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Their comments on the lithostratigraphy subdivision and sequence stratigraphy sections of this publication were of immense benefit. Some of the sequence and lithostratigraphic interpretations presented here are still developing and are not necessarily held by all members of the SBEA Project team.

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The contribution to this volume by Peter Price (APG Consultants) is gratefully acknowledged. His paper reviews and revises the palynostratigraphic nomenclature and subdivision of the Bowen and Surat Basins.

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THE SURAT AND BOWEN BASINS SOUTH-EAST QUEENSLAND

THE SURAT AND BOWEN BASINS, SOUTH-EAST QUEENSLAND

P. Green (Editor)

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PROJECT AIMS AND ACTIVITIES, EXPLORATION HISTORY AND GEOLOGICAL INVESTIGATIONS IN THE BOWEN AND OVERLYING SURAT BASINS, QUEENSLAND

P.M. Green, K.L. Hoffmann, T.J. Brain & A.R.G. Gray

(Geological Survey of Queensland)

SUMMARY

The National Geoscience Mapping Accord (NGMA) "Sedimentary Basins of Eastern Australia" (SBEA) Project undertook an integrated basin analysis of the Bowen, Gunnedah and Surat Basins with the emphasis on their tectonic, structural, sedimentary and thermal histories, in order to determine their hydrocarbon potential. The results presented in this REVIEW relate primarily to the investigations undertaken by the Geological Survey of Queensland (GSQ) of the Queensland Department of Minerals and Energy (QDME) as part of the SBEA Project. These investigations were carried out on the Surat and underlying Bowen Basins in the southern Taroom Trough and focussed on basement terrains, lithostratigraphy and petroleum generation potential.

Basement rocks beneath the Bowen and Surat Basins in the SBEA Project area cover a complex region of the Tasman Fold Belt System, comprising the Thomson and Lachlan Fold Belts to the west of the Taroom Trough, and the New England Fold Belt to the east. The distribution of the basement terrains throughout the Roma Shelf and those underlying the southern Taroom Trough has been mapped and their relationships assessed.

The lithostratigraphic framework of the Bowen and Surat Basins has been revised. The revision was based on a regional grid of correlation lines incorporating representative petroleum exploration wells and GSQ stratigraphic bores. This framework forms the standard for the interpretation of formation tops included in the Queensland Petroleum Exploration Database (QPED). The relationships between seismic sequences and lithostratigraphy are also discussed, with emphasis on lateral facies distribution. The palynological biostratigraphy of the Bowen and Surat Basins has been revised.

With respect to petroleum generation potential, new vitrinite reflectance data has been acquired to assist in the determination of the thermal maturity levels in the Bowen and Surat Basins in the study area. This data has assisted in constraining the thermal history of these basins. The source assessment involved determination of source richness plus the estimation of expulsion efficiencies of the source rocks in selected Permian and Triassic units in the Bowen Basin. The quality and expulsion efficiencies of these rocks were also mapped and used to delineate key areas of oil and gas generation. An assessment of the basins with areas worthy of future exploration is provided.

Keywords: Petroleum exploration, stratigraphy, palynology, sequence stratigraphy, source bed, petroleum potential, maturation, Bowen Basin, Surat Basin.

INTRODUCTION

The Surat Basin and underlying Bowen Basin have provided oil and natural gas for south-east Queensland for over 30 years. New discoveries and appraisal drilling on existing fields are not offsetting increased production and in 1996, the supply of gas from these basins is unlikely to be able to meet the expected demand. The "Sedimentary Basins of Eastern Australia" (SBEA) Project was initiated as a response to the declining reserves in the oil and gas fields in the Bowen and Surat Basins. The Project was designed to increase exploration as well as the success rate in these basins.

The Project was undertaken jointly by the Geological Survey of Queensland (GSQ) of the Queensland Department of Minerals and Energy (QDME), the Australian Geological Survey Organisation (AGSO), the New South Wales Department of Mineral Resources (NSWDMR), with cooperation from CSIRO, universities, and industry. The results presented in this REVIEW relate primarily to the investigations undertaken by the GSQ.

AIMS AND OBJECTIVES

The aim of the SBEA Project was to undertake an integrated analysis of the Bowen, Gunnedah and Surat Basins, with the emphasis on sedimentary, structural, tectonic and thermal histories, in order to assess their economic potential for hydrocarbons (Figure 1).

Strategies applied to meet the objectives of the SBEA Project were:

1. determine the spatial and temporal distribution of various sedimentary packages as an aid towards understanding the distribution and nature of hydrocarbon resources,
2. determine the structural geometry, tectonic setting and evolution of the sedimentary packages,
3. determine the maturation and burial history, and
4. provide an integrated geological history of the basin systems.

PROJECT HISTORY

The SBEA Project began in 1989 with the acquisition by AGSO of deep crustal seismic data in the northern part of the Bowen Basin (Korsch & others, 1992). The major phase of the Project started in 1990 when AGSO began the interpretation of company seismic lines within a regional framework. In January 1991, the GSQ began its contribution to the SBEA Project. Investigations were confined to the southern Bowen Basin and overlying Surat Basin in Queensland between latitudes 25°S and 29°S and longitudes 147°E and 151°E (Figures 1 and 2).

The area studied is approximately 176 000km^2 and includes the southern Taroom Trough of the Bowen Basin and the Roma and Walgett Shelves to the west. The Denison Trough, which lies in the northernmost part of the SBEA Project area was not included in the GSQ study. The focus of the GSQ contribution was on basement terrains, lithostratigraphy and petroleum generation potential. The GSQ also participated with AGSO in the sequence stratigraphic study and the assessment of source rock quality.

FORTHCOMING SBEA PROJECT REPORTS

Other aspects of the SBEA Project for which results are becoming available include those for the sequence stratigraphic study which will be published by Brakel & other**s (in preparation)**. These results cover both the Denison Trough and central and southern Taroom Trough in the Bowen Basin and the Surat Basin in Queensland. Regional seismic maps (structural contour and isopach) and digital data sets of all the seismic horizons will be available.

AGSO personnel will further use the results of the sequence stratigraphic study to analyse the structural history of the Bowen and Surat Basins. This analysis will be based, in part, on the regional seismic maps using two-way time. Additional information on the subsidence history of selected wells will be incorporated into the analysis.

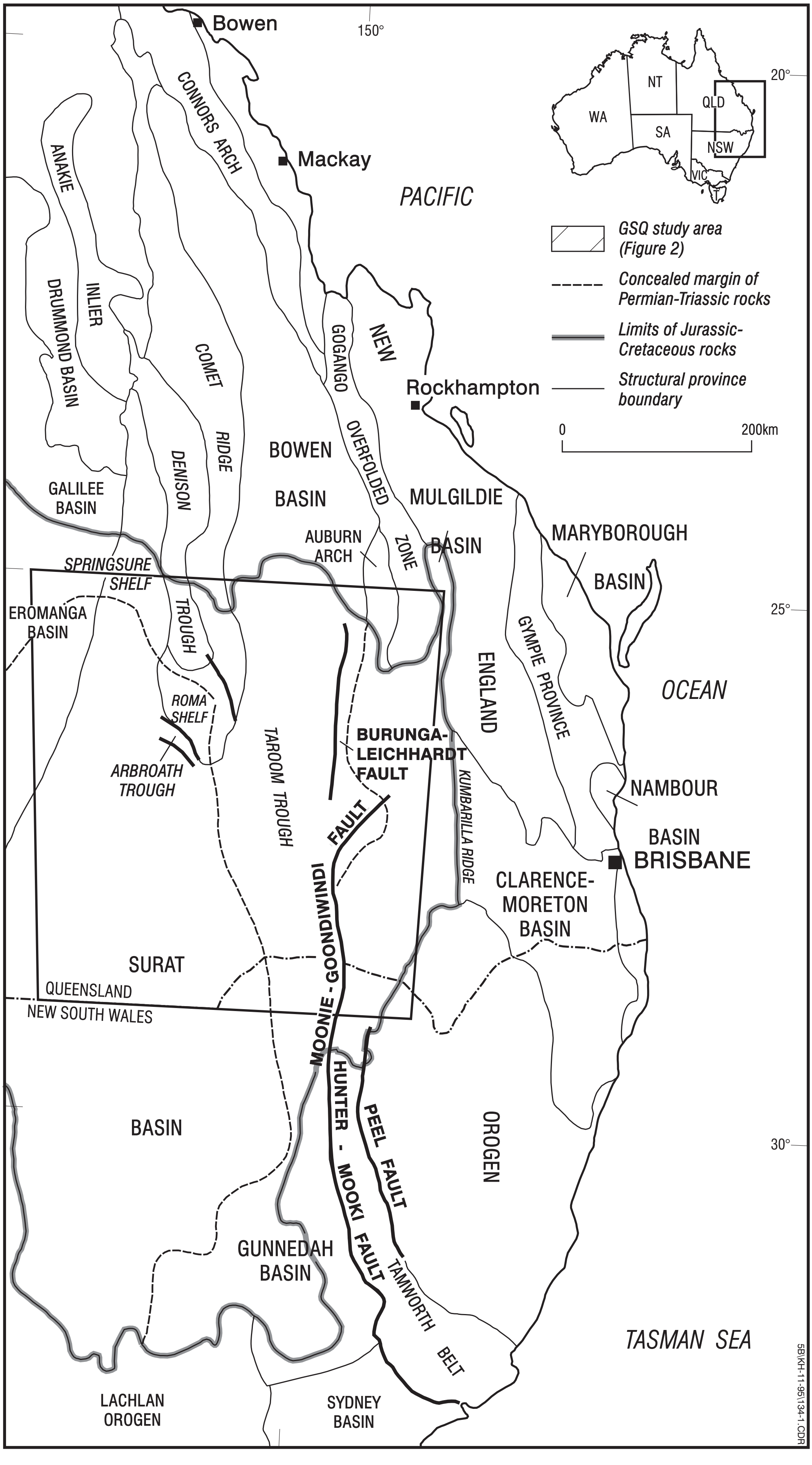

Figure 1: Sedimentary Basins of Eastern Australia (SBEA) Project area.

The results of the assessment of the thermal history of the southern Taroom Trough using fission track analysis have been presented by Raza & others (1995). The results of this analysis will be incorporated by AGSO personnel into a petroleum generation model for the whole of the Bowen and Surat Basins in Queensland.

A detailed compilation of taxonomy, biostratigraphy of Jurassic palynofloras and palaeography in the Surat Basin (Queensland) has been undertaken (McKellar, in preparation). Price (this volume) has produced a revised zonation scheme for the Permian–Cretaceous interval in the Bowen and Surat Basins.

GEOLOGICAL SETTING

BOWEN BASIN

The Bowen Basin forms the northern extension of the Bowen–Gunnedah–Sydney Basin system in eastern Australia and the southern part of this basin is covered by the Surat Basin in Queensland (Figure 1). Sedimentary rocks of shallow marine and terrestrial origin and volcanics of Permian–Triassic age comprise the deposits in the Bowen Basin, which obtain thicknesses up to 10km in the Taroom and Denison Troughs. The basin crops out approximately between latitude 20°S (near Collinsville) and latitude 25°S. South of the latter latitude, the Bowen Basin is unconformably overlain by the Surat Basin and continues in the subsurface into New South Wales, where it is contiguous with the Gunnedah Basin.

The Bowen Basin began as an extensive north–south trending back-arc basin to the west of the continental Camboon Volcanic Arc. This arc developed as the result of continent–ocean plate convergence (Veevers & others, 1982; Day & others, 1983; Murray, 1985; Murray & others, 1987; Fielding, 1990; Fielding & others, 1990b). Early Permian back-arc extension on the western margin of the Bowen Basin produced a series of half-grabens, such as those of the Denison and Arbroath Troughs, where initial deposition commenced (Draper, 1985; Department of Resource Industries, Queensland, 1990; Fielding & others, 1990a,b; Elliott, 1993). Contemporaneously, andesite and volcaniclastics associated with the arc were laid down on the eastern margin of the basin.

A phase of thermal subsidence followed, allowing the incursion of the sea over the arc and westwards across the basin (Fielding & others, 1990a). Deltaic facies developed around the western and northern edges of the basin. These deltas persisted into the Late Permian resulting in the formation of coastal swamps and the subsequent accumulation of extensive coal deposits.

During the Late Permian, compressive deformation related to the arc resulted in the shedding of large quantities of volcanolithic sediments from uplifted areas to the east and restriction of the sea to the central west. By the close of the Permian, infilling of the sea by southward and westward prograding deltas

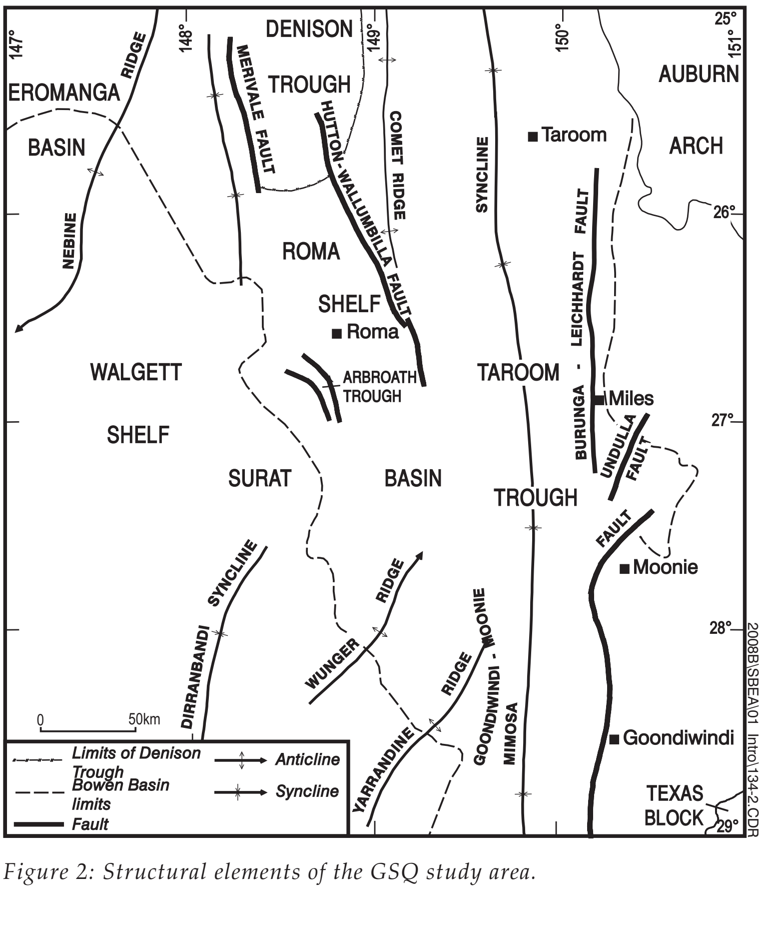

Figure 2: Structural elements of the GSQ study area.

resulted in the formation of peat-forming wetlands and associated fluvial systems (Fielding & others, 1990a).

During the latest Permian, initial deposition of the volcanolithic alluvial sediments of the Rewan Group occurred across the basin. This Group includes the lower part of a thick succession of mainly terrestrial rocks deposited during the Early Triassic. The quartzose sandstones of the overlying Middle Triassic Clematis Group, reflect a change in provenance with sediments being sourced predominantly from the uplifted western craton instead of the arc in the east (Fielding & others, 1990a). The Showgrounds Sandstone, the subsurface equivalent of the upper part of the Clematis Group on the western side of the basin, shows evidence of being deposited in a body of standing water such as a lake or a sea (Butcher, 1984).

The Middle Triassic Moolayember Formation is the youngest unit in the Bowen Basin and its lithology reflects a return to sourcing from a volcanic province in the east. The Formation consists mainly of fluvial and lacustrine deposits (Alcock, 1969; Kassan, 1993). The dark, fine-grained Snake Creek Mudstone Member at the base of the Moolayember Formation is believed to have been deposited in a marginal marine or tidal-flat environment (Butcher, 1984).

Major compressive deformation during the Middle–Late Triassic resulted in regional uplift, folding and the erosion of up to 3000m of section (Fielding & others, 1990b). There is evidence for strike-slip movement along fault lines to accommodate the compressional forces.

The sense of direction, whether dextral or sinistral, is still the subject of debate (Evans & Roberts, 1980; Brown & others 1983; Korsch & others, 1989; Fielding, 1990; O'Brien & others, 1990). Some normal faults have been reactivated to become reverse faults. The present eastern margin of the Bowen Basin is bounded by a series of north-south trending faults which are generally westward directed thrusts (Murray, 1985).

SURAT BASIN

After a long period of erosion and peneplanation, a large intracratonic sag which eventually formed the Great Australian Basin, was initiated. A number of shallow platform basins, including the Surat, Carpentaria, Clarence–Moreton, and Eromanga Basins, were formed as a result. Deposition occurred in these basins until the Early Cretaceous (or Cenomanian at the latest) (Figure 1).

The driving force for the formation of these basins is still controversial. One theory has suggested the basins formed as a result of thermal sag after the cessation of rifting associated with the Camboon Volcanic Arc (Korsch & others, 1989). Alternatively, Kingston & others (1983) have described similar extensive intracratonic sags developing under a tensional regime resulting from divergent plate motion.

Rifting around the southern and western margins of the Australian continent began during the late Middle–Late Jurassic when Gondwana began to break-up, but did not commence until the Late Cretaceous along the eastern margins (Branson, 1976; Falvey & Mutter, 1981; Exon & Colwell, 1994; Ramsay & Exon, 1994). Therefore divergent plate motion is unlikely to be the driving force behind the inception of these Mesozoic basins.

On the other hand, workers such as Exon & Senior (1976) and Veevers & others (1982) have concluded that these Mesozoic basins were pericratonic basins behind a final volcanic arc system, which was well to the east of the earlier Camboon Volcanic Arc active during Bowen Basin time. This theory would explain the presence of tuffs and volcanogenic sediments in the basins during this time. Gallagher & others (1994), from their work on subsidence histories, argue that the subsidence of the Mesozoic basins was controlled by sublithospheric convection related to subduction along the eastern margin. This agrees with the view that the basins were pericratonic.

Sedimentation began during the latest Triassic in the Clarence–Moreton, Nambour and Maryborough Basins, and was intermittent in the Eromanga and Surat Basins (Day & others, 1983; Wecker, 1989; Gallagher, 1990). By the Early Jurassic, deposition was continuous into the Eromanga and Mulgildie Basins, and subsequently expanded into Carpentaria and Laura Basins in the Middle Jurassic. Most of these basins contain economically important coal resources, and the Surat, Eromanga and Carpentaria Basins supply artesian groundwater (Day & others, 1983).

The Surat and Eromanga Basins also have important petroleum reserves.

The Surat Basin extends across south-east Queensland into New South Wales and unconformably overlies the Bowen and Gunnedah Basins. Initial sedimentation in the Surat Basin was centred in the Mimosa Syncline, which overlies the thickest Permian Triassic rocks in the Taroom Trough. The latest Triassic–earliest Cretaceous succession in the Surat Basin consists of five fining-upwards sedimentary cycles dominated by fluvio-lacustrine deposits (Exon, 1976; Exon & Burger, 1981; Day & others, 1983; Gallagher, 1990). The lower part of each cycle is predominantly sandstone with mostly siltstone, mudstone, and coals in the upper part. During the Cretaceous, two cycles accumulated in the Surat Basin depositing coastal plain and shallow marine sediments as a result of inundation of the land by increases in sea level.

Sedimentation in the Surat Basin ceased in the Middle Cretaceous. This cessation coincided with a compressional event which was responsible for the uplift and erosion of the Bowen and Surat Basins and their associated volcanic arcs in the Middle Cretaceous (Elliott, 1994). Phases of deformation also occurred during the Late Cretaceous and Tertiary due to epeirogenic movements as well as forces relating to divergent plate motion during the break-up of Gondwana (Exon, 1976; Veevers & others, 1982; Fielding & others, 1990b; Elliott, 1993).

EXPLORATION HISTORY

PETROLEUM EXPLORATION

The western Bowen and overlying Surat Basins in the southern Taroom Trough region of Queensland are the major sources of natural gas for the south-east Queensland markets, in particular Brisbane and the Gold and Sunshine Coasts. These basins are also major producers of oil, condensate, and liquid petroleum gas (LPG).

The first discovery of gas in Australia was at Hospital Hill, Roma, in 1900, in a bore drilled to supply the township with water (Mott, 1952; Elliott & Brown, 1988). Gas measured at over 1200 m^3/day was met at 1123m in the Jurassic sandstones. By 1904 the rate had increased to over 2000 m^3/day. In 1906, ten days after gas

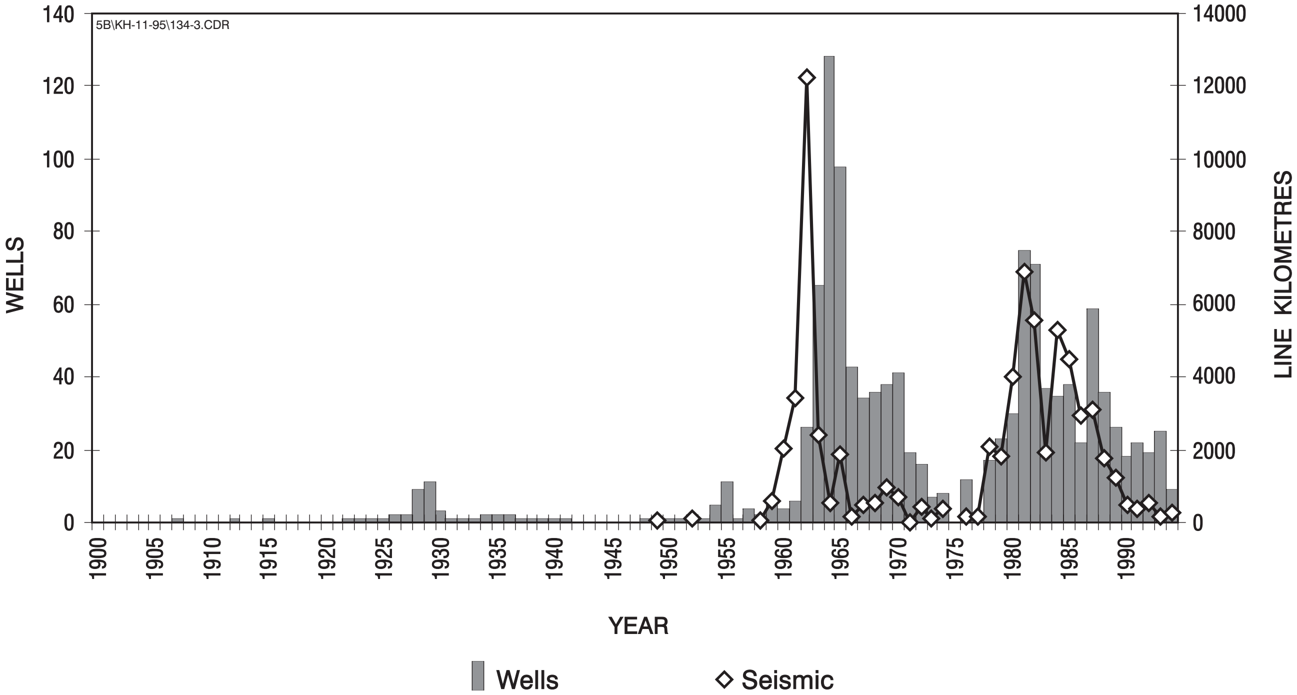

Figure 3: Seismic line kilometres and wells drilled between 1900 and 1994.

pipes and street lighting had been installed throughout the town to use the supply, the gas flow suddenly ceased because of a blockage in the bore (Geological Survey of Queensland, 1960).

In 1928, gas from another bore on Hospital Hill was utilised for its condensate, and production continued intermittently until 1931. This success induced a minor boom in the Roma district. Non commercial discoveries of oil were subsequently obtained from wells drilled at Blythdale and Mt Bassett (Geological Survey of Queensland, 1960). In the mid-1930s, drilling extended to the Injune and Arcadia Valley areas, north of Roma.

Exploration strategies changed in the 1950s with the introduction of seismic exploration into the search for hydrocarbons (Figure 3). The Australian Geological Survey Organisation [formerly the Bureau of Mineral Resources (BMR)] conducted the first seismic surveys in the region and demonstrated the value of this technique in subsurface mapping (Elliott & Brown, 1988).

The early recordings were of single-fold, analogue data which were poor quality compared to the multi-fold, digital data recorded since 1976. The distribution of multifold data is shown in Figure 4.

Exploration continued sporadically in the Roma district until 1960 when gas was discovered in seismic closures at Timbury Hills and Pickanjinnie; and condensate was discovered at Cabawin on the eastern side of the Surat and Bowen Basins. These discoveries and the discovery of the Moonie oil field in 1961 (estimated original reserves of 22 million barrels), produced an exploration boom during the 1960s (Figure 3).

Exploration activity waned in the mid 1970s due to the Federal Government introducing

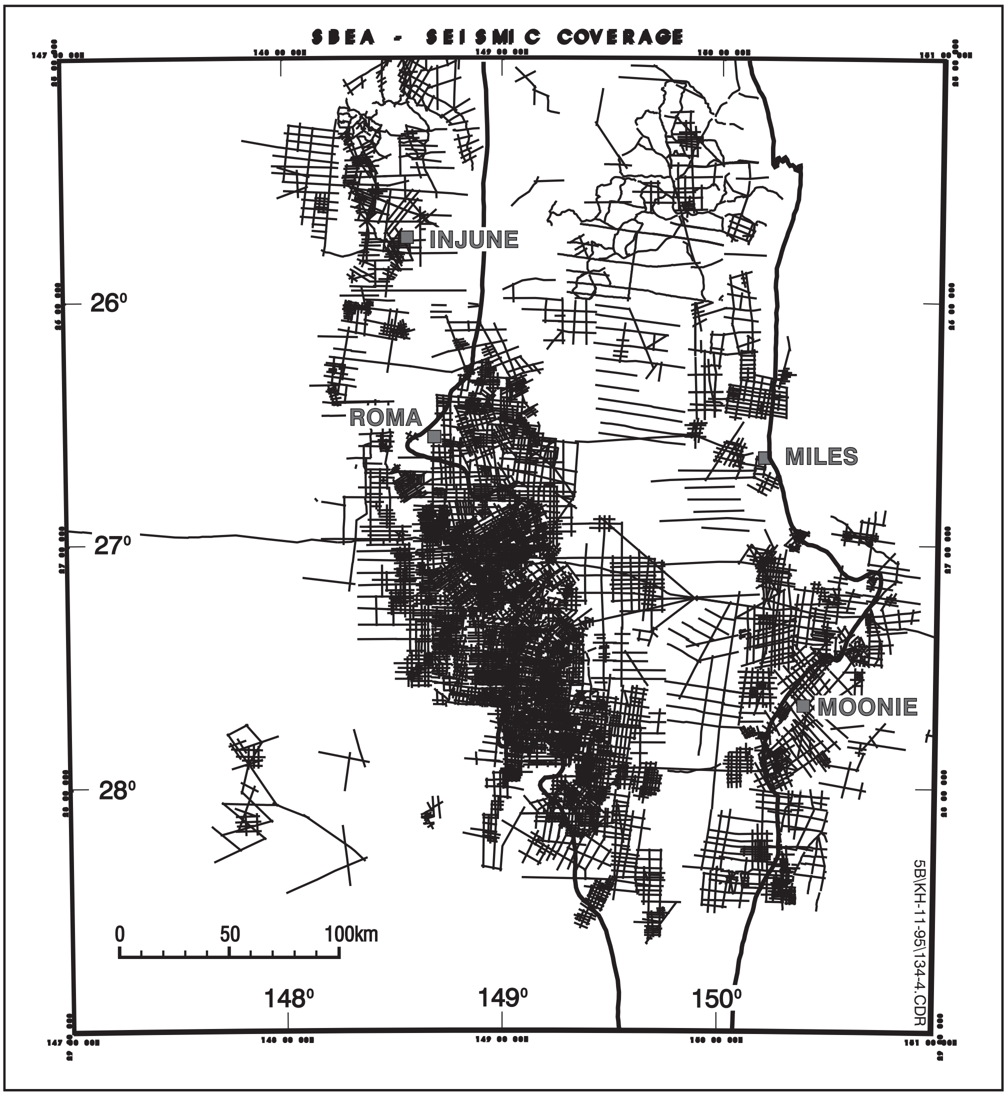

Figure 4: Seismic multifold data in the study area (Permian limits shown).

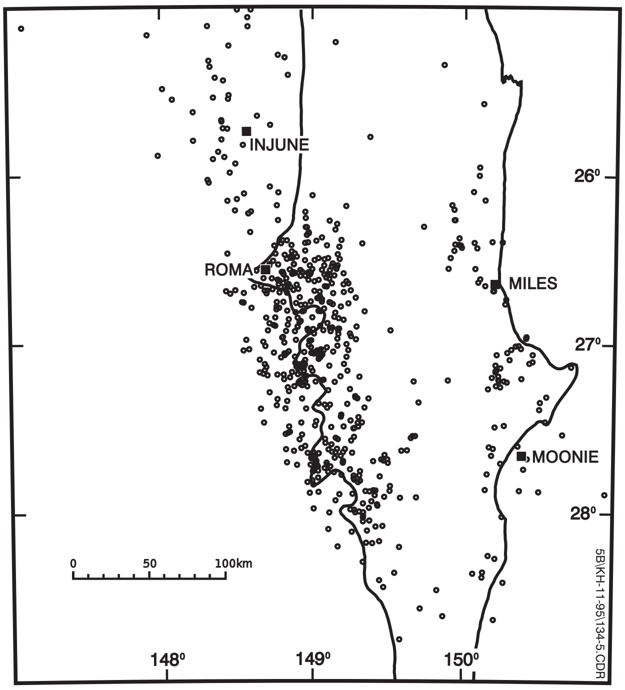

Figure 5: Exploratory wells in GSQ study area (Permian limits shown).

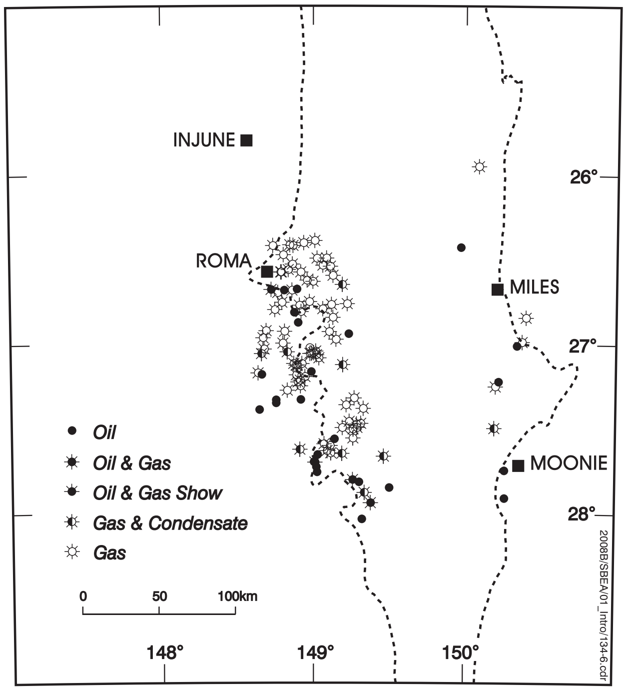

Figure 6: Hydrocarbon occurrences in the Taroom Trough and overlying Surat Basin in the study area (Permian limits shown).

new energy policies, mainly involving the withdrawal of income tax concessions for explorers and the termination of the Petroleum Search Subsidy Scheme. In the late 1970s, the acquisition of high quality seismic data resulted in the resumption of exploration, with peak activity occurring in 1981. Because of improved technology, the success rate of exploration drilling increased from 6% to 20% (Elliott & Brown, 1988). Figure 3 illustrates an apparent relationship between the number of seismic line kilometres and the number of wells drilled in the succeeding years, showing a general 1-2 year lag.

A total of 1204 petroleum wells (exploratory, appraisal, development, methane drainage) and 70 260 seismic line kilometres have been completed within the GSQ study area of the SBEA Project at December 1994 (Figure 3). In addition, the Queensland Department of Minerals and Energy drilled 58 continuously cored and wireline logged stratigraphic bores between 1963 and 1984, providing valuable information in this area. The location of the exploratory wells is shown in Figure 5.

Gas and oil have been discovered mainly on the western side of the southern Taroom Trough, on and adjacent to the Roma and Walgett Shelves. On the eastern side of the Trough, besides the Moonie Oil Field, only a few small oil and gas discoveries have so far been made (Figure 6).

INFRASTRUCTURE

The main infrastructure in the SBEA Project area includes the Jackson-Moonie-Brisbane oil pipeline, the Wallumbilla-Brisbane gas pipeline, and the State Gas Pipeline from Wallumbilla to Gladstone. Spur lines connect the gas fields in the Surat and Roma areas to Wallumbilla.

RESERVES

Recoverable reserves for gas fields on the Roma Shelf average 10 – 50 x 106m^3 which are relatively small compared to the Walgett Shelf fields at 30 – 400 x 106m^3. Most of the reserves are confined to the Showgrounds Sandstone in the Bowen Basin and the Precipice Sandstone and Evergreen Formation in the Surat Basin (Elliott & Brown, 1988; Department of Resource Industries, Queensland, 1990).

REGIONAL GEOLOGICAL STUDIES

During the 1960s, the BMR and the GSQ mapped the surface geology of the Surat and Bowen Basins in the Project area at a scale of 1:250 000.

Dickins & Malone (1973) and Exon (1976) provided comprehensive reports on the geology of the Bowen and Surat Basins, respectively. The Permian-Triassic stratigraphy and sedimentation in the Bowen Basin are outlined in Alcock (1969), Jensen (1975) and Fielding & others (1990a,b).

Subsurface mapping of the Surat and Bowen Basins has been significantly assisted by the petroleum exploration drilling undertaken since 1960, mainly because of the wireline logging undertaken.

A Departmental proline auger drilling program, for palynological and stratigraphic information to support petroleum exploration, was initiated in 1963 (Gray, 1968a); and this was followed by a shallow (45-498m) program of stratigraphic core drilling and wireline logging in the Surat/Bowen Basins between 1965 and 1970 (Gray, 1968b, 1972).

Further core drilling, with some holes reaching more than 1000m, was undertaken by the Department between 1971 and 1984. Reviews of the stratigraphic drilling in the Project area have been provided by Hawkins & Balfe (1980), Noon & Coote (1983), Coote (1986) and John (1987).

Studies of the geological evolution of the Surat and Bowen Basins have been carried out by a number of workers (Power & Devine, 1970; Allen, 1976; Exon, 1976; Porter, 1979; Exon & Burger, 1981; Elliott, 1989; Fielding & others, 1990b; Korsch & others, 1992; Elliott, 1993). The results of these investigations are summarised in the following sections.

Recent revisions and reviews of the biostratigraphic subdivision of the Surat and Bowen Basins have been undertaken by Price & others (1985; this volume), Draper & others (1990), Burger (1992a,b) and McKellar (1992).

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BASEMENT TERRANES BENEATH THE BOWEN AND SURAT BASINS, QUEENSLAND

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INTRODUCTION

Basement rocks beneath the Bowen and Surat Basins in the Study area are part of the Tasman Fold Belt System which occupies the eastern third of the Australian continent (Figure 1). This section describes the basement rocks, and places them within the overall framework of the Tasman Fold Belt System using the techniques of terrane analysis (Jones & others, 1983).

At least until Late Devonian time, all of the basement units within the study area must be considered as suspect terranes. This implies that their palaeotectonic setting, and their original palaeogeographic relations to one another, are uncertain. It should not be assumed that basement terranes which are now in contact were always positioned adjacent to one another. Their juxtaposition must be proved by provenance linkages, overlap sequences, or stitching plutons (Jones & others, 1983). This study is based on examination of basement cores and interpretation of geophysical data. Cores from 108 petroleum exploration wells and 3 GSQ stratigraphic boreholes were examined. All of the cores stored at the Department of Minerals and Energy's Exploration Data Centre (EDC) at Zillmere were examined. In addition, 126 thin sections (including sections from all cores not currently available at the EDC) were described. Thin sections referred to in this report are identified by their number in the GSQ slide collection. Descriptions of the cores and thin sections are included in a compilation of basement core data from the entire Tasman Fold Belt System in Queensland (Murray, 1994). In assigning basement cores to tectonostratigraphic units, particular emphasis was placed on the structure of metasedimentary rocks and on the provenance of sandstones determined from a QFL plot.

In determining the proportions of quartz, feldspar and lithics in the sandstones, the distinction of lithic clasts and some altered feldspar grains from the recrystallised matrix was a major problem. For this reason, the proportions were not determined solely by point counting. For quartzose sandstones, the best method was to determine the quartz content of the rock by point counting, and then to use this as a guide to estimate the proportion of feldspar and lithics using a low power objective. The difference from 100% was assumed to be matrix. It is probable that this method underestimates the proportion of lithic clasts in the sandstones.

SUPER-TERRANES WITHIN THE TASMAN FOLD BELT SYSTEM

The study area covers a complex region of the Tasman Fold Belt System comprising the junction between the Thomson, Lachlan and New England Fold Belts (Figure 1).

The Thomson Fold Belt was originally distinguished from the Lachlan Fold Belt to the south by different gravity anomaly trends (Wellman, 1976; Murray & Kirkegaard, 1978).

Subsequently, this distinction was reinforced by studies of short and medium wavelength magnetic anomalies as well as gravity, which were used to define the boundary between these two fold belts (Wellman, 1988, 1990). The boundary coincides with the position of the Foyleview geosuture identified by the 1984 BMR Eromanga-Brisbane deep crustal seismic reflection profile. This shallow dipping structure extends to the base of the crust and separates continental blocks with very different seismic character (Finlayson & others, 1990). The New England Fold Belt is the easternmost and youngest part of the Tasman Fold Belt System, and is separated from the Thomson and Lachlan Fold Belts by the Bowen-Sydney Basin. Deep seismic reflection profiling shows that the Thomson Fold Belt has a characteristic non-reflective upper crust which differs from the crustal structure of the New England Fold Belt to the east (Finlayson & others, 1990).

Leitch & Scheibner (1987) refer to the Thomson, Lachlan and New England Fold Belts as super-terranes, emphasising that they are made up of a collage of individual terranes which cannot be assumed to have formed in their present positions. For example, the oldest provenance linkage which proves juxtaposition of the Lachlan and New England Fold Belts is in the Late Devonian (Flood & Aitchison, 1992), leaving earlier palaeogeographic relations between these two super-terranes uncertain. Similarly, Wellman (1976, 1990) argued that gravity and magnetic trends indicate that the Lachlan Fold Belt was accreted, perhaps progressively, onto a proto-Australian continent which already included the Thomson Fold Belt.

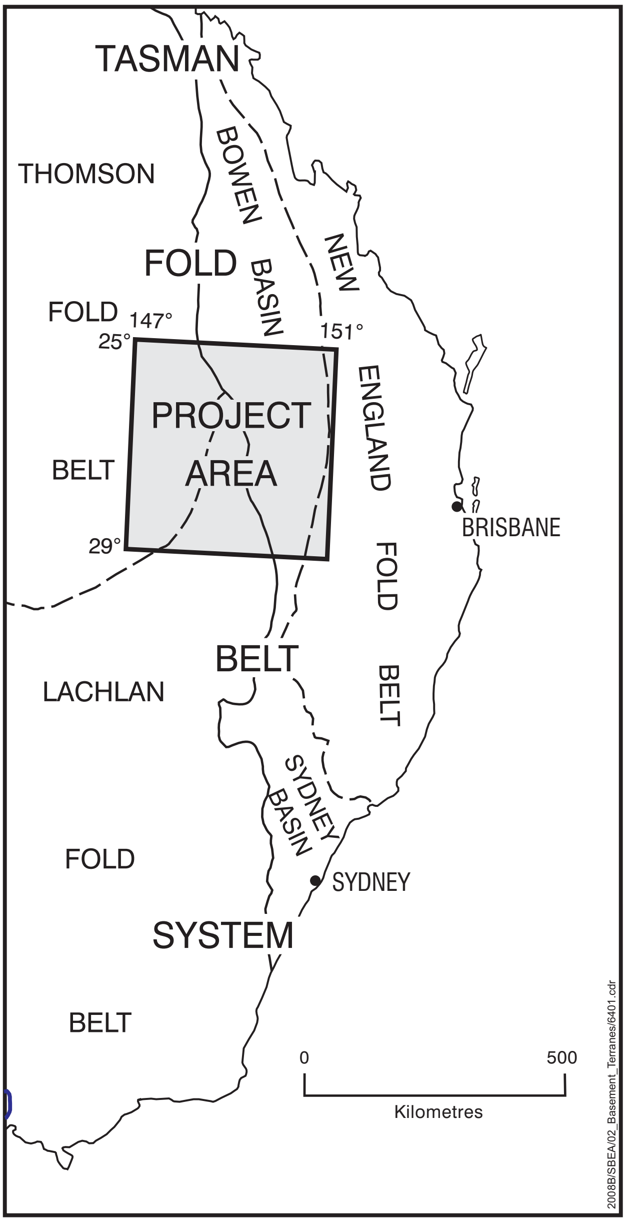

Figure 1: Subdivisions of the Tasman Fold Belt System of eastern Australia, after Scheibner (1993), showing the study area.

THOMSON AND LACHLAN FOLD BELTS

Geological setting

Basement rocks west of the Taroom Trough have been assigned to the Thomson and Lachlan Fold Belts. The geophysical boundary between these major tectonostratigraphic units or super-terranes runs generally east-west, but swings to the north at its eastern end within the study area (Figures 1 and 2).

Most previous descriptions have referred to these rocks merely as basement to the Bowen and Surat Basins, and have therefore used terms such as Roma Shelf, Wunger Ridge, Yarrandine Ridge, and Walgett Shelf or St George/Bollon Slope (Power & Devine, 1970; Exon, 1976; Thomas & others, 1982). In contrast, this report attempts to place these basement rocks into their regional context within the Tasman Fold Belt System.

The basement geology is shown in Figure 2. The density of drilling in the Roma Shelf region has made it possible to compile a geological map of the basement in this area with a considerable degree of confidence. Two basement units have been recognised in this area, the Timbury Hills Formation and the Roma granites. Figure 2 also shows the distribution of the Combarngo Volcanics, which are regarded as economic basement even though they represent the basal unit of the Bowen Basin succession. While examination of basement cores has provided the basic lithological information presented in this report, it should be noted that the basement geology of the Roma Shelf region in Figure 2 was compiled from reported rock types in all exploration and appraisal wells which penetrated basement. In addition, the delineation of granite boundaries has been based partly on contours around prominent gravity lows which are centred on known granite masses.

Nebine Ridge

Previous investigations

The Nebine Ridge is a broad basement high trending south-south-west from the exposed Anakie Inlier. It was a positive feature early in the depositional history of the Eromanga Basin to the west and the Surat Basin to the east, because Mesozoic sediments of these basins onlap the ridge. It has even been postulated that the Nebine Ridge was in existence as a sediment source from the beginning of the Permian (Harrington & others, 1989).

The Nebine Ridge coincides with a relatively positive gravity feature (Murray & others, 1989) which is emphasised by gravity lows related to granites to the east (see Figure 2) and to the Westgate Trough of the Adavale Basin to the west.

Lithology

Basement cores from the Nebine Ridge and from NAI Whyenbirra 1 to the south (Figure 2) are all metamorphic rocks derived from sedimentary rocks. They include chlorite-muscovite phyllite, chlorite-biotite-muscovite phyllite, and garnet-muscovite-biotite schist. Original sedimentary layers are preserved in phyllites from AOP Dulbydilla 1 and NAI Whyenbirra 1, but are folded and disrupted.

Structure

Most of the cores show evidence of multiple deformations. In the coarser-grained schists, the dominant foliation, which is moderately to steeply dipping, is folded by small-scale open folds.

Phyllitic rocks preserve a more complex history, with at least three deformational events. In phyllite from AOP Dulbydilla 1, the dominant steeply dipping foliation is a second generation crenulation which is itself folded by small-scale open folds. Phyllite from NAI Whyenbirra 1 has a dominant cleavage defined by muscovite flakes parallel to the lithological (?sedimentary) layering, which dips steeply. This cleavage is cut at a moderate angle by a prominent foliation or crenulation along which relatively large biotite grains have grown. A third generation of small-scale open folds appears as a prominent crenulation.

Metamorphism

Metamorphic grade apparently ranges from lower greenschist facies (AOP Dulbydilla 1) to probable amphibolite facies (AOP Alba 1 and GSQ Mitchell 1). In NAI Whyenbirra 1, the highest grade of metamorphism, represented by formation of biotite, appears to be associated with a second generation foliation or crenulation. Chlorite may be a late-stage retrograde mineral in some or all of the metamorphics.

Age and correlation

Biotite from AOP Alba 1 has been dated by the K-Ar method at 416 ± 2 Ma (Silurian) (Murray, 1986). The biotite is reasonably fresh (7.06% K) and undeformed, and the absence of Silurian granitic intrusives in the region suggests that this is a good measure of the age of regional metamorphism.

The Silurian date and their more complex deformational history indicate that the Nebine Ridge metamorphics are older than the low-grade metasedimentary rocks of the Timbury Hills Formation to the east (Figure 2), which are at least in part of Devonian age. The southern part of the Timbury Hills Formation is of higher metamorphic grade, including probable amphibolite facies rocks in HPP Bendiboi 1. If these higher grade rocks in the Timbury Hills Formation are older than the Devonian metasedimentary rocks to the north, rather than being due to an increase in metamorphic grade southwards, they could be equivalent to the Nebine Ridge cores. However, this possible correlation is not supported by the fact that samples of Timbury Hills Formation closest to the Nebine Ridge, in AOP Strathmore 1 and AAO Glenroy 1 (Figure 2), are typical low-grade metasedimentary rocks in which original sedimentary textures are well preserved.

Basement rocks of the Thomson Fold Belt to the west of the Nebine Ridge are also low-grade

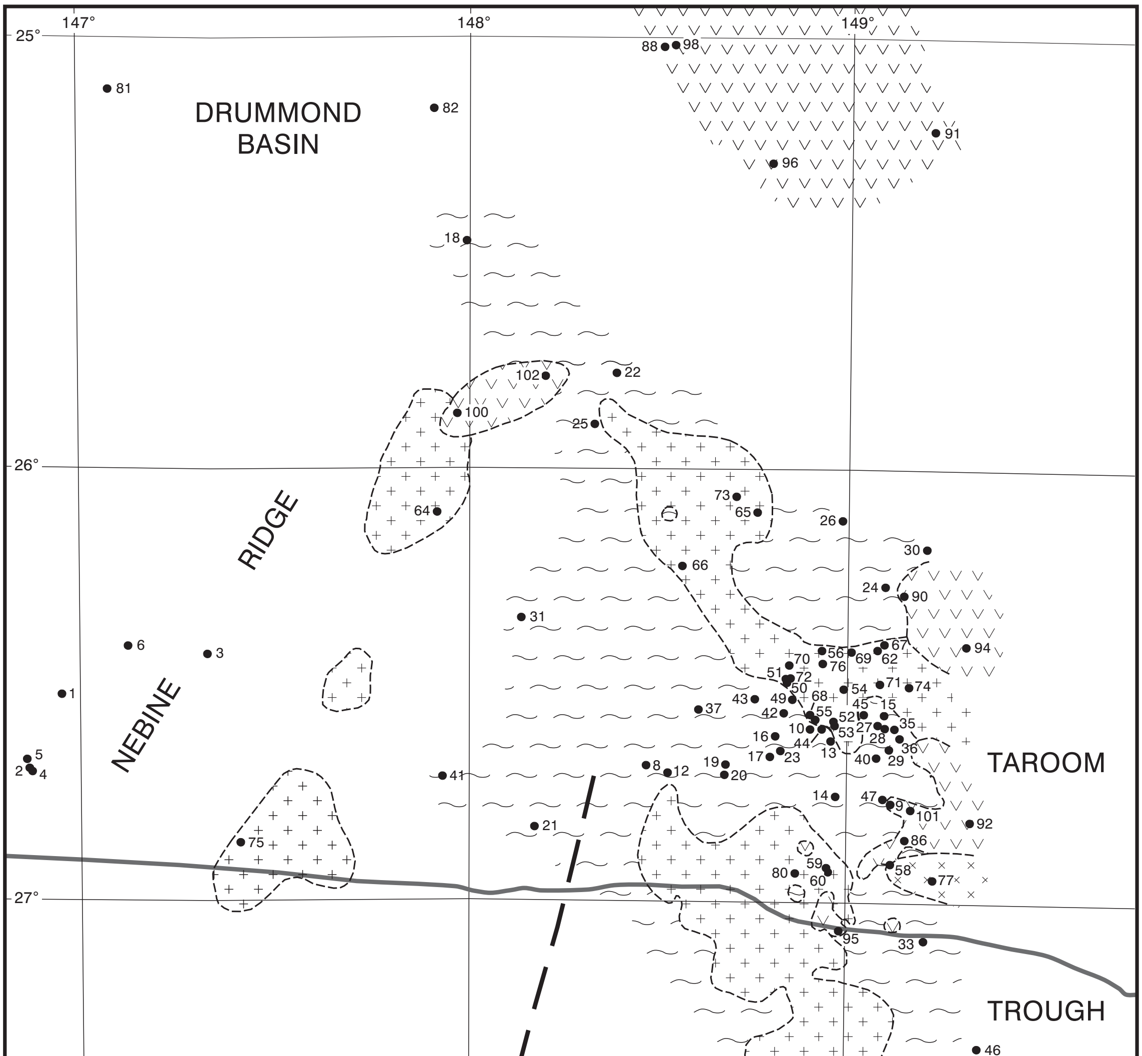

Figure 2. Basement geology of the study area west of the Taroom Trough, showing location of basement cores, the position of the BMR deep crustal seismic reflection profile, and the boundary between the Thomson and Lachlan Fold Belts interpreted by Wellman (1990) from gravity and magnetic anomalies.

NEBINE RIDGE

WELL №	WELL NAME
1	AOP ALBA 1
2	OOC CRICHTON 1
3	AOP DULBYDILLA 1
4	OOC LOWOOD 1
5	OOC MARYVALE 1
6	GSQ MITCHELL 1
7	NAI WHYENBIRRA 1

TIMBURY HILLS FORMATION

WELL №	WELL NAME
8	AAO ARBROATH 1
9	APN BACK CREEK 1
10	AAO BELLA FARM 1
11	HPP BENDIBOI 1
12	AAO BINYA 1
13	AAO BLYTH CREEK 1
14	AAO BONEY CREEK 1
15	BORE VIEW 1
16	BUCKENAN DOWNS 1
17	AAO COOLIBAH 1
18	PEC CRYSTALBROOK 1
19	AAO DIRINDA 1
20	AAO DIRINDA SOUTH 1
21	AAO GLENROY 1
22	AAO GLENTULLOCH 1
23	AAO INGLE 1
24	EOC JENAVALE 1
25	AAO KILLORAN 1
26	AAO KOORINGA 1
27	AAO LATEMORE 1
28	AAO LATEMORE EAST 1
29	AAO LATEMORE SOUTH 1
30	AAO MEELEEBEE 1
31	GSQ MITCHELL 2
32	UOD MOOMBAH 1
33	UOD MYALL CREEK 1
34	HPP NAMARAH 1
35	AAO PICKANJINNIE 1
36	AAO PICKANJINNIE 2
37	GSQ ROMA 8
38	UOD SAINT GEORGE 1
39	BON SILVER SPRINGS 4
40	AAR SIX MILE 1
41	AOP STRATHMORE 1
42	AAO TIMBURY HILLS 2
43	AAO TINEEN 1
44	AAO WAROOBY SOUTH 1
45	AAO WATTANOOKA 1
46	UOD WERIBONE 1
47	AAO WINNATHOOLA 1
48	UOD WUNGER 1
49	AAO YANALAH 1

ROMA GRANITES

WELL №	WELL NAME
50	AAO AAO2 (ROMA)
51	AAO AAO3 (ROMA)
52	ARO ARO 4 (BLYTHDALE)
53	ARO ARO 11 (BLYTHDALE)
54	ARO ARO 14 (BLYTHDALE)
55	AAO BEAUFORT 1
56	AAO BELBRI 1
57	HPP BENDEE 1
58	AAO BOONDARA 1
59	AAO BRUCEDALE 1
60	AAO BRUCEDALE EAST 1
61	HPP BYANBUNNOO 1
62	AAO DALMUIR 1
63	HPP DONGA 2
64	AOP DONNYBROOK 1
65	AAO KALIMA 1
66	LOA LOA 3 (ORALLO)
67	AAO MOUNT HOPE 1
68	OSL OSL 1 (WAROOBY)
69	AAO PLEASANT HILLS 1
70	AAO QUIBET 1
71	AAO RASLIE 1
72	RBO RBO 1 (MOUNT BASSET)
73	AAO ROSEWOOD 1
74	AAO SAWPIT CREEK 1
75	AOP SCALBY 1
76	AAO SLEEPY CREEK 1
77	AAO SUNNYBANK 1
78	UOD TALWOOD 1
79	CON WONOLGA 1
80	APN YALEBONE 1

DRUMMOND BASIN

WELL №	WELL NAME
81	AOP CUNNO 1
82	PEC WARRONG 1

COMBARNGO VOLCANICS AND EQUIVALENTS

WELL №	WELL NAME
83	UOD ALTON 1
84	CON BEARDMORE SOUTHWEST 1A
85	BON BOGGO CREEK 2
86	AAO COMBARNGO 1
87	HPP CROWFOOT 1
88	GSQ EDDYSTONE 5
89	UOD FLINTON 1
90	EOC GLENARDON 1
91	MPA GLENHAUGHTON 1
92	AAO LORELLE 1
93	UOD LYNROCK 1
94	EOC MUGGLETON 1
95	HEP NEWINGTON 2
96	OSL OSL 3 (ARCADIA)
97	BON ROCKY GLEN 1
98	SQD SQD 1 (MORELLA)
99	BON TAYLOR 4
100	PEC TOOLOOMBILLA 1
101	APN WALLABELLA 1
102	AAO WOMBLEBANK 1

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Legend for Figure 2.

metasedimentary rocks preserving sedimentary textures. These rocks are intruded by Silurian granites, and are considered to be early Palaeozoic (mainly Ordovician) in age. They could be lower-grade equivalents of the Nebine Ridge metamorphics.

Because it trends south-south-west from the southern end of the Anakie Inlier, and has a similar gravity pattern, the Nebine Ridge is often considered to be a subsurface continuation of the exposed inlier. In fact, Lonsdale (1965) and Darby (1969) applied the term Anakie-Nebine Regional Gravity high to the combined gravity expression of these two features. Although some rocks of the Anakie Inlier are similar to the basement cores from the Nebine Ridge, metamorphic ages from the exposed inlier are considerably older (Cambrian to Ordovician; Withnall & others, 1993) than the single date from AOP Alba 1.

Tectonic setting

Because of its higher metamorphic grade, the Nebine Ridge may be either a structurally uplifted block of mid-crustal fold belt rocks, or a separate tectonic unit altogether.

Seismic reflection profiles support the interpretation of the Nebine Ridge as uplifted mid-crustal rocks of the Thomson Fold Belt. The minimum thickness of non-reflective upper crust over the Nebine Ridge is about 6 km, whereas it is much thicker (minimum of about 15 km) to the west under the central Eromanga Basin (Finlayson & others, 1990). This difference is consistent with uplift and erosion of Thomson Fold Belt rocks in the Nebine Ridge area.

Uplift and erosion in this region may have been related to collision of major crustal blocks. If the Foyleview geosuture represents some sort of collisional boundary between different continental blocks, metamorphism and/or uplift of the Nebine Ridge may have been related to this event. At present this hypothesis is speculative, as the age of the Foyleview geosuture and therefore the timing of the possible collision are completely unknown. Wellman (1990) considered that the Nebine Ridge was in a "reworked zone" at the margin of the Thomson Fold Belt crustal block, but did not specify the process involved or a causative mechanism.

The second alternative was first suggested by Harrington (1974), who proposed that the Nebine Ridge represented an early Palaeozoic volcanic arc split off from the Precambrian craton to form a marginal sea. While the absence of volcanic rocks in basement cores appears to rule out the possibility of a volcanic arc setting, it is still feasible that the Nebine Ridge is an exotic terrane. However, the available evidence favours the first alternative.

Timbury Hills Formation

Previous investigations

The name Timbury Hills Formation was introduced by Derrington (1961) for metasedimentary rocks in the Roma area. He described the unit in AAO Timbury Hills 2 as "dominantly silty with thin interbeds of sandstone and shale. The siltstone is grey and grey-green, hard, compact, siliceous, variably calcareous. It has been fractured and dips at 60-80 degrees." In AAO Pickanjinnie 1 and 2, "the unit is a light grey-green, fine to very fine grained hard, tight quartzose sandstone grading to a siltstone." Traves (1966) described the Timbury Hills Formation as "indurated and compacted, steeply dipping siltstone, shale and sandstone which in many places have a phyllitic appearance, although metamorphic minerals are found only in the contact metamorphic zones bordering granite." In his Table 1, Traves described the Timbury Hills Formation in more detail:- "The unit is dominantly silty in character with thin sandstone and shale laminations. The *Siltstone* is grey and grey-green, hard, compact, siliceous and variably calcareous. The *Sandstone* is medium to fine grained, grey-green to white, slightly argillaceous, calcareous and quartzose. The *Shale* is mainly dark grey. Quartz and calcite veining is common. Pyrite, siderite and iron staining occur. Severe fracturing is common, slickensiding is present and not uncommonly the rock has a phyllitic appearance."

Despite this detailed description, the name Timbury Hills Formation has been applied rather indiscriminately to a variety of basement rocks in the Roma region, including granite and flat-lying ignimbritic volcanics. Only those metasedimentary rocks which obviously fall within the description, and higher grade metamorphics to the south, are considered to be part of the Timbury Hills Formation in this report. It should of course be acknowledged that the unit cannot have the status of a Formation under the Australian Code of Stratigraphic Nomenclature. However, the name is extremely useful for collective reference to a group of essentially similar low grade metasedimentary rocks.

Lithology

Basement cores included in the Timbury Hills Formation show a great deal of uniformity. They are exclusively metasedimentary rocks, with the possible exception of a questionable tuffaceous band in AAO Bony Creek 1. Typically they consist of interbedded pale grey quartzose sandstone, grey to green siltstone, and dark grey cleaved argillite. The finer-grained rocks are thin bedded to laminated. The sandstone beds are up to 1 m thick (APN Back Creek 1) but are mostly much less. Possible cross-bedding was noted in a few cores, and rare graded bedding.

In thin section the sandstones are seen to be fine-grained, quartzose-rich to quartz-intermediate (Crook, 1974), subangular to subrounded (for the largest grains) and poorly sorted. A bimodal distribution of clast sizes was noted in some specimens. Quartz clasts are subangular except for the largest grains, which are subrounded to rounded.

Compositionally the sandstones are quartzose. In all specimens examined, quartz is the dominant detrital constituent. According to the classification of Crook (1974), they are quartz-rich to quartz-intermediate. The quartz is of both plutonic/metamorphic and volcanic derivation. Volcanic quartz is particularly abundant in sandstones from AAO Timbury Hills 2.

Lithic clasts are second in abundance to quartz. Overall, metasedimentary rocks (including siliceous varieties) are the main lithics, but felsic volcanic clasts are widespread. Intermediate volcanic grains are extremely rare, with a single clast noted in AAO Bore View 1. Single crystal carbonate clasts, possibly fossil fragments, occur in a few specimens.

Plagioclase is by far the dominant feldspar, with only minor microperthite and other alkali feldspars. Minor and accessory components are muscovite (which is ubiquitous), biotite, tourmaline, apatite and zircon.

Siltstones are compositionally similar to the sandstones with a greater proportion of matrix. Argillites appear to be typical pelitic sediments.

Depositional environment

Sedimentary features of the Timbury Hills Formation indicate that they were deposited in a large body of relatively deep water. Following a detailed examination of cores from GSQ Roma 8 and GSQ Mitchell 2, P.J.Conaghan (personal communication, 1988) concluded that the strata probably represent turbidites.

Plant fossils are extremely rare, and the presence of single crystal calcite clasts (possibly derived from marine fossils) suggests that the deposits are marine. The quartzose nature of the sandstones clearly indicates a continental setting.

Structure

Structural features of the Timbury Hills Formation are:

- Dips are generally steep (60° or greater);
- Most cores have a single slaty cleavage essentially parallel to bedding; and
- Cross cutting cleavage is most common where bedding is shallow (for example in AAO Buckenan Downs 1 and AAR Six Mile 1).

These features suggest that the Timbury Hills Formation has undergone one phase of folding to produce upright, tight to isoclinal folds. However, no tight small-scale folding has been observed in any core.

Crenulation of the primary cleavage or foliation has been observed only in fine-grained argillite and phyllite from two wells, AAO Arbroath 1 and UOD Saint George 1, both of which come from the western part of the Timbury Hills Formation. The significance of this crenulation, which appears to have been developed only locally, is uncertain.

Metamorphism

All specimens of Timbury Hills Formation have been metamorphosed to at least lower greenschist facies. Because the greenschist facies minerals define the dominant cleavage or foliation in these rocks, this metamorphism is believed to have been regional in nature, synchronous with folding, and to have pre-dated the intrusion of the Roma granites. In the sandstones, the effect of this metamorphism was replacement of the matrix by sericitic muscovite, chlorite and calcite. In some cases, feldspar and lithic grains were replaced by these minerals. Quartz grain boundaries were sutured. The highest grade pelitic rocks are chlorite-muscovite-albite-quartz phyllites (AAO Dirinda 1 and UOD Saint George 1).

These lower greenschist facies assemblages have been contact metamorphosed by the Roma granites to produce hornfelses (AAO Warooby South 1, AAO Wattanooka 1, AAO Winnathoola 1, and AAO Yanalah 1), some of which contain cordierite. It may also have produced the interstitial biotite in AAO Bore View 1 and AAO Pickanjinnie 2. All of these exploration wells except AAO Winnathoola 1 are located near granite contacts (Figure 2).

There are other metamorphic rocks whose origin is not as clear. HPP Bendiboi 1 intersected a coarse-grained garnet-muscovite-biotite schist or gneiss of probable amphibolite facies, and the metamorphics in UOD Moombah 1 and BON Silver Springs 4 are also higher grade than the general lower greenschist facies of the Timbury Hills Formation. The high-grade of HPP Bendiboi 1 could be attributed to proximity to granite, but UOD Moombah 1 and BON Silver Springs 4 appear to be remote from any subcrop of the Roma granites (Figure 2). Alternative explanations such as an increase in regional metamorphic grade southwards in the Timbury Hills Formation, or the existence of older metamorphics in the south, are therefore possible. A southward increase in regional metamorphic grade is favoured because of the compositional similarity of all the rocks assigned to the Timbury Hills Formation, and the presence of intermediate grade metamorphic rocks in UOD Weribone 1.

Table 1: Isotopic dates from the Roma granites

Sample	Age	Reference
Near Roma (well not specified	2448Ma	Evernden & Richards, 1962
AAO Rosewood 1 (632.2m)	3567Ma	Webb & others, 1963
AAO Pleasant Hills 1 (1060.7m)	3377Ma	Webb & others, 1963
AAO Brucedale 1 (1599.6-1601.7 m)	304Ma	Harding, 1969
AAO Mount Hope 1 (777.2m)	355Ma	Harding, 1969
AAO Sawpit Creek 1 (1140.9m)	343Ma	Harding, 1969
AOP Scalby 1 (858.6-863.2m)	33112Ma	Bennett & others, 1975

Age and correlation

If the Timbury Hills Formation does represent a single stratigraphic succession, its age must be confined to the Devonian. Plant fragments from AAO Pickanjinnie 2 include material assigned to *Psilophyton rectissimum* Hoeg from Norway, which is regarded as Devonian. The presence of land plants virtually excludes the possibility of an earlier age. An upper limit for the age is provided by the Roma granites which fall close to the Devonian-Carboniferous boundary.

