Toolachee Formation is a suitable basal boundary of a unit for lithofacies analysis as sedimentation, once begun, would have spread throughout the basin over a relatively short space of time, because erosion had created a mature land surface. Furthermore, a basal unconformity, while it may be slightly diachronous, does not present the problem of intertonguing of other facies for lithofacies analysis, which a diachronous conformable boundary does.

The sandstones, shales and coals of Upper Stage 5′ were deposited within a fluvial regime: the lower part of the section is dominated by point-bar and channel sandstones, but in the upper part, shales and coals became increasingly important (Battersby, 1976; Stuart, 1976). The Gidgealpa 6 cores contain fining upwards successions indicative of a fluvial origin. Sediments were deposited from rivers of gradually declining flow gradient until marsh and lacustrine conditions prevailed for long periods of time (Thornton, 1973).

Distribution of Sediments

Upper Stage 5′ rocks are widespread in comparison with most of the earlier Stages (Fig. 49). Furthermore, in spite of the fact that this is a relatively thick unit, thickness variations, especially across the major faults, are slight and deposition in much of the eastern part of the basin is thicker than during previous periods. This relative increase in thickness is especially noticeable on the Tickalara and Wolgolla anticlinal trends, and in Orientos (Sect. C-C, Fig. 8). The Patchawarra Trough, in contrast, contains only a thin section.

Deposition commenced on a surface of low relief, either a peneplain or pediplain. The gentle thickness gradients, the blanketing of most of the anticlinal trends by thick sections of sediment, and the relatively uniform thickening from the margins to the centre of the basin, all support this concept. However, erosion probably did not completely flatten the relief on some of the most pronounced anticlines, which remained as minor hills (Battersby, 1976).

Some of the anticlines along the GMI and Karmona Trends, and perhaps the Murteree structure, were probably topographic features, which stood above the level of the peneplain throughout Upper Stage 5′ deposition. The anticlines along these trends are bare of Upper Stage 5′ sediments, but are covered by a thick section of Triassic Nappamerrie Formation. The absence of Upper Stage 5′ sediments cannot be attributed to erosion because deposition was continuous from Toolachee Formation to Nappamerrie Formation throughout the rest of the basin. This interpretation of the absence of sediments representing non-deposition on topographic features carries with it the corollary that Upper Stage 5′ sediments have onlap relationships, with the anticlines along the Merrimelia-Innnamincka and Murteree Trends. The three wells whose stratigraphic sections contain the Nappamerrie Formation without underlying Upper Stage 5′ sediments are Spencer 1 and Merrimelia 2 located at the southwest and centre of the GMI Trend, and Tallalia 1 on the Karmona Trend.

An alternative theory to explain the absence of Upper Stage 5′ sediments on the above structures is that local erosion denuded these anticlines late in Upper Stage 5′. If this concept is correct, then the depositional surface was flat to begin with, and the anticlinal structures were uplifted during the early part of Upper Stage 5′. Then, erosion lowered the structures to the level of the depositional plain before the Nappamerrie Formation was deposited. This suggestion can be rejected because it implies a rather more structurally active environment than other evidence indicates. For example, the lack of large variations in thickness across most of the main faults (Fig. 49) suggests that Upper Stage 5′ was a fairly stable period. It is probable that gentle subsidence was more the tectonic style than vigorous uplift.

During deposition of Upper Stage 5′, the eastern half of the basin appears to have been the area most prone to subsidence, because it accumulated the thickest sequence of sediments. On the other hand, the very thin section in the Patchawarra Trough presumably indicates that it had a lesser rate of subsidence than areas to the south of the GMI anticlinal trend.

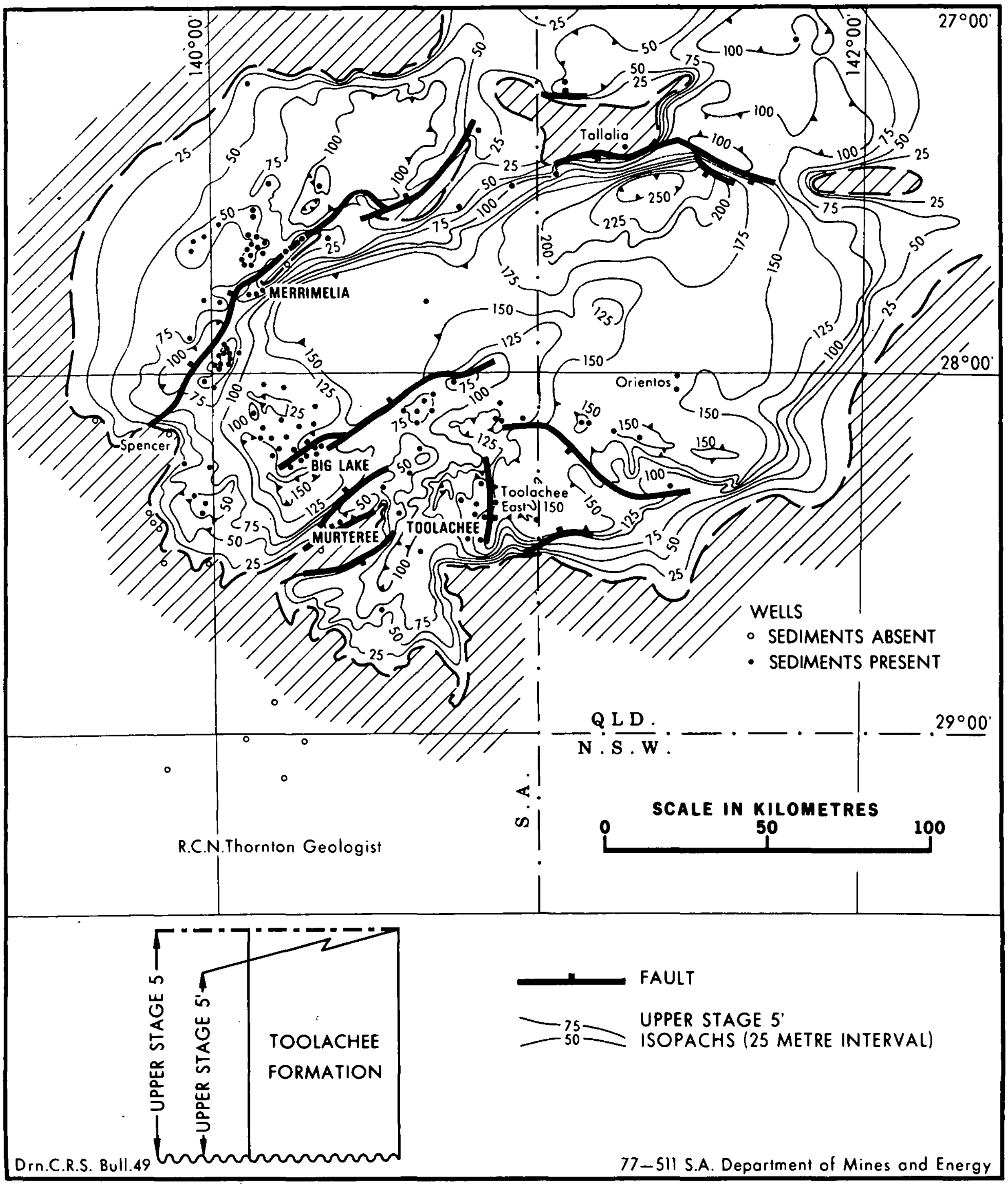


Fig. 49. Upper Stage 5' isopach map

Lithofacies

Upper Stage 5' rocks consist of much more equal proportions of sandstone, shale and coal than the Early Permian sediments. As a result, clastic ratios are low on the lithofacies map (Fig. 50), mixed facies predominate on the 'D'-function map (Fig. 51), and single lithology facies are virtually absent from both. However, sandstone is predominant on the western flank, whereas coal-rich facies occur along the southern margin and the GMI anticlinal trend.

Some of the anticlinal structures are characterised on the facies maps by an increase in shale content over their crests. The best examples are Tirrawarra, on the lithofacies map, and Toolachee on the 'D'-function map. At Toolachee, lithofacies boundaries parallel the

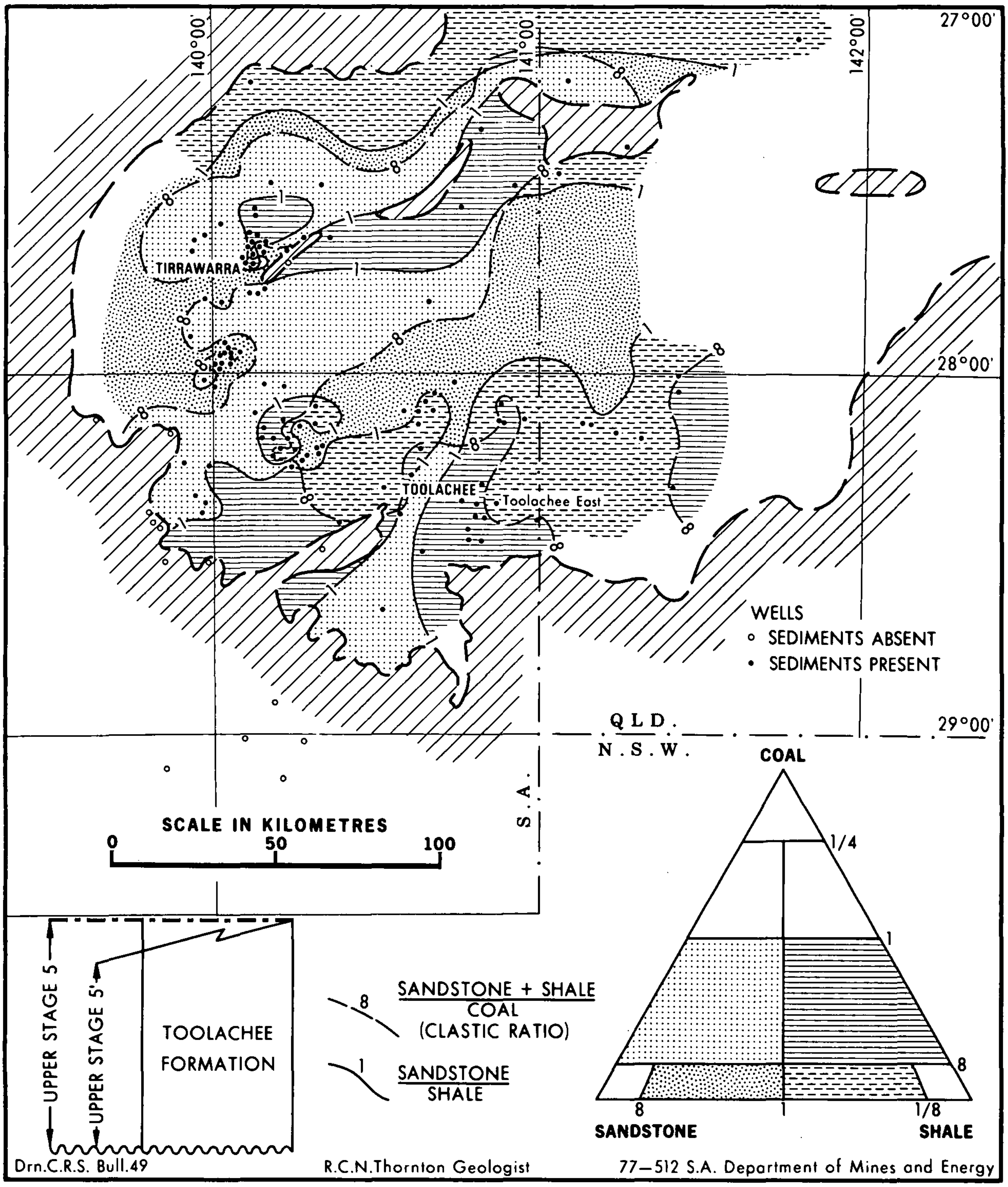


Fig. 50. Upper Stage 5' lithofacies map

major fault. Toolachee East, on the downthrown side of the fault, contains a thicker Upper Stage 5' section than any other Toolachee Field well (Fig. 49). These two facts combined lead to the interpretation that downwarp across the fault affected the facies distribution. River channels were attracted to the zone of most rapid subsidence on the floodplain, away from the structural crest, which consequently was covered by overbank deposits.

Palaeogeography and Geologic History

During Upper Stage 5', the Cooper Basin was tectonically quiescent. It was covered by extensive floodplains, across which meandered large rivers (Fig. 52). Coal-forming forests and lakes covered large tracts of land for long periods of time. Most sediment was brought into the basin from the west by rivers which flowed

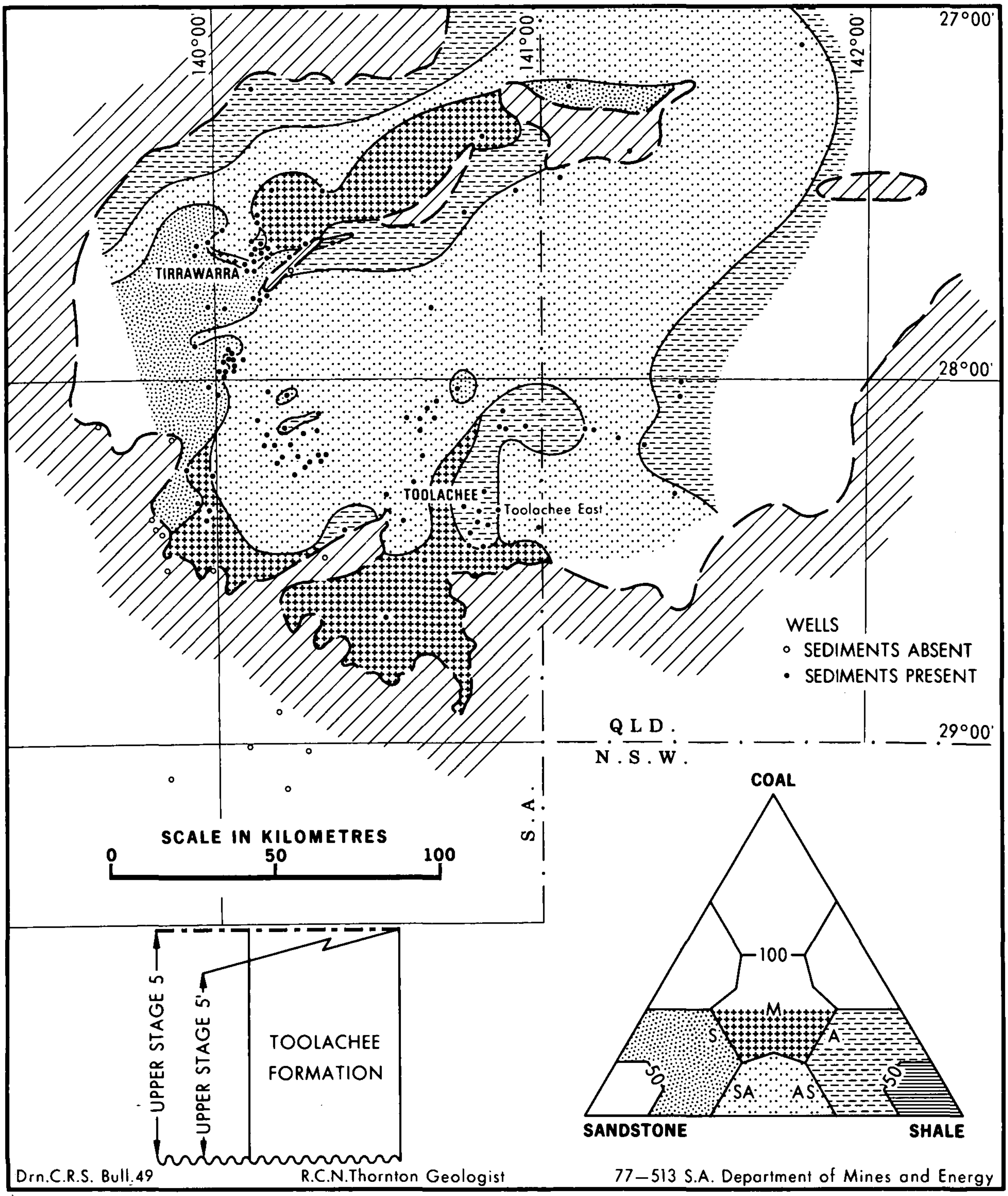


Fig. 51. Upper Stage 5' 'D'-function map

eastwards, ultimately to reach the seas somewhere in the vicinity of the southern Bowen Basin.

The main area of sediment intake on the western flank of the basin is marked by the sandy facies on the 'D'-function map. This source fed the rivers and streams in the Patchawarra Trough, and probably also supplied some rivers in the Nappamerrie Trough, crossing the GMI Trend between Gidgealpa and Merrimelia. Perhaps, the Gidgealpa area has a sandstone content higher than other regions along the GMI Trend partly because it was closer to the sand source. The head of the other possible main river channel 'fairway' is located in the eastern part of the basin, running northwards through Epsilon and Roseneath. This interpretation of the major channel zones disagrees in part with Stuart's (1976) opinion that most rivers entered the basin from near

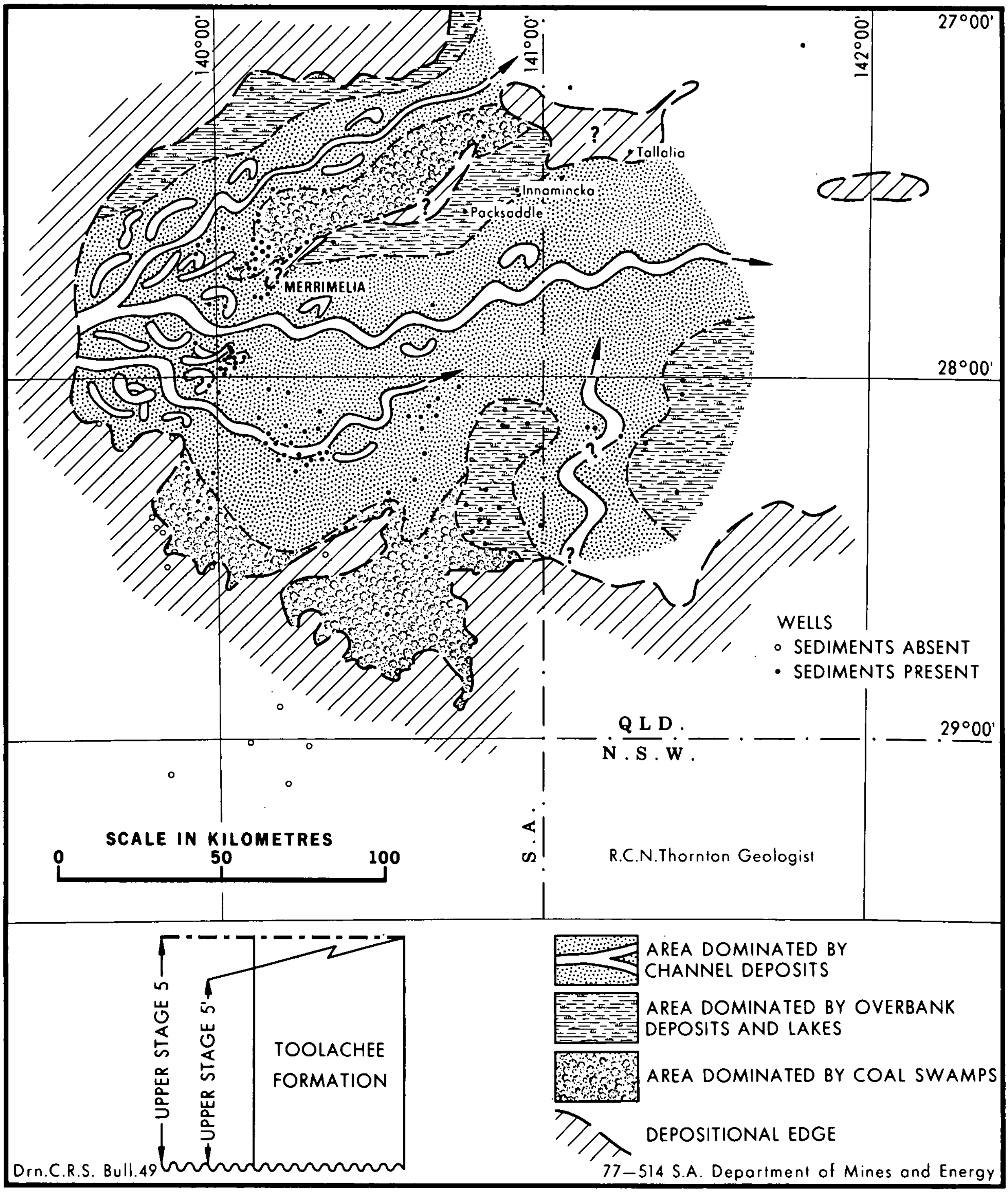


Fig. 52. Palaeogeography during Upper Stage 5'

Murteree, and only minor rivers flowed in from the west.

Coal swamps developed throughout most of the basin. However they were particularly prevalent along the southern margin and around the flanks of the Merrimelia, Packsaddle, Innamincka and Tallalia hills, away from the zones of preferred river channel paths. This row of hills separated the Cooper Basin into two major depositional regions.

Scanty lithofacies evidence suggests that lakes may have existed during most of Upper Stage 5' along the northern and eastern margins of the basin. Corroboration for this interpretation is provided by Stuart's (1976) belief that the wireline logs of the most easterly Cooper Basin wells indicated dominantly lacustrine conditions. Thus, by analogy with the findings of Ferm and Cavaroc (1968) that the amount of shale in a fluvial succession increases towards the shoreline, the rivers flowed eastwards to the sea.

The latter period of Upper Stage 5' was one of major fluvial, coal formation deposition throughout the eastern Permian basins (Fig. 25). At the beginning of Upper Stage 5', when deposition of Toolachee Formation commenced, marine deposits were being laid down in shallow water in the Denison Trough (Blenheim Subgroup) and deep water on the eastern side of the Bowen Basin (Boomer Formation). As part of a major Late Permian regression, deposition of coal formations extended to the Galilee Basin next, and then encroached progressively eastwards, until all the Permian basins were accumulating coal measures (Blackwater Group). This includes the southern part of the Bowen Basin, which until late Upper Stage 5 time had experienced only marine conditions during the Permian.

Cyclic Sedimentation Study—Theory and Methods

The search for cyclic sedimentation assists in the understanding of geologic successions (Duff *et al.*, 1967, p.251). Irrespective of conclusions reached on the regularity or reality of sedimentary cycles, their study directs attention to the distribution of facies through space and time. In the previous section, lithofacies maps were used to show how sedimentary environments in the Cooper Basin changed with time. In this chapter, the rhythmicity of sedimentation is studied in order to learn more about the processes which caused the changes.

Two methods of analysis have been used in the study: the simpler method uses histograms of cycle types to define the most common (modal) cycle. Markov analysis is the second method. Both techniques are quantitative and are designed to give as objective an analysis of the section as possible. Such approaches offer dispassionate tests of hypotheses of rock ordering (Doveton, 1971). To assist objectivity of interpretation, rock types have been rigidly defined.

The method of histogram analysis was conceived by Duff and Walton (1962) in their study of the East Pennine Coalfield, England. Duff (1967a) later applied the same technique to the Permian coal measures of New South Wales. Markov analysis is much more complex statistically. It was first applied to a geologic problem by Vistelius (1949) in his examination of flysch sequences from the Caucasus, but it was not until 15 years later that its applications were recognised by anyone else (Allégre, 1964). Since then a considerable amount has been written about Markov analysis following further pioneer work by Vistelius and Fass (1965a, 1965b) and Vistelius and Feygel'son (1965). Schwarzacher (1975) critically discusses the subject, and stresses the time aspect of sedimentary cycles.

CHOICE OF LITHOLOGIC STATES

Statement

Five lithologic types were interpreted from the gamma-ray and sonic logs. They are sandstone, thick sandstone, shale, mixture of sandstone and shale, and coal (Table 6). The constraints on lithologic definition were imposed by working with only wireline logs, but even so the intention was that the lithologic states chosen should be easily recognisable (with good repeatability) and geologically significant (Krumbein, 1958).

Table 6 *Lithologic units used in coal cyclicity study.*

Lithology	Symbol	Definition
Coal	C	≥0·3 m
Shale	A	≥0·6 m
Sandstone	S	≥0·6≤3 m.
Thick sandstone	X	>3 m
Mixture	M	(S≤1·2 m) (A≤1·2 m) (A≤1·2 m) or (S≤1·2 m) (S≤1·2 m) (A≤1·2 m)

Rigid criteria were set up to define the lithologic units as shown in Table 6. All coals equal to, or greater than, 0·3 m thick were counted and in an attempt to avoid innumerable repetitions of thin sandstone and shale bands, a minimum thickness for sandstone and shale was used. Duff (1967a) found 0·6 m to be a valid figure in his examination of the Permian coal measures of New South Wales, and the same value has been used in this study. In a further attempt to eradicate the meaningless repetition of thin units, a category called mixture was defined as the repetition of three or more sandstone and shale bands, each equal to or less than 1·2 m thick.

Sandstones were divided into two categories, on the basis of thickness, thick sandstones being greater than 3 m thick. Doveton (1971) in his study of the Coal Measures of Ayrshire considered that the sandstone bodies he observed originated in a variety of environments. He felt that the setting of sandstones as a single state would lead to an average generalisation of their transition behaviour. Consequently, he arbitrarily split them on the simple criterion of thickness. A similar procedure has been used herein.

Discussion

Various workers (Schwarzacher, 1976; Johnson and Cook, 1973; Doveton, 1971) stress the need for the lithologic steps, which by implication are various episodes of sedimentation, to be genetically commensurate. Doveton (1971) included all rootlet horizons (which he equated with coal) regardless of thickness, because they can be considered loosely as planes of vegetative colonisation, and therefore have a distinctly different character of other lithologic types. Similarly, Johnson and Cook (1973) recognised coal seams 50 mm thick. In the present study, it was felt that coals thinner than 0·3 m thick could not be identified reliably from the logs, and consequently, average cycle lengths will be much greater in this study than has been reported elsewhere, as the large minimum thickness of 0·3 m for coal cuts out a lot of coal-splitting cycles.

Johnson and Cook (1973) have extended the concept of equating various lithologic thicknesses with approximately equivalent depositional significance. Thus, minimum thicknesses for the rock types were 50 mm for coal, 0·3 m for claystone, 0·6 m for sandstone and 1·5 m for conglomerate.

The concept of mixture was conceived originally as a means to shorten the number of states in cycles using the histogram technique. In geologic terms it represents a poor substitute for siltstone with thickness ranges from 1·8 to 3·6 m. Recognition of mixture in a sequence automatically implies a built-in oscillation in depositional processes.