There is, of course, a possibility that the Timbury Hills Formation includes strata of different age, even in typical rocks of the unit. For example, a thin section (GSQ 23136) from AAO Timbury Hills 2 which contains a substantial proportion of volcanic quartz is virtually identical to some sandstones from the Late Ordovician Fork Lagoons beds at the southern end of the Anakie Inlier (I.W.Withnall, personal communication, 1993).

Significant differences in metamorphic grade in the Timbury Hills Formation could easily be explained if there was an older, higher grade metamorphic unit in contact with quartzose metasedimentary rocks which are at least in part of Devonian age. The higher grade metamorphic rocks could be correlatives of the Silurian upper greenschist to amphibolite facies schists along the Nebine Ridge.

Traves (1966) regarded Late Devonian metasedimentary rocks in AFO Purbrook 1 which contain *Leptophloeum australe* as part of the Timbury Hills Formation on the basis of lithological similarity. However, the strata in AFO Purbrook 1, located about 55 km north-east of GSQ Eddystone 5, are similar to strata in PEC Warrong 1, and represent a subsurface extension of the Late Devonian -Early Carboniferous Drummond Basin (Figure 2).

Tectonic setting

On a QFL plot (Figure 3), sandstones of the Timbury Hills Formation fall in the recycled orogen field of Dickinson & Suczek (1979) and Dickinson & others (1983). This implies that the sandstones were sourced from uplifted belts of folded and faulted strata from which recycled detritus of sedimentary or metasedimentary origin was especially prominent. Dickinson & Suczek (1979) identified three types of source orogens:

- subduction complexes of deformed oceanic sediments and lavas;
- collision orogens formed by convergence of continental blocks; and
- uplifted foreland fold-thrust belts.

The lack of detrital chert and mafic lava fragments clearly rules out a subduction complex provenance. Either of the other two types of source orogens is possible. However, sandstones of the Timbury Hills Formation most closely fit the descriptions of sandstones of collision orogen provenance:- "Collision-derived sediment is mainly shed longitudinally from the evolving orogen into closing remnant ocean basins as turbidites. Typical sands composed largely of recycled sedimentary materials, have intermediate quartz contents, a high ratio of quartz to feldspar, and an abundance of sedimentary-metasedimentary lithic fragments" (Dickinson & Suczek, 1979, page 2178).

The subsequent deformation of the Timbury Hills Formation itself makes it unlikely that structures associated with earlier orogenic belts could be recognised beneath the sedimentary cover of the Bowen, Surat and Eromanga Basins. However, geophysical data provide two lines of evidence that the Timbury Hills Formation could have been derived from a collisional orogen. The first is that the Timbury Hills Formation overlaps the boundary between the major crustal blocks of the Thomson and Lachlan Fold Belts deduced by Wellman (1990) and shown on Figure 2. The second is the existence of the Foyleview geosuture which extends to the base of the crust and dies out upwards within the Timbury Hills Formation. It could be the trace of an ancient continental collision zone which produced an uplifted orogenic belt and thereby provided detritus for the overlap succession of the Timbury Hills Formation. At present this hypothesis is speculative, as the age of the Foyleview geosuture and therefore the timing of the possible collision are completely unknown.

An alternative hypothesis is that the Foyleview geosuture represents a west-dipping detachment surface associated with crustal extension which formed the basin in which the Timbury Hills Formation was deposited (named the Timbury Hills Basin by Murray, 1986). This basin may have had a similar history to the Cobar Basin in the Lachlan Fold Belt of New South Wales. The Cobar Basin formed as a transtensional or extensional basin above an east-dipping detachment in latest Silurian time, and was filled by a thick succession of Early Devonian siliciclastic rift-phase and sag-phase turbidites before inversion in the late Early Devonian. Locally, the basin fill is strongly folded with a regional subvertical cleavage, and is

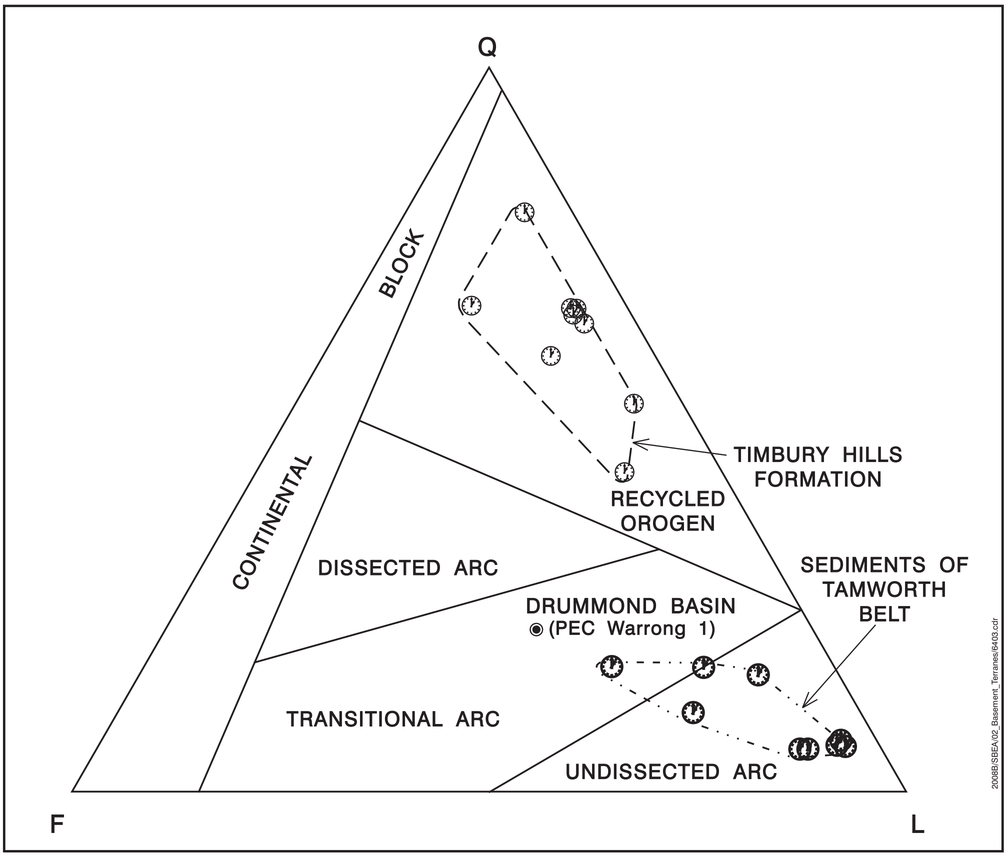

Figure 3: QFL plot of sandstones from the Timbury Hills Formation, Drummond Basin (PEC Warrong 1), and Tamworth Belt in relation to provenance fields of Dickinson & Suczek (1979) and Dickenson & others (1983). See text for discussion.

metamorphosed to greenschist facies (Glen, 1990; Glen & others, 1994). The apparent similarity between the Timbury Hills and Cobar Basins in the timing of basin formation and their subsequent structural evolution supports this hypothesis. However, this model does not explain the fact that the Foyleview geosuture marks the contact between major crustal blocks with markedly different seismic characteristics. Another difference is the presence of large granite plutons which intruded the Timbury Hills Formation shortly after its deformation.

Whatever its origin, the Timbury Hills Formation has subsequently had a very different tectonic history from coeval strata of the Adavale Basin west of the Nebine Ridge. In contrast to the steeply dipping, cleaved and metamorphosed Timbury Hills Formation, the Devonian succession of the Adavale Basin is essentially undeformed and unmetamorphosed, and generates prominent flat-lying reflections on seismic sections.

Roma granites

Previous investigations

Granite basement has been intersected by numerous petroleum exploration wells in the Roma Shelf region. These rocks, which are collectively referred to as the “Roma granites”, were first described by Houston (1964). She concluded that:

- Granitic rocks form a large part of the basement in the Roma region and occur in at least three distinct masses;
- All the intrusives are similar and consist of mica-bearing granite or adamellite;
- All the intrusives are related to one batholith which is continuous at depth below the Timbury Hills Formation;
- The plutonic rocks were weathered before being overlain by younger sediments or volcanics;
- The Roma granites intrude the Timbury Hills Formation; and
- Isotopic dating indicates a Carboniferous age.

In the present investigation, all the material described by Houston (1964) was re-examined, and basement cores from subsequent exploration wells were studied.

Lithology

The Roma granites can be subdivided into at least two distinct groups. The most widespread group consists dominantly of muscovite-biotite granite (under the IUGS classification as outlined by Streckeisen, 1973) with some muscovite granite. The presence of probable altered cordierite in two of the more muscovite-rich rocks suggests that these are S-type granites, and this is supported by chemical analyses from AAO Belbri 1, HPP Bendee 1, AAO Dalmuir 1, HPP Donga 2, AAO Mount Hope 1 and AAO Quibet 1 (B.Chappell, personal communication, 1995). A second group, represented by only two specimens, is much less quartz-rich, has a greater relative plagioclase content, and straddles the granite and granodiorite fields of Streckeisen (1973) (Figure 4). Probable altered hornblende has been recognised in one specimen, and these granitoids are regarded as I-type. They appear to form a discrete pluton to the east of a larger mass of S-type granite (Figure 2).

The probable S-type granites are massive, medium to coarse-grained granitoids (grain size 1 to 15 mm) which are pink, grey or white in colour. The main minerals are quartz, alkali feldspar, plagioclase, biotite and muscovite. The relative proportions of quartz, alkali feldspar and plagioclase are plotted in Figure 4. Inaccuracies in these estimates result from the alteration of many specimens, and the large grain size relative to the size of the sectioned rock sample. However, Figure 4 gives a good overall indication of the range of proportions of the felsic components.

Quartz occurs both as single grains and as aggregates of anhedral, interlocking crystals. It shows evidence of strain (undulose extinction) in all thin sections. Microperthite is the typical alkali feldspar, and forms phenocrysts in some specimens. Although it resists weathering better than plagioclase, it is always altered to some degree, with a characteristic cloudy appearance. Locally the microperthite forms graphic and myrmekitic intergrowths with quartz. Plagioclase commonly forms zoned, anhedral to subhedral crystals in which the more calcic cores are extensively replaced by sericite, clay minerals and calcite. In highly weathered rocks, plagioclase may be completely altered to clay minerals. Biotite is partially altered to chlorite and darkened by oxidation due to weathering in many specimens. When fresh, the biotite is pleochroic from pale brown or yellow-brown to red-brown. It usually makes up 5 to 15% of the rocks, but the core from HPP Bendee 1 is a melagranite with about 30% biotite. Muscovite is normally subordinate to biotite, and occurs as relatively large grains which are obviously not an alteration product. Some specimens contain as much as 10% muscovite and no biotite (AAO Quibet 1 and APN Yalebone 1). In the tourmaline-muscovite granites from LOA LOA 3 (Orallo) and AAO Quibet 1, muscovite occurs as large flakes and also as networks replacing microperthite and along grain boundaries.

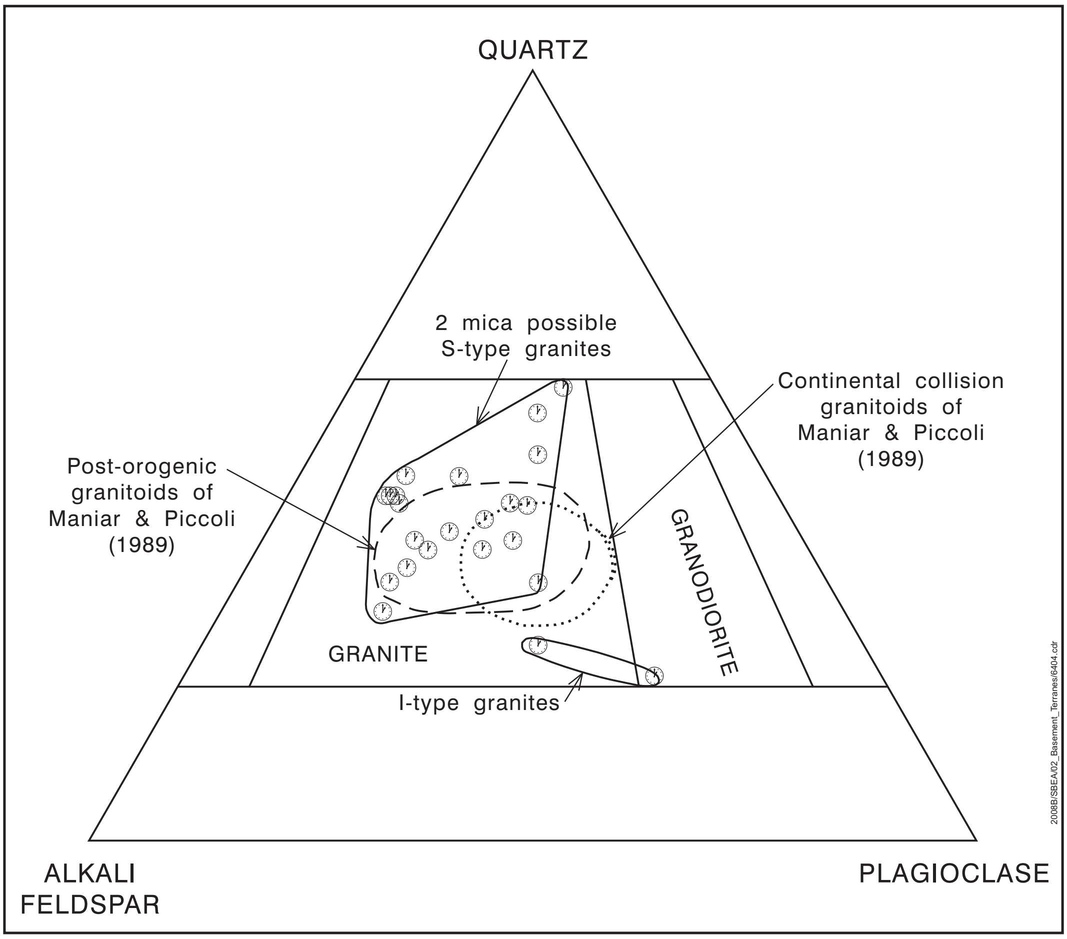

Figure 4: QAP plot of Roma granites. Granitoid classification is fromStreckeisen (1973). Fields of post-orogenic and continental collision granites of Maniar & Piccoli (1989) are shown for comparison.

Minor and accessory minerals include tourmaline, ?altered cordierite, apatite and zircon. Tourmaline is a late stage mineral in the muscovite-rich granites in LOA 3 (Orallo), AAO Quibet 1, and AOP Scalby 1. Probable altered cordierite occurs in AAO Dalmuir 1 and AOP Scalby 1. In AOP Scalby 1, altered cordierite forms crystals up to 1 cm long consisting mainly of fine grained pale green pinite cut by a rectangular network of coarser muscovite flakes. The altered cordierite in AAO Dalmuir 1 forms smaller grains and is replaced by a mixture of pinite and randomly oriented muscovite.

The mineralogical composition of these possible S-type granites most closely resembles that of post-orogenic or continental collision granitoids of Maniar & Piccoli (1989). Modal proportions of quartz and feldspars correlate best with their post-orogenic granites (Figure 4), whereas the presence of tourmaline and possible cordierite is characteristic of their continental collision granitoids.

Samples from AAO Boondara 1 and AAO Sunnybank 1 are considered to be I-type granites. They are massive, medium-grained, pink to fawn to grey granitoids. The main minerals are quartz, alkali feldspar, plagioclase and biotite. These two specimens plot in an entirely separate field from the S-type granites on a QAP diagram (Figure 4).

Quartz forms anhedral grains and rare aggregates. Some grains show undulose extinction, but the rocks appear to be less strained than the S-type granites. Alkali feldspar (microperthite) is cloudy and forms interstitial grains which enclose plagioclase crystals. Plagioclase occurs as corroded subhedral laths surrounded by quartz and microperthite. More calcic cores are partly replaced by sericite, calcite and clay minerals. Biotite makes up from 5 to 10% of the rocks. It is mainly fresh in AAO Sunnybank 1, but almost completely altered to sphene and chlorite in AAO Boondara 1. Pleochroism is pale brown to brown.

Minor and accessory minerals are altered hornblende, opaques, sphene, apatite and zircon. Altered hornblende has been recognised in AAO Sunnybank 1 (GSQ 3100) only because the characteristic cleavage has been preserved in one grain. Other altered hornblende grains enclose subhedral plagioclase laths. The presence of opaques is considered to be significant because they are absent from the S-type granites apart from very rare small grains associated with altered biotite. Sphene forms discrete grains as well as being an alteration product of biotite in AAO Boondara 1 (GSQ 34), and supports the interpretation of these granitoids as I-type.

Weathering and alteration

All basement granitoids from the region of the Roma Shelf are altered to some extent. In most cases this alteration can be attributed to surface weathering when the granites were exposed. Houston (1964) described several of the more highly weathered rocks as intrusive-derived clastic sedimentary rocks. In most cases, description of these rocks as sedimentary is incorrect - they are simply partially decomposed granites which have been weathered in place. The weathering was accompanied by a significant increase in volume and by severe fracturing.

During this process, biotite grains expanded and deformed. Fractures were subsequently filled with clay minerals and calcite. Fragments of primary minerals included in these veins locally give the appearance of a clastic texture. However, the original igneous texture is largely retained. Of the specimens described as intrusive-derived sedimentary rocks by Houston (1964), only that from ARO ARO 14 (Blythdale) is considered to be a clastic rock. Significantly, this was the only core sample that she described as bedded.

Clastic sedimentary rocks derived from granite (“granite wash”) are present in basement cores from AAO Belbri 1, HPP Bendee 1, AAO Brucedale East 1, HPP Byanbunnoo 1, and HPP Donga 2. In some of these cores, the 'granite wash' directly overlies weathered granite.

Age and relationships

Several of the Roma granites have been isotopically dated using K-Ar dating on biotite (Table 1).

All dates have been recalculated using the constants recommended by Steiger & Jager (1977). In addition, the dates from Evernden & Richards (1962) and Webb & others (1963) have been corrected for an error in the calibration spike (J.R.Richards, personal communication, 1987). It is probable that the same correction should be applied to the samples from AAO Brucedale 1, AAO Mount Hope 1 and AAO Sawpit Creek 1. This would slightly increase all these ages by about 6 or 7 Ma judging by the amendments to AAO Rosewood 1 and AAO Pleasant Hills 1.

All the dated samples are from the probable S-type granites. Because all the samples are altered to some degree, these results must be considered to be minimum ages. Assuming that all the intrusives are related and of the same age, the dates from AAO Mount Hope 1 and AAO Rosewood 1 would therefore be the most reliable.

It is concluded that the S-type Roma granites have an age of about 355 to 360 Ma, very close to the Devonian-Carboniferous boundary, which has been placed at 363 Ma by Harland & others (1990) and measured as 353.2±4.0 Ma by Claoue-Long & others (1992). The I-type granitoids represented in AAO Boondara 1 and AAO Sunnybank 1 have not been dated, and their age relative to the S-type suite is not known.

An age close to the Devonian-Carboniferous boundary is consistent with the stratigraphic relationships of the Roma granites. The granites intrude the Timbury Hills Formation which is at least partly of Devonian age. They are overlain by the Combarngo Volcanics which are Late Carboniferous to earliest Permian, and by younger sedimentary rocks of the Bowen and Surat Basins.

Tectonic setting

At the time of emplacement of the Roma granites near the Devonian-Carboniferous boundary, the active eastern margin of the Australian continent was located in the New England Fold Belt close to the present coastline. The Roma granites are situated 250km inland from the position of the Devonian-Carboniferous subduction complex of the New England Fold Belt, and at least 150km inland from the axis of the associated volcanic arc which is believed to be exposed in the Auburn Arch (see, for example, articles by Murray, 1990 and Korsch & others, 1990).

The mineralogy of the Roma granites, and their tectonic setting, are remarkably similar to a belt of Mesozoic peraluminous two-mica granites in the Cordilleran interior of western North America, inland from major coeval coastal batholiths such as the Sierra Nevada (Miller & Bradfish, 1980; Miller & Barton, 1990). These muscovite-bearing granites were intruded into old, stable crust more than 400km from the continental margin and the trench associated with an east-dipping subduction zone. No continental collision or extensional tectonism was involved, but the granitoids are associated in time and place with a zone of major thrusting.

Despite the great distance from the offshore trench, Miller & Barton (1990) concluded that the belt of muscovite granites was directly related to subduction, probably reflecting a very shallow subduction zone. In contrast, Pitcher (1983) proposed that granites of this type are produced far from the influence of active subduction zones by crustal thickening due to compression and thrusting, in many cases as a result of continental collision. Miller & Barton (1990) countered this proposal by pointing out that thrusting was essentially synchronous with granite emplacement, not allowing time for thermal relaxation to produce melting. Instead, they suggested that the thrusting was a consequence of crustal melting, rather than its cause.

In view of these arguments, it seems possible that the Roma granites were related to the west-dipping subduction zone associated with the New England Fold Belt. However, a more plausible theory of origin may be that the granites were produced by melting of a thickened crust following compressional folding and metamorphism of the Timbury Hills Formation, and can simply be classified as post-orogenic granitoids.

An obvious cause for the deformation of the Timbury Hills Formation and subsequent production of granites could have been the accretion of an Early to Middle Devonian oceanic island arc succession of the New England Fold Belt to the eastern margin of the Australian continent. An intra-Devonian unconformity at Mount Morgan (Kirkegaard & others, 1970; Leitch & others, 1992) and provenance linkages with the Lachlan Fold Belt (Flood & Aitchison, 1992) provide strong evidence that the collision took place at the beginning of the Late Devonian. The relative timing of the collision, compressional deformation, and melting of the thickened crust would be precisely that required to generate the Roma granites as post-orogenic plutons.

Although the Foyleview geosuture represents a possible collision zone between different continental blocks in the subcrop area of the Roma granites, any such collision must have pre-dated deposition of the Timbury Hills Formation, and would therefore have been much too old to be a causative mechanism for granite genesis.

Drummond Basin

Previous investigations

The Drummond Basin is a large intracontinental basin of Late Devonian-Early Carboniferous age in central Queensland. Most recently, it has been interpreted as an extensional back-arc basin related to the Late Devonian-Carboniferous continental margin magmatic arc of the New England Fold Belt (Johnson & Henderson, 1991; de Caritat & Braun, 1992). The basin fill consists of basal volcanics overlain by a thick succession of mainly fluviatile sedimentary rocks.

The subsurface limits of the Drummond Basin are not well known. Vine (1972) concluded that the basin did not extend west or south-west of its outcrop area. However, interpretation of seismic reflection profiles (eg. Pinchin, 1978) indicates that the basin is much more extensive than surface exposures. The extension of the Drummond Basin to the south-east of its outcrop area is proved by basement cores in AOP Cunno 1 and PEC Warrong 1 (Figure 2), and in APN Cometside 1, AOD Penjobe 1, AFO Purbrook 1, GSQ Springsure 12 and PEC Warrinilla 3 to the east (Murray, 1994). However, it is not yet possible to delineate the limits of the basin in this region, and no boundary is shown on Figure 2.

The basal volcanics crop out along the western edge of the Anakie Inlier and have been named the Silver Hills Volcanics. They consist dominantly of rhyolitic ignimbrite with subordinate rhyolite, dacite, trachyandesite and minor sediments (Withnall & others, 1993). Interpretation of seismic reflection profiles suggests that the volcanics thicken westwards beneath the main outcrop of the Drummond Basin, where they are up to 3 km thick (Pinchin, 1978).

In the sedimentary succession, Olgers (1972) recognised three distinct depositional cycles separated by minor epeirogenic events associated with volcanism. The first cycle was dominated by volcanics and associated volcaniclastic sediments; the second was quartzose, possibly derived from uplifted basement blocks along the western basin margin; and the third consisted mainly of volcaniclastic detritus sourced from an active arc to the east (Olgers, 1972; Johnson & Henderson, 1991).

Lithology

The basement core from AOP Cunno 1 is a massive rhyolitic ignimbrite with quartz and alkali feldspar crystals in a compacted and welded groundmass which has been partly recrystallised to spherulitic texture.

The basal core from 1079-1079.9m in PEC Warrong 1 consists mainly of poorly sorted pebbly sandstone to conglomerate with abundant quartz clasts. Pale grey quartzofeldspathic sandstone is interbedded with micaceous, carbonaceous siltstone at the bottom of the core. Two cores from the interval 882.7-970.8m are purple to brown to greenish grey lithic-rich sandstone and conglomerate containing abundant volcanic and sedimentary rock fragments and subordinate quartz and feldspar grains.

Alteration

The volcanic basement in AOP Cunno 1 is partially altered. Feldspar crystals are cloudy, and sparse grains of an unidentified mineral have been completely replaced by an extremely fine-grained, irresolvable aggregate of secondary minerals.

Depositional environment

Ignimbrite in AOP Cunno 1 was probably erupted subaerially. The sandstones and conglomerates in PEC Warrong 1 are considered to have been deposited fluvially.

Structure

Dips in the basal sediments in PEC Warrong 1 range from 5 to 15°. Even the finer-grained rocks lack cleavage, exhibiting only a bedding plane fissility which is attributable to depositional and/or compaction effects. These features indicate that the Drummond Basin sediments are folded into broad, open, large-scale folds, as revealed by surface exposures and seismic sections.

Metamorphism

The sediments are metamorphosed to no more than lower greenschist facies.

Age and correlation

A feldspar concentrate from Core 5 of AOP Cunno 1 gave a K-Ar isotopic date of 191 ± 20 Ma (Bennett & others, 1975; recalculated to new constants). This Jurassic age is much too young, because the basal ignimbrite is overlain by Permian sediments of the Springsure Shelf between the Galilee and Bowen Basins.

The basal volcanics in AOP Cunno 1, together with rhyolitic ignimbrites intersected in several exploration wells west of the seismically-defined boundary of the Drummond Basin, are most readily correlated with the Silver Hills Volcanics on the basis of stratigraphic position and geographic distribution. This correlation indicates a Late Devonian to earliest Carboniferous age. The subsurface volcanics may be either erosional remnants of a thin and very extensive sheet, or isolated eruptive centres.

The basal sediments in PEC Warrong 1 are lithologically and structurally similar to cores from several petroleum exploration wells and stratigraphic drillholes to the north-east which have yielded Late Devonian and Early Carboniferous microfloras (Playford, 1977; Anderson, 1981).

Olgers (1972) considered the bottom core from PEC Warrong 1 to represent the second, quartz-rich depositional cycle of the Drummond Basin. He assigned the overlying volcaniclastic sediments from the interval 882.7-970.8m to the red-bed deposits of the third cycle, and correlated them with the Early Carboniferous Ducabrook Formation. Sandstone from 967.4m in Core 11 of PEC Warrong 1 contains a larger proportion of lithic clasts, most of which are felsic volcanics, than sandstones of the second cycle (Figure 3).

Tectonic setting

There seems little doubt that the Drummond Basin formed as an intracontinental back-arc extensional basin floored by a thick sequence of dominantly rhyolitic volcanics generated by crustal melting.

Sediments of the second depositional cycle represent erosion of basement sources during the sag phase of basin evolution, including possible uplifted basement along the western margin (Johnson & Henderson, 1991). The Ducabrook Formation of the third cycle was the product of mature fluviatile and lacustrine sedimentation with a substantial volcaniclastic component, prior to compression and inversion which ended deposition in the Drummond Basin in mid-Carboniferous time.

NEW ENGLAND FOLD BELT

Geological setting

During the Carboniferous, the New England Fold Belt is interpreted to have been an active Andean-type continental margin with parallel belts representing volcanic arc in the west, forearc basin in the centre, and accretionary wedge in the east (Murray & others, 1987; Murray, 1990; Korsch & others, 1990). The magmatic arc is largely concealed in the south, but is exposed in the north in the Connors and Auburn Arches. The forearc-basin and accretionary-wedge sequences are separated by major fault zones (Peel and Yarrol Faults) marked by serpentinite lenses. The New England Fold Belt is now divided into northern and southern sections by Mesozoic cover of the Surat and Clarence-Moreton Basins.

Petroleum exploration companies have referred to the concealed basement rocks of the New England Fold Belt east of the Taroom Trough simply as "Kuttung". The stratigraphic name Kuttung Series was originally applied to continental Late Carboniferous strata exposed in the western part of the Tamworth Belt (or Block or Zone) of the New England Fold Belt in New South Wales. These Late Carboniferous deposits were believed to overlie the marine Early Carboniferous Burindi Series. Later it was realised that the top of the marine Burindi Series was deposited synchronously with the bottom part of the terrestrial Kuttung Series (David & Browne, 1950, page 287). The combined

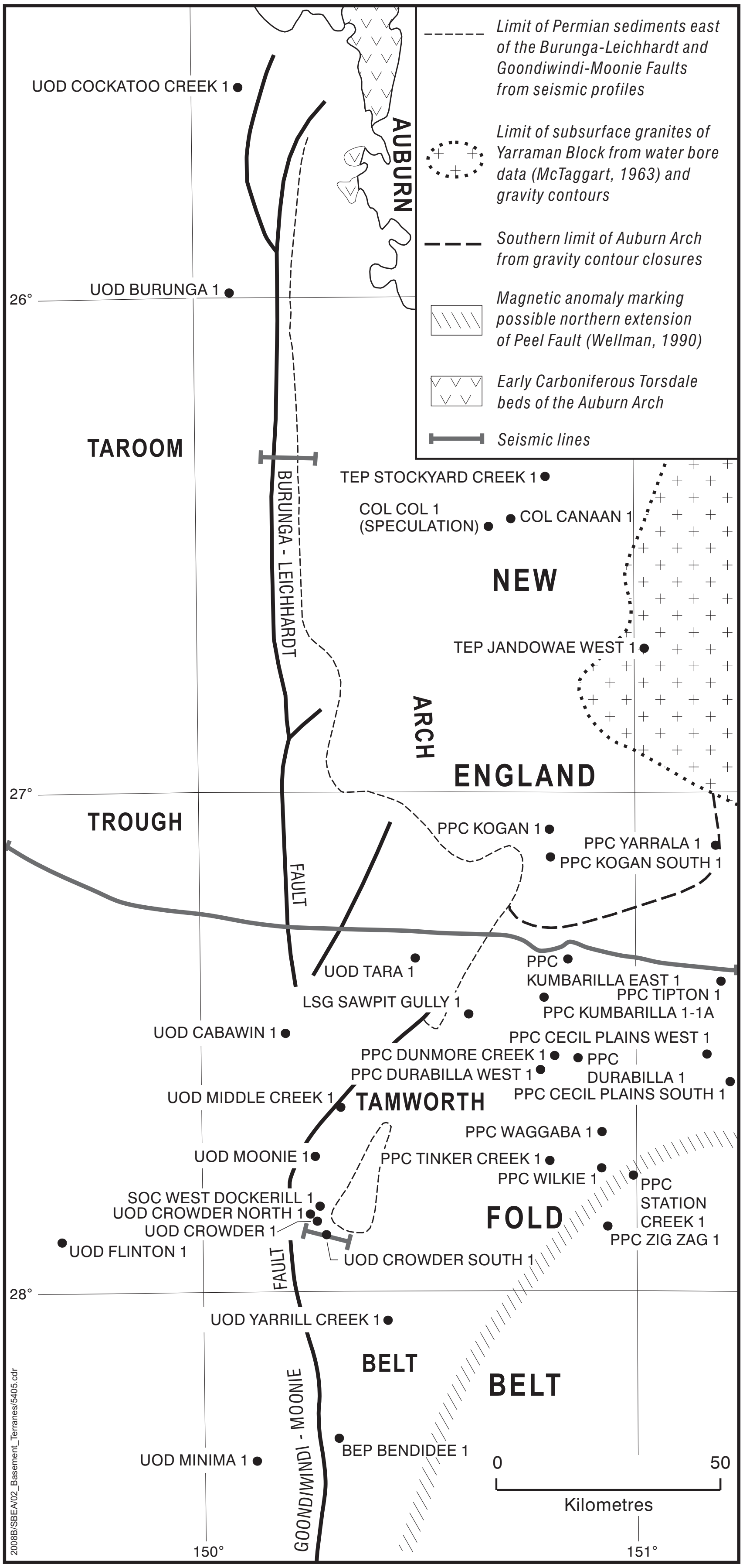

Figure 5: Basement terranes of the New England Fold Belt east of the Taroom Trough, showing locations of basement cores, the position of the BMR deep crustal seismic reflection profile, and the positions of the seismic reflection profiles displayed in Figures 6 and 7.

Burindi and Kuttung Series are now interpreted as forearc basin-arc fringe deposits. The name 'Kuttung' is not used in this report because:

- it has been used in the past as a rock, time-rock and facies name (Campbell, 1969, page 245);
- the Kuttung Series has now been subdivided into a number of stratigraphic units and the name is superseded;
- the basement includes marine sedimentary rocks at least as old as Early Carboniferous; and
- the basement comprises two contrasting crustal blocks or terranes, the Auburn Arch in the north and the Tamworth Belt in the south (Figure 5).

The identification of two different crustal blocks is based on seismic and gravity data. In the north, Permian to Middle Triassic strata equivalent to those in the Taroom Trough form a westward-thickening wedge along the eastern side of the Burunga-Leichhardt Fault (Figures 5 and 6). The basement in this area lacks seismic reflectors and is interpreted as a southern extension of the volcanic-arc assemblage exposed in the Auburn Arch. This interpretation is supported by the continuation of a very prominent north-south trending gravity high coincident with the Auburn Arch southwards to about 27°15'S latitude, just south of PPC Kogan South 1 and PPC Yarrala 1 (Murray & others, 1989).

In the south, seismic sections east of the Goondiwindi-Moonie Fault demonstrate conclusively that the basement rocks beneath the Surat Basin cover form a highly reflective, gently folded, conformable succession up to several kilometres thick (Figure 7). This layered basement is considered to be equivalent to the exposed Late Devonian to Early Permian strata of the Tamworth Belt to the south.

Most basement cores from the Auburn Arch and Tamworth Belt are volcanic and sedimentary rocks of Carboniferous age.

Volcanic rocks of the Auburn Arch

Previous investigations

Volcanics along the western flank of the exposed Auburn Arch comprise the Early Carboniferous Torsdale beds (Figure 5), overlain unconformably or disconformably by the Early Permian Camboon Volcanics. The Torsdale beds are dominantly felsic pyroclastic rocks; only locally are andesites as abundant as the felsic volcanics (Dear & others, 1971; Whitaker & others, 1974).

Lithology

Basement cores are all andesite and basalt.

Basalt is present in PPC Kogan 1, and andesite in TEP Stockyard Creek 1 and PPC Yarrala 1. In addition, PPC Kogan South 1 intersected an andesitic crystal tuff.

Alteration

All of the volcanics are altered to some degree. The mafic volcanics are altered to calcite, chlorite, epidote and ?zoisite. In parts of the core from PPC Kogan 1, the alteration is so extreme that the original texture of the rock is entirely destroyed. Cores of plagioclase laths are partly replaced by sericite and/or clay minerals.

Depositional environment

The volcanics could have been either subaerial or submarine deposits.

Structure

The volcanics do not appear to have been deformed, but dips cannot be determined.

Age and correlation

A mafic concentrate described as chloritised amphibole from PPC Kogan 1 gave a K-Ar age of 341 ± 30 Ma (Harding, 1969; recalculated to new constants). This date must be regarded as a minimum age and may be unreliable. There is no amphibole in the basement basalt from PPC Kogan 1, and chlorite occurs as a secondary alteration product and in amygdales. The concentrate contained only 0.165% K, and may have consisted of chlorite, clinopyroxene and epidote.

Despite its doubtful accuracy, this date is almost identical to the K-Ar age of 343 Ma from volcanics of the Torsdale beds (Whitaker & others, 1974). This supports the view that basement volcanics north of the Moonie Fault are a southern extension of the volcanic-arc assemblage of the Auburn Arch.

Although the dominance of andesitic volcanics distinguishes these basement rocks from the Torsdale beds, a general correlation with exposed Late Devonian to Early Carboniferous rocks of the New England Fold Belt is supported by the greater proportion of mafic and intermediate volcanics in these rocks compared to Late Carboniferous successions (Nashar, 1969).

It is possible that some of the volcanics may be Early Permian, as andesites have been described from the Narayen and Nogo beds of this age to the east of the Auburn Arch (Whitaker & others, 1974).

Tectonic setting

The abundance of andesite is consistent with the interpretation that the volcanics are part of the Andean-type magmatic arc which formed the westernmost belt in the New England Fold Belt from Late Devonian to Carboniferous time.

Sedimentary rocks of the Auburn Arch

Previous investigations

Lithic-rich sedimentary rocks of Carboniferous age occur in and adjacent to the exposed Auburn Arch. Interbedded with the volcanics of the Torsdale beds along the western side of the arch are polymictic conglomerate, volcanolithic sandstone, and siltstone. Conglomerates contain clasts of aplite, granite, quartz porphyry and felsic to intermediate volcanics (Dear & others, 1971; Whitaker & others, 1974). Similar conglomerates occur locally along the eastern flank of the Auburn Arch, and are equivalents either of the Early Carboniferous Torsdale beds, or of the Late Carboniferous-earliest Permian Youlambie Conglomerate (Dear & others, 1971).

Lithology

Cores from COL Canaan 1 and COL 1 (Speculation) consist exclusively of polymictic conglomerate and coarse-grained pebbly sandstone. The largest clasts are of biotite granodiorite or quartz diorite, and these are dominant in the conglomerate. In the pebbly sandstones and finer-grained conglomerates, felsic to intermediate volcanics are the main clasts, with subordinate granitic, metasedimentary, plagioclase and quartz grains. The matrix is either opaque (probably iron oxide), or recrystallised to sericite ± quartz ± epidote.

Depositional environment

The conglomerates were probably deposited in a fluviatile or shallow-marine environment.

Structure

The massive nature of the conglomerates prevents determination of dip, but the rocks appear relatively undeformed.

Metamorphism

Metamorphic grade is no higher than lower greenschist facies.

Age and correlation

The basement cores from COL Canaan 1 and COL 1 (Speculation) are similar to the conglomerates of Early Carboniferous or Late Carboniferous-earliest Permian age which flank the Auburn Arch. A Carboniferous age is therefore probable, but a more precise determination is not possible.

Tectonic setting

The abundance of coarse granitic detritus and the presence of substantial proportions of quartz and metasedimentary clasts suggest that the sedimentary rocks were derived from a dissected volcanic arc. Deposition occurred relatively close to the source.

Sedimentary rocks of the Tamworth Belt

Previous investigations

Wellman (1990) proposed that the curved magnetic anomaly shown on Figure 5 represents the northern continuation of the Peel Fault. If so, the extent of the subsurface Tamworth Belt is defined by:

- The Goondiwindi-Moonie Fault to the west;
- A closed gravity contour around the Auburn Arch to the north; and
- The curved magnetic anomaly to the south-east.

Basement rocks to the south-east of the magnetic anomaly should be steeply-dipping mafic volcanic and sedimentary rocks of the accretionary wedge assemblage. Only two

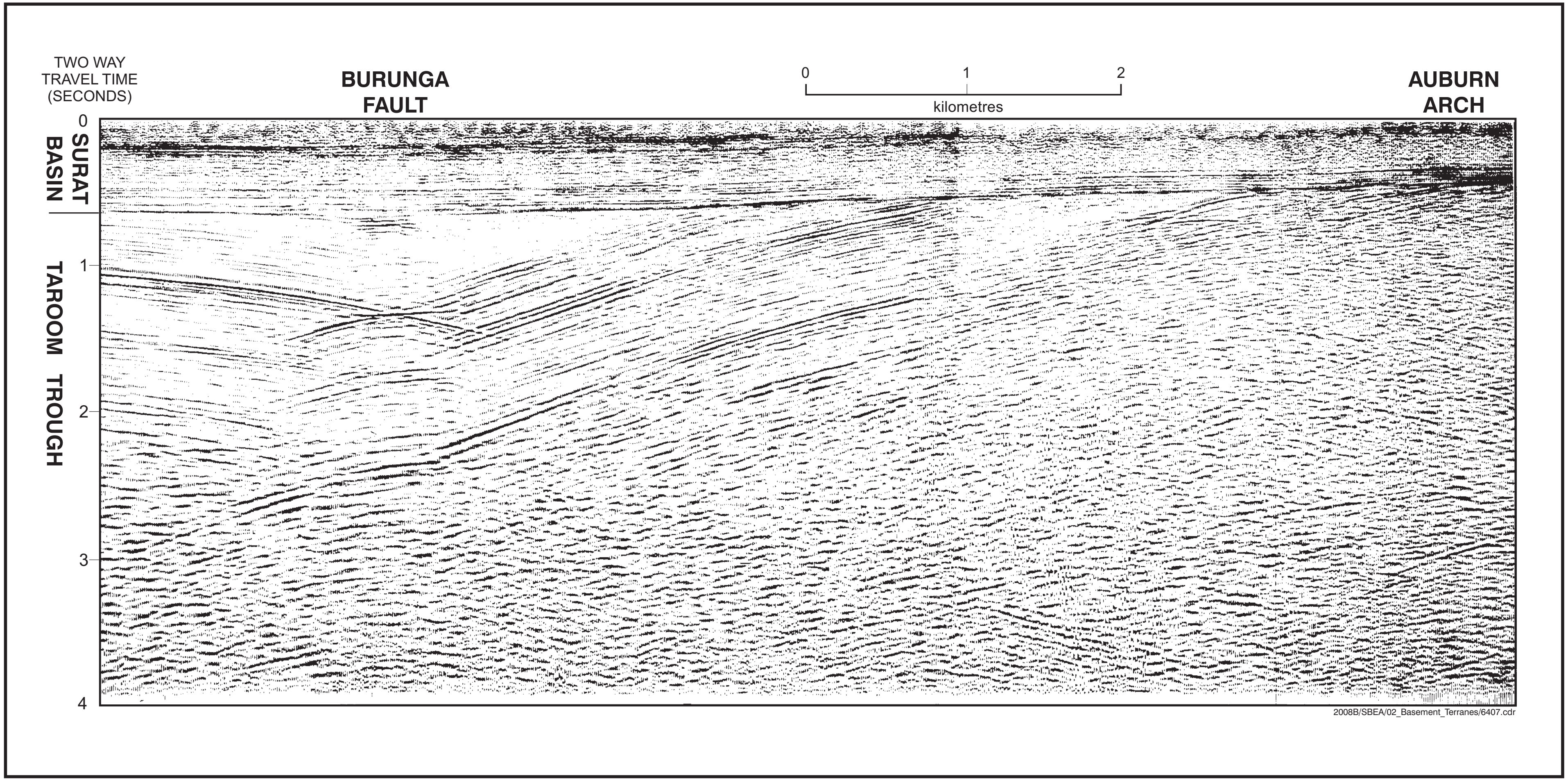

Figure 6: Central part of Tin Hut seismic survey lone 85-273 across the Burunga Fault, showing non-reflective basement rocks of the Auburn Arch beneath the Surat Basin succession east of a west-dipping wedge of Taroom Trough sediments.

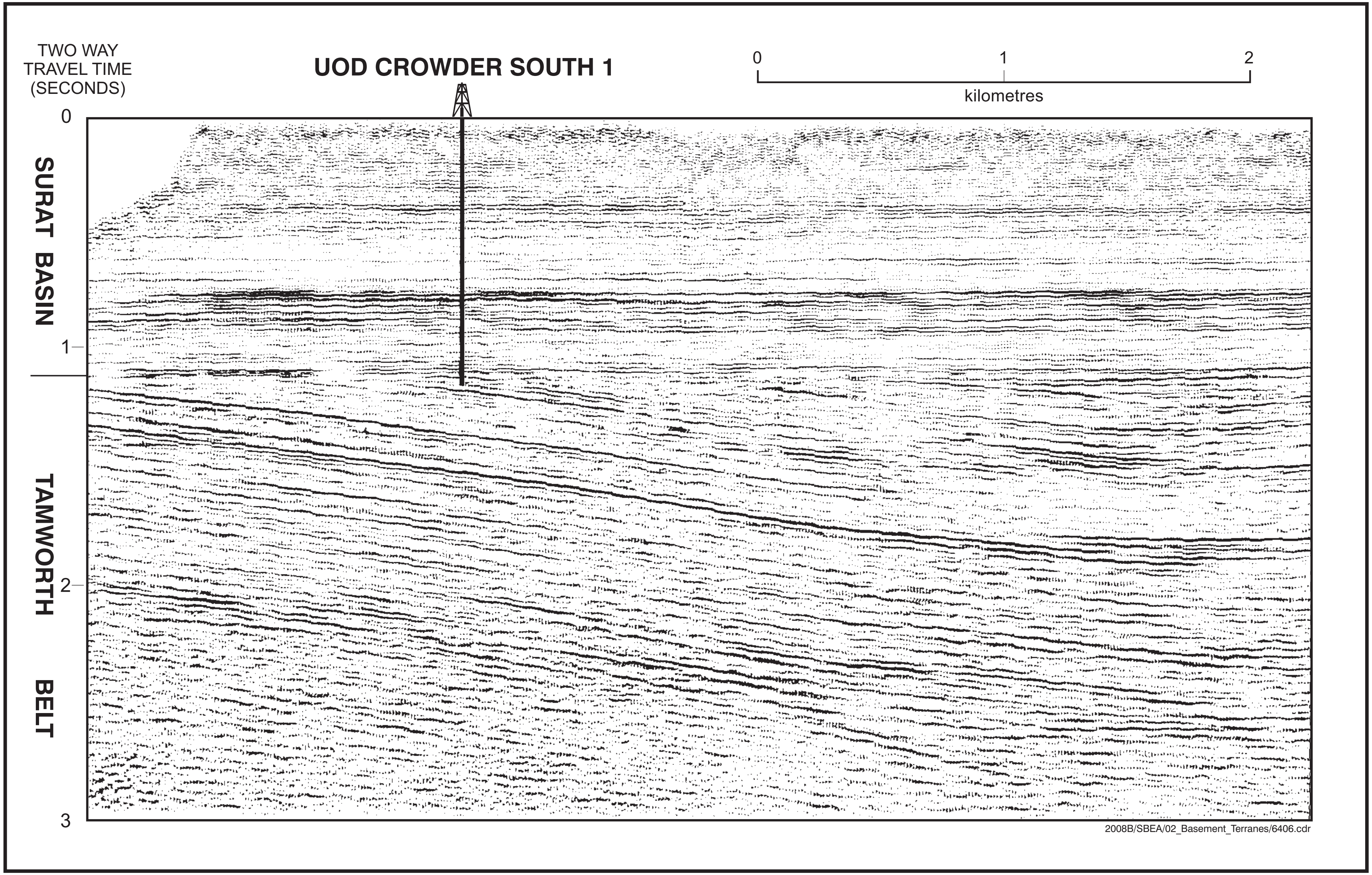

Figure 7: Western end of Dockerill seismic survey line 84-14 through UOD Crowder South 1 well, showing the thick, highly reflective, gently folded Tamworth Belt sequence unconformably beneath flat-lying Surat Basin sediments.

sedimentary basement cores are located south-east of the anomaly:

- The core from PPC Zig Zag 1 is a hornfelsed mudstone with disrupted bedding, and could be from either forearc basin or accretionary wedge; and

- The core from PPC Station Creek 1 is indistinguishable in lithology or structure from the remainder of the sedimentary cores assigned to the Tamworth Belt.

Lithology

Basement cores are grey to greenish grey volcanolithic sandstone and conglomerate, and subordinate interbedded dark grey shale and siltstone, locally carbonaceous with coaly laminae. The coarser-grained rocks are typically massive; shale and siltstone are laminated to thin-bedded.

Examination of cores and thin sections shows that the sandstones and conglomerates are composed mainly of felsic to intermediate volcanic rock fragments. Granitic detritus is locally abundant, for example in the core from UOD Middle Creek 1. Metasedimentary and sedimentary grains are much more widely distributed than granitic material, but are always very subordinate to volcanic clasts. The main mineral clasts, plagioclase feldspar and quartz, are much less abundant than lithic fragments; in general plagioclase content is about twice that of quartz. The quartz is largely but not exclusively of volcanic origin.

Minor and accessory components (not present in all specimens) are calcite, muscovite, biotite, opaques, clinopyroxene and zircon. Calcite occurs mainly as single-crystal fragments of possible biogenic origin. Definite bioclastic material, probably of algal origin, is also present. A carbonised wood fragment in PPC Cecil Plains South 1, and a probable rotaliid foraminifer in PPC Durabilla 1, were also noted. There may be a few calcareous ooids in some samples (PPC Cecil Plains South 1, PPC Durabilla 1), but these could be the result of calcite replacing lithic and plagioclase grains. Fresh clinopyroxene was observed in specimens from PPC Station Creek 1, PPC Wilkie 1, and UOD Yarrill Creek 1.

Early Permian sediments in PPC Cecil Plains West 1 are uniform dark grey bioturbated mudstone-siltstone.

Depositional environment

Most of the rocks appear to have been deposited in a shallow-marine environment. The overall coarse-grain size suggests deposition close to their source.

Structure

Almost all of the Carboniferous sediments dip at moderate to shallow angles, and this is supported by seismic reflection profiles which show broad, open folding (Figure 7). Only the core in PPC Wilkie 1 appears to be steeply dipping based on the orientation of elongate sedimentary clasts. There are local shear zones, but no development of cleavage.

The Early Permian sediments in PPC Cecil Plains West 1 dip at about 40°. Their structural relationship to flat-lying Carboniferous strata in PPC Durabilla 1 to the west is unknown.

The apparently simple structure may be misleading, as the presence of low-angle eastward dipping thrust faults in the sequence are apparent on some seismic sections, including Figure 7.

Metamorphism

Apart from hornfels in PPC Zig Zag 1, the metamorphic grade is lower greenschist or zeolite facies.

Age and correlation

The basement cores have yielded microfloras of Early Carboniferous, Late Carboniferous-earliest Permian, and Early Permian age, and Early Permian corals in PPC Cecil Plains West 1.

Core 15 from PPC Durabilla 1 yielded a diverse microflora originally described as Namurian (mid-Carboniferous) (de Jersey, 1966), but now regarded as Visean (Early Carboniferous) (N.J. de Jersey, personal communication, 1978).

Late Carboniferous to earliest Permian microfloras (Stages 1 and 2 of Kemp & others, 1977, equivalent to Stages APC4 and APP1 of Draper & others, 1990) are known from basal sediments in several wells, including:

- UOD Brigalow Creek 1 near UOD Middle Creek 1 (unpublished well completion report);

- PPC Durabilla 1, Core 8 (P.L. Price, personal communication, 1994);
- HEP Keggabilla 1 about 20km east of UOD Crowder 1 (unpublished well completion report);
- UOD Moonie 6 (de Jersey & Paten, 1963);
- AAR Warrawa 1 just west of SOC West Dockerill 1 (P.L. Price, personal communication, 1994); and
- UOD Yarrill Creek (de Jersey, 1966).

A seismic reflection profile through HEP Keggabilla 1 shows a conformable layered sequence at least a few kilometres thick beneath the dated sediments.

Early Permian microfloras (Stage 3 and possibly Stage U4A of Kemp & others, 1977 or Stages APP2 and APP3 of Draper & others, 1990) have been obtained from cuttings and sidewall cores from the bottom of UOD Boonderoo 1, UOD Dockerill 1 and HEP Gilgai 1 (P.L. Price, personal communication, 1994; unpublished well completion report for HEP Gilgai 1). These wells are located within a synclinal core of Permian sediments east of the Goondiwindi-Moonie Fault (Figures 5 & 7).

The probable coniferous wood fragment in PPC Cecil Plains South 1 suggests a mid-Carboniferous or younger age (J.F. Rigby, personal communication, 1993).

An Early Permian age has been suggested for the basal sequence in PPC Cecil Plains West 1 based on the coral *Euryphyllum* (J.S. Jell, personal communication, 1984).

These results indicate that the basement sequence ranges in age from at least as old as Early Carboniferous to Early Permian. The great thickness evident on seismic sections suggests that it continues down into the Devonian. These rocks can therefore be correlated with the conformable and essentially continuous Late Devonian to Early Permian section in the western part of the Tamworth Belt (McPhie, 1984).

The Permian sedimentary rocks intersected in UOD Boonderoo 1, UOD Dockerill 1 and HEP Gilgai 1 have been equated with the Back Creek Group of the Taroom Trough to the west (unpublished well completion reports). However, this correlation must be regarded as tentative.

Tectonic setting

A plot of sandstone compositions on a QFL triangular diagram (Figure 3) forms a coherent group which mainly falls within the undissected arc field of Dickinson & Suczek (1979) and Dickinson & others (1983). The uniform composition of the sandstones is considered to be strong evidence for a common origin.

The association with volcanics, the coarse-grain size, and the volcaniclastic composition of the sediments clearly indicate that they are proximal deposits sourced from an active Carboniferous volcanic arc along the western margin of the New England Fold Belt. All evidence from exposed parts of the fold belt suggests that this was a continental margin arc, with a forearc basin to the east. The forearc basin was mainly marine in the Early Carboniferous, but became increasingly emergent in Late Carboniferous time.

The apparently simple structure and open-fold style is typical of forearc-basin strata of the New England Fold Belt. The folding and possible low-angle thrust faulting reflect westward directed compression during the mid- to Late Permian Hunter-Bowen Orogeny.

Volcanics of the Tamworth Belt

Previous investigations

Volcanics were widespread in the western part of the exposed Tamworth Belt in Late Carboniferous time. Although rhyolitic ignimbrites are most abundant and extensive (McPhie, 1984), andesites are present locally (Cook & Dawson, 1988). Felsic volcanism persisted right up until the end of the Carboniferous Period, as ignimbrites from the Currabubula Formation have given K-Ar ages of 293±4 Ma and 302±4 Ma (McPhie, 1984). The style of volcanism changed from subduction related to extension related in the Early Permian when the Werrie Basalt was erupted (Leitch & others, 1988; Flood & others, 1988).

The widespread volcanics in the concealed Tamworth Belt basement (Figure 5) are correlatives of these Late Carboniferous to Early Permian volcanics.

Lithology

The volcanics are dominantly of felsic composition, but range from basalt to rhyolitic ignimbrite.

Basalt is present in BEP Bendidee 1, and andesite in PPC Durabilla West 1 and PPC Tipton 1. The core from PPC Durabilla West 1 may contain altered olivine and is possibly a basaltic andesite.

Rhyolitic crystal and lithic tuffs are the most common rock types in the basement cores, being represented in UOD Crowder 1, UOD Crowder South 1, PPC Kumbarilla 1-1A and UOD Moonie 1. The tuff in PPC Kumbarilla 1 shows compacted pumice fragments characteristic of an ignimbrite.

Alteration

Apart from replacement of some mafic minerals to chlorite and serpentine, the andesitic volcanics are relatively unaltered.

In the rhyolitic volcanics, feldspar clasts are cloudy and the glassy groundmasses have been devitrified to fine grained quartzofeldspathic aggregates. Some relict shard texture can still be recognised.

Depositional environment

Textures in the rhyolitic volcanics indicate that they were probably erupted subaerially. However, the mafic volcanics could have been either submarine or subaerial deposits.

Structure

Dips in the volcanics are difficult to determine, but in PPC Kumbarilla 1-1A appear to be shallow to moderate. The associated sedimentary rocks and seismic sections (Figure 7) indicate flat-lying to relatively shallow dips.

Age and correlation

Isotopic age determinations have been carried out on two samples of volcanics.

An age of 300±10 Ma has been reported from the volcanic basement in UOD Moonie 1 (Union Oil Development Corporation, 1964, page 15). No details of sample type, method or constants are available. It is probable that the determination was by the K-Ar method either on the whole rock or on a biotite concentrate. If so, the result would have to be considered a minimum age because of the nature of the basement rock (rhyolitic tuff) and the alteration of the biotite. Recalculation to new constants would give an age of 306±10 Ma. Both original and recalculated ages overlap within error limits with the date of 302±4 Ma from ignimbrite of the Currabubula Formation in the western part of the exposed Tamworth Belt (McPhie, 1984).

A second date of 220±3 Ma has been obtained from hornblende phenocrysts in andesitic tuff in volcanics at the bottom of the SOC Deep Crossing 1 well about 12.5km west of LSG Sawpit Gully 1 (unpublished well completion report). This age is anomalously young. The almost total lack of volcanic detritus in Late Triassic sediments of the Horrane Trough immediately east of the study area suggests that there was no active volcanism in the region at this time.

The date from UOD Moonie 1, the common Late Carboniferous to earliest Permian microfloras in associated sedimentary rocks, and the occurrence of the rhyolitic tuff in UOD Crowder South 1 towards the top of the layered basement sequence (Figure 7) all support correlation of the felsic volcanics with those of the Currabubula Formation of the exposed Tamworth Belt.

The andesites from PPC Durabilla West 1 and PPC Tipton 1 may also be of this age. However, the basalt from BEP Bendidee 1 is more likely to be a correlative of the Early Permian Werrie Basalt.

Tectonic setting

The tectonic setting of the Late Carboniferous volcanics is believed to have been similar to that proposed for the exposed Tamworth Belt, where a mixed sedimentary and volcanic sequence was deposited on the flanks of an Andean-type continental arc (McPhie, 1987). The basalt correlated with the Early Permian Werrie Basalt is related to a change from subduction related to extensional tectonics and magma generation.

Displacement of the Tamworth Belt

Evidence from seismic sections, gravity anomalies and basement cores shows that the concealed basement rocks of the New England Fold Belt comprise the volcanic-arc sequence of the Auburn Arch in the north, and forearc-basin strata of the Tamworth Belt in the south. These two contrasting tectonostratigraphic assemblages are now collinear in the same north-south trending zone (Figure 5), rather than forming parallel belts with the forearc basin east of the volcanic arc, implying substantial offset from their original positions.

Offsets of tectonic units in the New England Fold Belt, first noted by Bryan (1925), have been attributed to oroclinal bending associated with large-scale strike-slip faulting (Korsch & Harrington, 1987; Murray & others, 1987). The oroclinal bending is expressed in the accretionary wedge assemblage in the Warwick-Texas area by large-scale curvature of bedding and cleavage trends (Lucas, 1960).

Interpretation of magnetic anomalies led Wellman (1990) to suggest that the possible northern extension of the Peel Fault beneath the Surat Basin cover was also curved around the Texas Orocline concordantly with the accretionary wedge (Figure 5). As noted by Wellman (1990, page 31), this implies that at least part of the forearc-basin sequence must also have been involved in the oroclinal bending (see Figure 2 of Harrington & Korsch, 1987).

Based on interpretation of filtered gravity data, Murray & others (1989) postulated that the forearc-basin strata of the Tamworth Belt had been thrust westward over the associated volcanic arc. This major displacement of the Tamworth Belt may have been a response to space problems caused by the oroclinal bending. The timing of the oroclinal bending and the relative age of the forearc-basin package are crucial issues in determining whether this is feasible, but no definitive answer is possible.

The oroclinal bending was either Late Carboniferous (Murray & others, 1987) or Early Permian (Korsch & Harrington, 1987). The conformable basement sequence includes strata of Early Permian age (Stage 3 and possibly Stage U4A of Kemp & others, 1977 or Stages APP2 and APP3 of Draper & others, 1990).

If the oroclinal bending was older than the youngest sediments in the basement package, a possible alternative cause of the westward movement of the Tamworth Belt was the mid- to Late Permian Hunter-Bowen Orogeny, which is known to have involved major east to west thrusting. Woodward (1995) estimated 75–85 km of westward thrusting of the Tamworth Belt (and probably the accretionary wedge assemblage to the east as well) in the New England region of New South Wales, mainly along the Mooki and Campo Santo thrust systems.

Reversal of this thrust movement would place the northern extension of the Tamworth Belt within the Study area completely to the east of the interpreted southern concealed extension of the Auburn Arch (Figure 5).

The east-west trending BMR deep seismic reflection profile which passed close to the PPC Tipton 1 well detected a prominent series of mid-crustal reflections which were named the Texas Mid-crustal Detachment (Finlayson & others, 1990). It is possible that this feature represents the detachment surface along which movement of the forearc basin strata took place, but this is considered unlikely because of its depth (about 20km) and its westerly dip.

If the juxtaposition of these two disparate tectonostratigraphic units was the result of westward thrusting of the Tamworth Belt, a corollary is that the tectonic evolution of the Goondiwindi-Moonie Fault must have been very different from that of the Leichhardt-Burunga Fault. In this context, it is significant that Elliott (1993, Figure 12) noted a fundamental change in structural style at the northern end of the Goondiwindi-Moonie Fault: to the south, basement rocks have been thrust westwards over the Taroom Trough; to the north, strata of the Taroom Trough have been thrust eastwards over the basement along back-thrusts related to large-scale duplex structures.

CONCLUSIONS

Examination of geophysical data and basement cores from beneath the Bowen, Surat and Moreton Basins has shown that:

- The greenschist to amphibolite facies metasedimentary rocks of the Nebine Ridge probably represent an uplifted block of mid-crustal rocks of the Thomson Fold Belt;
- The Roma Shelf straddles the junction between the Thomson and Lachlan Fold Belts, which have different gravity and magnetic signatures, and which may have collided along the Foyleview geosuture; basement rocks comprise the Timbury Hills Formation intruded by the Roma granites;
- The Timbury Hills Formation consists of steeply-dipping quartzose turbidites of probable Devonian age which may be an overlap sequence sourced from a collisional orogen, or the fill of an extensional basin;
- The Roma granites are chiefly two-mica, S-type, post-orogenic granites with an age close to the Devonian-Carboniferous boundary; a small I-type pluton is located to the east of the main S-type batholith; the granites may have been related to a west-dipping subduction zone associated with the New England Fold Belt, or to collisional orogenesis;
- The intracontinental Late Devonian-Early Carboniferous Drummond Basin, containing basal felsic volcanics overlain by a thick fluvial sedimentary succession, extends into the northern part of the study area;
- Evidence from seismic sections, gravity anomalies and basement cores reveals that the concealed basement rocks of the New England Fold Belt east of the Taroom Trough can be divided into two contrasting terranes, the volcanic arc sequence of the Auburn Arch in the north, and forearc basin strata of the Tamworth Belt in the south; the juxtaposition of these two contrasting tectonostratigraphic assemblages is considered to be due to large-scale westward thrusting of the Tamworth Belt over its associated volcanic arc, either during oroclinal bending or during the Hunter-Bowen Orogeny; this suggests that the tectonic evolution of the Goondiwindi-Moonie Fault was totally different from that of the Burunga-Leichhardt Fault;
- Basement cores from the Auburn Arch consist of Early Carboniferous basalt and andesite and volcaniclastic conglomerates with a high proportion of granodiorite clasts;
- Seismic sections and basement cores show that the Tamworth Belt forms a gently folded conformable sequence of volcanolithic sedimentary rocks and calc-alkaline volcanics up to several kilometres thick ranging in age from at least as old as Early Carboniferous to Early Permian.

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LITHOSTRATIGRAPHIC UNITS IN THE BOWEN AND SURAT BASINS, QUEENSLAND

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INTRODUCTION

The aim of this segment of the SBEA Project was to review the lithostratigraphy of the Bowen and Surat Basins. This was achieved through correlation, on a regional framework, of selected petroleum exploration wells and Departmental stratigraphic bores (Figure 1). The project also included review of relevant core and cuttings descriptions, as well as examination of some cores and cutting; review of palynological studies previously undertaken in the basins, and the application of some seismic stratigraphy.

The methodology adopted for the lithostratigraphic interpretation was to divide the succession in these basins into three parts: Permian, Triassic and Jurassic/Cretaceous. The datum for the top of the Permian sections was the top of the Baralaba Coal Measures/ Bandanna Formation, the Triassic at the top of the Moolayember Formation and the Jurassic/Cretaceous at the top of the Bungil Formation. The relationships of the Permian rocks in the southern Taroom Trough in the Bowen Basin were reinterpreted in a basin-wide correlation.

The southern Denison Trough is located in the north-western part of the study area. The Permian units of the Denison Trough were not correlated with the Permian in the Taroom Trough because of their different tectonic setting.

The wireline log features used in picking formation tops for the Bowen Basin and Surat Basin were based on those given in Gray (1986). Formation tops for wells on the correlation lines are stored in the Department's Queensland Petroleum Exploration Database (QPED).

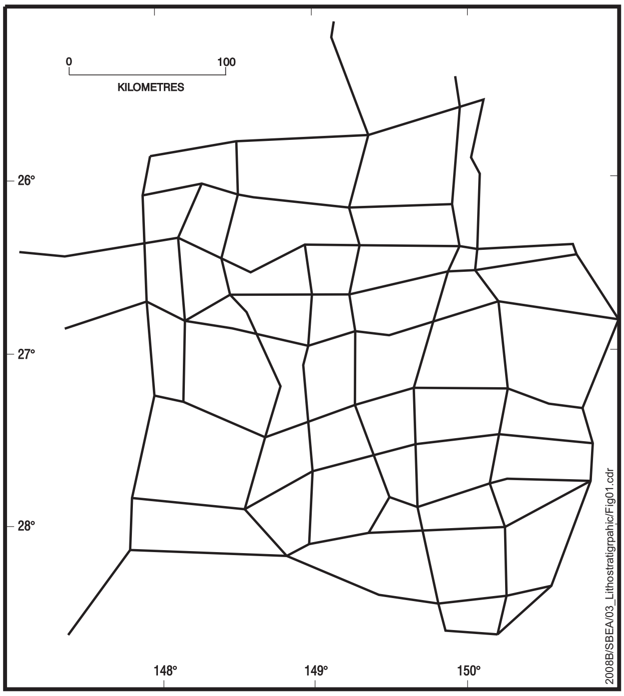

Figure 1: Well correlation framework in the study area.

The wireline logs used for the correlations were the gamma-ray (GR), resistivity (RES, IEL, ILD, LLD, LLS, LN) and sonic (DT) logs. If available, the original digital wireline log data for a well was used. The logs for wells without digital data were digitised using the LogSCAN software package. A lithology column for each well or bore was compiled from the cuttings and core descriptions. Production of individual log plots and correlation lines were made using GEOLOG log analysis software.

For each formation, the nomenclature, rock types, relationships and boundary criteria, wireline log character, thickness, age and depositional setting are discussed. Isopach maps for most units were produced using PETROSEIS software. The subcrop and outcrop limits of the formations were modified after Exon (1976) using the available well data. The isopach maps represent regional trends as only data from the wells and bores incorporated into the regional framework, and not all wells, were used to generate the contours.

Spore-pollen biostratigraphic units cited in this report are those of Price & others (1985) and Filatoff & Price (1988), as modified by Filatoff & Price (1991) and Price (1994; 1995; this volume; *in* Draper & others, 1990), and reviewed by Burger & others (1992). Dinoflagellate biostratigraphic units are those of Helby & others (1987).

LITHOSTRATIGRAPHY - BOWEN BASIN

The stratigraphic subdivision of the Permian and Triassic succession in the southern Taroom Trough of the Bowen Basin is shown in Figure 2.

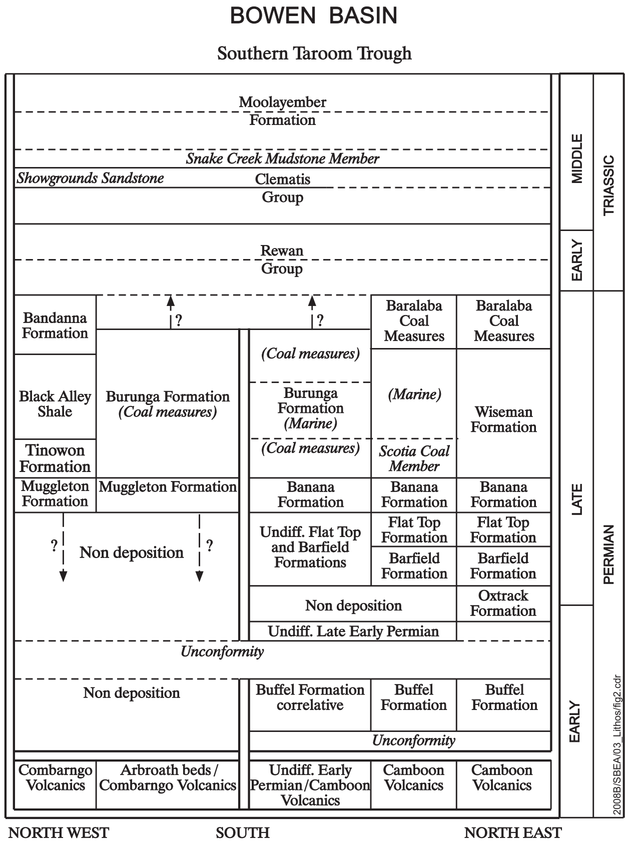

Figure 2: Permian and Triassic stratigraphic units - southern Taroom Trough.

CARBONIFEROUS-PERMIAN

Combarngo Volcanics

Nomenclature

The name Combarngo volcanics was first used by Traves (1966) for andesitic volcanics in AAO Combarngo 1 well, about 50km south of Roma. He correlated these rocks with the Camboon Andesite along the eastern margin of the Bowen Basin, and assigned an Early Permian or older age. Subsequently, numerous exploration wells in the Roma Shelf area have penetrated volcanics at the base of the Permian succession, and it has proved useful to refer to these collectively as the Combarngo Volcanics. Sufficient information is probably available to enable formal definition of this unit under the Australian Code of Stratigraphic Nomenclature.

Rock Types

The Combarngo Volcanics range in composition from olivine basalt through andesite to rhyolite.

Olivine basalt or andesite is present in AAO Lorelle 1. Andesitic volcanics are well represented and include flows (GSQ Eddystone 5, EOC Glenarden 1, and SQD 1 (Morella)), and pyroclastics (UOD Flinton 1 and possibly MPA Glenhaughton 1).

Oligomictic andesitic conglomerate in OSL 3 (Arcadia) was obviously derived from a local source of andesitic volcanics.

Felsic volcanics are the most widespread types in the Combarngo Volcanics. Rhyolitic crystal and crystal-lithic tuffs are most abundant, some with compacted pumice fragments (fiamme) typical of ignimbrites.

Although not significantly deformed, all samples of Combarngo Volcanics are altered to some degree, and in several cases the alteration is extreme. Typical alteration products are sericite, clay minerals, calcite and chlorite. In the majority of specimens, alteration is most obvious in the feldspar microphenocrysts which show ubiquitous replacement by varying combinations of these minerals, but it also extends to the groundmass. Where alteration is more intense (AAO Combarngo 1), the rocks are so sericitised that it is impossible to be certain of the original composition.

Relationships and Boundary Criteria

Volcanics and volcaniclastic sedimentary rocks in a similar stratigraphic position have been intersected in MPA Glenhaughton 1, OSL 3 (Arcadia) and SQD 1 (Morella) exploration wells and in GSQ Eddystone 5 stratigraphic borehole at the northern margin of the study area. These are considered to be correlatives of the Combarngo Volcanics.

The volcanics are obviously unconformable on the Timbury Hills Formation which is Devonian in part. A few wells in the Roma area are reported to have penetrated volcanics before bottoming in Roma granites (AAO Boondara 1, HPP Crowfoot 1, BON McGregor 1 and HEP Taralga 1).

The eastern limits of the Combarngo Volcanics have not been established because of limited drilling in the central part of the Taroom Trough. The Camboon Volcanics which are similar to the Combarngo Volcanics in lithology, age and stratigraphic position occur in outcrop and subcrop along the eastern margin of the Taroom Trough. A variety of formation names including Kuttung, Cracow and Camboon has been applied to these volcanics in the subsurface on the eastern side of the Taroom Trough. It has been suggested from drillhole data that the volcanics along both the eastern and western flanks of the Taroom Trough thicken towards the trough axis (Cosgrove & Mogg, 1985). Applying this observation, and current tectonic models for the origin of the Bowen-Gunnedah-Sydney Basin (Murray, 1990), the conclusion can be reached that the entire Taroom Trough is floored by volcanics, and that the Combarngo Volcanics are essentially continuous with and equivalent to the Camboon Volcanics along the eastern margin of the trough. This correlation was first suggested by Traves (1966).

Wireline log character

The wireline log response of the Combarngo Volcanics is poorly known due to the limited intersections in petroleum exploration wells. Generally, the formation has a higher resistivity response and faster sonic velocities that the overlying Permian clastic units. Gamma-ray responses may have the same or slightly higher baselines compared to the Permian units. The change to the higher values is generally gradational although some sharp contacts are present.

Thickness

The maximum thickness of the Combarngo Volcanics so far intersected is 145m in BON Rocky Glen 1. Dips in the Combarngo Volcanics are difficult to determine, but appear to range from shallow or flat-lying to moderate.

Age

In all but one case, rocks assigned to the Combarngo Volcanics and correlatives are overlain by Permian strata of the Bowen Basin. The oldest overlying strata are the Reids Dome beds in GSQ Eddystone 5 (Draper & Green, 1983); the oldest palynofloras recovered from the Reids Dome beds have been assigned to APP2 (= Stage 3; Kemp & others, 1977; Draper & others, 1990). The minimum age for the Combarngo Volcanics is therefore Early Permian.

APP1 (Stage 2) palynofloras have been obtained from the basal volcaniclastic strata of AFO Comet 1 about 140km north of GSQ Eddystone 5 (Kemp & others, 1977). This is consistent with the interpretation that the strata were synchronous with, and sourced from, the Combarngo Volcanics and correlatives. If so, a latest Carboniferous to earliest Permian APP1 age can be assigned to the Combarngo Volcanics (Murray, 1994).

A maximum age is more difficult to determine, because few exploration wells have penetrated the complete succession. The volcanics overlie the granites nonconformably, indicating an age younger than the Devonian-Carboniferous boundary (see Murray this volume).

It therefore appears that a Late Carboniferous to earliest Permian age is most likely for the Combarngo Volcanics and correlatives.

Depositional Setting

A probable tectonic model for latest Carboniferous–earliest Permian volcanism and basin formation along the axis of the Bowen Basin is rifting related to back-arc extension (Murray, 1990; Fielding, Gray & others, 1990; Baker & others, 1993). The extensional magmatic activity and subsidence occurred behind (west of) a continental margin volcanic arc formed above a westdipping subduction zone. The Combarngo Volcanics were erupted subaerially in this geological setting. The epiclastic sedimentary succession in OSL 3 (Arcadia) was probably deposited in a fluviatile environment.

The long-held view that continental rifts are associated exclusively with bimodal volcanism is now known to be incorrect. For example, the onset of crustal extension in the Basin and Range Province of southwestern USA broadly coincided with the extrusion and intrusion of andesitic as well as felsic magmas. These magmas were produced by crustal melting and magma mixing following the rise of mantle-generated basalt (Mutschler & others, 1987; Gans & others, 1989). A similar process in the Bowen Basin could have led to the eruption of the Combarngo Volcanics with a significant proportion of andesitic compositions.

Camboon Volcanics

Nomenclature

The Camboon Volcanics overlie Carboniferous volcanics along the western edge of the Auburn Arch, and form the basal unit of the Taroom Trough. The unit was originally defined as the Camboon Andesite, and described as andesite and andesitic tuff (Derrington & others, 1959). Subsequent mapping identified andesitic and basaltic lavas and andesitic to dacitic welded tuff as the main rock types, with subordinate agglomerate, volcanic breccia, trachyte and pebble to boulder conglomerate, with interbedded marine strata in one area (Dear & others, 1971; Whitaker & others, 1974). Because of this diversity of rock types, Briggs & Waterhouse (1982) changed the name from Camboon Andesite to Camboon Volcanics.

Rock Types

Most cores from the Camboon Volcanics consist of andesitic to basaltic flows. Alteration makes precise identification difficult, but the basal core in UOD Cabawin 1 can confidently be termed an andesite. Volcanics in UOD Burunga 1, UOD Cockatoo Creek 1 and UOD Minima 1 are more mafic and are basalts or basaltic andesites. UOD Tara 1 bottomed in an andesitic or dacitic crystal tuff consisting of euhedral plagioclase laths in a devitrified glassy groundmass. The andesitic to basaltic flows show typical alteration associated with lowgrade burial metamorphism. Mafic minerals and possible interstitial glass are replaced by chlorite, and calcic cores of plagioclase grains are partly altered to clay minerals or chlorite.

Wireline log character

The Camboon Volcanics can be recognised from their wireline log response. The formation generally has low gamma-ray, high resistivity responses and fast sonic velocities (Figure 3). The change of baseline for these responses may be either gradational or sharp. The presence of gradational contacts makes determination of the boundary with the overlying Permian formations difficult to determine.

Thickness

The maximum thickness of Camboon Volcanics intersected in the study area is 350m in

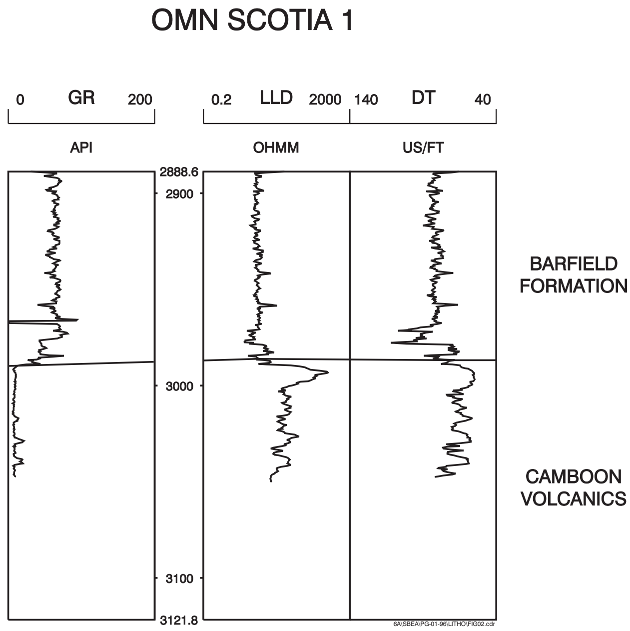

Figure 3: Wireline log responses - Camboon Volcanics.

stratigraphic bore GSQ Mundubberra 10. The maximum thickness intersected is 658m in APN Abercorn 1 drilled to the east of the study area. The Camboon Volcanics are not significantly deformed. However, the crystal tuff in UOD Tara 1 appears to be shallowly dipping.

Age

The Camboon Volcanics exposed along the western edge of the Auburn Arch have been dated at 294 and 281Ma (Runnegar, 1979), they contain the Permian plant *Glossopteris* (Whitaker & others, 1974), and are overlain by Early Permian sedimentary rocks. The outcropping volcanics have therefore been assigned an Early Permian age. The basement cores are correlated with the Camboon Volcanics on the basis of similar stratigraphic relationships and tectonic position, and are also considered to be Early Permian.

A palynoflora recorded by de Jersey (1963a) from the Camboon Volcanics in UOD Undulla 1 (cuttings sample 2673.1-2676.1m) is characterised by a significant proportion of monosaccate pollen, rare striate disaccate pollen, and the occurrence of *Granulatisporites micronodosus.* Assignment to unit APP12 is indicated by this association, together with a latest Carboniferous-earliest Permian age.

Depositional setting

The Camboon Volcanics have been interpreted as part of a major Early Permian volcanic arc which developed over the site of the former Late Devonian-Carboniferous continental margin arc. Formation of the marine Bowen Basin separated the arc from the Australian continent to the west, producing a palaeogeography which may have been similar to that of the presentday Indonesian island arc (Murray, 1985). The inception of the Bowen Basin has been attributed to back-arc extension (Murray, 1990; Fielding, Gray & others, 1990; Baker & others, 1993). Volcanics which floor the Taroom Trough, and the very narrow and continuous Meandarra Gravity Ridge which coincides with the depositional axis of the trough, are believed to be related to magmatic activity associated with back-arc extension (Murray & others, 1989; Murray, 1990). The basement volcanics were probably erupted subaerially in either an arc or back-arc environment.

EARLY PERMIAN

Arbroath Beds

Nomenclature

Early Permian rocks were intersected in the lower part of AAO Arbroath 1 (Mines Administration Pty Ltd, 1963a) and in other wells drilled in the fault-bounded Arbroath Trough in the western part of the study area. A formal nomenclature has not been applied to the rocks intersected in this well, originally regarded as ‘Unit 8 (Permian P1)’ by Mines Administration Pty Ltd.

Rock Types

Rock types present are shale and siltstone with lesser sandstone and conglomerate and minor coal (Mines Administration Pty Ltd, 1963a).

The shale is generally medium grey to black, micaceous, carbonaceous with coal laminae. Plant fossils and pyrite are present in part. The siltstone, in part sandy, is commonly grey and occurs in lenses and laminations. Minor pyrite, mica and carbonaceous material are also present. Graded and current bedding have been reported in cores.

The sandstone is fine to medium-grained with angular to sub-rounded grains of quartz, green-grey siltstone and dark grey carbonaceous material. Current and graded bedding are present. The conglomerate consists of clasts of siltstone, claystone, shale and sandstone up to 75mm in diameter in a matrix of green-grey to pale grey carbonaceous siltstone. The siltstone and claystone clasts are green-grey, angular to sub-rounded; some are dark grey, carbonaceous. The shale clasts are green-grey, laminated, and the laminations define alternating light and dark bands. The sandstone clasts are grey-white, quartzose with a silica cement. Black carbonaceous flecks and pyrite are commonly present throughout all rock types.

Coal is well developed towards the bottom of the formation and is commonly black and shaly in part (Mines Administration Pty Ltd, 1963a).

Relationships and Boundary Criteria

The Early Permian rocks in the Arbroath Trough unconformably overlie the Timbury

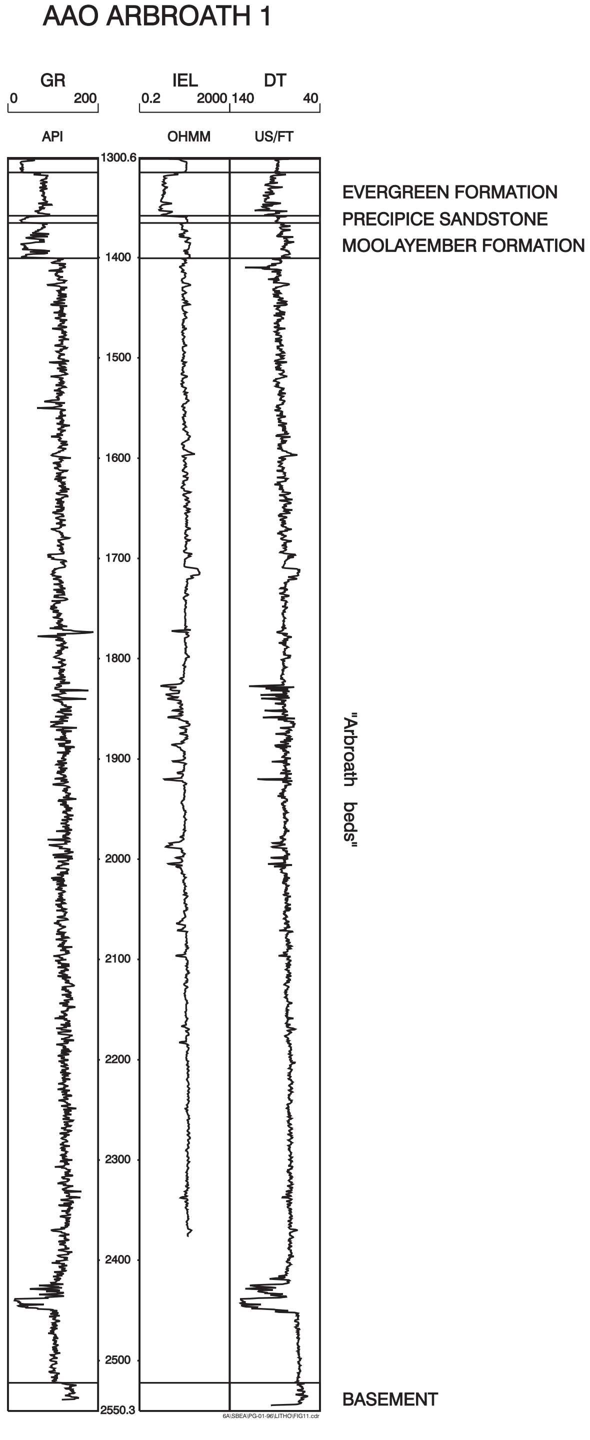

Figure 4: Wireline log responses - Arbroath beds.

Hills Formation and are unconformably overlain by the Middle Triassic Moolayember Formation of the Bowen Basin, which in turn is unconformably overlain by the Surat Basin succession.

The Arbroath beds are correlatives of the undifferentiated Early Permian rocks in COE Inglestone 1 in the southern Taroom Trough, the Reids Dome beds in the Denison Trough to the north and the units in the Tamworth Belt east of the Moonie-Goondiwindi Fault (Murray, 1994).

Wireline Log Character

The wireline log responses are relatively uniform, especially the gamma-ray log (Figure 4). The resistivity and sonic logs exhibit variation due to the presence of carbonaceous material and the interbedded sandstones and conglomerates. The coal towards the bottom of the interval intersected in AAO Arbroath 1 is reflected in a lower gamma-ray log response, higher resistivity values and very slow sonic velocities.

Thickness

The maximum thickness of the Early Permian rocks intersected in the wells in the Arbroath Trough is 1149m in AAO Arbroath 1. Greater thicknesses are present in the deeper parts of the Trough.

Age

Palynofloras recorded by Evans & Hodgson (1963) from AAO Arbroath 1 between 1402.1 and 2447.5m were assigned to unit P1 (Evans, 1962b). However, the presence of *Pseudoreticulatispora pseudoreticulata* in assemblages from 1990.3-1991.3m (core 5) and 2105.3-2108.3m (core 7), in the absence of *Phaselisporites cicatricosus*, is indicative of assignment to unit APP2. Samples in the interval from 1402.01 to 1920.2m, although they lack *P. pseudoreticulata*, are also presumably of the same age. Moreover, records of *Granulatisporites trisinus* at 2429.3m (cuttings) and 2286m (core 9), as well as de Jersey's (1963b) record of the species from 2101.6-2104.6m (core 6) point to an APP22 age. However, as identification of *G. trisinus* was taxonomically less definitive at that time than now, these occurrences of the species should be disregarded in view of the more recent work of Price (1987; personal communication):

(1) unit APP21 at 2105.3m (core 7), 2171.1m (core 8), 2286.3m (core 9), and 2365.2m (core 10);

(2) unit APP22 at 1702.6m (core 1), 1770.3m (core 2), 1838.2m (core 3), and 1918.1m (core 4).

An Early Permian (Sakmarian) age is indicated.

Depositional Setting

The Arbroath beds represent a half-graben fill. The conglomerates at the base represent material from the footwall of the developing halfgraben. The coal near the base indicates that the supply of clastic material was insufficient to fill the space created by the developing half-graben and this allowed ponding of water and the development of coal swamps.

The coal swamps were replaced by fluvial conditions that prevailed throughout most of the infill of the Trough. The last phase of sedimentation preserved in the Trough was the progradation of alluvial fans and the deposition of conglomeratic units.

Palynology indicates a non-marine environment during deposition of these rocks.

UNDIFFERENTIATED EARLY PERMIAN ROCKS

Inglestone Area

Nomenclature

Undifferentiated Early Permian rocks of variable type were intersected in COE Inglestone 1. No formal nomenclature has been applied to these rocks.

Rock Types

The Early Permian rocks consist of conglomerate and sandstone with lesser mudstone and minor coal. Conglomerate is abundant in the lower part whereas the upper part consists mainly of sandstone, mudstone and coal with minor conglomerate.

The conglomerate is grey to green-grey with pebbles and cobbles of white to light greengrey siliceous volcanic rock, quartz and argillite in a tuffaceous sandstone matrix. Minor siltstone streaks are also present.

The sandstone is grey, fine to coarse-grained. Pebbles and minor cobbles of volcanic rock fragments and chert and minor quartz sand grains are present in some of the beds.

Mudstone is medium to dark grey, interbedded and laminated with streaks and bands of carbonaceous material. Disseminated fine volcanic grains are scattered throughout. Traces of gold-brown mica and pyrite are also present.

Coal is black to brown-black, hard, with minor shale laminae. Medium to thickly bedded coal seams are relatively abundant.

Relationships and Boundary Criteria

The undifferentiated Early Permian rocks appear to conformably overlie the ?Camboon Volcanics. The rocks are unconformably overlain by the a correlative of the Buffel Formation.

Wireline Log Character

The rocks in COE Inglestone 1 consist of a uniform gammaray and variable, spiky resistivity and sonic responses. The variable responses are probably due to the presence of coals in this interval.

Thickness

The unit is present only in COE Inglestone 1 on the regional correlation framework. It is 200m thick.

Age

A palynoflora associated with a sidewall core (SWC 15/3720.1m) from the undifferentiated Early Permian rocks in COE Inglestone 1 is conformable with unit APP22 as it contains the related index, Granulatisporites trisinus (C.B. Foster, personal communication). An Early Permian (Sakmarian) age is therefore indicated; and the occurrence of spinose acritarchs is suggestive of a saline influence in the depositional environment.

Depositional setting

The presence of conglomerates at the bottom of the interval and abundant coals in the upper part suggest deposition in a fluvial setting. The conglomerates may have been deposited as alluvial fans next to faults. The coals were deposited when coal swamps and meandering streams dominated the depositional setting. Shells have been reported in cuttings from the upper part of this interval and may indicate a deltaic environment.

Buffel Formation

Nomenclature

The Buffel Formation was defined by Wass (1965) as an interval of limestone and siltstone with lesser sandstone and conglomerate outcropping near Cracow homestead in the southeastern Bowen Basin. Flood & others (1981) redefined the formation to include the lower part of the Buffel Formation of Wass (1965) and they also named two new overlying units, the Pindari Formation and Brae Formation. These later units which were broadly mapped in the upper part of the original Buffel Formation, but in fact are stratigraphically younger than the strata in Wass's type section, are only locally developed in outcrop and were not recognised in the subsurface in the southern Taroom Trough.

Rock Types

The Buffel Formation in outcrop consists predominantly of fossiliferous limestones, siltstones and lesser sandstones. Flood & others (1981) subdivided their Buffel Formation into a lower sandstone member, a middle limestone member and an upper siltstone member. Fossils present include brachiopods, bryozoans, corals, pelmatozoa and sponges (Briggs & Waterhouse, 1982). A threefold subdivision was not recognised in the subsurface.

The Buffel Formation in the subsurface consists of sandstone, siltstone, shale and limestone. The proportion of sandstone decreases upwards.

The sandstone is grey-white medium to coarse-grained with a clay matrix and contains pebbles of quartz and fragments of tuffaceous shale. A few sub-rounded black lithic grains and minor pyrite and trace mica are also present. Siltstone is medium grey to dark brown, tuffaceous with a trace of mica and carbonaceous material. Shale is light to dark grey and dark brown, slightly silty with carbonaceous material. Minor shell fragments are present. Limestone is grey-brown and white and contains abundant shell fragments and crinoid stems.

Relationships and Boundary Criteria

The nature of the contact between the Buffel Formation and the underlying Camboon Volcanics is uncertain, but in the subsurface, an unconformable relationship seems likely. Flood & others (1981) considered the contact with the underlying Camboon Volcanics to be clearly unconformable with the younger members progressively onlapping basement. Gray & Heywood (1978) have reported the presence of sedimentary rocks interbedded with andesitic volcanics in the bottom of GSQ Mundubbera 8 drilled north-west of Cracow; this suggests a continuous depositional history between the two units. The top of the formation is marked by an unconformity with Late Permian rocks.

The APP3 age recorded from HOM Alick Creek 1 along the eastern margin of the Trough is consistent with the age of the Buffel Formation in outcrop (Parfrey 1988). A correlative of the Buffel Formation unconformably overlies the undifferentiated Early Permian rocks in COE Inglestone 1.

The Buffel Formation is also recognised in UOD Undulla 1. The recognition of the formation in this well and in HOM Alick Creek 1 is based on the difference in structural orientation between the Buffel Formation and overlying units.

Wireline Log Character

The Buffel Formation is characterised by slightly lower gamma-ray log values, higher resistivity log values and faster sonic velocities in comparison with the overlying formation (Figure 5). There is an interval of higher resistivity near the top of the Buffel Formation in UOD Undulla 1 that may reflect the presence of limestone. The upward decrease in the proportion of sandstone noted from cuttings descriptions is not always apparent from the wireline log responses.

Thickness

The Buffel Formation has a variable thickness throughout the study area with the maximum thickness being 100m in HOM Alick Creek 1. The regional trend in thickness variations is difficult to estimate but the formation appears to be relatively thin except in areas next to the eastern margin faults.

Age

In HOM Alick Creek 1, Price (1981) assigned two sidewall core samples (2707m, 2735m) from strata associated with the Buffel Formation to upper stage 4a (= unit APP32, Artinskian). In the higher of these (2707m), Price recorded sparse spinose acritarchs, on the basis of which a depositional environment with a marginal marine influence was suggested. Palynological correlation with some part of the upper Cattle Creek Formation-basal Aldebaran Sandstone interval in the Denison Trough was therefore proposed by Price.

In Price's (1981) palynofloral distribution chart for HOM Alick Creek 1, *Microbaculispora villosa* (*Acanthotriletes villosus*), the index species of upper stage 4b (= unit APP33 of the currently used nomenclature), is documented against the sample from 2735m. However, P. Price (personal communication) has stated that his records clearly indicate that this is a typographical error and that the assemblage is indeed typical of unit APP32.

Depositional Setting

Deposition of the Buffel Formation represents a major Early Permian marine transgression that occurred throughout the southern Taroom Trough. The sea was elongated north-south and was located mainly adjacent to the faults along the eastern margin of the study area. Bioclastic limestones were deposited in some parts and onlap of the Buffel Formation onto basement is also apparent. Flood & others (1981) considered the formation to be a valley fill with the younger members onlapping the basement volcanics. They also noted that volcanic extrusions probably occurred elsewhere while these rocks were being deposited.

Buffel Formation Correlative

Nomenclature

Correlatives of the Buffel Formation in the southern part of the study area were intersected in COE Inglestone 1 and in UOD Goondiwindi 1 and UOD Macintyre 1 in northern New South Wales. The thickest interval is in UOD Goondiwindi 1 drilled on the western downthrown side of the Goondiwindi-Moonie Fault. Totterdell (personal communication, January 1995) considers the correlative to be a northwards extension of the Maules Creek Formation into Queensland.

Rock Types

The Buffel Formation correlative consists of conglomerate and sandstone with lesser mudstone. Coal is present near the top of the correlative in UOD Goondiwindi 1 and UOD Macintyre 1 and is absent in COE Inglestone 1.

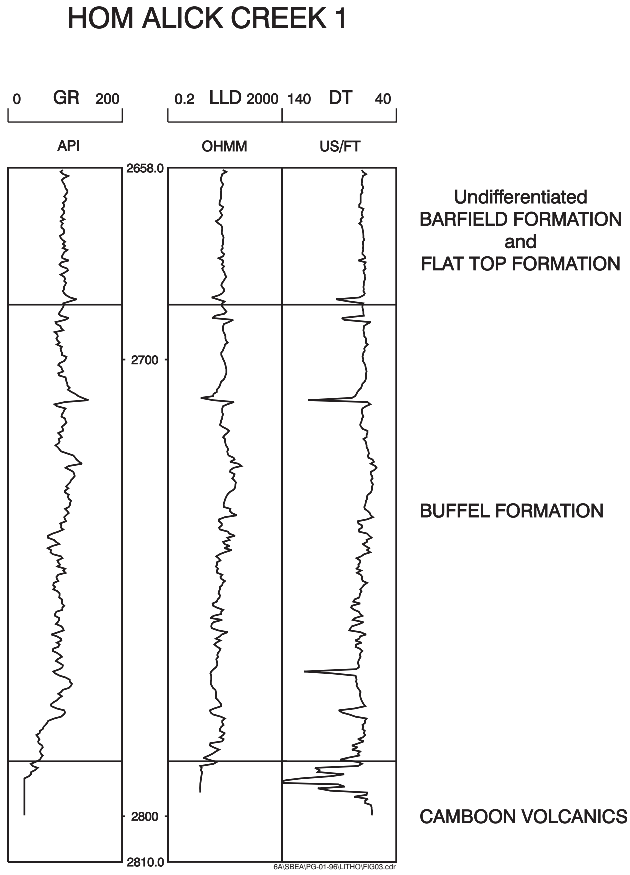

Figure 5: Wireline log responses - Buffel Formation.

The conglomerate is grey to green-grey with pebbles and cobbles of white to light greengrey siliceous volcanic rock, quartz and argillite in a tuffaceous sandstone matrix. Minor siltstone streaks are also present.

The sandstone is grey, fine to coarse-grained. Pebbles and minor cobbles of volcanics and chert and minor quartz sand grains are present in some of the beds.

Mudstone is medium to dark grey, interbedded and laminated with streaks and bands of carbonaceous material. Disseminated fine grains of volcanics are scattered throughout. Traces of gold-brown mica and pyrite are also present.

Coal is black to brown-black, hard, with minor shale laminae.

Relationships and Boundary Criteria

The Buffel Formation correlative unconformably overlies the Camboon Volcanics and is unconformably overlain by late Early Permian strata in UOD Goondiwindi 1. In COE Inglestone 1, the correlative unconformably overlies the undifferentiated Early Permian interval and is unconformably overlain by the Banana Formation.

The APP31-APP32 age indicated below for palynofloras derived from these rocks supports correlation with the Buffel Formation in the Taroom Trough and some part of the upper Reids Dome beds -basal Aldebaran Sandstone interval in the Denison Trough.

Wireline Log Character

The Buffel Formation correlative forms a distinct wireline-log unit characterised by variable gamma-ray responses and higher resistivity values and slower sonic velocities than overlying units.

The correlative in UOD Goondiwindi 1 consists of a uniform gammaray and variable, spiky resistivity and sonic log responses. The variable responses are probably due to the presence of coals in this interval.

Thickness

The Buffel Formation correlative is thickest along the eastern margin of the southern Taroom Trough adjacent to the Goondiwindi-Moonie Fault. The maximum thickness intersected is 331m in UOD Goondiwindi 1.

Age

Palynofloral assemblages recovered from COE Inglestone 1 (SWC 37/3625.6m; C.B. Foster, personal communication) and UOD Goondiwindi 1 (core 6/1959.9m; de Jersey, 1964) respectively contain the unit APP31 and unit APP32 indices, Praecolpatites sinuosus and Phaselisporites cicatricosus. Foster has suggested a maximum (no older than) APP32 age for the low-yield, poorly preserved, non-marine Inglestone palynoflora he recorded; and the non-marine assemblage documented by de Jersey appears to have given a reasonable yield of palynomorphs, supporting assignment to APP31.

Depositional setting

The depositional setting of the Buffel Formation correlative consisted of alluvial fan and fluvial conditions resulting in the deposition of conglomerates and coarsegrained sandstones. Conglomerates are more abundant closer to the Goondiwindi-Moonie Fault and contain material derived from the uplifted volcanic areas to the east of the Fault

LATE EARLY PERMIAN ROCKS

Nomenclature

Rocks of late Early Permian age have been recognised by Totterdell (personal communication, January 1996) in UOD Macintyre and UOD Goondiwindi 1 in northern New South Wales. Rocks of this age are also likely to be present in the southernmost part of the southern Taroom Trough in Queensland.

Rock Types

The late Early Permian rocks consist dominantly of sandstone, mudstone and siltstone with lesser tuff and conglomerate.

Sandstone is light grey to green-grey, medium to coarsegrained grading to granule and pebble conglomerate and labile. Rounded to sub-rounded multicoloured chert, lithics and clear and milky quartz grains are also present. Quartz and calcite cement as well as abundant grey to white tuffaceous and siliceous matrix occur throughout. Rare carbonaceous material, traces of pyrite and some calcareous fossils are also present.

Mudstone is light to dark grey, slightly calcareous and grades to siltstone. Carbonaceous material may be abundant and plant fossils are apparent in some cores. Marine fossils, including bivalves and brachiopods, are also present.

Siltstone is blue-grey to dark grey and contains a few fine-grained quartz grains. Rare tuffaceous laminae and calcite are present in places. Minor plant fragments and traces of shell fragments are scattered throughout. Rare pebble bands are present.

Tuff is generally grey-green, tan, brown, white, medium to coarse-grained with a siliceous matrix. Rare fractures infilled with calcite are also present.

Conglomerate consists of granules to pebbles of grey argillite, volcanics, white quartz, green quartzose sandstone and tuffaceous fragments in a silty argillaceous matrix.

Relationships and Boundary Criteria

The late Early Permian rocks unconformably overlie equivalents of the Buffel Formation in the southern part of the Taroom Trough and are unconformably overlain by the Banana Formation in UOD Macintyre 1 and the Moolayember Formation in UOD Goondiwindi 1.

The base of the interval is readily recognisable as the upwards transition to a dominantly sandstone, siltstone, mudstone succession. Tuff is more abundant at the base of this interval in UOD Macintyre 1 than in UOD Goondiwindi 1.

Rocks of late Early Permian age appear restricted to the southern part of the study area. They are of the same age as the upper part of the Aldebaran Sandstone in the Denison Trough.

Wireline Log Character

The wireline log responses over the late Early Permian rocks are relatively distinctive being fairly uniform in character, especially the gamma-ray log. The presence of tuff at the bottom of the interval in UOD Macintyre 1 is highlighted by lower gamma-ray and higher resistivity log responses and faster sonic velocities.

Thickness

The late Early Permian rocks are 295m and 229m thick in UOD Goondiwindi 1 and UOD Macintyre 1 respectively.

Age

A sample from core 4/1697.13-1698.34m in UOD Goondiwindi 1 provided a unit APP42 palynoflora embracing *Praecolpatites sinuosus*, *Phaselisporites cicatricosus*, *Granulatisporites trisinus*, and the attendant index, *Didecitriletes ericianus* (C.B. Foster, personal communication). An assemblage recorded previously by de Jersey (1964) from this core at 1697.7m lacked the latter species, but contained P. sinuosus, the index for unit APP32, in the apparent absence of species which make their first appearance at higher levels in the stratigraphic sequence. However, Foster's analysis clearly demonstrates that the APP32 age suggested by de Jersey's assemblage record can be regarded as no more than a maximum age.

A latest Early Permian (Kungurian) age is indicated, together with a non-marine environment of deposition.

Depositional Setting

The depositional setting for the late Early Permian interval, as indicated by the abundant shells, is in a shallow sea, although palynology suggests non-marine conditions. The presence of granule to pebble conglomerate in UOD Goondiwindi 1 suggests that the supply of coarse material is related to active fault movements in this area. In UOD Macintyre 1, the abundance of tuffs at the bottom of the interval and mudstones throughout the interval in UOD Macintyre 1 may reflect an offshore depositional setting.

LATE PERMIAN (EASTERN MARGIN)

Oxtrack Formation

The Late Permian Oxtrack Formation was named by Derrington & others (1959) from the type area, Oxtrack Creek, north of Cracow. Wass (1965) restricted the name to the upper unit in the Oxtrack Formation of Derrington & others (1959) to include a succession of fossiliferous calcareous siltstones and limestones. Flood & others (1981) further restricted the formation to buff fossiliferous limestone and calcareous shale containing abundant crinoid ossicles which comprise the uppermost part of the earlier definitions.

The formation was previously interpreted to be present in UOD Cockatoo Creek 1 (Gray & Heywood, 1978), about 22km south-west of the closest outcrop. The high resistivity log responses and fast sonic log velocities on wireline logs over this interval are taken to indicate the presence of carbonates. The interval, regarded as Oxtrack Formation in

UOD Cockatoo Creek 1, is relatively thin and lacks any distinctive lithological character in the cutting descriptions. In this report, the interval has been assigned to the lower part of the Barfield Formation which infers that the Oxtrack Formation is restricted mainly to outcrop and is not widely recognised in the subsurface.

Barfield Formation

Nomenclature

The Barfield Formation was defined by Derrington & others (1959) as a succession of olive-green mudstones, in part conglomeratic, and siltstones, with lesser felspathic lithic sandstones, tuffs, volcanic breccias and limestones, outcropping near Barfield Station 22km south-east of Banana. The southernmost outcrops of the Barfield Formation lie within the north-eastern part of the study area.

Rock Types

The Barfield Formation consists dominantly of mudstones and siltstones with lesser sandstones, tuffs, and conglomerates. Marine fossils are present throughout the formation.

Mudstone is light to dark grey, slightly calcareous and grades to siltstone. Carbonaceous material may be abundant and plant fossils are apparent in some cores. Marine fossils, including bivalves and brachiopods, are also present. Siltstone is blue-grey to dark grey and contains a few fine-grained quartz grains. Rare tuffaceous laminae and calcite are present in places. Minor plant fragments and traces of shell fragments are scattered throughout. Rare pebble bands are present. Sandstone is brown-grey to grey. Variations in grain size are apparent with sandstones in the northern part of the study area being very fine to finegrained, fairly sorted, lithic labile whereas in the southern part, the sandstones are medium to coarsegrained grading to granule conglomerate. Rounded to sub-rounded multicoloured chert, lithics and clear and milky quartz grains are also present. Quartz and calcite cement as well as abundant grey to white tuffaceous and siliceous matrix occur throughout. Rare carbonaceous material and traces of pyrite are also present. Gray & Heywood (1978) reported the presence of graded bedding in sandstones, consistent with deposition from turbidity currents. Tuff is generally greygreen, tan, brown, white, medium to coarse-grained with a siliceous matrix. Rare fractures infilled with calcite are also present. Conglomerate consists of granules to pebbles of grey argillite, white quartz and green quartzose sandstone in a silty, slightly calcareous matrix.

Relationships and Boundary Criteria

The Barfield Formation unconformably overlies either the Camboon Volcanics or the Buffel Formation in the subsurface. The angular discordance between the Buffel Formation and the Barfield Formation is apparent on the dipmeter logs from HOM Alick Creek 1 and UOD Undulla 1 where the boundary is placed at 2688m and 2583m respectively. However, this discordance may reflect local structuring and elsewhere a disconformable relationship may exist.

The top of the Barfield Formation is placed at the contact between the uppermost thick mudstone or siltstone bed, and sandstone or conglomerate of the overlying Flat Top Formation.

The Barfield Formation is restricted to the north-eastern part of the study area. A fivefold informal subdivision of the Barfield Formation has been recognised in the subsurface in the Theodore area by Gray & Heywood (1978). This subdivision could not be recognised in the study area. Locally distinctive subunits are present also in UOD Cockatoo Creek 1 and UOD Burunga 1, but correlation of these subunits between the wells was not possible.

Wireline Log Character

The wireline log responses over the Barfield Formation are particularly distinctive with relatively uniform gamma-ray and low resistivity responses and slow sonic velocities (Figure 6). Distinctive subdivisions can be recognised from the logs but they cannot be correlated for any distance.

The coal seams are highlighted by the slow sonic velocities and to a lesser extent by high resistivity and low gamma-ray log values.

Thickness

The depocentre for the formation is in the north-eastern part of the study area where it is 714m thick in UOD Cockatoo Creek 1.

Age

An assemblage recorded by de Jersey (1962) from the Barfield Formation in UOD Burunga 1 (core 20/2413.2m) is characterised by the common occurrence of *Acanthotriletes villosus* in the apparent absence of *Dulhuntyispora* spp. and *Didecitriletes ericianus*. This is suggestive of assignment to unit APP33, but, in view of the limited data, this determination is unreliable and can only be regarded as a maximum age. However, in GSQ Mundubbera 6, Foster (1982) attributed palynofloras from the upper part of the Barfield Formation to his then newly-established *Dulhuntyispora parvithola - Triplexisporites playfordii* Interval Zone (= unit APP5). A Late Permian (Djulfian) age is therefore indicated.

Depositional Setting

The depositional setting for the mostly marine Barfield Formation is complex and exhibits regional variations, especially in the early stages. Coals are present in the lowermost beds around UOD Burunga 1 in the northeastern part of the study area. These coals indicate that marine conditions were not present initially but developed later. The coals probably formed as the result of rising sea level producing back-barrier and coastal swamps rather than the development of deltas.

Marine conditions dominated the depositional history of the Barfield Formation. This is supported by spinose acritarchs recorded from the Barfield Formation in GSQ Mundubbera 6 by Foster (1982), suggesting a brackish to marine influence during deposition of the formation. The abundance of mudstones in the uppermost part suggest continuing deepening of the sea with time. Gray & Heywood (1978) reported sandstones with graded bedding which are most likely turbidites. A moderate depth of water is suggested for the deposition of this unit.

Flat Top Formation

Nomenclature

The Flat Top Formation was defined by Derrington (1959) as a succession of moderately indurated, labile sandstones, mudstones and limestones outcropping along the Dawson Highway to Biloela, about 6km east of Banana.

Rock types

The Flat Top Formation consists dominantly of siltstone with lesser sandstone, shale, conglomerate, tuff and coal. A three-fold lithological subdivision can be recognised. The lowermost subdivision is dominated by conglomerate and lesser sandstone and shale.

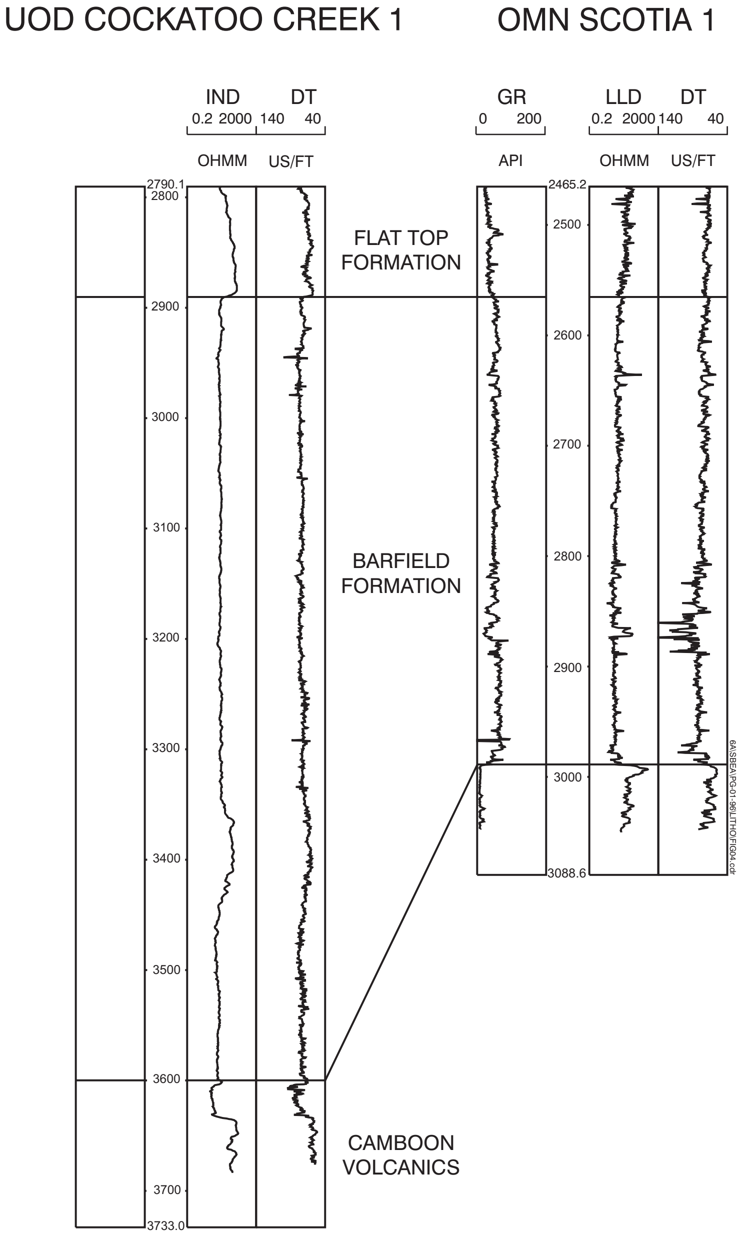

Figure 6: Wireline log responses - Barfield Formation.

The middle subdivision exhibits regional lithological variation and in UOD Cockatoo Creek 1 contains siltstone, shale and coal (the equivalent interval in UOD Burunga 1 consists of shale, siltstone and lesser sandstone). The upper subdivision consists dominantly of sandstone with lesser siltstone and shale.

Shale is commonly dark grey, firm to hard, carbonaceous and silicified. Minor calcite veining, disseminated pyrite and quartz pebbles are also present. Coal fragments occur on some laminae.

Siltstone is dark grey to dark brown, slightly sandy, calcareous with abundant disseminated pyrite. Minor poorly preserved plant fossils and reworked tuffaceous material are present. Tuff is light grey to grey-green, slightly shaly, silicified with fractures infilled with calcite. Silty to coarse-grained irregular inclusions of grey-green tuffaceous shale are also present. Sandstone is more abundant towards the base of the formation than at other depths, and is also present as thin interbeds in the shale. It is commonly medium grey and composed of very fine to granule-sized quartz grains in a siliceous tuffaceous matrix. Abundant finely disseminated pyrite is associated with carbonaceous material in some beds. Conglomerate is dark grey and consists of angular pebbles and cobbles of white and light grey crystal tuff in a matrix of dark grey, sandy, carbonaceous, spot calcareous siltstone.

Relationships and Boundary Criteria

The Flat Top Formation was recognised only in the north-eastern part of the study area. It conformably overlies the Barfield Formation. The boundary is generally placed at the top of the uppermost mudstone or siltstone in the Barfield Formation. A conglomerate is generally present at the base of the Flat Top Formation reflecting a major change in depositional setting from that of the underlying Barfield Formation. In UOD Burunga 1, the boundary between the Barfield and Flat Top Formations is taken at the top of a thick tuff rather than a mudstone or siltstone bed. Westerly thinning suggests that the Flat Top Formation passes laterally into finer-grained marine units.

A succession of mudstones and sandy mudstones, similar to a combined Barfield and Flat Top Formations interval, is present in the south. The absence of a distinctive sandstone/siltstone-dominated interval equivalent to the Flat Top Formation in this area means that subdivision into these formations is not possible. Nevertheless, this southern succession is considered to be the correlative of both formations.

Wireline Log Character

The three-fold subdivision of the Flat Top Formation in the north-east is reflected on the wireline log responses (Figure 7). The lower subdivision has high resistivity log values and fast sonic velocities. The middle subdivision has lower resistivity log values and slow sonic velocities and the presence of coal in the middle subdivision in UOD Cockatoo Creek 1 is distinctive on the sonic log. The upper subdivision has high resistivity log responses and relatively fast sonic velocities.

Thickness

The Flat Top Formation has a maximum thickness of 494m in UOD Cockatoo Creek 1. From seismic data, the formation has a relatively limited areal distribution and thins to the west (O. Dixon, personal communication, December 1994).

Age

The Flat Top Formation in GSQ Mundubbera 5 and 6 has yielded palynofloras which were referred by Foster (1982) to his *Dulhuntyispora parvithola - Triplexisporites playfordii* Interval Zone (= unit APP5). A Late Permian (Djulfian) age is therefore indicated.

Depositional Setting

The Flat Top Formation was probably sourced locally from the east, because of its limited distribution and thinning to the west. Marine or brackish-water influences in the environment of deposition are indicated by the occurrences of spinose acritarchs (Foster, 1982).

The lowermost subdivision reflects deposition in a shallow sea as indicated by the presence of corals, brachiopods and bivalves. The initial input of sediments was relatively rapid as shown by the conglomeratic deposits at the bottom of the formation. The presence of fossils associated with the conglomerates may indicate relatively shallow water or the deposition in deeper water of shallow waterderived material by debris flows or from turbidity currents.

The coals in the middle interval in UOD Cockatoo Creek 1 indicate deposition in a fluviodeltaic environment. Lateral facies changes are apparent as siltstone and mudstone are the dominant rock types in the equivalent interval in UOD Burunga 1. Thus coal swamps were present in the north while marine conditions were present in the south.

The depositional setting of the upper interval is uncertain but the sparsity of fossils suggests deposition in a restricted shallow sea or nearshore.

Overall, the Flat Top Formation was deposited as an easterly or north-easterly sourced fan delta in to a shallow sea. The progradation of the delta was relatively rapid as indicated by the conglomerates in the lowermost beds.

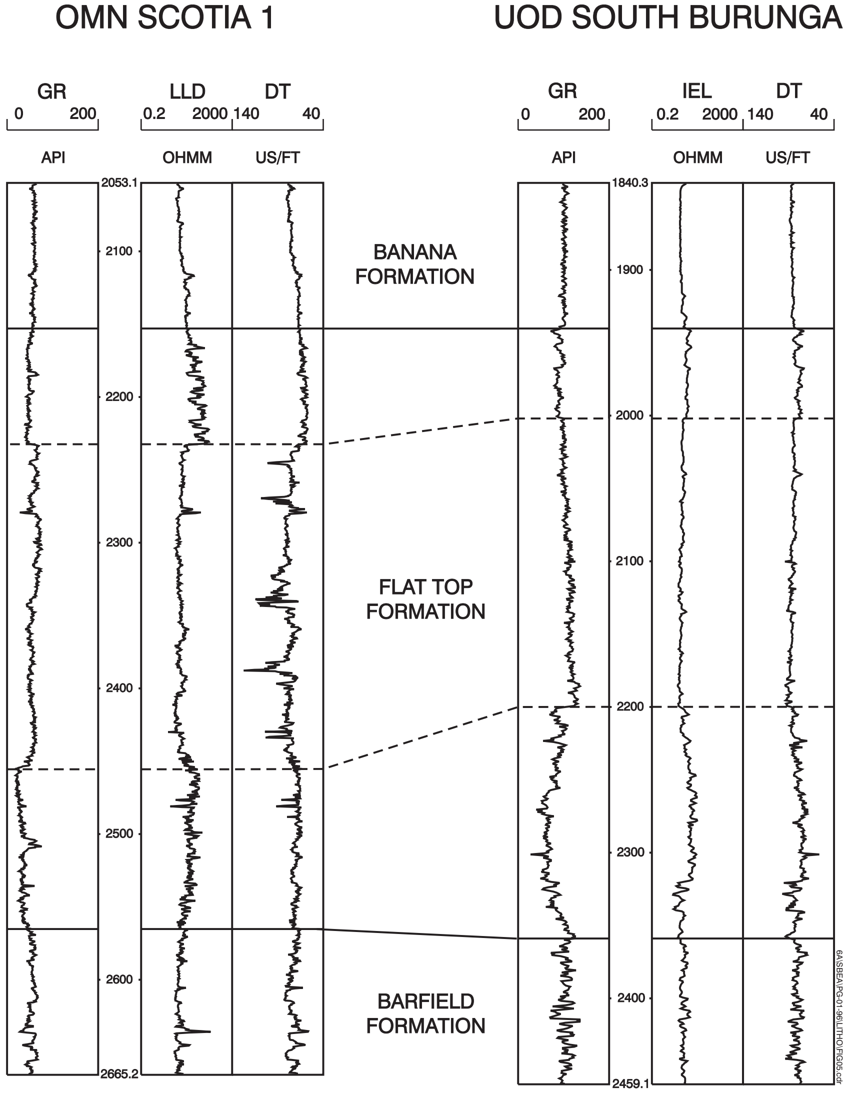

Figure 7: Wireline log responses - Flat Top Formation.

Banana Formation

Nomenclature

The Banana Formation was proposed by Glover (1955) and formally defined by Derrington & others (1959) as an interval of dominantly olive-green mudstones and siltstones and lesser medium to coarse-grained feldspathic sandstones and minor coal, locally well exposed near Banana. The formation is equivalent to the lower part of the Gyranda Formation of Dear & others (1971).

Rock Types

The Banana Formation consists dominantly of siltstone and shale with minor tuff and sandstone and rare coal.

Siltstone is generally light grey, poorly sorted, tuffaceous, in part calcareous and has disseminated carbonaceous material and laminae. The siltstone is commonly interlaminated or interbedded with shale. Shale is light grey, brown grey and in part dark grey and is commonly hard and tuffaceous. Finely disseminated carbonaceous material, and calcite as numerous fine veins, are present. Tuff is dominantly white to pale green, silty, calcareous and occurs in laminae and thin beds throughout the formation. Sandstone is generally very fine to fine-grained, rarely medium-grained, poorly sorted, soft, labile, tuffaceous with a calcareous cement.

Relationships and Boundary Criteria

The Banana Formation conformably overlies the Flat Top Formation in the north-eastern part of the study area and is readily recognisable where the latter is present. The formation conformably overlies an undifferentiated Barfield and Flat Top Formations unit in the south and also onlaps the Camboon Volcanics and Combarngo Volcanics. The top of the formation in the west is taken at the transition from dominantly marine mudstones to deltaic coal measures of the overlying Tinowon Formation.

Wireline Log Character

The Banana Formation is readily distinguishable on wireline logs due to its lower more uniform resistivity and sonic log responses in comparison with the enclosing formations (Figure 8).

Thickness

The Banana Formation has a maximum thickness of 526m in UOD Cockatoo Creek 1 in the north-eastern part of the study area. The formation thins into the basin and has a relatively consistent thickness of about 120m in the south.

Age

Palynofloras from the Banana Formation are of Late Permian age and are conformable with unit APP5. In HOM Alick Creek 1, an upper stage 5 assemblage (= unit APP5) was recovered from a SWC/2419m by Price (1981) in strata here assigned to the formation. Moreover, APP5 assemblages, attributed by Foster (1982) to his *Dulhuntyispora parvithola - Triplexisporites playfordii* Interval Zone, are associated with the Banana Formation in GSQ Mundubbera 5 and Mundubbera 6. In these bore holes, they occur in strata previously identified with the Gyranda Formation by Gray & Heywood (1978) and referred to that lithostratigraphic unit by Foster.

Depositional Setting

The occurrence of spinose acritarchs in palynological assemblages recorded by Price (1981) and Foster (1982) suggests brackish-water or marine influences in the depositional environments. The dominance of mudstone and siltstone suggests relatively calm water conditions.

Wiseman Formation

Nomenclature

The Wiseman Formation was defined by Derrington & others (1959) from the work of Glover (1954, 1955) as a strongly outcropping succession of olive-green to brown medium to coarsegrained calcareous sandstones interbedded with mudstones and siltstones near Mt Wiseman, south of Banana.

Colton (1970) recognised a three-fold subdivision of the formation in the Banana area. Dear & others (1971) did not formally recognise the Wiseman Formation but established a two-fold subdivision in the Gyranda Formation. The upper part is considered to be equivalent to the Wiseman Formation, the lower, the Banana Formation.

The Wiseman Formation was intersected only in UOD Cockatoo Creek 1 in the north-eastern part of the study area.

Rock Types

The Wiseman Formation in the study area records a coarsening-up, thickening-up series of cycles. Each cycle starts with mudstone passing upwards through siltstone and sandstone. Thin coal beds are present at the top of some of the sandstones before a return to mudstone deposition. Rare tuff beds and laminae of siltstone are also present.

The shale is fawn to dark grey with disseminated carbonaceous material. Carbonaceous stringers and laminae are abundant towards the top of the formation. Siltstone is grey-brown and grey-green to dark grey, carbonaceous, hard and very siliceous with rare calcite veins and pyrite. Sandstone is green to grey, medium to coarse-grained, lithic labile. Quartz cementation is present in some beds. Tuff is commonly white, medium grey, grey-green, hard, siliceous and slightly sandy.

Relationships and Boundary Criteria

The Wiseman Formation conformably overlies the Banana Formation. The nature of the contact suggests that there was a gradual change in depositional conditions. The top of the formation is represented by the change to completely fluvial sedimentation of the Baralaba Coal Measures.

In the study area, the Wiseman Formation is the northern correlative of the Burunga Formation and represents a southward migration of deltas into a sea, contrary to a dominantly fluvial origin considered for this unit at outcrop further north.

Wireline Log Character

The Wiseman Formation in UOD Cockatoo Creek 1 is characterised by sandstones with resistivity log values which increase upwards and by more variable sonic log responses than the underlying Banana Formation (Figure 9). These responses reflect an overall coarsening upwards of the formation with the sandstone beds becoming thicker and more common, and coal more abundant.

Thickness

The Wiseman Formation is interpreted to be present only in UOD Cockatoo Creek 1 where it is 321m thick.

Age

The Wiseman Formation embraces Late Permian palynofloras of unit APP5. Assemblages conformable with this biounit have been recorded from the formation in GSQ Mundubbera 5 by Foster (1982), who assigned them to his then newly established (and equivalent) *Dulhuntyispora parvithola-Triplexisporites playfordii* Interval Zone. In that bore hole, they occur in the upper part of the section (214-520m) previously referred to the Gyranda Formation (Gray & Heywood, 1978; Foster, 1982).

Depositional Setting

The Wiseman Formation is generally considered to have been deposited in a fluvial setting based on the presence of medium to coarse-grained cross-bedded sandstones.

The coarsening-up and thickening-up cycles present in GSQ Mundubbera 5 (Gray & Heywood, 1978) are inconsistent however with a fluvial setting. Such cycles are more typical of progradational events of a delta system. The coal present at the top of the sandstone beds reflects the presence of swamps on the delta top.

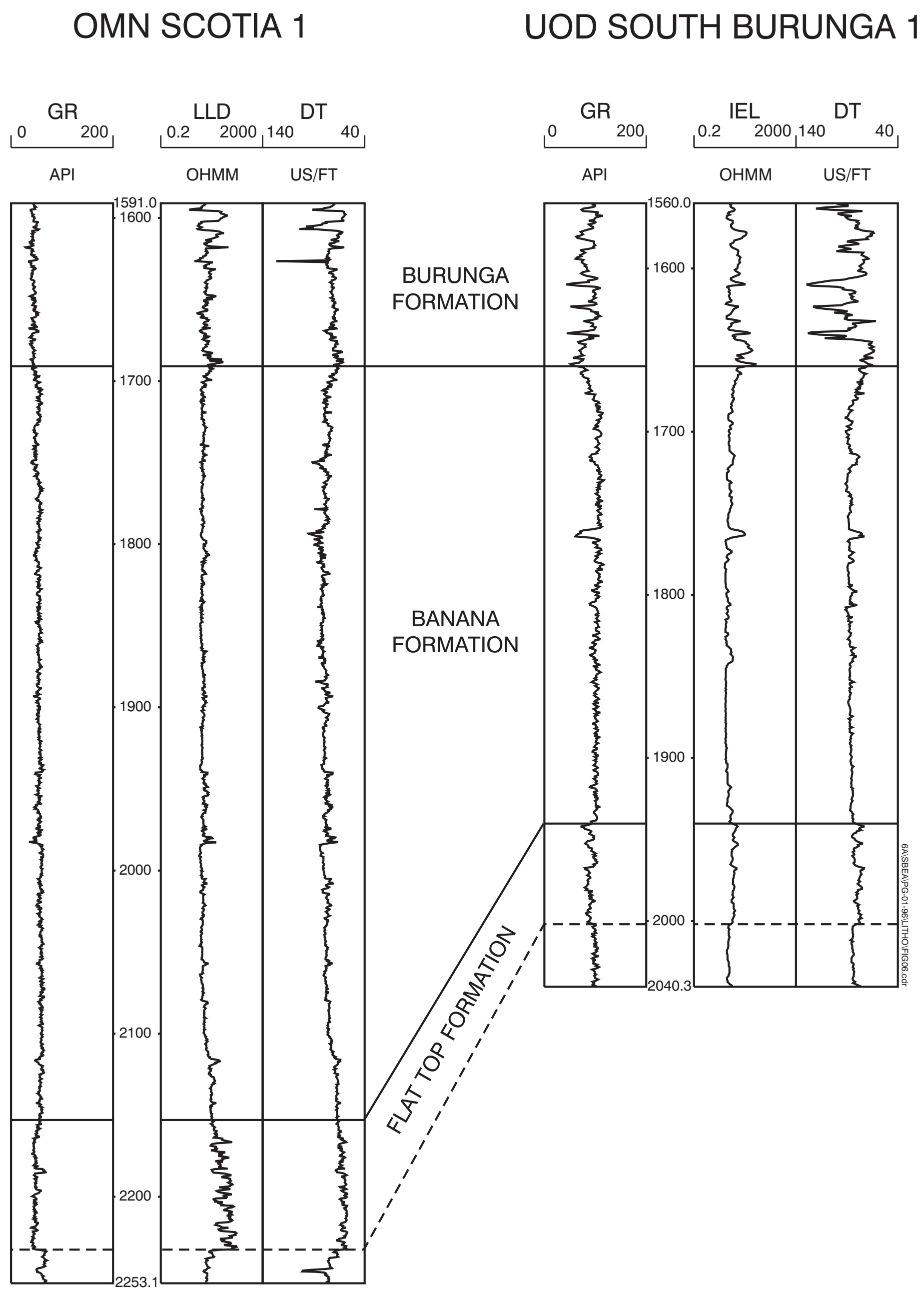

Figure 8: Wireline log responses - Banana Formation.