The choice of thick sandstone as a separate lithology poses considerable statistical problems. There are no signs of multi-modal populations on cumulative plots of sandstone thickness for any of the Stages. If there were a geologic reason for splitting sandstones, then this should be reflected on the cumulative curves. A more meaningful way of splitting sandstones might have been on the basis of gamma-ray log character. Porter (1976) recognises two types of sandstones, each with different porosity/permeability characteristics. However, at the present state of knowledge it is doubtful whether it could be proved satisfactorily that such a differentiation would have similar genetic implications throughout the basin.

HISTOGRAM ANALYSIS

The method of histogram analysis, as described by Duff and Walton (1962), defines the vertical order of rock types which occurs most frequently in a succession. The modal cycle and composite sequence (defined below) are determined by examination of a histogram of all cycles in the succession. In this manner, the presence of cyclic sedimentation is established quantitively. One advantage of this method over Markov analysis is its statistical simplicity. Therefore the correctness of results obtained is less open to argument on the grounds of statistical validity.

Definitions

To prevent ambiguity, terms used in this study are as described by Duff and Walton (1962):

> *Cycle:* '(a) cycle (is) a group of rock units which tend to occur in a certain order and which contains one unit which is repeated frequently through the succession.'
> *Modal cycle:* 'The modal cycle is that group of rock types which occurs most frequently through any succession . . . The term 'modal' emphasises its statistical basis and . . . allows reference to primary and secondary modes within polymodal distributions.'
> *Composite sequence:* 'The composite sequence consists of all the rock types investigated in a cyclic succession, arranged in the order in which they tend to occur within the cycles. Once the modal cycle(s) has (have) been erected, then it is possible to consider any extra lithology and assess its position with respect to the units of the modal cycles.'

Procedure

Histograms of every cycle, ending in a coal, were compiled and printed out by computer. The primary modal cycle is that which occurs most frequently on the histogram. The composite sequence is derived by inserting any lithology that does not occur, into the modal cycle in the postion shown to be most likely from examination of all the cycles on the histogram.

In the manner of Duff (1967a), coal has been chosen as the bounding lithology which defines the end of each cycle. This is because coal formation represents a period of virtually total non-clastic depostion when vegetation grew *in situ.* Read and Dean (1976) considered that this definition was reasonably adequate for dominantly deltaic successions because the vegetation horizon marks a critical stage in delta out-building. They felt that the definition was less suitable for a meandering river environment, and considered that a better definition might be one based on grain size. Nonetheless, they recognised that the two methods would produce only very slightly different results in the cases where cycles culminated in fine-grained overbank deposits.

MARKOV CHAIN ANALYSIS

As used in the study of sediments, Markov analysis differentiates between successions that are purely random and those that are affected by a previous lithology. In addition, it provides an objective description of the ordering of rock units within a geologic section. This ordering can be related to geologic hypotheses concerning both its nature and the factors which control it (Doveton, 1971).

Markov analysis has some advantages over histogram analysis. In general, no prior assumptions are needed about definitions of cycles, nor relationships among the strata. The method involves the compilation of a matrix which shows all the upward lithologic transitions in a rock section. This is then compared with a randomly derived matrix to determine which transitions occur more frequently than anticipated on the basis of chance.

The Markov Process

Rock sections can be thought of as a succession of events in time, where events can be considered as rock types, faunal assemblages, or other characters of interest (Doveton, 1971). Doveton continues: 'Any time series of events will satisfy some mathematical model found within a spectrum of possibilities ranging from perfectly ordered (deterministic), such as the days of the week, to perfectly disordered (independent events), as for instance the results of coin tossing trials or roulette wheel spins. The intermediate class between these two extremes represents a range of schemes of partial ordering where there is a tendency for events to happen in certain sequences not dictated entirely by the extremes of absolute certainty or pure chance probability. A degree of randomness is implied and models of this type come within the class of stochastic models'.

The Markov process is the simplest stochastic process, in which a random variable depends on its past history (Schwarzacher, 1975). In this present study, each random variable is a lithologic unit. The dependency on a previous lithology is known as the 'memory' of the process. Cyclic sedimentation is proved if there is a tendency for lithologic units to follow one another in a more orderly fashion than would be expected purely from random processes for the given number of units.

Sedimentary successions do not result from random events, and a random succession is therefore the very last one would expect in nature (Selley, 1970). This is why the random model is the most effective model to test against the observed data. The alternative test for cyclicity would be to compare the section with a series of subjectively defined ideal cycles in order to see which was the best fit (see Pearn, 1964).

Types of Markov Chains

Markov chains can be classified according to dependence, order, and step length (Harbaugh and Bonham-Carter, 1970, p. 125). In this study, the simplest case has been examined, which is the single dependence, first order chain with one step transition. This means that in the analysis of a transition on the Markov chain, only the effect of one preceding state is considered, and that is the immediately preceding state. In addition, each transition involves a single step of unit length.

A wide variety of geologic phenomena seem to possess the Markov property, but many of these processes are probably not represented by chains of such simple form. Instead, they involve more complex, multiple-dependence chains (Harbaugh and Bonham-Cartger, 1970, p. 131). A few workers such as Doveton (1971) have tested for a second-order Markov property. Schwarzacher (1967) simulated a Pennsylvanian cyclothem using a two stage Markov chain, whereby transitions were affected by the lithology to be found 47 m below this stage in the spectrum.

In this study, Markovian dependency higher than first order was not tested for, because for reasons to be explained later, the procedure adopted does not satisfy absolutely the laws of statistics. At the simple level of first-order dependency adopted here, the statistical irregularities do not mar geologic interpretation. However, the existence of second, or higher order dependencies requires statistical proof, which in this case would be highly suspect.

Advantages over the Histogram Method

Read (1969) suggests that Markov analysis is an improvement over Duff and Walton's (1962) technique for three reasons. Firstly, it can be used conveniently to summarise the essential characteristics of the thick and complex sedimentary succession in a single matrix of upward transition probabilities. This matrix yields an empirical description of how the different lithologic types succeed one another (Carr *et al.*, 1966).

Secondly, the method avoids the difficulty of having to group into separate categories closely related cycles that may differ only in the presence or absence of a single lithologic member in a particular position. Thirdly, it avoids having to make the subjective choice of which lithology defines the top of a cycle, or, as Selley (1970) puts it, sedimentologic insight into the structuring of the data is not required before analysis.

In addition, the approach is useful in that it can point out subtle relationships in the stratigraphic succession that would not otherwise be noticed or intuitively sought out (Miall, 1973). These relationships can be seen irrespective of whether or not cyclicity is proved. This consideration applies especially to the minor lithologies, which are ignored in the histogram technique until their incorporation into the composite sequence.

Analytical Method

The method is based on that described by Harbaugh and Bonham-Carter (1970, Chapter 4), and Gingerich (1969). This description draws heavily on that of Miall (1973).

Transition Count matrix (f_{ij})

The transition count matrix is a two dimensional array which tabulates the number of transitions which occur from one state to another. If there are three states, S_1, S_2 and S_3, then the transition count matrix, f_{ij}, is written.

$$f_{ij} = \begin{array}{c|ccc} & S_1 & S_2 & S_3 \\ S_1 & f_{11} & f_{12} & f_{13} \\ S_2 & f_{21} & f_{22} & f_{23} \\ S_3 & f_{31} & f_{32} & f_{33} \end{array}$$

Where i = row number, and j = column number. Therefore, f_{11} = the number of transitions from S_1 to S_1; f_{12} = the number of transitions from S_1 to S_2; etc.

Transition Probability Matrix (p_{ij})

This matrix is the transition count matrix in probability form. Thus

$$p_{ij} = f_{ij}/s_i$$

where s_i is the sum of the f_{ij} for the i^{th} row of the f matrix. In other words, the probability of S_2 overlying S_1 is the number of transitions from S_1 to S_2, divided by the sum of transitions from S_1 to S_1, S_1 to S_2, and S_1 to S_3.

Independent Trials Matrix (r_{ij})

The independent trials matrix is also derived from the transition count matrix, and represents the probability of a given transition occurring randomly. The probability of S_2 overlying S_1 is dependent only on their relative proportions. Therefore,

$$r_{ij} = s_j/t$$

where t = total number of beds

$$= \sum_{ij}^{n} f_{ij}$$

n = the rank of the matrix, i.e. the total number of rows or columns used; and s_j is the sum of the f_{ij} for the j^{th} column of the f matrix.

In this study, a rock type cannot change to itself, in other words, $i = j$ transitions are not permitted, and the total range of possibilities is set to exclude them. Then the above formula becomes:

$$r_{ij} = s_j/(t - s_i)$$

and the remaining probability values are thereby increased proportinally along each row of the r matrix, although remaining the same relative to one another.

This means that the probability of S_2 overlying S_1 equals the number of S_2 states divided by the number of non S_1 states.

Schwarzacher (1975) considers the term independent trials matrix somewhat misleading, because it is specified in calculating this matrix that transitions from one state to an identical state are impossible. In a truly random matrix, all the numbers in any one column would be identical.

Difference Matrix (d_{ij})

The values in the p matrix sum to unity along each row, and will necessarily reflect the presence of any Markovian dependency relationship. However, the p matrix will show higher probability for more abundant states, even if random (Selley, 1970). Therefore, a difference matrix is derived which is not affected by the relative abundance of states:

$$d_{ij} = p_{ij} - r_{ij}$$

Values in each row of the d matrix should sum to zero. Then, positive entries represent those transitions which have a better than random chance of occurring. Equally, negative numbers imply a greater than random chance that transitions will not occur.

In this study, two states (S and X) are not able to change to one another in the f and p matrices. However, transitions in the r matrix are possible. Had they been disallowed and the relative proportions for the other transitions in the S and X rows been recalculated, these two rows would have been identical. The relevant cells in the d matrix have been cleared to zero as a final step in the calculation, to remove the meaningless values. This means that the S and X rows in the d matrix do not sum to zero. Therefore only large number values are meaningful.

In virtually all the d matrices produced, the number of transitions from S and X to A are very high, and the S and X rows sum to a positive number much greater than zero. Empirically, it was discovered that removal of half the number in excess of zero from the X to A and S to A cells in the X and S rows results in the row totals approximating to 1. This has been done in order that the transition probabilities from S and X should be comparable with these from other states.

Facies Relationship Diagram

This term was originally conceived by De Raaf, *et al.* (1965), to describe a diagram which showed all the upward and downward transitions in a vertical section. In the modified form used herein (Tables 9-13 incl.), the facies relationship diagram shows the non-random upwards transitions, as deduced from the d matrix. The numbers on the arrows are the numbers from the relevant cell in the d matrix.

Modal Sequence

Schwarzacher (1975, p. 265) suggests the use of the term 'modal sequence' to indicate the sequence most likely to occur. 'The modal sequence differs from the modal cycle because in theory, at least, it can be calculated for any length of group', and does not have to return to the state from which is started. 'The modal sequence can be read from the transition probability matrix directly by searching for the highest probabilities from each stage' (Schwarzacher, 1975).

Structuring of the Section

There are three ways of structuring Markov chains: by sampling at bedding planes; at equal thickness intervals; or at lithologic boundaries. The third method is used in this study because it is the most useful for environmental interpretation. The first method could not be considered because bedding planes cannot be recognised on logs. Sampling at lithologic boundaries avoids the problems inherent in sampling at fixed intervals. By sampling at lithologic boundaries, each lithologic unit, regardless of its thickness, forms a step in the Markov chain. No return to the same state is possible, and therefore the leading diagonal of the transition matrix must have zero elements. Markov models which describe sequences structured this way are 'embedded Markov chains' (Doveton, 1971).

Structuring the Markov chains by lithologic states is the most useful method in environmental evaluation because it is the order in which rock types (and therefore environments) occur which is of interest. The focus is on the evolution of the depositional process (Miall, 1973; Selley, 1970). Sampling at equal intervals emphasises the relative frequencies of the different rock types, a facet which has been explored fully using facies maps.

Because the lithologic data were derived from logs, it was not possible to record multi-storey lithologic successions such as shale going to shale. The concept of multi-storey lithologic units assumes that a given unit can be subdivided on the basis of grain size, sedimentary structures, fauna, etc., or erosion surfaces (Carr *et al.*, 1966; Selley, 1970). Even if it were possible to structure the section in this way, Read (1969) considers that no author has yet defined criteria whereby adjacent rock types can be estimated to be sufficiently different to constitute separate divisions of a multi-storey lithologic unit and yet not be a different rock type.

Artificial multi-storey lithologic successions can be created by sampling the section at a fixed thickness interval. The major difficulty with this system, however, is the choice of sampling interval. Krumbein (1967, p. 3) shows that if the magnitude of the interval chosen is too great, transitions occur along the main diagonal only for the thickest units. In addition, thin rock units are missed entirely. Conversely, if the measuring interval is too small, the number of transitions from one state to itself is unrealistically high ('with an infinitesimally small sampling interval, the matrix tends to have a probability of 1·00 in the diagonals, and 0·00 elsewhere, for any sample of finite length'). Testing against the null hypothesis of independent events, gives a 'memory' due to successive observations along the sequence being of the same state (Doveton, 1971). Krumbein and Scherer (1970) examined this problem empirically in an analysis of well-log data.

A similar procedure was rejected for this study because a very thick and extensive sediment pile, with probably many depositional environments, is being studied. In addition, individual lithologic units vary in thickness from less than 1·0 m to many metres. The process involved in obtaining statistically satisfactory sampling intervals would have been extremely laborious and time consuming.

Testing for the Markov Property

Differences between the *p* matrix and *r* matrix may appear to be considerable. In fact, the differences may themselves be due to random chance (Miall, 1973). Ideally therefore, tests of significance should be applied to the results. Most workers have applied a x^2 (chi square) test, such as that shown by Harbaugh and Bonham-Carter (1970, p. 121) which tests the *p* matrix against the null hypothesis that events are independent of one another. However, in this study it has not been possible to test statistically for first-order Markovian dependency, because of the way in which the chains have been structured.

In this study, transitions from one lithologic state to an identical state are forbidden, and therefore the leading diagonal of the transition matrix must have zero-elements. 'Matrices of this type can never result from an independent random process and it is, therefore, meaningless to test against' the null hypothesis of an independent random process (Schwarzacher, 1975, p. 116). The reason for this is that forbidding transitions from one state to an identical state automatically prevents the process from being random. x^2 testing for first-order Markov property is absent from the work of Duff and Walton (1973) because of this problem (Duff, University of Strathclyde, pers. comm., 1973).

In the Gidgealpa Group, the inability to test statistically for Markovian dependency is not an insurmountable problem. The existence of cyclicity within coal measure sequences was recognised and accepted prior to the use of Markov analysis in geology (Miall, 1973). First order Markovian dependency virtually can be taken for granted. The relationships between the lithologic units provide sedimentologic information, which can be obtained from a section quite irrespective of whether or not the section possesses the property of cyclicity (Schwarzacher, 1975, p. 262).

Test for Stationarity

Tests have been applied to examine whether there are statistically significant differences between transition matrices derived for the different Stages mapped. Stationarity implies that transition probabilities are constant throughout a section. Different transition count distributions from one vertical section sampled at the bottom, middle and top, show that the nature of cyclicity changed with time (Miall, 1973). This is non-stationary Markovian dependency. The concept of stationarity applies horizontally through a succession, as well as vertically.

Harbaugh and Bonham-Carter (1970, p. 124) give the x^2 test the used in this study (originally conceived by Anderson and Goodman, 1957) for determining whether or not a sequence exhibits stationarity:

$$-2 \log_e \lambda = 2 \sum_{t}^{T} \sum_{i-j}^{m} n_{ij}(t) \log_e \left| \frac{p_{ij}^{(t)}}{p_{ij}} \right|$$

The number of degrees of freedom = $(T - l)[m(m - l)]$

where m = number of states

T = number of time subintervals

$n_{ij}(t)$ = frequency tally for the transition from state i to state j in the t^{th} subinterval.

Comparison has been made between transition matrices derived from wells in both geologic regions and different lithofacies areas. This has been done in order to test the theory of Harbaugh and Bonham-Carter (1970, p. 125) that certain transition matrices might be diagnostic for different sedimentary regimes.

Cyclic Sedimentation Study—Interpretation of Results

Histogram and Markov chain analyses were carried out on all the time-rock and lithologic units for which lithofacies maps were prepared. In addition, each of these units was subdivided on the basis of both lithofacies and geography to investigate whether different depositional processes occurred within different parts of the basin.

Only a very few cycle types occur regularly and these have been related to the depositional environments most likely to have caused them. Cycles originating in fluvial, interdistributary bay, deltaic, and shoreline environments have been recognised. The computer programs used to carry out the histogram and Markov analyses were written by M. Mannik of the Systems Section in the South Australian Department of Mines and Energy. They are filed in the Systems Section.

TREATMENT OF DATA

An attempt has been made to study the vertical ordering of sequences within each Stage both as a whole, and when subdivided in two different ways. The first subdivision of the Stages is on geographic grounds, and separates the Patchawarra Trough from the rest of the basin (designated here as Cooper Basin Main). The second subdivision, is on the basis of lithofacies, as defined by 'D'-function maps. Three facies were chosen, namely sandy (shown by the symbol S on the 'D'-function triangles), mixed (AS/SA + M), and shaly (A + AC). Markov analysis was conducted on 29 sets of data, comprising six complete units, plus ten subdivisions on geographic grounds, and thirteen on lithofacies grounds. Histograms were drawn where there was sufficient data (Table 7).

Horizontal stationarity on the basis of both the geographic and facies splits described above was tested for each of the Stages. Vertical stationarity within the Patchawarra Formation was also examined (Table 8). The test is set up so that for the null hypothesis of stationarity to be accepted, then the calculated value of x^2 must be less than the tabulated value at some preselected level of significance for the number of degrees of freedom (Harbaugh and Bonham-Carter, 1970, p. 125).

From each of the histograms, modal cycles and composite sequences were derived, and modal sequences were drawn from the transition probability matrices. With few exceptions, the modal sequences provide very little extra information to the composite sequences, especially as they do not include

Table 7 *Stage subdivisions used in Cooper Basin coal cycle analysis*

Stage/Formation	Subdivisions: Geography			Subdivisions: Lithofacies		
	Description	M*	H*	Description ('D'-f. classification)	M*	H*
Upper Stage 5'	Total	X	X	Sandy (S)	X	X
	Patchawarra Trough	X	X	Mixed (SA/AS + M)	X	X
	Cooper Basin Main	X	X	Shaly (A)	X	X
'Daralingie Beds'	Total	X	X			
Epsilon Formation	Total	X	X			
	Patchawarra Trough	X		Mixed (SA/AS + S)	X	
	Cooper Basin Main	X		Shaly (A)	X	
Upper Stage 4'	Total	X	X	Sandy (S)	O	
	Patchawarra Trough	X		Mixed (SA/AS + M)	X	
	Cooper Basin Main	X		Shaly (A + AC)	X	
Lower Stage 4	Total	X	X	Sandy (S + SC)	X	
	Patchawarra Trough	X		Mixed (SA/AS + M)	X	
	Cooper Basin Main	X		Shaly (A + AC)	X	
Stage 3'	Total	X	X	Sandy (S)	X	X
	Patchawarra Trough	X	X	Mixed (SA/AS + M)	X	X
	Cooper Basin Main	X	X	Shaly (A + AC)	X	X

*M = Markov analysis
*H = Histogram analysis
X = analysed
O = unreliable due to too few transition

minor lithologic types. However, they do provide substitute information in the cases where histograms were not drawn. Both composite and modal sequences indicate what transitions occur most commonly, whereas the facies relationship diagram shows the transitions with a more than random chance of happening.

The results of the histogram and Markov analyses are shown in Tables 9-13. (The histogram analysis results and the Markov chain matrices are retained on file in the South Australian Department of Mines and Energy).

RESULTS AND GENERAL CONCLUSIONS

In all the Stages, the number of different modal cycles is very small, and each cycle generally contains only two or three lithologic units in addition to coal. The environmental implication is that there was frequent repetition of only a few, simple depositional processes. Although there is a very large number of different cycle types, most of these occur very infrequently.

In every case studied, more than 50 per cent of all the cycles consist of one of three types. These are AC, A($^{S}{}_{X}$)AC, ($^{S}{}_{X}$)AC. Looked at another way, the simplicity of the modal cycle is shown by the number of rock units in each cycle. With few exceptions, more than 60 per cent of the cycles in any Stage or subdivision contain no more than one or two units in addition to coal, and generally well over 70 per cent contain no more than three units (Table 14).

Primary modal cycles and facies relationship diagrams differ from one stage to another. These differences reflect the variations in depositional environment through time. Additionally, however, within any one stage the results for the whole basin are averages over various areas which have different depositional histories. Facies relationship diagrams for the geographic and facies subdivisions are simpler than for the whole basin.

The vertical ordering of lithologic units differs from one lithofacies to another, and therefore so must the depositional environments. The three part split on the basis of lithologic facies produces considerably different modal cycles and facies relationship diagrams. These data indicate that fluvial deposition predominated in the sandy facies, lacustrine deposition predominated in the shaly facies, and an environment intermediate between these two extremes occurred in the mixed facies. The differences between these facies are statistically significant, as shown by the lack of stationarity (Table 8). Because transitions were measured at bed boundaries, and not on the basis of thickness, the vertical ordering of lithologic units must be different in the different lithofacies.

Further indication to suggest that the pattern of preferred transition paths is environmentally controlled is provided by the strong similarity between some facies relationship diagrams from one Stage to another. The consistency in the pattern of upward transitions through time discounts the possibility that the processes which caused them were unique to any one period of time.

ENVIRONMENTAL IMPLICATIONS

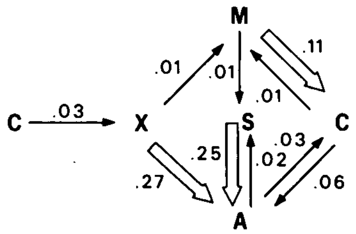
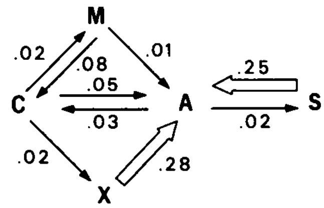
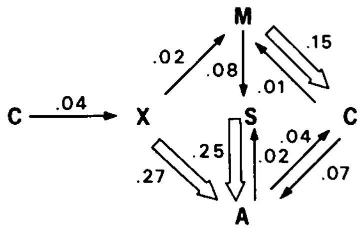
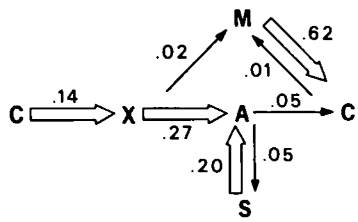
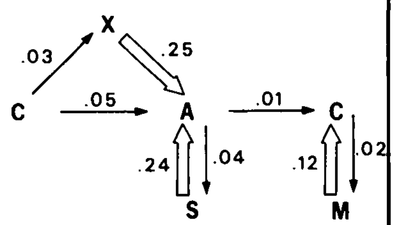
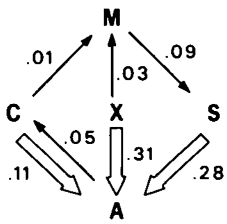
The study of the ordering of vertical successions relies for its validity on two concepts. The first of these is that the vertical succession reflects the horizontal ordering of facies. The second is that

Table 8 *Results of tests for horizontal stationarity and vertical stationarity*

Stage/Formation	Subdivisions tested*	x^2 value	Number of degrees of freedom	Limiting Value+ 99·5%	Limiting Value+ 95%	Markov Process
			HORIZONTAL STATIONARITY			
Upper Stage 5'	Geographic	57·7	20	40·0	31·4	Non-stationary
	Lithofacies	132·9	40	66·8	55·8	Non-stationary
Upper Stage 4'	Geographic	16·0	20	40·0	31·4	Stationary
Lower Stage 4	Geographic	25·2	20	40·0	31·4	Stationary
	Lithofacies	63·8	40	66·8	55·8	Stationary at 99·5%
Stage 3'	Geographic	62·3	20	40·0	31·4	Non-stationary
	Lithofacies	161·5	40	66·8	55·8	Non-stationary
			VERTICAL STATIONARITY			
Patchawarra Formation	Total Cooper Basin	86·4	40	66·8	55·8	Non-stationary
	Patchawarra Trough	71·6	40	66·8	55·8	Non-stationary
	Cooper Basin Main	50·5	40	66·8	55·8	Stationary

* Geographic subdivisions: Patchawarra Trough and Cooper Basin Main
Lithofacies subdivisions: sandy, mixed, shaly facies.
\+ From: Hald (1952)

Table 9. *Results of histogram and Markov analysis—Stage 3'.*

STAGE 3'							
SUB-DIVISION	HISTOGRAM ANALYSIS				MARKOV ANALYSIS		
	No. of Cycles	Modal Cycle(s)	%*	Composite Sequence(s)	No. of transitions	Modal Sequence(s)	Facies Relationship Diagram
Total	*801*	AC XAC SAC ASAC AXAC	30 7) 6) 13 8) 4) 12	(X)/(S) MAC A (S)/(X) MAC	*3424*	CAC CASAC	
Patchawarra Trough	*347*	AC ASAC AXAC SAC XAC	24 10) 5) 15 9) 4) 13	ASAMAC SAMAC	*1613*	CASAC (C (S)/(X) AC)	
Cooper Basin Main	*454*	AC XAC SAC ASAC AXAC	34 10) 4) 14 6) 4) 10	(X)/(S) MAC	*1811*	CAC CA (S)/(X) AC	
Sandy facies	*109*	XAC SAC AC AXAC ASAC ASC AXC	23) 5) 28 14 7) 1) 8 5) 4) 9	XMAC	*439*	CXAC CA (S)/(X) AC	
Mixed facies	*328*	AC SAC XAC ASAC AXAC	25 6) 6) 12 6) 4) 10	(S)/(X) AMAC A (S)/(X) AMAC	*1575*	CASAC	
Shaly facies	*364*	AC ASAC AXAC SAC XAC	40 11) 3) 14 8) 4) 12	A (S)/(X) MAC (S)/(X) MAC	*1410*	CAC (CASAC)	

%* = Modal cycle percentage of total number of cycles X—THICK SAND S—SAND A—SHALE M—MIXTURE C—COAL