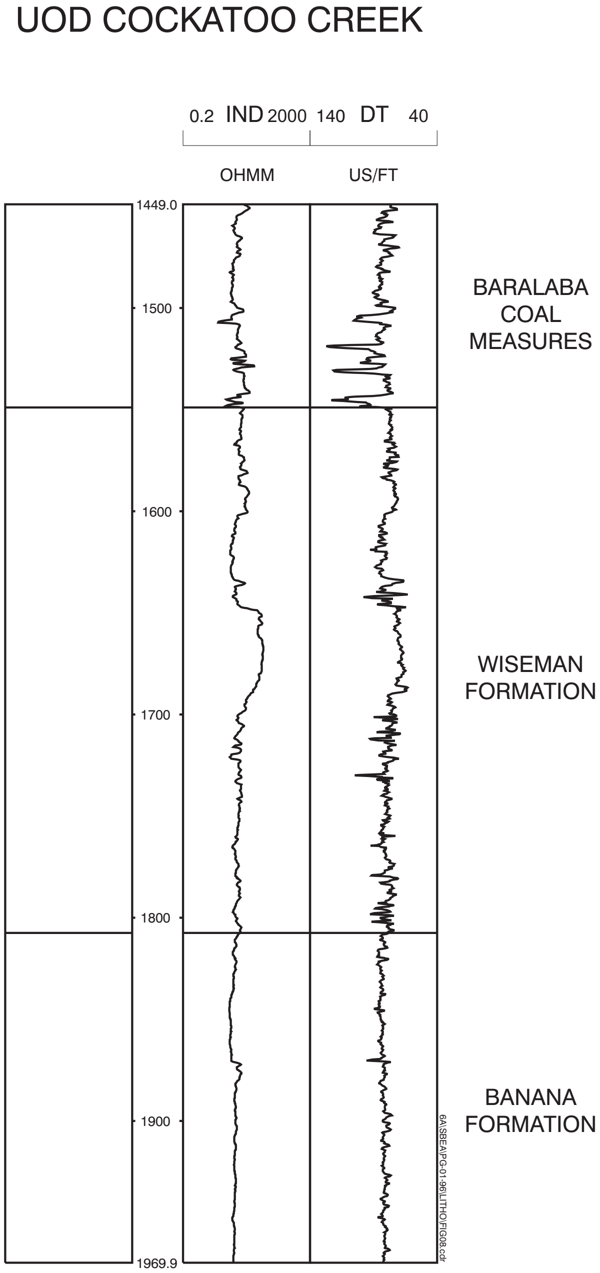

Figure 9: Wireline log responses — Wiseman Formation.

From palynology, in Foster's (1982) range chart for GSQ Mundubbera 5, spinose acritarchs are only sporadically distributed in the Wiseman Formation (= Foster's upper Gyranda Formation) compared with the underlying Banana Formation (= Foster's lower Gyranda Formation). This suggests a decreasing marine/brackish influence in progression to the Wiseman Formation.

Burunga Formation

Nomenclature

The Burunga Formation (Beeston & Green, 1995) is recognised along the eastern and southern margins of the study area. It is equivalent to the upper part of the Gyranda Formation of Gray & Heywood (1978) in UOD Cockatoo Creek 1 and thus equivalent to the Wiseman Formation.

Rock Types

The Burunga Formation exhibits a wide variety of rock types and regional variations. The formation will be considered in two areas; north-eastern and southern.

NORTH-EASTERN AREA: In the north-east, the Burunga Formation consists of the Scotia Coal Member at the base overlain by marine strata.

SCOTIA COAL MEMBER: The Scotia Coal Member comprises sandstone, shale, siltstone, coal and tuff. Coal is present in identifiable seams.

The sandstone is grey-brown, fine to dominantly medium-grained and in part coarse-grained to pebbly, fairly to poorly sorted, and contains subangular to subrounded quartz and lithic grains. Calcareous cement is common; minor pyrite is also present. Shale is dominantly brown-grey to dark grey, hard to soft, laminated with disseminated carbonaceous material. Minor calcite is also present. Siltstone is light to dark grey, dominantly hard and in part sandy. Grains are composed of lithics, volcanics and quartz. Tuff is also present as thin beds and laminae. It is mostly varicoloured white to light green, orange and grey-green and is commonly associated with calcite.

UPPER INTERVAL: The upper interval comprises sandstone, siltstone and tuff.

The sandstone is white to pale cream and is composed of fine to predominantly mediumgrained, sub-angular to rarely sub-rounded quartz and lithic grains with a clay matrix and calcareous cement. Carbonaceous fragments are scattered throughout. The siltstone is light brown in part sandy and slightly speckled with carbonaceous material. Tuffaceous material and calcite cement are common. Tuff is white to cream and generally very hard because of calcite cementation.

Marine shells and poorly preserved plant material have been recorded throughout the Burunga Formation in the north-eastern part of the Taroom Trough.

SOUTHERN AREA: The Burunga Formation in the southern part of the study area consists of three intervals; lower and upper coal measures separated by a marine mudstone interval in part fossiliferous. Because of the similarity of the rock types present in the 3 intervals, an overall description is sufficient.

The sandstone is grey, fine to medium, in part coarse-grained to pebbly and is poorly sorted with a volcanics-derived matrix and a siliceous cement.

The sand grains comprise quartz, lithics and volcanic fragments. The pebbles are commonly siliceous shale, volcanics and coal. The shale is grey and brown-grey to black, commonly tuffaceous with scattered carbonaceous material. Minor tuffaceous laminae are also present. The tuff is generally white to light grey and hard due to the siliceous cement.

Some softer tuffs are present where intermixing with argillaceous material has occurred. Some carbonaceous material is also present. The coal is black and commonly grades into carbonaceous shale. Tuff laminae are common to abundant.

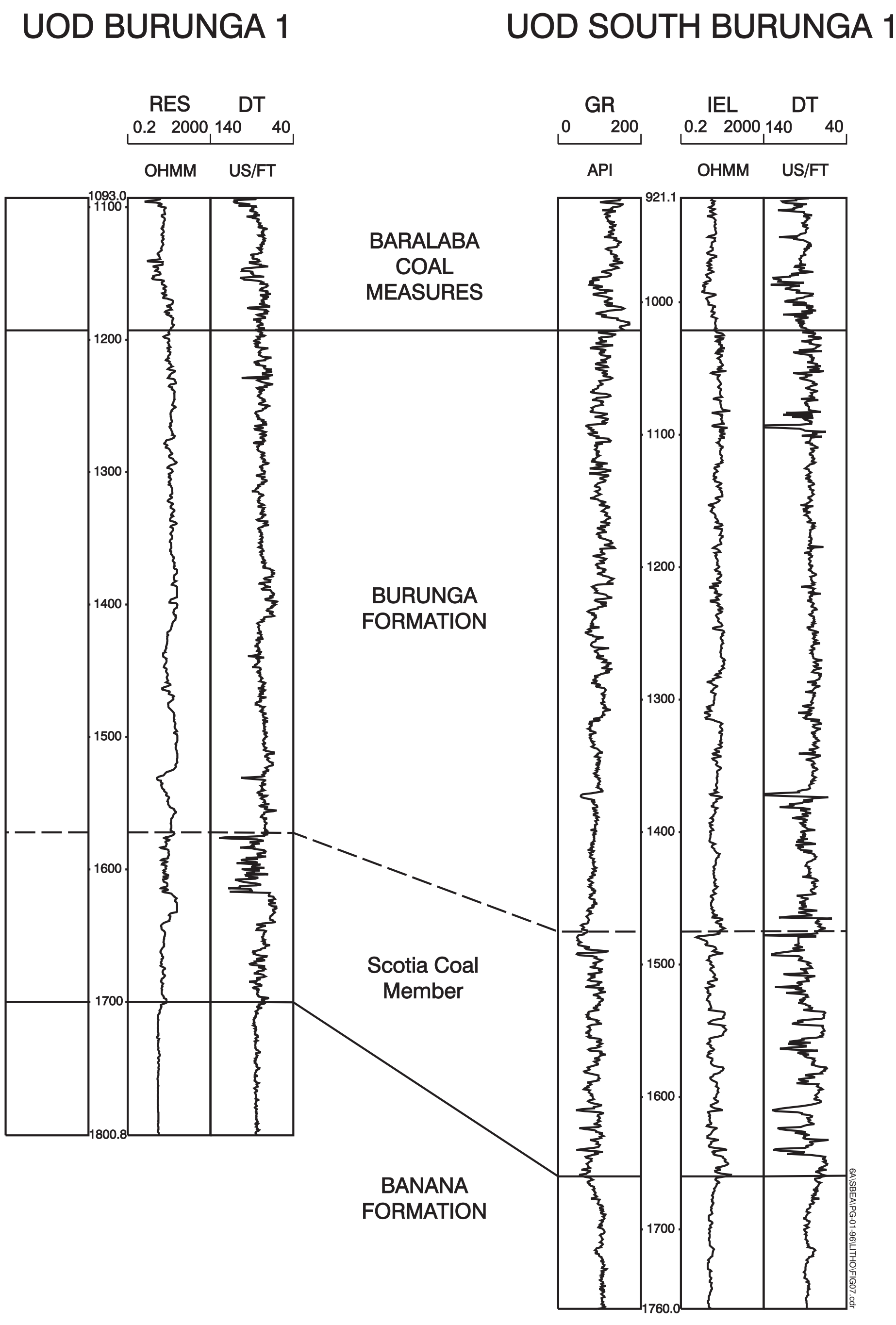

Figure 10: Wireline log responses - Burunga Formation, north-eastern area.

The volcanic conglomerate is composed of subrounded to rounded clasts of volcanic rocks, shale, coal and siliceous shale in a matrix of white to green shale with scattered quartz grains. Minor calcareous cement is also present.

The middle interval of marine mudstone is not always well developed and in some areas the formation may consist of interfingering coal and mudstone intervals with scattered marine fossils, particularly near the base (Beeston & Green, 1995).

Relationships and Boundary Criteria

The Burunga Formation conformably overlies the Banana Formation along the northeastern margin of the study area and the Muggleton Formation on the southern Roma Shelf. The contact between the Banana Formation and the overlying Scotia Coal Member in the north-east appears to be gradational with the amount of sandstone in the Banana Formation increasing in the upper part of the formation. The top of the Burunga Formation is placed at the transition from marine to the fluvial conditions represented by the Baralaba Coal Measures.

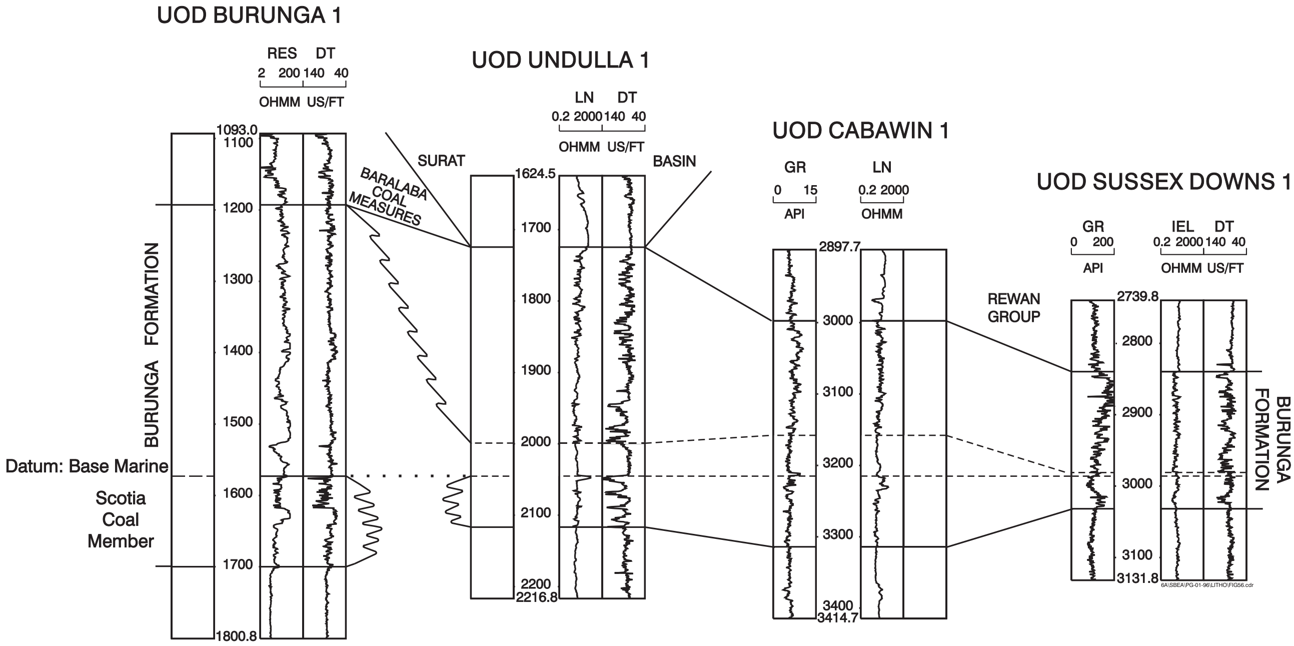

Figure 11: Wireline log responses — Burunga Formation, southern area.

This change is commonly reflected by an overall increase in grain size of the sandstones, and more coal.

Lateral continuity between the base of the marine intervals in the north and south, with deposition representing the same transgressive event, is supported by correlation along the eastern margin of the study area. Because the same transgression is represented, the base of the marine interval in the north is the same age as the base of the marine interval in the south. The upper coal measures in the south have no lithological correlative in the north.

Although lateral continuity of the Scotia Coal Member with the lower coal measures in the south seems likely, it cannot be demonstrated conclusively. Because of this, the name Scotia Coal Member has not been applied to this interval in the south.

The Burunga Formation can be correlated with the Wiseman Formation to the north but the relationship of the Scotia Coal Member to the Wiseman Formation is uncertain. The base of the Scotia Coal Member is considered to correspond to the base of the Wiseman Formation.

Wireline Log Character

The Burunga Formation in the north-eastern part of the study area has a relatively high resistivity log response and faster sonic velocities in comparison with the underlying Banana Formation (Figure 10). The gamma-ray log response increases towards the top of the formation. The Scotia Coal Member is very distinctive with its higher more noisy resistivity and sonic log responses in comparison with the underlying Banana Formation. The gamma-ray log response exhibits greater variation, reflecting the presence of different rock types in the Member.

Owing to the greater diversity of rock types in the southern part of the study area, the Burunga Formation displays more wireline log character than in the north (Figure 11). Although a well-developed marine mudstone interval is present in the middle part of the unit in some wells in the south, this mudstone cannot be mapped continuously for any great distance in the southern part of the area.

Thickness

The Burunga Formation is thickest along the eastern margin of the southern Taroom Trough. A maximum thickness of 677m was intersected in UOD South Burunga 1.

Age

Late Permian palynofloras conformable with unit APP5 are associated with the Burunga Formation. Assemblages of this age have been derived from strata here associated with the formation [for example, HOM Alick Creek 1 (Price, 1981: SWC/2152m, SWC/2244m, cuttings 22672279m, SWC/2285m); UOD Cabawin 1

(Evans, 1961: cuttings 3017.5-3020.6m; de Jersey & Dearne, 1961, 1964: cuttings 3008.4-3014.5m, core 32/3030.8-3030.9m, core 33/3034.5-3034.7m, core 34/3037.3m, core 36/3040.13040.2m, core 39/3082.7-3082.8m, cuttings 3127.2-3130.3m, cuttings 3221.7-3237m, cuttings 3261.4-3264.4m)].

Depositional setting

The depositional setting for the Burunga Formation was complex. In the north-east, coal deposition, represented by the Scotia Coal Member, followed the marine sedimentation of the Banana Formation. In many respects the Scotia Coal Member is more genetically related to the underlying Banana Formation than the Burunga Formation as the Member appears to be the end result of a coarsening upwards cycle. The Scotia Coal Member could be assigned to the Banana Formation.

The transgression recorded in the formation can be readily recognised and is reflected in the widespread distribution of marine fossils throughout the area. The marine fossils in the Burunga Formation in UOD South Burunga 1 are stratigraphically the highest in the Permian in the study area, and for the Bowen Basin in general. The Burunga Formation in the north-east reflects the last marine sedimentation in the basin.

Baralaba Coal Measures

Nomenclature

The name "Baralaba Coal Measures" was applied by Reid (1944) to the Permian coal measures cropping out along the Dawson River near Baralaba in central Queensland. Subsequently, Reid (1945a) used the name "Baralaba - Kianga Coal Measures" for these measures. However, the same author reverted to his original name in the investigation of the coal resources in the Baralaba coalfield. A tuffaceous unit, the Kaloola Member (Dear & others, 1971) forms the lowermost part of the Baralaba Coal Measures. The Member forms a distinctive series of ridges over much of the eastern Bowen Basin.

The Baralaba Coal Measures in the subsurface are restricted to the northern half of the study area. The coal measures in the south, that were considered by earlier workers to be part of the Blackwater Group or Kianga Formation, are now considered to be part of the Burunga Formation.

Rock Types

The Baralaba Coal Measures overall consist of sandstone, siltstone, mudstone, coal and tuff. The sandstone is white, cream and grey, generally fine to medium-grained, in part pebbly, well sorted, lithic labile to sublabile with a calcareous and siliceous cement. Clay matrix is present in part. Carbonaceous material is common, rare mica flakes are also present. The siltstone is grey-brown, with abundant carbonaceous material grading to coal. Siliceous and calcareous cements are also present. Shale is light grey to green, tuffaceous with laminae of white tuff. Coaly streaks and minor disseminated carbonaceous matter are present.

Coal is generally black-brown with minor shale laminae scattered throughout. Calcite veins are also present. Tuff is commonly white to green and has mostly been reworked. Scattered quartz grains and disseminated carbonaceous matter are present. Bedding, highlighted by biotite and quartz grains, is also apparent.

The Kaloola Member comprises blue-grey to white silicified mudstone, siltstone, feldspathic and lithic sandstone, tuff and conglomerate. Beds crowded with Glossopteris sp. leaves are common. Uneconomic coal seams and fossilized wood are present in some areas.

Relationships and Boundary Criteria

The Baralaba Coal Measures conformably overlie the Burunga Formation. Recognition of the boundary in the north is readily apparent from the abundant coal seams in the Baralaba Coal Measure compared with the sandstones and siltstones with marine shells of the underlying upper Burunga Formation.

The Kaloola Member could not be recognised as a distinct interval at the bottom of the Baralaba Coal Measures in the subsurface. In the northern part of the study area, tuffs are particularly abundant in the uppermost part of the marine interval in the Burunga Formation and in the lowermost part of the Baralaba Coal Measures but they are not sufficiently distinct to form a separate unit. The top of the Baralaba Coal Measures is transitional with the overlying fluvial Rewan Group. In some areas the Baralaba Coal Measures are unconformably overlain by the Early Jurassic Precipice Sandstone.

The Baralaba Coal Measures are commonly correlated with the Bandanna Formation. However in this report, the lower part of the Bandanna Formation is related to the Burunga Formation making the Baralaba Coal Measures a correlative of only the upper part of the Bandanna Formation.

The coal measures in the upper part of the Burunga Formation in the south contain abundant tuffs which suggests that these coal measures are more likely a correlative of the marine interval in the Burunga Formation and the overlying Kaloola Member (basal Baralaba Coal Measures) in the north. Thus the name Burunga Formation is preferred to Baralaba Coal Measures in the south to highlight the earlier development of coals.

Wireline Log Character

The Baralaba Coal Measures exhibit distinctive wireline log responses, particularly the resistivity and sonic logs (Figure 12). The resistivity log generally has a lower baseline in comparison with the underlying Burunga Formation; peaks generally reflect the presence of coal. Coal is also reflected by slow velocities on the sonic log. The gamma-ray log response is commonly similar to that of the underlying Burunga Formation.

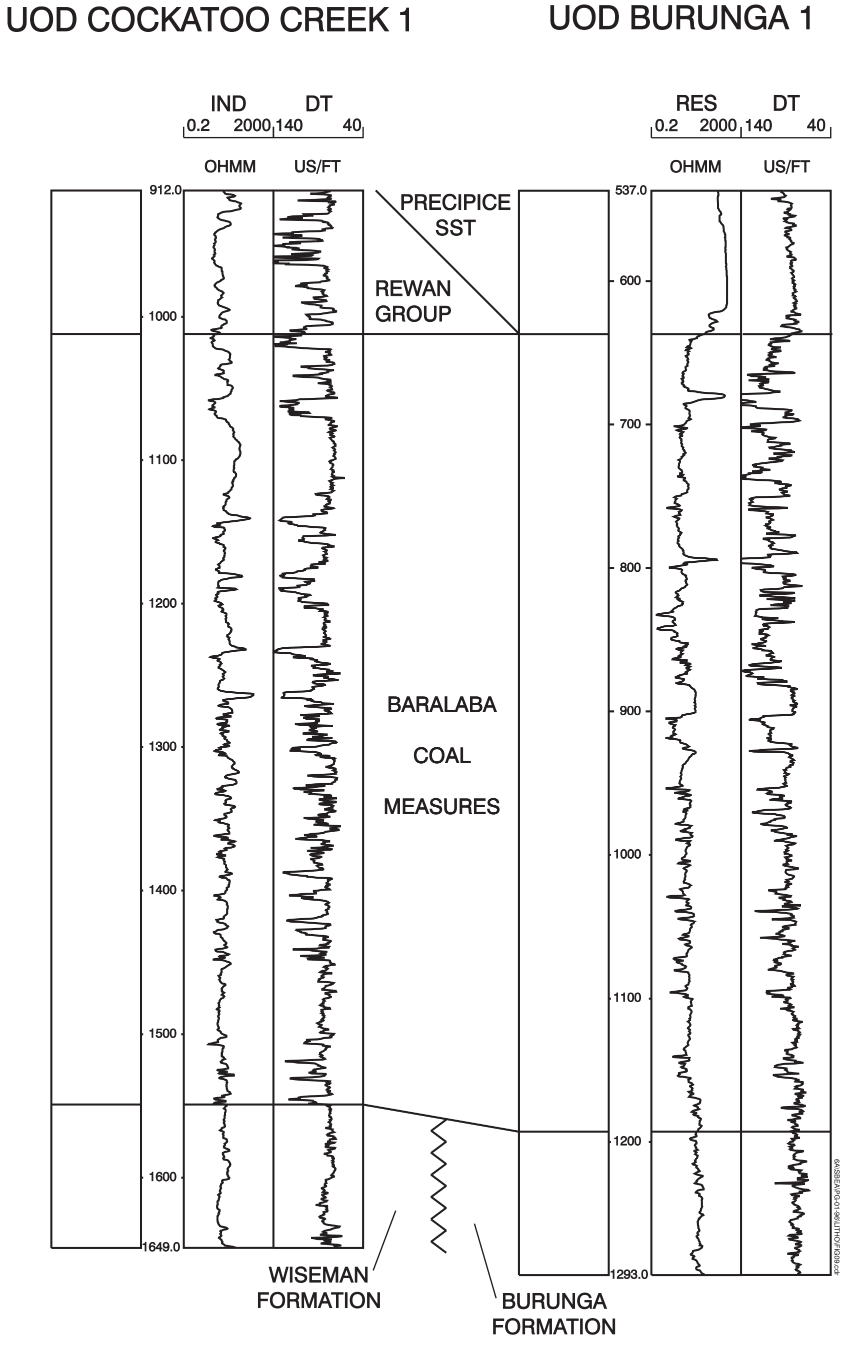

Figure 12: Wireline log responses - Baralaba Coal Measures.

Thickness

The Baralaba Coal Measures are restricted to the north-eastern part of the study area. The formation has a maximum thickness of 556m in UOD Burunga 1 where it is overlain by Surat Basin rocks.

Age

Late Permian palynofloras of the Baralaba Coal Measures are identified with unit APP5, and at the formation's upper limit, with unit APP6. The latter zone extends into the overlying basal Rewan Group, with which it is primarily associated (Price, this volume; also see Foster, 1979).

Depositional setting

The Baralaba Coal Measures represent the latest Permian coal measure deposition in the study area. By the start of deposition the sea had completely withdrawn and fluvial conditions prevailed. Occasional incursions of brackish waters into the depositional environments is suggested by a few records of spinose acritarchs (Foster, 1979, 1982).

LATE PERMIAN (WESTERN MARGIN)

Muggleton Formation

Nomenclature

The name Muggleton Formation was given by Paten & Groves (1974) to the lowermost part of the Permian succession in the Roma area. They also recognised the Lorelle Sandstone Member, a quartzose sandstone unit with minor shale, siltstone, coal and tuff, near the middle of the formation. The Member is only locally developed and in this investigation could not be recognised in the regional correlations.

Rock Types

The Muggleton Formation consists of shale, siltstone and sandstone and minor coal and tuff. Marine fossil horizons are present (Paten & Groves, 1974).

Shale is dark grey, hard, silty, non-fissile, locally pyritic, micaceous, and carbonaceous. Siltstone is dark grey, hard, carbonaceous and micaceous and locally pyritic. Sandstone is grey, fine to coarse-grained, locally conglomeratic, poorly sorted, quartzose, feldspathic, lithic with a clay matrix and calcareous cement.

Sandstone of the Lorelle Sandstone Member is medium to coarse-grained, rarely conglomeratic, subangular, poorly sorted, quartzose with a few dark lithics, and a white clay matrix. Minor pyrite and calcite cement are also present. Coal is present in scattered thin seams as well as minor shale, siltstone and tuff.

Relationships and Boundary Criteria

The Muggleton Formation unconformably overlies either the Timbury Hills Formation or the Combarngo Volcanics. The top of the Muggleton Formation is placed at the transition from the dominantly marine strata of the latter to the fluvio-deltaic Tinowon Formation. This boundary corresponds to an upwards increase in the percentage of sandstone.

The Muggleton Formation is the correlative of the Banana Formation on the eastern side of the Trough. Both form a regional key marker horizon that can be correlated throughout the study area.

Wireline Log Character

The Muggleton Formation, excluding the Lorelle Sandstone Member, has uniform gammaray, resistivity, and sonic log responses (Figure 13). This uniformity is the distinguishing feature of the formation and enables it to be recognised along the southern and western margins of the study area. The Lorelle Sandstone Member has lower gamma-ray values, slower sonic velocities and a higher spontaneous potential log response in comparison with the responses for the rest of the formation (Paten & Groves, 1974; figure 5).

Thickness

The Muggleton Formation is distributed mainly along the western margin of the study area. It has a maximum thickness of 197m in EOC Muggleton 1 (Figure 14).

Age

Palynofloras recorded by Evans (1962a) from strata now identified with the Muggleton Formation in AAO Meeleebee 1 are generally conformable with unit APP5 of Late Permian age. A rich spinose acritarch assemblage has been reported by Paten (1967b) from AAO Bengalla 1 (core 2/2117.7m). However, the associated miospores recorded collectively for this and the other (non-acritarch bearing) samples (core 1/ 2094.4, 2101.6, 2105.9, 2106.8m) suggest a unit APP31 age, but presumably this can only be reliably regarded as a maximum age considering the poorly preserved character of the assemblages and the limited number of species listed. Nonetheless, firmer palynostratigraphic control is required on these and equivalent strata (previously identified with the Lorelle Sandstone Member) in order to be more confident of their age and their biostratigraphic relationship with the upper part of the Muggleton Formation.

Depositional Setting

The presence of marine fossils in parts of the Muggleton Formation indicates deposition, at times, in a shallow sea. The marine conditions that formed this unit were the most expansive development of the sea in the study area during the Permian.

The sea conditions during this time were relatively quiet, resulting in the deposition of a uniform shale, siltstone and sandstone interval. The presence of coal in the formation and in the Lorelle Sandstone Member reflects the nearshore deposition. Paten & Groves (1974) highlighted the restricted development of the Lorelle Sandstone Member along the western margin, reflecting local delta development. The presence of spinose acritarchs in the Muggleton Formation in AAO Meeleebee 1 (Evans, 1962a; Paten, 1967c) and in AAO Bengalla 1 (Paten, 1967b) also suggests environments ranging from brackish to marine.

Tinowon Formation

Nomenclature

The name Tinowon Formation was given by Paten & Groves (1974) to the earliest Permian formation containing significant coal measures on the Roma Shelf. The major coal interval in the formation was named the Wallabella Coal Member. A shelly horizon, present at the top of the Tinowon Formation, is considered to be equivalent to the Mantuan Productus bed of the Denison Trough.

Rock Types

The Tinowon Formation consists dominantly of shale, siltstone with lesser sandstone and coal. Marine fossils have been recorded throughout (Paten & Groves, 1974).

The shale is grey to black and silty, especially in the lower parts. Carbonaceous material, mica and pyrite are common, as are shell fossils and spines. The siltstone is light to dark grey, carbonaceous, micaceous, pyritic and commonly calcareous. The sandstone is white to grey, fine to medium-grained, subangular, rarely subrounded, poorly sorted, quartzose with rare lithic grains. Calcareous cement and clay matrix are present. Tuff is pale grey to white, soft and waxy.

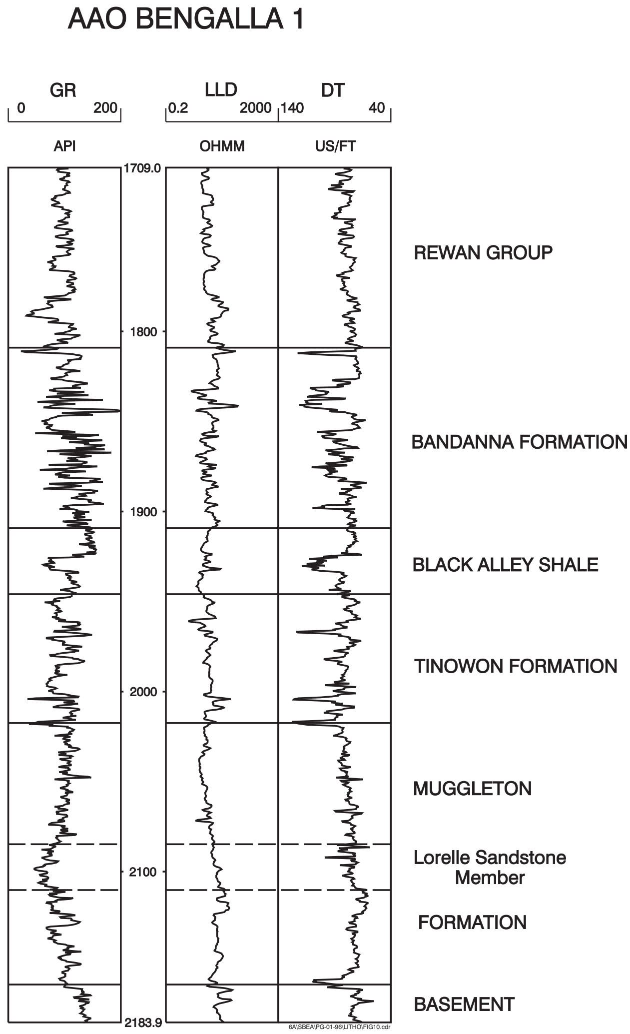

Figure 13: Wireline log responses — Permian units, western margin.

The Wallabella Coal Member consists of coal, with interbedded shale, siltstone, tuff and minor sandstone, lithologically similar to the rest of the Tinowon Formation. Sandstones in this Member tend to have a slightly larger grain size than the rest of the formation.

Relationships and Boundary Criteria

The Tinowon Formation conformably overlies the Muggleton Formation. Paten & Groves (1974) consider that the Tinowon Formation contains more coal than the underlying Muggleton Formation.

The top of the Tinowon Formation is placed at the top of a shelly horizon equivalent to the *Mantuan Productus* bed and represents the transition from fluvio-deltaic to restricted marine conditions of the overlying Black Alley Shale. This boundary corresponds to a change from mainly sandstone to mudstone.

The Tinowon Formation is the correlative of the coal measures at the bottom of the Burunga Formation in the north-eastern and southern parts of the Taroom Trough.

Wireline Log Character

The wireline log responses for the Tinowon Formation are distinctive and display more character compared with the underlying Muggleton Formation (Figure 13). The gamma-ray log has a slightly higher baseline and the sonic and resistivity logs have more character which generally reflects the presence of coals.

Thickness

The thickness of the Tinowon Formation is generally in the order of 50 to 70m with a thicker development of 99m in AAO Meeleebee 1.

Age

Late Permian palynofloras of unit APP5 are associated with the Tinowon Formation (for example, AAO Meeleebee 1: SWC/1371.6m, core 9/1362.35-1362.5m; based on Evans, 1962a). Spinose acritarchs, suggesting a brackish to marine influence in the depositional environment, were reported in the higher sample, as well as in an assemblage recovered from SWC/1347.21m.

The APP5 index, *Dulhuntyispora parvithola*, was not recorded in the latter (Evans, 1962a), which is assigned a unit APP42 maximum age based on the documented occurrence of *Didecitriletes ericianus*. This assemblage nonetheless falls within the APP5 succession in AAO Meeleebee 1, as it is constrained by palynofloras of that age.

Depositional Setting

The occurrence of marine fossils and coal at various levels in the Tinowon Formation suggests deposition in a deltaic setting. The presence of spinose acritarchs also suggests a brackish to marine influence. The greater diversity of rock types compared with those of the underlying Muggleton Formation, indicates a more shoreward depositional environment.

The relatively thick and continuous Wallabella Coal Member represents extensive coal swamp development associated with deltaic

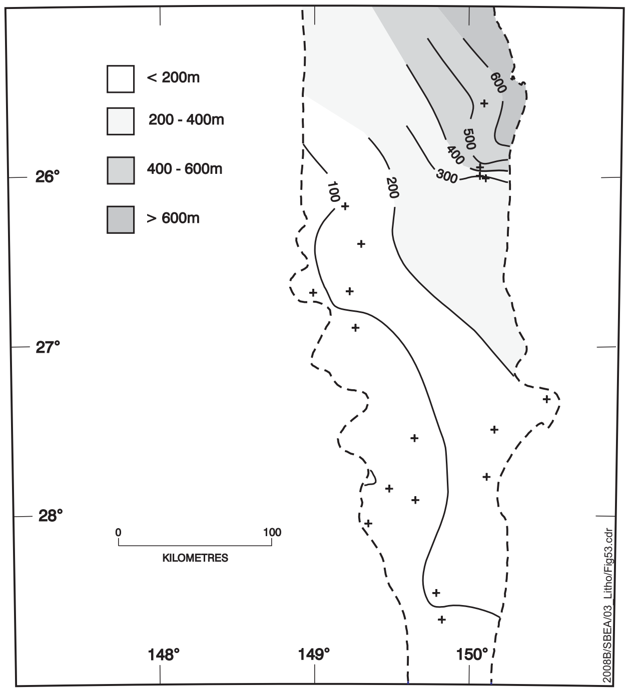

Figure 14: Isopach map — Banana Formation/Muggleton Formation interval.

progradation. The sediment to build the delta was sourced from the Roma Shelf to the west. A source in this area (from granite and low-grade metamorphics) explains the more quartzose composition of the formation in comparison with the more labile Burunga Formation which was sourced mainly from the east (from volcanics).

The supply of clastic material into the sea was relatively synchronous and resulted in the development of coal swamps around the edges of the sea. The Tinowon Formation represents the initial development of coal swamps along the western margin.

Black Alley Shale

Nomenclature

Mollan & others (1969) used the name Black Alley Shale for a succession of dominantly black mudstones with white tuff beds overlying the Peawaddy Formation throughout the Denison Trough and on the Springsure Shelf. It conformably overlies the *Mantuan Productus* bed and has the P3c acritarch zone near its base. Paten & Groves (1974) traced the Black Alley Shale as far south as the Roma Shelf and they recognised the Winnathoola Coal Member as a thin prominent coaly zone occupying a medial position in the Black Alley Shale.

Rock Types

The Black Alley Shale consists of shale, siltstone, tuff and coal with minor sandstone.

Shale is grey to black, silty, tuffaceous, abundantly carbonaceous and may grade into coal. The shale is generally micaceous with minor pyrite. Siltstone is grey to black or brown, micaceous, carbonaceous and commonly pyritic. Tuff is commonly white to cream and soft.

The coal of the Winnathoola Coal Member is commonly black to brown, dull with minor pyrite. Sandstone associated with the Member is white to grey, medium to coarse-grained, friable in part and is composed of sub-angular to sub-rounded poorly sorted quartz grains and some lithics in a clay matrix. Minor calcareous cement is present (Paten & Groves, 1974).

A shell horizon, possibly equivalent to the Mantuan Productus bed of the Denison Trough, underlies the Black Alley Shale in some wells.

Relationships and Boundary Criteria

The Black Alley Shale conformably overlies the Tinowon Formation on the western side of the Taroom Trough and Roma Shelf. The boundary with the overlying Bandanna Formation reflects the change from restricted marine and brackish depositional conditions to mainly fluvio-deltaic conditions.

The Black Alley Shale is the correlative of the marine middle part of the Burunga Formation in the southern and eastern parts of the Trough and of most of the Wiseman Formation in the north-east.

Wireline Log Character

The log character of the Black Alley Shale is not significantly different from that of the underlying Tinowon Formation. The Black Alley Shale has a slightly more blocky character reflecting the more uniform lithological composition of the formation. Differentiation of the formation using wireline-log responses is difficult (Figure 13).

Thickness

The Black Alley Shale in the study area has a restricted distribution being present mainly in the north-western and northern parts. In the north-west the formation is generally less than 50m thick. The formation thickens into the southern Denison Trough where it is commonly 100–200m thick. Further east it was found to be 358m in MPA Glenhaughton 1. The formation thins southwards and passes laterally into the Burunga Formation. The thickness of the Tinowon Formation/Burunga Formation — Black Alley Shale interval is shown in Figure 15.

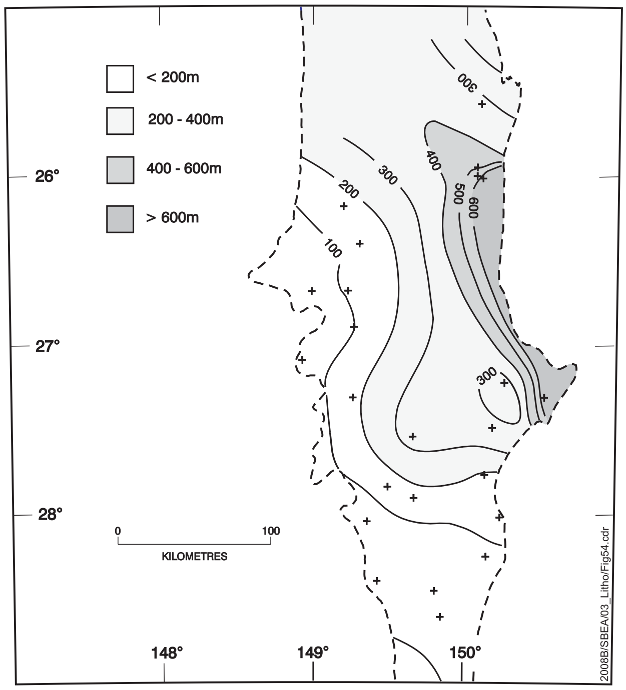

Figure 15: Isopach map — Tinowon Formation/Burunga Formation, Black Alley Shale interval.

Age

The Black Alley Shale is associated with Late Permian palynofloras of unit APP5 and encompasses the *Micrhystridium evansii* Acme-zone (Price, 1983; = unit P3c of Evans, 1962b), which has been recorded from the basal part of the formation or from the underlying upper Peawaddy Formation (*Mantuan Productus* bed) in the Denison Trough. In GSQ Eddystone 1, the upper part of the Peawaddy Formation has yielded abundant M. evansii (Heywood, 1978; McKellar, 1978), in the absence of the *Mantuan Productus* bed.

In assemblages characterised by the P3c acritarch swarm, *M. evansii* constitutes up to 90% of the palynomorphs present. Although this species has been recorded both lower and higher in the section and outside of the Denison Trough, it is only a minor component of assemblages (Price, 1983). In GSQ Mundubbera 5 and 6 (north-eastern Taroom Trough), *M. evansii* occurs throughout the

Barfield Formation-Baralaba Coal Measures interval, but acritarchs overall are not quantitatively major components of any assemblage [Foster (1982); recorded *Micrhystridium evansii* Price, 1983 as *Micrhystridium* sp. C, following the nomenclature of Foster (1979, page 110)].

Depositional Setting

The Black Alley Shale records the effects of a major transgression in the north-western and northern parts of the study area.

Mollan & others (1969) suggest that depositional conditions were variable. Acritarchs at the bottom of the formation suggests initial deposition was in a large basin with limited direct access to the sea, providing brackish-marine conditions. Final deposition was in a restricted freshwater lake. The Winnathoola Coal Member reflects the development of deltas along the eastern margin of the Roma Shelf.

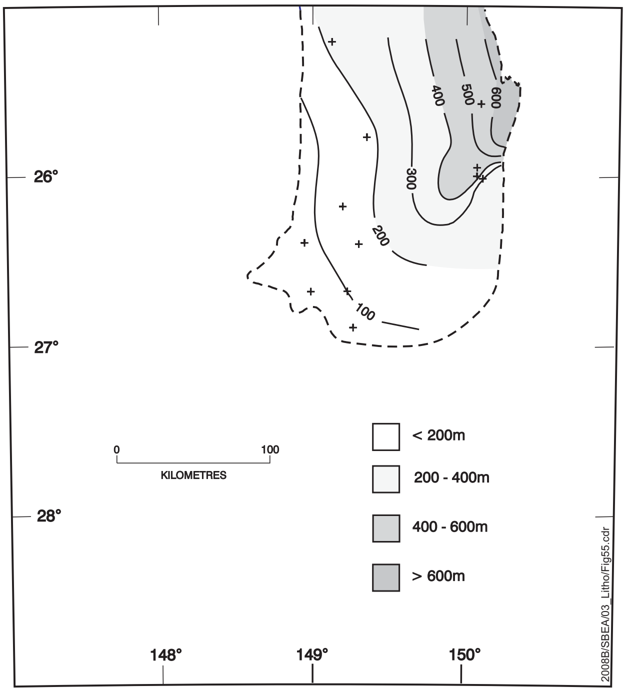

Figure 16: Isopach map - Bandanna Formation/Baralaba Coal Measures.

Bandanna Formation

Nomenclature

The Bandanna Formation of Shell (Queensland) Development Pty Ltd, was formally defined by Hill (1957) who recognised a lower dominantly shale interval and an upper dominantly sandstone and coal interval. It was named after Bandanna homestead near Carnarvon Gorge. Power (1967) restricted the name to the upper sandstone and coal interval of Hill (1957). The lower shale interval was subsequently named the Black Alley Shale by Mollan & others (1969). The two-fold subdivision of the Bandanna Formation into lower non coalbearing and upper coal-bearing subunits noted by Beeston & Draper (1991) in the Denison Trough, could not be recognised in the study area.

Rock Types

The Bandanna Formation consists of mudstone, siltstone, sandstone and coal.

The mudstone and siltstone are dominantly grey to dark grey with disseminated laminae of carbonaceous material. The sandstone is grey, white to cream, fine to medium-grained, fairly to well sorted, lithic labile with disseminated plant material. Clay matrix is common and a calcite cement is also present. Coal is black with varying amounts of interbedded mudstone.

Relationships and Boundary Criteria

The Bandanna Formation conformably overlies the Black Alley Shale. The contact between the two formations is gradational. Recognition of the Bandanna Formation in the south is dependent upon the development of the Black Alley Shale. Where the Black Alley Shale is absent, the Bandanna Formation cannot be distinguished from the underlying Tinowon Formation. The combined Tinowon Formation — Bandanna Formation interval in the south is referred to as the Burunga Formation.

The Bandanna Formation has been correlated southward from the Denison Trough to the Roma Shelf (Paten & Groves, 1974). The Bandanna Formation on the Roma Shelf has restricted distribution and is absent on the southern part.

The lowermost Bandanna Formation on the Roma Shelf is a correlative of the upper part of the Burunga Formation and the lower part of the Rewan Group in the south. The upper part of the Bandanna Formation is a correlative of part of the Baralaba Coal Measures in the east.

Wireline Log Character

The Bandanna Formation can be distinguished from the overlying Rewan Group on wireline logs but can be difficult to differentiate from the underlying Black Alley Shale or Tinowon Formation.

The main distinguishing feature on the logs relates to the coal seams which have the effect of inducing peaks and troughs reflecting low gamma-ray and high resistivity log values and slow sonic velocities (Figure 13).

Thickness

The Bandanna Formation is thickest in the northern part of the study area where it is 173m thick in COE Tiggrigie Creek 1. Along the north-western margin of the area, the formation has a thickness of between 50 and 100m. The regional thickness variation of the Bandanna Formation/Baralaba Coal Measures is shown in Figure 16.

Age

The Bandanna Formation embraces Late Permian palynofloras that are conformable with unit APP5 and, in the uppermost parts of the formation, unit APP6. In the Denison Trough, basal Triassic palynofloras of unit APT1 are associated with the youngest horizons of the Bandanna Formation (Price & others, 1985; also see de Jersey, 1979).

Depositional Setting

The Bandanna Formation is interpreted as having been deposited in a deltaic system infilling a large lake or land-locked sea represented by the Black Alley Shale (Beeston & Draper, 1991). The depositional setting of the Bandanna Formation in the Denison Trough was a lower noncoaly lower delta-plain with the upper part containing the major coal accumulations, representing the middle and upper delta plain. The similarity in the rock types and their distribution in the southern Taroom Trough suggests that this type of depositional setting probably existed for the formation in this area, although Beeston & Draper's (1991) twofold subdivision was not recognised.

The minor occurrences of spinose acritarchs reported from the Bandanna Formation by de Jersey (1979) suggest that brackish-water influences may have occasionally existed.

TRIASSIC

Rewan Group

Nomenclature

The term 'Rewan Series' was first used by Shell (Queensland) Development Pty Ltd (1952) and later by Isbell (1955) for the 'sandstones and unbedded clays lying below the Clematis sandstones' in the Carnarvon Range area. Hill (1957) referred to the Rewan Formation and Mollan & others (1964) considered the unit to be a synonym for the 'Rewan Series' of earlier workers. Mollan & others (1969) proposed a 515m thick type section of the Rewan Formation north of Rewan homestead, in the south-eastern part of the Springsure 1:250 000 Sheet area. The Rewan Formation was upgraded to group status after Jensen (1975) recognised two constituent formations; the Sagittarius Sandstone and the overlying Arcadia Formation.

In the subsurface in the south-eastern part of the Taroom Trough, a conglomeratic unit overlying Permian coal measures in UOD Cabawin 1 well was first referred to as 'Cabawin Formation' by Union Oil Development Corporation (1961). It was later described by Mack (1963). The Cabawin Formation was not recognised as a subdivision of the Rewan Group by Jensen (1975). The conglomeratic intervals previously referred to as the Cabawin Formation are equated with and referred to as the Rewan Group in this report.

Rock Types

The type section of the Rewan Group is dominated by red-brown, green and khaki mudstones interbedded with green and khaki siltstones and fine to medium-grained, labile sandstones.

The Sagittarius Sandstone comprises light green-grey, calcareous, fine to medium-grained, rarely very coarse-grained lithic sandstones interbedded with green to brown mudstones and siltstones with scattered carbonaceous plant material. The sandstone contains numerous shale and siltstone clasts at some depths (Jensen, 1975).

The overlying Arcadia Formation consists dominantly of red-brown mudstone and silty mudstone interbedded with lesser amounts of green siltstone and very fine to medium-grained sandstone. The boundary with the underlying Sagittarius Sandstone is taken at the change upwards from dominantly sandstone to thick beds of red-brown mudstone.

The Cabawin Formation of Mack (1963) comprises conglomerate, conglomeratic sandstone and some mudstone.

The Rewan Group, in thick intersections in MPA Glenhaughton 1, COE Tiggrigie Creek 1 and EOC Muggleton 1, can be subdivided on wireline logs (in particular the sonic log) into three informal subunits (Figure 17). The lower and middle subunits, from cuttings, are dominantly green-grey siltstone and very fine-grained sandstone with minor red-brown mudstone. The middle subunit is a transitional zone where the rocks are generally finer grained, and red-brown mudstones are more abundant towards the top. The upper subunit comprises mainly red-brown mudstone with minor green-grey siltstone. In COE Tiggrigie Creek 1, the lower subunit comprises interbedded very fine to fine, occasionally coarse to very coarse-grained lithic sandstone and siltstone and the upper subunit comprises mainly mudstones and siltstones with minor very fine to fine-grained sandstone.

Cuttings descriptions from EOC Muggleton 1 suggest that the lower and middle subunits may be equivalent to the Sagittarius Sandstone and the upper subunit to the Arcadia Formation.

Sandy intervals, 23m and 169m thick, occur at the top of the Rewan Group in COE Inglestone 1 and UOD Wandoan 1 respectively. In COE Inglestone 1, the interval consists of conglomeratic sandstones, siltstones and shales. The sandstones are generally quartzose, lithic in part, and have a white clay matrix. Varying amounts of volcanic fragments are included in the sandstones. The siltstones and shales are grey-brown and fawn to grey respectively. Shale is more common in the upper part of the interval and in COE Inglestone 1, 7m of fawn to brown shale is interpreted to form the top of the Rewan Group. A shaly interval also occurs at the top of the Rewan Group in UOD Wandoan 1.

On wireline logs alone, the sandy interval in the COE Inglestone 1 could be included with the Clematis Group/Showgrounds Sandstone.

Relationships and Boundary Criteria

The Rewan Group extends westward into the Galilee Basin and then as far north as the Hughenden – Pentland area where it forms the lower part of the Warang Sandstone. In the Bowen Basin, its eastern extent is limited by the Goondiwindi – Moonie and Burunga – Leichhardt Faults.

The Late Permian to Early Triassic Rewan Group (Foster, 1983) conformably overlies the Bandanna Formation and Baralaba Coal Measures over most of the Taroom Trough. Towards the margins and on the Roma Shelf, the relationship with the coal measures is considered to be unconformable (Price & others, 1985; Filatoff & Price, 1990; Fielding, Falkner & others, 1990).

The base of the Rewan Group has been placed at either the base of the Sagittarius Sandstone (equivalent to the Brumby Sandstone of Reeves (1947); Mollan & others (1969)), the base of the lowest red mudstone (Arcadia Formation) when the Sagittarius Sandstone is absent, or at the top of the highest coal seam of the underlying coal measures (Jensen, 1975). The most reliable criteria for selecting the base of the Rewan Group is at the top of the highest coal seam which has been used in the regional mapping of the Bowen Basin.

The boundary between the Rewan Group and the Clematis Group (Showgrounds Sandstone on the Roma Shelf) is taken where the fine-grained lithic rocks of the Rewan Group are overlain by the quartzose sandstone-dominated Clematis Group.

In many wells on the eastern side of the Taroom Trough, generally north of latitude 27°20′S, and in wells adjacent to the southern part of the Hutton – Wallumbilla Fault, the Early Jurassic Precipice Sandstone directly overlies the Rewan Group. The boundary between these two formations is placed where the predominantly lithic fine-grained sandstones, siltstones and mudstones of the Rewan Group change to fine to very coarsegrained, porous, quartzose sandstones of the Precipice Sandstone.

Wireline Log Character

The Rewan Group shows moderate to high gamma-ray log values, moderate resistivity log values and relatively fast to moderate sonic velocities. The resistivity log baseline of the

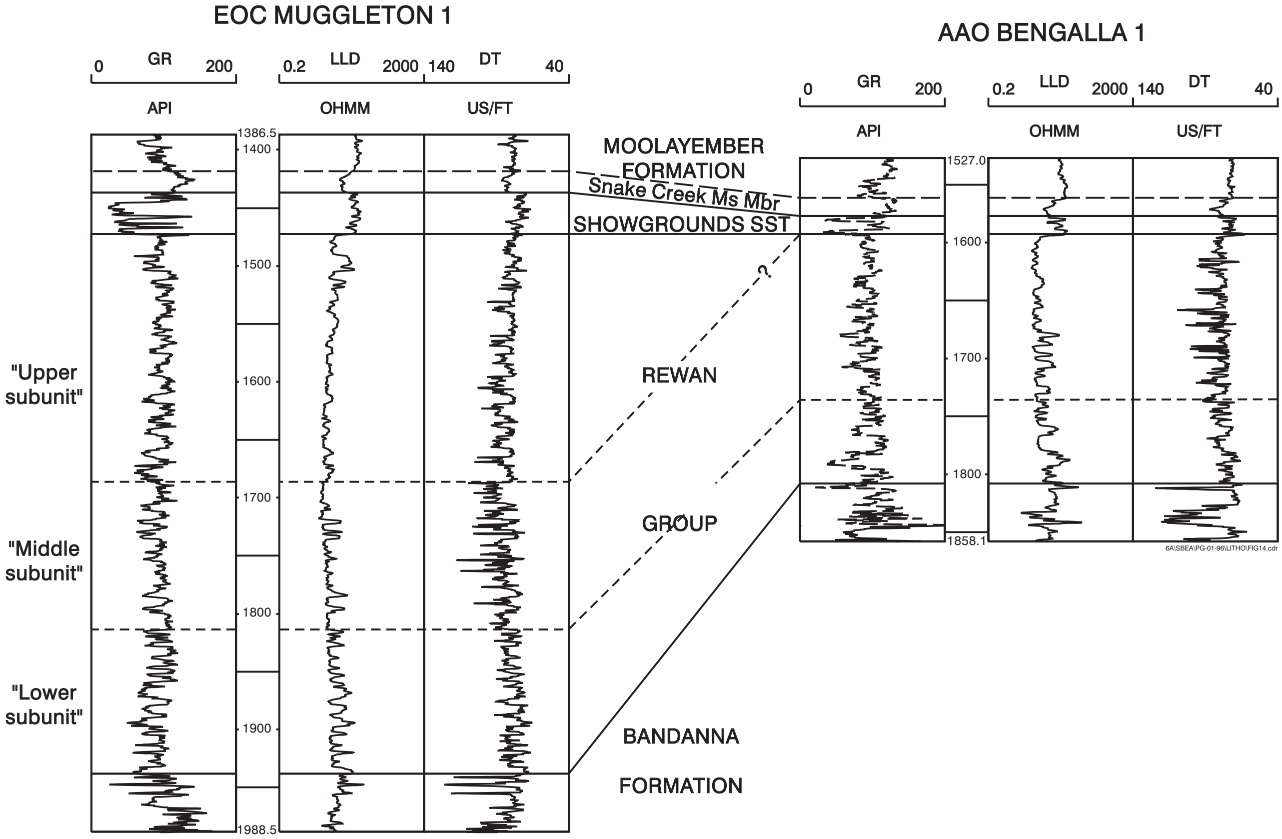

Figure 17: Informal subdivisions of the Rewan Group – Roma Shelf.

Rewan Group is generally lower and the gamma-ray log baseline higher than that of the overlying Triassic units (Figure 17).

The informal lower subunit of the Rewan Group displays wireline log characteristics similar to those of the middle subunit. The resistivity log of the lower subunit displays a slightly blocky character reflecting the thickly interbedded nature of the sandstones and siltstones. The middle subunit is characterised by a relatively 'noisy' sonic log and the slowest sonic velocities of the entire Rewan Group. The top of the middle subunit is identified on wireline logs by an abrupt change in character of the sonic log (Figure 17). In the upper subunit the gamma-ray log displays a relatively constant baseline although the resistivity log values tend to slightly increase towards the top of the interval as in EOC Muggleton 1 between 1472m and 1570m (Figure 17).

Subdivision of the Rewan Group may be used to identify areas where erosion has occurred. Such may be the case as shown in AAO Bengalla 1 (Figure 17) where the upper subunit of the Rewan Group is interpreted to have been eroded prior to deposition of the Showgrounds Sandstone.

Although the boundaries between these subunits may be unconformable, the nature of the boundaries cannot be deduced from wireline log data. Intra-Rewan Group unconformity surfaces have been interpreted from seismic data in the Raslie area on the Roma Shelf by Cosgrove and Mogg (1985). Results from seismic data used in this project confirm that unconformities are present within the Rewan Group on the Roma Shelf and also in the Taroom Trough.

Thickness

The maximum thickness intersected in the study wells is 1363m in UOD Wandoan 1. Isopachs show that the Rewan Group thickens in a north-easterly direction towards the Burunga – Leichhardt Fault (Figure 18).

Adjacent to the Goondiwindi – Moonie Fault further south, the Group also thickens in a northerly direction with a maximum thickness of 669m in UOD Cabawin 1. This suggests that in Rewan time, subsidence was greater in this direction. Thinning of the Group to the west and south-west suggests onlap onto the relatively stable Roma Shelf and Walgett Shelf.

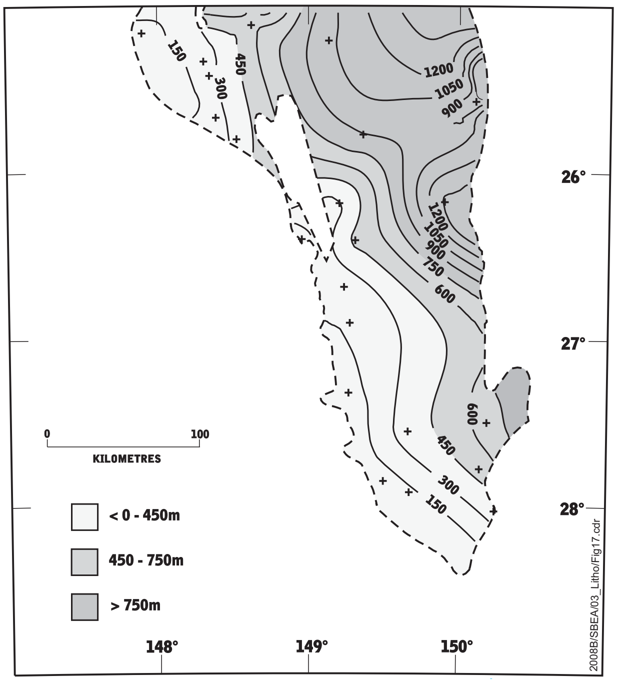

Figure 18: Isopach map – Rewan Group.

Uplift and erosion of the Rewan Group to the east of the Taroom Trough and in the vicinity of the northern Roma Shelf is indicated from truncation of the contours (Figure 18).

Age

The Rewan Group is generally associated with palynofloras conformable with units APP6, APT1 and APT2. In the Taroom Trough, according to Price & others (1985), basal sections of the Rewan Group have been assigned to (uppermost) unit APP5, but, on the Roma Shelf, an hiatus of variable magnitude, largely involving parts of the APP6-APT1 succession, has been recorded at the boundary with the underlying Bandanna Formation. The Rewan Group is of latest Permian to Scythian (Early Triassic) age (Burger & others, 1992).

Depositional Setting

Jensen (1975) interpreted that the Rewan Group was deposited by meandering and anastomosing channel systems in the same drainage basin as the underlying coal measures. In the northern part of the study area, palaeocurrents were directed generally towards the north. Kassan (1993, page 52) considered that the Rewan Group was deposited in fluvial and lacustrine environments in an internally drained, rapidly subsiding basin.

In the south-eastern part of the area, conglomerates of probable alluvial fan origin (Cabawin Formation) were deposited as a result of contemporaneous uplift on the eastern side of the GoondiwindiMoonie Fault system.

The climate during deposition of the Rewan Group was considered to be warm with arid or strongly seasonal rainfall conditions prevailing (Dickins, 1982). Minor occurrences of spinose acritarchs (de Jersey, 1979) are suggestive of occasional brackish influences in an otherwise terrestrial depositional regime.

Clematis Group

Nomenclature

The name Clematis Sandstone was introduced by Jensen (1926) for the quartzose sandstones between the 'Upper Bowen Beds' and the younger 'Ipswich Beds' north of Injune. Whitehouse (1955) nominated the type area as the gorge of Clematis Creek in the Expedition Range south-east of Rolleston. Jensen (1975) raised the Clematis Sandstone to group status and formally subdivided the group into the Glenidal Formation and the overlying Expedition Sandstone. No angular discordance was observed by Jensen (1975) between the two formations.

On the Roma Shelf the interval referred to as the Showgrounds Sandstone in the subsurface is generally accepted as being equivalent to the upper part of the Clematis Group or Expedition Sandstone.

Showgrounds Sandstone: The Showgrounds Sandstone was first recognised and named, but not formally defined, in AAO 4 (Hospital Hill) well at Roma (Derrington & Mott, 1955). Traves & Thralls (1960) recognised the 'Showground Sandstone' as one of three Mesozoic gas sands in the Roma area. Traves (1966) equated the Showgrounds Sandstone with the Clematis Sandstone. Swindon (1968) considered the Showgrounds Sandstone to be equivalent to the upper part of the Clematis Sandstone, and to be unconformable on the Rewan Formation.

Rock Types

Clematis Group: In the Glenidal Formation (lowest Clematis Group), sandstone is more common than siltstone and mudstone. The sandstone is white to dark brown, very fine to medium-grained, and sublabile. Mudstone is generally red or red-brown and in part

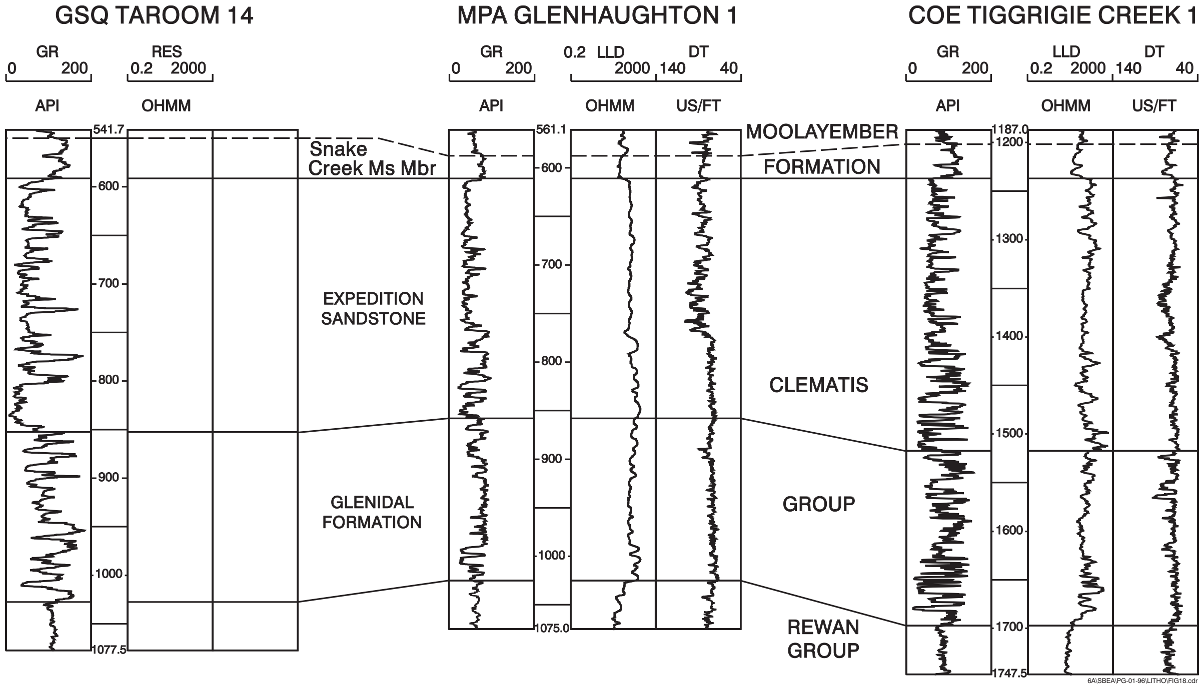

Figure 19: Formal subdivision of the Clematis Group.

yellow-green or grey, and carbonaceous. Siltstone is grey, mottled brown and red, laminated, generally micaceous and in part carbonaceous. The formation is characteristically thinly bedded.

The overlying Expedition Sandstone consists mainly of pale grey to white, medium to very coarse-grained, sublabile to quartzose sandstone, conglomeratic in part, interbedded with lesser amounts of fine-grained lithic and sublabile sandstone, siltstone and mudstone. The finer grained rocks are generally grey with some red siltstone and mudstone interbedded in the lower part.

Showgrounds Sandstone: The Showgrounds Sandstone is a pale grey to white, medium to very coarse-grained, poorly sorted, subangular, quartzose sandstone which is generally clean with a sugary texture (Gray, 1969). Subangular to angular granule to pebble conglomerates are also present.

An informal two-fold subdivision of the Showgrounds Sandstone into lower and upper intervals can be recognised in the south-western part of the Taroom Trough. The lower interval comprises medium to coarse-grained quartzose sandstones and the upper, sandstone, siltstone and shale. The latter has been cored in SOC Bellbird 1 (Lawrence, 1984) and CON Rednook 1 (Wiltshire, 1988). The upper interval grades upwards from a fine to medium-grained light grey quartzose sandstone to interbedded fine-grained quartzose sandstone, siltstone and shale, and finally to dark grey siltstone and dark brown-grey to grey shale.

Relationships and Boundary Criteria

Clematis Group: The Clematis Group extends westward into the Galilee Basin and then as far north as the Hughenden – Pentland area where it forms the middle or upper part of the Warang Sandstone. In the Bowen Basin it's eastern extent is limited by the Goondiwindi – Moonie and Burunga – Leichhardt Faults.

Jensen (1975), Exon (1976) and Stevens & McClung (1983) concluded that the Clematis Group generally overlies the Rewan Group conformably. However, in the Springsure 1:250 000 Sheet area, Mollan & others (1969, p50) stated that the Clematis Sandstone is apparently disconformable on the Rewan Formation at outcrop. On the basis of a marked change in the wireline log character, it appears that the boundary between the Rewan and Clematis Groups may be unconformable over most of the basin, excepting the deepest parts. An unconformable relationship is supported by a distinct change in sandstone composition over this boundary in most areas (Phillips, 1960; Gray, 1984; Elliott, 1993).

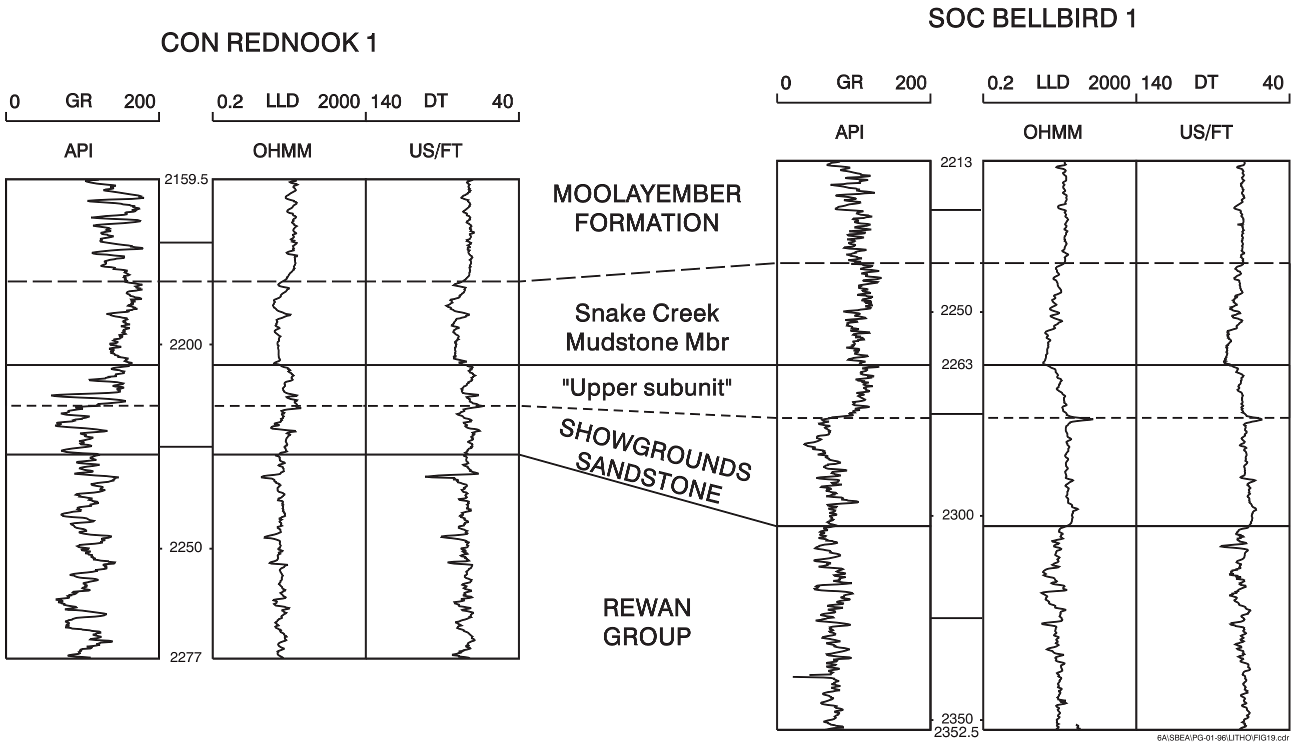

Figure 20: Wireline log responses - Showgrounds Sandstone.

The Clematis Group cannot be subdivided into Glenidal Formation and Expedition Sandstone other than in the northern part of the Taroom Trough. The wells in the study area in which these formations have been identified include GSQ Taroom 14, MPA Glenhaughton 1 and COE Tiggrigie Creek 1 (Figure 19).

Showgrounds Sandstone: Although the Clematis Group is believed to rest conformably on the Rewan Group in the deeper parts of the basin, the Showgrounds Sandstone unconformably overlies the Rewan Group and older units on the Roma Shelf and south-western flanks of the Trough.

The top of the Showgrounds Sandstone is taken where the quartzose sandstones are overlain by the dark grey to black shales of the Snake Creek Mudstone Member of the Moolayember Formation, or rarely, where the latter is absent, by the generally sublabile to lithic sandstones, siltstones and mudstones of the Moolayember Formation.

Wireline Log Character

Clematis Group: The mainly quartzose sandstones of the Clematis Group are represented by predominantly low gamma-ray log values, moderate to high average resistivity log values, and in some wells, a marked increase in sonic velocities (Figure 19). The Expedition Sandstone exhibits a lower gamma-ray log baseline compared with the underlying Glenidal Formation (Figure 19).

The upper boundary of the Clematis Group is recognised from wireline logs primarily where there is a marked decrease in the resistivity log response, a decrease in sonic log velocities and an increase in the gamma-ray log response (Figure 19).

Showgrounds Sandstone: The Showgrounds Sandstone forms a good marker horizon with relatively high resistivity and low gamma-ray log values (Gray, 1986). The informal upper Showgrounds Sandstone interval of the south-western Taroom Trough displays relatively high gamma-ray and resistivity log responses and little or no variation in the character of the sonic log (Figure 20).

This upper interval is interpreted to be a transitional sequence from fluvially deposited medium to coarse-grained quartzose sandstones of the lower Showgrounds Sandstone (low gamma-ray and high resistivity log values) to lacustrine dark grey to black shales (high gamma-ray and low resistivity log values) of the Snake Creek Mudstone Member of the Moolayember Formation.

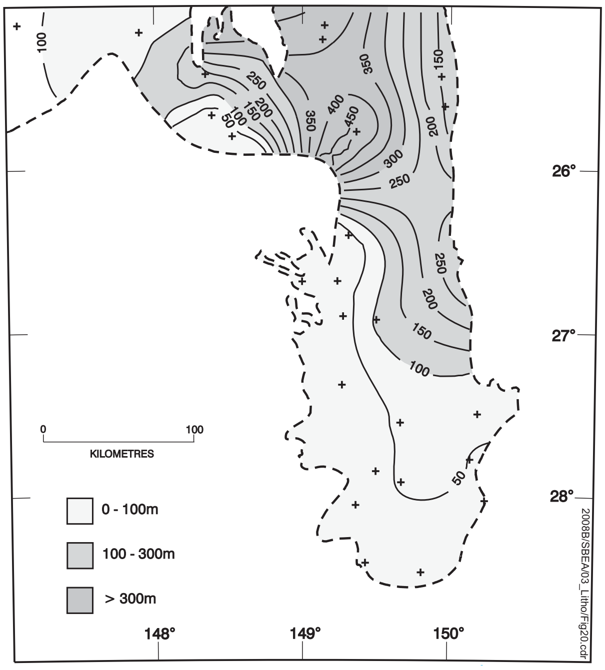

Figure 21: Isopach map - Clematis Group.

Thickness

The maximum thickness intersected in the study wells is 460m in COE Tiggrigie Creek 1 in the northern Taroom Trough. Isopachs indicate that the Group generally thins towards the east and south of COE Tiggrigie Creek 1 (Figure 21). In the southern and south-western parts of the Taroom Trough and on the Roma Shelf, the Clematis Group (Showgrounds Sandstone) is generally less than 40m thick.

Progressive onlap of sediments onto the Walgett Shelf and to the south probably reflects tectonic stability of the cratonic margin in these areas. Erosion of the Clematis Group (Showgrounds Sandstone) has occurred in the northern part of the Roma Shelf due to movement on the Hutton-Wallumbilla high-angle reverse fault.

Age

Palynofloras of the Clematis Group are of late Early to early Middle Triassic age and are attributable to the upper part of unit APT2 and the lower part of unit APT3. In COE Tiggrigie Creek 1, assemblages recorded by Hekel (1984) and associated with the Glenidal Formation embrace unit APT2, and those associated with the Expedition Sandstone, unit APT2 and the lower part of unit APT3 (probably APT31, but older than APT33). Palynological data from the Glenidal Formation and Expedition Sandstone in GSQ Taroom 14 (Harris, 1986) indicate APT22 and APT31 ages respectively.

Palynofloras derived from the Showgrounds Sandstone in SOC Bellbird 1 (McMinn, 1984, Pickering, 1986) suggest an APT31-32 age for the formation. However, based on Pickering's sample at 2274.7m, the lower part of the Showgrounds Sandstone may be as old as APT22, but this is uncertain, as the absence of APT3 indices may be more apparent than real. Additional sample control is required. Price (this volume) has indicated an APT31 age for the Showgrounds Sandstone.

Depositional Setting

Clematis Group: Jensen (1975) interpreted that sediments of the Glenidal Formation were deposited by meandering streams in a flood plain environment and those of the Expedition Sandstone by braided streams.

Showgrounds Sandstone: On the basis of grainsize and angularity, Hogetoorn (1970) interpreted that the Showgrounds Sandstone was deposited by streams flowing in an easterly direction from a granitic terrain to the west. Exon (1976) considered that the Showgrounds Sandstone was also partially derived from the quartzveined Timbury Hills Formation.

The depositional environment of the Showgrounds Sandstone was also interpreted to be fluvial with some marine influences suggested by the presence of acritarchs (Butcher, 1984; Schroder, 1988). Barrenger (1992) supported Butcher's (1984) interpretation and suggested that the main channels forming deltas, flowed easterly from the western side of the Taroom Trough. He also considered that the western depositional edge of the Showgrounds Sandstone generally coincides with the eastern limit of the granitic basement.

Moolayember Formation

Nomenclature

The Middle Triassic strata conformably overlying the Clematis Group at the top of the Bowen Basin succession were first referred to by Reeves (1947) as the 'Moolayember Shale'. Whitehouse (1955) specified the type locality as a series of road cuttings where the Carnarvon Highway descends to Moolayember Creek north of Injune. Phillips (1960) renamed the

'Moolayember Shale' the Moolayember Formation. Subsequently it was formally defined by Mollan & others (1972).

The Snake Creek Mudstone Member at the bottom of the Moolayember Formation, was first referred to as 'Subunit 9' by Mines Administration Pty Ltd (1963b) and was formally defined by Hogetoorn (1970).

Rock Types

The Moolayember Formation in its type area consists dominantly of interbedded olive, greenbrown and green-grey mudstones and lithic to sublabile, medium to coarse-grained sandstones. Other rock types include grey to black carbonaceous shale, siltstone, mudstone, coal, conglomerate and minor tuff and limestone. The Snake Creek Mudstone Member on the Roma Shelf dominantly comprises dark grey to black mudstone with minor laminae and thin beds of very fine-grained quartzose sandstone (Hogetoorn, 1970).

A probable equivalent of the Snake Creek Mudstone in Basin Creek, 54km north-north-east of Injune, comprises grey to dark grey laminated siltstone and mudstone with several interbeds, from 50 to 250mm thick, of medium to very coarse-grained quartzose sandstone with megaripples (Gray, 1972). The megaripples are almost symmetrical with a wave length of about 1m and amplitude of 0.15m.

On the western side of the southern Taroom Trough, where the Moolayember Formation is about 250m thick, it can be subdivided informally into lower and upper subunits above the Snake Creek Mudstone Member (Figure 22). The lower subunit, which is from 100-120m thick, is dominated by fine to medium-grained sandstones and the upper subunit by siltstones, mudstones, sandstones and thin coal seams.

In the central and northern parts of the study area, where the Moolayember Formation is over 500m thick in COE Tiggrigie Creek 1 and MPA Glenhaughton 1, the formation cannot be subdivided as readily. The equivalent of the lower subunit may occur from 515 to 587m in MPA Glenhaughton 1 (Figure 2 in Gray (1985)). The equivalent of the upper subunit in this area, distinguished by low average resistivity values, consists mainly of interbedded shale, mudstone, siltstone, and very fine-grained sandstone with very minor tuff, coal and limestone. Individual channel sandstones, one of which produced a gas flow in COE Tiggrigie Creek 1, are also developed in this subunit.

On the eastern side of the Taroom Trough, pebbly sandstones, clast and matrix-supported polymictic conglomerates and lesser interbedded siltstones and mudstones occur in the lowermost 553m of the Moolayember Formation intersected in GSQ Taroom 13 (Gray, 1984). Further south, in the area adjacent to the northern part of the Burunga-Leichhardt Fault, conglomerates, minor fine to medium-grained sandstones and rare mudstones and siltstones constitute the lowermost 515m of the Moolayember Formation underlying the Surat Basin succession in GSQ Taroom 16 (Holmes, 1984).

Relationships and Boundary Criteria

The Moolayember Formation extends westward across the Springsure Shelf into the Galilee Basin. In the Bowen Basin its eastern extent is limited by the Goondiwindi – Moonie and Burunga – Leichhardt Faults.

The Snake Creek Mudstone Member conformably overlies the Clematis Group (and Showgrounds Sandstone) throughout most of the southern and western parts of the Taroom Trough and on the Roma Shelf. The top of the Snake Creek Mudstone Member is taken where the dark grey to black mudstone-dominated interval is overlain by fine to medium-grained sandstone, siltstone and mudstone.

The boundary between the Moolayember Formation and the unconformably overlying Precipice Sandstone of the Surat Basin is taken generally where fine to medium-grained lithic sublabile sandstones, siltstones and shales change upwards to porous fine to very coarse-grained quartzose sandstones.

Where the Evergreen Formation directly overlies the Moolayember Formation, the boundary is generally difficult to pick on lithological grounds because of very similar rock types. Palynological data greatly assists in determining the position of the boundary.

Wireline Log Character

The Snake Creek Mudstone Member is characterised by increasing resistivity and decreasing gamma-ray log values upwards. Gamma-ray log values for this Member are generally higher than for the rest of the

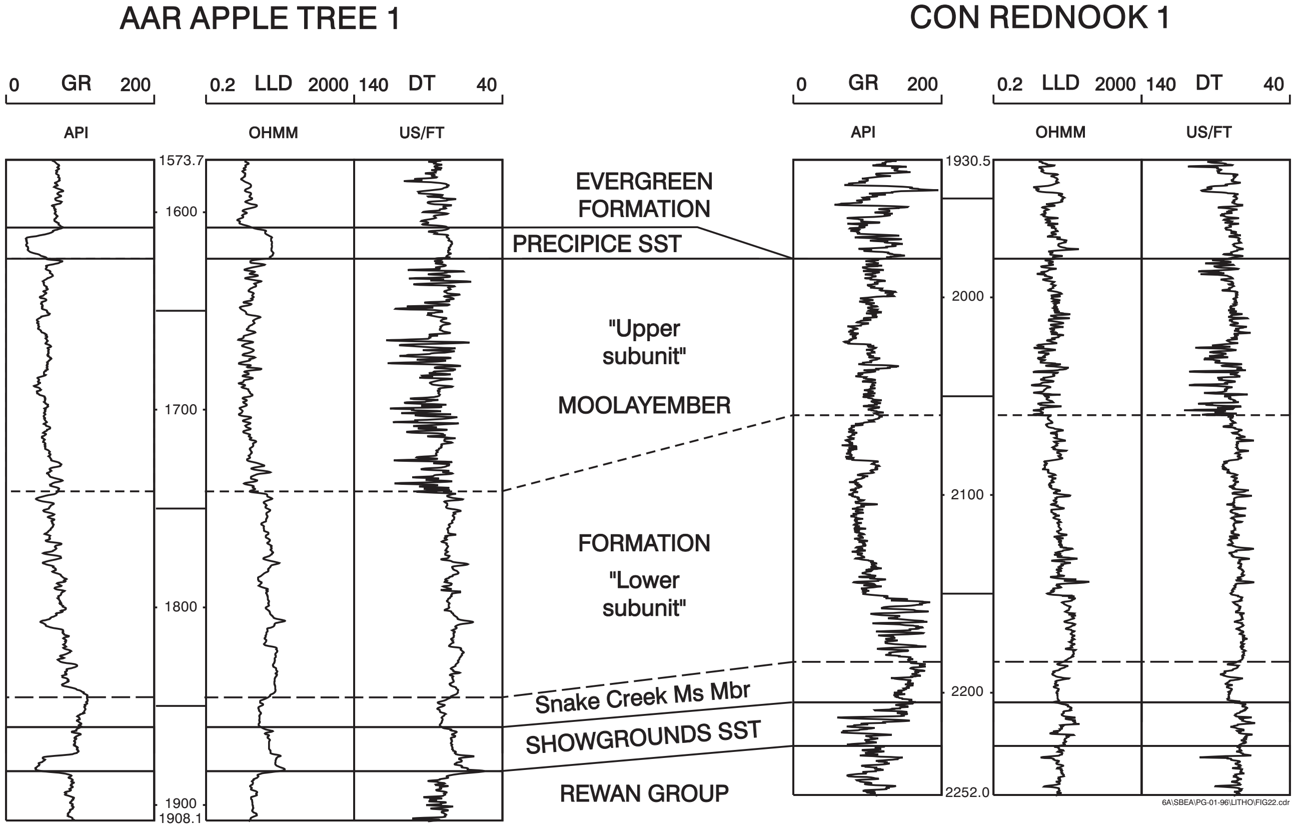

Figure 22: Wireline log responses – Moolayember Formation.

Moolayember Formation. Sonic velocities are generally slower than those of bounding units (Figure 22).

The informal lower subunit of the Moolayember Formation displays a slightly higher resistivity log baseline than that of the upper subunit and values tend to increase with depth. The sonic log response of the lower subunit displays velocities which are less variable than the upper subunit, reflecting the dominance of sandstone and the lack of coals in the lower subunit. In the lower subunit, gamma-ray log values generally increase with depth suggesting that the sandstones are more labile towards the bottom.

The boundary between the Moolayember Formation and the Precipice Sandstone is depicted on wireline logs by a generally marked change upwards to lower gamma-ray log responses (reflecting the cleaner, more quartzose composition), an increase in resistivity log values and generally more constant sonic velocities.

When the Precipice Sandstone is absent, the boundary between the lithologically similar Moolayember Formation and Evergreen Formation is difficult to pick on wireline logs.

Thickness

The maximum thickness of the Moolayember Formation (including Snake Creek Mudstone Member) intersected in the study wells is 736m in GSQ Taroom 16 in the north-eastern part of the area. The regional increase in thickness towards the eastern and north-eastern margins of the Taroom Trough (Figure 23) is due to greater subsidence and sediment accumulation on the down-thrown western side of the Burunga – Leichhardt Fault.

On the western side of the Goondiwindi – Moonie Fault, thinning of the formation from the axis of the Taroom Trough towards the south-east may indicate relative stability on this fault compared with the Burunga – Leichhardt Fault, during deposition.

The regional thickness trends of the Snake Creek Mudstone Member (Figure 24) are similar to those of the entire Moolayember Formation with a maximum of 41m in GSQ Taroom 14. Thickening of the Member in the eastern and northern parts of the Taroom Trough indicates that during its deposition, the basin was subsiding at a greater rate in these areas than elsewhere in the basin.

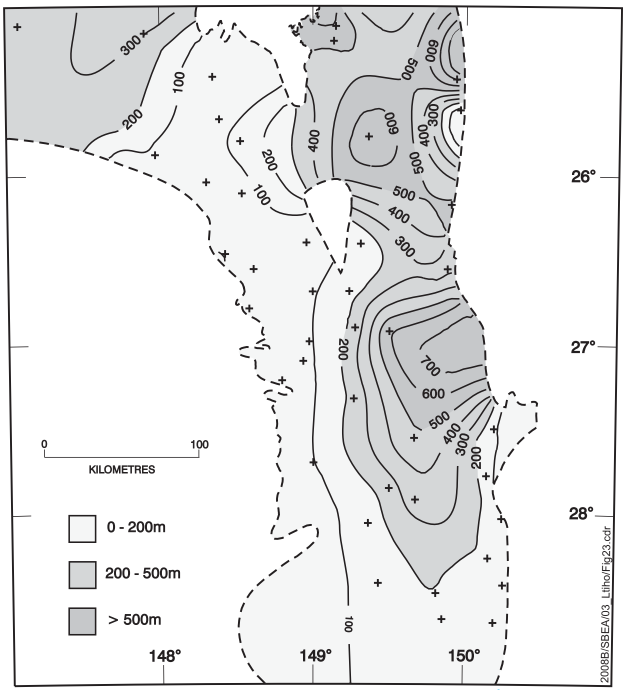

Figure 23: Isopach map – Moolayember Formation.

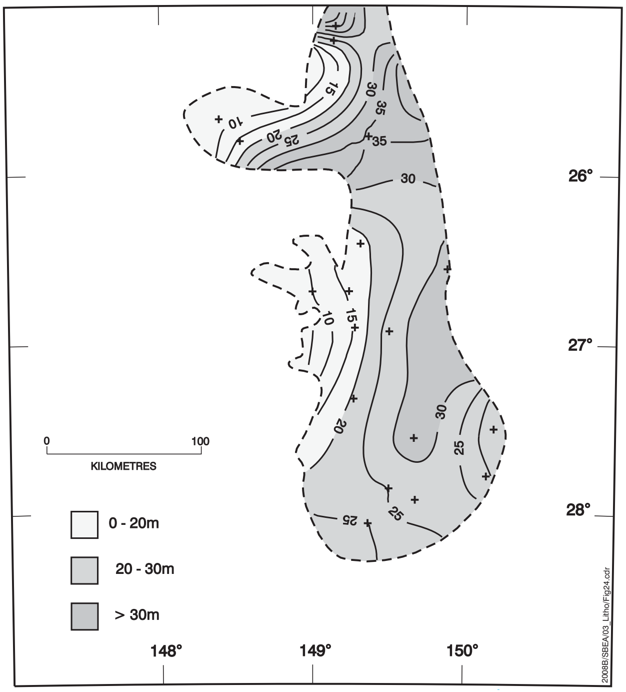

Figure 24: Isopach map – Snake Creek Mudstone Member.

Progressive onlap, as suggested by thinning of the Moolayember Formation onto the Roma and Walgett Shelves represents tectonic stability on the western margin of the Taroom Trough.

Age

Middle Triassic palynofloras from the Moolayember Formation are largely associated with the unit APT31-APT33 but in some regions, the uppermost part of the formation extends into unit APT34 (Price this volume). Assemblages from the Snake Creek Mudstone Member are conformable with units APT31-APT32.

Depositional Setting

The Moolayember Formation was deposited in a dominantly fluvial-lacustrine environment in an internally drained basin (Mollan & others, 1972). The Snake Creek Mudstone Member is interpreted by most workers to have been deposited under lacustrine conditions; interbedded coarse-grained sandstones with megaripples may reflect an estuarine or tidal channel environment (Alcock, 1969). Butcher (1984) interpreted a marginal marine or tidal flat environment of deposition for this Member.

The overlying informal lower and upper subunits are interpreted by Estensen (1984) to have been deposited by sandy braided and meandering distal river systems respectively. North-east of Taroom at outcrop, the lower part of the formation comprises thick conglomerates interpreted to have been deposited by fluvial systems sourced from elevated areas to the east (Alcock, 1969).

Kassan (1993) has suggested that a stream-dominated alluvial fan setting deposited the conglomerates intersected in the Moolayember Formation in GSQ Taroom 16. Brakel & others (1993) considered immature sediments entered the basin via marginal alluvial fans and were deposited in meandering stream and lake facies.

On the western side of the basin, acritarchs in abundances of up to 5% have been reported in the upper part of the Moolayember Formation in the Carnarvon Range area (Alcock, 1969), which provides evidence that at least brackish conditions prevailed during deposition of some horizons.

Wandoan Formation

The Wandoan Formation was defined by Union Oil Development Corporation (1962) in UOD Wandoan 1, with the type section from 1076 to 1468m, directly underlying the Precipice Sandstone. The Wandoan Formation was considered by Union to be younger than the Moolayember Formation and 'Clematis

Formation'. Petrological studies of samples from UOD Wandoan 1 by Fehr (1965), Bastain (1965), Bastain & Arman (1965), and palynological studies by de Jersey & Hamilton (1969) suggest however, that the Formation is equivalent to the Clematis Group and lower part of the Moolayember Formation.

Following its definition, the name Wandoan Formation was used by Union for strata between the Precipice Sandstone and their Cabawin Formation (Rewan Group) or Kianga Formation (Permian coal measures) in many wells throughout the basin. Wandoan Formation was also used by some companies for strata between the Precipice Sandstone and Showgrounds Sandstone on the Roma Shelf and western flanks of the Taroom Trough. Subsequent studies have shown that the Wandoan Formation in this sense is equivalent to the Moolayember Formation.

In the northeastern part of the study area where the Wandoan Formation was defined, the Clematis Group and Moolayember Formation are difficult to distinguish on wireline logs. This is supported by the comparison of the wireline logs from UOD Wandoan 1 with other wells in the area and with Departmental deep stratigraphic bores GSQ Taroom 13, 14 & 16 further to the north. There may be justification for retaining the name Wandoan Formation in this part of the basin. Generally, the names Clematis Group and Moolayember Formation are used where possible in this report, in preference to the name Wandoan Formation.

LITHOSTRATIGRAPHY - SURAT BASIN

The lithostratigraphic subdivision of the Late Triassic - Early Cretaceous succession of the Surat Basin is shown in Figure 25.

LATEST TRIASSIC

“Eddystone Beds”

Nomenclature

The occurrence of strata of latest Triassic age in the Surat Basin, where deposition is always considered to have commenced in the Early Jurassic, was originally recognised by McKellar (1978) from palynology undertaken in GSQ Eddystone 1. These latest Triassic strata were included in the lowermost part of the Precipice Sandstone because of similarity of rock types (Heywood, 1978). As a result of the age difference, these latest Triassic strata became informally known as the “Eddystone beds” (Price & others, 1985). Additional investigations on the geographic and stratigraphic distribution of these rocks are required before they can be named formally.

Rock Types

The latest Triassic strata consist mainly of sandstone, with mudstone and coal dominating the uppermost 2.6m of the interval in GSQ Eddystone 1.

The sandstone is white to cream, dominantly medium to coarse-grained (minor very coarse), fairly to poorly sorted, quartzose, with a white clay matrix. Minor mica fragments and a few carbonaceous siltstone laminae and carbonaceous fragments are scattered throughout. Well developed visible porosity is present in part. The mudstone is generally dark grey to brown and carbonaceous in part. A 0.3m thick bed of coal is associated with the mudstone in GSQ Eddystone 1.

Relationships and Boundary Criteria

The undifferentiated Late Triassic rocks unconformably overlie Early Triassic Rewan Group in GSQ Eddystone 1 and the Middle Triassic Moolayember Formation in GSQ Taroom 12–12A. The similarity of rock types with the overlying Precipice Sandstone makes recognition of these strata difficult and identification depends solely on palynology.

Recent palynostratigraphic investigations have shown that, in relation to the 'Eddystone beds' in GSQ Eddystone 1, rocks of a marginally later Triassic age are present in GSQ Taroom 12-12A located over 50km south-southeast (Price, 1995). Thus, the distribution of latest Triassic rocks in the Surat Basin may be more

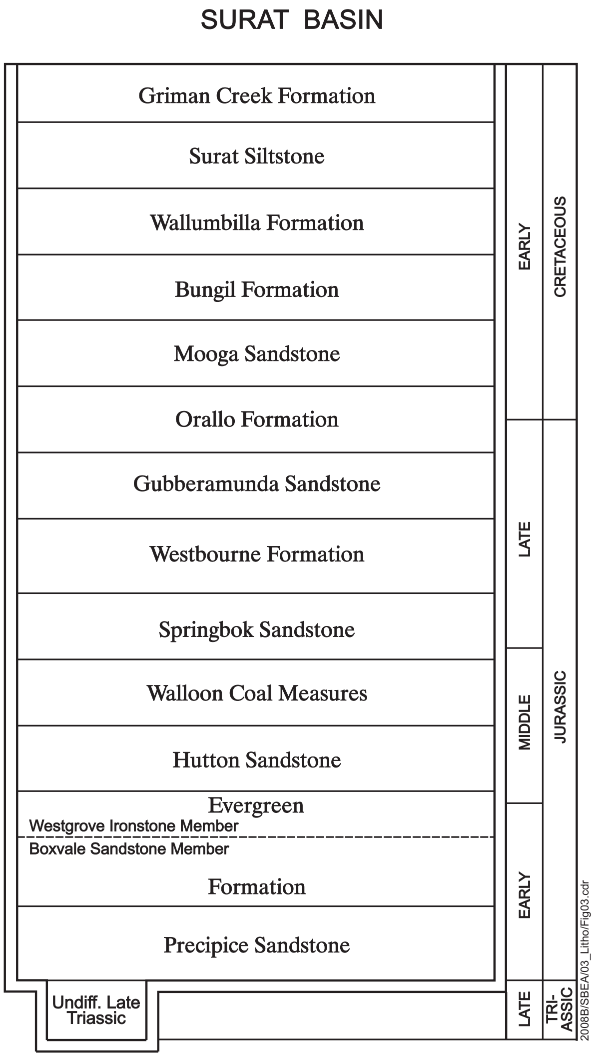

Figure 25: Late Triassic - Early Cretaceous stratigraphic units - Surat Basin.

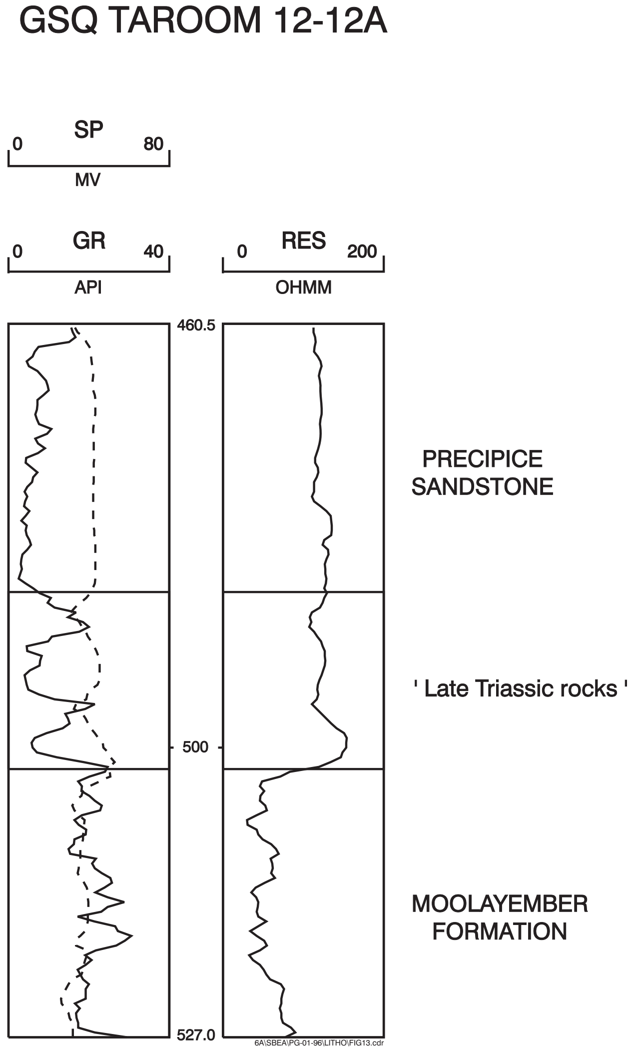

Figure 26: Wireline log responses - "Eddystone beds".

widespread and may have been deposited over a longer period than initially envisaged.

Wireline log character

The latest Triassic rocks are relatively thin and their wireline-log responses are not distinctive being similar to those of the overlying Precipice Sandstone. The gamma-ray log over the shale intervals in both bores has a low base line in comparison with the underlying units of the Bowen Basin (Figure 26).

High resistivity log values occur over the latest Triassic sandstones in GSQ Taroom 12–12A. There is no resistivity log for GSQ Eddystone 1.

Thickness

The latest Triassic rocks are over 11m and 16m thick in GSQ Eddystone 1 and GSQ Taroom 1212A respectively.

Age

Latest Triassic strata in GSQ Eddystone 1 are attributable to unit APT5211 of Norian–Rhaetian age. They were initially identified by a palynoflora [ascribed to Assemblage A of de Jersey (1976)], which, in the adjacent Moreton Basin, is associated with the Aberdare Conglomerate-Raceview Formation succession at the base of the Bundamba Group (McKellar, 1978). Heywood (1978) assigned these and the immediately overlying *Corollina/Classopollis*-rich strata (units APJ1-APJ2) strata in GSQ Eddystone 1 to the Precipice Sandstone, although a minor unconformity was indicated from the palynological data (McKellar, 1978).

This depositional scenario is broadly representative of the sequence in GSQ Ipswich 19-22R in the Toowoomba area, western Moreton Basin, where de Jersey (1976) recognised a hiatus of similar magnitude between Raceview Formation equivalents and the Ripley Road Sandstone. This is within the section referred to previously by de Jersey and other authors as the Helidon Sandstone.

In GSQ Taroom 12-12A, palynofloral assemblages equivalent to Assemblage B [(of de Jersey (1976) and assigned to units APT5212 (493.5m) and APT5213 (487.0m)] were recently encountered (Price, 1995; also see Price, this volume). These palynofloras were recovered from strata logged as Precipice Sandstone. Assemblage B embraces the Triassic-Jurassic boundary, which has been delimited palynologically by the first appearance of *Retitriletes austroclavatidites* (de Jersey & Raine, 1990, page 66).

As the above-cited Surat Basin palynofloras lack this species (Price, 1995), they are here regarded as latest Triassic (latest Norian-Rhaetian) in age. Assemblage B/APT5212-APT5213 palynofloras have not been recorded in the Surat Basin hither to, being documented only from the lower Ripley Road Sandstone in the eastern Moreton Basin (de Jersey, 1976). The possibility exists that a brief hiatus exists in GSQ Taroom 12-12A between the assemblages at 487.0m and the *Corellina/Classopollis*-rich strata at 436.45m, which were assigned to unit APJ1202 (Price, 1995). The immediately succeeding interval, corresponding to the time break within the Ripley Road Sandstone (Helidon Sandstone) in the western Moreton Basin is associated with the marked Hettangian regression referred to by Helby & others (1987) and Bradshaw & Yeung (1990).

Depositional Setting

The latest Triassic strata represent initial infilling of the undulate surface of the underlying Bowen Basin succession by fluvial and overbank deposits. The undulate topography probably developed during the Late Triassic, after major tectonic uplift and erosion. The slight difference in the latest Triassic ages of the rocks in the two stratigraphic bores suggests that there was more than one episode of erosion and infill.

The latest Triassic palynofloras are indicative of deposition in a continental environment.

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Precipice Sandstone

Nomenclature

The name Precipice Sandstone was first used by Whitehouse (1952) for the lowermost formation of the 'Bundamba Series'. The type area was later defined by Whitehouse (1955) as "the sandstone cliffs in the gorge of Precipice Creek, a tributary of the Dawson River”, approximately 50km north-east of Injune (Exon, 1976).

Rock Types

Mollan & others (1972) described the Precipice Sandstone in the type section in a tributary of the Dawson River near 'Fairview' homestead north-east of Injune, as consisting of thick-bedded, cross-stratified, fine to coarse-grained, pebbly quartzose sandstone with minor lithic sublabile sandstone, siltstone and argillite. Exon (1976) subdivided the Precipice Sandstone into a lower coarser subunit and an upper finer subunit. The lower subunit consists of white, fine to very coarse-grained, in part pebbly, thin to very thickly bedded, porous, quartzose sandstone with a white clay matrix. The upper subunit consists of fine to medium-grained, thinly bedded, sublabile, semi-porous sandstones and siltstones in which ripple marks, worm trails and leaf impressions are common. The Precipice Sandstone in this report is mostly equivalent to Exon’s (1976) lower subunit.

Relationships and Boundary Criteria

The Precipice Sandstone unconformably overlies Triassic or Permian units of the Bowen Basin and Devonian/Carboniferous basement rocks. The formation grades laterally into the Helidon Sandstone of the Moreton Basin to the east and the lower subunit is mostly absent on the Kumbarilla Ridge which separates the two basins in the subsurface. The Precipice Sandstone is absent on the Nebine Ridge and Walgett Shelf to the west and south-west, but extends into the Eromanga Basin across the Nebine Ridge at outcrop in the north-west where it is equivalent to the lower part of the ‘basal Jurassic’ unit. The top of the Precipice Sandstone is taken where the highest massive porous quartzose sandstone underlies the less porous sublabile sandstones and mudstones of the Evergreen Formation.

Deposition of the Precipice Sandstone represents the start of the first major sedimentary cycle in the Surat Basin.

Wireline Log Character

The Precipice Sandstone is characterised by a low gamma-ray log baseline, consistently high resistivity log values and a quiet sonic log response with fast sonic velocities. The change in the resistivity log response to the overlying Evergreen Formation can be either abrupt or gradual and reflects the porosity and permeability. The gradual change (Figure 27) occurs where sublabile sandstones of the lowermost Evergreen Formation with limited porosity and permeability overlie the Precipice Sandstone. The abrupt change normally occurs when sandstones of the overlying Evergreen Formation are sublabile to labile and have very low porosity and permeability.

The 2-fold subdivision identified at outcrop by Exon (1976) was found on the wireline logs of only a few wells. There was no obvious regional distribution on the basis of the wells selected.

Thickness

The Precipice Sandstone is thickest in the north-western, north-eastern and south-eastern parts of the study area (Figure 28). The maximum thickness intersected in the study wells is 106m in UOD Gurulmundi 1 in the axial part of the Mimosa Syncline. In the eastern part of the study area, thickest development of the Precipice Sandstone occurs in the axial part of the Mimosa Syncline. This reflects greater subsidence and sediment accumulation in this area in Precipice time. The Precipice Sandstone also reaches a thickness of up to 100m near its present outcrop limit in the north-western part of the study area.

Age

The Precipice Sandstone is generally attributable to units APJ1 and APJ22 (Late Hettangian to Sinemurian). The base of the Precipice Sandstone is also diachronous and generally youngs to the west, with basal strata being associated variously with units APJ1, APJ21 and APJ22, such that the Precipice Sandstone is not present in some areas and the Evergreen Formation rests unconformably on

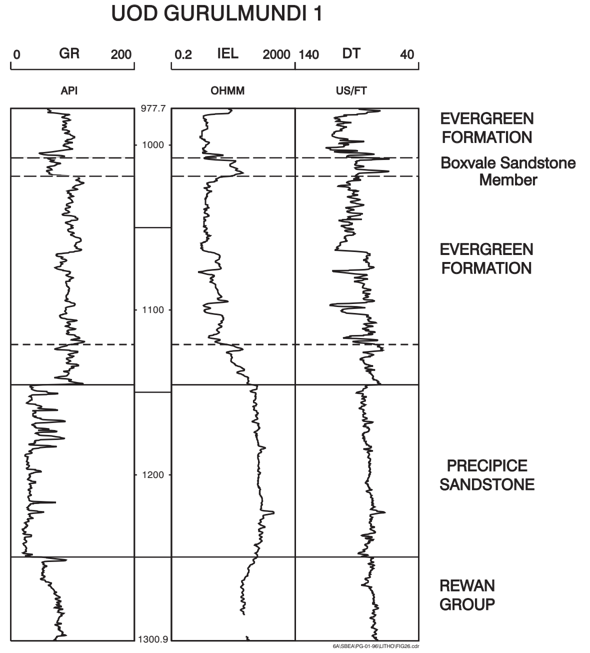

Figure 27: Precipice Sandstone/Evergreen Formation boundary - gradational change.

older strata. This younging trend is more apparent in a regional context, as the Precipice Sandstone is generally continuous in the east with the upper part of the Ripley Road Sandstone in the western Moreton Basin.

Depositional Setting

Martin (1981) interpreted that the Precipice Sandstone was deposited in transverse bars in a braided stream system, with stream flow being from west to east. He regarded the Precipice Sandstone as being a diachronous unit which transgressed to the west with deposition of the upper part on the Roma Shelf during the final stages. The sandstones on the Roma Shelf are finer-grained than in other parts of the basin and they represent a low-energy fluviatile meandering system. Sell & others (1972) interpreted that in the Roma area, the Precipice Sandstone was deposited by north-northeasterly flowing streams. Palynofloras from the Precipice Sandstone are indicative of deposition in a continental environment.

Evergreen Formation

Nomenclature

Whitehouse (1955) applied the name 'Evergreen Shales' to the shaly interval between the Precipice Sandstone and the Boxvale Sandstone of Reeves (1947) in the valley of the Dawson River, north of Injune. Jensen & others (1964)

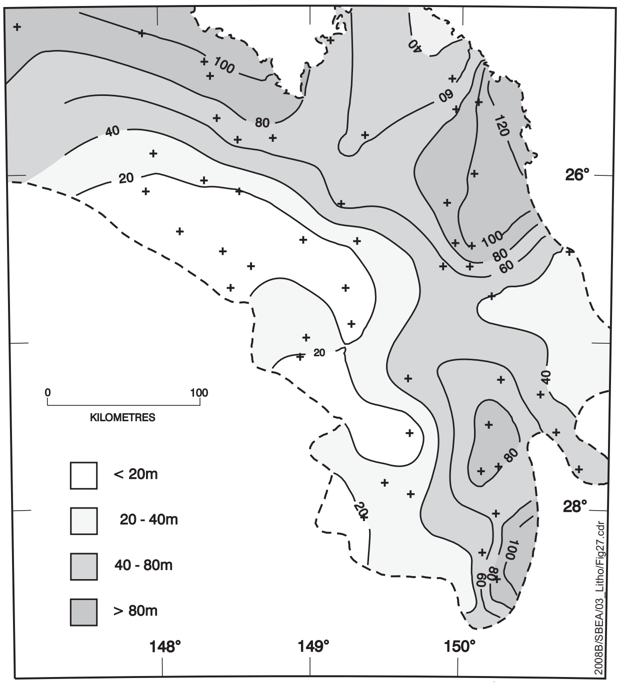

Figure 28: Isopach map — Precipice Sandstone.

defined the Evergreen Formation to include the 'Evergreen Shales' as the lower unit, the overlying Boxvale Sandstone as a member and an upper unit of mudstone, siltstone and sandstone containing an oolitic member at its base. Mollan & others (1965) named and described the latter as the Westgrove Ironstone Member. Mollan & others (1972) confined the Westgrove Ironstone Member to the western side of the Mimosa Syncline as it was found to wedge out at outcrop near "Currajong" homestead, west-north-west of Taroom. On the eastern side of the Mimosa Syncline east of Taroom, a prominent oolitic ironstone member occurs at approximately the same stratigraphic level in the Evergreen Formation. It has not been defined formally.

Rock Types

The Evergreen Formation below the Boxvale Sandstone Member comprises green-grey, labile and sublabile, fine to medium-grained sandstone, carbonaceous mudstone and argillite and minor carbonaceous siltstone, shale and coal. The Boxvale Sandstone Member commonly comprises thinly to thickly bedded, fine to coarse-grained, cross-bedded, quartzose sandstone, with some argillaceous clay matrix. Intervals of thinly bedded, very fine-grained, porous quartzose sandstone with carbonaceous siltstone, shale and coal interbeds also occur. The upper Evergreen Formation between the Boxvale Sandstone Member and the base of the Hutton Sandstone, mainly comprises dark grey

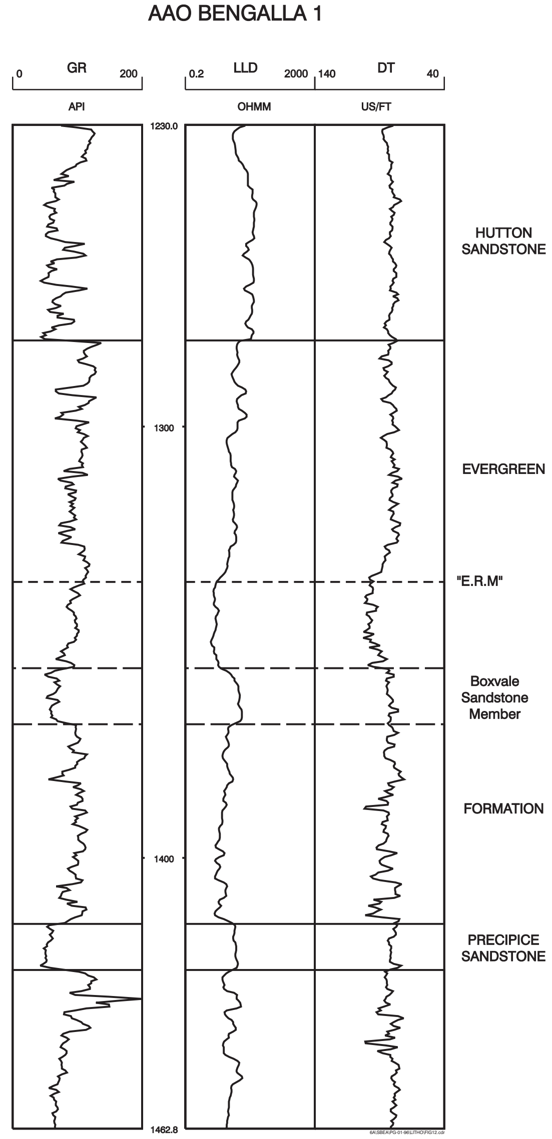

Figure 29: Wireline log responses — Evergreen Formation, western margin.

to black mudstone, laminated with sandstone, siltstone and shale and fine-grained, sublabile to labile sandstone. The Westgrove Ironstone Member forms the lower part of this interval and comprises interbedded mudstone and chamositic mudstone with a pelletal or oolitic structure and sideritic cement, and minor labile sandstone.

Over much of the area Evergreen Formation has a basal sandy interval characterised by mainly sublabile sandstones. In the past this interval commonly has been placed in the upper part of the Precipice Sandstone.

Sandstones in the basal part of the Evergreen Formation on the Roma Shelf are important petroleum reservoirs.

Relationships and Boundary Criteria

The Evergreen Formation conformably overlies the Precipice Sandstone and in some areas unconformably overlies Bowen Basin strata or pre-Permian basement. The formation is laterally continuous with the lower part of the Marburg Formation (new Sub-Group) in the Moreton Basin to the east (Gray, 1975) and with the 'basal Jurassic' unit in the Eromanga Basin to the west.

The top of the Evergreen Formation is taken where the labile sandstones, siltstones and mudstones of the Evergreen Formation are overlain by the sublabile porous and permeable sandstones of the Hutton Sandstone.

Mollan & others (1972) and Exon (1976), consider that the Boxvale Sandstone Member occurs only west of the axis of the Mimosa Syncline. In this investigation, the Boxvale Sandstone Member has been identified in the subsurface on both sides of the Mimosa Syncline.

Wireline Log Features

The Evergreen Formation exhibits low average resistivity log values, a high gamma-ray log baseline and a 'noisy' sonic log with moderate sonic velocities (Figure 29). The basal sandy interval has a high gamma-ray log response with respect to the underlying Precipice Sandstone and moderate to high resistivity values relative to the rest of the Evergreen Formation. The porous quartzose sandstones of the Boxvale Sandstone Member are characterised by a low gamma-ray and high resistivity log response. The Westgrove Ironstone Member does not display any characteristic wireline log features. Thin ironstone bands interbedded with mudstones and oolite bands exhibit small resistivity peaks in the oolite member in GSQ Chinchilla 4 on the eastern side of the Mimosa Syncline (Figure 30).

The Evergreen Resistivity Marker (ERM) is a feature on the resistivity log used as a reference horizon by many exploration companies on the western side of the basin. The ERM is a point of inflection about 30m below the top of the Evergreen Formation at which the resistivity log response decreases downwards to a uniform shale baseline for some 15m to 30m.

The Evergreen Formation-Hutton Sandstone boundary is distinguished generally by an

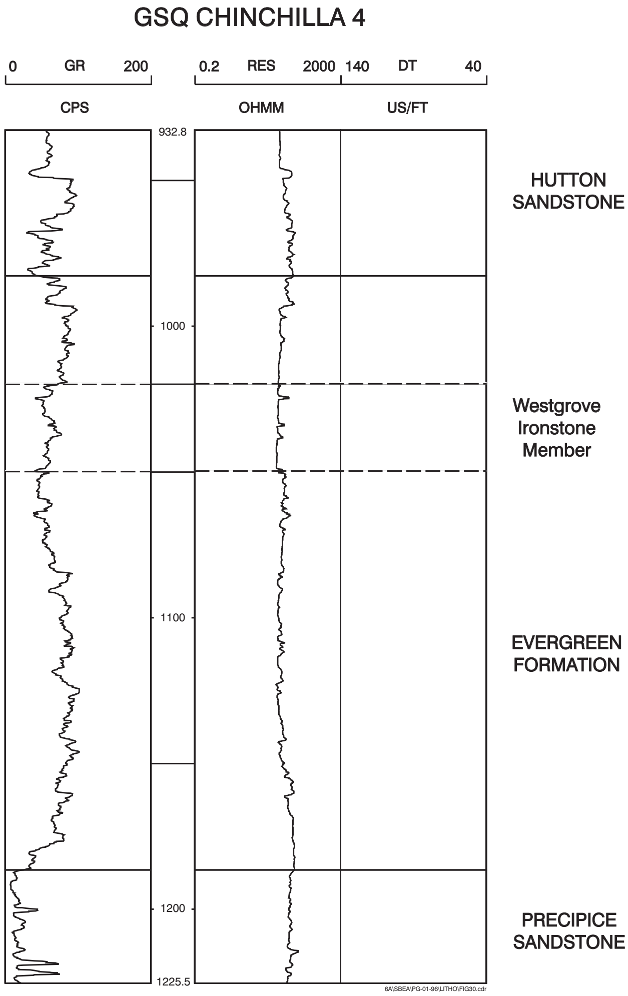

Figure 30: Wireline log responses — Evergreen Formation, eastern margin.

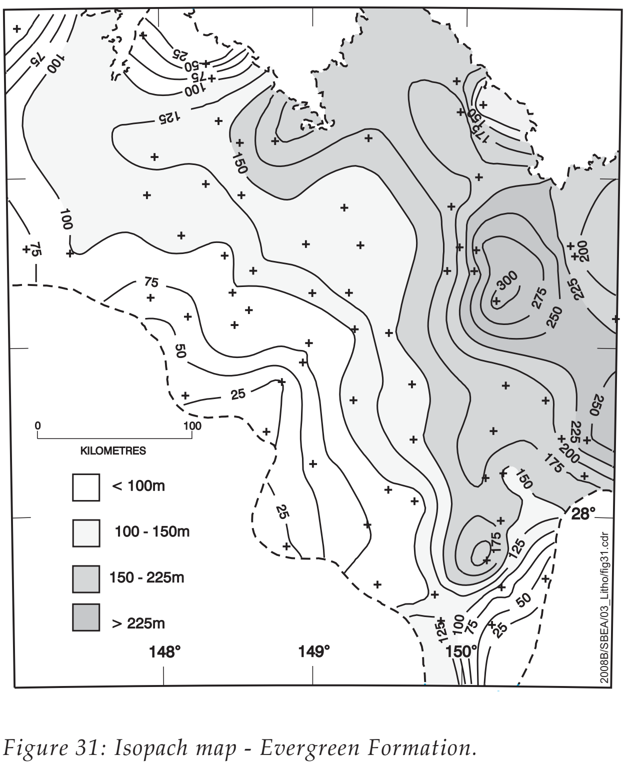

Figure 31: Isopach map - Evergreen Formation.

upwards decrease in gamma-ray log responses and an increase in resistivity values.

Thickness

The maximum thickness of the Evergreen Formation intersected in the study wells is 307m in GSQ Chinchilla 4, south of Miles. The main axis of deposition is the Mimosa Syncline with the thickest sections in the Miles area (Figure 31). Excluding the axial part of the Syncline, the Evergreen Formation is relatively thin in the north compared with the Precipice Sandstone. The areal extent of the Evergreen Formation increases in the south-western, southern and eastern parts of the study area, when compared with that of the Precipice Sandstone.

The gradual thinning of the Evergreen Formation to the south-west and south is due to onlap.

Age

Palynofloras from the Evergreen Formation are largely Pliensbachian–Toarcian in age and are associated with units APJ21 (uppermost part, if present), APJ22, and APJ3, with the APJ3-APJ4 boundary, based on the first appearance of *Retitriletes circolumenus*, occurring within the lower to mid-Hutton Sandstone. The appearance of *Staplinisporites manifestus* (normally within the Westgrove Ironstone Member) delimits unit APJ32, which extends into the succeeding upper Evergreen Formation. Approximately at the level of the lower Westgrove Ironstone Member and/or the underlying but partly coeval Boxvale Sandstone Member (and occurring within unit APJ31), a significant change, indicative of a major shift in environmental parameters, is featured in the palynological succession. In the main, this involves a very notable reduction in the frequency of Corollina/Classopollis pollen, which was employed by Evans (1966) to define the base of his unit J2.

Although spinose acritarchs (predominantly *Micrhystridium*/Baltisphaeridium) and leiospheres are common to abundant in the upper part of the unit associated with the Boxvale Sandstone and Westgrove Ironstone Members, (Evans, 1966; Paten, 1967a; Reiser & Williams, 1969; McKellar, 1974), definite fossil indicators of a marine environment are absent.

Depositional Setting

The Evergreen Formation below the Boxvale Sandstone Member is interpreted to have been deposited in freshwater lakes (Mollan & others, 1972) or by meandering streams in coastal plains and in deltas (Exon, 1976). Fielding (1989; cf. Browne & Hart, 1990) interpreted that the upper part of the Boxvale Sandstone Member was deposited as part of a prograding lacustrine delta system. He concluded that during deposition of the Boxvale Sandstone, the Surat Basin consisted of a series of small lakes fed by fluvial systems with associated deltas.

The Boxvale Sandstone Member has not been recognised in all wells and is commonly absent in those near the limit of deposition of the Evergreen Formation. This restriction is most likely due to a limitation of the 'Evergreen lake systems' which formed towards the centre of the basin. Fluvial systems flowing into the lakes and providing a source of sediments for the Boxvale Sandstone, would have occurred near the edges of the basin.

Mollan & others (1972), interpreted that the Westgrove Ironstone Member was deposited under shallow marine conditions based mainly on the presence of the ironstone oolites. Cranfield & others (1994) have shown the ironstone oolites in the Surat, Clarence-Moreton, Nambour and Maryborough Basins were deposited in a lake environment. Bradshaw & Yeung (1990, 1992) and Bradshaw & Challinor (1992) associated a paralic environment with the ironstone oolite facies. It was suggested that the rise of sea level to a peak in the mid Toarcian caused the inflow of brackish water into the lacustrine (lagoonal) systems of eastern Australia, but the contribution of freshwater from the surrounding hinterland of rivers, lakes and coal swamps prevented marine conditions from fully developing. Although such a scenario appears likely for the acritarch-bearing Boxvale Sandstone and Westgrove Ironstone Members (and adjacent acritarch-bearing strata of the Evergreen Formation), the occurrence of brackish, lacustrine-delta systems without connection to the sea cannot be discounted.

Along the eastern and western margins, the Evergreen Formation has a higher percentage of sandstone than in other areas. This is interpreted to reflect the distance from the sediment supply, with the coarser sediments being deposited at first around the edges of the basin and then the finer sediments being transported to the centre.

Hutton Sandstone

Nomenclature

The name Hutton Sandstone was first used by Reeves (1947) for the sandstones that form the sandy soils on Westgrove Station north-west of Injune. He regarded the Hutton Sandstone as the top member of the 'Bundamba Series'. Mollan & others (1965) redesignated the Hutton Sandstone to formation status. Mollan & others (1972) nominated a type section for the Hutton Sandstone near Hutton Creek, 19km east-northeast of Injune.

Rock Types

The Hutton Sandstone consists mainly of sandstone with interbedded siltstone and shale and minor mudstone and coal.

The sandstone is white to light grey, fine to medium-grained, well sorted, sublabile to quartzose, partly porous with some pebble bands and shale and siltstone clasts in the lower part.

Siltstone and shale are light to dark grey, micaceous, carbonaceous and commonly interlaminated with very fine-grained sandstone.

In the southern part of the study area, the lower Hutton Sandstone in the subsurface tends to have a higher percentage of siltstone and shale than the equivalent part in the north. As well, a distinct 2-fold subdivision is present in some wells (Figure 32), reflecting the presence of a lower mainly sublabile sandstone and siltstone subunit and an upper more quartzose sandstone and siltstone subunit.

Relationships and Boundary Criteria

The top of the Hutton Sandstone is taken at the top of the uppermost sublabile to quartzose sandstone below the sublabile to labile sandstones and mudstones of the Walloon Coal Measures or Eurombah Formation where present. The Hutton Sandstone is the most widespread Jurassic unit in the Great Artesian Basin and is continuous into, and forms the upper part of the Marburg Sub-Group in the Moreton Basin to the east. The formation extends westward into the Eromanga Basin. It

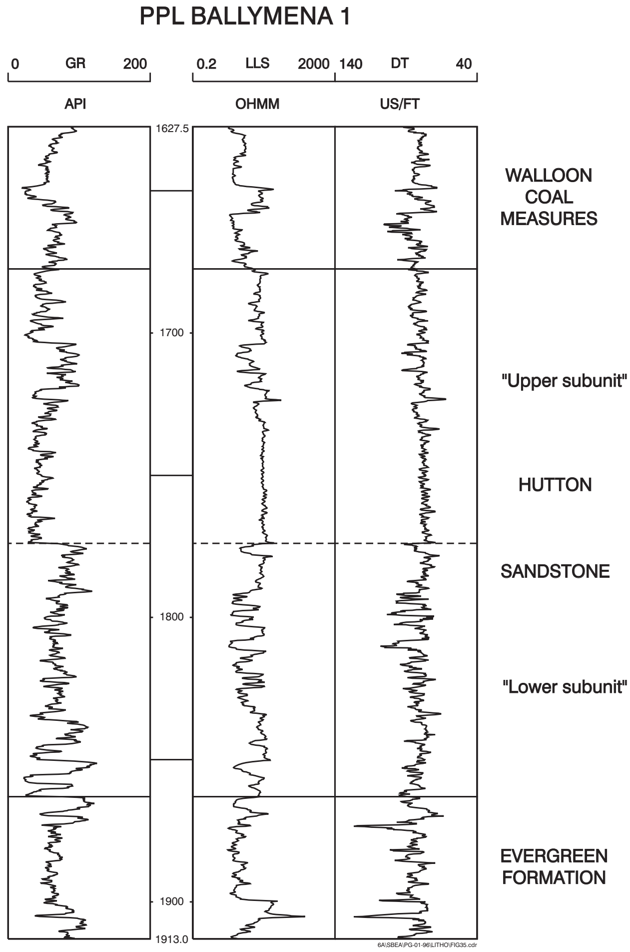

Figure 32: Informal subdivision in the Hutton Sandstone, southern part of the study area.

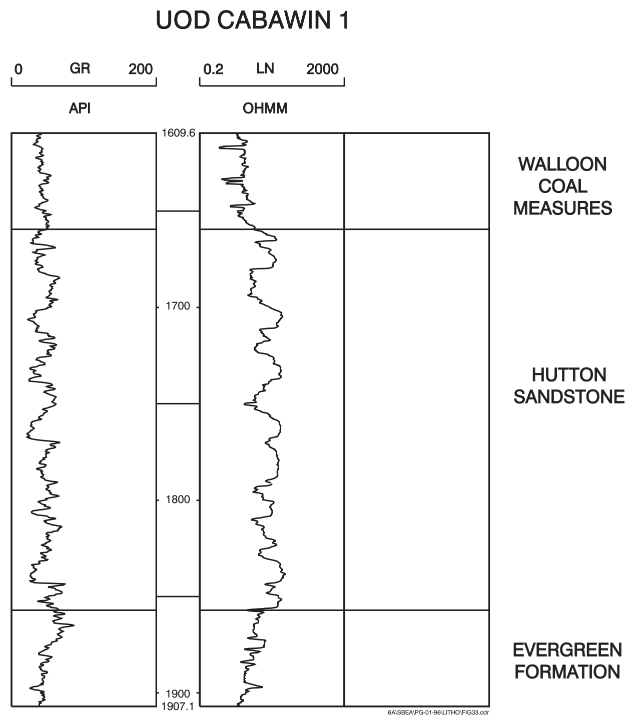

Figure 33: Wireline log responses - Hutton Sandstone, gradational resistivity top.