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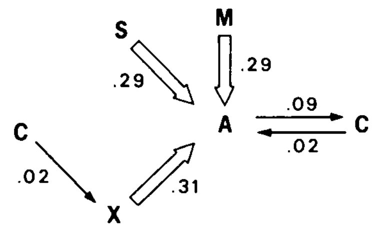
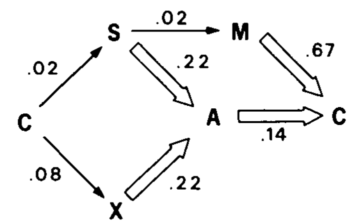
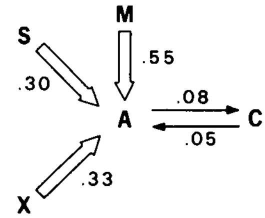
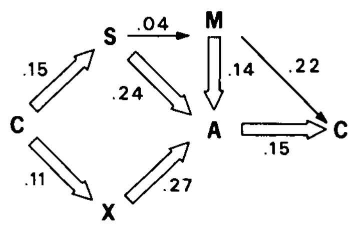
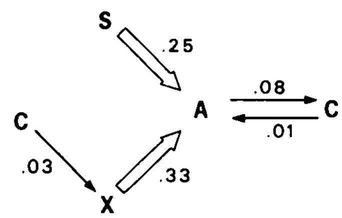
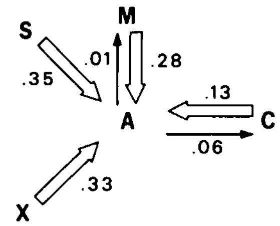
Table 10. *Results of histogram and Markov analysis—Lower Stage 4.*

LOWER STAGE 4							
SUB-DIVISION	HISTOGRAM ANALYSIS				MARKOV ANALYSIS		
	No. of Cycles	Modal Cycle(s)	%*	Composite Sequence(s)	No. of trans-itions	Modal Sequence(s)	Facies Relationship Diagram
Total	*191*	AC XAC SAC	40 12) 22 10)	$^{(X)}_{(S)}$AMAC	*655*	CAC (CA$^{(S)}_{(X)}$AC) C$^{(S)}_{(X)}$AC	
Patchawarra Trough					*144*	(C$^{(S)}_{(X)}$AC) CAC	
Cooper Basin Main					*511*	CAC CA$^{(S)}_{(X)}$AC	
Sandy facies					*126*	CXAC CSAC	
Mixed facies					*291*	CAC (CA$^{(S)}_{(X)}$AC)	
Shaly facies					*238*	CAC	

%* = Modal cycle percentage of total number of cycles

X—THICK SAND S—SAND A—SHALE M—MIXTURE C—COAL

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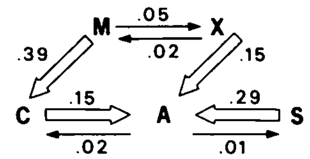
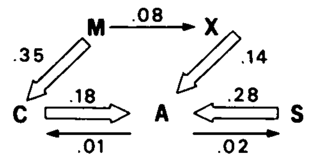
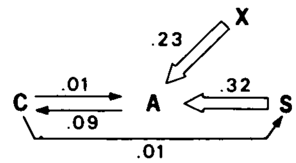
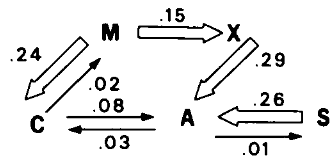
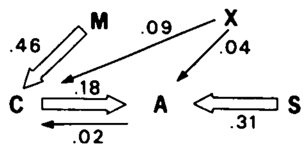
Table 11. *Results of histogram and Markov analysis—Upper Stage 4'.*

UPPER STAGE 4'							
SUB-DIVISION	HISTOGRAM ANALYSIS				MARKOV ANALYSIS		
	No. of Cycles	Modal Cycle(s)	%*	Composite Sequence(s)	No. of trans-itions	Modal Sequence(s)	Facies Relationship Diagram
Total	*131*	AC ASAC SAC	38 11 10	ASAMAC SAMAC	*475*	CAC CASAC	
Patchawarra Trough					*376*	CAC CASAC	
Cooper Basin Main					*96*	CAC	
Sandy facies					*10*		Too few transitions
Mixed facies					*171*	CAC CASAC	
Shaly facies					*293*	CAC CASAC	

%* = Modal cycle percentage of total number of cycles

X—THICK SAND **S**—SAND **A**—SHALE **M**—MIXTURE **C**—COAL

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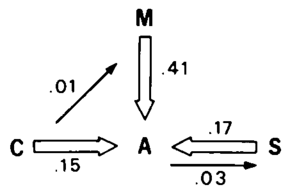
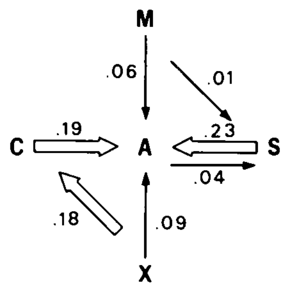
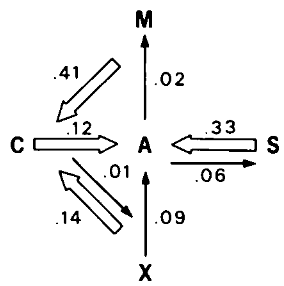
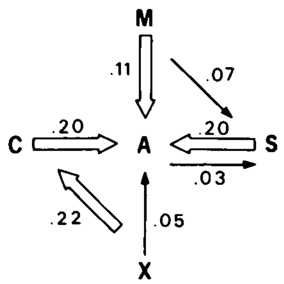
Table 12. *Results of histogram and Markov analysis—Epsilon Formation and 'Daralingie Beds'.*

SUB-DIVISION	HISTOGRAM ANALYSIS: No. of Cycles	HISTOGRAM ANALYSIS: Modal Cycle(s)	HISTOGRAM ANALYSIS: %*	HISTOGRAM ANALYSIS: Composite Sequence(s)	MARKOV ANALYSIS: No. of trans-itions	MARKOV ANALYSIS: Modal Sequence(s)	MARKOV ANALYSIS: Facies Relationship Diagram
'DARALINGIE BEDS'							
Total	*54*	AC ASAC ASC	43 7 7	AMASC	*224*	CASAC CAC	
EPSILON FORMATION							
Total	*115*	AC ASAC ASC	55 21 17	AMSAC AMSC	*727*	CASAC	
Mixed facies					*152*	CASAC	
Shaly facies					*575*	CASAC CAC	

%* = Modal cycle percentage of total number of cycles

X—THICK SAND **S**—SAND **A**—SHALE **M**—MIXTURE **C**—COAL

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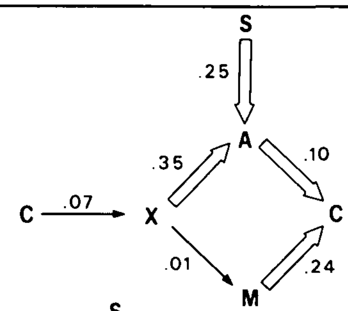
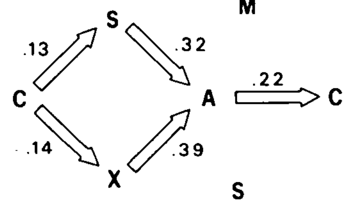
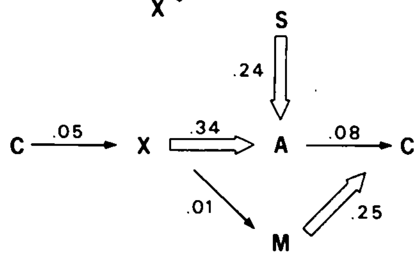
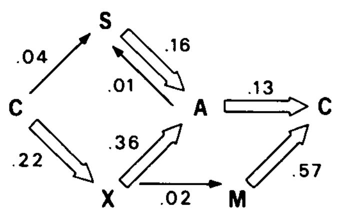
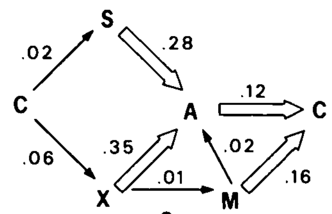
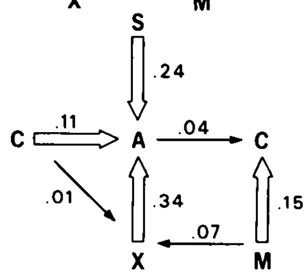
Table 13. *Results of histogram and Markov analysis—Upper Stage 5'.*

<table>
<tr><th colspan="9">UPPER STAGE 5'</th></tr>
<tr><th rowspan="2">SUB-DIVISION</th><th colspan="4">HISTOGRAM ANALYSIS</th><th colspan="3">MARKOV ANALYSIS</th></tr>
<tr><th>No. of Cycles</th><th>Modal Cycle(s)</th><th>%*</th><th>Composite Sequence(s)</th><th>No. of trans-itions</th><th>Modal Sequence(s)</th><th>Facies Relationship Diagram</th></tr>
<tr><td>Total</td><td>809</td><td>AC
XAC
SAC</td><td>16
15)
11) 26</td><td>(X)
(S) MAC</td><td>2981</td><td>CAC
C(S)(X)AC</td><td>
</td></tr>
<tr><td>Patchawarra Trough</td><td>119</td><td>SAC
XAC
AC</td><td>22)
22) 44
13</td><td>(S)
(X) AC</td><td>413</td><td>C(S)(X)AC</td><td>
</td></tr>
<tr><td>Cooper Basin Main</td><td>690</td><td>AC
XAC
SAC</td><td>29
14)
9) 23</td><td>(X)
(S) MAC</td><td>2568</td><td>CAC
C(S)(X)AC</td><td>
</td></tr>
<tr><td>Sandy facies</td><td>112</td><td>XAC
SAC
AC</td><td>30)
10) 40
9</td><td>(X)
(S) MAC</td><td>430</td><td>CXAC</td><td>
</td></tr>
<tr><td>Mixed facies</td><td>481</td><td>XAC
SAC
AC</td><td>15)
12) 27
26</td><td>(X)
(S) MAC</td><td>1754</td><td>C(S)(X)AC
CAC</td><td>
</td></tr>
<tr><td>Shaly facies</td><td>216</td><td>AC
ASAC
AXAC
SAC
XAC</td><td>36
11)
6) 17
9)
7) 16</td><td>A (S)
(X) AMAC
(S)
(X) AMAC</td><td>780</td><td>CAC
CASAC</td><td>
</td></tr>
<tr><td colspan="9">%* = Modal cycle percentage of total number of cycles   X—THICK SAND   S—SAND   A—SHALE   M—MIXTURE   C—COAL</td></tr>
<tr><td colspan="9">Drn.C.R.S. Bull.49   R.C.N.Thornton Geologist   78—793 S.A. Department of Mines and Energy</td></tr>
</table>

a particular vertical succession is the result of deposition in a particular environment.

The first concept was originally elucidated by Walther (1894, p. 979). Walther's Law of correlation of facies states '. . . only those facies and facies-areas can be superimposed primarily which can be observed beside each other at the present time' (translated from the original German by Middleton, 1973). Visher (1965) took this idea one step further, and said that 'each fundamental sedimentary process produces *both* a specific environmental distribution and a specific vertical profile'. Visher considered that there are only a limited number of sedimentary processes, and therefore that most sediments may be grouped into a limited number of sedimentary models. Using this concept, he was able to construct idealised profiles, representative of the major environments.

It is recognised that usually some of the sediments, which were deposited, are removed by erosion. As a result, the full vertical succession is seldom preserved in the geologic record. Therefore it is necessary to use a statistical technique to discover the most common rock succession, with the attitude that this is likely to be closest to the ideal. The idealised profile is set up following detailed examination of modern sediments.

Results of this study show that only a very few cycle types are common (Tables 9-13), and that the vast majority of them contain either one, two or three units between each coal (Table 14). In order of decreasing frequency, the modal cycles are (1) shale ⟶ coal; (2) sand ⟶ shale ⟶ coal; (3) shale ⟶ sand ⟶ shale ⟶ coal; (4) shale ⟶ sand ⟶ coal. The most probable environments for those successions can be elucidated by comparison with the results of research into modern sediments and other cyclicity studies.

Shale ⟶ coal cycles

Shale ⟶ coal cycles were deposited in swamp environment where the accumulation of vegetation alternated with clay, and the transition from coal to shale was indicative of waning vegetational control (Duff and Walton,

Table 14 *Coal cycle analysis: breakdown of the number of rock units per cycle*

Subdivision	Percentage of cycles: With 1 unit + coal	With 2 units + coal	With 3 units + coal	With 4 units + coal	With 5 or more units + coal	Percentage of cycles: With no more than 2 units + coal	With no more than 3 units + coal
STAGE 3'							
Total	35	19	16	8	22	54	70
Patchawarra Trough	29	17	20	11	23	46	66
Cooper Basin Main	40	21	13	7	19	61	74
Sandy facies	24	35	14	7	20	59	73
Mixed facies	31	17	16	9	27	48	64
Shaly facies	42	18	16	7	17	60	76
LOWER STAGE 4							
Total	44	26	12	5	13	70	82
UPPER STAGE 4'							
Total	43	19	15	6	17	62	77
EPSILON FORMATION							
Total	34	22	18	7	19	56	74
'DARALINGIE BEDS'							
Total	48	13	9	8	22	61	70
UPPER STAGE 5'							
Total	31	31	14	11	13	62	76
Patchawarra Trough	20	46	15	14	5	66	81
Cooper Basin Main	33	28	14	10	15	61	75
Sandy facies	17	48	7	14	14	65	72
Mixed facies	32	29	13	12	14	61	74
Shaly facies	39	23	19	7	12	62	81

1962; Doveton, 1971), or slightly increased water depth.

The particular abundance of shale ⟶ coal cycles in Permian coals was noted by Duff (1967a), who stated that such cycles were much thicker and more abundant in the Sydney Basin sediments than in the Carboniferous coal-bearing deposits of the Northern Hemisphere. Johnson and Cook (1973) also perceived the frequency of coal ⟷ shale oscillations in sediments of the Sydney Basin, and attributed this phenomenon to periods of low net subsidence. Duff (1967a) found that the shale ⟶ coal cycles were generally due to seam splitting (intra-seam cycles) and considered them to be rather a special case. Wanless *et al.* (1969) discovered that extensive seam splitting was indicative of proximity to a supply of clastic sediment.

The shale ⟶ coal cycles in the Cooper Basin on average are slightly thinner than most other cycle types, admittedly largely because they comprise only two units (Table 15). The lateral extent of the shales has not been studied, but detailed correlation of Moomba wells indicates that some would cover an area in the order of hundreds of square kilometres.

Where shale overlies coal, forest growth terminated with flooding of the area. Duff (1967b), however, suggests that flooding may be the result, rather than the cause, of cessation of coal formation. Either edaphic or climatic factors could slow down the accumulation of peat causing it to fail to keep up with subsidence. Duff preferred the former process, and quoted studies in both tropical and temperate swamps where thick accumulations of peat had so altered the edaphic conditions that a forest vegetation could no longer be supported. Thus flooding might occur without either increasing subsidence or raising sea level.

Certainly, the internal composition of Australian coal seams varies from bottom to top (Smyth, 1972). Shiboaka and Smyth (1975) found cyclic variations within a seam from dirt band, through vitrinite rich, then poor, and back to dirt band. This reflects the change from forest vegetation, which could grow in relatively deep water (vitrinite rich), to shallow water shrub grass (vitrinite poor). Smith (1962) originally proposed that the non-random variations through coal seams must be due to edaphic and climatic factors in his study of Carboniferous coals. However, Shiboaka and Smyth (1975) considered that the presence of the complete cycle was a function of deposition under conditions of steady, slow subsidence rather than in unstable basins. Analyses of coal from the Patchawarra Trough showed that the area was tectonically stable during deposition.

A combination of edaphic and tectonic stability concepts leads to the conclusion that given time a coal swamp will destroy itself. This means that no factor external to the basin, such as eustasy or isostasy, is necessary to cause the cyclic sedimentation.

Table 15 *Cooper Basin coal cycles: means and standard deviations in metres*

Stage/Formation	Property	Cycle type								
		AC	SC	XC	ASC	AXC	ASAC	AXAC	SAC	XAC
Upper Stage 5'	Number of cycles	213	26	14	24	5	55	37	88	122
	Mean thickness	4·0	3·0	7·9	3·7	9·8	8·9	13·5	5·7	10·6
	Standard deviation	4·7	3·2	6·7	3·7	6·3	6·1	7·8	4·5	7·1
	Mean thickness without coal	2·9	1·7	6·1	4·0	8·8	7·8	12·3	4·4	8·8
	Standard deviation without coal	3·7	0·7	3·1	2·5	3·8	4·2	5·3	2·3	3·5
'Daralingie Beds'	Number of cycles	23	2	0	4	0	4	0	2	0
	Mean thickness	6·8	3·2	—	8·3	—	13·0	—	10·8	—
	Standard deviation	7·4	3·4	—	7·5	—	9·0	—	9·4	—
	Mean thickness without coal	5·8	2·1	—	7·5	—	12·6	—	9·6	—
	Standard deviation without coal	6·5	0·4	—	6·5	—	8·1	—	6·3	—
Epsilon Formation	Number of cycles	63	1	2	19	8	24	3	9	5
	Mean thickness	5·8	2·1	11·7	9·2	11·9	12·9	15·5	7·2	10·5
	Standard deviation	5·9	—	15·6	7·5	5·8	8·8	9·6	6·5	8·6
	Mean thickness without coal	4·4	0·9	7·5	7·9	11·2	11·8	14·6	5·6	8·5
	Standard deviation without coal	4·4	—	4·1	5·4	3·9	7·2	7·7	4·1	4·3
Upper Stage 4'	Number of cycles	50	2	2	4	1	15	2	13	4
	Mean thickness	4·6	1·4	7·6	4·6	7·3	9·0	19·7	6·8	12·1
	Standard deviation	4·9	1·4	8·2	3·3	—	5·3	10·0	4·8	9·0
	Mean thickness without coal	3·1	1·1	5·2	4·0	7·0	8·4	18·7	5·6	10·1
	Standard deviation without coal	3·2	0·6	0·4	1·6	—	4·0	4·5	2·5	2·8
Lower Stage 4	Number of cycles	77	6	3	3	4	12	6	20	23
	Mean thickness	3·6	2·4	10·2	4·1	9·7	7·0	11·8	5·6	11·5
	Standard deviation	4·6	2·2	7·9	3·8	7·1	5·3	6·1	4·3	6·5
	Mean thickness without coal	2·5	1·6	8·6	3·7	9·1	5·5	11·1	4·1	10·5
	Standard deviation without coal	3·1	0·8	4·3	2·9	5·9	2·1	4·2	1·6	4·3
Stage 3'	Number of cycles	241	18	11	27	10	62	33	52	60
	Mean thickness	4·9	4·4	10·0	4·4	13·6	9·1	14·1	6·9	13·5
	Standard deviation	5·9	6·1	6·5	4·2	9·3	7·3	9·3	6·7	11·0
	Mean thickness without coal	3·0	1·9	8·8	3·6	12·5	8·2	12·2	5·1	10·9
	Standard deviation without coal	3·5	2·3	4·3	3·3	7·3	5·8	5·6	3·3	6·4

Sand → shale → coal cycles
Sand → shale → coal cycles are indicative of deposition from meandering streams. The modal cycle: sand → shale → coal, and its composite sequence: sand → mixture → shale → coal, are very similar to cycles encountered by others who have studied Permian coal measures (Duff, 1967a; Johnson and Cook, 1973; Hobday and Mathew, 1975). Duff (1967a) and Hobday and Mathew (1975) both found sedimentary structures indicative of a fluvial regime. In addition, Doveton (1971) discovered fining upwards cycles in the Carboniferous Ayrshire coal measures. He interpreted thick sandstones (thicker than 6 m) at the base of these cycles to be fresh water channel deposits from their elongate geometry, internal sedimentary characters and facies associations.

The fining upwards cycle is exactly that found in modern floodplains (Allen, 1965a). Therefore, there can be little doubt that most of the sands in such cycles were deposited by lateral accretion on the point bars of meandering rivers. Sand deposition was followed by vertical accretion of shales, as a result of overbank flooding, and finally coal formation in swamps. However, Cant and Walker (1976) recognised that braided stream deposition resulted in a similar fining upwards sequence, except that the vertical accretion component was relatively minor.
Shale → sand → shale → coal cycles
The sequence: shale → sand → shale → coal has two modern sedimentary analogues, depending on cycle thickness and sand grain size. Thick cycles compare with the section encountered on the deltaic plain, whereas thinner cycles, sometimes with silt in the middle rather than sand, are similar to interdistributary bay deposits. Coleman and Gagliano (1964) showed that sediments of the Mississippi River deltaic plain were deposited cyclically. Each of the cycles represents the building of a delta lobe, subdelta or crevasse splay into the basin of deposition. Each deltaic lobe is composed of a detrital lens or complex of lenses bounded on all sides by essentially non-detrital sediments indigenous to the basin of deposition. When the channel shifts laterally, the abandoned delta undergoes coastal retreat and inundation by reworked and *in situ* deposits due to continuing subsidence. As a result, the ideal vertical succession is shale → siltstone → sandstone → siltstone → shale → coal. The thickness of cycles ranges from 75 m for large overlapping lobes to 3-12 m for crevasse systems.

Fine → coarse → fine cyclicity has been recognised by Duff and Walton (1962), Read (1969), Doveton (1971), Casshyap (1975a) and Hobday and Mathew (1975). A deltaic to interdistributary bay environment is proposed in each case. Proximity to the shoreline in the case of the first three authors is indicated by the presence of marine to marginal marine fossils.
Shale → sand → coal cycles
The shale → sand → coal cycles are equated with coarsening upwards sequences, which can have deltaic, shoreline (Visher, 1965; Gould, 1970; LeBlanc, 1972), interdistributary bay (Elliott, 1976), or freshwater (Allen, 1965a; Elliott, 1976) origin, as discussed previously in the environmental interpretation of the Gidgealpa 6 cores. However, Hobday and Mathew (1975) interpreted such cycles as the result of progradation of a shoal water delta, to form laterally continuous sand sheets approximately 35 m thick.

INTERPRETATION

Stage 3'

Thirty per cent of all the coal cycles in Stage 3' are of the form shale → coal (Table 9), and this cycle type is dominant in all the subdivisions except sandy facies. Sand → shale → coal, and shale → sand → shale → coal cycles are the only other common types. In both cases, thin sand is much more common than thick, except in sandy facies (and Cooper Basin Main in the case of SAC). Analysis suggests that only inconclusive environmental interpretations result from subdividing the Cooper Basin on geographic grounds. However, subdividing the basin on lithofacies criteria shows that sandy facies was dominated by rivers, shaly facies by lakes, and mixed facies by an intermediate environment.

Stage 3' has a lack of horizontal stationarity for both lithofacies and geographic subdivisions (Table 8). This shows that the depositional conditions varied significantly throughout the Cooper Basin. Nonetheless, in all but the sandy facies, by far the most cycles consist of shale ⟷ coal oscillations. Therefore, considerable tracts of land must have existed as either lakes or coal swamps for long periods of time. Environmental continuity is exemplified by 20 m thick coal seams in the Patchawarra Trough.

Markov and histogram data do not differentiate satisfactorily between the Patchawarra Trough and Cooper Basin Main, although there is some indication of a greater fluvial influence in the south. The x^2 stationarity values are greater for Stage 3' than for any subsequent period. This shows that there was more difference between the different geographic areas during Stage 3' than during any later Stage, even though the facies relationship diagrams for the Patchawarra Trough and Cooper Basin Main are very similar, except for the X → and M → S transitions in the latter (Table 9). Histogram data show the same, except that fining upwards cycles are marginally more common than fine → coarse → fine in Cooper Basin Main. Thus fluvial influence is perhaps marginally more important in the southern part of the basin. This is supported by the fact that there are proportionately more fining upwards cycles starting with thick sand in Cooper Basin Main.

The prevalence of interdistributary bay deposits (as shown by ASAC and AXAC cycles) throughout is indication that substantial areas were submerged under shallow water. The fact that ASAC cycles are twice as common as AXAC cycles shows that there is a twice as great a chance that the interbedded sand will be less than 3 m thick. This in turn implies that the water depth commonly was less than 3 m deep, because sand bodies in shoal water deltas are slightly thicker than the depth of water (Gould, 1970).

Both ASAC and AC cycles may be indicative of proximity to shorelines. However in Stage 3′, the data are inconclusive, because shale → coal is more abundant in Cooper Basin Main, but fine → coarse → fine is marginally more abundant in the Patchawarra Trough. The presence of fine → coarse → fine cycles may imply a marginal marine environment, although a similar succession can be achieved by crevassing or delta building into a lake, wherever it may be situated. AC cycles may be shoreline indicators, on the evidence of the Pennsylvanian Allegheny Formation, which has a lithologic assemblage similar to the Patchawarra Formation, and crops out on the Appalachian Plateau (Ferm and Cavaroc, 1968; Ferm *et al.*, 1975). In the Allegheny Formation, the proportion of backswamp deposits (clay, siltstone, seat rock) increases towards the shoreline. In addition coals tend to be thinner and more continuous . By analogy, therefore, a greater proportion of lake deposits should indicate closer proximity to the shoreline.

The different facies relationship diagrams and histogram results for the three lithofacies are easier to interpret than are the geographic subdivisions (Table 9). In the sandy facies, the facies relationship diagram indicates predominantly fining upwards successions, with only very minor oscillations. Histogram evidence shows that nearly a quarter of all cycles comprise XAC. Therefore, the sandy facies was dominated by rivers, probably mostly with a meandering form. Water depth in these rivers generally exceeded 3 m. Relatively few lakes developed.

On the other hand, in the shaly facies, lakes dominated. Only occasionally did the land dry out and become covered by rivers. Even then, these streams were shallow, seldom being greater than 3 m deep. By comparison with the Allegheny Formation, shaly facies should be closer to the shoreline.

The mixed facies is the result of depositional environments intermediate between the extremes of dominantly fluvial or lacustrine.

Lower Stage 4

Shale → coal, and sand → shale → coal cycles together comprise 62 per cent of all cycle types, which suggests that lacustrine and fluvial deposition dominated. Compared with Stage 3′, the facies relationship diagrams are simpler because there are fewer oscillations between lithologic units (Table 10). Presumably this means that there was less variation in depositional environments, which in turn is probably a function of the thinner Lower Stage 4 section. Another difference is that, unlike Stage 3′, C → S transitions are non-random in two of the subdivisions (PatchawarraTrough and sandy facies). This is interpreted to indicate that more of the rivers were shallow during Lower Stage 4 than previously.

The facies relationship diagrams and modal sequences are very similar for the Patchawarra Trough and sandy facies. Both show a perfect fining upwards sequence with no reverse non-random transitions. A fluvial regime is indicated, particularly in the sandy facies, where the likelihood of coal being followed by sand is especially strong. The greater possibility of C → S than C → X transitions suggests that many of the rivers were shallow.

In the mixed facies, lake deposition was more important than in the sandy facies. The dominant environmental sequence was one of forest growth followed by inundation, and then a return to forest growth. In general, this rhythm could be broken only by the action of a major deep river (only C → X is non-random), presumably because the vegetation provided a sufficient barrier to the influx of sediments carried by minor streams.

Upper Stage 4′

The test for stationarity shows that the depositional environment was very similar throughout the basin during Upper Stage 4′ (Table 8). The facies relationship diagrams and modal sequences (Table 11) show that to a large degree cyclicity was restricted to CAC and CASAC, indicating deposition in lakes and interdistributary bays. This applies particularly to the Patchawarra Trough, from where 80 per cent of the transitions were recorded.

In the Cooper Basin Main, the fining upwards sequence shows that the fluvial regime was a more important depositional system than interdistributary bay, although lake deposition was important. Most rivers were shallow, because X holds no memory for C. The distinct opposite to this environment is that shown for the shaly facies where virtually all transitions pass to shale.

Patchawarra Formation

Results of tests for vertical stationarity for the three Stages into which the Patchawarra Formation has been divided imply that cyclicity varied enough with time in the Patchawarra Trough for the vertical sequence to be non-stationary, but that it was relatively static in Cooper Basin Main (Table 8). This suggests that there was more variation in depositional environment in the Patchawarra Trough than in Cooper Basin Main, where a comparison of modal sequences (Tables 9-11) indicates that a lacustrine influence was more consistently important.

Epsilon Formation

Both the histogram and Markov analysis data show that the depositional environment of the Epsilon Formation was considerably different to that of much of the Patchawarra Formation (Table 12). The analyses indicate that deposition occurred in shallow water, lacustrine or offshore, with sand bodies formed in shoreline environments. The Epsilon Formation shows most similarity with the shaly facies of Upper Stage 4'. There is no indication of fining upwards cyclicity indicative of the fluvial regime.

More than half of all cycles are of the form AC, and nearly another quarter comprise ASAC. Therefore, lakes and interdistributary bays formed the major environments. In addition, the coarsening upwards cycles suggest the presence of shoreline deposition.

The facies relationship diagrams substantiate this interpretation. In particular, the thick sand $\longrightarrow$ coal transition was not encountered in the Patchawarra Formation other than for shaly facies in Upper Stage 4'. Even so, coal has a much stronger memory for thick sand in the Epsilon Formation, than in Upper Stage 4'. This situation is interpreted to be the result of swamp development on top of a regressive sand, such as a beach, chenier or delta front.

'Daralingie Beds'

The analysis results for the 'Daralingie Beds' are very similar to those of the Epsilon Formation (Table 12). Therefore, deposition occurred during a lacustrine regression in shallow water with the sands being deposited in deltas, beaches, and other shoreline environments. Unlike the Epsilon Formation, the 'Daralingie Beds' contain very few thick sands. This lack implies that water depths were shallower during the second regression.

Upper Stage 5'

All the facies relationship diagrams for the various subdivisions of the Upper Stage 5' period, with the exception of shaly facies, are very similar (Table 13). The dominant transitions are those of the fining upwards succession, which is interpreted as being formed by meandering rivers. The fact that all the subdivisions, other than shaly facies, have very similar facies relationship diagrams, is indicative of the similarity of the depositional environment throughout the basin.

The fining upwards cyclicity is exemplified best by the Patchawarra Trough, where all transitions in the facies relationship diagram are markedly non-random. In addition M is almost absent and as by definintion, M involves oscillation between thin shale and sand bands, its virtual absence is further indication of the almost invariable upwards fining lithologic succession. Therefore, during Upper Stage 5', the Patchawarra Trough area was an alluvial plain dominated by meandering rivers. The small proportion of AC cycles shows that few lakes developed in the region.

Sandy and mixed facies have very similar facies relationship diagrams, but with progressively diminishing proportions of fining upwards cycles in the latter. This indicates that the locus of major river transport was in the sandy facies, and that rivers meandered less frequently across the mixed facies. The dominance of XAC cycles in sandy facies also means that, on the whole, larger rivers crossed the sandy facies than mixed facies.

The shaly facies are the only areas where backswamp development occurred to any major degree.

Bivariate Correlation Analysis

Bivariate correlation analysis has been conducted on pairs of six variables. These are: total thickness of mapped unit; number of cycles; average cycle thickness; average cycle thickness excluding coal; total coal thickness; and average coal thickness. Linear regression lines have been computed and means calculated for the same data. The purpose has been to discover if linear relationships noted elsewhere in the world apply to the Cooper Basin, and to compare the slopes of linear regression lines with those from different areas and environments.

Results indicate that almost invariably the number of cycles bears a strong linear relationship with total thickness. This indicates that cycles were caused by intrabasinal factors, such as sedimentation and subsidence. However, the Patchwarra Trough during certain periods may have been the exception, with cyclicity being controlled by external causes. The other four variables analysed show only a few significant correlations, both amongst themselves, and with total thickness, and number of cycles.

Different depositional environments show no diagnostic differences under linear regression analysis. In addition, depositional environment is not a major factor affecting cycle thickness.

PURPOSE

The purpose of the bivariate correlation analysis is to study the statistical relationships between total thickness, number and thickness of coal cycles, and total and average coal thickness. The ultimate aim is to derive further information on the sedimentation history of the basin.

One aim of the present study has been to discover whether the relationships which apply in the Cooper Basin are the same as those from elsewhere. The pioneer study, which showed a linear relationship between number of cycles and total thickness, was conducted by Duff and Walton (1964) on the coal measures of the East Pennine coalfield. Since then, a linear relationship between these and other pairs of variables has been recognised in coal-bearing rocks from Scotland (Read and Dean, 1967, 1975 and 1976), Germany (Casshyap, 1975a and 1975b), and Australia (Duff, 1967a; Johnson and Cook, 1973).

A further aim has been to compare results from this and previous studies. The equations for linear regression lines in some of the above-mentioned experiments have been published. These equations are derived from sedimentary sections with widely divergent geographic distribution and depositional environments. The slopes on the regression lines reflect the average thickness of cycles (Read and Dean, 1976), in particular.

METHOD

Pearson correlation coefficients (r) have been calculated for pairs of the six variables (listed in Table 16) and tested for significance (S) using Student's t test. If S = 0·001 in the data, then r is correct for 99·9 per cent of cases. (Essentially, S is a measure of whether the number of samples was great enough for confidence to be placed on the estimation of r).

Table 16 *Stratigraphic variables tested by bivariate correlation analysis*

	Abbreviation
Thickness of mapped unit (= sum of thickness of complete cycles in unit)	TOTHICK
Number of cycles in unit	CYNO
Average cycle thickness	AVTHICK
Average thickness of clastic component of the cycle (i.e. excluding coal)	AVWCOAL
Total coal thickness	TOTCOAL
Average coal thickness	AVECOAL

Correlation coefficients were computed on data from each of the six units for which facies maps were drawn, viz. Stage 3', Lower Stage 4, Upper Stage 4', Epsilon Formation, 'Daralingie Beds', and Upper Stage 5'. In addition, the same geographic and lithofacies subdivisions as those used for the coal cyclicity analysis have been investigated. The results are tabulated (Tables 17-19) for all pairs of variables where r is significant at the 0·009 level, or better. Means and standard deviations were also calculated (Tables 20-22).

For those pairs of variables which showed high correlation (and S = 0·001), the data points were plotted out on scattergrams, and the equations for least-squares linear regression computed (Tables 23, 24). The equations for three pairs of variables are shown pictorially (Figs. 53-55).

Linear regression allows the results to be interpreted in terms of geologic phenomena on the assumption that the relationship between variables is a simple linear one. A mathematically more correct equation might be obtained using polynomial regressions. However, other workers (Johnson and Cook, 1973; Read and Dean, 1976) have found that no further information is gained by using second and third-degree polynomials.

The computer programs used to carry out all the methods of regression analysis are part of the 'Statistical Package for the Social Sciences' (Nie *et al.*, 1975).

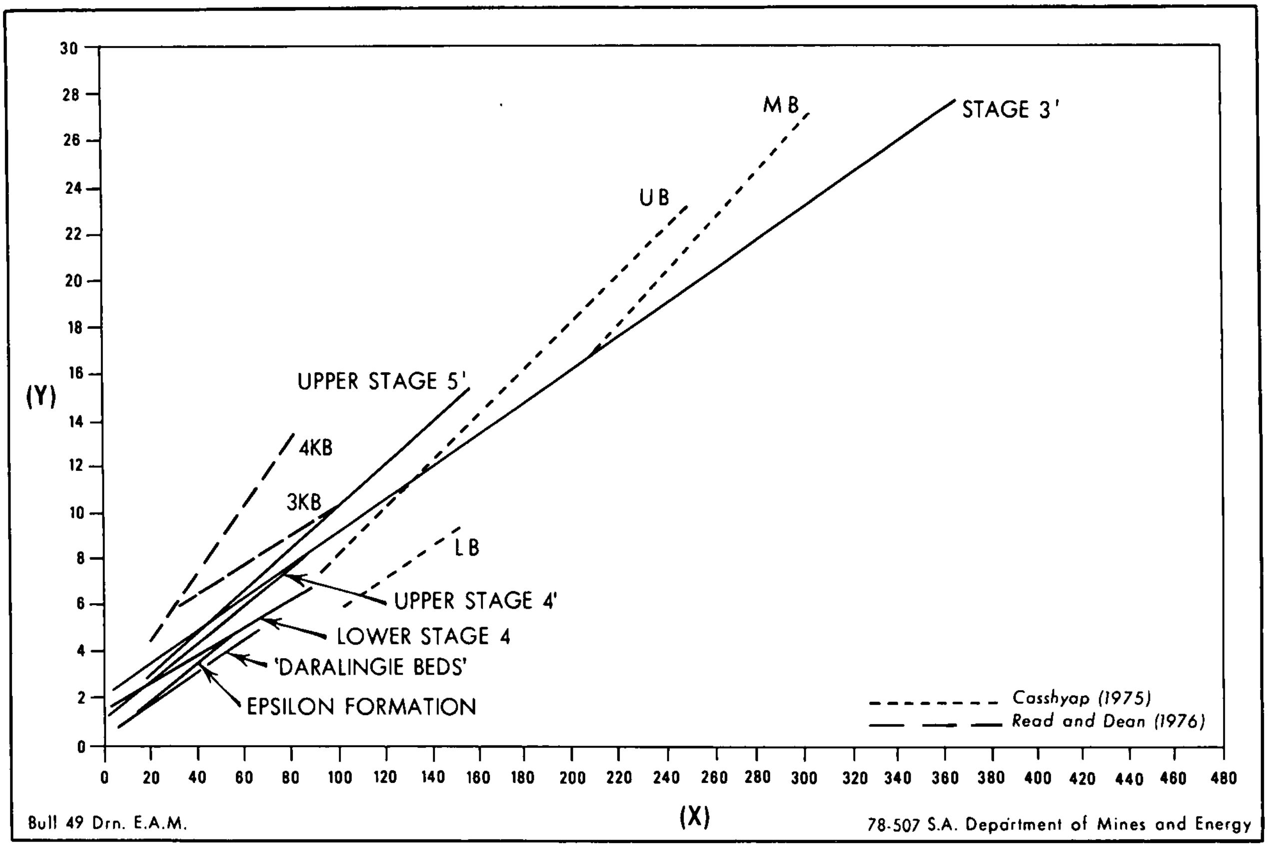


Fig. 53. Linear regression lines for number of cycles (y) vs. total thickness in metres (x)

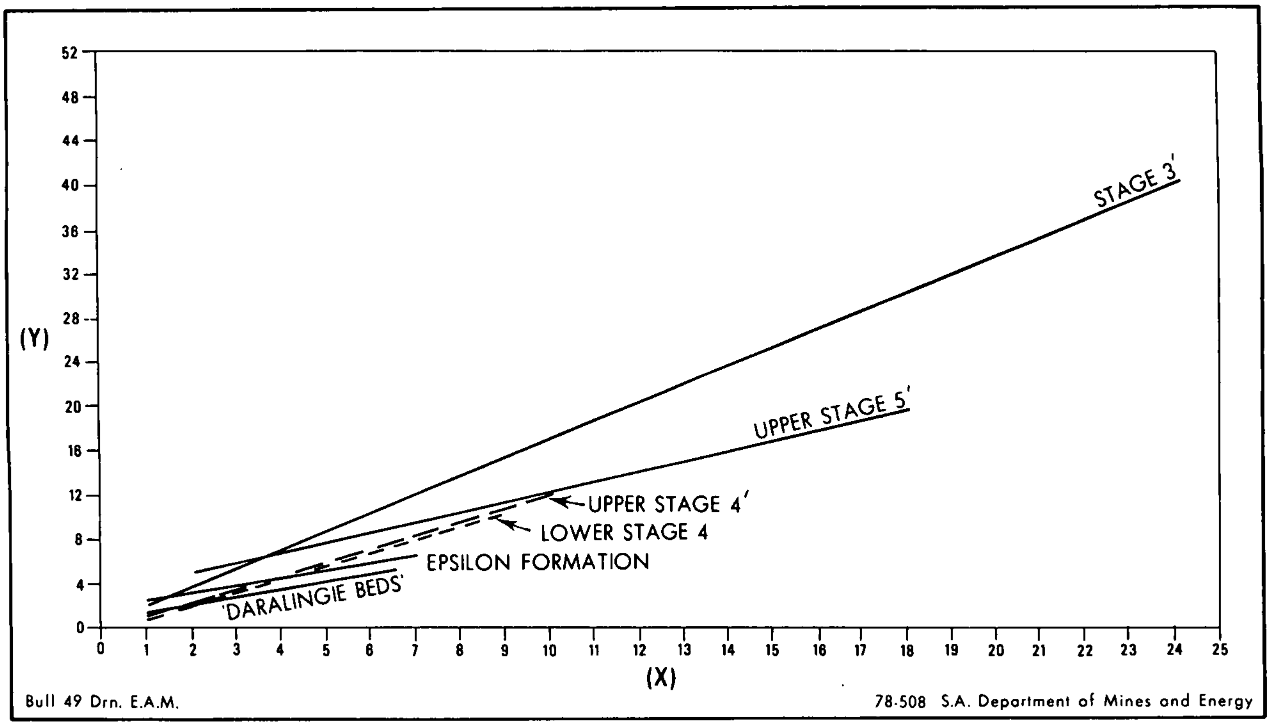


Fig. 54. Linear regression lines for total coal thickness in metres (y) vs. number of cycles (x)

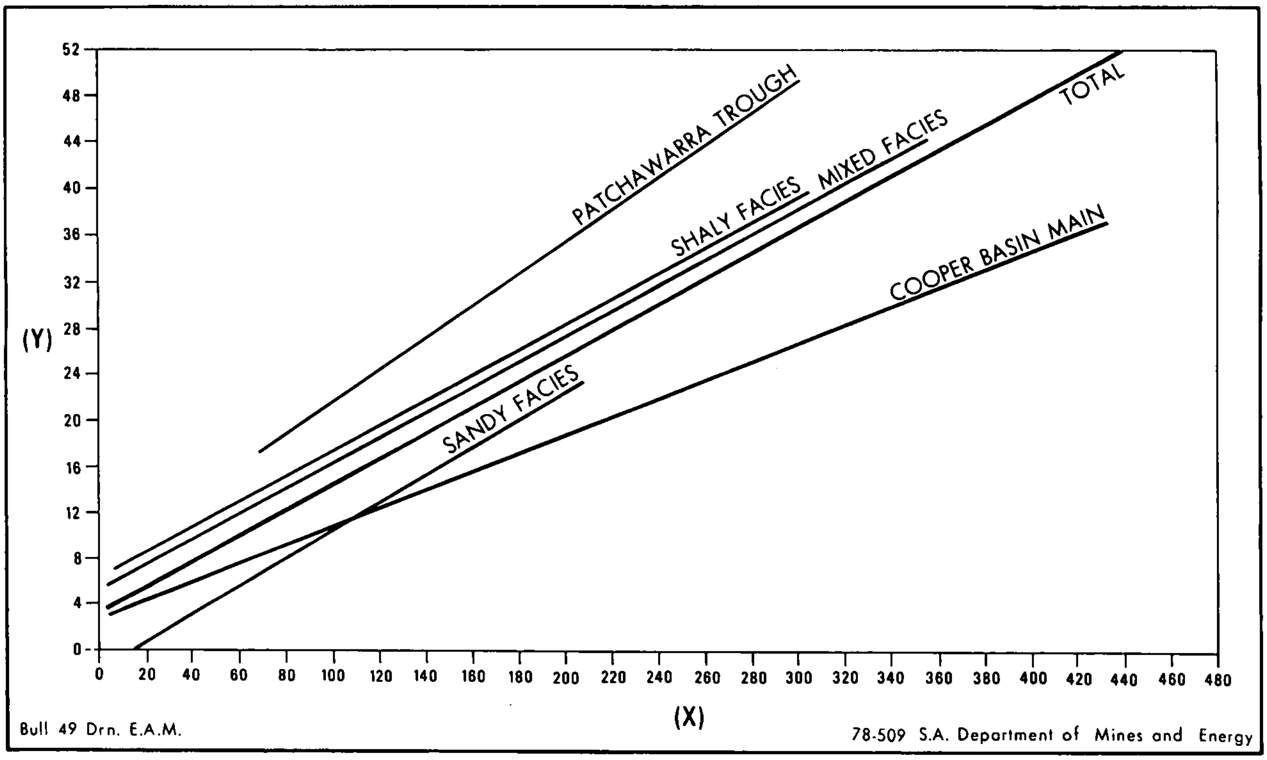


Fig. 55. Linear regression lines for total coal thickness in metres (y) vs. total thickness in metres (x) in Stage 3'

RESULTS AND DISCUSSION

Correlation coefficients, significant to at least the 0·009 level, occur between only a few of the pairs of variables studied (Tables 17-19). Nonetheless, the strong linear relationship between total thickness and number of cycles (Table 23; Fig. 53) shows that in general, cycles were formed by purely local depositional processes. The lack of this relationship in the Patchawarra Trough during Upper Stage 5' perhaps indicates that some external factor influenced deposition. Overall, depositional environment appears not to have affected cycle thickness, which remained uniform throughout Gidgealpa Group deposition (Tables 20-22).

Total coal thickness generally correlates strongly with the number of cycles, but only in the case of Stage 3' does it correlate with total thickness (Table 24; Figs. 54 and 55). The lack of correlation between thickness of the clastic component of a cycle and average coal thickness implies that factors controlling deposition of the clastic fraction of a cycle may have been largely independent of those that controlled coal formation.

Total Thickness of Strata (TOTHICK) and Number of Coal Cycles (CYNO)

Of all the pairs of variables, total thickness and number of cycles is the only one for which a strong linear relationship almost invariably occurs. This linear relationship shows that the great majority of cycles were formed by the interaction of purely local processes of subsidence and sedimentation (Read and Dean, 1976). The fact that section was removed by erosion from units mapped in some of the wells does not appreciably affect this interpretation. Read and Dean (1967) considered that if cyclic sedimentation was caused by eustatic sea level rises, or wide-spread epeirogenic changes in the level of basement, or tectonic uplifts in the source area, then there should be a similar number of cycles almost everywhere in the basin. This is not the case in the Cooper Basin.

The extent of correlation varies from one Stage to another. Correlation coefficients range from 0·48 to 0.98, and most are significant at 0·001 level. Correlation coefficients are highest in Stage 3', both for the complete section and all subdivisions, and lowest in Lower Stage 4. In the Patchawarra Trough during Upper Stage 5', the

Table 17 *Cooper Basin coal cycles: correlation coefficients (R) and significance (S)*

Variables		Total	Patchawarra Trough	Cooper Basin Main	Sandy facies	Mixed facies	Shaly facies
STAGE 3'							
No. in sample		80	25	55	17	31	32
TOTHICK-CYNO	R	·86	·68	·87	·94	·84	·88
	S	·001	·001	·001	·001	·001	·001
TOTHICK-AVTHICK	R	·51		·52		·71	·66
	S	·001		·001		·001	·001
TOTHICK-AVWCOAL	R	·48		·50		·68	·71
	S	·001		·001		·001	·001
TOTHICK-TOTCOAL	R	·76	·83	·75	·93	·67	·83
	S	·001	·001	·001	·001	·001	·001
CYNO-AVTHICK	R		—·53				
	S		·003				
CYNO-TOTCOAL	R	·85	·78	·92	·93	·85	·82
	S	·001	·001	·001	·001	·001	·001
CYNO-AVECOAL	R		—·57				
	S		·002				
AVWCOAL-AVECOAL	R		·76				
	S		·001				
LOWER STAGE 4							
No. in sample		67	22	45	18	27	22
TOTHICK-CYNO	R	·54		·51		·48	·58
	S	·001		·001		·006	·002
TOTHICK-AVTHICK	R	·47	·53	·47	·60	·55	·58
	S	·001	·006	·001	·004	·002	·002
TOTHICK-AVWCOAL	R	·47	·53	·45	·60	·57	·51
	S	·001	·006	·001	·001	·001	·008
TOTHICK-TOTCOAL	R	·49	·55	·52			·73
	S	·001	·004	·001			·001
CYNO-AVTHICK	R						
	S						
CYNO-TOTCOAL	R	·64	·68	·68		·60	·80
	S	·001	·001	·001		·001	·001
CYNO-AVECOAL	R						
	S						
AVWCOAL-AVECOAL	R						
	S						

Table 18 *Cooper Basin coal cycles: correlation coefficients (R) and significance (S)*

UPPER STAGE 4'

Variables		Total	Patchawarra Trough	Cooper Basin Main	Sandy facies	Mixed facies	Shaly facies
No. in sample		32	19	13	1	11	21
TOTHICK-CYNO	R	·74	·56	·72		·81	·69
	S	·001	·006	·003		·001	·001
TOTHICK-AVTHICK	R						
	S						
TOTHICK-AVWCOAL	R						
	S						
TOTHICK-TOTCOAL	R	·84	·74	·77		·95	·75
	S	·001	·001	·001		·001	·001
CYNO-AVTHICK	R						
	S						
CYNO-TOTCOAL	R	·83	·68	·87		·88	·80
	S	·001	·001	·001		·001	·001
CYNO-AVECOAL	R						
	S						
AVWCOAL-AVECOAL	R						
	S						

EPSILON FORMATION

Variables		Total	Patchawarra Trough	Cooper Basin Main	Mixed (+ sandy) facies	Shaly facies
No. in sample		66	23	43	16	50
TOTHICK-CYNO	R	·70	·74	·62	·62	·67
	S	·001	·001	·001	·001	·001
TOTHICK-AVTHICK	R					
	S					
TOTHICK-AVWCOAL	R					
	S					
TOTHICK-TOTCOAL	R					
	S					
CYNO-AVTHICK	R	—·52	—·53	—·64	—·62	—·55
	S	·001	·005	·001	·005	·001
CYNO-TOTCOAL	R	·41	·50		·66	
	S	·001	·008		·003	
CYNO-AVECOAL	R					
	S					
AVWCOAL-AVECOAL	R					
	S					

Table 19 *Cooper Basin coal cycles: correlation coefficients (R) and significance (S)*

'DARALINGIE BEDS'

Variables		Total
No. in sample		26
TOTHICK-CYNO	R	·27
	S	·001
TOTHICK-AVTHICK	R	
	S	
TOTHICK-AVWCOAL	R	
	S	
TOTHICK-TOTCOAL	R	
	S	
CYNO-AVTHICK	R	
	S	
CYNO-TOTCOAL	R	·77
	S	·001
CYNO-AVECOAL	R	
	S	
AVWCOAL-AVECOAL	R	
	S	

UPPER STAGE 5'

Variables		Total	Patchawarra Trough	Cooper Basin Main	Sandy facies	Mixed facies	Shaly facies
No. in sample		109	26	83	24	62	22
TOTHICK-CYNO	R	·76		·72	·81	·68	·77
	S	·001		·001	·001	·001	·001
TOTHICK-AVTHICK	R	·29	·51	·32		·39	
	S	·001	·004	·001		·001	
TOTHICK-AVWCOAL	R	·35	·54	·36		·45	
	S	·001	·002	·001		·001	
TOTHICK-TOTCOAL	R	·53		·55		·31	·76
	S	·001		·001		·007	·001
CYNO-AVTHICK	R	—·34	—·64	—·36		—·36	
	S	·001	·001	·001		·002	
CYNO-TOTCOAL	R	·69		·72	·74	·56	·84
	S	·001		·001	·001	·001	·001
CYNO-AVECOAL	R	—·38		—·32		—·35	
	S	·001		·002		·003	
AVWCOAL-AVECOAL	R						
	S						

number of cycles does not show a correlation with total thickness. This is the most important exception to the normal thickness-number of cycles correlation in the Cooper Basin.

The lack of correlation between cycle number and thickness, together with two other lines of evidence, lead to the interpretation that there may have been some non-sedimentary control on cyclic sedimentation within the Patchawarra Trough during Upper Stage 5'. The other contributing factors to this interpretation are the uniformly low number of cycles, and the uniformly thin section in the Patchawarra Trough.