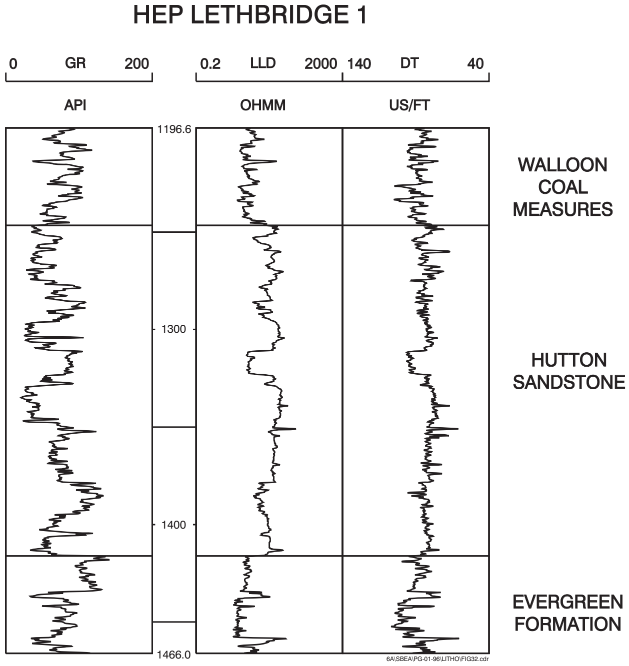

Figure 34: Wireline log responses — Hutton Sandstone, abrupt resistivity top.

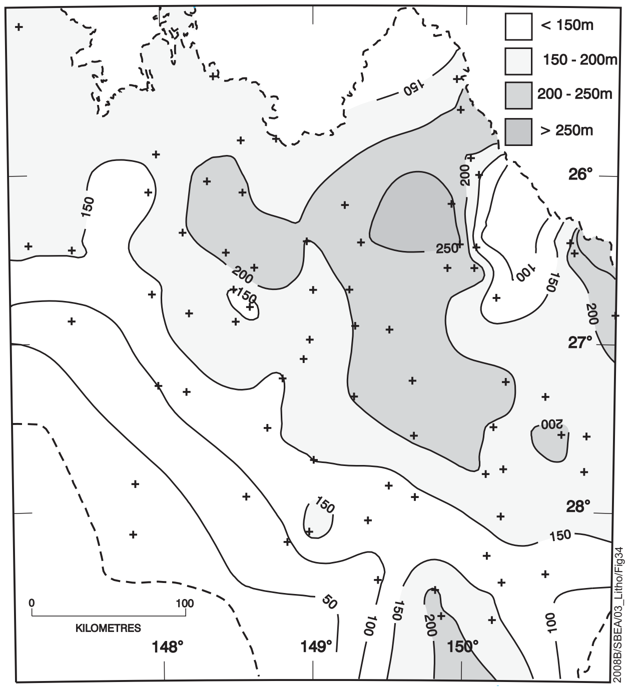

Figure 35: Isopach map — Hutton Sandstone.

overlaps basement rocks on the Walgett Shelf to the south-west. Deposition of the Hutton Sandstone represents the start of the second major sedimentary cycle in the Surat Basin.

Wireline Log Character

The Hutton Sandstone is characterised by high average resistivity log values, low 'sand baseline' gamma-ray log values and a sonic log which is quiet with fast velocities. The top of the Hutton Sandstone generally has an abrupt change in gamma-ray log response to higher values and either a gradational (Figure 33), or abrupt decrease in resistivity log values (Figure 34).

Thickness

The maximum thickness of the Hutton Sandstone intersected in the study wells is 266m in UOD Juandah 1, close to the axis of the Mimosa Syncline. Throughout most of the basin it is between 120 and 180m thick (Exon, 1976). There is a general thickening of the Hutton Sandstone along the axis of the Mimosa Syncline and towards the north (Figure 35).

Age

Palynofloral assemblages from the Hutton Sandstone are assigned to units APJ33, APJ41 and APJ42 of mid Jurassic (Aalenian to Bathonian) age.

Depositional Setting

Exon (1976) interpreted that the Hutton Sandstone was deposited by meandering streams on a broad floodplain with generally quartz-rich sediments sourced primarily from the north-east, south-east and south-west. The groundwater in the lower part of the formation commonly has a high concentration of sodium chloride, calcium sulphate and sodium carbonate. This suggests that the lower part of the formation, at least, may have been deposited in brackish water (Mollan & others, 1972). Non-marine environments are indicated from palynology.

Eurombah Formation

Nomenclature

The name Eurombah beds was first used by Exon & others (1967) to describe the thickly cross-bedded, fine to coarse-grained labile to sublabile sandstones and interbedded siltstones and mudstones outcropping in Eurombah Creek, north of Roma.

In this report, the Eurombah Formation has been included in the Walloon Coal Measures as it was not possible to consistently differentiate the Eurombah Formation from the Walloon Coal Measures. Additional work is required to determine the applicability of the formation.

Relationships and Boundary Criteria

Exon (1971) included the Eurombah beds in the bottom of the Injune Creek Group because of the presence of andesitic detritus which is common in sedimentary rocks of the Injune Creek Group but absent in the underlying Hutton Sandstone. Swarbrick & others (1973) elevated the Eurombah beds to formation status and defined the unit and nominated a type section from 27m to 120m in stratigraphic bore DRD 22, drilled near outcrop of the unit. Core of the type section consists of very fine to very coarse-grained, argillaceous sublabile sandstone and minor interbedded conglomerate and carbonaceous mudstone.

The Eurombah Formation sandstones are more labile than those of the Hutton Sandstone and less labile than those of the Walloon Coal Measures. The Eurombah Formation conformably overlies the Hutton Sandstone and is more restricted in extent than either the Hutton Sandstone or the Walloon Coal Measures.

Depositional Setting

The environment of deposition was interpreted to be mainly fluviatile with periods of rapid sedimentation.

Walloon Coal Measures

Nomenclature

Cameron (1907) used the name Walloon beds for the strata outcropping in the Walloon, Rosewood and Dugandan districts of the Clarence–Moreton Basin. Reid (1921) changed the name Walloon beds to Walloon Coal Measures when he mapped the Walloon-Rosewood Coalfield. Whitehouse (1955) nominated the type area as the mining region about the township of Walloon. The type section was designated by Cameron (1970) from 7m to 235m in drillhole N.S. 84 in the Ebenezer district.

In the north-eastern Surat Basin, Swarbrick (1973) subdivided the Walloon Coal Measures into six lithostratigraphic units. On the basis of this subdivision, Jones & Patrick (1979) raised the Walloon Coal Measures to Subgroup status and in stratigraphic order formally defined the Taroom Coal Measures, the Tangalooma Sandstone, and the Juandah Coal Measures.

Rock Types

In the Surat Basin, the Walloon Coal Measures in the subsurface consist of very fine to medium-grained, labile, argillaceous sandstone, siltstone, mudstone and coal, with minor calcareous sandstone, impure limestone and ironstone (Swarbrick, 1973). Typically, the coals are located in the upper half to three-quarters of the Measures, with mudstones, siltstones and lithic sandstones dominant in the lower part.

West of approximately longitude 148°30’E, the percentage of coal in the Walloon Coal Measures decreases markedly.

Relationships and Boundary Criteria

The Walloon Coal Measures conformably overlie the Hutton Sandstone.

The Walloon Coal Measures are laterally continuous with the Birkhead Formation of the Eromanga Basin, but the Birkhead Formation has little or no coal. Swarbrick (1973) placed the boundary between the two formations in the western part of the Surat Basin between Injune and the eastern flanks of the Nebine Ridge. In this report, it was not possible to draw a boundary between the two formations in the cross-sections. Instead, the boundary was found to be transitional (Figure 36). The present study suggests that the name Birkhead Formation should be restricted to the Eromanga Basin.

The top of the Walloon Coal Measures is taken at the topmost coal or thick mudstone interval below the sandstones of the Springbok Sandstone.

Wireline Log Character

The Walloon Coal Measures exhibit low average resistivity log values, high gamma-ray log values and a noisy sonic log with slow velocities owing to the coal seams (Figure 36).

Thickness

The maximum thickness of the Walloon Coal Measures intersected in the study wells is 507m in UOD Dulacca 1, in the axial part of the

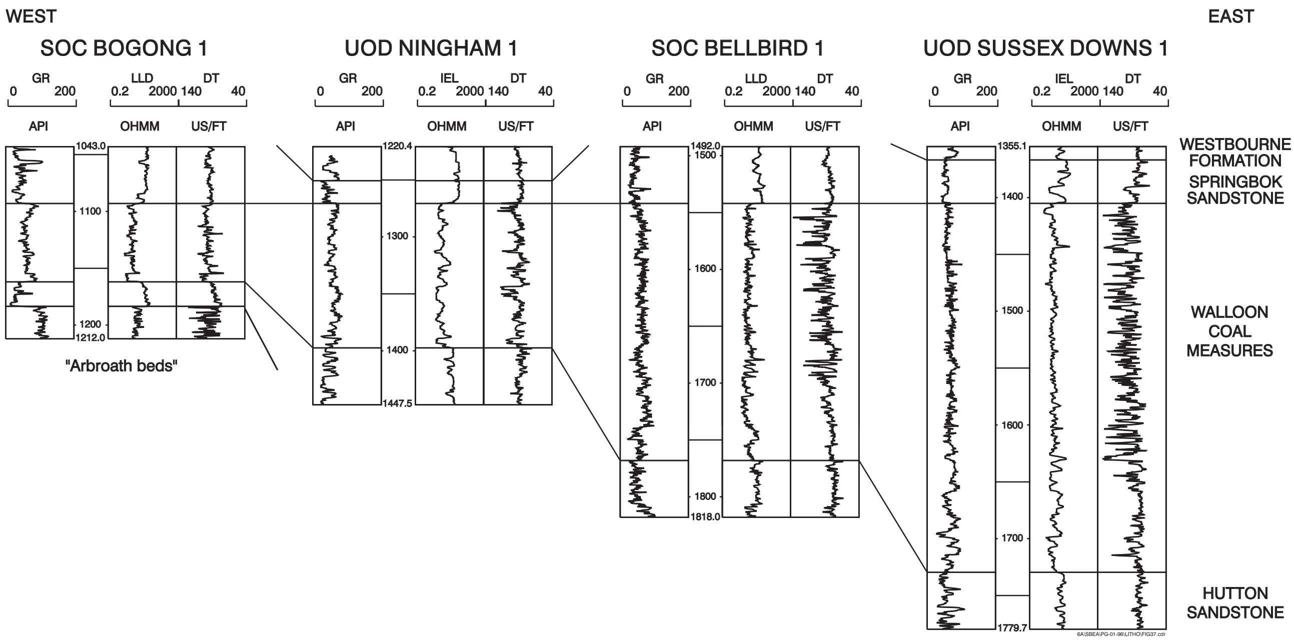

Figure 36: East–west correlation of the Walloon Coal Measures.

Mimosa Syncline, west of Miles. The formation thins to the south-west and onlaps the Roma and Walgett Shelves (Figure 37).

Age

The Walloon Coal Measures embrace palynofloras of late Middle Jurassic age (Bathonian to Callovian), which are attributable to units APJ42, APJ43 and APJ5. The lower part of the formation is associated with either (the upper part of) APJ42 or APJ43, the latter being a new unit (Price, 1995) defined by the first appearance of *Contignisporites glebulentus* and conformable with the *C. glebulentus* Zone of McKellar (in preparation). Unit APJ5, based on the occurrence of *Murospora florida*, encompasses the upper part of the Walloon Coal Measures and extends into the overlying formation. Variation indicated in stratigraphic placement of the APJ42–APJ43 boundary with respect to the Hutton Sandstone–Walloon Coal Measures boundary suggests that there is some variation in age of the latter in the Surat Basin (McKellar, in preparation).

Depositional Setting

Most of the Walloon Coal Measures were deposited as coal swamps with the lower part comprising mainly overbank deposits (Exon, 1976). McLean-Hodgson & Kempton (1981) concluded that the Walloon Coal Measures were deposited in a high sinuosity fluviatile environment dominated by meandering streams. Clark & Cooper (1985) interpreted the depositional environment of the Walloon Coal Measures from core in GSQ Dalby 1 and Chinchilla 3, to be a fine-grained meander-belt river system.

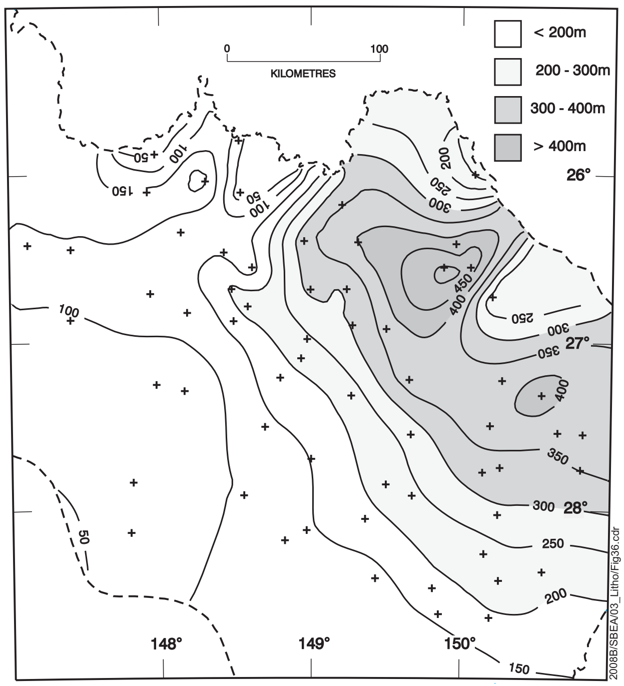

Figure 37: Isopach map – Walloon Coal Measures.

Springbok Sandstone

Nomenclature

Exon (1966) referred to the sandstones outcropping in the uppermost Birkhead Formation south-west of Injune as the

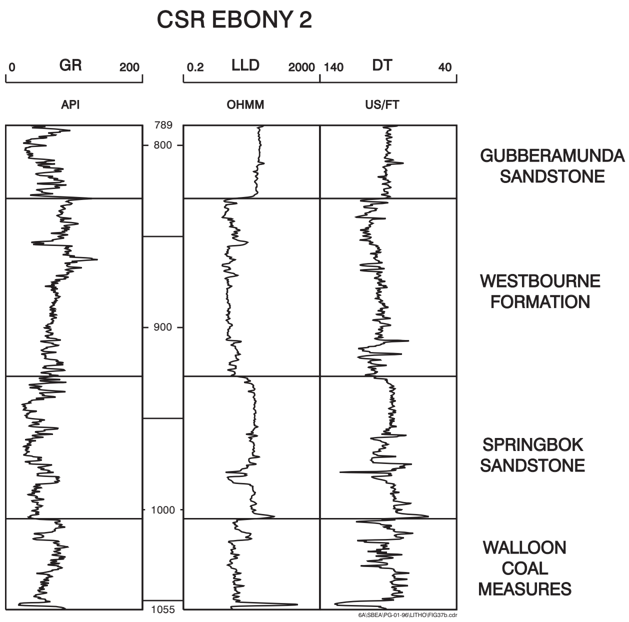

Figure 38: Wireline log responses – Springbok Sandstone.

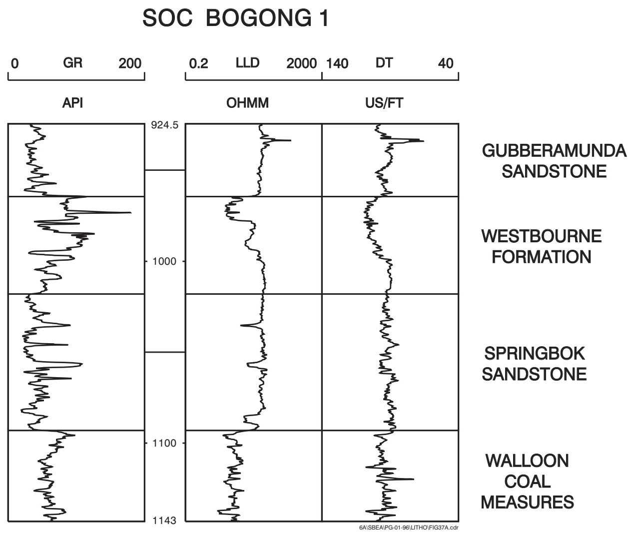

Figure 39: Gradational Springbok Sandstone/Westbourne Formation boundary.

'Springbok Sandstone Lens'. Exon & others (1967) renamed the unit the Springbok Sandstone Member when its extent in the Surat Basin became known. Power & Devine (1968) raised the unit to formation status following a regional subsurface study of the Surat Basin. The lower part of the Springbok Sandstone appear to be equivalent to the 'Proud Sandstone', a name used by Mines Administration Pty Ltd in the Roma area in the early 1960s.

Rock Types

In the type section from 38m to 50m in BMR Mitchell 3 and in Departmental stratigraphic bores, the Springbok Sandstone consists mostly of feldspathic sublabile to lithic sandstones, commonly with a calcareous cement. The sandstones are very fine to coarse-grained, although some very coarse-grained poorly sorted, pebbly beds also occur. Minor interbedded siltstones and mudstones and thin coal seams are also present, mainly in the upper part of the unit.

In GSQ Taroom 7 stratigraphic bore in the western Mimosa Syncline, the Springbok Sandstone is characterised by porous, permeable and friable sandstones. The lowermost 6m consists of very coarse-grained to pebbly quartzose sandstone with an erosional base (Swarbrick, 1973).

Relationships and Boundary Criteria

The Springbok Sandstone conformably overlies the Walloon Coal Measures (Exon, 1976). However, there appears to be scouring at the base in some areas and sandstones from both formations are lithologically different suggesting an unconformity. Deposition of the former represents the start of the third major sedimentary cycle in the Surat Basin. The Springbok Sandstone has no correlative in the Moreton Basin. It is laterally equivalent to but not continuous with the Adori Sandstone in the Eromanga Basin. The latter is generally more quartzose than the Springbok. In the south, the

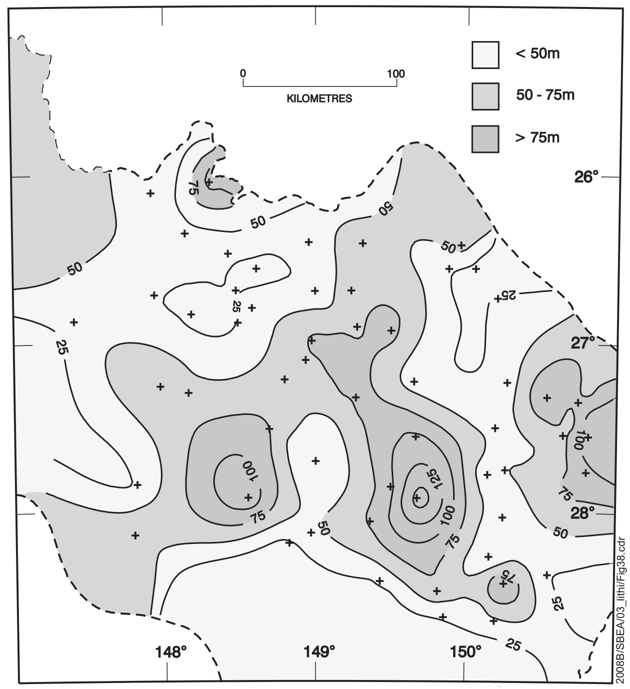

Figure 40: Isopach map – Springbok Sandstone.

Springbok Sandstone interfingers with the lower part of the Pilliga Sandstone (Exon, 1976), and in the east forms the lowermost part of the Kumbarilla beds.

Wireline Log Character

The Springbok Sandstone is characterised by relatively low gamma-ray and high average resistivity log values compared with the underlying Walloon Coal Measures and overlying Westbourne Formation (Figure 38). In some wells the boundary between the Springbok Sandstone and the overlying Westbourne Formation is transitional and difficult to pick, especially if the lowermost Westbourne Formation is sandy. In these wells, the change in the gamma-ray log baseline from low to high values probably denotes the top of the Springbok Sandstone. It is possible however that the increase in gamma-ray log values seen in the lowermost Westbourne Formation in SOC Bogong 1 (Figure 39) is due to an increase in K-feldspar in the sandstone and the boundary with the Westbourne Formation is higher and corresponds to a decrease in the resistivity log above 1000m.

Thickness

The maximum thickness intersected in the study wells is 157m in UOD Flinton 1 in the southern part of the Mimosa Syncline. The Springbok Sandstone has an uneven thickness trend across the Surat Basin with no main depocentre apparent (Figure 40). Consistent thinning towards the margins seen in the underlying formations is not readily apparent in this unit. The lack of any apparent trend in change of thickness probably reflects the difficulty in picking the top of the formation in some wells, as discussed, resulting in inconsistent thicknesses.

Age

Palynofloras associated with the Springbok Sandstone are attributable to unit APJ5 of Callovian–Oxfordian age. The lithostratigraphic equivalent of the formation in the Eromanga Basin, the Adori Sandstone, is younger (unit APJ6). In places, the palynofloral succession suggests that there is a time break between the Adori Sandstone and the underlying Birkhead Formation (Walloon Coal Measures equivalent) [Green & McKellar, 1996a, b; McKellar, unpublished information].

Depositional Setting

Deposition of the Springbok Sandstone was mainly by streams with some overbank and swamp deposits in the upper part of the unit indicating that streams became less energetic with time (Exon, 1976). Sediment transport was mainly towards the centre of the basin. Lithic

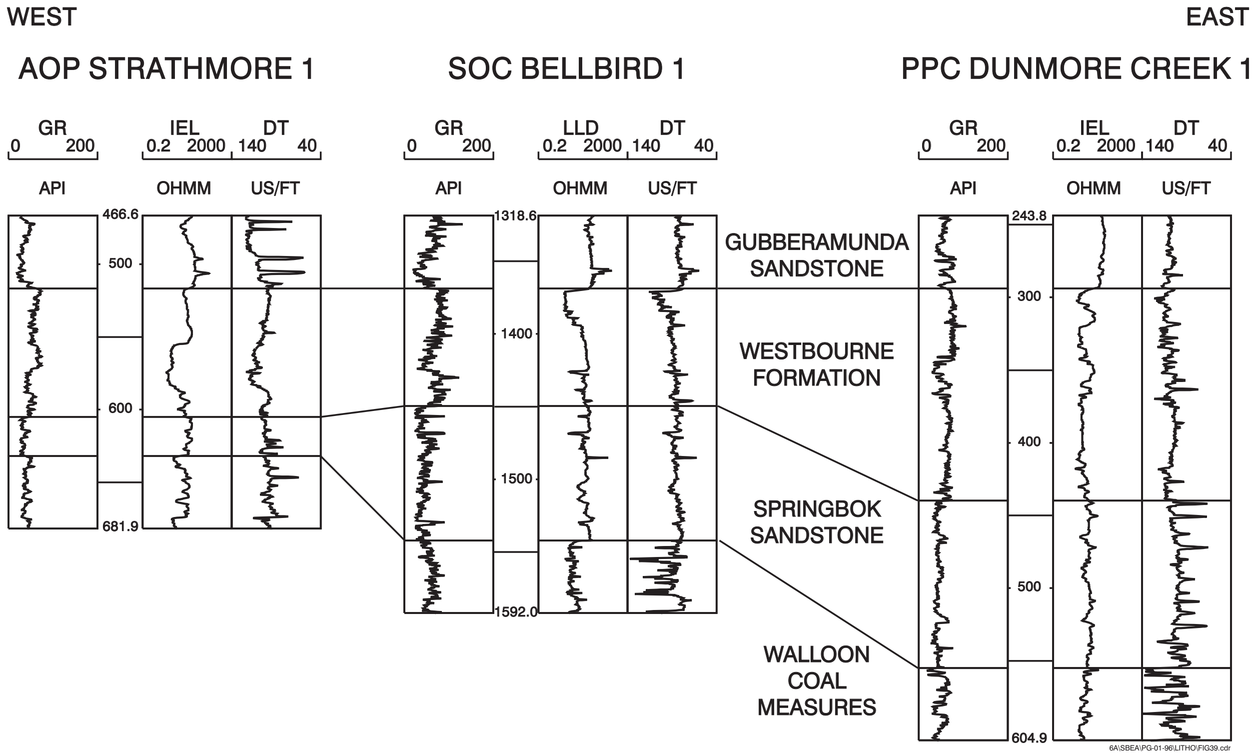

Figure 41: East–west correlation of the Westbourne Formation.

sandstones present in the Springbok, derived from the north and east indicate contemporaneous volcanism, whereas in the south, sandstones are more quartzose suggesting sediment supply from mainly a granitic terrain.

Westbourne Formation

Nomenclature

The Westbourne Formation was defined by American Overseas Petroleum Ltd (1964) with the type section from 389m to 503m in AOP Westbourne 1 well south of Tambo, in the Eromanga Basin. A modified version, incorporating field work, was published in Exon (1966).

A well developed mudstone, sandstone, siltstone and coal unit, the Norwood Mudstone Member forms the lower part of the Westbourne Formation over much of the Surat Basin (Swarbrick & others, 1973).

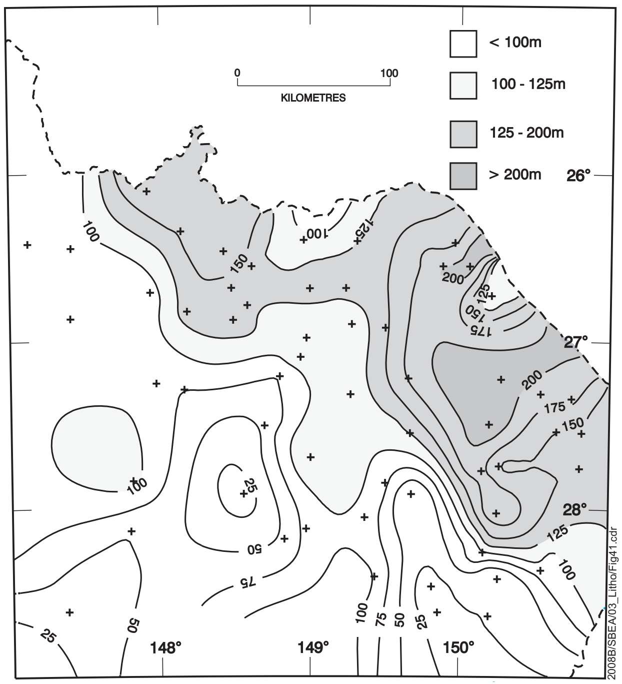

Figure 42: Isopach map – Westbourne Formation.

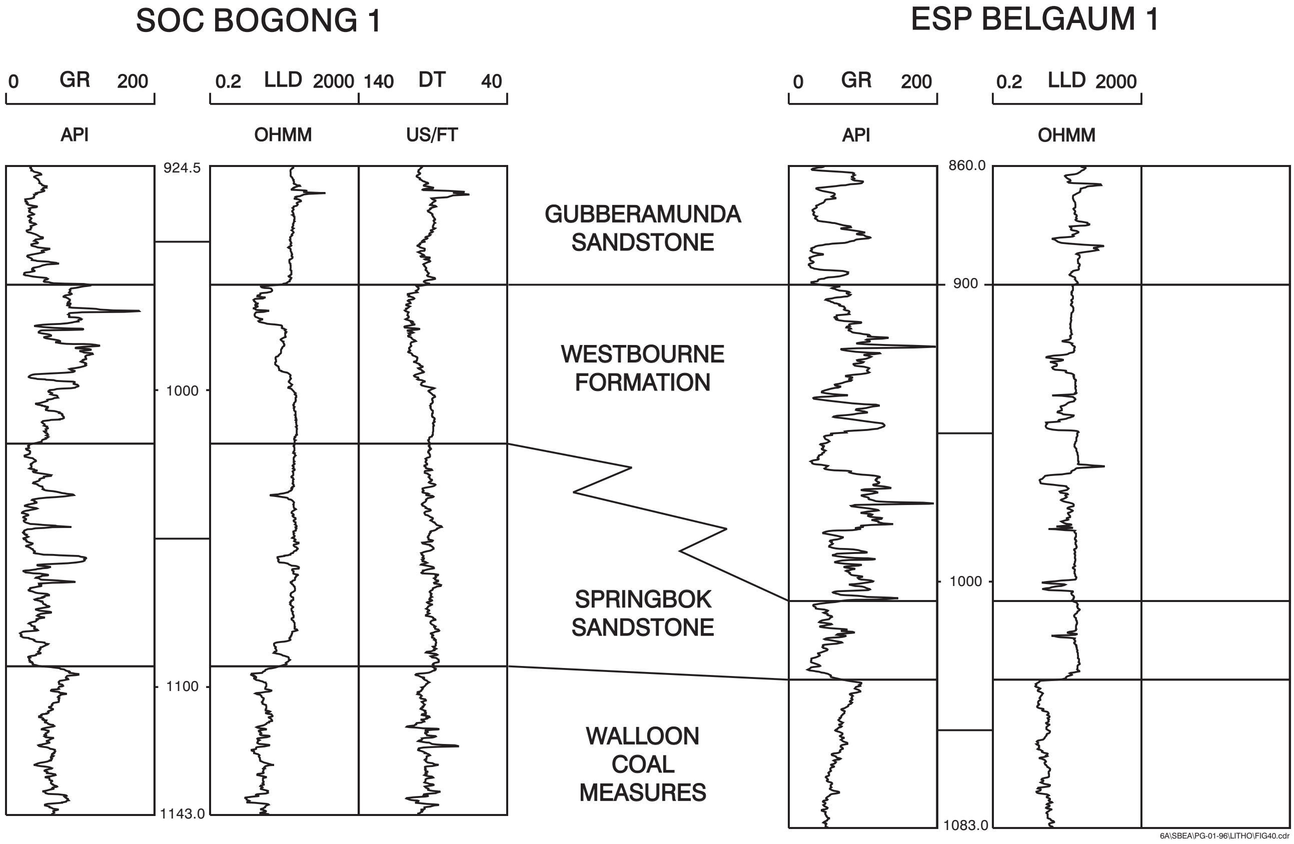

Figure 43: Facies relationship between the Springbok Sandstone and the Westbourne Formation.

Rock Types

In the type section in AOP Westbourne 1 in the Eromanga Basin, the formation consists of 114m of interbedded shales and siltstones and very fine-grained, quartzose sandstones. In the Surat Basin, the formation is similar but contains a higher proportion of sandstone.

The shales are commonly light grey and green-grey, laminated to thinly bedded. Minor roots and burrows are present. Rare coal laminae are associated with root development.

The siltstones are light grey to grey, well sorted and laminated to thinly bedded. Erosive bases to beds and ripple laminations are common. Minor carbonaceous material and bioturbation are also present.

The sandstones are very fine to medium-grained, in part very coarse-grained, fairly to poorly sorted, sublabile to quartzose. Bedding is massive; medium cross-beds are present in places. Sandstones are better developed along the eastern margin with thick porous beds present in GSQ Dalby 1. Argillaceous, in part chloritic matrix and minor calcite cement are present. Rare coal fragments and rip-up clasts also occur.

On the Roma and Walgett Shelves the proportion of sandstone also increases towards the south and west respectively.

The type section of the Norwood Mudstone Member (lowermost Westbourne Formation) in GSQ Roma 7 on the western side of the Mimosa Syncline consists of interbedded mudstone and fine to coarse-grained lithic labile sandstone with minor siltstone and coal. The sandstone generally fines upwards and increases in quartz content.

Relationships and Boundary Criteria

The Westbourne Formation, although defined in the Eromanga Basin, is recognised throughout the Surat Basin in the subsurface. At outcrop, it cannot be recognised further east than approximately longitude 148o55'E. The Westbourne Formation conformably overlies the Springbok Sandstone. It is the oldest of the Surat Basin formations whose subcrop fully extends across the basement rocks in the south-western part of the study area. The Westbourne Formation and underlying Springbok Sandstone both intertongue with and grade into the Pilliga Sandstone in the south (Exon, 1976).

Wireline Log Character

The Westbourne Formation typically has low average resistivity log values and the gammaray log values generally increase towards the top of the formation reflecting increasing mudstone/siltstone content. The gamma-ray log response of the latter is generally the highest of all the Jurassic formations in the Surat Basin which is a characteristic of the Westbourne Formation in the Eromanga Basin (Figure 41).

Thickness

The maximum thickness intersected in the study wells is 220m in UOD Cabawin 1 along the eastern side of the southern Taroom Trough. Additional depocentres are in the north-east and north with the axis of deposition trending north-westwards (Figure 42). Thickness ranges from less than 100m in the west to over 250m in the east (Exon, 1976).

The interval from the base of Springbok Sandstone to the top of the Westbourne Formation commonly displays a relatively constant thickness in adjacent wells whereas the thicknesses of the individual formations may vary greatly (Figure 43). This may be explained by two units representing two facies of the same fluvial cycle.

Age

The Westbourne Formation encompasses continental palynofloras conformable with units APJ5 and APJ6. Algal palynomorphs suggest that environmental conditions were partly lacustrine. An Oxfordian-Kimmeridgian age appears most likely. The Westbourne Formation in the Eromanga Basin appears to be the time equivalent of only the upper part of the formation in the Surat Basin.

Depositional Setting

The Westbourne Formation was interpreted by Exon (1966) to have been deposited in a lacustrine environment. More recent work by Shield (1991) in the Augathella area of the eastern Eromanga Basin has described the environment of deposition as characteristic of a lacustrine deltaic plain environment which is supported by the presence of thin coal and oolite beds.

The isopach map of the Westbourne Formation in the Surat Basin suggests that the streams feeding the deltas and lake systems flowed to the north-eastern and northern parts of the basin. The Norwood Mudstone Member was deposited in a low energy, back-swamp environment with associated meandering stream channels (Swarbrick & others, 1973).

Gubberamunda Sandstone

Nomenclature

Reeves (1947) was the first to use the name Gubberamunda Sandstone for the porous ridge-forming sandstones outcropping north of Roma that yield large artesian flows in water bores over much of the Surat Basin. The formation was formalised by Day (1964) and the type area is near Bungil Creek, approximately 35km north of Roma.

Rock Types

The Gubberamunda Sandstone in the type area consists mainly of medium and coarse-grained, virtually uncemented quartzose sandstones. Exon (1976) considered the unit to consist of quartzose to sublabile, poorly sorted sandstone with lesser conglomerate, siltstone, mudstone and claystone. In Departmental stratigraphic bore DRD26 north-west of Roma, the Gubberamunda Sandstone consists of nearly equal amounts of sandstone and thinly bedded and laminated sandstone, siltstone and shale (Gray, 1972). The sandstones contain minor nodular pyrite.

Relationships and Boundary Criteria

The Gubberamunda Sandstone regionally conformably overlies the Westbourne Formation but locally is disconformable, particularly around the margins of the basin. Deposition of the Gubberamunda Sandstone represents the start of the fourth major sedimentary cycle (Exon, 1976). The formation is considered to correlate with the lower part of the Hooray Sandstone in the Eromanga Basin to the west. In the east in many wells, the Gubberamunda Sandstone can be recognised as the middle part of the Kumbarilla beds.

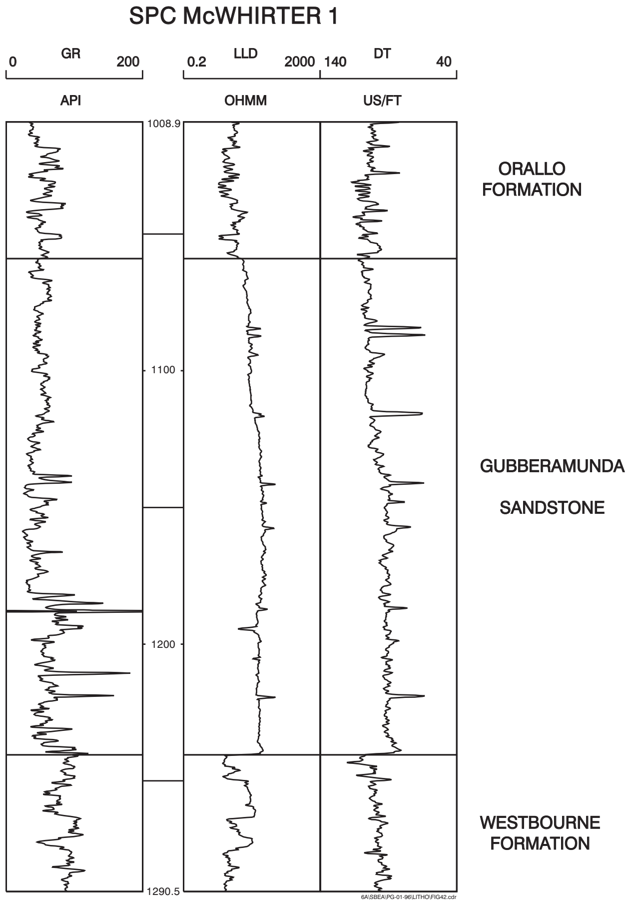

Figure 44: Wireline log responses – Gubberamunda Sandstone.

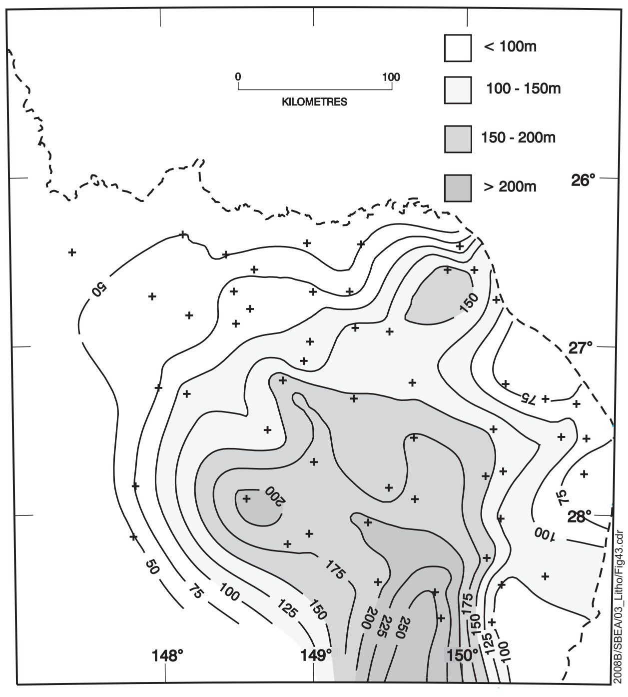

Figure 45: Isopach map – Gubberamunda Sandstone.

Wireline Log Character

On the resistivity log, the Gubberamunda Sandstone commonly displays a distinctive bellshaped (values decrease in the upper parts) or blocky pattern, reflecting the porous, quartzose nature of the sandstones (Figure 44). The Gubberamunda Sandstone generally has the highest average resistivity log values of all the Surat Basin formations. Gamma-ray logs show low average values which commonly increase in the uppermost parts, corresponding to the decrease in values on the bell-shaped resistivity log and a decrease in porosity. The top of the unit is taken where the quartzose sandstones are overlain by the siltstones, shales and sublabile to labile sandstones of the Orallo Formation. This is best seen by the decrease in value in the resistivity log baseline. The boundary with the Orallo Formation is commonly transitional and is difficult to pick if the lowermost Orallo Formation is mostly sandstone.

Thickness

The maximum thickness intersected in the study wells is 298m in UOD Macintyre 1 in the southern part of the area, but it is generally about 100m thick. The Gubberamunda Sandstone is thinnest around the margins of the basin and thickens towards the southern part of the axis of the Mimosa Syncline (Figure 45).

Age

Palynofloras from the Gubberamunda Sandstone are considered to be of Tithonian age and are associated with units APJ62 and APK1. A time break of variable magnitude occurs at the Westbourne Formation–Hooray Sandstone boundary in some areas of the Eromanga Basin (Burger, 1986, 1989; Green & McKellar, 1996a, b), but the lithostratigraphically equivalent Westbourne Formation–Gubberamunda Sandstone contact in the Surat Basin appears to be conformable. Some uncertainty exists however, as palynological data are limited in this part of the section.

Depositional Setting

Day (1964) suggested that the Gubberamunda Sandstone was deposited in a high energy, shallow-water, possibly fluviatile environment.

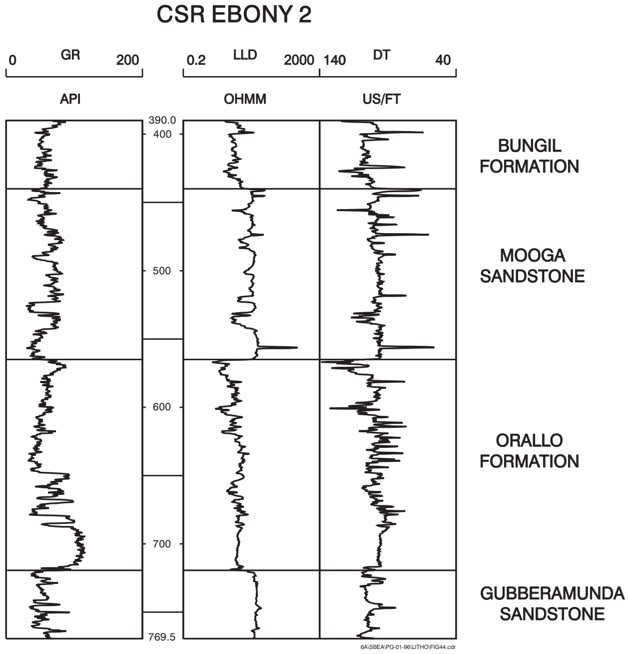

Figure 46: Wireline log responses – Orallo Formation and Mooga Sandstone.

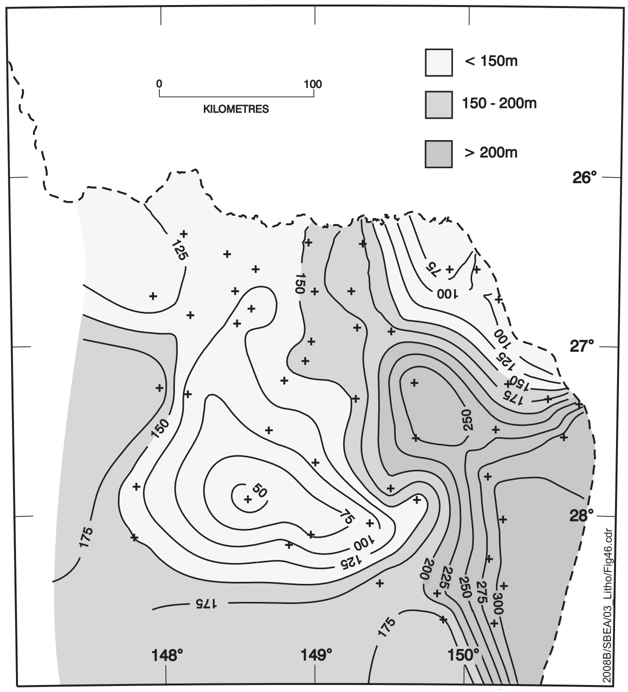

Figure 47: Isopach map – Orallo Formation.

Exon (1976) stated that braided and meandering stream systems draining surrounding highlands deposited the Gubberamunda Sandstone. The isopach map (Figure 45) suggests that the outlet of the drainage was probably to the south along the axis of the Mimosa Syncline. A non-marine environment of deposition is supported by palynology.

Orallo Formation

Nomenclature

Strata belonging to the lower part of the present Orallo Formation and probably mostly the underlying Westbourne Formation were named Orallo Coal Measures and Orallo Measures by Jensen (1926). Reeves (1947) used the name 'Fossil Wood Stages or Series' for the present Orallo Formation, later called the 'Fossil Wood Beds' by Whitehouse (1955) in his Blythesdale Group.

Day (1964) proposed the name Orallo Formation for the latter and designated the type area near Bungeworgorai Creek, in the vicinity of the abandoned Orallo rail siding north-west of Roma.

Rock Types

The Orallo Formation consists mainly of friable, medium to coarse-grained, sublabile to labile sandstone, in part calcareous, and lesser interbedded carbonaceous siltstone, silty mudstone, bentonite and coal. Fossil wood commonly is included in the sandstones and in some areas, conglomerates also are interbedded within the sandstones.

Bentonite occurs at the top of the formation in DRD 26 drilled near the type area and in several intervals throughout the formation in GSQ Roma 2 north of Jackson (Gray, 1972). It is mined commercially north and south of Miles.

Wireline Log Character

The shales, siltstones and sandstones produce an overall slightly more subdued resistivity log response in comparison with the enclosing formations (Figure 46). In some wells intervals of porous sandstones are indicated by higher resistivity and spontaneous potential log values. Average gamma-ray log values over the Orallo Formation are slightly higher than the enclosing formations.

Relationships and Boundary Criteria

The Orallo Formation conformably overlies the Gubberamunda Sandstone. The top and bottom of the Formation are generally defined by shales and siltstones. On the western side of the basin, at outcrop north of Muckadilla, the Orallo Formation grades into the lower part of the Southlands Formation which in turn interfingers with the lower part of the Hooray Sandstone north-west of Mitchell (Exon, 1971a). On the eastern side of the basin, an Orallo Formation equivalent is recognisable within the upper part of the Kumbarilla beds in some areas (Exon & Vine, 1970).

Thickness

The maximum thickness intersected in the study wells is 306m in PPL Ballymena 1 in the south-east. It is mostly 150–250m thick (Exon, 1976). The Orallo Formation is thickest over the central and southern parts of the Mimosa Syncline and thins to the north-east over the Roma Shelf, and to the west over the eastern Walgett Shelf (Figure 47).

Age

The Orallo Formation encompasses palynofloral assemblages attributable to unit APK1. A Berriasian age appears likely, but precise placement of the Jurassic-Cretaceous boundary is uncertain in the (pre-marine) continental succession of the Surat Basin (also see Burger & others, 1992; Burger, 1995; Price, this volume).

Depositional Setting

Day (1964) interpreted that the depositional environment for the Orallo Formation was fluvial with local ponding. Drainage restriction is suggested by the finer grained deposits and the abundance of calcareous material. The presence of coals and interbedded tuff indicate a lacustrine environment with periods of volcanic activity, particularly during deposition of the uppermost beds. According to Exon (1976), streams generally flowed towards the centre of the Surat Basin. The isopach map suggests that the outlet of the drainage was probably to the south-east.

CRETACEOUS

Mooga Sandstone

Nomenclature

The name Mooga Sandstone was first used by Reeves (1947) for a succession of fine to medium-grained sandstones and sandy shales with quartz pebble conglomerates near the base, outcropping in the Parish of Mooga in the

Roma area. The formation yields large artesian flows in the water bores near Roma. Day (1964) renamed the Mooga Sandstone as the Mooga Sandstone Member of the Blythesdale Formation and nominated a type area along Blyth Creek, 24km to 34km east-north-east of Roma. Exon & Vine (1970) renamed the unit the Mooga Sandstone and nominated a new type area near the junction of Bungil and MoogaMooga Creeks, 16km north of Roma.

Rock Types

In the type area, the Mooga Sandstone consists of 30m of mainly sublabile to quartzose sandstone with minor clayey sandstone, siltstone and mudstone. Exon (1976) recognised three major subunits at outcrop. These are a lower subunit less than 5m thick of sublabile to quartzose sandstone commonly conglomeratic, a middle subunit of mudstone of similar thickness, and a thicker upper subunit of interbedded finer-grained sublabile sandstone and siltstone.

Relationships and Boundary Criteria

The Mooga Sandstone generally overlies the Orallo Formation conformably, although local disconformities occur (Exon, 1976). Exon considers that sandstone bodies in the Mooga Sandstone occur as discontinuous lenses and because of this, the upper and lower boundaries of the formation tend to move up and down the stratigraphic column. To the west the Mooga Sandstone grades into the upper part of the Hooray Sandstone and to the east, an equivalent is present within the upper Kumbarilla beds.

Deposition of the Mooga Sandstone represents the start of the fifth major sedimentary cycle in the Surat Basin.

Wireline Log Character

The higher quartz content and increased porosity and permeability of the Mooga Sandstone in comparison with that of the enclosing formations is reflected in an interval of markedly higher average resistivity log values. Distinctly lower gamma-ray log values occur in the lower part of the formation in some wells. The top of the Mooga Sandstone commonly displays a sharp decrease in resistivity log values (Figure 46).

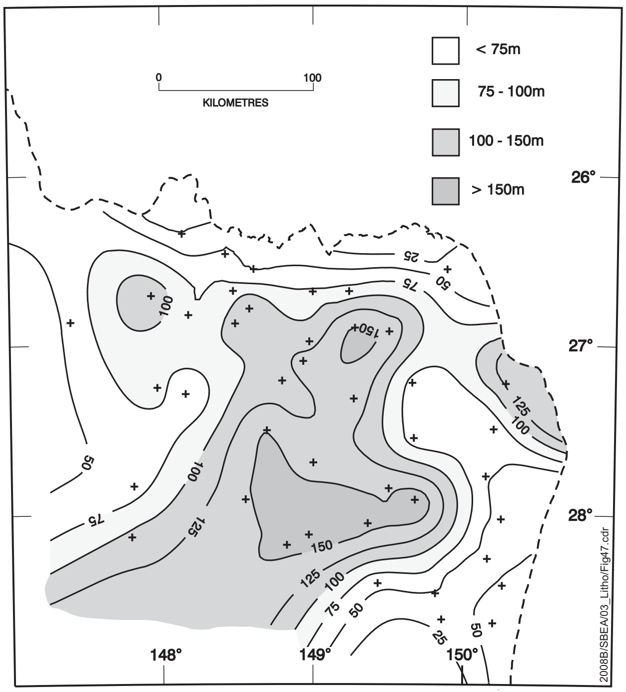

Figure 48: Isopach map – Mooga Sandstone.

Thickness

The maximum thickness intersected in the study wells is 168m in UOD Flinton 1 in the southern part of the Mimosa Syncline. It is seldom over 100m thick in northern parts but it thickens southward into the basin. The main axis of deposition is in the central region of the study area between the Mimosa Syncline and the Roma and Walgett Shelves. The Mooga Sandstone thins to the north-west, north and south-east (Figure 48).

Age

Terrestrial palynofloras from the Mooga Sandstone are generally conformable with the upper part of unit APK1, but may extend into the lower part of unit APK21. A Berriasian-early Valanginian age has been suggested for the formation (Burger & others, 1992).

Depositional Setting

The Mooga Sandstone was deposited by south-westerly flowing streams varying from braided to meandering (Exon, 1976). The higher quartz content and better sorting of the sandstones compared with those of the underlying Orallo Formation indicates more reworking and lower stream gradients. The isopach map (Figure 48) suggests that outlet of the drainage was probably to the south-west which is in accord with Exon (1976).

Bungil Formation

Nomenclature

Exon & Vine (1970) defined the Bungil Formation as approximately 75m of interbedded sandstones and mudstones outcropping along Bungil Creek, 5–15km north of Roma. The formation corresponds to the Transition beds of Whitehouse (1955). Day (1964) recognised the Kingull, Nullawurt Sandstone and Minmi Members (of the Bungil Formation) in the area north of Roma and included them with the Mooga Sandstone (Member) within his Blythesdale Formation. Mollan & others (1972) recognised the Claravale Sandstone Member as an additional member of the Bungil Formation in the Merivale Syncline north-east of Mitchell in the western Surat Basin.

Rock Types

The Bungil Formation consists of fine-grained lithic sandstones, siltstones and mudstones, commonly carbonaceous, with minor sublabile and quartzose sandstone. Calcareous and glauconie-rich beds, some with marine fossils, are common in the upper part. The three members described at outcrop by Day (1964) are not readily recognised in the subsurface (Exon, 1976). The Bungil Formation contains a higher proportion of sandstone in the central-western part of the study area, as seen in AAO Glenroy 1.

Relationships and Boundary Criteria

The Bungil Formation conformably overlies the Mooga Sandstone. The top of the formation is taken at the top of the uppermost sandstone below the mudstones of the Doncaster Member of the Wallumbilla Formation. The Bungil Formation correlates with the Cadna-owie Formation in the Eromanga Basin to the west, and in the Surat Basin to the south-east, an equivalent forms the uppermost part of the Kumbarilla beds.

Wireline log Character

The Bungil Formation has a subdued resistivity and gamma-ray log response with values markedly less than those of the Mooga Sandstone (Figure 49). The top of the formation is identified on the resistivity log as the uppermost moderate resistivity peak below the almost featureless resistivity log of the Doncaster Member of the Wallumbilla Formation. A sharp break also occurs on the sonic log.

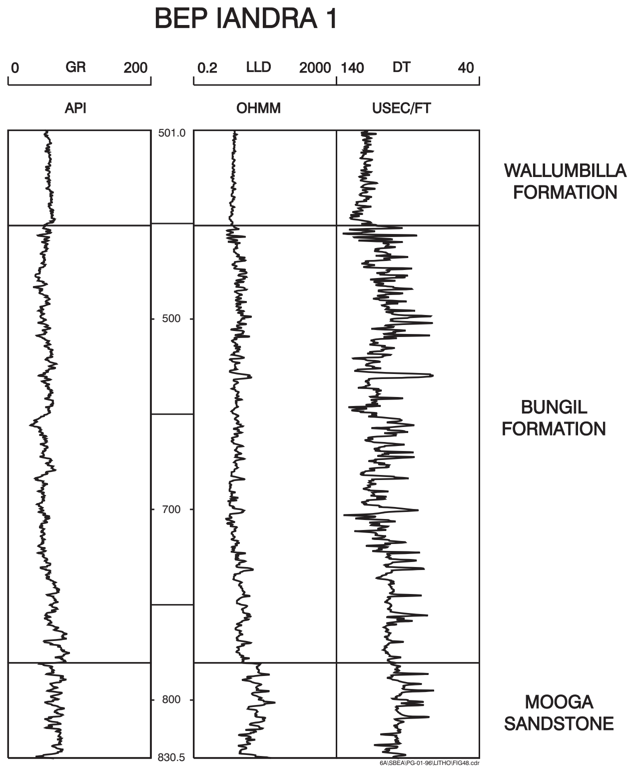

Figure 49: Wireline log responses - Bungil Formation.

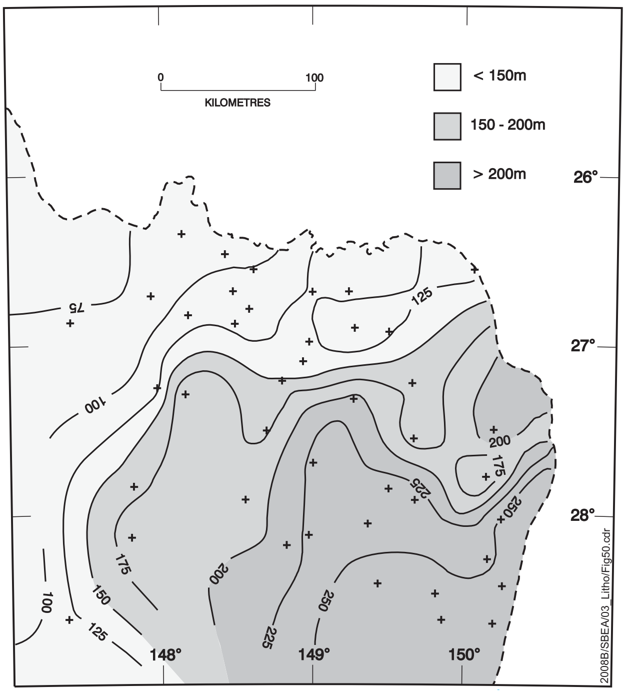

Figure 50: Isopach map - Bungil Formation.

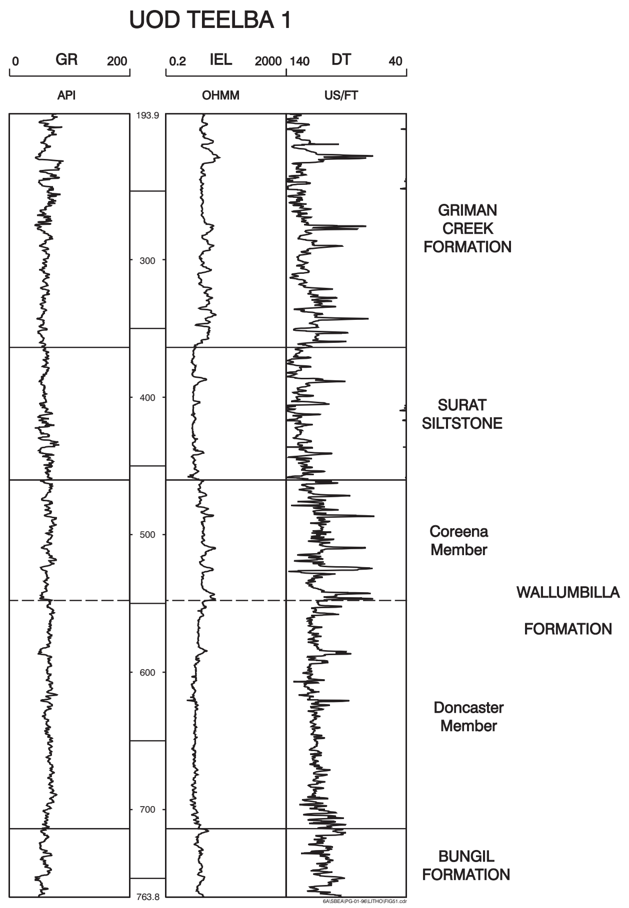

Figure 51: Wireline log responses - Early Cretaceous units.

Thickness

The maximum thickness intersected in the study wells is 269m in UOD Macintyre 1 in the southern part of the Mimosa Syncline. The Bungil Formation is thickest in the south-east and east (up to 300m) and thins towards the west and north-west to less than 100m (Figure 50).

Age

The Bungil Formation encompasses palynofloras associated with units APK2 and APK3, but assemblages from the lower part of the formation are conformable with the uppermost part of unit APK1 (Price & others, 1985; Burger & others, 1992; Price, this volume). A Valanginian to Aptian age has been assigned to the formation by the cited authors.

Distinct marine and brackish-marine influences are apparent in the Nullawurt Sandstone Member and Minmi Member (Burger, 1980). Dinoflagellate assemblages from the latter (dated as early Aptian) are conformable with the *Odontochitina operculata* Oppel Zone (of Morgan, 1977; modified by Helby & others, 1987; see Burger, 1980; Burger & others, 1992).

Depositional Setting

The environments of deposition are interpreted to be sluggish-fluviatile to paralic, grading to shallow water marine in the upper part of the formation. The latter is supported by palynology and the presence of marine macrofossils. Deposition of the Bungil Formation represents the first major marine transgression into the Surat Basin. The increased sandstone content in the central-west of the area may reflect proximity to either sand-rich source areas or to a beach sand facies predominating in this area.

Wallumbilla Formation

Nomenclature

The Wallumbilla Formation comprises the Doncaster Member and the overlying Coreena Member.

Vine & Day (1965) first named and defined the Doncaster Member near the Flinders River north-east of Hughenden. It forms the lower part of the Wilgunya Formation of the northern Eromanga Basin. The Coreena Member at the top of the Wallumbilla Formation was named by Vine (1966) and formally defined by Vine & others (1967) with a type area at Coreena Station near Barcaldine in the Eromanga Basin. The latter authors named and defined the Wallumbilla Formation in the Surat Basin with the type section in Wallumbilla Creek, near Roma.

Rock Types

The type section of the Wallumbilla Formation contains a succession of mudstones and siltstones with concretionary limestones, locally common, and minor lenticular sandstones, conglomerates and cone-in-cone limestones.

Exon (1976) described the Doncaster Member in the Surat Basin to consist mainly of mudstones with subordinate siltstones and sandstones. Marine fossils occur at several horizons. The Coreena Member consists mainly of siltstone with lesser mudstone with minor coal. Calcareous beds, coquinites and intraformational conglomerates are commonly interbedded.

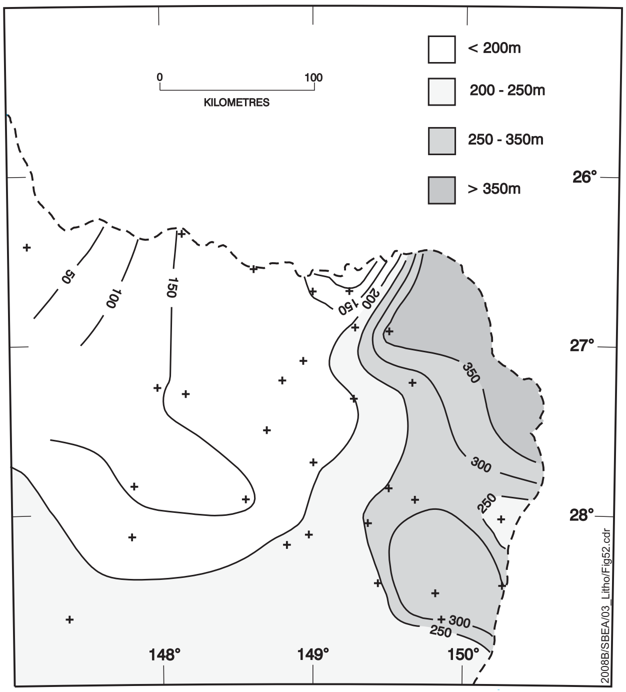

Figure 52: Isopach map - Wallumbilla Formation

Relationships and Boundary Criteria

The Wallumbilla Formation conformably overlies the Bungil Formation. The formation is continuous into the Eromanga Basin to the west.

Wireline Log Character

The mudstone dominant Doncaster Member displays an almost featureless resistivity log with low values and gamma-ray log with moderate values. The Coreena Member displays a mostly subdued resistivity log response and noisy sonic log owing to the interbedded calcareous siltstones and sandstones. The boundary between the two members is taken where there is an upwards increase in character and value of the resistivity log (Figure 51). The boundary with the overlying Surat Siltstone is shown on the logs by a decrease in resistivity and increase in gamma-ray log values.

Thickness

The maximum thickness intersected in the study wells is 475m in UOD Booberanna 1 in the southern part of the Mimosa Syncline. The Wallumbilla Formation thickens over the Mimosa Syncline and thins to the west and north-west (Figure 52).

Age

Spore-pollen assemblages of units APK3 and APK4 occur within the Wallumbilla Formation (Price & others, 1985; Burger & others, 1992; Price, this volume). The Doncaster Member is associated with APK3, and the succeeding Coreena Member, with APK4. In the Eromanga Basin, the latter member is also associated with unit APK5, which, in the Surat Basin, occurs in the mid to upper part of the succeeding Surat Siltstone and the overlying Griman Creek Formation (Price & others, 1985; Burger & others, 1992; Price, this volume).

The Doncaster Member is the most extensive of all units in the Surat and Eromanga Basins and represents the peak of the transgressive phase. It contains the late Aptian 'Roma' faunas. The Coreena Member has been assigned an early Albian age (Burger, 1980; Burger & others, 1992). Regression of the sea at this time resulted in a complex of brackish and marine environments.

In the Surat Basin, dinoflagellate assemblages from the Doncaster Member are associated with the *Odontochitina operculata* Oppel Zone and the lower part of the succeeding *Diconodinium davidii* Interval Zone. Those from the Coreena Member are also associated with the *D. davidii* zone and the following *Muderongia tetracantha* Interval Zone (=unit ADK19; Price, this volume).

Depositional Setting

Exon (1976) interpreted that the Doncaster Member was formed by a rapid marine transgression with deep water conditions in the centre of the basin grading to shallow marine/coastal environments around the margins. This was followed by a fall in sea level when shallow marine conditions prevailed across the entire basin. Exon (1976) interpreted that the Coreena Member was laid down during a regression and depositional environments ranged from shallow open marine to coastal mud flats, lagoons and swamps.

Surat Siltstone

Nomenclature

The Surat Siltstone was named and defined by Reiser (1970) as 125m of dominantly mudstone and siltstone continuously cored from 15m to

140m in GSQ Surat 1 drilled beside UOD Myall Creek 1 well near Surat.

Rock Types

The formation consists mainly of thinly interbedded carbonaceous siltstones and mudstones with numerous fine to very fine-grained labile to lithic labile sandstone lenses. In the type section the lowermost one-fifth of the Surat Siltstone is dominantly mudstone. In the eastern part of the basin, lithic sandstones are the dominant lithology (Exon, 1976).

Relationships and Boundary Criteria

The Surat Siltstone conformably overlies the Coreena Member of the Wallumbilla Formation. Unlike the Coreena Member, the Surat Siltstone is confined to the Surat Basin. Palaeontological evidence suggests that the formation is a time correlative of the upper part of the Coreena Member and the Toolebuc Limestone (Formation) in the Eromanga Basin (Exon, 1976).

Wireline Log Character

The mudstones and siltstones of the Surat Siltstone are relatively uniform in composition and display almost featureless resistivity and gamma-ray logs. The display is very similar to that given by the Doncaster Member of the Wallumbilla Formation (Figure 51). Interbedded sandstones are commonly displayed as small peaks on the resistivity log.

Thickness

Owing to the limited amount of well data available, no isopach maps were produced for the Surat Siltstone. It is fairly uniform in thickness, ranging from 100–130m.

Age

The Surat Siltstone embraces spore-pollen assemblages conformable with units APK4 and APK51 (Price & others, 1985; Burger & others, 1992; Price, this volume). According to the latter author, dinoflagellate assemblages in the formation are conformable with units ADK19 and ADK21, respectively equivalent to the Munbdrongia tetracantha and the Canninginopsis denticulata Interval Zones of Helby & others (1987). An Albian age is indicated.

Depositional Setting

The environment of deposition was interpreted by Reiser (1970) to be shallow marine. The presence of abundant foraminifera, small shell fossils, glauconite, and the fine-grained, thinly bedded nature of the strata also support deposition in a shallow sea, mainly on tidal flats and in protected bays (Exon, 1976). Plant roots recorded in the upper part of the formation on the eastern side of the basin, and carbonaceous material in some of the mudstones and siltstones also suggest deposition in coastal swamps.

Griman Creek Formation

Nomenclature

The name Griman Creek Group (Jenkins, 1959), later amended to Griman Creek Formation (Jenkins, 1960) were the names first used for most of the Cretaceous rocks cropping out south and east of Surat. The overlying deeply weathered part of the Griman Creek Group was named the Telgazli Formation by Jenkins (1959). Thomas & Reiser (1968) expanded the Griman Creek Formation of Jenkins (1960) to include the Telgazli Formation in the informally named Griman Creek beds. Reiser (1970) redefined the Griman Creek beds as the Griman Creek Formation and nominated a 338m thick reference section as continuous core from 8m to 346m in GSQ Surat 3.

Rock Types

The Griman Creek Formation consists of thinly bedded and interlaminated fine to medium-grained labile sandstones, siltstones and mudstones, with thick sandstone beds and minor muddy siltstones, intraformational conglomerates and coal. Brackish or fresh water fossils in shelly coquinas occur in the lower part of the formation (Exon, 1976). Coal seams, intraformational conglomerates and freshwater pelecypods occur in the upper part.

Relationships and Boundary Criteria

The Griman Creek Formation conformably overlies the Surat Siltstone. Like the Surat Siltstone, the Griman Creek Formation is confined to the Surat Basin. Palaeontological evidence suggests that the Griman Creek

Formation is older than the lithologically similar Winton Formation in the Eromanga Basin.

Wireline Log Character

The sandstones and siltstones of the Griman Creek Formation produce a relatively subdued gamma-ray log with a baseline slightly lower and a resistivity log with a higher baseline and more character than the underlying Surat Siltstone (Figure 51). The increase in character is caused by the interbedded porous and permeable sandstones. On gamma-ray logs which are available for many water-bores, the boundary with the Surat Siltstone is commonly difficult to pick.

Thickness

No isopach maps were produced for the Griman Creek Formation owing to limited well data. The formation is up to 400m thick to the south-east of Surat, but thins towards the margins of the basin (Exon, 1976).

Age

Palynofloras of unit APK5 are associated with the Griman Creek Formation (Price & others, 1985; Burger, 1980; Burger & others, 1992; Price, this volume). An Albian age has been indicated by the cited authors.

Depositional Setting

The environments of deposition were interpreted to be initially regressive beach or near shore marine, followed by paralic to deltaic conditions with the upper part being fluvial floodplain.

CONCLUSIONS

The review of the lithostratigraphy of the southern Bowen and Surat Basins has shown that:

- The entire Taroom Trough is probably floored by volcanics. The Combarngo Volcanics in the west are essentially continuous with the Camboon Volcanics along the eastern margin.
- The Permian succession of the southern Taroom Trough consists of four sedimentary cycles.
- The outcropping marine Late Permian Oxtrack and Barfield Formations of the north-eastern margin (Cycle 2), are not widely recognized in the subsurface.
- The Late Permian Banana Formation of the north-eastern margin (lower Cycle 3), can be recognized throughout the basin. Its deposition represents the onset of widespread marine conditions throughout the whole of the southern Taroom Trough. The overlying Burunga Formation (upper Cycle 3) is dominantly marine in the north-eastern part of the study area but is fluvio-deltaic in southern parts.
- The marine fossils in the Burunga Formation in UOD South Burunga 1 well on the eastern side of the Taroom Trough represent the latest marine Permian sedimentation in the Bowen Basin.
- The Kaloola Member at the bottom of the Baralaba Coal Measures, could not be recognized as a distinct interval in the subsurface of the eastern Bowen Basin.
- The Baralaba Coal Measures are restricted to the north-eastern part of the study area and are a correlative of only the upper part of the Bandanna Formation of the western Bowen Basin and Roma Shelf.
- Thick intersections of the Rewan Group in the northern Taroom Trough can be subdivided informally into 3 subunits - the lower two comprise sandstone and siltstone, the upper, mudstone and minor siltstone.
- The Clematis Group can be subdivided in the subsurface into the Glenidal Formation and Expedition Sandstone only in the northern part of the Taroom Trough.
- The Moolayember Formation above the Snake Creek Mudstone Member on the

western side of the southern Taroom Trough, can be subdivided informally into 2 subunits. The lower is dominated by sandstones, the upper by interbedded siltstones, mudstones, sandstones and thin coal seams.

- In the north-eastern part of the study area around Wandoan, the Clematis Group and Moolayember Formation are difficult to distinguish as separate units in the subsurface and there may be some justification for retaining the originally proposed name, Wandoan Formation for the entire unit.

- Undifferentiated Late Triassic rocks first recognized at the bottom of the Surat Basin succession in GSQ Eddystone 1 may be more widespread than initially thought.

- The Walloon Coal Measures extend throughout the Surat Basin, and the name Birkhead Formation used for these strata in the western part of the Surat Basin, should be restricted to the Eromanga Basin.

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STRATIGRAPHIC IMPLICATIONS OF SEISMIC-BASED SEQUENCE STRATIGRAPHY

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INTRODUCTION

The Surat and Bowen Basin fill was subdivided into 15 depositional sequences based on the identification of genetically-related strata (Totterdell & others, 1995). Each sequence accumulated as a depositional system under a unique set of physical processes. They are bounded by mappable boundaries (sequence boundaries) which represent a change in conditions involving a lowering of the base level. These changes may have resulted in widespread erosion or non-deposition especially at the basin margins. Thus sequence boundaries, which occur on a regional scale, mark unconformities and their correlative conformities. It is important to note that all positions on the sequence boundary do not represent the same time-span however there is one instant of time common along its length (Wilson, 1991).

The major aspect of this paper is to provide an integrated approach in the assessment of the regional depositional history of the southern Taroom Trough. The approach involved incorporating the results of the lithostratigraphic study and the seismic interpretation to provide the depositional models for the Bowen and Surat Basins. The 15 sequences and their environments of deposition are discussed separately below. The sequence boundaries are correlated with the Surat/Bowen Basin stratigraphy, wireline log breaks and the mapped seismic horizons.

The general principles of sequence stratigraphy applied to both marine and non-marine sequences and the methodology adopted in this investigation are outlined below.

PRINCIPLES

MARINE SEQUENCES

Shallowing-upward stratal units in marine successions are bounded by marine-flooding surfaces and comprise the building blocks of system tracts in sequences.

These units represent progradational (Lowstand System Tract, LST), retrogradational (Transgressive System Tract, TST), and aggradational (Highstand System Tract, HST) depositional systems which have predictable relationships within a sequence. A summary of the three main system tracts in a marine passive margin setting (after Vail 1987; Van Wagoner & others, 1990; Wilson, 1991)(Figure 1) follows:

Lowstand Systems Tract: When eustatic sea-level fall exceeds subsidence the result is a lowstand leaving the shelf subaerially exposed and starved of sediment. The most landward deposits are fluvial and estuarine sandstones which accumulate in incised valleys in the shelf.

Sediments feed directly onto the slope via incised valleys and turbidity currents, and are deposited as deltas and submarine fans. The basin-floor fans consist of massive sandstone, while turbidites and delta facies are deposited on the slope.

Transgressive Systems Tract: A subsequent rapid rise in relative sea-level causes flooding of the shelf, restricting deposition to higher reaches of the shelf and starving the slope and basin-floor. Therefore only condensed sections, consisting of thin marine beds of pelagic and hemipelagic sediments, form in these deeper areas. Sediments onlap onto the sequence boundary in a landward direction. The top of the TST is the surface of maximum flooding onto which the overlying HST downlaps.

Highstand Systems Tract: The rate of relative sea-level rise progressively slows during this last phase of the sequence. It is commonly widespread across the shelf and shows both aggradational and progradational deposits. Fluvial rocks characterise the upper part of the HST. The top is terminated by an unconformity produced by the next relative fall in sea level. As a result, this systems tract can be significantly truncated and may be thin and shale-prone when preserved.

Marine sequence stratigraphy relates these systems tracts to relative changes in sea level (Vail, 1987; Van Wagoner & others, 1990; Wilson, 1991). Hence the occurrences of sequence boundaries are correlated to sea level drops whereas condensed sections are associated with rises in sea level. Each marine systems tract is associated with the sequence boundary along its length.

Although the Bowen Basin is associated with an active margin, this passive margin model has been used in the interpretation of the Permian marine succession due to the similarity of the observed strata and that predicted by the model.

NON-MARINE SEQUENCES

In marine and coastal plain environments, base level is equivalent to sea level. However, in interior non-marine basins, relative sea level has shown to have little effect on sedimentary processes except in the lower reaches of a river system by way of tidal fluctuations (Boyd & Diessel, 1994; Koss & others, 1994). In the upstream region, the major influences on the development of recognisable sequences are tectonics and climate.

In continental strata, sequence boundaries are difficult to recognise except for the most obvious angular relationships. The occurrence of erosional surfaces is dependant on the rate and magnitude of the base level fall. Sequence boundaries may be invisible or show minimal erosion if the fall in base-level is gradual, allowing time for the depositional system to adjust.

However stratal geometries showing features such as an abrupt increase in grain size, a sudden change in grain composition, and a greater degree of lateral amalgamation of sandstone bodies would imply a drop in base level and a change in the amount of accommodation space, hence it represents the commencement of a new sequence (Flint, 1993; Shanley & McCabe, 1994). Such features are evident from seismic data, outcrop, core, palynology, and wireline logs.

Generally, the lower part of a non-marine sequence consists of widespread sandstone sheets and grades up into predominantly siltstones, mudstones, and coals in the upper part (Flint, 1993; Boyd & Diessel, 1994; Shanley & McCabe, 1994). The top of the succession may be missing or eroded owing to widespread scouring during base level fall associated with the subsequent depositional system. This is very much an idealised succession and deposition is dependant on various parameters such as sediment supply, climate, tectonism, base level, and sea level. The non-marine sequence can be summarised as follows (Figure 2):

Slow Base Level Rise: The basal amalgamated sandstone sheets are deposited during a slow rise in base level (lowstand systems tract, LST). They are areally restricted and lap onto the basin flanks. This facies may overlie the sequence boundary unconformity. It is characterised by multilateral, multistorey channel fills which exhibit coarsening upwards. They are usually deposited by high energy braided streams.

Most of the fine-grained sediments are 'cannibalised' by channel migration. According to Posamentier & Vail (1988), the degree of connectivity between the sandstone bodies is dependant on the rate of base level rise; a slow rise allows amalgamated sandstone sheets to

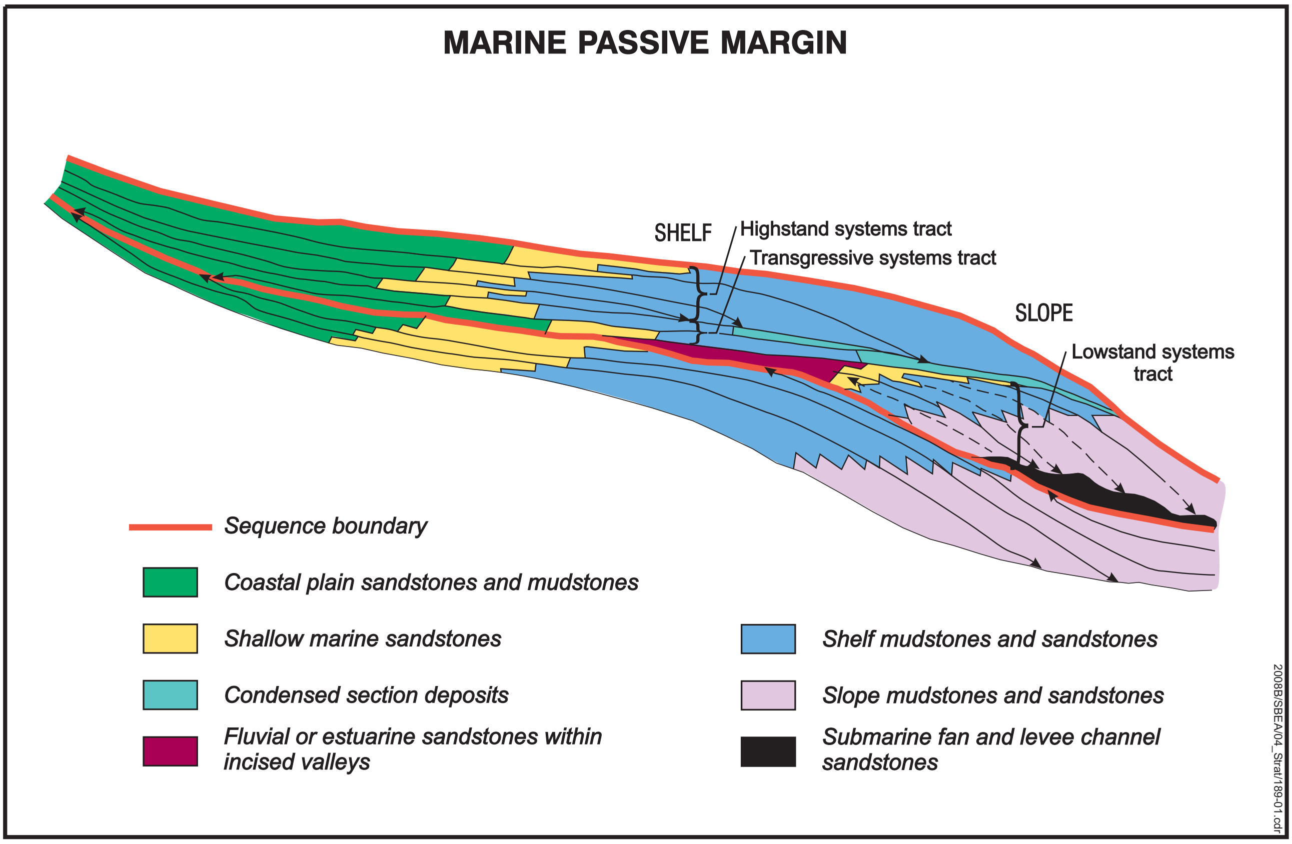


Figure 1: Idealised marine sequence in a passive margin setting (from Van Wagoner & others, 1990) File 18B-01.cdr

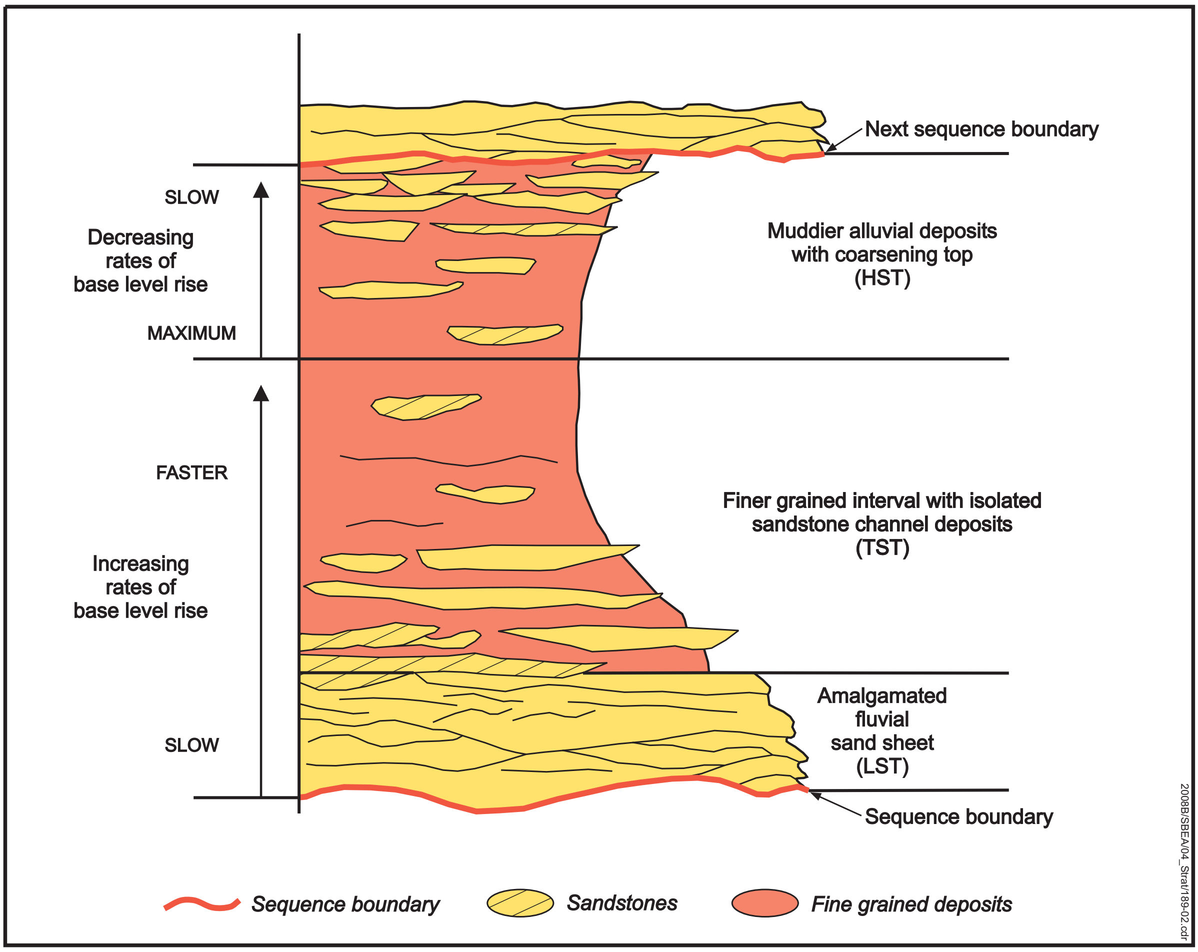


Figure 2: Idealised non-marine sequence (from Olsen & others, 1995)

develop. Outside the river valleys subaerial exposure and thin coals can develop.

Faster Base Level Rise: As the rate of base level rise increases, accommodation is created and finer-grained sediments and isolated sandstone channel deposits accumulate (transgressive systems tract, TST). The sandstones are laid down by meandering and anastomosing streams. Interbeds of fine-grained alluvial plain strata occur. This facies has a wider aerial extent than the LST deposits. Once the groundwater table reaches the sediment surface peat can be preserved.

Maximum Base Level Rise: A maximum base level rise completes the cycle (highstand systems tract, HST), laying down mainly muddier alluvial deposits with some channel sandstones and coals. The HST may include a lacustrine or marine transgression. These rocks represent maximum accommodation space and hence the most widespread deposition.

Base Level Fall: If the cycle of sedimentation is followed by a sudden fall in base level of sufficient magnitude it will cause stream incision and subaerial exposure on a regional scale. The resultant erosional surface is the base of the next cycle and also represents the sequence boundary. Accommodation space becomes negative leading to a phase of erosion and non-deposition as the channel migrates laterally. A rise in base level commences a new cycle in sedimentation.

The TST and HST phases comprise a more widespread and thicker deposit than the underlying LST phase (Shanley & McCabe, 1994). Olsen & others (1995) believe that base level rise begins to slow during the HST phase resulting in a coarsening-upward trend at the top of the sequence instead of the suspension deposits proposed by Flint (1993) and Shanley & McCabe (1994).

It is probable that both situations occur, being dictated by external influences on base level rates. However, the coarse upper deposits of the HST aren't frequently preserved due to the subsequent erosion associated with the next sequence.

METHODOLOGY

This sequence stratigraphic study is based on the interpretation of a regional seismic framework.

Stratigraphic control was provided using velocity surveys and synthetic seismograms from petroleum wells and stratigraphic bores in or near the framework. Details on the methodology and conclusions of this aspect of the project are given in Totterdell & others (1991), Wells & others (1993), Dixon & others (1993), Totterdell & others (1995), Brakel & others (1996), and Hoffmann & others (1996).

The boundaries between sequences were delineated by tracing prominent seismic reflectors that exhibited either stratal terminations (truncations, onlap, offlap, and downlap of the adjacent strata), erosional features such as channels, the separation of packages of reflections of different character, and by the identification of unconformities from well and palynological data.

Totterdell & others (1995) identified 7 sequences in the Permian strata of the Bowen Basin (Sequences A1-2 and B to F) and 5 sequences in the Triassic succession (Sequences G, H1-2, and I1-2). Three fining-upwards sequences (Sequences J, K, and L) were evident in the Late Triassic to Middle Jurassic succession in the Surat Basin.

The relationships between the sequences, seismic horizons and the lithostratigraphic subdivision for the Bowen and Surat Basins in the project area are given in Figure 3. These sequences form the basis for this interpretation of the depositional histories of the basins. The relationship between the Late Permian sequences in the southern Taroom Trough and those identified by Totterdell & others (1995) in the Denison Trough are also discussed.

The description of the lithostratigraphic units has been given previously in this volume. Formation names, where appropriate, will be used in this discussion as a means of highlighting the internal variations in the sequences throughout the study area.

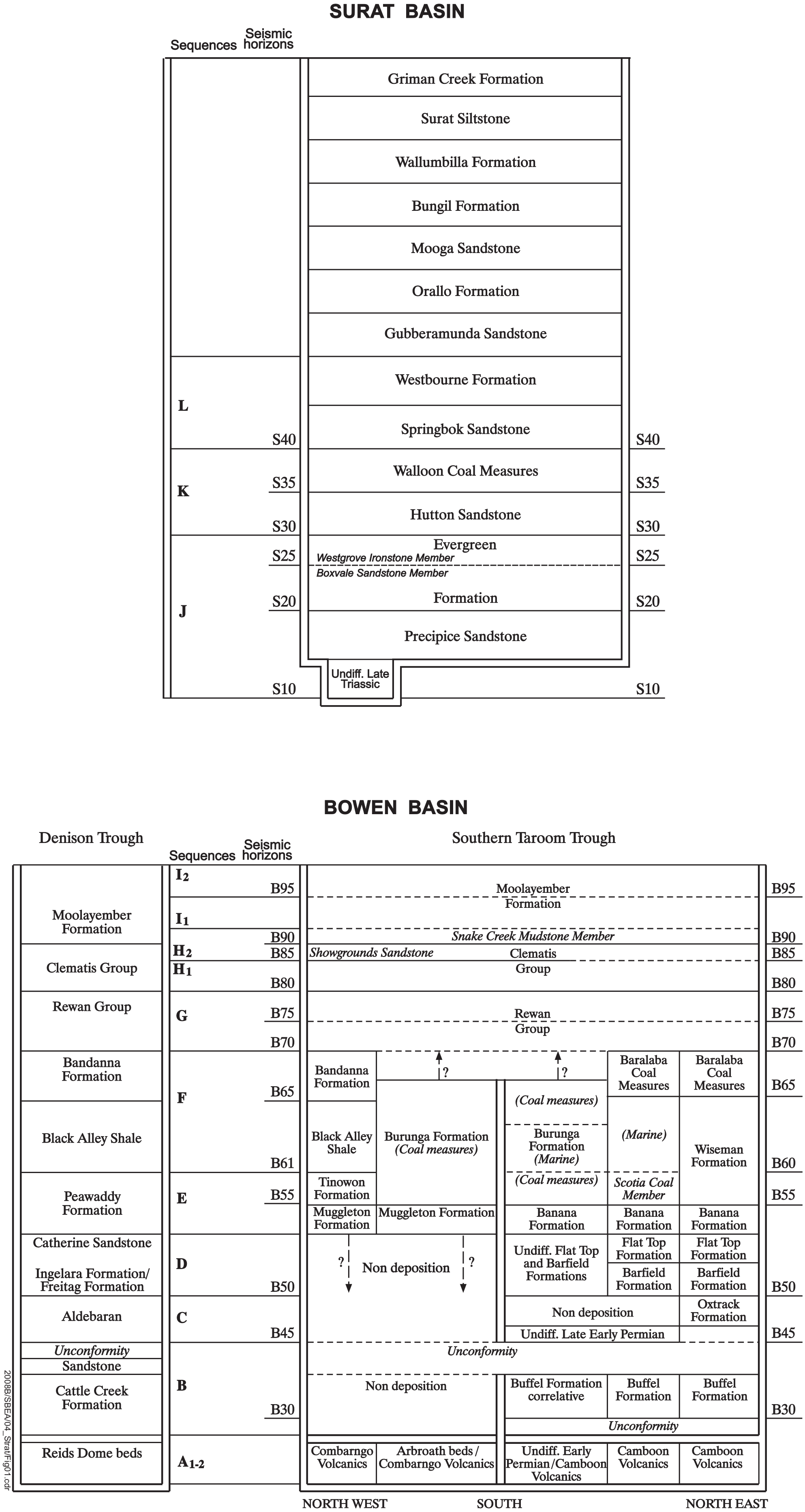


Figure 3: Relationship of the lithostratigraphic and seismic stratigraphic subdivisions for the Bowen and Surat Basins, southern Taroom Trough - relative base level fluctuations are also shown.

SOUTHERN TAROOM TROUGH SEQUENCES

SUPERSEQUENCE A

Supersequence A refers to the Combarngo Volcanics and Early Permian sedimentary rocks and volcanics deposited in a series of troughs and half grabens associated with a north-striking extensional fault system in the west, undifferentiated Early Permian rocks in the south and the Camboon Andesite in the east (Korsch & Totterdell, 1995).

In the western part of the study area, the supersequence includes the synrift sediments deposited in the Arbroath Trough and associated half grabens. The supersequence was intersected in COE Inglestone 1 where it consists of a lower conglomeratic and an upper sandstone interval and onlaps the Combarngo Volcanics.

Totterdell & others (1995) noted that the top of the supersequence is a possible truncation/onlap surface (B30) and this is consistent with the sharp log break at its top in COE Inglestone 1.

In the east, Totterdell & others (1995) noted that the Camboon Volcanics are at least partly equivalent in age to the supersequence. They noted that the supersequence is well-developed east of the Goondiwindi-Moonie Fault and suggested that it forms the uppermost part of a succession that ranges from possibly Devonian to Early Permian. The strata were considered to be a correlative of the Tamworth Belt succession that crops out in New South Wales.

Owing to limited data, the palaeogeographical setting for the supersequence in the southern Taroom Trough is difficult to ascertain. Conglomerates probably developed adjacent to the eastern bounding faults. The presence of marine fossils interbedded with coal (Bell & Associates, 1982) near the top in COE Inglestone 1 suggests possible deltaic influences in the upper part of the sequence in this well. Volcanism, as represented by the Camboon and Combarngo Volcanics, dominated the eastern and north-western parts of the Taroom Trough. The Camboon Volcanics intersected in UOD Sussex Downs 1 are shown to be a thick sequence with a layered seismic character (Figure 4).

SEQUENCE B

Sequence B represents the first sequence in the thermal subsidence phase and consists of the Buffel Formation and its correlatives. The sequence is common in the northern part of the project area but is less widespread in the south, being restricted to the eastern margin of the Trough.

The Buffel Formation, in outcrop, consists predominantly of limestone, siltstone and lesser sandstone deposited in a mostly marine setting. In the subsurface it consists of similar rock types and exhibits an overall fining upwards corresponding to a decrease in the proportion of sandstone. Age correlatives of the Buffel Formation are present in COE Inglestone 1 in Queensland and in UOD Goondiwindi 1 and UOD Macintyre 1, in northern New South Wales. These rocks consist mainly of conglomerate and lesser sandstone and coal (Green & others, this volume).

The base of the Buffel Formation (B30) is readily recognisable on seismic sections in the northern part of the area. However, in the south, the incoherent nature of the seismic data and the paucity of biostratigraphic data do not allow delineation of this package (Totterdell & others, 1995) although palynological data confirms the presence of Sequence B (J.L.McKellar, personal communication, 1995).

In wells, the top of Sequence B can be recognised from the difference in the structural orientation between the Early Permian rocks and overlying units. The dipmeter data for UOD Undulla 1 (Union Oil Development Corporation, 1963) and HOM Alick Creek 1 (Bell, 1981) suggest that Sequence B is unconformably overlain by later units. The unconformity in these holes represents the late Early–early Late Permian compressional event which is the same event that produced the mid-Aldebaran Sandstone unconformity in the Denison Trough (Elliott, 1993; Korsch & Totterdell, 1995).

Away from the structurally deformed areas, the younger units may disconformably overlie Sequence B. The top of the sequence is then taken at the base of the relatively uniform marine interval of the overlying cycle. This

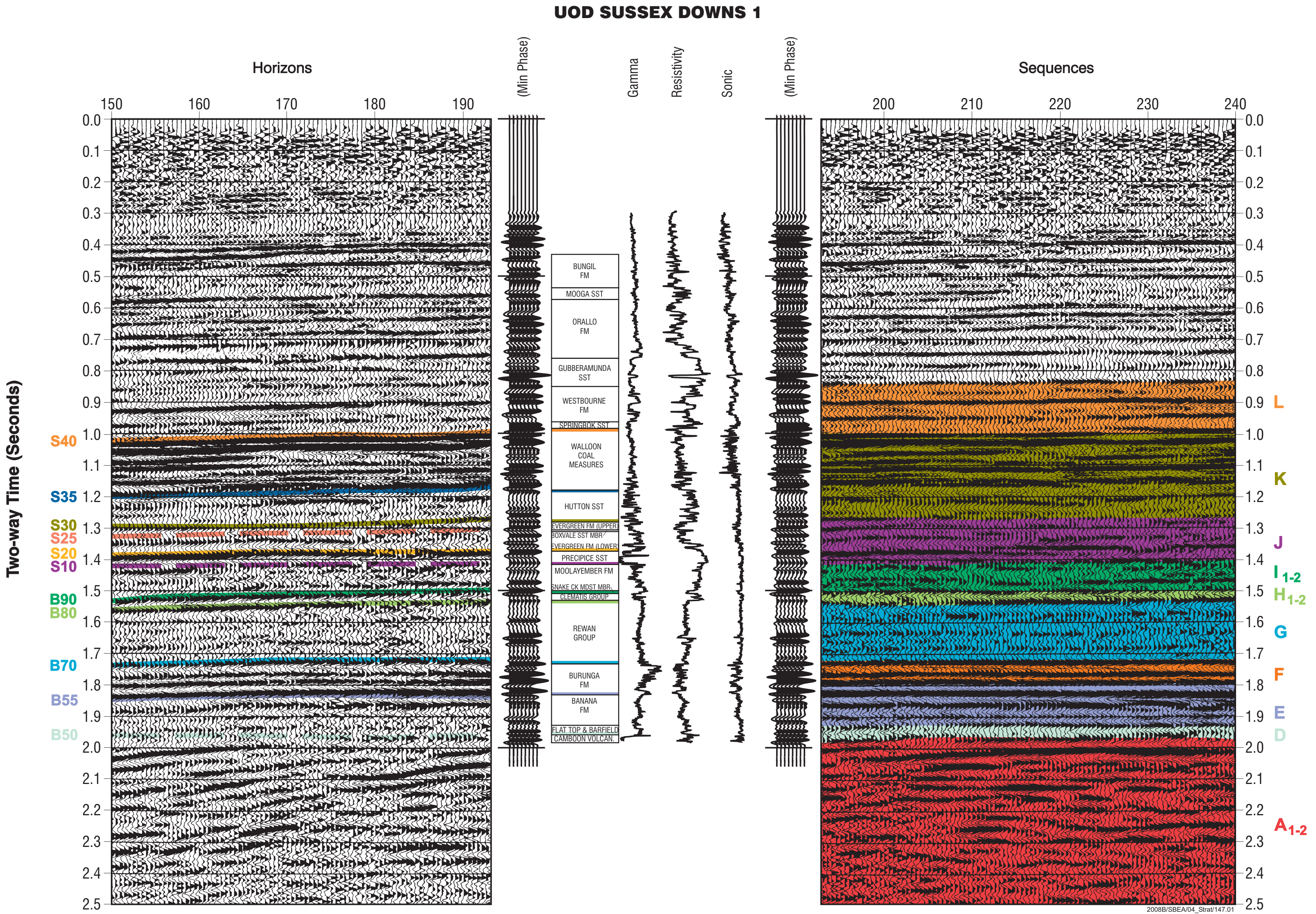


Figure 4: UOD Sussex Downs 1 synthetic seismogram correlated with wireline logs and seismic section B83-8.

boundary commonly corresponds to a sharp break on gamma-ray, resistivity and sonic logs.

The depositional environments associated with Sequence B exhibit complex regional variations. At outcrop in the north, the sequence B infills the undulate topography at the top of the Camboon Volcanics (Flood & others, 1981) and in the subsurface can be recognised where it directly overlies the Camboon Volcanics, indicating that marine sedimentation was continuous from the Early Permian. However, in the south the sedimentation at this time was predominantly fluvial with conglomerates and minor coals being deposited in a delta (Figure 5). The distribution and thickness of these conglomerates are influenced by their proximity to faults in this area. The sea may never have reached the area around UOD Goondiwindi 1 but probably extended as far south as COE Inglestone 1, (west of Moonie).

The fluvial strata in the south are contemporaneous with the marine rocks in the north and suggest that the sea transgressed from the east or north. Totterdell & others (1995) concluded that Sequence B is represented by the Cattle Creek Formation and lower Aldebaran Sandstone in the Dension Trough (Figure 3). These units suggests that the lower marine shale, limestone, and coal succession represent the TST phase of a marine sequence and the overlying nearshore deltaic deposits comprise the HST phase.

The sequence could not be delineated in the southern Taroom Trough owing to geographically scattered seismic and well data and a paucity of biostratigraphic information. Thus the depositional setting for the sequence is not fully understood (Totterdell & others, 1995). The B30 horizon is considered to be a sequence boundary which underlies the TST and HST phases in Sequence B.

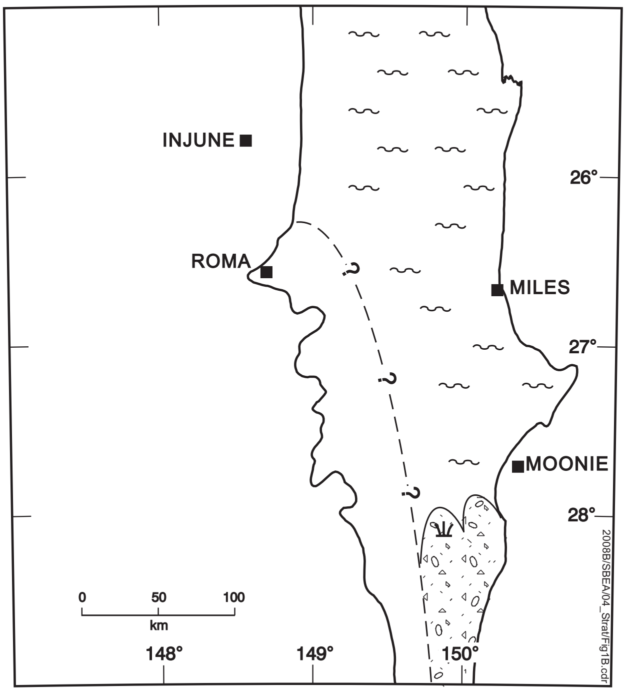
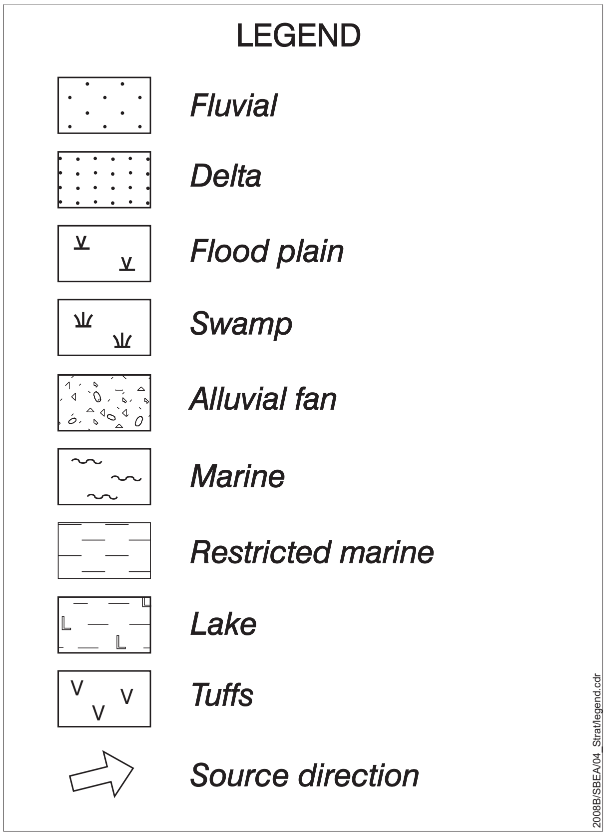


Figure 5: Depositional environment for Sequence B, Buffel Formation, southern Taroom Trough.



Legend for Figures 5-27

SEQUENCE C

Sequence C is represented by the Oxtrack Formation in the Taroom Trough and the upper part of the Aldebaran Sandstone in the Dension Trough (Totterdell & others 1995). The Oxtrack Formation was not recognised in the subsurface of the study area in either seismic or wireline log data. A correlative of the upper part of the late Early Permian Aldebaran Sandstone, has been recognised in UOD Goondiwindi 1 in northern New South Wales. The sequence is either very thin or only locally developed in the southern Taroom Trough in the study area but is better developed in New South Wales. The base of the sequence is a regional unconformity which can be traced to the mid-Aldebaran Sandstone angular unconformity in the Denison Trough.

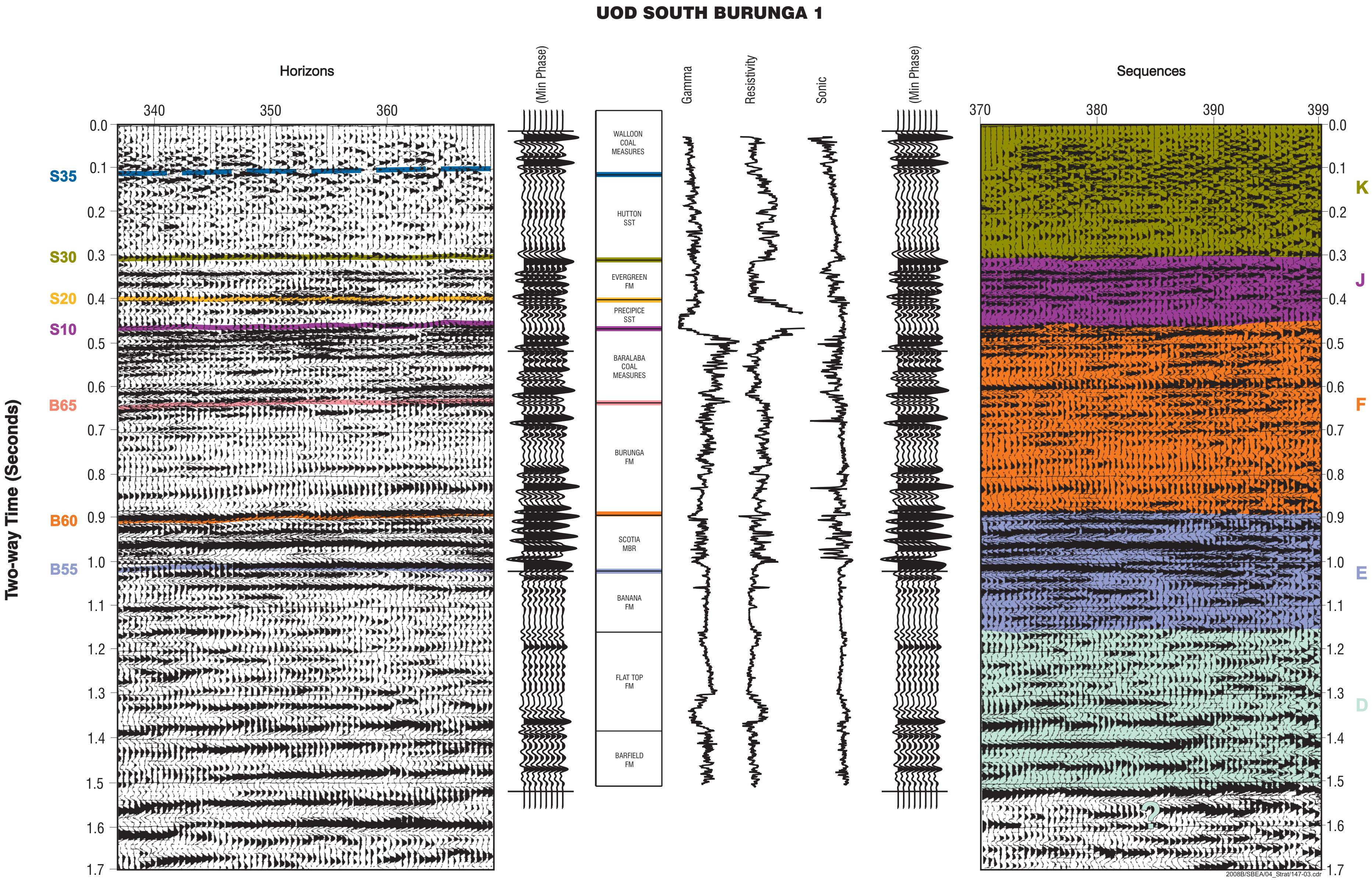


Figure 6: UOD South Burunga 1 synthetic seismogram correlated with wireline logs and seismic section DC85-290.

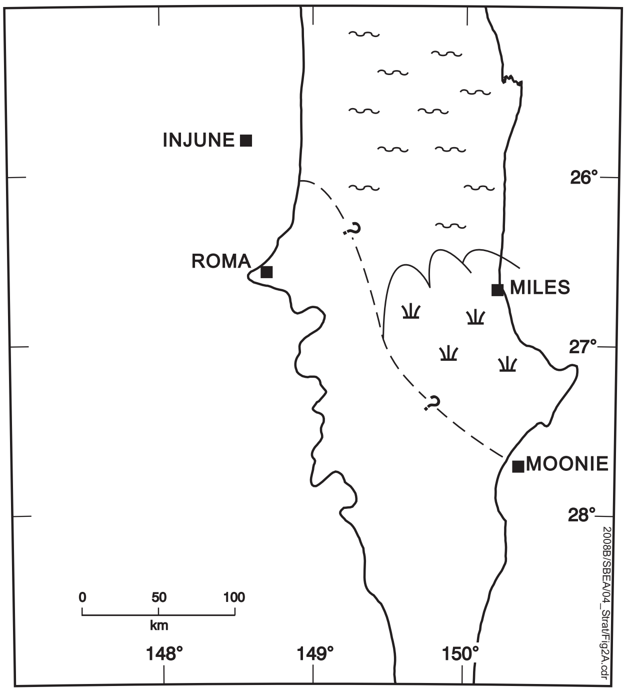


Figure 7: Depositional environment for lower Sequence D, Barfield Formation, southern Taroom Trough.

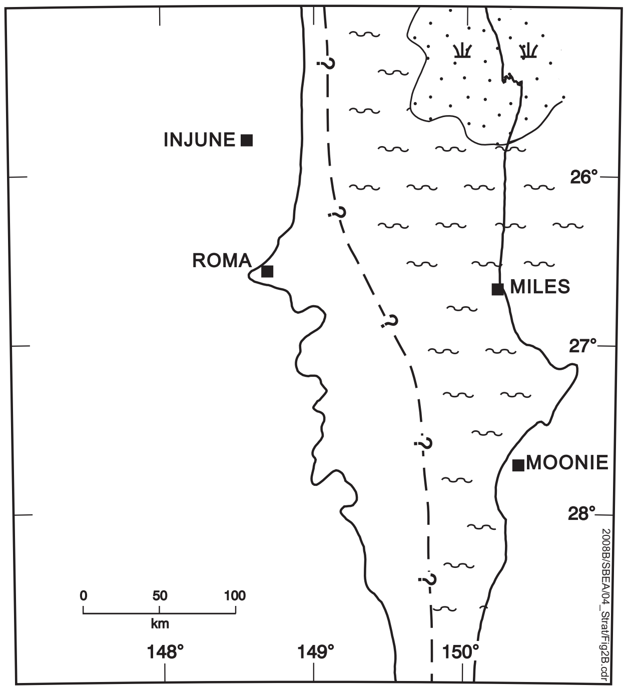


Figure 8: Depositional environment for upper Sequence D, Flat Top Formation, southern Taroom Trough.

A shallow marine depositional environment has been deduced from the fossiliferous limestones and calcareous siltstones and sandstones of the Oxtrack Formation (J.J.Draper, personal communication, 1992) implying the unit probably forms the TST phase of a marine sequence. This sequence, in UOD Goondiwindi 1, consists mainly of marine sandstones and mudstones which are consistent with a series of TST - HST cycles (Totterdell, 1996; personal communication). Additional data is required to ascertain the subsurface extent of the sequence and to explain the absence of the HST phase associated with the Oxtrack Formation in outcrop.

SEQUENCE D

Sequence D consists mainly of marine mudstones (Barfield Formation) with an overlying sandstone-dominated unit in the east (Flat Top Formation) which is partly fluvial in origin. The sequence is not recognised along the western margin of the Trough. In the south, the sequence is significantly thinner, consisting of marine mudstone and sandy mudstones and the two formations seen in the east cannot be recognised separately. The sequence records the first Late Permian extension of the sea into the southern Taroom Trough.

The base of Sequence D cannot be recognised in the seismic data. Totterdell & others (1995) have noted that owing to the thinness and restricted distribution of Sequence C, the surface at the base of Sequence D would be coincident with the base of Sequence B (B30) and hence is not resolvable. However, distinct wireline-log breaks are associated with the base of the sequence especially where it overlies volcanic units. There is no mappable horizon separating Sequences D and E (Figure 6).

Sequence D has a complex depositional history, with regional variations being common. In the north-eastern part of the study area, the Barfield Formation contains coals at its base (OMN Scotia 1) indicating that fluvial or fluvio-deltaic conditions initially prevailed in this area (Figure 7). The absence of coals and fluvial deposits in the south suggests that the southerly inundation by the sea into the southern Taroom Trough was relatively rapid and back-stepping coal swamps did not develop. The predominance of mudstones later in the sequence suggests a deepening of the sea with time, but still relatively shallow.

The sandstone-dominated Flat Top Formation, is not widely recognised, being restricted to the north-eastern part of the study area. Seismic data suggests that the Flat Top Formation occurs mainly in the north-east and it thins to the west (Beeston & others, 1995). This is consistent with a deltaic setting. Marine fossils are present in the upper and lower informal units of the Flat Top Formation but the coal in the middle informal unit indicates a fluvio-deltaic depositional setting (Green & others, this volume) (Figure 8). The development of a delta system in the north-east reflects either a highstand, stillstand or drop in sea level to explain the progradation of the Flat Top Formation over the marine Barfield Formation. However, similar effects are not noted elsewhere and a highstand with local sourcing is preferred.

A rising sea level during deposition of mudstones of the Barfield Formation together with fluvio-deltaic rocks as correlatives in other parts of the Trough suggest the Formation represents the TST in a marine sequence. The overlying predominantly deltaic rocks of the Flat Top Formation comprise the HST prograding into the basin. Like Sequence B, deep water facies do not appear to be associated with this sequence. However, fluvio-deltaic deposits at the base of the sequence could represent the facies attributed to the upper reaches of the LST and therefore a full sequence may be represented in Sequence D.

The transgressive event associated with the Barfield Formation is considered to be the same event recorded by the Freitag Formation/Ingelara Formation in the Dension Trough. The HST associated with this sequence is also recognisable in both areas with the Catherine Sandstone and the Flat Top Formation reflecting highstand deposition.

SEQUENCE E

Following the HST represented by the Flat Top Formation, marine conditions continued to dominate the depositional setting resulting in the deposition of a widespread uniform mudstone interval (Banana Formation in the east and the Muggleton Formation in the west) in the lower part of Sequence E. These Formations grade up into the overlying Scotia Coal Member in the north-east, the lower coal interval of the Burunga Formation in the south and Tinowon Formation in the west (Figure 3).

The thinning and eventual absence of the marine interval in the Burunga Formation in the south-west and south makes the recognition of the top of Sequence E difficult. The base of the sequence has only been mapped by Totterdell & others (1995) in the west as this horizon could not be traced confidently into the Taroom Trough. Neither truncation nor onlap has been observed in association with this horizon (Figures 6 & 9).

The Banana Formation is a uniform mudstone unit reflecting minimal supply of coarser clastic material from the east (Figure 6). Input of sediment from the west resulted in the deposition of the sandstone-prone Muggleton Formation. The Lorelle Sandstone Member of the Muggleton Formation represents local delta development with associated coal swamps on the delta top (Figure 10). Seismic mapping and palynological data for the Muggleton Formation suggest that they may be partially time equivalents to Sequence D, however further research is required to verify this (Figure 3).

The upper part of Sequence E is characterised by coals and abundant sandstones and mudstones; these are evident in seismic data (Figure 6). The base of these upper deposits has been mapped as the B55 horizon The coal measures are also readily recognisable on the wireline logs owing to the presence of a greater variety of rock types in comparison with the underlying marine sequence. Tuffs are commonly present in the coals.

Wireline log responses for the Scotia Coal Member and the underlying marine-dominated rocks of the Banana Formation in some petroleum wells in the north suggest continuous deposition. Totterdell & others (1995) noted that fluvially deposited conglomeratic sandstones overlie marine mudstones in the southern part of the Taroom Trough which is consistent with the stratigraphic model of a marine sequence.

Coal measures deposition appears to have extended throughout most of the study area. This interpretation is consistent with the continuation of seismic reflectors across the whole of the area. The Tinowon Formation contains the Wallabella Coal Member, the first major coal development on the Roma Shelf, as well as a prominent coquinite, the Mantuan Productus bed equivalent (at the top). Marine fossils in association with coals indicate deposition in a shallow marine to deltaic setting for the sequence in the west (Paten & Groves, 1974)(Figure 11).

Totterdell & others (1995) consider that the *Mantuan Productus* bed in the Denison Trough

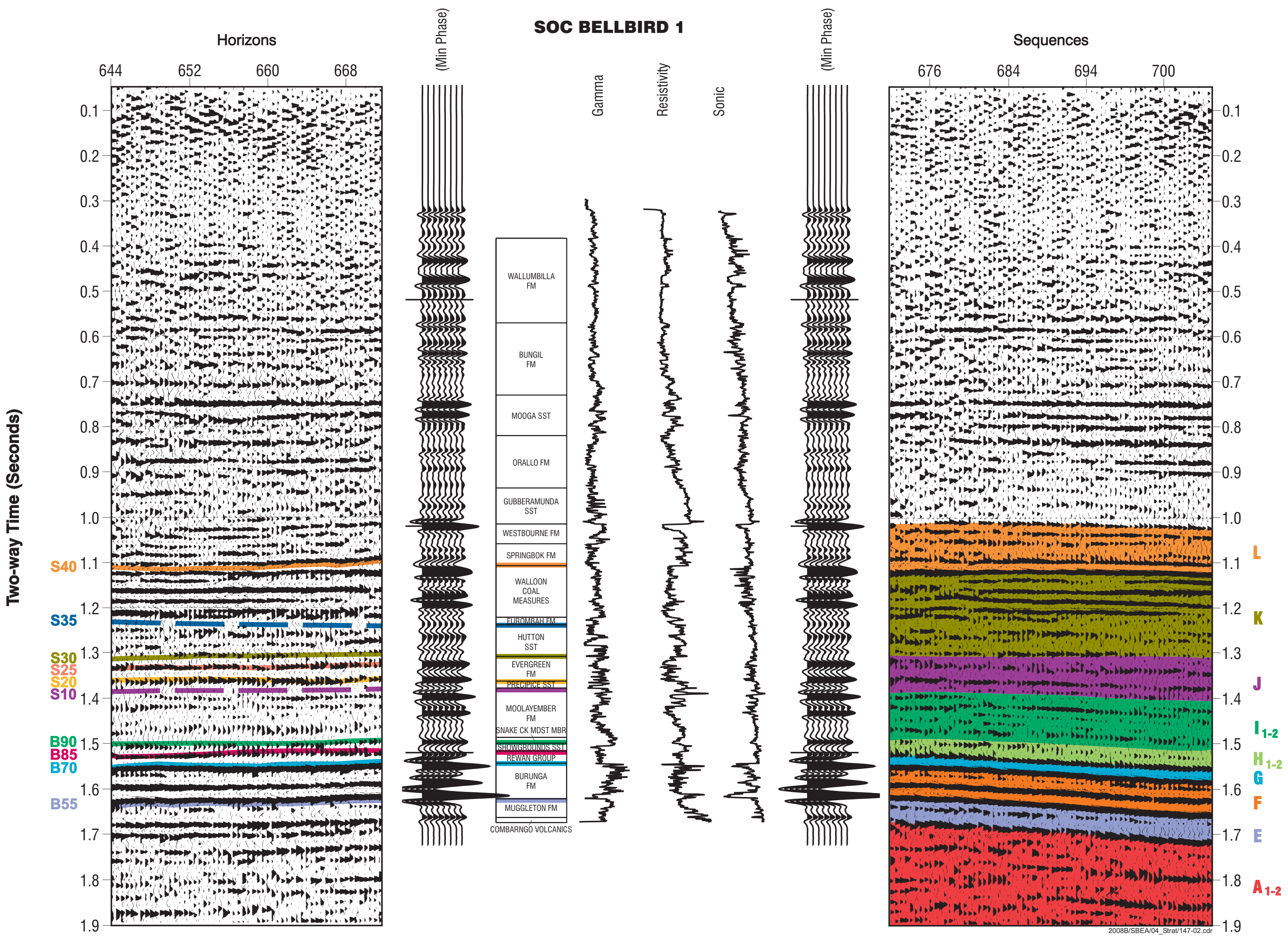


Figure 9: SOC Bellbird 1 synthetic seismogram correlated with wireline logs and seismic section P81–122.

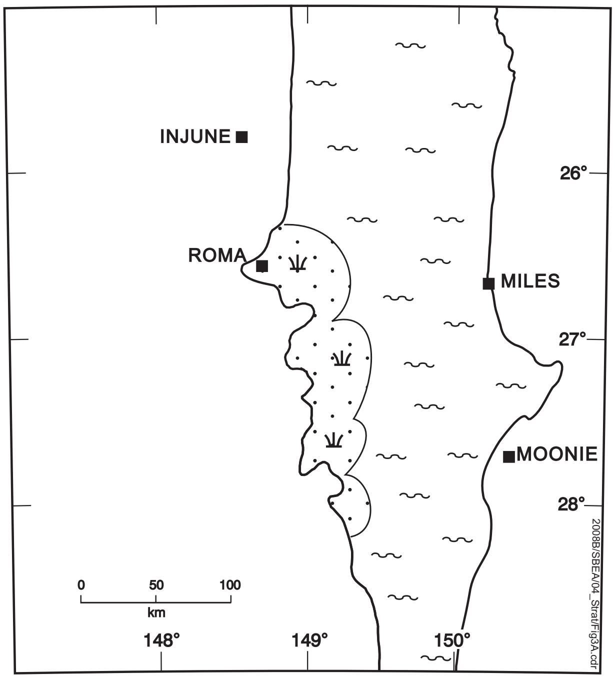


Figure 10: Depositional environment for lower Sequence E, Muggleton and Banana Formations, southern Taroom Trough.

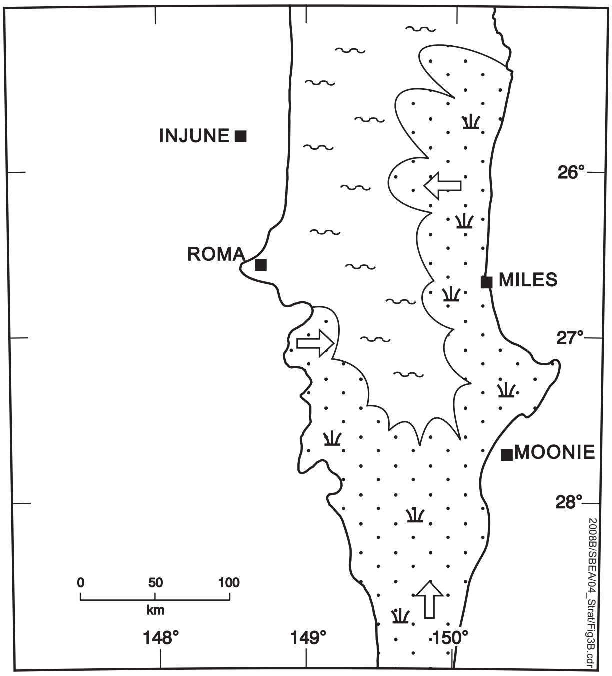


Figure 11: Depositional environment for upper Sequence E, Tinowon Formation and lower Burunga Formation, southern Taroom Trough.

is either a coquina, beach facies or high energy near-shore deposit. The bed was considered to have formed as a progradational parasequence. Alternatively, the *Mantuan Productus* bed may represent the slowing of clastic sedimentation resulting in the development of a fossil concentration. Field data from Reids Dome, Queensland (Serocold Anticline on Springsure 1:250 000 sheet) reveals that mostly complete bivalves are preserved with bryozoan encrustations in a muddy sandstone matrix indicating a quiet depositional setting. This slowing of sedimentation may be related to sea-level rise.

The gradational nature of the contact between the base of the Burunga Formation/Scotia Coal Member and the underlying transgressive marine Banana Formation suggests that they may be genetically related. The Scotia Coal Member and the Tinowon Formation therefore are interpreted to be the HST of Sequence E.

The underlying extensive shallow marine deposits of the Banana Formation represent the TST phase. The only boundary mapped at the base of the sequence from seismic data was in the west, at the base of the Muggleton Formation, where it overlies basement or volcanic units of Supersequence A.

The geological history recorded in this sequence is also present in the Denison Trough. There the lower part of the Peawaddy Formation is equivalent to the lower TST of the Banana and Muggleton Formations.

The upper HST of the sequence is related to the fluvio-deltaic deposition associated with the upper part of the Peawaddy Formation in the Denison Trough and the Scotia Member and lower Burunga Formation in the Taroom Trough.

SEQUENCE F

Sequence F records the change from marine to totally fluvial deposition. The bottom of the sequence corresponds to the base of the Black Alley Shale in the west, the Wiseman Formation in the far north-east, and the middle marine unit of the Burunga Formation in the south (Figure 3). The sequence culminates in coal measures deposition of the Bandanna Formation in the west and the Baralaba Coal Measures in the east.

The rock types in Sequence F are varied. Marine mudstones are common in the lower part and coals with associated sandstones and mudstones dominate the upper part. Tuff is also present and provides a marker bed to determine stratigraphic relationships between the units in the sequence.

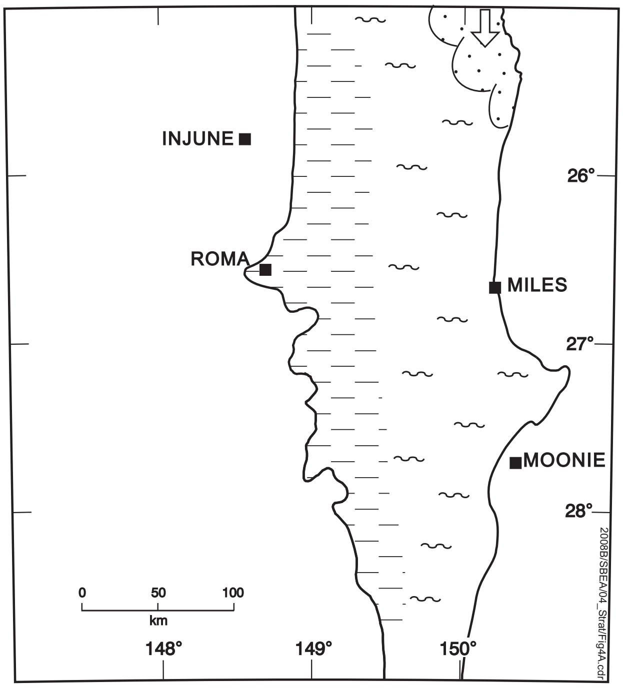


Figure 12: Depositional environment for lower Sequence F, Black Alley Shale, Burunga Formation, and Wiseman Formation, southern Taroom Trough.

The base of the sequence has been mapped by Totterdell & others (1995) as the B60 horizon in the southern Taroom Trough and the B61 horizon in the western part of the study area (Figure 6). This horizon has some underlying truncations, and westerly to south-westerly onlapping strata have been interpreted in some seismic sections and in outcrop.

To the north of the study area, downlapping relationships of southerly-prograding delta foresets can be seen (Totterdell & others, 1995). Hence the B60/B61 horizon which forms the base of the Black Alley Shale, base of marine Burunga Formation and the Wiseman Formation is considered to be a sequence boundary.

A seismic horizon (B65) has been mapped at the base of the coal measures throughout the study area (Figure 6). This horizon does not generally show features associated with sequence boundaries but minor truncations of the underlying beds have been noted by Totterdell & others (1995). Downlaps directed towards the south are fairly common which is consistent with regional delta progradation. Totterdell & others (1995) have tentatively interpreted the B65 horizon as a facies or parasequence boundary although a sequence boundary is possible. Thus the B65 horizon is likely to be diachronous owing to the development of coal swamps on the prograding deltas.

The sequence is readily recognisable on the wireline-logs with distinctive breaks both at the base and top. The base is easily identified where thick marine mudstones with a uniform log response overlie the coal measures of the preceding sequence with a spiky log response. The base of the sequence is more difficult to recognise where the marine mudstone is thin. This difficulty is due to the similarity in log response of the mudstones in the marine and coal measures units. The presence of fossils can identify the base of the marine mudstone interval. If the marine mudstone is relatively thin and fossils are absent, then the identification of the base of the sequence in the coal measures is nearly impossible. This situation primarily exists in the southern and south-western parts of the study area where the name Burunga Formation is used.

The top of Sequence F is generally taken at the top of the uppermost coal which produces a strong reflector in contrast to the overlying fluvial sandstone package and is easily identified on wireline-logs.

A sea-level rise resulted in the formation of a restricted sea and the deposition of the Black Alley Shale in the Denison and southern Taroom Troughs. Acritarchs at the bottom of the formation suggest initial deposition was in a large basin with limited direct access to the sea (Mollan & others, 1969). The lack of fossils in these black shales also indicates that the circulation was poor and restricted conditions existed in the west (Figure 12).