In the Patchawarra Trough, the variation in cycle number is much smaller than elsewhere in the basin. The mean cycle number is 5, with a standard deviation of only 1 (Table 22). In addition, the mean total thickness of 44·5 m is thinner, and less variable, than for any other

Table 20 *Cooper Basin coal cycles: means ($\overline{X}$) and standard deviations (s) in metres*

STAGE 3′

Variable		Total	Patchawarra Trough	Cooper Basin Main	Sandy facies	Mixed facies	Shaly facies
No. in sample		80	25	55	17	31	32
TOTHICK	$\overline{X}$	117·7	170·4	93·9	82·9	135·3	119·5
	s	94·8	50·6	100·9	63·7	99·4	101·5
CYNO	$\overline{X}$	10	14	8	6	11	11
	s	7	5	7	5	7	8
AVTHICK	$\overline{X}$	11·3	13·1	10·4	13·4	11·9	9·4
	s	5·2	4·0	5·5	5·5	5·5	4·0
AVWCOAL	$\overline{X}$	9·8	10·7	9·1	12·5	10·1	7·9
	s	4·9	3·4	5·5	5·5	5·2	3·7
TOTCOAL	$\overline{X}$	17·1	31·7	10·4	8·2	19·8	18·9
	s	14·3	8·5	11·0	8·2	16·2	13·1
AVECOAL	$\overline{X}$	1·5	2·4	1·2	1·2	1·5	1·8
	s	0·9	0·6	0·6	0·6	0·9	0·9

LOWER STAGE 4

Variable		Total	Patchawarra Trough	Cooper Basin Main	Sandy facies	Mixed facies	Shaly facies
No. in sample		67	22	45	18	27	22
TOTHICK	$\overline{X}$	23·8	17·1	26·8	20·1	23·8	26·2
	s	16·5	10·4	18·0	13·1	16·2	18·9
CYNO	$\overline{X}$	3	2	3	2	3	4
	s	2	1	2	1	2	2
AVTHICK	$\overline{X}$	9·4	9·1	9·8	12·2	9·1	7·9
	s	7·0	5·5	7·9	9·8	6·4	4·9
AVWCOAL	$\overline{X}$	8·5	7·6	8·8	10·4	8·2	6·7
	s	7·0	5·5	7·9	10·1	6·4	4·9
TOTCOAL	$\overline{X}$	3·0	3·0	3·0	3·0	2·1	4·3
	s	3·0	3·0	3·0	3·0	1·2	4·3
AVECOAL	$\overline{X}$	1·2	1·5	0·9	1·5	0·9	1·2
	s	0·9	1·2	0·6	1·2	0·6	0·6

subdivision. The thinner sediment pile in the Patchawarra Trough compared with elsewhere, indicates that less subsidence occurred north of the GMI anticlinal trend. This is supported also by the fact that total thickness correlates linearly with more variables in the Cooper Basin Main than in the Patchawarra Trough. Perhaps the Patchawarra Trough region was a stable area that was more prone to intermittent subsidence as a result of tectonic re-adjustment such as occurs along a major strike slip fault.

Throughout the deposition of the Gidgealpa Group sediments, the average cycle thickness tended to be about 9-12 m (Tables 20-22). The very similar slope on the regression lines for the variation between total thickness and cycle number (Table 23; Fig. 53) shows that this is true especially for the subdivisions within both Stage 3′ and Upper Stage 5′.

The lack of difference in slope on linear regression lines for units deposited in different depositional environments suggests that environment had no significant effect on cycle thickness. The slopes are not significantly different for linear regression lines between environments which are dominantly fluvial meandering (Lower Stage 4 , Upper Stage 5′), lacustrine regressive sequences (Upper Stage 4,′ Epsilon Formation, 'Daralingie Beds'), and indeterminate (Stage 3′). It would seem probable therefore that the factor affecting the thickness of cycles in any particular area is a combination of the rate of subsidence and the amount of sediment supplied, rather than the depositional environment.

Table 21 *Cooper Basin coal cycles: means ($\overline{X}$) and standard deviations (s) in metres*

UPPER STAGE 4′

Variable		Total	Patchawarra Trough	Cooper Basin Main	Sandy facies	Mixed facies	Shaly facies
No. in sample		32	19	13	1	11	21
TOTHICK	$\overline{X}$	36·3	47·5	19·8		36·9	34·7
	s	24·1	23·2	13·7		32·3	20·7
CYNO	$\overline{X}$	4	5	2		4	4
	s	3	2	2		3	2
AVTHICK	$\overline{X}$	10·4	9·4	11·3		10·4	9·8
	s	6·1	4·3	7·9		8·8	4·6
AVWCOAL	$\overline{X}$	9·1	7·9	11·0		9·8	8·5
	s	6·1	4·0	7·9		8·8	4·6
TOTCOAL	$\overline{X}$	4·6	7·0	1·2		4·3	4·9
	s	4·0	3·4	1·8		4·9	3·7
AVECOAL	$\overline{X}$	0·9	1·2	0·6		0·9	1·2
	s	0·6	0·6	0·3		0·6	0·6

EPSILON FORMATION

Variable		Total	Patchawarra Trough	Cooper Basin Main	Mixed (+ sandy) facies	Shaly facies
No. in sample		66	23	43	16	50
TOTHICK	$\overline{X}$	32·3	22·6	37·5	25·9	34·1
	s	14·0	10·4	13·1	13·1	13·4
CYNO	$\overline{X}$	3	2	3	2	3
	s	2	1	2	1	2
AVTHICK	$\overline{X}$	12·5	11·6	12·8	12·8	12·2
	s	5·2	4·3	5·8	6·4	4·9
AVWCOAL	$\overline{X}$	11·0	9·8	11·6	11·6	11·0
	s	5·2	4·3	5·5	6·1	4·9
TOTCOAL	$\overline{X}$	3·7	3·0	4·0	3·0	3·7
	s	2·7	2·1	2·7	0·6	0·3
AVECOAL	$\overline{X}$	1·5	1·5	1·2	1·5	1·2
	s	1·2	1·2	1·2	1·2	1·2

Read and Dean (1976) found that different depositional environments showed no diagnostic differences under linear regression analysis. They examined vertical sections from various environments, ranging from alluvial floodplain (Fig. 53, 4KB) to distal deltaic (Fig. 53, 3KB), and found that different environments could not be differentiated on the basis of the slope on regression lines between total thickness and cycle number. In most cases, slopes are somewhat greater than in the Cooper Basin sections indicating thinner average cycle thicknesses. However, some German deltaic formations (Casshyap, 1975a) have a range of thickness and cycle thickness very similar to Stage 3′ (Fig. 53, LB, MB and UB).

Extrapolation of the linear regression lines, shows that all but one cross the y axis between 0 and 2·5 cycles (Table 23; Fig. 53). This apparently absurd situation can be explained largely by the size of the standard error of estimate.

Total Coal Thickness (TOTCOAL) and Number of Coal Cycles (CYNO)

Total coal thickness correlates strongly with the number of coal cycles (Tables 17-19). However, slopes of the linear regression lines vary considerably (Table 24; Fig. 54).

Two exceptions to significant positive correlation between coal thickness and cycle number are the sandy facies of Lower Stage 4, and the Patchawarra Trough during Upper Stage 5′. In neither of these cases, does cycle number correlate with total thickness, which for the Patchawarra Trough, at least, can have been attributed to some factor external to the depositional basin.

Table 22 *Cooper Basin coal cycles: means ($\overline{X}$) and standard deviations (s) in metres*

'DARALINGIE BEDS'

Variable		Total
No. in sample		26
TOTHICK	$\overline{X}$	22·9
	s	15·8
CYNO	$\overline{X}$	2
	s	2
AVTHICK	$\overline{X}$	12·5
	s	6·1
AVWCOAL	$\overline{X}$	11·3
	s	6·4
TOTCOAL	$\overline{X}$	2·1
	s	1·5
AVECOAL	$\overline{X}$	1·2
	s	0·9

UPPER STAGE 5'

Variable		Total	Patchawarra Trough	Cooper Basin Main	Sandy facies	Mixed facies	Shaly facies
No. in sample		109	26	83	24	62	62
TOTHICK	$\overline{X}$	72·8	44·5	81·7	52·1	72·8	96·3
	s	35·1	12·2	35·4	25·9	32·3	38·4
CYNO	$\overline{X}$	7	5	8	5	8	10
	s	4	1	4	2	4	4
AVTHICK	$\overline{X}$	10·4	10·4	10·4	11·6	10·1	10·1
	s	4·0	4·0	4·0	3·4	4·3	3·7
AVWCOAL	$\overline{X}$	9·1	8·5	9·1	9·8	8·8	8·8
	s	4·0	4·0	4·0	3·4	4·3	3·7
TOTCOAL	$\overline{X}$	9·4	7·9	10·1	7·6	9·1	12·5
	s	4·9	3·4	5·2	2·7	4·6	5·8
AVECOAL	$\overline{X}$	1·5	1·8	1·2	1·8	1·2	1·2
	s	0·6	0·9	0·6	0·6	0·9	0·3

Total Coal Thickness (TOTCOAL) and Total Thickness (TOTHICK)

Only Stage 3' and its subdivisions have strong positive correlation between the amount of coal and total thickness (Tables 17-19, 24; Fig. 55). Strong correlation between coal and total thickness implies that there was no region in the depositional basin which was preferentially suitable for the accumulation of coal deposits. Instead, the amount of coal that was laid down and preserved was a function of subsidence.

Average Thickness of the Clastic Component of a Cycle (AVWCOAL) and Average Coal Thickness (AVECOAL)

Only in the Patchawarra Trough during Stage 3' does the thickness of the clastic component of the cycle and average coal thickness correlate with one another (Table 17). The absence of correlation between thickness of the clastic sediments and thickness of coal in a single cycle implies that cycle development is the result of two separate sets of processes, which can operate independently of one another.

That thickness of the clastic component of a cycle and average coal thickness do correlate in the Patchawarra Trough during Stage 3', suggests that both portions of the coal cycle were subjected to the same depositional controls. Furthermore, total thickness, and the number and thickness of coal cycles, vary much less in the Patchawarra Trough during Stage 3' than elsewhere in the basin (Table 20). A combination of these factors leads to the interpretation that the depositional environment was uniform everywhere in the Patchawarra Trough, and changed uniformly throughout. A possible cause for such change might be intermittent subsidence.

Table 23 *Equations of linear regression lines*

NUMBER OF CYCLES (y) Vs. TOTAL THICKNESS IN METRES (x)

Stage/ Formation	Subdivision	1st-Degree polynomial†	Correlation coefficient (r)*
Upper Stage 5′	Complete	y=1·26 + 0·09x (±5·03)	·76
	Patchawarra Trough	—	
	Cooper Basin Main	y=1·61 + 0·08x (±5·52)	·72
	Sandy facies	y=1·09 + 0·07x (±2·54)	·81
	Mixed facies	y=1·91 + 0·08x (±5·57)	·68
	Shaly facies	y=2·08 + 0·08x (±5·21)	·77
'Daralingie Beds'	Complete	y=0·39 + 0·07x (±2·27)	·72
Epsilon Formation	Complete	y=0·42 + 0·08x (±2·21)	·70
Upper Stage 4′	Complete	y=1·09 + 0·08x (±3·57)	·74
Lower Stage 4	Complete	y=1·49 + 0·06x (±2·91)	·54
Stage 3′	Complete	y=2·19 + 0·07x (±7·28)	·86
	Patchawarra Trough	y=2·03 + 0·07x (±7·55)	·68
	Cooper Basin Main	y=2·18 + 0·07x (±7·26)	·87
	Sandy facies	y=2·17 + 0·07x (±3·55)	·94
	Mixed facies	y=2·30 + 0·06x (±7·89)	·84
	Shaly facies	y=3·27 + 0·07x (±7·59)	·88

† 95 per cent fiducial limits (i.e. 1·96 times the Standard Error of Estimate) are given in brackets
* Pearson correlation coefficients are all significant at the 0·001 level

Table 24 *Equations of linear regression lines*

TOTAL COAL THICKNESS IN METRES (y) Vs. NUMBER OF CYCLES (x)

Stage/ Formation	Subdivision	1st-Degree polynomial†	Correlation coefficient (r)*
Upper Stage 5′	Complete	y=3·20 + 0·84x (±6·89)	·69
'Daralingie Beds'	Complete	y=0·55 + 0·69x (±1·87)	·77
Epilson Formation	Complete	y=1·60 + 0·68x (±4·68)	·41
Upper Stage 4′	Complete	y=−0·30 + 1·22x (±4·34)	·83
Lower Stage 4	Complete	y=−0·18 + 1·14x (±4·75)	·64
Stage 3′	Complete	y=0·50 + 1·65x (±14·90)	·85

TOTAL COAL THICKNESS IN METRES (y) Vs. TOTAL THICKNESS IN METRES (x)

Stage/ Formation	Subdivision	1st-Degree polynomial†	Correlation coefficient (r)*
Upper Stage 5′	Complete	y=4·20 + 0·07x (±8·05)	·53
'Daralingie Beds'	Complete	—	r not significant at ·001
Epsilon Formation	Complete	—	r not significant at ·001
Upper Stage 4′	Complete	y=−0·27 + 0·14x (±4·30)	·84
Lower Stage 4	Complete	(not calculated)	·49
Stage 3′	Complete	y=3·53 + 0·11x (±18·09)	·76
	Patchawarra Trough	y=7·59 + 0·14x (±9·78)	·83
	Cooper Basin Main	y=2·72 + 0·08x (±14·14)	·75
	Sandy facies	y=−1·68 + 0·12x (±6·25)	·93
	Mixed facies	y=5·10 + 0·11x (±23·77)	·67
	Shaly facies	y=6·04 + 0·11x (±14·78)	·83

† 95% fiducial limits (i.e. 1·96 times the Standard Error of Estimate) are given in brackets
* Pearson correlation coefficients are all significant at the 0·001 level

Summary of Depositional History

TIRRAWARRA SANDSTONE

The Tirrawarra Sandstone was deposited from braided streams: the sands mostly accumulated as in-channel deposits which were laid down in medial bars between anastamosing channels.

The Tirrawarra Sandstone was deposited in a northerly trending depositional basin (Fig. 20) cut across presently existing structural highs, which did not exist at the time. Rivers entered the basin from the eastern side.

The change from Tirrawarra Sandstone to Patchawarra Formation was caused by a gradational change from braided to meandering stream environments as a result of diminishing regional gradient. The change occurred from west to east.

STAGE 3′

Depositional environments during Stage 3′ ranged from a fluvial regime on an alluvial plain to paludal (Fig. 24). Considerable tracts of land were under water, or covered by coal swamps, for long periods of time. In addition, the preferred locations for the deepest meandering rivers were in the sandy facies, while streams were shallow in the shaly facies where lakes predominated (Fig. 22). Lakes and bays were commonly less than 3 m in depth, with deep rivers possibly most prevalent in the southern part of the basin.

Most coal cycles were formed by the interaction of purely local processes of subsidence and sedimentation. External controls, such as eustatic sea level rises, need not be invoked.

The depositional regime in the Patchawarra Trough was different from the rest of the Cooper Basin, although in fact, this difference may be not so much a difference between Patchawarra Trough and Cooper Basin Main, as between the areas of thick sedimentation (Patchawarra and deep Nappamerrie Troughs) and thin (elsewhere). Any similarities between the two troughs cannot be gauged, because only Burley 1 has been drilled into the deep part of the Nappamerrie Trough.

The Gidgealpa-Merrimelia-Innamincka anticlinal trend marked a boundary between the Patchawarra Trough and the Cooper Basin Main subenvironments. It is possible, that at Gidgealpa, the trend acted as a physical barrier between the two regions, but it was not emergent over most of its length.

In the Cooper Basin Main, the depositional surface had a relatively uneven basal topography, and some 'islands' existed, which were never inundated completely. It is possible that the land surface had been created by glacial action during the deposition of the Merrimelia Formation. Most sediment was carried from the southernmost tip of the basin, northwards across the Murteree-Nappacoongee anticlinal trend, which was not an emergent feature, to the Moomba region, and on into the Nappamerrie Trough. The rate of subsidence was greatest in the sandy facies, which delineates the channel region, and overbank deposits predominated to either side of this central channel zone. The alluvial plain gradually filled, and onlap progressively occurred up both the western and eastern flanks: the western margin of the basin, in particular, was covered almost totally with backswamps and coal swamps. By the end of Stage 3′ most of the topographic lows had been filled.

The Patchawarra Trough was a very different region. Firstly, the depositional surface was a smooth, mature land surface, and the Patchawarra Formation was underlain virtually everywhere by Tirrawarra Sandstone and Merrimelia Formation. Secondly, the Stage 3′ section is uniformly very thick compared with Cooper Basin Main sequence. Depositional environments tended to be the same all over the trough, and environmental changes occurred uniformly throughout. The Patchawarra Trough was a much more suitable region for coal formation, as exemplified by the 20 m thick seam.

Structural movements during Stage 3′ were considerable and virtually all the faults recognised in the basin were very active during the period. In particular, intermittent movement along the GMI anticlinal trend may have caused the uniform environmental changes in the Patchawarra Trough.

LOWER STAGE 4

Fluvial conditions occurred throughout the basin, in much the same environments as were present during Stage 3′ (Fig. 29) and although depositional conditions everywhere tended to be similar, differences remained between the Patchawarra Trough and the Cooper Basin Main. North of the GMI anticlinal trend, meandering river deposition dominated, but lake deposition was more common in the southern part of the basin.

In the Patchawarra Trough, only a very thin sedimentary section was deposited, in a stable region very suitable for coal formation. Presumably, subsidence occurred at the optimum rate to preserve the peat, which was not eroded by the next prograding meander.

In the southern part of the basin, sediment was transported from the south and east, mainly by rivers flowing across the areas mapped as sandy facies. The north-trending channel region, extending from Kumbarie to Spencer, was flanked on its western side especially by backswamps. The MN anticlinal trend was not emergent, and in fact, particularly in the southeast, depositional trends were not dominantly affected by subsidence.

Very limited evidence suggests that the far northeastern area of the basin, in the vicinity of Durham Downs, may have been extensively covered by lakes.

UPPER STAGE 4'

The Patchawarra Formation sediments of Upper Stage 4' age were deposited largely under different conditions to those of earlier Stages. Lake conditions predominated to the extent that much of the Cooper Basin Main was permanently covered by water (Fig. 33). Sediment was brought into the basin from both the east around Wolgolla and from the west, near Lake Hope. Those rivers that did occur in Cooper Basin Main were shallow and sluggish, with a low bed load capacity, and passed through a senile topography. The land was gradually inundated by encroachment of the lake from the east.

In the Patchawarra Trough, the amount of sediment deposited decreased from the southwest to the northeast, probably as a result of only gradual subsidence. Deposition occurred mostly in lakes and bays.

By the end of the period, topographic highs in the east to southeast part of the basin, which had been emergent during earlier Stages, were finally covered, and structures such as Epsilon, Wolgolla, and Orientos, are marked by thinning over their apices. On the other hand, thinning over other structures, such as Tirrawarra and Murteree-Strzelecki indicates that they were subsiding less rapidly than their surroundings. In addition, movement continued along at least some of the major faults.

MURTEREE SHALE

The Murteree Shale was deposited throughout most of the basin from a large body of water, in which the upper part of the Patchawarra Formation was laid down. This body of water was either a restricted sea or a freshwater lake (Fig. 35). Since no evidence of marine conditions have been found, the water was either non-saline, or else conditions were unsuitable for carbonate precipitation and preservation. Conditions suitable for the non-precipitation of carbonate could perhaps be either extreme cold, or high clastic intake similar to that being experienced in Po Hai, the restricted sea at the mouth of the Hwang Ho.

EPSILON FORMATION

The Epsilon Formation records the eastwards withdrawal of the Murteree Lake, followed by a second transgression (Fig. 39). Most deposition occurred in the Nappamerrie Trough, where deposition commenced on an essentially flat surface. In the Patchawarra Trough, only a thin blanket of sediments was laid down, some of which was eroded later.

The Epsilon Formation was deposited mostly in lakes and interdistributary bays, but additionally, in swamps developed on top of shoreline sands such as beaches or cheniers.

River development was very minor, compared with the Patchawarra Formation. Rivers were never very large, and evidence suggests that they mostly entered the basin from the southeast around Tickalara, and west near Lake Hope.

ROSENEATH SHALE

After the minor regression represented by the Epsilon Formation, a lake comparable to that which deposited the Murteree Shale again flooded into the Cooper Basin to lay down the Roseneath Shale (Fig. 39). The depositional basin was probably smaller than during deposition of Murteree Shale, with the southwestern and northern parts of the basin not being submerged.

'DARALINGIE BEDS'

The 'Daralingie Beds' record the second and final lacustrine regression (Fig. 48). South of the GMI anticlinal trend, two prograding delta systems moved northeastwards into the deepest part of the basin, one on either side of the MN anticlinal trend. Isolated coal swamps developed on the flanks of the delta channels. Deltas built out into water shallower than during Epsilon Formation deposition.

Only very minor deposition took place in the southern Patchawarra Trough.

The final phase of the regression, namely erosion, followed the deltaic deposition of the 'Daralingie Beds' northwards, until finally, a flat eroded topography was achieved.

UPPER STAGE 5'

The Toolachee Formation was laid down on a surface of low relief, be it peneplain or pediplain from a meandering river system (Fig. 52). Anticlines along the Merrimelia-Innamincka, and Murteree Trends, were the only emergent features during sedimentation. The depositional area was more widespread than at any time since the oldest part of the Patchawarra Formation was deposited, and unlike earlier periods, the eastern part of the basin was a major area for sediment accumulation. Controls on sedimentation were more uniform throughout the basin during this period than previously.

Meandering rivers were the main depositional media, especially in the Patchawarra Trough, where the major sediment intake area was from the west. This source area fed both the Patchawarra and Nappamerrie Troughs. The deepest and largest rivers flowed across those areas mapped as sandy facies (Figs. 50 and 51). Backswamps and coal swamps developed around the margins of the basin, especially in the south and southeast.

Overall, the Cooper Basin was tectonically stable, and suitable for considerable coal development, although at least some of the major faults were still active during this period, for example the Big Lake and Toolachee Faults.

Deposition in the Patchawarra Trough appears to have been controlled by slightly different factors to the rest of the basin. Subsidence was less than elsewhere, with only a thin development of mainly overbank deposits in the north. In addition, there was possibly a non-sedimentary control on cyclic sedimentation. Such a control could have been intermittent tectonic readjustment along a strike slip fault zone, and this might indicate lateral movement along the GMI anticlinal trend.

A new phase of sedimentation commenced with deposition of the Nappamerrie Formation sediments: a change in deposition that may have been the result of climatic change.

Evaluation of Methods and Future Studies

This Bulletin has incorporated a number of techniques in the stratigraphic interpretation of the Cooper Basin. These are the definition of time-rock units based on palynology, lithologic interpretation of cores, isopach mapping, lithofacies mapping, the study of cyclicity, and regression analysis. In general, each approach has provided some useful insight on the stratigraphy of the Cooper Basin, some more successfully than others. The lithofacies mapping, based on wireline-log interpretation, provides the major framework for the palaeogeographic reconstructions, but each of the other approaches contributed to the interpretation of depositional environments.

In some ways, some of the methods used in this Bulletin constitute a pilot study of their applicability to the Cooper Basin, and these have plenty of room for further extensive application. For example, the subdivision of time-rocks units, the lithologic interpretation of cores, and Markov analysis could be extended in their scope.

Each of the techniques has pointed up related, but different studies, which might prove useful in understanding the Cooper Basin stratigraphy. The most important of these are a study of the environmental implications of microfloral assemblages, computerised wireline-log interpretation, and detailed studies in areas of good well control, which integrate all available data.

The methods used in this study are far from exhaustive and a number of approaches outside the scope of this work hold promise of providing additional knowledge of the Cooper Basin geologic history. A structural analysis of the basin is one such example. Studies of provenance and climate are other avenues of research.

DEFINITION OF TIME-ROCK UNITS

The use of palynology to define the boundaries of a set of time-rock units has been partly successful, especially for the purpose of subdividing the Patchawarra Formation. However, shortcomings in the method arise from a lack of of microfloral data in some wells particularly those drilled in the deeper parts of the basin, and the long time duration of the Stages.

Scope for subdividing the Gidgealpa Group into more time-rock units, with a shorter time span than those used herein, lies in a reinterpretation of palynologic data, in order to identify basin-wide time units recognised in only the most recently drilled wells. Reinterpretation perhaps could lead also to definition of time units on the basis of variations in microfloral assemblage, rather than on the present method of first arrival of new forms. In addition, definition of more precise time-rock units might be achieved by combining palynologic data with lithologic marker horizons.

Palynologic research, related to the more accurate definition of time units, might clarify the problem of the age and duration of unconformities within the Permian section, and also throw light on any environmental implication of the microfloral assemblages. Other studies, which would make use of the time units, include the location of valley traps for petroleum, and detailed field studies to examine the geologic history of small areas with good well control.

Lithofacies maps and palaeogeographic reconstructions will achieve more precision in the future as new exploration wells are drilled, provided that sufficient palynologic work is carried out. The determination of Stage boundaries is basic to such mapping. Currently, lithofacies mapping is hampered by the imprecision of definition of Stage boundaries in some wells. This applies especially to Stages 2, 3 and 4, especially in the case of those wells drilled in the Nappamerrie Trough.

The main problem of the time subdivisions used in this study, apart from the lack of data in some areas, is the long time duration of each Stage (about 50 million years for all five Stages). As a consequence of this, lithofacies variations at any one point during each Stage are very great, and therefore mapping of the complete Stage blurs depositional trends. It is for this reason that the three time-transgressive units 'Daralingie Beds', Epsilon Formation and Upper Stage 4', were mapped in preference to the appropriate time units.

A full reinterpretation of palynologic slides from wells already drilled in the Cooper Basin, might result in the recognition throughout the basin, of additional time units. For example, palynologic determinations on material from the most recently drilled exploration wells have enabled a younger unit within both Upper Stage 4 and Lower Stage 5 (Upper Stage 4b and Lower Stage 5b; Table 1) to be differentiated. Facies mapping following palynologic reinterpretation could provide important geologic information, especially the direction of regression and transgression, because both subdivisions encompass a major formational boundary.

With additional palynologic study, it may be possible to subdivide some Stages on the basis of variations in microfloral assemblages, rather than the first arrival of a diagnostic flora. Any such subdivision would be particularly valuable in Upper Stage 5, where preservation of microfloras is generally good, because the depositional environment varies considerably through time (Thornton, 1973; Stuart, 1976).

It may be possible to break up most of the stages into time-rock units on the basis of extremely careful correlation of marker horizons (Weimer, 1966) in conjunction with palynologic data. Thornton (1973) subdivided the Toolachee Formation into three time-rock units over a limited area, while Stuart (1976) was able to extend his time-slices in the Toolachee Formation throughout the southern Cooper Basin.

The definition of time-stratigraphic units using Weimer's (1966) method works best in shales over small areas, where phantom horizons can be correlated. However, Power and Devine (1970) were able to correlate similar time markers over distances of about 200 km in the Surat Basin. Nonetheless, the results of basinwide correlation using this sort of method must be open to doubt in fluvial successions, such as the Toolachee Formation. This is because the lithologic units, including the most extensive coals, are discontinuous.

Research into the potential use of palynologic data as environmental indicators is warranted. It is perhaps no coincidence that the two lacustrine regressive phases of the Epsilon Formation and Daralingie Beds are associated with diagnostic microfloras (Upper Stage 4b, Lower Stage 5b). The implication is that perhaps there is environmental control on these microfloral assemblages, in which case the subdivisions would not be time units. Further avenues of research include microscopic studies on coal mineralogy with the aim of differentiating between different types of coal swamp (Hacquebard and Donaldson, 1969), or rate of subsidence (Shiboaka and Smyth, 1975).

Detailed palynologic study is also needed in an attempt to resolve the problem of the extent of the unconformities within the Gidgealpa Group succession. Price (1973) has identified a depositional break between the Daralingie Beds and the Toolachee Formation based on microfloras of lowermost Upper Stage 5 age recognised in the Bowen Basin, not being found in the Cooper Basin. On the other hand, Stuart (1976) suggests that deposition was continuous between these two formations over the Moomba field, although he recognises the existence of an unconformity over structural highs.

Price (1973), also suggests that there may have been a break in sedimentation within the Tirrawarra Sandstone at the Stage 2-Stage 3 boundary. In this study, palaeogeographic determinations have been based on the premise that the Patchawarra Formation conformably overlies at least the upper part of the Tirrawarra Sandstone. Battersby (1976) considers it possible that there is a disconformity between the two. Perhaps future sedimentologic work will show that the Tirrawarra Sandstone in fact should be treated as two, or more, individual rock units, which were laid down under disparate conditions.

One valuable result of mapping time units in the Patchawarra Formation has been the ability to map the progressive onlap of sediments up the flanks of the basin. This process could be followed better by mapping subdivisions of shorter time span. Nonetheless, potential areas for valley-type stratigraphic traps have been delineated (see next chapter). These areas warrant very detailed seismic coverage, in an attempt to locate and map pinchout edges.

The stratigraphic analysis in this report has used regional maps. An alternate approach could be to study small areas in detail, and then integrate the results into a regional picture. Separate areas, each with good well control, would be chosen from different parts of the basin. Then, in each area the Stages would be subdivided into, say, three time-rock units on the basis of palynology and lithologic markers, which would be approximately, but not exactly, equivalent basin wide. Thus, the geologic history would be determined within each area. Finally, the results of the individual field studies would be tied together to form a composite palaeogeographic analysis.

LITHOLOGIC INTERPRETATION

Whilst core logging can more accurately define rock types in a section than can wireline-log interpretation, the accuracy of the log interpretation was adequate for the purpose of regional mapping. The main shortcoming of the log interpretation lies in the possible misinterpretation of thinly interbedded rock units. Scope for extending log interpretation techniques lies in computerisation, both for the reason of objectivity, and also to interpret a rock type intermediate between sandstone and shale.

Possible related studies involve the integration of all sources of data in order to derive the maximum understanding of depositional environments. Forms of research that fit this category include core studies, correlation of logs with sand-body geometry and internal characteristics, and the identification of different facies within a sandstone body. Other studies which may assist in palaeogeographic reconstruction involve the mapping of petrologic parameters, such as heavy-mineral distribution.

Of the two methods of lithologic interpretation used in this study, core logging was much more precise than wireline-log interpretation. However, when the sandstone, shale and coal percentages were averaged out, results between the two methods were similar. The major problem with the log interpretation method proved to be the artibrary categorisation of units of finely interbedded sandstone and shale, as either sandstone or shale, depending on slight differences in API value on the gamma-ray log. This notwithstanding, the log interpretation resulted in objective lithologic determinations throughout the basin.

Computer interpretation of wireline logs would increase the objectivity of lithologic determinations, and at the same time remove the possibility of human error (Krumbein, 1958). Rock types are identified by correlating density, neutron and sonic log crossplots. Wireline logs have to be digitised in order to use this sort of system.

For detailed field studies, it should be possible to differentiate on wireline logs between clean sand and either silty sand or interbedded sand and shale, by calibrating logs with the available cores. One possible use would be the mapping of the silting out of individual sands (for example, the delta front sands at Moomba, Fig. 47). Again, detailed facies mapping on the basis of a tetrahedron (Krumbein and Sloss, 1963, p. 471) using sandstone, siltstone, shale, and coal as the end members, might help to map more accurately trends of reservoir sands. Ultimately, this may lead to log typing being accurate enough throughout the basin for the log signature to be diagnostic of particular depositional regimes.

Extensive coring programs in future wells should bear dividends in increased knowledge of the depositional environment. Core studies probably have the greatest potential of all possible avenues of research for unravelling the depositional history of the basin in detail. This present study has shown that considerably more work is warranted on the sedimentary structures and trace fossils. Stuart (1976), in his important study, was able to recognise sand bodies as originating from a variety of environments on the basis of core lithology, especially graded bedding, gamma-ray log signature, and trace fossils. Narrow V-shaped burrows were identified as originating from shoreline deposits, as distinct from worm tubes, which represent floodplain environments.

Visher *et al.* (1971) advocate an integrated approach to the reconstruction of particular subenvironments by correlating vertical sedimentary patterns (as shown from logs) with sand-body geometry, palaeocurrents, sedimentary structures, mineralogy, textures, and petrography.

Palaeochannel directions and river size have been calculated from outcrop sections in Canada by Cant and Walker (1976). These workers were able to define eight distinctive sandstone facies, which they found were deposited within a braided stream environment. The continuously cored section of the Tirrawarra Sandstone through virtually all the Tirrawarra Field wells (Gostin, 1973) probably provides adequate well control to carry out a study using Cant and Walker's (1976) methods.

Cooper Basin palaeochannel directions were mapped by Devine and Gatehouse (1977) in their analysis of the reservoir geology of Toolachee Field. If petrographic data were to be included into such a study, they might well provide additional criteria by which to define reservoir limits.

Directions of sediment transport can sometimes be determined by mapping certain petrologic parameters across the basin, such as maximum pebble size and heavy-mineral distribution. A pilot heavy-mineral study in the Cooper Basin using this approach has proved discouraging so far, due to a dearth of heavy minerals (C. G. Gatehouse, S.A. Dept. Mines and Energy pers. comm., 1976), although better results could be obtained now following modification of the sampling procedure.

ISOPACH MAPPING

The isopach maps prepared for the various subdivisions have been useful in showing variations between structural and isopach strike (Krumbein, 1952), and areas of anomalously thick or thin sedimentation as compared with the rest of the basin. Duration of fault activity and relative up or down movements across some of the faults has been shown by the sequence of maps. As mentioned previously, the maps are particularly valuable for locating the optimum areas in the search for pinchout edges.

LITHOFACIES MAPPING

The two types of lithofacies map, together with the facies change maps, have successfully delineated depositional trends, and the derived palaeogeographic maps provide a framework within which detailed work can be integrated. The maps have helped both to define sedimentary environments, and to clarify the structural evolution of the basin.

The lithofacies maps show the areal distribution of the facies most likely to produce gas (see next section).

Scope exists for mapping the areal distribution of the regressive rock units, and their potential reservoir sandstone bodies. In definition.

Possible studies related to the lithofacies mapping involve the preparation of different types of facies map. These could show, for example, percentage of porous sandstone, variation in the amount of genetic units, or variations in sand-body thickness.

The two different types of lithofacies map have both been useful for showing depositional trends, with one being more easy to interpret for some stages and the other for the rest. Results of the Gidgealpa 6 core investigations suggest that the 'D'-function map might be more accurate than the triangle facies map, where the sandstone-shale ratio is approximately 1. The 'D'-function maps can be made much more complex by using all the intra-facies contours, although the additional information has not been used in this study. No doubt, the extra contours could be important where a detailed study was being conducted, as long as care was taken that the detail was not greater than log calibration would permit.

The facies change maps proved to be very useful for palaeogeographic reconstruction and when further time-rock units have been defined, by whatever process, additional facies change maps should be equally helpful.

The facies maps were compiled without using either the present structural pattern of the basin, or any depositional model to assist in drawing the facies patterns in areas of low well density. Results have vindicated this approach, because mapping has helped to show depositional trends without the use of circular reasoning. For example, a model has been proposed for the Murteree-Nappacoongee anticlinal trend, which suggests that it was not an anticlinal feature during most of the basin development.

The maps can be used to predict the whereabouts of as yet undiscovered channels, deltas and shoreline sands. Probably the formation with the most obvious potential at this stage is the Daralingie Beds. The direction of delta progradation is interpreted to be towards the deeper part of the Nappamerrie Trough (this study; Stuart, 1976). There is also scope for predicting the location of other delta sands in the manner of Busch (1971).

Additional types of lithofacies map could be drawn to show the amount of depositional control of certain reservoir parameters, and to clarify depositional trends. For example, comparison of maps showing the percentage of sandstone with porous sandstone might indicate the extent to which sandstone porosity was related to depositional factors, or subsequent diagenesis.

Detailed studies involving facies mapping of such features as variations in the amount of genetic units (Stuart, 1976) or variations in sand-body thickness (Ferm and Cavaroc, 1968) should help to clarify depositional trends. In the search for stratigraphic traps, Pirson (1970, p. 59) explains the need to restore sand bodies to their original positions, by removing the effects of structural deformation. For this method time markers, such as thin shales, silts or coals are used as datum. Radioactive markers in the Cooper Basin, such as the shale in the Moomba Field (Thornton, 1973), would provide ideal markers for such a study.

The Epsilon Formation, even though it is thin (mostly 50-100 m), records a lacustrine regression, followed by a transgression. It is important that these two stages be differentiated and their areal extents mapped, because of the different kinds of sand body which would have been deposited. The best potential reservoirs would have been laid down during the initial regression. Ferm and Williams (1965) were able to differentiate between transgressive, stable and regressive phases of the 20 ± m thick lower Kittaning, which was deposited during a marine invasion that covered 5 000 km^2. Their diagnostic criteria were faunal content and petrology. Although on present knowledge the former is inapplicable to the Cooper Basin, it might be possible to use the latter plus other properties in a similar sort of study on the Epsilon Formation.

STRUCTURAL ANALYSIS

No attempt has been made in this study to carry out a structural analysis of the Cooper Basin. However clarification of the structural history of the basin is long overdue (S. B. Devine, SAOG,pers. comm., 1973-76), and is of the utmost importance if the history of hydrocarbon migration and entrapment is ever to be fully understood. In addition, attention has already been drawn to problems such as whether or not anticlinal structures were emergent during certain periods.

Over the last few years, the quality of seismic results has improved a great deal. In particular, intra-Permian reflectors can now be mapped with considerable precision. Therefore, high quality data (Thiele *et al.*, 1973; Hollingsworth *et al.*, 1976) are now available on which to base structural analyses, such as detailed study of fault patterns.

One important feature of some of the modern seismic sections is that they exhibit properties apparently indicative of wrench tectonics, namely very high angle normal and reverse faulting (Harding, 1973, 1976). The *en echelon* nature of anticlines along the GMI anticlinal trend is another indicator of this tectonic style. However, up to this time, interpretations of Cooper Basin geological history have been based mainly on the concept of growth faulting (for example, Stuart, 1976). The palaeogeography will have to be re-evaluated if it can be shown that there has been significant lateral movement along many of the faults.

PROVENANCE AND CLIMATE STUDIES

The effect that variations in provenance or climate may have had on lithofacies distributions has not been discussed in this thesis. Undoubtedly, both could have influenced the amount and type of sediment brought down by the rivers to be either deposited or carried out to sea. In addition, climate may have been a major factor in the marine transgressions and regressions. However, both subjects warrant detailed study, which has not been conducted, because it was considered to be outside the scope of this present work. Thus, any comments that could have been made in this report would not have had factual backing.

CYCLIC SEDIMENTATION STUDY

Each method of analysing the cyclic nature of sedimentation has been helpful in recognising different depositional environments, both through time and in different regions of the basin. These depositional environments have been related to particular lithofacies on the 'D'-function maps. In addition, some ideas on water depths have been formulated. Nonetheless, a major shortcoming is that most conclusions on coal cycle formation have been fairly general. In future work, more specific results could be obtained by carrying out Markov analysis on cored sections. In addition, such work might provide data on the time aspects of cyclic sedimentation.

Both histogram and Markov analyses gave similar results for most of the Stages. Histogram analysis was suitable because of the large amount of data accumulated, and it has the advantage over the Markov process in being statistically simple and very easy to interpret. On the other hand, Markov analysis is suitable for much smaller amounts of data.

Depositional environments, as determined by the cyclicity analysis, have been related to lithofacies. For those Stages with enough data, the Cooper Basin was subdivided into three different facies, as defined by the 'D'-function map. As a result, it was possible to show that fluvial deposition dominated the sandy facies, and lacustrine deposition dominated the shaly facies. In the mixed facies, the depositional regime was intermediate between these two.

The two statistical irregularities, in the Markov analysis used in this study, have meant that it was not possible to prove that the sequence of rock units was not random (Schwarzacher 1975, p. 116). The first of these is the fact that transitions were picked at bed boundaries, and therefore zeros had to fill the leading diagonal in the transition matrix. The second reason was the choice of two types of sandstone based on thickness, there was no statistical reason for the choice of 3 m as the boundary between sandstone and thick sandstone. Nonetheless, as a result of the subdivision, it was possible to make geological interpretations concerning water depth that would have been impossible had only one sandstone lithology been used. However, it has not been shown, that a thickness of say 6 m, would not have been a more informative cut-off.

The results, on the whole, have been very general. To obtain more detailed results, it will be necessary to work from cores. The general nature of the results is largely because only five lithologic states were defined. More detailed specifications of lithologic units (such as in Cant and Walker, 1975) will enable further environmental information to be determined. Possible states could be, for example, a scoured basal surface (de Raaf *et al.*, 1965), conglomerate bands, sandstones with different bedding characteristics, or interbedded sandstone and shales.

By studying core material, it would be possible to pick transitions between similar lithologic units (i.e., multi-storey lithologic units). This would remove one statistical irregularity in the present method by filling the leading diagonal in the transition matrix. It is felt therefore, that considerable potential for Markov analysis lies in detailed work on core material, rather than on regional analysis as in this study.

Schwarzacher (1975, p.281) believes that major advances in the knowledge of cyclic sedimentation can only be achieved if the cycles carry time information. In order to relate time, sedimentation rates, and the rock section, it is necessary to structure the Markov chain by picking transitions either at bedding planes or at equal thickness intervals. In these cases, the thickness of each individual lithologic unit has to be measured, and therefore data accumulated for this study would be inapplicable.

BIVARIATE CORRELATION ANALYSIS

The results of the regression analysis showed that in most cases cyclic sedimentation was controlled by intrabasinal factors. However, analysis was able to show that this generalisation did not always apply in the Patchawarra Trough. Although these results are useful, further work is probably not warranted until considerably more data are available.

The Cooper Basin has had a history of successful petroleum exploration since 1963, when the Gidgealpa Field was discovered, and it appears to have a potential for considerably more petroleum discoveries. From 72 wildcat wells, 23 fields were discovered, giving a success ratio of 1 success to every 3·1 wells drilled. The main gas reservoirs occur in the Toolachee and Patchawarra Formations, although the Daralingie Beds, the Epsilon Formation and the Tirrawarra Sandstone also contain economic amounts of gas. In addition, the Tirrawarra Sandstone produces a little oil. So far, petroleum has only been found in anticlinal traps.

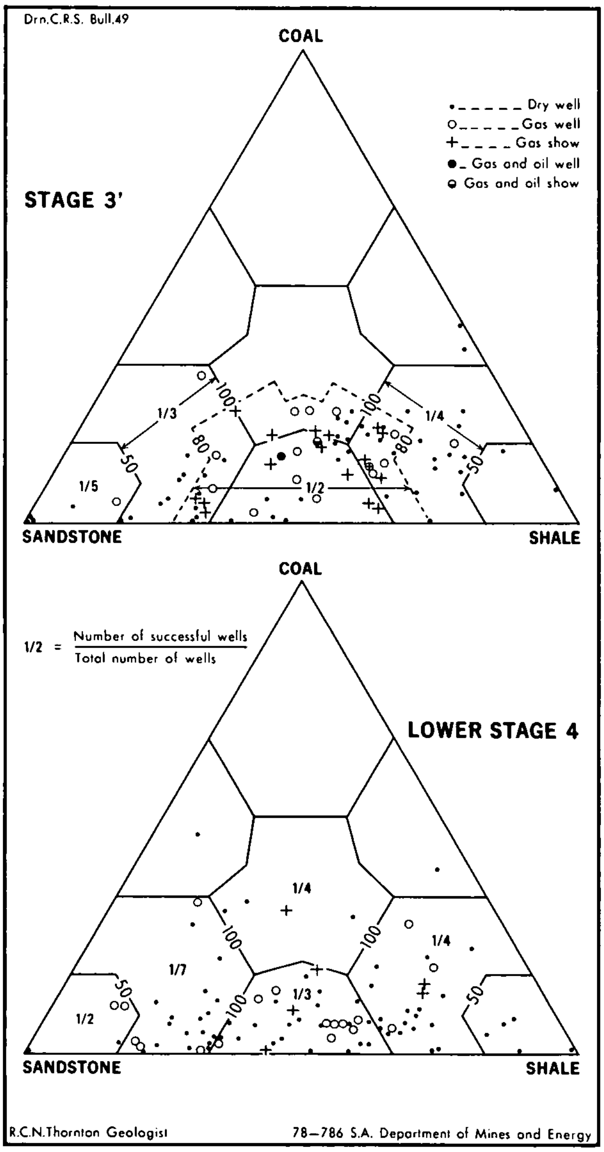


Fig. 56. Lithologic plots on 'D'-function triangles for Stage 3' and Lower Stage 4

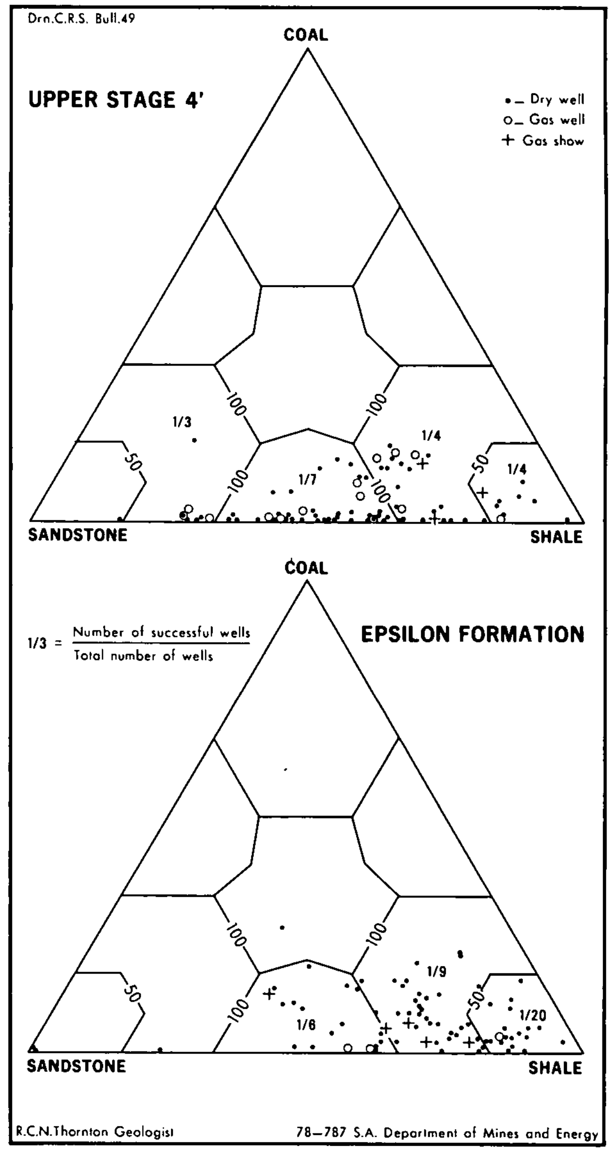


Fig. 57. Lithologic plots on 'D'-function triangles for Upper Stage 4' an Epsilon Formation

There is a good chance that further petroleum discoveries will be made from structural traps as many anticlines are as yet undrilled, although most of the larger ones have been tested. Additional seismic coverage can also be expected to delineate further targets and possible structural traps may exist along the flanks of the major faults. Nevertheless, it is probable that the success ratio will decline with future drilling, because the best targets have been drilled already.

The potential for discovering petroleum in stratigraphic traps is considerable, although the cost of such a discovery may increase significantly, because the successful delineation of a prospect will probably require the drilling of more wells than for structural trap exploration. Four types of stratigraphic trap may prove to be valuable plays. These are valley traps due to onlap, pinchouts of reservoir formations, delta

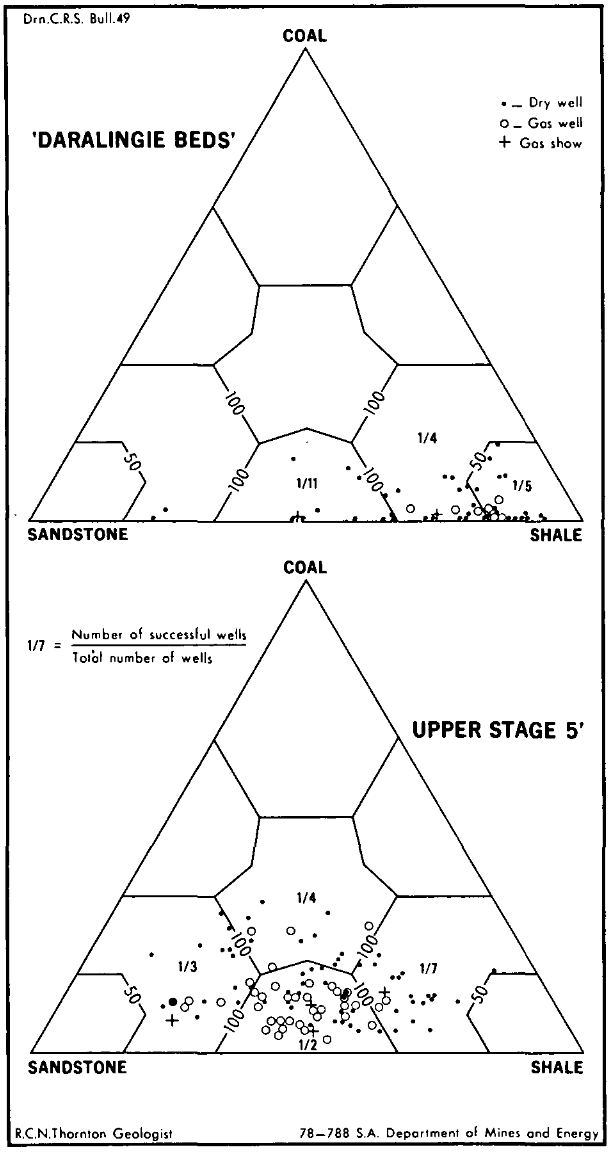


Fig. 58. Lithologic Plots on 'D'-function triangles for 'Daralingie Beds' and Upper Stage 5'

front sandstone bodies enclosed in shales, and sandstone channel bodies on the flanks of monoclines.

The relationship between success or failure in drilling and lithofacies is an avenue for predicting the most favourable areas for future exploration. In this study, the 'D'-function maps for the Stages have been used to delineate these most prospective areas. However, as all but two of the Cooper Basin wells were drilled on seismically defined structures, the results can only show that certain facies are more prospective than others when looking for structural traps. Until proven otherwise, these facies need not be applicable to exploration for different types of play.

In order to compare drilling performance with the facies distributions in the Stages mapped, the lithologic compositions of each well in terms of sandstone, shale and coal, have been plotted on triangular graph paper, with the 'D'-function 100 and 50 boundaries marked (Figs. 56-58). In addition, the status (gas, gas show, oil, oil show, dry) of each well is plotted, as is the success ratios for each particular lithofacies. For this latter purpose, gas shows have been considered to be 'successful'. In general, mixed facies appear favoured, although individual Stages show variations on this trend.

TIRRAWARRA SANDSTONE

Most Tirrawarra Sandstone discoveries have been made in the Patchawarra Trough (Fig. 59) and consequently, the major potential in the Tirrawarra Sandstone is probably in that same area. However, the western flank of the basin in the vicinity of Gidgealpa to Big Lake (Fig. 18) may be prospective, if suitable locations for valley traps can be found. The lower part of the Patchawarra Formation provides an adequate seal to the Tirrawarra Sandstone in the area, as is shown by the presence of petroleum, in sub-economic amounts, at Gidgealpa and Big Lake. Therefore the opportunity for valley traps exists, because the areal extent of Stage 3' (Fig. 21) is greater than that of the Tirrawarra Sandstone.

STAGE 3'

The sediments of Stage 3' hold a potential for petroleum pools of three kinds: the anticlinal trap, the channel sandstone system trap, and the wedgeout trap in areas of onlap at the margins of deposition.

The greatest density of gas bearing anticlines is in the Patchawarra Trough, although Merrimelia, Packsaddle, Gidgealpa, Daralingie, Big Lake, Dullingari and Toolachee also contain gas (Fig. 60). The high success ratio of drilling in the Patchawarra Trough makes it the most prospective area; the success being probably largely due to the thickness of sediments, and abundance of coal for source rock (Brooks, 1970). The presence of seismically defined leads in the Patchawarra Trough, and elsewhere, shows that the anticlinal play has not yet been fully assessed.

Data on the 'D'-function triangle show that gas is slightly more likely to occur in a well from one of the two mixed facies, than from either the sandy or shaly facies. There is a 1 in 2 chance of gas occurring in wells whose sandstone, shale, and coal percentages are such, that they plot within the area bounded by 80A, 80S, and 80M (dotted line on Fig. 56).

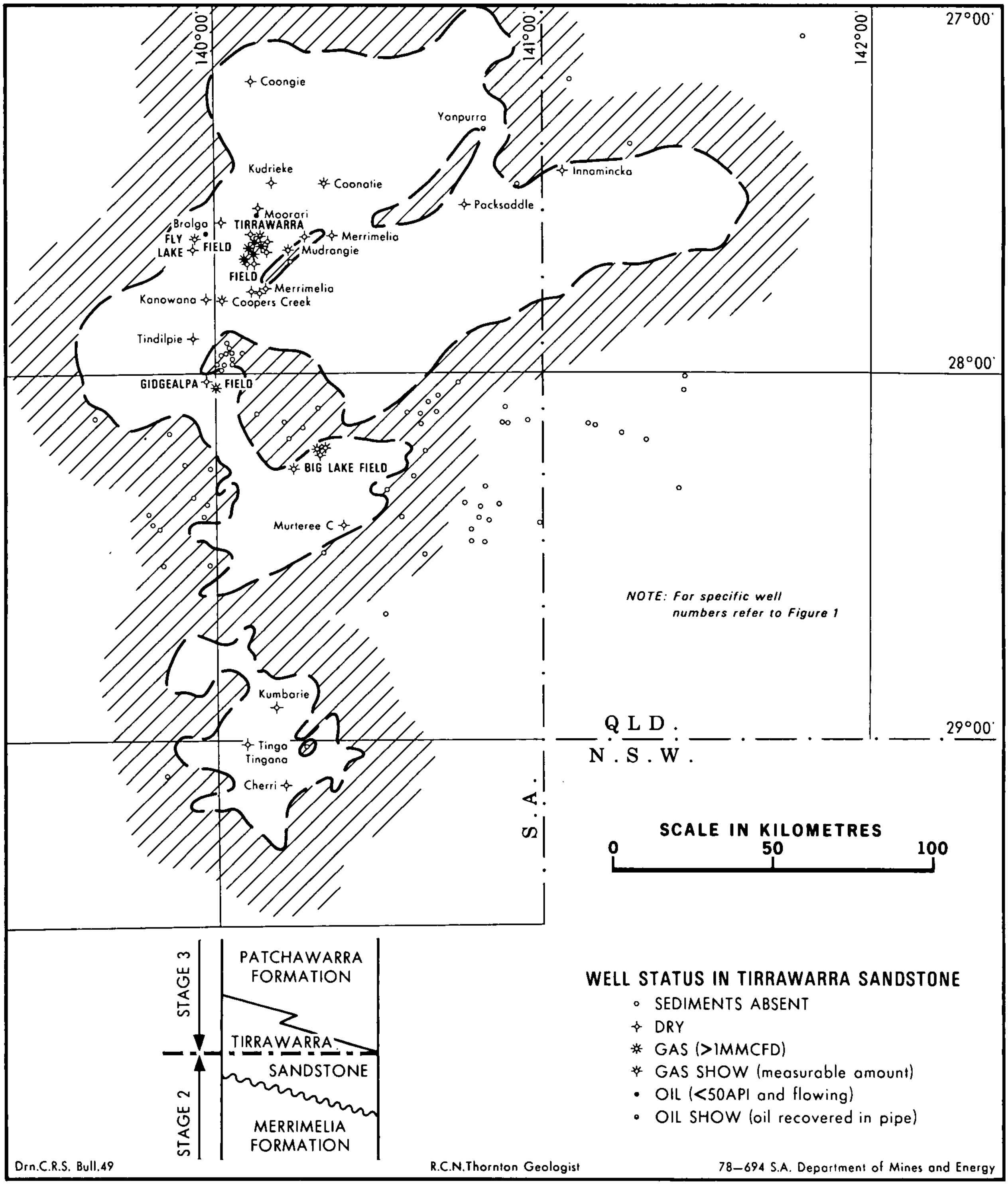


Fig. 59. Petroleum potential for Tirrawarra Sandstone

The least prospective areas on the basis of lithologic percentage (Fig. 60), equate with the sandy and shaly 'D'-function facies (Fig. 23). They occur on the eastern and western flanks of the southern part of the basin.

Valley traps as a result of onlap are potentially important. Onlap occurred during deposition of the Patchawarra Formation throughout the southern part of the basin. Thick shales within the Patchawarra Formation would provide suitable cap rocks. The main area of onlap was along the eastern flank of the basin (Fig. 60), where rocks of Lower and Upper Stage 4 age extend further than those of Stage 3' age. This margin warrants extensive seismic coverage in an attempt to map the depositional edge of the lower part of the Patchawarra Formation.

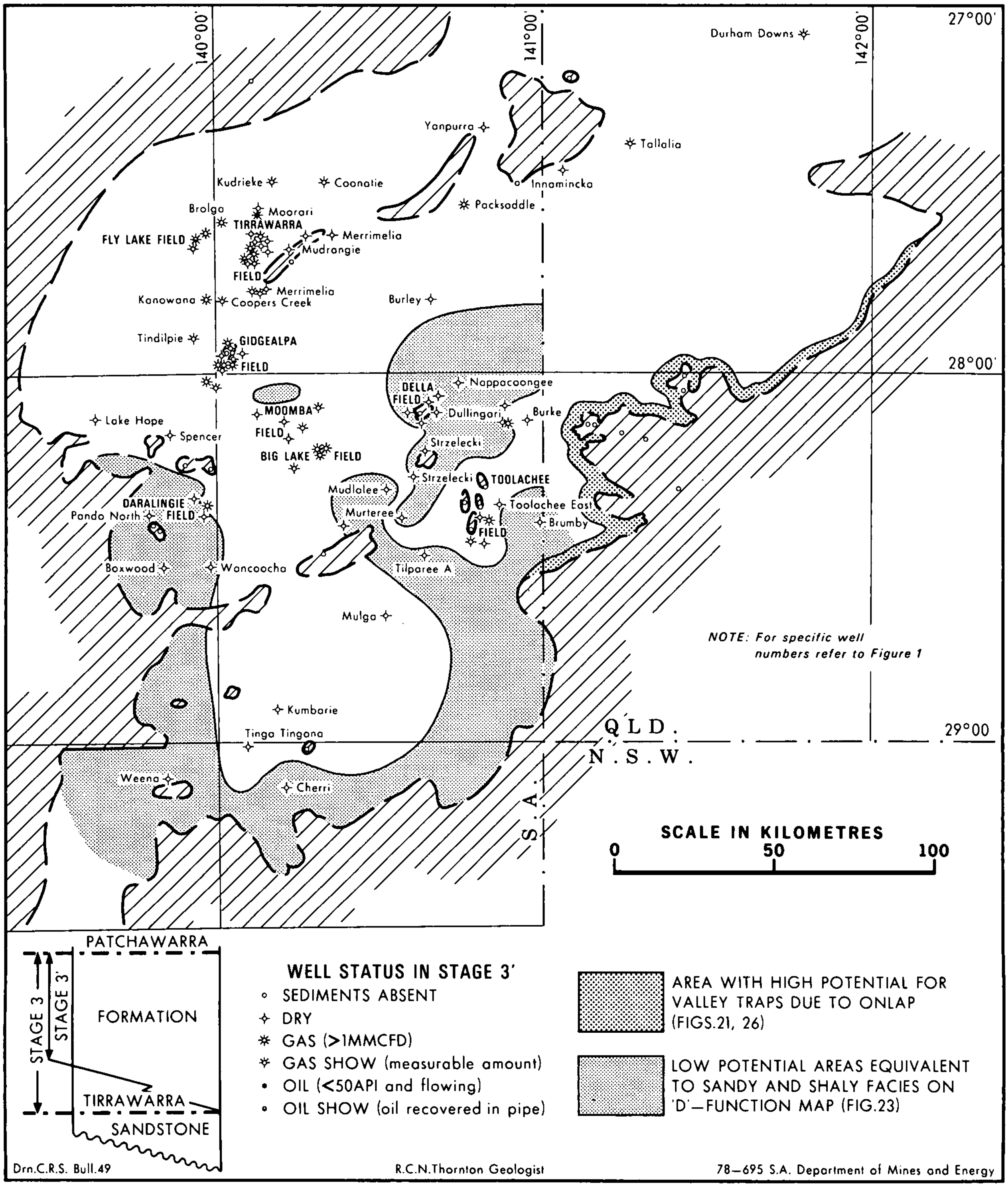


Fig. 60. Petroleum potential for Stage 3'

Linear sandstone channel systems, enclosed in shales, have reservoir potential when they are situated on the flanks of monoclines, such that their long axes parallel the structural strike. This is because gas migrates to the updip edge of the body where it is trapped. Devine and Gatehouse (1977) showed that sandstone bodies in the Toolachee Field exhibit this sort of relationship. However, detailed interpretation work, including extensive drilling, will be required if this sort of trap is to be located.

LOWER STAGE 4

The petroleum potential for Lower Stage 4 rocks is essentially the same as for the Stage 3' section, because the depositional environments and tectonic history were largely the same for the two periods. Anticlinal and valley type traps are perhaps the most prospective.

In the prediction of areas suitable for anticlinal traps, 'D'-function data (Fig. 56) lead to the

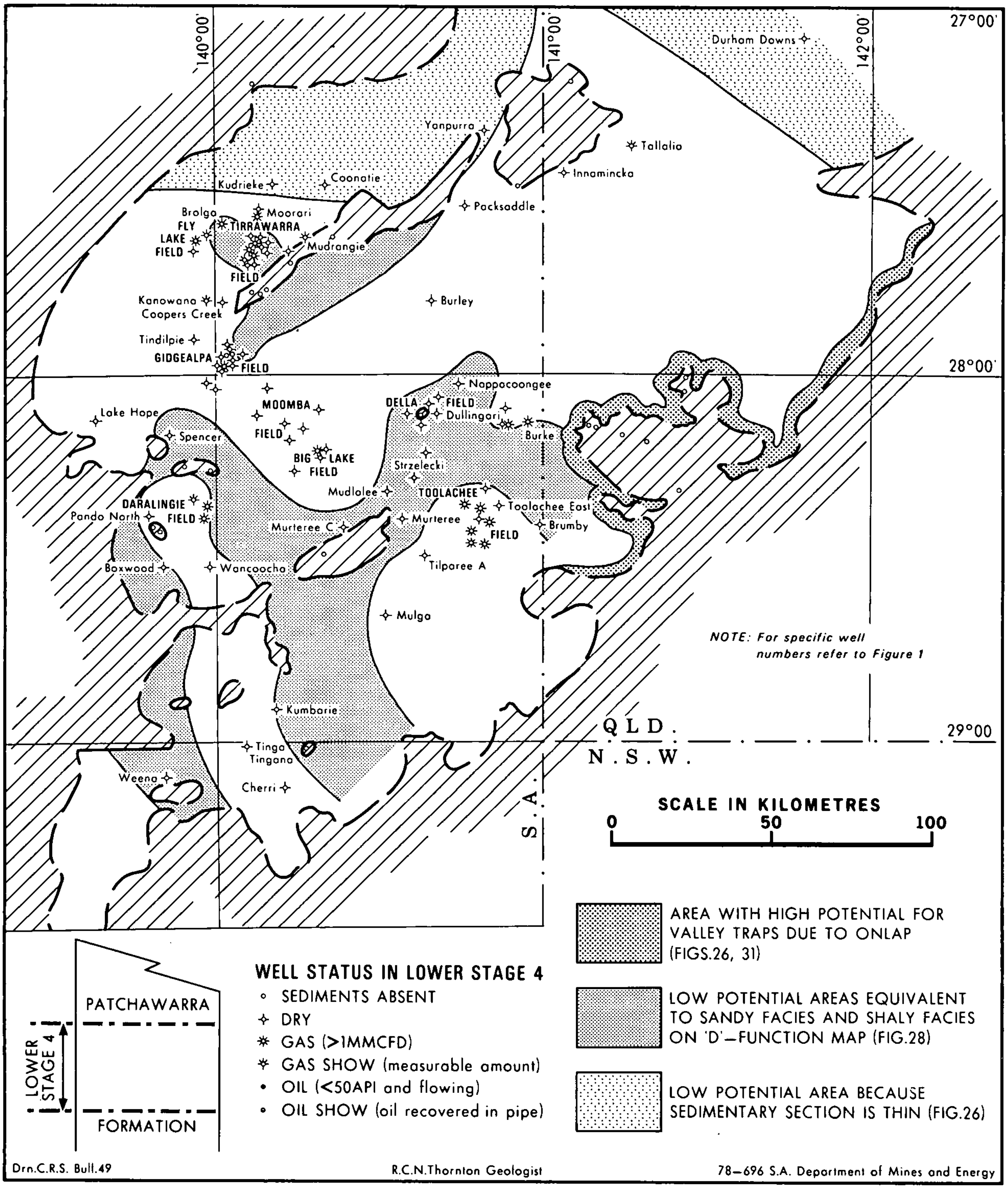


Fig. 61. Petroleum potential for Lower Stage 4

interpretation that the mixed facies are slightly more prospective than either sandy or shaly facies, as is shown on Figure 61. On the other hand, the thinness of the sedimentary section in the north reduces that area's prospectivity; a thinness due to non-deposition, and not later erosion. Therefore, there was a slower rate of subsidence than to the southwest and opportunities for preservation of organic matter, and ultimately the potential to produce petroleum, are reduced as a consequence.

The likelihood of valley type traps in the eastern part of the basin is enhanced by the proximity of a region of major channel development (Fig. 29). The opportunity for such traps is the same as for Stage 3', except for the additional factor of a heightened chance that better developed fluvial reservoir sands will be found. This interpretation conflicts slightly with the 'D'-function reasoning.

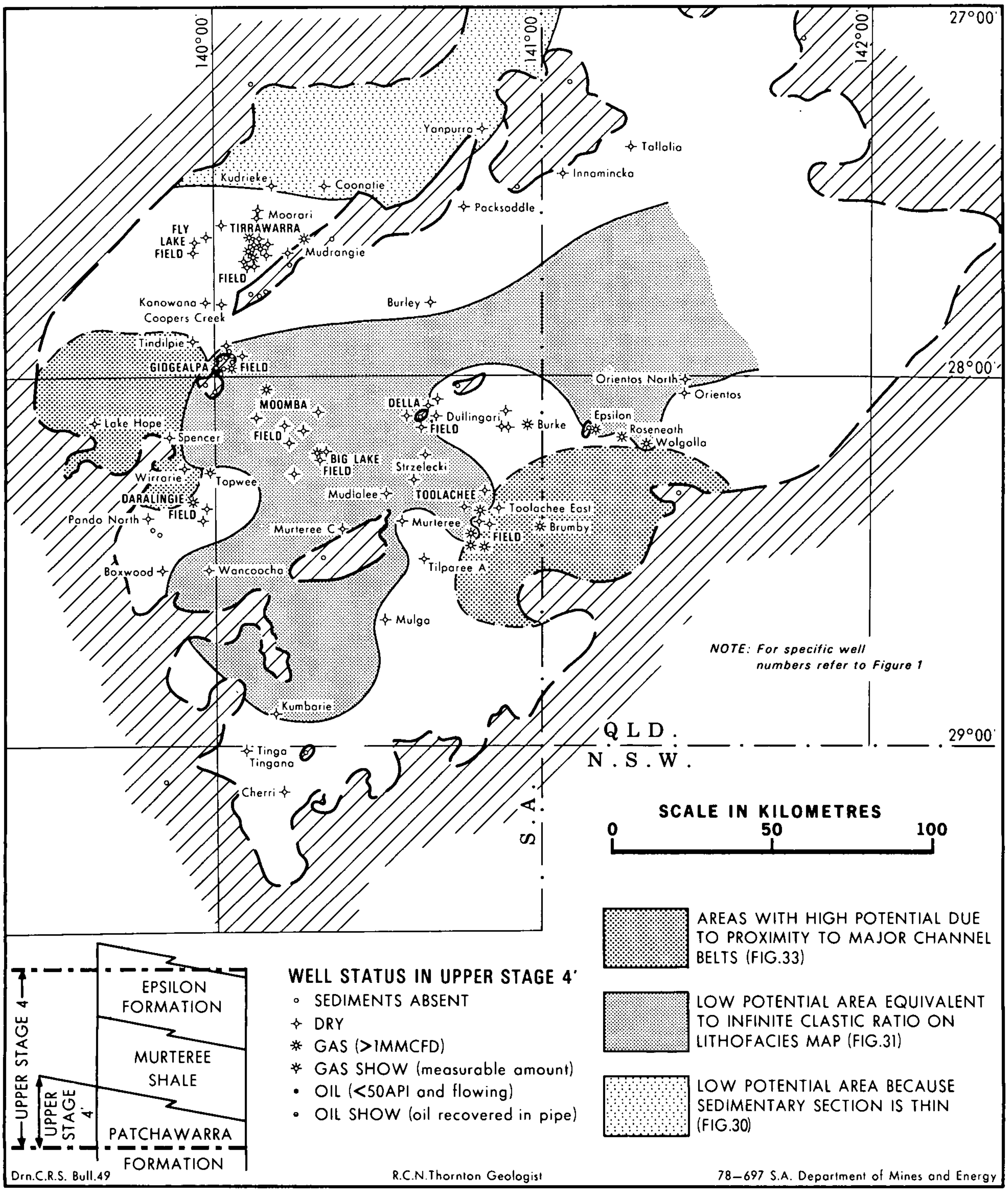


Fig. 62. Petroleum potential for Upper Stage 4'

UPPER STAGE 4'

The petroleum potential of Upper Stage 4' age is less than for earlier periods, primarily because the section contains fewer thick sandstone bodies. Nonetheless, the scope for discovering anticlinal traps exists, as evidenced by gas reservoirs at Tirrawarra, Daralingie and Moomba, and in fields in the eastern part of the basin (Fig. 62).

'D'-function criteria do not show conclusively any particularly favourable facies for petroleum entrapment in anticlines (Fig. 57). However, the infinite clastic ratio on the lithofacies map (Fig. 31) defines the least prospective area of the basin, which was permanently underwater at the time. This submerged region has the least potential, because of both the lack of coals as source rocks and sand body geometry. The amount of coarse sediment being transported

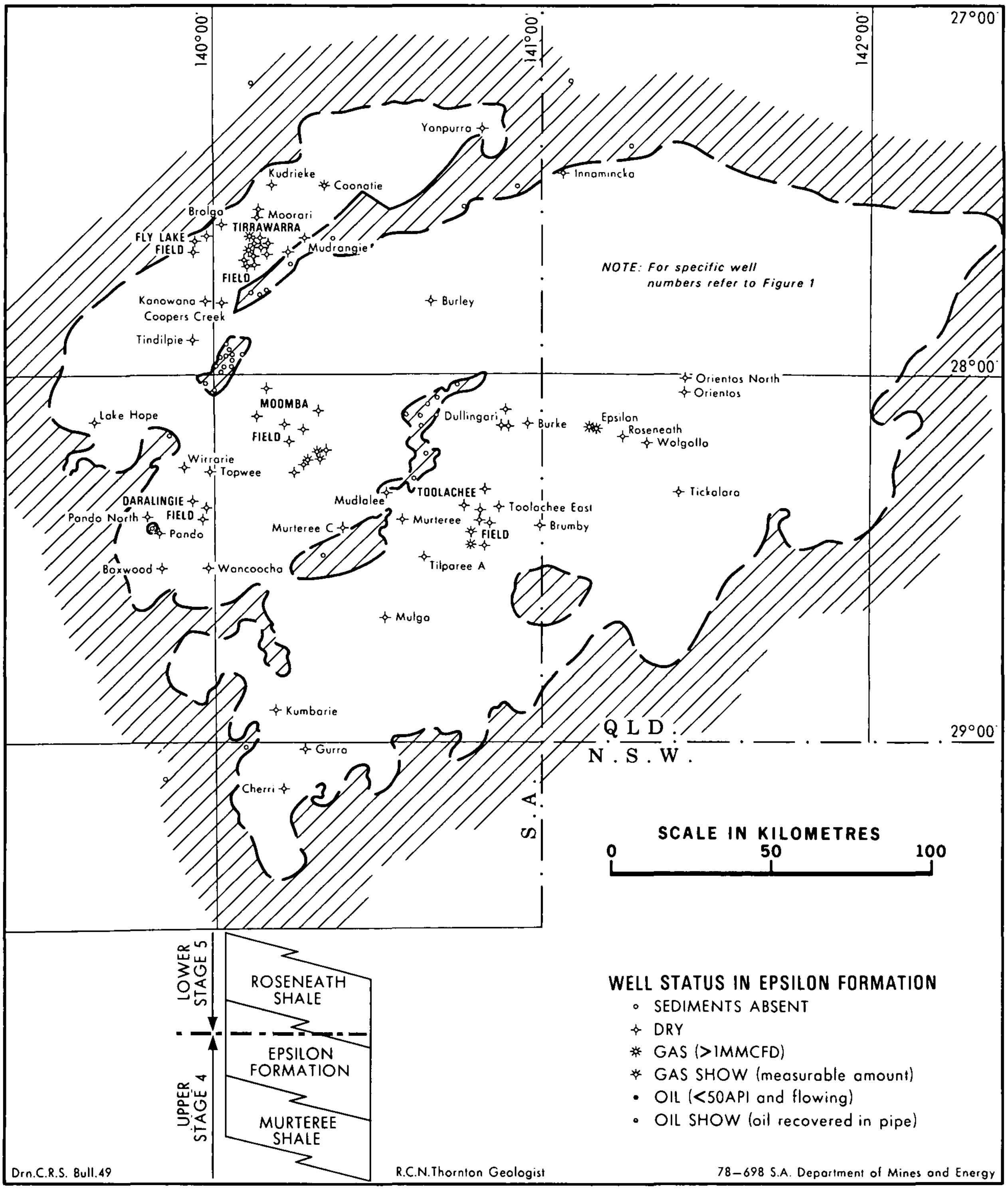


Fig. 63. Petroleum potential for Epsilon Formation

into the lake was low compared with previous periods: the land was being progressively submerged and shoreline sands would have been reworked due to wave and current activity, and deposited as thin sheet sands by the gradually encroaching lake.

The two areas with the greatest potential for anticlinal and linear sandstone body traps are at the southwestern end of the Patchawarra Trough, and to the east, in the Toolachee-Wolgolla region. These are the regions of best sand development both onshore and offshore, because of their proximity to the main river systems.

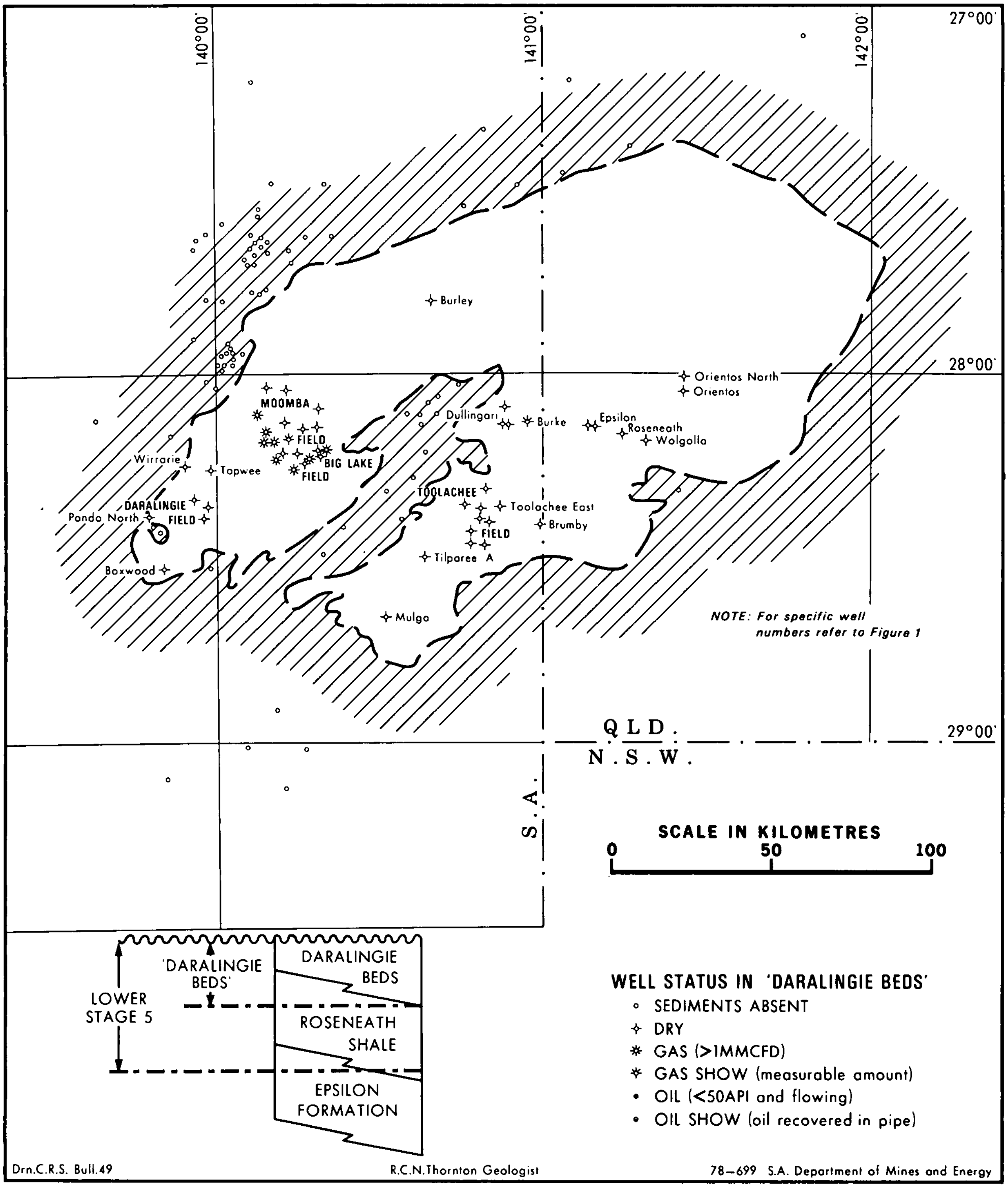


Fig. 64. Petroleum potential for 'Daralingie Beds'

EPSILON FORMATION

The Epsilon Formation holds considerable petroleum potential from stratigraphic plays because of its depositional history. Shoreline sandstone bodies enclosed in shales, and reservoir pinchouts are the most likely types of stratigraphic trap.

The potential for purely structural traps is limited, as is shown by the low success ratios on the 'D'-function triangles (Fig. 57) and on Figure 63. The reason for the low prospectivity is the generally shaly nature of the Epsilon Formation. However, a few anticlinal traps have been discovered where the section contains good reservoir sands. If the distributions of these

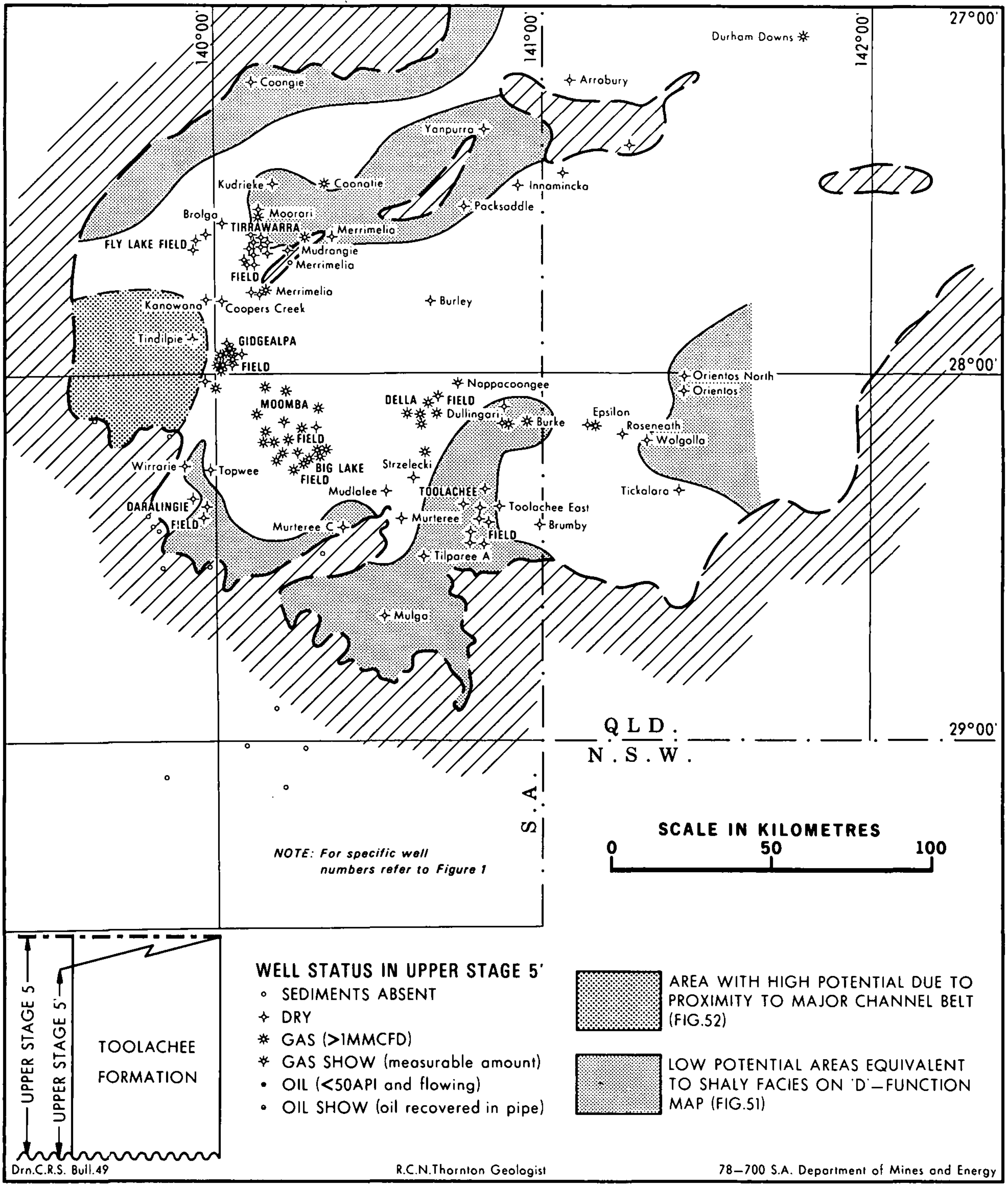


Fig. 65. Petroleum potential for Upper Stage 5'

sands can be mapped, anticlinal plays will become more prospective.

The Epsilon Formation sands most likely to hold gas are the sandstone bodies at the base of the section, which were deposited during the eastwards retreat of the Murteree lake. These sands would have been deposited from deltas, or as beaches, cheniers and other shoreline deposits. The best reservoirs will occur in those sands deposited at the head of rivers. By mapping the paths of individual rivers, it may be possible to locate individual shoreline reservoirs as the lake retreated (see Busch, 1971).

The Epsilon Formation may pinch out in the eastern part of the basin. If it does, then the pinchout edge holds considerable potential in regions where it parallels structural strike. The lower part of the Epsilon Formation was laid down behind the retreating Murteree lake. However, as the upper part of the Epsilon Formation records the transgression of the Roseneath lake (Fig. 36), it is possible that the Murteree lake never left the basin completely, and in the eastern part, Murteree Shale could be directly overlain by Roseneath Shale. The easterly limit of the Epsilon Formation deposition therefore would be a prime location for pinchout traps. This possible limit is marked on the palaeogeography map (Fig. 39).

'DARALINGIE BEDS'

Potential shoreline sandstone reservoirs in the 'Daralingie Beds' are the same as for the lower part of the Epsilon Formation, because of their similar depositional framework. However, unlike the Epsilon Formation, the accurate locations of two delta lobes have been interpreted (Fig. 48) and the delta front sandstone bodies at Moomba (Fig. 47), in the path of one of these deltas, are prolific gas reservoirs. Gas shows occur in the path of the other at Burke. Additional regressive sandstone bodies along the paths of the two major channels must exist, both downdip and updip from the known delta locations.

UPPER STAGE 5'

Rocks of Upper Stage 5' age have considerable reservoir potential in anticlinal traps and perhaps also as channel sandstones enclosed by shale.

Drilling for Upper Stage 5' structural targets has been very successful, as evidenced by the four major fields, Gidgealpa, Moomba, Big Lake and Della (Fig. 65). The most prospective areas are those defined on the 'D'-function map by the mixed and sandy facies (Fig. 58). There has been a success ratio of 1 in 2 for finding a gas well (rather than just a gas show) with wells which fall in the mixed facies, and a 1 in 3 ratio for wells in the sandy facies. The prospective regions for Upper Stage 5' anticlinal traps are in the centre of the basin (Fig. 65), where rivers ubiquitously deposited suitable reservoir sands.

The most likely area for stratigraphic traps is probably at the southwestern end of the Patchawarra Trough (Fig. 65). This region is interpreted to have been the main sediment intake area to the basin (Fig. 52), and consequently would be an optimum area for channel development. It is possible, however, that not enough shales have been preserved to act as caprocks.

Conclusions

The depositional history and palaeogeography of the Gidgealpa Group have been clarified by the stratigraphic analysis in this bulletin. The lithofacies and isopach mapping of a sequential set of time-rock units, defined primarily by palynologic criteria, have shown the major areas for channel development, directions of sediment transport, directions of transgressions and regressions, the locations of deltas, and the optimum facies for petroleum development. This mapping has provided the major framework for palaeogeographic reconstructions, but the core study, histogram and Markov analyses of coal cyclicity, and regression analysis, have all contributed additional information.

The use of palynologically defined time-rock units has made it possible to show that virtually all the Early Permian rock boundaries are diachronous, and allowed the directions of facies change to be mapped. However, in most cases, the units mapped are of long time duration, with the result, that local deposition trends have been hidden by the regional picture. Considerable scope exists to refine the time-rock units by using a combination of palynology and lithologic marker horizons. As additional units of short-time duration are defined and mapped, so the depositional models for the Cooper Basin will become more accurate.

Both types of lithofacies map used in this study, triangle lithofacies and 'D'-function, have helped in the preparation of the palaeogeographic maps to show the basin's geologic history. Perhaps, the standard triangle lithofacies maps using sandstone-shale and clastic ratios, have been more useful for the purpose of palaeogeographic reconstruction. However, the 'D'-function maps have provided valuable information on depositional environments when used in conjunction with the results of coal cycle analysis.

In this study, the determination of depositional models has been assisted by comparing the vertical succession of lithologic units, in both core material and coal cycles, with that in modern day environments. The Gidgealpa 6 cores in the Patchawarra Formation have been interpreted to show that deposition took place on an alluvial floodplain, and with time, the depositional site on the floodplain was situated increasingly closer to a shoreline. Some of the youngest sediments were deposited offshore, or at least in interdistributary bays. By constrast, Toolachee Formation sedimentation was dominated by meandering streams which deposited point-bar sandstones.

Study of the coal cycles by histogram and Markov analyses has shown that there are only four types of cycle that occur at all frequently, and that each one of these is diagnostic of certain specific depositional environments. The most common cycle type, shale to coal, indicates lake and swamp environments whilst the next most common type is the fining upwards, sandstone to shale to coal cycle, indicative of meandering rivers. Shale to sandstone to shale to coal cycles indicate deltas or interdistributary bays, and coarsening upwards, shale to sandstone to coal cycles generally indicate shoreline environments, but may represent fluvial conditions.

Results of histogram and Markov analyses have confirmed the findings of the lithofacies mapping in two ways. Firstly, they have shown that sediments deposited in areas mapped as sandy facies on the 'D'-function maps were laid down mainly in a fluvial regime: those from shaly facies were deposited mostly in lakes, and mixed facies sediments originated in environments intermediate between these extremes. Secondly, the nature of cyclicity in the time-rock units coincided with what it ought to have been if the depositional model developed from the lithofacies and palaeogeographic maps was correct. Thus, fining upwards cycles prevailed in the time-rock units interpreted to represent fluvial deposition, but cycles indicative of near shore and shoreline environments dominated the units interpreted as regressive.

Linear regression analysis has shown that the great majority of coal cycles was formed by the interaction of the purely local processes of subsidence and sedimentation. One area of the basin, where this may not have held completely true, is the Patchawarra Trough. During certain periods, cyclicity in that region may have been affected by external factors, such as intermittent movement along major faults. Regression analysis results also indicate that throughout the basin, coal cycles thicknesses were not significantly different for different depositional environments.

The palaeogeographic picture of the Cooper Basin, which has been drawn from the results of the various methods of analysis, is one of floodplain deposition oscillating with marine transgressions. Gidgealpa Group deposition commenced on an uneven land surface, which may have been created by glacial scour, as a result, Tirrawarra Sandstone was laid down from braided streams in the form of laterally shifting medial bars. As topographic relief diminished, rivers began to meander, and as a consequence, overbank deposits of the Patchawarra Formation were formed.

Valleys were progressively filled with sediment during deposition of the Patchawarra Formation until the land surface was essentially one of low relief. Over this flat surface encroached a large inland, apparently fresh water 'sea' from the east, to deposit the Murteree Shale, before it retreated ahead of the shoreline sediments of the Epsilon Formation. Later the 'sea' once more inundated the basin to deposit the Roseneath Shale before withdrawing a second time. Daralingie Beds deltas prograded out into this receding 'sea'.

A major period of non-deposition occurred at the end of Early Permian, during which time, the basin's major northeasterly anticlinal trends were uplifted and eroded. When the final phase of Gidgealpa Group deposition commenced, some of these features remained as hills standing above an otherwise flat alluvial plain. Sediments of the Toolachee Formation were deposited from meandering rivers, lakes and coal swamps, on this plain.

On a continental scale, the palaeogeography of the Cooper Basin appears to be related to that of the Galilee and Bowen Basins to the east, primarily because the 'sea' entered the Cooper Basin from the east. All the basins were ultimately connected with the open sea, somewhere in the vicinity of the present day coastline of eastern Australia. However, connection between the Cooper Basin and the open sea could not have been by way of the Permian basins as they are known today. This is because deltas were prograding eastwards into the Bowen Basin at the same time as the 'sea' was moving westwards into the Cooper Basin. Access was probably by way of a region to the south of the Galilee Basin.

The final phase of Permian deposition in the Cooper, Galilee and Bowen Basins was one of coal formation. Deposition of the Toolachee Formation coal measures started before marine condition had died out in the east, but encroached progressively further eastwards, and finally enveloped areas which during the earlier Permian had only ever experienced marine deposition.

The Cooper Basin has considerable opportunities for the discovery of further amounts of petroleum in both structural and stratigraphic traps. The main potential rests in the Patchawarra and Toolachee Formation, in anticlinal and fault traps as well as stratigraphic plays. Wedgeout traps as a result of onlap of progressively younger sediments may be important in the Tirrawarra Sandstone and Patchawarra Formation. The Epsilon Formation and Daralingie Beds, by their very nature of being regressive sandstone units, have excellent stratigraphic trap potential in the form of deltaic, and other shoreline, sandstones. However, very detailed palaeogeographic analysis will be required to locate such reservoirs.

This study has provided the framework of a regional geological history of the Cooper Basin. Future detailed work will be able to build onto this skeleton by developing depositional models for localised areas. In this manner, hopefully, the sites of stratigraphic petroleum traps will be located, and the basin's resources will be fully developed.

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APPENDIX 1

Development of Palynologic Stages

At the present time, the biostratigraphic subdivision of the Cooper Basin section comprises nine units, which have been recognised essentially on a series of overlapping ranges of specific palynomorphs (Price, 1973). These are: Stage 2, Stage 3, Lower Stage 4, Upper Stage 4a and 4b, Lower Stage 5a and 5b, Upper Stage 5, and the *P. reticulatus* Assemblage Zone (Table 1). Each unit is defined by a single species because of the high degree of variability in the microfloral elements, some of which may be attributed to post-depositional factors such as carbonisation. The diagnostic forms used are the more robust and distinctive forms, which generally would be identified in fairly adverse conditions of preservation (Price, 1973). Table 25 shows these nine units together with their diagnostic microfloras.

Nearly two-thirds of the total number of Cooper Basin wells have been drilled since 1969. As a result, understanding of the microfloral assemblages has advanced considerably since then, mainly due to palynologic studies carried out by R. J. Paten and P. L. Price, of Mines Administration Pty Ltd. Unpublished reports by these authors occur as appendices in the relevant well completion reports, and show the final development of palynologic concepts to the stage at which they occur today.

The first palynologic evidence of Permian sediments was found by Balme (in Ryan, 1961, Appendix 2) out of cuttings from Innamincka 1, the first well drilled in the basin. Balme studied the microfloras from coal horizons and dated them as Kungarian-Kazanian. It was also Balme (1964) who first subdivided the Australian Permian into stages on the basis of its microfloral content, to give the *Nuskoisporites, Vittatina* and *Dulhuntyispora* Assemblages.

Evans (1964, 1966a), working in the Bowen Basin, also erected a set of palynologic units for the presumed Late Carboniferous to Late Permian sequence. As a result of a microfloral study from Chandos 1 in the northeastern Cooper Basin, he compared the microfloras from the Cooper and Galilee Basins, and observed that a three-fold subdivision of the Permian microfloral succession was possible (Evans, 1966b). This subdivision could be related to the Merrimelia Formation, the Patchawarra Formation through to Daralingie Beds, and the Toolachee Formation.

A major breakthrough in the understanding of the Permian microfloras of eastern Australia was made by Evans (1967) when he subdivided the original three assemblages of Balme (1964) into five Stages. Stage 1 (Late Carboniferous) and Stage 2 (Early Permian) were equivalent to the *Nuskoisporites* Assemblage, Stages 3 and 4 (Early Permian) to the *Vittatina* Assemblage, and Stage 5 (Early-Late Permian) to the *Dulhuntyispora* Assemblage. These Stages were based purely on spores and pollen, and were a significant advance on Evans' previous units, which also used acritarchs to define the assemblages. The palynologic Stages now developed for the Cooper Basin are merely refinements of this system.

Paten (1969) recognised Stages 2, 3, 4, and 5 of Evans (1967) in the Merrimelia Formation and Gidgealpa Group sequences. Furthermore, he was able to divide Stages 4 and 5 each into two subunits, giving an overall six-fold division.

Paten (1969) explained that palynologic investigation in the Cooper Basin had been hampered in some areas by poor preservation of the microfossils. Of thirty-three wells he studied, only half yielded workable microfloras. In many cases microfossils were highly carbonised and Paten was able to show that there was at least a superficial relationship between degree of preservation and bottom hole temperature, with the best preserved assemblages coming from wells with the lowest geothermal gradients.

The *Protohaploxypinus reticulatus* Assemblage, the youngest Permian unit, was named by Helby (1973). He showed that the decline and replacement of the *Glossopteris* flora, and its attendant *Striatites* microflora, occurs immediately prior to the *P. reticulatus* Assemblage, and not at the end of the Permian as suggested by Balme (1964).

Table 25 *Cooper Basin palynology (Price, 1973)*

Stage (Age)	Diagnostic Microflora	Comments
Protohaploxypinus reticulatus Assemblage Zone (Late Permian)	*Tigrisporites playfordii*	Includes many distinctive forms which are not known in the underlying Upper Stage 5 microfloras. Basal part of the assemblage includes a distinctive striate pollen (*'Paravittatina'* sp. 258).
Upper Stage 5 (Late Permian)	*Dulhuntyispora parvithola*	Distinctly different from the older Stage 5 microfloras. It is dominated by Striatiti and includes relatively few cryptogamic forms. *D. parvithola* may be rare or common, but *D. dulhuntyi* is very rare or absent.
Lower Stage 5b (Early Permian)	*Didecitriletes ericianus*	Similar in overall character to lower unit, but *'D'* sp. 205a, and possibly *'D'* sp. 205b, probably do not occur.
Lower Stage 5a (Early Permian)	*Dulhuntyispora dulhuntyi* (form 296)	Characterised by diverse suite of cryptogams, including most of the forms present in the older units.
Upper Stage 4b (Early Permian)	*Microbaculispora villosa*	Several new forms occur, including *Granulatisporites* sp. 204, *G.* sp. 206, *'Dulhuntyispora'* sp. 205a and *'D'* 205b.
Upper Stage 4a (Early Permian)	*'Marsupipollenites' sinuosus*	The general increase of *Kraeuselisporites* spp., *Granulatisporites* spp., and other apiculate forms, observed through Stage 3 and Lower Stage 4 continues in Upper Stage 4a.
Lower Stage 4 (Early Permian)	*Polypodiidites cicatricosus*	Younger Stage 3 microfloras are similar to Lower Stage 4 assemblages and they are difficult to distinguish without *P. cicatricosus.*
Stage 3 (Early Permian)	*Verrucosisporites pseudoreticulatus*	Where well preserved, assemblages are more diverse than those from Stage 2. They include non-striate and striate bisaccate pollen, as well as *Marsupipollenites triradiatus, M. striatus* and *Apiculatisporis* spp.
Stage 2 (Early Permian)		Characterised by relatively common occurrence of monosaccate pollen together with *Rugulatisporites* sp. 124, some distinct cavate cingulate spores and striate bisaccate pollen.

APPENDIX 2

A—Reliability of 'P' Horizon Structure Contour Map and Gidgealpa Group Isopach Map

'P' Map—The 'P' Horizon map is based on a reflected event on the seismic records of fair to good character and continuity throughout most of the area, except on structural crests (Pfitzner, 1971a and 1971b; Moore and Proctor, 1972a and 1972b; Thiele and Proctor, 1972a and 1972b; Thiele *et al.*, 1973). Consequently, most of the map area is considered to have good reliability (see information source diagram). It should be pointed out that the reliability categories on this diagram are purely relative and qualitative terms.

The good reliability area on the 'P' map coincides very closely with the relatively well-explored area of Devine (1975, fig. 5). To date, with the exception of Durham Downs 1, all the known hydrocarbon accumulations occur within this area. The validity of the 'P' map depends on seismic control and well information, to which to tie the geophysical data. Thus the area of good reliability is where the most seismic work and drilling have been carried out, because exploration has been the most successful in this region.

The area of fair reliability was taken from a compilation map produced by Delhi Int. Oil Corp. in 1970. This map was also used primarily for the poor and very poor reliability areas, but the information was augmented by verbal discussions (W. K. Thiele, Delhi Int. Oil Corp., 1974).

Gidgealpa Group Isopach Map—The Gidgealpa Group isopach map was derived from seismic and compilation maps in a similar manner to the 'P' map, but the data reliability is considerably different.

Seismic surveys in the Cooper Basin, before the Mudlankie survey, used as an energy source either dynamite in a near-surface hole or a 'Thumper' (large weight dropped from the back of a truck onto the ground). Because of various errors inherent in these systems, no more than six-fold C.D.P. (common depth point) stack was used in the preparation of seismic records. In most cases, considerably less than six-fold stack was used. As a result, the seismic event representative of the base of the Gidgealpa Group ranges in character and continuity from good to very poor (for example, Moore and Proctor, 1972a and 1972b). Poor data often coincides with areas of steep dip (Thiele and Proctor, 1972b).

In the Andree survey, over the western portion of the Patchawarra Trough, a seismic horizon related to the Patchawarra coal (and therefore near the centre of the Patchawarra Formation) was mapped in preference to the base of Gidgealpa Group, because of poor record quality (Thiele and Proctor, 1972a). In this area, the isopach could only be derived from a 'fudged' base of the Gidgealpa horizon using well data as control, and the Patchawarra coal horizon contours as form lines.

The Mudlankie seismic survey used a vibrating input source placed on the ground. The frequency of the sound wave was controlled, thus allowing for much more accurate filtering of extraneous noise from the seismic records. As a result, continuously twelve-fold C.D.P. stacked seismic records could be prepared. These provided much more stratigraphic and structural information below the 'P' Horizon than had been obtained previously (Thiele *et al.*, 1973).

For the first time, the base of the Gidgealpa Group could be mapped with reasonable accuracy over most of the survey area, with the resultant good reliability of data for the Gidgealpa isopach. In the Patchawarra Trough, however, the same problem was encountered as described above for the Andree survey, leading to poor reliability.

The data reliability in the northeastern portion of the map is very poor due to an extremely thick sedimentary section, sparse cover by old seismic data, and virtually non-existent well control.

B—Procedure Used in Preparation of Time-Stage Isopach Maps

In the preparation of the five Time-Stage isopach maps, eleven cross-sections were drawn (with a vertical exaggeration of 25 x) in an approximately northerly direction, through as many wells as possible. The 'P' Horizon was plotted and the Gidgealpa Group thickness added to give a lower bounding surface. The thickness of the Time Stages as interpreted at each well were plotted, and then carried through from one well to the next. Thus the reliability of the method is heavily dependent on well density. No seismic information from intra-Gidgealpa Group reflectors was used. However, because the cross-sections are fairly close together, no section could be drawn without reference to and comparison with its neighbours, thereby maximising the value of the available well control. Also, thickening trends (such as in the Nappamerrie Trough) were plotted consistently from one cross-section to the next.

The thickness of each Stage was measured at regular intervals (normally about every 20 mm) along each cross-section and then plotted on a map. Well thicknesses were also plotted and these data points were then contoured using the Gidgealpa Group isopach map as control. In this way, a zero edge was derived.

In the southwestern Nappamerrie Trough (cross-section B-B, Fig. 7), evidence from Boxwood 1, Wancoocha 1, and Mudlallee 1, led Paten (1969) to place the boundary between Lower and Upper Stage 3 within the Murteree Shale. This evidence was the first appearance of *M. sinuosus* (Appendix 1), the significance of which had been understood only shortly before. At that time, significant palynologic control was not available throughout the Cooper Basin, but was concentrated in the southwestern region. Subsequently, examination of microfloras from wells elsewhere in the basin has not identified a sequence in which the Upper Stage 4/Lower Stage 4 boundary does not occur within the Patchawarra Formation. This applies particularly to the nearby, later drilled wells, Pando North 1 and Murteree C 1. As a result, Paten's (1969) determination is considered to be incorrect, and the amended boundary between Lower and Upper Stage 4 is shown on cross-section B-B (Fig. 7).

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Fig. 9 Stratigraphic cross-section D-D

Fig. 7 Stratigr phic cr ss-section B-B

Fig. 6 Stratigraphic cross-section A-A

Fig. 8 Stratigraphic cross-section C-C

Fig. 10 Stratigraphic cross-section E-E

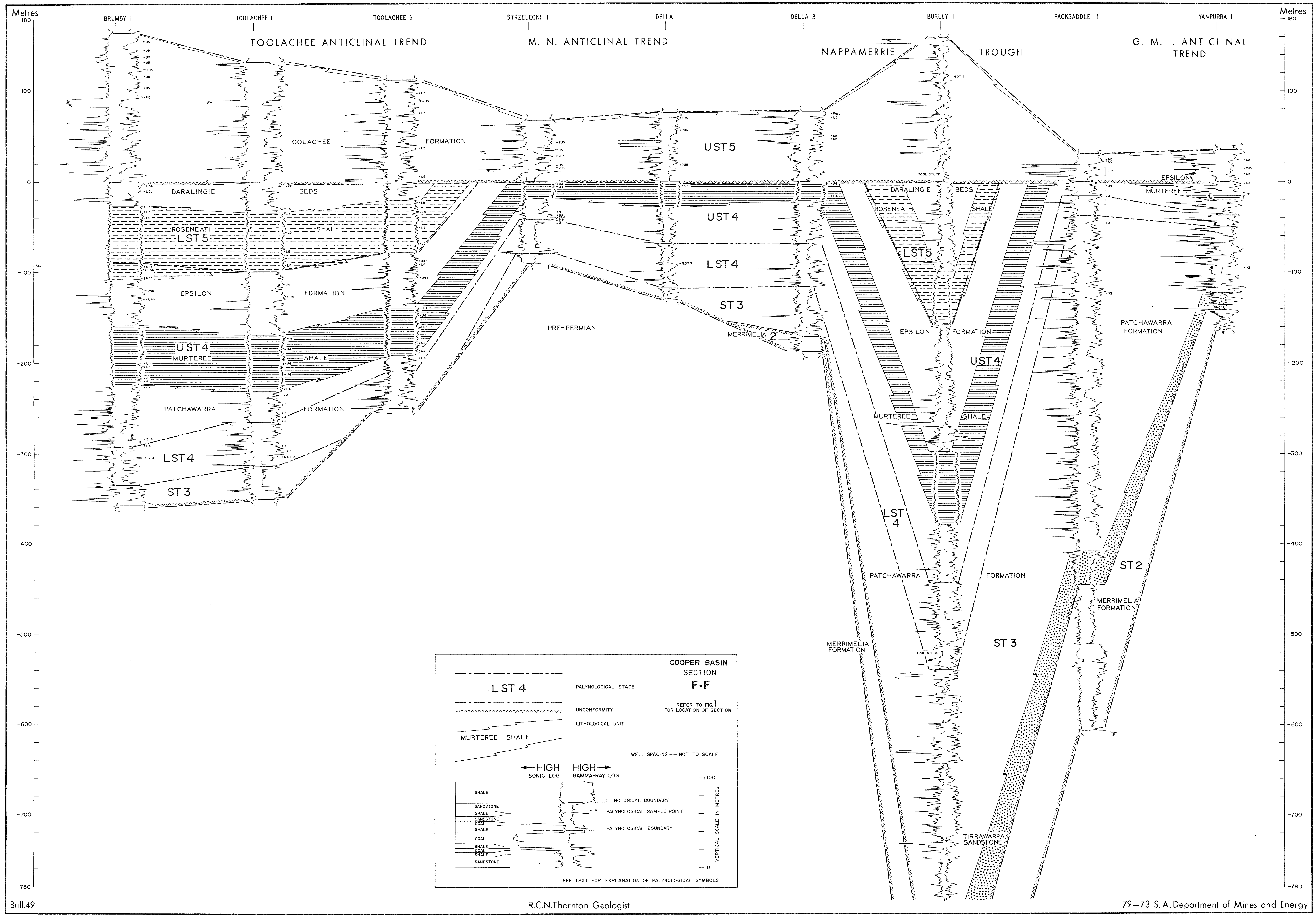

Fig. 11 Stratigraphic cross-section F-F