Marine fossils occur at stratigraphically higher positions in the Burunga Formation in the Miles area. This indicates that marine conditions persisted in this area while stagnant conditions existed elsewhere. The maintenance of marine conditions in this area is a reflection of the proximity to the open sea. It appears that the connection of the Bowen Basin to the sea was in the vicinity of Miles during this time (Beeston & others 1995) (Figure 13) rather than to south as previously thought (Fielding & others, 1990).

The Wiseman Formation in the north-east represents a lateral change in the depositional environments from marine conditions to fluvial-dominated deltas and finally fluvial conditions. The southwards migration of these deltas into the sea represented by the Burunga Formation is consistent with the southerly-prograding delta foresets noted by Totterdell & others (1995) in seismic data.

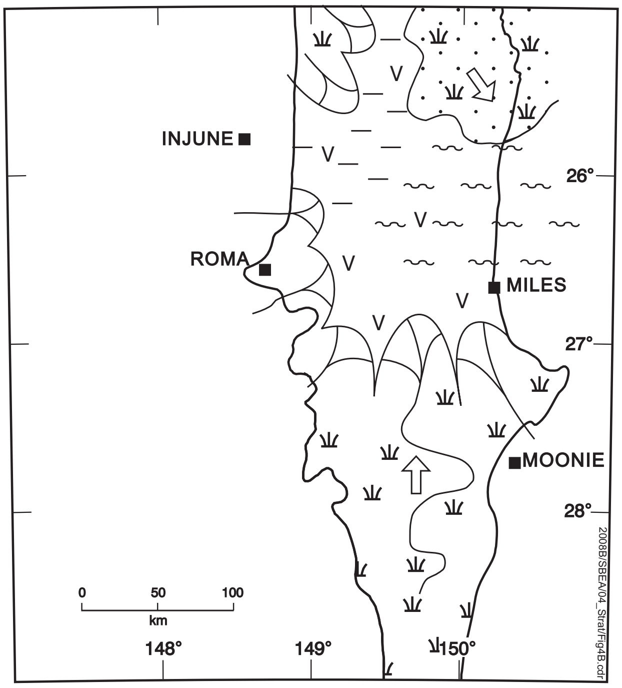


Figure 13: Depositional environment for middle Sequence F, Bandanna, Burunga and Wiseman Formations, southern Taroom Trough.

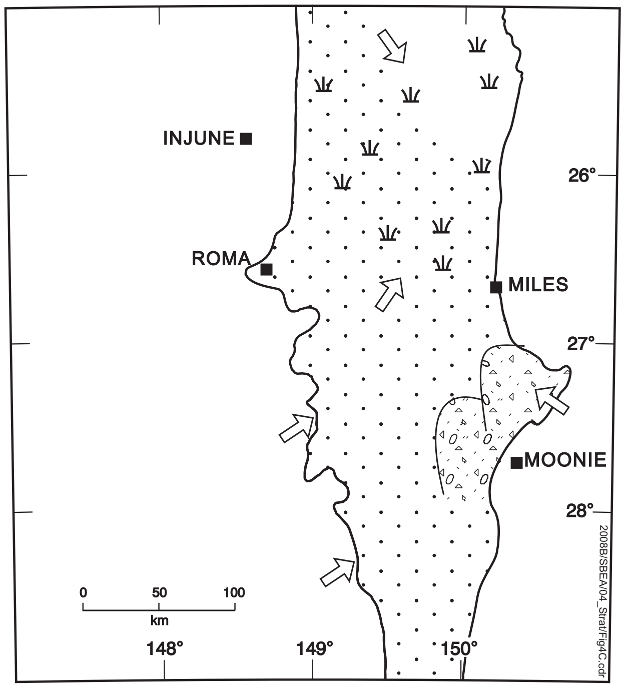


Figure 14: Depositional environment for upper Sequence F, Bandanna Formation, Rewan Group, and Baralaba Coal Measures, southern Taroom Trough.

In the north-western part of the study area, the restricted marine conditions were quickly replaced by fluvio-deltaic deposition associated with the lower part of the Bandanna Formation. The short duration of restricted conditions resulted in the deposition of only a thin Black Alley Shale. Finally, fluvial conditions prevailed in the upper part of the Bandanna Formation (Beeston & Draper, 1991). The truncation of underlying beds by the B65 seismic reflector is consistent with these beds being foresets overlain by deltaic coals (Totterdell & others, 1995).

Numerous interbedded tuffs indicate extensive volcanic activity during deposition of the early part of this sequence. Tuff occurs in the coal measures in the south, throughout the marine interval of the Burunga Formation and in the basal part of the Baralaba Coal Measures in the north. This variability in the stratigraphic position of the tuffs indicates that coal measures deposition was occurring in fluvio-deltaic settings in the south while marine conditions persisted in the north. The presence of a sea in the northern part of the study area has previously been postulated by Swaine (1971) based on the presence of boron in coals in the northern Bowen Basin. The boron distribution is consistent with a connection to the open sea in the vicinity of Miles.

Deposition of the upper part of Sequence F represents a basinward shift in facies and the infilling of the Permian sea. The upper part is dominated by the Baralaba Coal Measures which have a restricted areal distribution and a totally fluvial depositional setting. This distribution is due to major changes in environments during the closing stages of deposition of this sequence. Towards the end of the sequence, the major stream drainage systems were to the south (Fielding & others, 1990). However in the south, the distribution of facies in the early part of this sequence, in particular, the northerly progradation of the deltas, suggests drainage to the north. The Baralaba Coal Measures therefore represent the contraction of coal swamps towards the north-east with fluvial conditions developing elsewhere (Figure 14).

The Baralaba Coal Measures post-date coal measures deposition in the Burunga Formation in the south, which suggests that fluvial conditions developed initially in the south before migrating northwards and the base of the coal measures is time transgressive. The result is the northerly progression of the coal measures environments in the southern Taroom Trough which mirrors the southerly progression of coal deposition in the northern Bowen Basin.

Similarities exist between the depositional setting of the sequence in the Denison and

Taroom Troughs. Deposition commenced with a transgression represented by the Black Alley Shale in the Dension Trough and western Taroom Trough and the marine Burunga Formation in the eastern part of the Taroom Trough. Progradation occurred in both areas. Moreover, the presence of tuffs in the coals of the Burunga Formation in the southern part of the study area suggests that deposition occurred there at the same time that Black Alley Shale and the marine interval of the Burunga Formation were being deposited in the Dension Trough and in the northern part of the study area respectively.

Major deltas occurred in the Dension Trough with the deposition of the Bandanna Formation. In the southern Taroom Trough, a similar environment of deposition appears to have been restricted to the north-western part of the study area. Elsewhere, infilling of the sea in the southern Taroom Trough probably started earlier and subsequently, fluvio-deltaic conditions developed rapidly throughout the study area.

SEQUENCE G

Sequence G, equivalent to the Rewan Group, records the widespread occurrence of fluvial deposition throughout the study area. A two-fold subdivision of Sagittarius Sandstone overlain by Arcadia Formation is recognised from the seismic data, with the B75 seismic horizon forming the basis of the subdivision within this sequence.

The Sagittarius Sandstone consists of fine to very coarse-grained lithic sandstones interbedded with mudstones and siltstones. The Arcadia Formation is characterised by thick mudstone intervals with lesser siltstone and sandstone beds.

Lower

The base of Sequence G (B70 seismic horizon) is generally taken as the uppermost coal seam in the underlying sequence. This top is readily recognisable on the seismic data where it is a well-defined reflection. Totterdell & others (1995) have reported direct onlapping, erosional relief and truncation associated with the B70 horizon in the northern Taroom Trough. This is supported by the presence of an hiatus as determined by palynological data (Green & others, this volume). Similar relationships occur in the Dension Trough (Totterdell & others, 1995). A slight angular unconformity of only 10o dip difference has also been identified across the contact. However, Beeston & others (1995) conclude that the lower Rewan Group is laterally continuous with the Permian coals in the southern Taroom Trough and Roma Shelf regions suggesting these areas may represent the conformable correlative of the unconformity.

The coals immediately below Sequence G are represented by a package of parallel reflectors. Detailed seismic interpretation of the B70 horizon shows the topmost reflectors of the package in the north-east gradually peter out towards the south and west (Figure 15). This suggests that the uppermost coal seam is not at the same stratigraphic position throughout the southern Taroom Trough. Therefore the southern and western extensions of the B70 horizon are interpreted to be correlative conformities in the lower part of the Rewan Group.

The wireline logs across the contact between the Rewan Group and underlying Permian coal measures show both a sharp and gradational breaks in the gamma-ray, resistivity and sonic logs. A readily recognisable change in sonic log character is present at the bottom of Sequence G in the south-western part of study area. This change in sonic log unit can be traced northwards along the western margin of the southern Taroom Trough. The stratigraphic position of the topmost coal relative to the change in the sonic log varies being higher in the north than in the south (Figure 16). This suggests that the stratigraphic position of the top coal in the north may be equivalent to a level in the lower part of the Rewan Group in the south. Therefore fluvial sedimentation was occurring in the south and probably the west while coal swamps were present in the northern part of the study area.

Foster (1979) recorded an abrupt change in the palynomorph assemblage at the boundary between the Baralaba Coal Measures and the Rewan Group. Also there is an increase in mean grain size and proportion of sandstone above the contact implying that the base of the Rewan Group is a sequence boundary. Thus the Sagittarius Sandstone represents the LST phase of a non-marine sequence.

The base of the Rewan Group has traditionally been considered to correlate with the Permian -

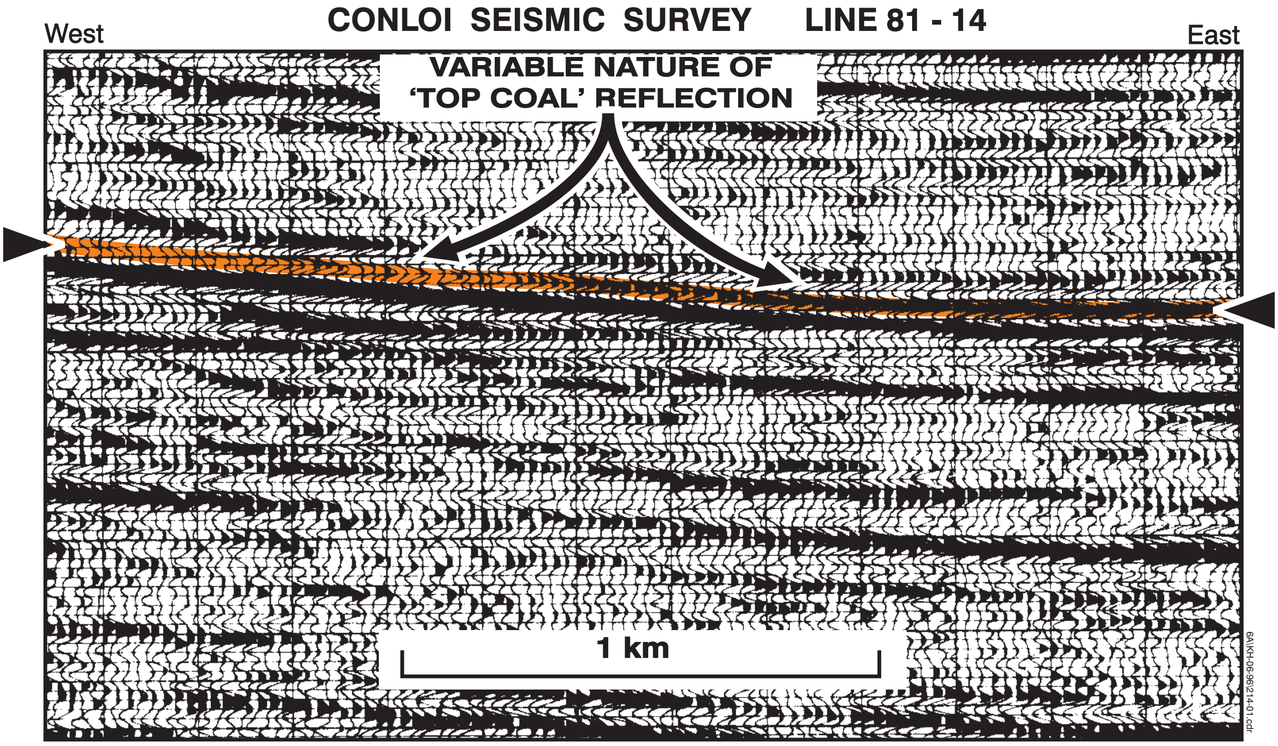


Figure 15: Example of seismic section showing the discontinuous nature of the coal seams (Conloi seismic survey, line 81-14).

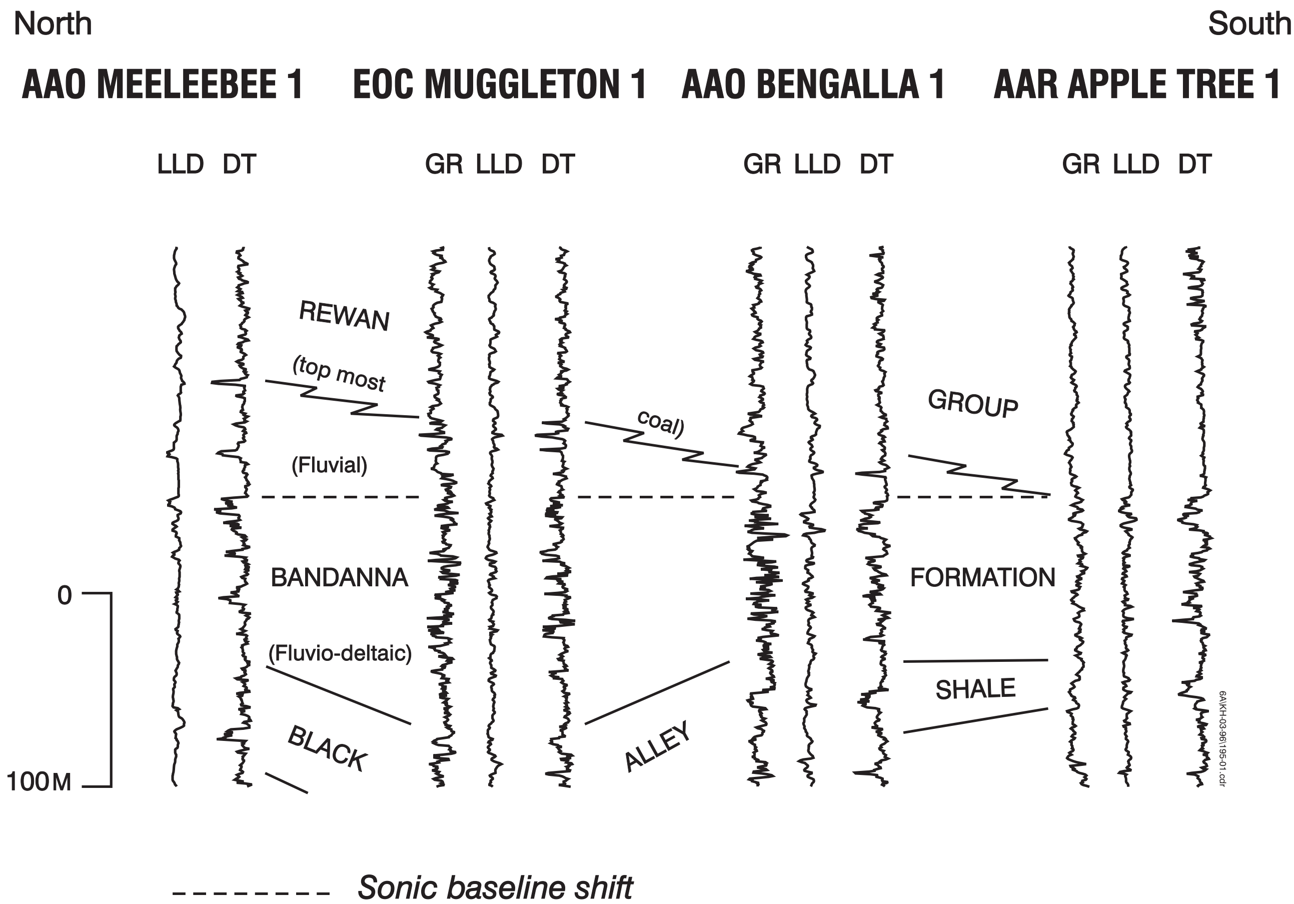


Figure 16: Well correlations showing the relationship between the log unit and the position of the topmost coal seams.

Triassic boundary. However, the seismic and well data for the study area suggest that the base of the Rewan Group is diachronous, younging to the east and north. The coal measures were being deposited near Miles while fluvial sedimentation occurred on the Roma Shelf and to the south.

An alternative interpretation of the palynological data is possible and consistent with there being a major break at the base of the Rewan Group. If the time break was of different extent in different parts of the basin, then in some areas sedimentation would have commenced earlier. Thus there will be areas where the initial sedimentation in the Rewan Group is younger but in the same palynological zone as the Baralaba Coal Measures. But where the break is greater, then a change from rocks of Permian to Triassic age is expected. The limitations associated with determining the correct relationship is probably a reflection of the relatively broad nature of the palynological zones.

Jensen (1975) has interpreted the interbedded sandstones, mudstones and siltstones of the Sagittarius Sandstone to be meandering river deposits (Figure 17). Local conglomeratic units in the south-east (Cabawin Formation) reflect alluvial fan development. The fans formed as the result of uplift on the eastern side of the Goondiwindi–Moonie Fault.

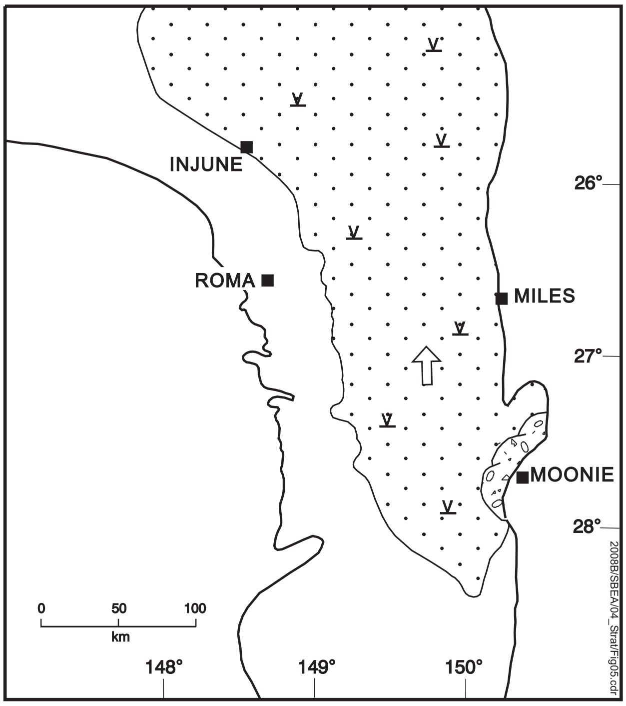


Figure 17: Depositional environment for lower Sequence G, Rewan Group, southern Bowen Basin.

Upper

The B75 seismic horizon corresponds approximately to the base of the Arcadia Formation. Onlap and truncation rarely abut this horizon in seismic data and basinwide, it is generally difficult to resolve seismically. An intra-Rewan Group unconformity has been reported by Cosgrove & Mogg (1985) in the Raslie area on the Roma Shelf. These terminations are believed to have been caused by local erosion and are not basinwide events.

The gamma-ray and resistivity logs show little change at the contact between the formations although there is a sharp break on the sonic log. The consistent nature of the gamma-ray and resistivity responses in the Rewan Group indicates that the two formations are probably part of the same depositional system. This agrees with the mainly featureless seismic signature that the Rewan Group exhibits across the basin (Figure 4). Therefore, the continuity of deposition with the underlying Sagittarius Sandstone and the predominance of mudstone in this unit suggest that the Arcadia Formation in Sequence G comprises the TST phase and may incorporate the HST phase. Hence, the fining-upwards of the Sagittarius Sandstone to the mudstones of the Arcadia Formation indicates that base level was rising during deposition. The lack of sharp log breaks or widespread seismic terminations along the B75 seismic horizon implies that it is a unit boundary and not a sequence boundary.

According to Jensen (1975) the fining-upwards Arcadia Formation which is capped by suspension-load deposits, was the result of meandering and then anastomosing river systems indicating an increase in accommodation space (or base level rise) during its deposition.

SUPERSEQUENCE H

Supersequence H can be subdivided into H1 and H2. Sequence H1 correspond to the Glenidal Formation and Sequence H2 to the Expedition Sandstone and its correlative the Showgrounds Sandstone as well as the overlying Snake Creek Mudstone Member of the Moolayember Formation. These sequences record major changes in both provenance and depositional style.

The Glenidal Formation or Sequence H1 consist of thinly bedded, very fine to medium-grained sublabile sandstones and common siltstones and mudstones. The Expedition Sandstone or Sequence H2 consists mainly of quartzose sandstones with minor sublabile sandstones, siltstones and mudstones.

The Showgrounds Sandstone is restricted to the subsurface in the western and southern parts of the Trough and consists mainly of medium to coarse-grained quartzose sandstones and conglomerates. The Snake Creek Mudstone Member is predominantly dark grey to black mudstone with minor very fine-grained quartzose sandstone.

Lower

Seismically, the B80 horizon which equates with the base of the Glenidal Formation, truncates the underlying B75 horizon within the Taroom Trough (Figure 4). Onlap, downlap, and erosional relief were observed associated with the B80 horizon on the basin flanks (Wells & others, 1993). Dickins & Malone (1973) concluded that the boundary is locally disconformable and Elliott & Brown (1988) have interpreted the base of the Glenidal Formation to be an erosional surface. Major changes in grain-size and sandstone provenance at the base of the Glenidal Formation lend further support to the idea that the B80 horizon is a sequence boundary.

The log breaks at the base exhibit pronounced shifts in the baseline supporting the major change in provenance from the mudstones and labile sandstones of the Arcadia Formation to the sublabile to quartzose sandstones of the Glenidal Formation. There is a general decrease in the proportion of fines in the Glenidal Formation compared with the underlying Arcadia Formation.

The Glenidal Formation probably constitutes an entire sequence although without the presence of any characteristic coarser-grained basal unit or uppermost fine-grained suspension deposits. Thus only the fine to medium-grained TST phase appears to be present. The HST phase was either never deposited or has been eroded due to a sudden change in base level. A gradual change in depositional environments could explain the absence of the LST phase. This concurs with Jensen's (1975) interpretation that the rocks of the Glenidal Formation were deposited by meandering streams and not braided streams (Figure 18).

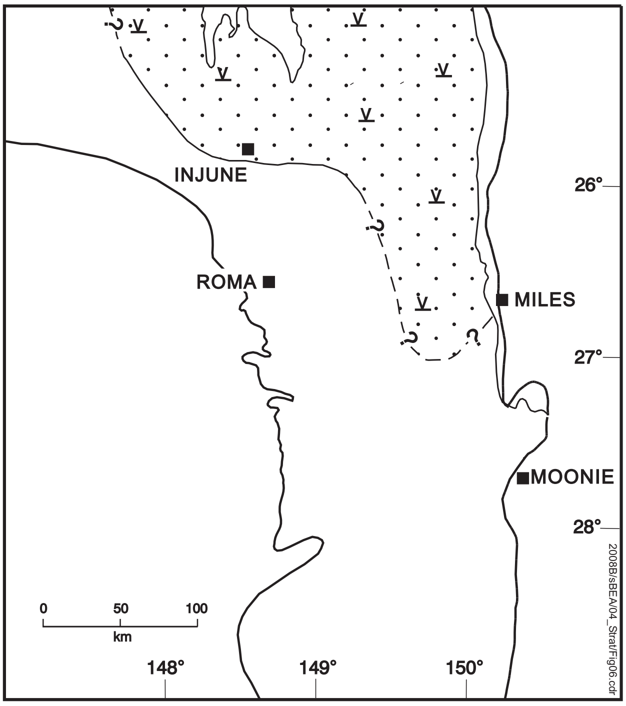


Figure 18: Depositional environment for Sequence H1, Glenidal Formation, southern Bowen Basin.

Upper

Sequence H2 corresponds approximately to the Expedition and Showgrounds Sandstones and the Snake Creek Mudstone Member of the Moolayember Formation. The base of the Showgrounds Sandstone is shown to represent a hiatus, especially on the Roma Shelf (Gray, 1972), and is believed to be erosional by Elliott & Brown (1988). The base of the Showgrounds Sandstone and Snake Creek Mudstone Member are mapped as B85 and B90 horizons, respectively in the seismic (Figure 9). Jensen (1975) recorded no angular discordance at the base of the Expedition Sandstone at outcrop, although some truncation, downlap and onlap are observed in seismic data (Totterdell & others, 1991). A hiatus, truncation and erosion are supported by a strong shift in the gamma-ray, resistivity, and sonic log baselines marking the introduction of mainly quartzose sandstone in the lowermost beds. Also, there is a decrease in the overall percentage of fine-grained rocks across the contact compared with the Glenidal Formation.

In the southern Taroom Trough in Queensland, the Showgrounds Sandstone consists of fining-upwards sandstones capped by mudstones with minor interbedded sandstones in the uppermost part. The unit is considered to be deposited by easterly flowing streams (Hoogetoorn, 1970)(Figure 19). The Snake Creek Mudstone Member appears conformable

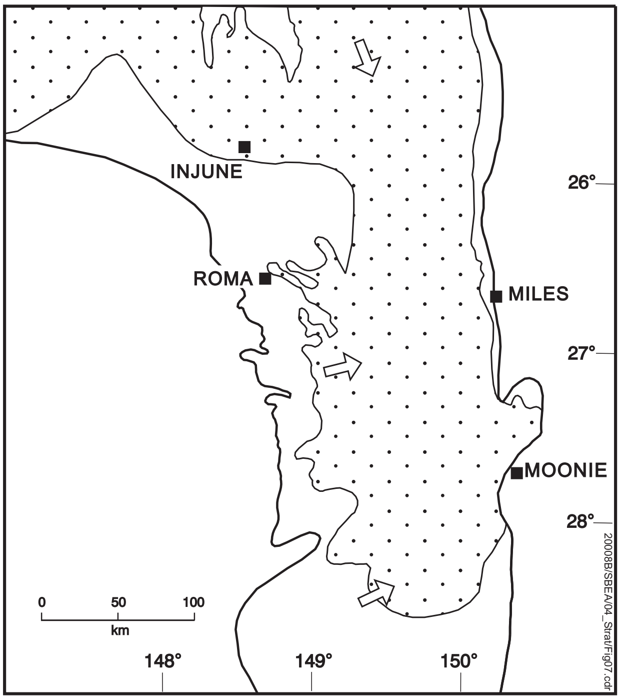


Figure 19: Depositional environment for lower Sequence H2 , Showgrounds Sandstone, southern Bowen Basin.

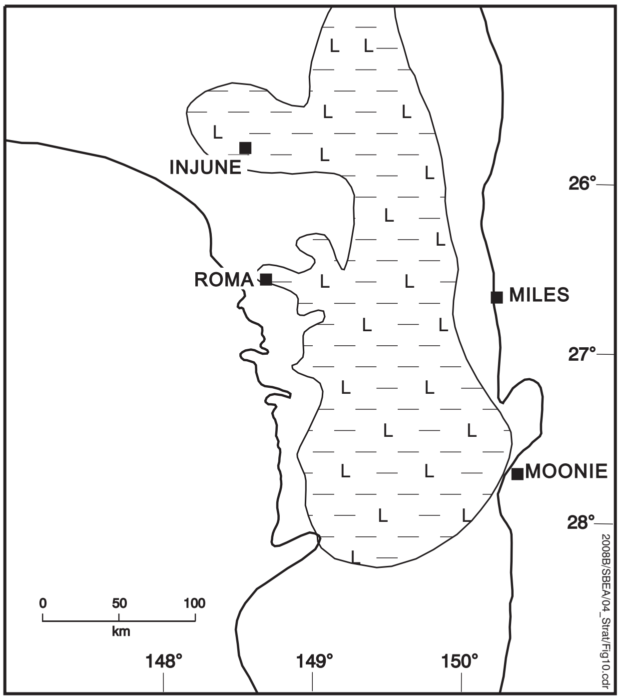


Figure 20: Depositional environment for upper Sequence H2, Snake Creek Mudstone Member, Moolayember Formation, southern Bowen Basin.

with the underlying Showgrounds Sandstone, especially where the uppermost mainly mudstone interval of the latter is present. Rare truncations of the strata beneath the B90 horizon (base of the Snake Creek Mudstone Member) are observed in the seismic data although the reflectors generally appear concordant with the Showgrounds and Expedition Sandstones (Wells & others, 1993).

The mudstones interbedded in the upper part of the Showgrounds Sandstone are interpreted to be lacustrine deposits transitional to the overlying Snake Creek Mudstone Member of the Moolayember Formation. The gamma-ray log does not change significantly over the contact, however the resistivity and sonic logs exhibit marked baseline shifts. Elsewhere in the basin there is a sharp break on all logs indicating a sudden change in grain size or composition.

Although the evidence is not equivocal regarding the relationship between the Snake Creek Mudstone Member and the Showgrounds and Expedition Sandstones, it is possible that the transition to mudstone may be explained by a sudden increase in base-level rise which is the non-marine equivalent of a maximum flooding event. Such an event may give an anomalous break in the logs.

The Showgrounds Sandstone and Expedition Sandstone represent a single depositional system consisting of the LST phase with the fine-grained TST or HST being represented by the overlying Snake Creek Mudstone Member. The Snake Creek Mudstone Member is interpreted by Butcher (1984) to have been deposited in a marginal marine or tidal-flat environment. However, the palynoflora which embrace low diversity spinose acritarchs, suggest a lacustrine setting, the depositional environment favoured by most workers (Figure 20)(Price, 1996, personal communication).

SUPERSEQUENCE I

On seismic evidence, Supersequence I is divided into Sequences I_1 and I_2. Sequence I1 incorporates the informal lower subunit of the Moolayember Formation which is defined at the top by the B95 seismic horizon. Sequence I_2 extends from the B95 horizon to the base of Surat Basin, the S10 horizon, equating with the informal upper subunit of the Moolayember Formation.

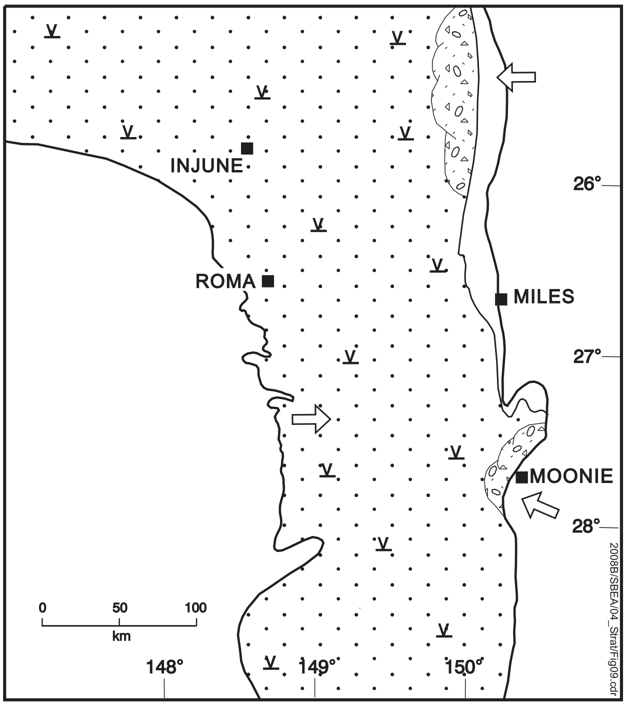


Figure 21: Depositional environment for Sequence I1 , informal lower unit, Moolayember Formation, southern Bowen Basin.

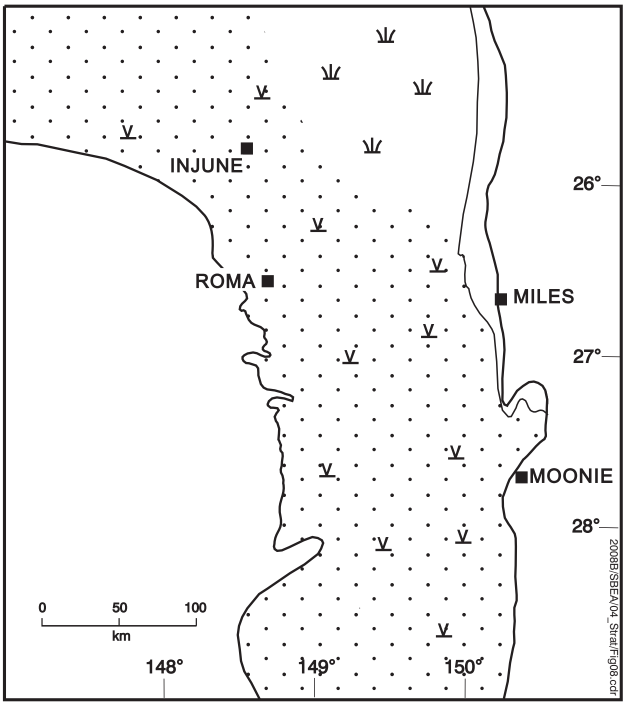


Figure 22: Depositional environment for Sequence I2, informal upper unit, Moolayember Formation, southern Bowen Basin.

Totterdell & others (1995) have interpreted the B95 horizon as an intra-Moolayember Formation sequence boundary owing to the presence of seismic terminations at that level. Wireline log data on the other hand tends to support a conformable, not unconformable relationship, between the subunits. Further information is required on the depositional history of the Moolayember Formation before the B95 seismic horizon can be confirmed as a sequence boundary.

Lower

The informal lower subunit consists dominantly of fine to medium-grained labile to sublabile sandstones. The Snake Creek Mudstone Member generally grades up into the informal lower subunit of the Moolayember Formation although slight shifts in the resistivity and sonic log baselines accompany the gradational change. The presence of gradational trends indicate that there was probably a relatively slow base level lowering allowing the rivers to adjust. From seismic data the informal lower subunit and the Snake Creek Mudstone Member were originally interpreted by Totterdell & others (1995) to be a non-marine sequence, owing to the mappable nature of the base of the Moolayember Formation and the association of terminations. However, further lithological work on the extent and nature of the Snake Creek Mudstone Member has led to a redefinition of the associated Triassic sequences as shown in Figure 3.

The informal lower unit of the Moolayember Formation was considered by Estensen (1984) to have been deposited by sandy braided river systems (Figure 21). Thick conglomerates in the lower Moolayember Formation on the eastern side of the basin were interpreted by Alock (1969) to have been deposited by fluvial systems sourced from elevated areas further to the east.

Upper

The base of Sequence I2 is recognised as the B95 seismic horizon. Only in the Taroom region in the northern part of the project area are there rare truncations associated with the B95 horizon (Totterdell & others 1991). Usually, the seismic traces on either side of the boundary are fairly homogenous.

The informal upper subunit of the Moolayember Formation consists of siltstones, mudstones, minor sandstones and coals interpreted by Estensen (1984) to have been deposited in meandering distal river systems (Figure 22). The presence of acritarchs provides evidence that at least brackish conditions prevailed during the deposition of some horizons (Alcock, 1969).

SURAT BASIN SEQUENCES

SEQUENCE J

Sequence J consists of the Precipice Sandstone and the overlying Evergreen Formation, which includes the Boxvale Sandstone Member and the Westgrove Ironstone Member (Figure 3). Three seismic horizons were mapped in relation to this sequence; the base of the Precipice Sandstone (S10 horizon), the base of the Evergreen Formation (S20 horizon), and the base of the Westgrove Ironstone Member (S25 horizon)(Figures 4,6, & 9).

Late Triassic rocks have been identified in the northwestern part of the study area from palynological data (McKellar, 1978; Price, 1995). These rocks are considered to be the basal unit of the Surat Basin succession owing to their lithological similarity to the Precipice Sandstone (Green & others, this volume). The Late Triassic unit could be widespread but has been difficult to recognise owing to its thinness, the absence of distinctive rock types and the paucity of palynological data. It could not be convincingly imaged in the seismic data. The Late Triassic rocks have been included with the Precipice Sandstone which is the basal lithostratigraphic unit associated with this sequence.

Lower

The lowermost interval in Sequence J corresponding to the Precipice Sandstone, is defined at the bottom and top by the S10 and S20 seismic horizons. The S10 horizon represents a major basinwide unconformity and is recognised in both outcrop and seismic data. The horizon separates the generally tilted Bowen Basin strata from the near-horizontal Surat Basin strata. The time span represented by this unconformity is approximately 20 million years. The sequence boundary on seismic sections shows truncation of the underlying strata but there is no associated onlap or downlap.

The Precipice Sandstone consists mainly of fine to coarse-grained pebbly quartzose sandstone deposited as extensive sheets.

Martin (1981) suggested that the base of the Precipice Sandstone youngs to the west and this is consistent with the palynological determinations by Price (1985) and McKellar (personal communication, 1994).

Wireline logs corresponding to the S10 seismic horizon all show a sharp break, signifying the unconformity between the basins. The presence of a basal unconformity, a palynological hiatus, extensive sandstones, and a sudden change in lithology from the underlying strata suggest that the Precipice Sandstone represents the basal LST component of Sequence J, defined by the S10 sequence boundary.

The Precipice Sandstone was deposited in a braided stream system and rivers flowed from west to east (Martin, 1981) (Figure 23). In the Roma area, Sell & others (1972) interpreted that the Precipice Sandstone was deposited by north-north-easterly flowing streams.

Upper

The uppermost interval in Sequence J corresponding to the Evergreen Formation, is defined at the bottom and top by the S20 and S30 seismic horizons respectively. The Evergreen Formation contains two distinct seismic packages: the first extends up to the base of the Westgrove Ironstone Member (S25 horizon) and the second up to the base of the Hutton Sandstone, S30 horizon.

There is rare onlap and truncation associated with the S20 horizon on the Roma Shelf. However, these terminations may be the result of localised erosion at the limit of deposition rather than a basinwide sequence boundary.

The gamma-ray, resistivity, and sonic log responses across the S20 horizon can be either sharp or gradational depending on the well position in the basin. According to Exon (1976), the Precipice Sandstone/Evergreen Formation contact is transitional and sandstones grade upwards into a finer-grained unit of predominantly siltstone. A gradational lithological contact between these formations suggests they are conformable.

Reiser and Williams' (1969) palynological results suggest that the base of the Evergreen Formation is diachronous. However, this now seems unlikely due to increased knowledge on the range of the index species used in the

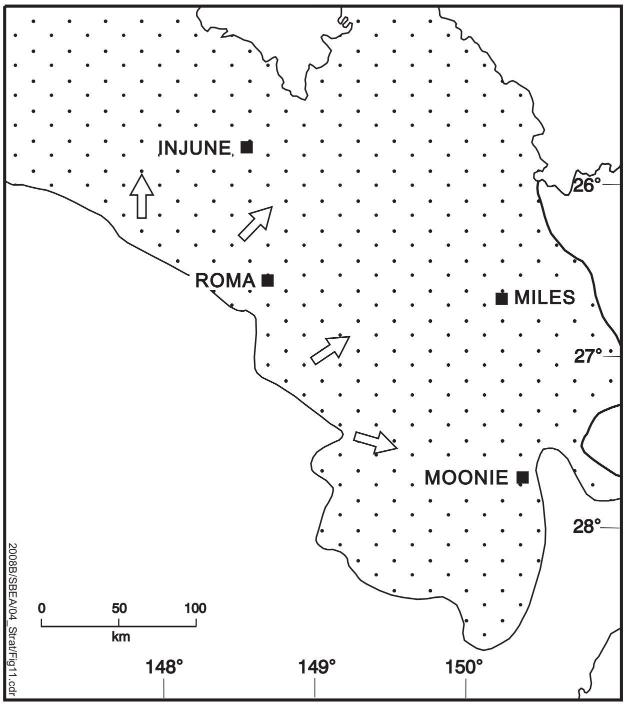


Figure 23: Depositional environment for lower Sequence J, Precipice Sandstone, southern Bowen Basin.

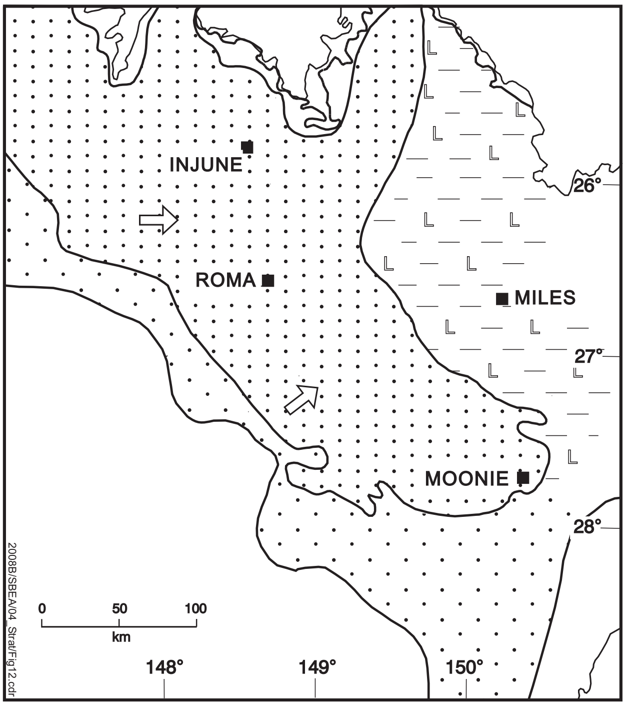


Figure 24: Depositional environment for upper Sequence J, Boxvale Sandstone Member, Evergreen Formation, southern Bowen Basin.

investigation (J.L. McKellar, personal communication, 1994). Palynological data shows that mudstones in the uppermost part of the Evergreen Formation have a consistent age across the basin which suggests that the sequence reached its maximum base level.

The Boxvale Sandstone Member occurs immediately below the S25 horizon. The Member consists mainly of friable quartzose sandstone and is readily recognisable on wireline logs owing to a low gamma-ray and high resistivity response. The base of the member may have either a sharp or gradational contact with the underlying strata. Although the Boxvale Sandstone is lithologically distinct, the similarity of the wireline log baselines above and below the member suggests that it is genetically related to the overall depositional setting of the Evergreen Formation.

The S25 horizon, equated with the base of the Westgrove Ironstone Member (WIM) and its correlatives, is readily recognisable in seismic sections as a strong reflector (Figure 9). The reflector is probably a result of the change in the velocity between the friable quartzose Boxvale Sandstone and the overlying dense black mudstones of the WIM. The dense mudstones directly underlie the Evergreen Resistivity Marker (ERM).

The Evergreen Formation is considered to represent the TST and HST phases of deposition of Sequence J. This is owing to the predominance of fine-grained strata, a generally gradational contact with the Precipice Sandstone, and the fact that the interbedded sandstones are limited in extent and generally immature in composition. Hence, the S20 horizon is a unit boundary. Isopachs derived from lithostratigraphic correlations reveal that the Evergreen Formation is thicker and areally more widespread than the underlying Precipice Sandstone of the LST phase, which is to be expected.

Fielding (1989) interpreted that the upper part of the Boxvale Sandstone Member was deposited as part of a prograding lacustrine delta system (Figure 24). Totterdell & others (1991) suggest that the overlying Westgrove Ironstone Member is marine and represents a maximum flooding surface, or if not marine, an onshore equivalent. Such surfaces represent a sudden increase in water depth and occur within the TST phase in the upper part of a sequence. Cranfield & others (1994) interpreted that ironstone oolites in the Clarence-Moreton Basin, similar to those in the Westgrove Ironstone Member, were formed in a temporary lake on a broad floodplain. Periodic emergence is also associated with these oolites. However, the stratigraphic position of the Westgrove Ironstone Member may reflect shallow water

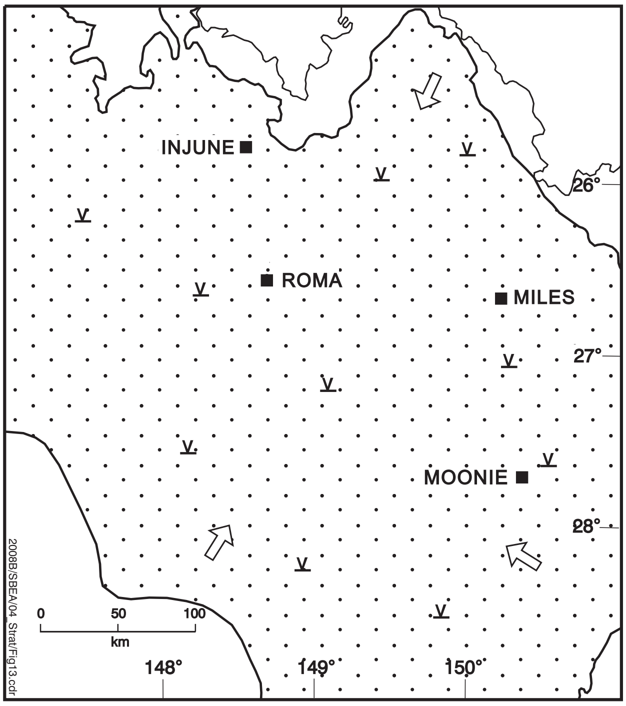


Figure 25: Depositional environment for lower Sequence K, Hutton Sandstone, southern Bowen Basin.

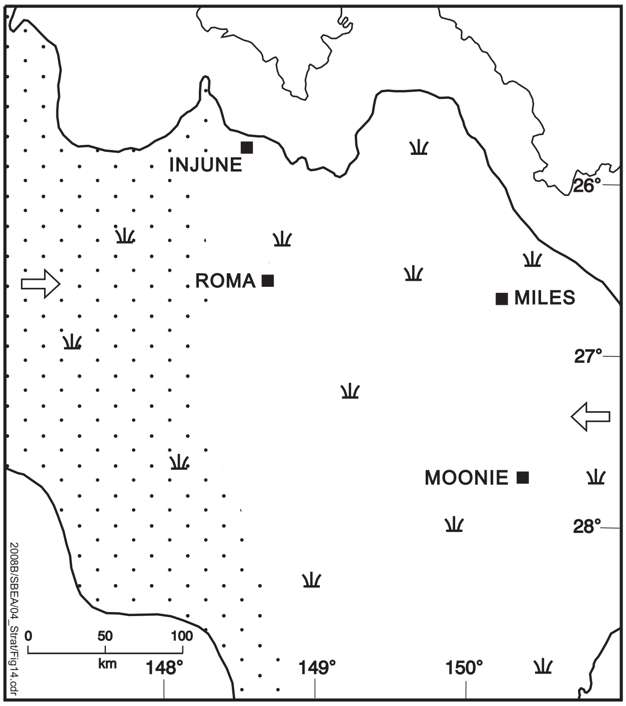


Figure 26: Depositional environment for upper Sequence K, Walloon Coal Measures, southern Bowen Basin.

deposition and/or exposure on the top of a delta (Boxvale Sandstone Member) in a large inland lake.

Maximum marine flooding events can be represented in non-marine environments by swamp and lake development due to a corresponding rise in the groundwater table (Blum, 1990; Shanley & McCabe, 1994). If so, either origin for the formation of the oolites, whether lacustrine or marine, is consistent with the Westgrove Ironstone Member being part of the TST phase.

SEQUENCE K

Sequence K consists of the Hutton Sandstone, Eurombah Formation and Walloon Coal Measures. Two seismic horizons were mapped in relation to this sequence; the base of the Hutton Sandstone (S30 horizon) and the base of the coal measures (S35 horizon).

Lower

The seismic resolution of the S30 horizon is generally weak and it is difficult to ascertain whether or not there is any associated onlap or truncation (Figures 4, 6, & 9). The base of the Hutton Sandstone is considered conformable with the Evergreen Formation (Exon, 1976).

However, in wells on the Roma Shelf, L.G. Elliott (personal communication, 1994) noted that major erosion of the top of the Evergreen Formation has occurred before deposition of the Hutton Sandstone.

The lack of terminations or an unconformity associated with this probable sequence boundary, can be explained if there is a gradual change in base level. The gamma-ray, resistivity, and sonic logs show both sharp and gradational breaks at the base of the Hutton Sandstone. The pronounced shift in the resistivity baseline between that of the Hutton Sandstone and the Evergreen Formation, reflects a change in provenance of the sandstones.

The Hutton Sandstone consists mainly of sublabile to quartzose sandstones and interbedded siltstones, shales with minor mudstones and coal. The unit was deposited by meandering streams on a broad floodplain with generally quartz-rich sediments sourced primarily to the north-east, south-east and south-west (Exon, 1976)(Figure 25). The predominance of sandstone sheets as well as the overall increase in grain size compared with the Evergreen Formation imply that the Hutton Sandstone represents the LST phase of the non-marine Sequence K. Its base is defined by the S30 sequence boundary.

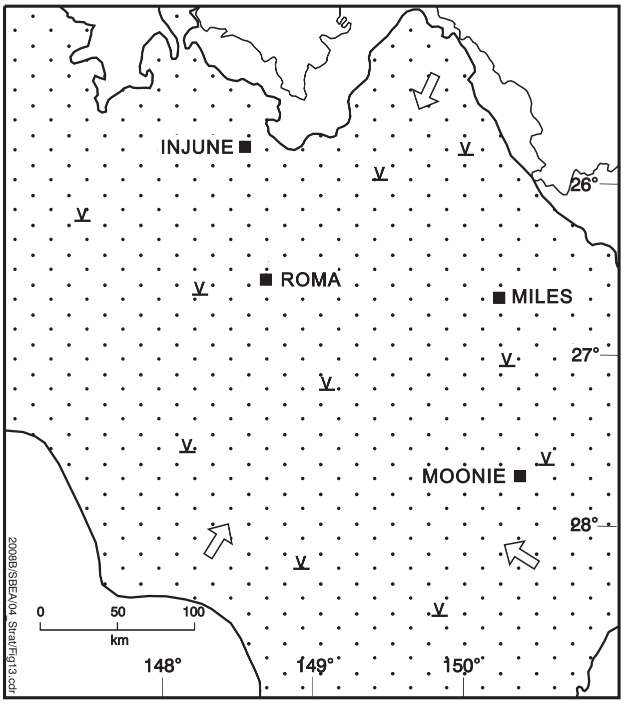


Figure 27: Depositional environment for lower Sequence L, Springbok Sandstone, southern Bowen Basin.

Upper

The upper part of Sequence K consists of the coal-dominant Walloon Coal Measures and includes the underlying Eurombah Formation of Swarbrick & others (1973). Generally, there is an abrupt change in log character from the sublabile to quartzose sandstone of the Hutton Sandstone to the lithic labile sandstones in the Walloon Coal Measures. However, a gradational change in sandstone composition and log character is apparent where the sublabile to labile sandstones of the Eurombah Formation are present.

The S35 horizon approximates the base of the coals which are imaged as strong reflectors in the seismic (Figures 4 & 9). The horizon is generally undulating with no associated onlap or truncation of adjacent strata. These undulations reflect lateral facies changes and the interfingering of clastics of the Eurombah Formation and the basal coals of the Walloon Coal Measures. The proportion of coal decreases to the west and coal seams are stratigraphically higher and less frequent in this area. Palynological data for the lowermost Walloon Coal Measures reveals there is an overall younging to the west (J.L. McKellar, personal communication, 1994).

The Walloon Coal Measures attain a greater thickness and are more extensive than the Hutton Sandstone. This fact, as well as the presence of gradational boundaries and the overall finer grain size suggest that the Walloon Coal Measures are equivalent to the TST and possibly the HST phases of deposition within Sequence K. The S35 horizon therefore represents a unit boundary.

The depositional setting of the Walloon Coal Measures was a meandering stream system associated with abundant coal swamps (McLean-Hodgson & Kempton, 1981; Clark and Cooper 1985)(Figure 26).

SEQUENCE L

The Springbok Sandstone and the Westbourne Formation comprise Sequence L. The base of the sequence, the S40 horizon, is equated with the base of the Springbok Sandstone and is the uppermost seismic reflector capable of being mapped in the project area owing to poor resolution or erosion of the younger Surat Basin units (Figures 4 & 9).

Lower

According to Exon (1976), the Springbok Sandstone is conformable with the Walloon Coal Measures. Nevertheless, all wireline log responses show a marked shift in baseline at the contact, implying the two formations are not genetically related. The shift in baseline reflects the change from the lithic labile sandstones and coals of the Walloon Coal Measures to the sublabile to quartzose sandstones of the Springbok Sandstone. Onlap and truncation are associated with the S40 adding further support to the idea that it is a sequence boundary.

Palynological data indicates that the Springbok Sandstone is older than the Adori Sandstone of the Eromanga Basin though no diachroneity has been identified within the Springbok Sandstone itself (J.L. McKellar, personal communication, 1994). Exon (1976) concluded that the Springbok Sandstone was deposited mainly by streams with some associated swamp development (Figure 27) . Lithostratigraphic and seismic data imply that the widespread sandstone sheets of the Springbok Sandstone would comprise the LST phase of deposition of Sequence L. The rest of the sequence, which comprises the Westbourne Formation, is not discussed here as only the base was resolvable in the seismic data.

DISCUSSION

More recent lithostratigraphic interpretation of the Permian succession in the Bowen Basin based on Beeston & others' (1995) work has lead to a minor revision of the sequence stratigraphic subdivision reported in Totterdell & others (1995). The Permian strata exhibit an alternation between shallow-marine and fluvial facies. Although the Bowen Basin was part of an active margin, the marine sequence stratigraphic model designed for a passive margin helps to explain the nature of the succession. The Permian succession of the Bowen Basin displays a similar style to that predicted for the continental shelf environment; an alternation between TST phase and the HST phase deposits (Figure 1). The continental slope and basin-floor environment described in the model are not represented in the foreland basin setting. Hence the LST and deeper TST facies of a marine sequence are not present in the Bowen Basin strata. Furthermore, the marine sequence stratigraphic model (Vail 1987, Van Wagoner & others, 1990 and Wilson, 1991) requires modification before it can be applied to marine basins associated with active margins such as the Bowen Basin.

The Triassic sequence subdivisions have also been modified from those published in Totterdell & others (1995) owing to further lithological evidence.Limitations in the use of sequence stratigraphy based on seismic data have become evident following the mapping of sequence boundaries such as the base of the Surat Basin, the S10 horizon. This major unconformity is generally only identified where the underlying rocks are inclined or irregular. In areas where the Surat Basin rocks lie directly on horizontal Triassic strata, well data indicate that the unconformity coincides with a broad seismic trough rather than a peak. Although the S10 horizon is a major sequence boundary, it is not easy to identify or map seismically. This also highlights the necessity of a framework of consistently picked wireline log formation tops, lithological data and palynological data to aid in the determinations.

CONCLUSIONS

- Minor revision of the Permian and Triassic sequence subdivision published by Totterdell & others (1995) has been undertaken because of more recent lithostratigraphic interpretation.

- The marine sequence stratigraphic model, designed for a passive basin margin by earlier workers, requires to be applied with caution to marine basins associated with active margins such as the Bowen Basin. A modified model needs to be developed.

- Sequences of Early Permian and late Early Permian age are poorly developed in the southern part of the study area.

- The Late Permian sequences can be subdivided on the basis of a series of major TST-HST events and these are recognisable in both the Denison and Taroom Troughs in the Bowen Basin.

- A facies relationship may exist between the Baralaba Coal Measures and the Rewan Group. Deposition of the Rewan Group may have begun earlier in the south while coal measures were being formed in the northern part of the study area.

- The Snake Creek Mudstone Member is considered to be genetically related to the underlying Showgrounds Sandstone rather than the overlying Moolayember Formation to which it is formally assigned.

- The Surat Basin succession contains elements of Lowstand Systems Tract, Transgressive Systems Tract and possibly Highstand Systems Tract phases in the context of the non-marine sequence stratigraphic model.

- The need for a multi-disciplinary approach to sequence stratigraphy by integrating seismic data using synthetic seismograms with consistently picked formation tops from wireline logs of petroleum wells, lithological data and palynological control has been highlighted.

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PERMIAN TO JURASSIC PALYNOSTRATIGRAPHIC NOMENCLATURE OF THE BOWEN AND SURAT BASINS

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INTRODUCTION

The application of palynostratigraphy as an aid to correlation of the Permian to Cretaceous Surat-Bowen Basin section commenced in the late 1950s and early 1960s with discrimination of the Early Jurassic, Triassic and Permian gas sands of the Roma Shelf and Denison Trough. The early biostratigraphic nomenclatures of the Bureau of Mineral Resources (BMR) [for example, 'Zones 1 to 4' of Evans, 1960; 'units P1 to P4' of Evans, 1962] embraced broadly defined assemblage zones, supplemented by marker taxa. With continuing petroleum exploration in the region during period 1963 to 1985, the initial palynostratigraphic subdivisions were modified by a number of authors, including de Jersey & Paten (1964), Paten (1966, 1969), Evans (1966a, b; 1969), Reiser & Williams (1969), de Jersey & Hamilton (1969), de Jersey (1975, 1976), Price (1973, 1982, 1983), Burger & Senior (1979), Exon & Burger (1981) and Burger (1984).

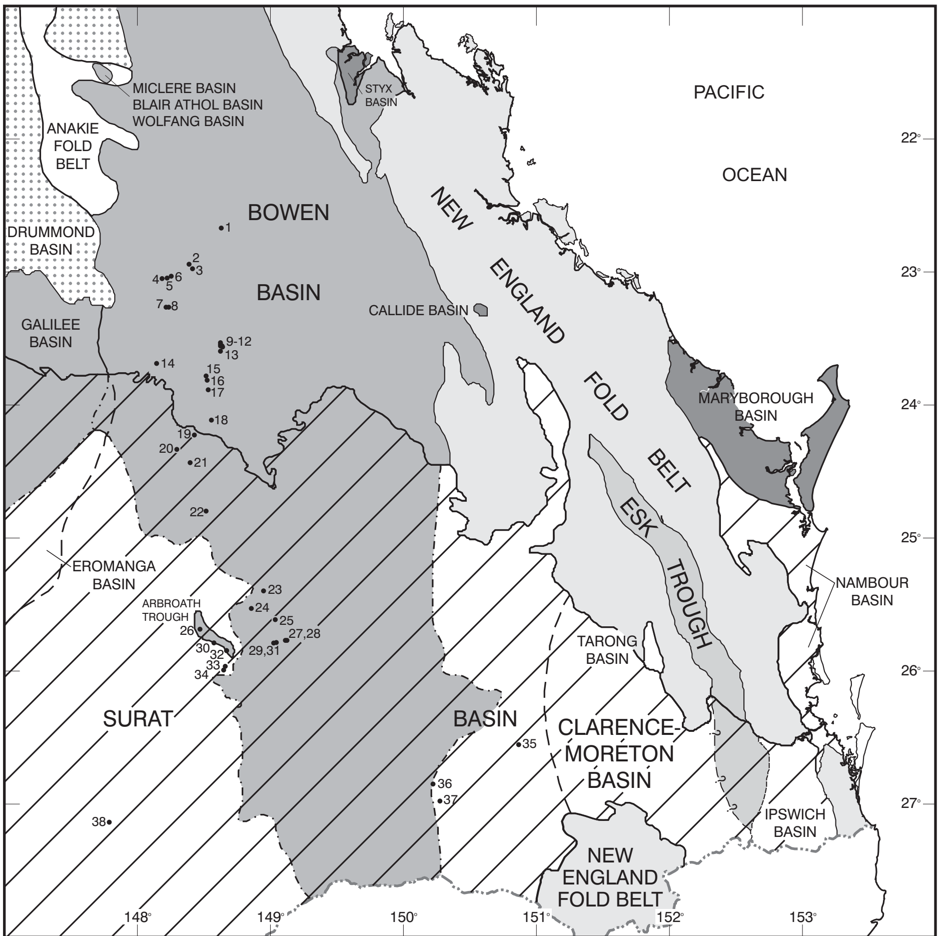
These revisions tended to adopt interval zones as the basic biostratigraphic unit, as the stratigraphic distribution of the index taxa became better known. By 1985, the palynostratigraphic subdivision and its relation to lithostratigraphy had been extensively and independently revised by a number of workers to the point where there was some confusion with the application of the various versions of Evans' (1962, 1966a, 1969) nomenclatural conventions. In response to this, and with the adoption of computer-data manipulation and storage systems, Price & others (1985) introduced a subdivision using a hierarchical format.

Revision of Price & others' (1985) palynostratigraphic nomenclature and subdivision of the Cooper - Eromanga and Bowen - Surat Basins form the basis of the present review. This incorporates revisions conducted between 1989 and 1996 supporting petroleum exploration in the Denison Trough and Roma Shelf, and coal exploration on the Comet Ridge and in the Capella Block.

Several of these studies were aimed at increasing the resolution of the palynostratigraphy and providing reference sections for the palynological units, as a basis of future correlation. However, they have not provided the biostratigraphic "reference points" of Runnegar & McClung (1975), enabling construction an independent time frame for lithostratigraphic (and sequence-stratigraphic) correlations, as the fickleness of distribution of certain of the land-plant palynomorphs (caused mostly by facies variation) has limited palynostratigraphic resolution to varying degrees in individual sections. Nonetheless, the palynostratigraphic subdivision, when applied in conjunction with petrophysical logs, seismic sections, and an understanding of facies variations of the palynofloras, provides the basis for close correlation of strata in the Surat - Bowen Basin region.

In terms of providing palynostratigraphic reference sections for the Permian of the Bowen Basin, the succession in the northern part of the Denison Trough was selected, as it is more complete and offers better palynomorph preservation. This region contains a series of cored holes drilled by the Geological Survey of Queensland (GSQ) through the dominantly sandy mid-Permian section in the Springsure area. This section contains thin shale bands that are difficult to sample by way of a sidewall-core program. However, for the upper, more shaley, Late Permian section, petroleum exploration wells (AGL Springton 1 and 2) were preferred, as they were sampled by sidewall cores and have a full suite of wireline logs. In order to extend the correlation established in the north, and to further increase biostratigraphic resolution, the study was extended to embrace the early Late Permian succession in the Rolleston-Christmas Creek region (AFO Rolleston 3, 6, 8; AAR Rolleston 11; CON Rolleston 12; SPO Dunellen 1; AAR Christmas Creek 1; PEC Warrinilla 1 and PEC Warrinilla North 1). Detailed species distribution lists and abundance charts for these reference sections have been presented by Filatoff & Price (1991) and Price (1994d). Examination of other exploration wells and coal bores from the Denison Trough has also contributed to the nomenclature revised here.

The reference sections for the Mesozoic for the Bowen and Surat Basins were constructed from a fragmented and scattered data set. These data were particularly incomplete in respect of the total extent of the mid-Triassic, upper Rewan Group-Clematis Group succession.



No.	WELL/BORE	No.	WELL/BORE	No.	WELL/BORE
1	AFO COMET 1	14	GSQ SPRINGSURE 19	27	APN BACK CREEK 1
2	AAR SPRINGTON 1	15	SPO DUNELLEN 1	28	APN BACK CREEK 2
3	AAR SPRINGTON 2	16	AAR CHRISTMAS CREEK 1	29	ASP TARRAWONGA NORTH
4	GSQ SPRINGSURE 17	17	PEC WARRINILLA NORTH 1	30	CSR CUSCUS 1
5	GSQ SPRINGSURE 16	18	PEC WARINILLA 1	31	SSL FAIRFIELD NORTH 1
6	GSQ SPRINGSURE 15	19	AGL YOOTHAPPINNA 1	32	AAR AVALON 1
7	GSQ SPRINGSURE 7	20	GSQ EDDYSTONE 1	33	AAR AVONDALE 1
8	GSQ SPRINGSURE 8	21	AAR YELLOWBANK 1	34	AAR AVONDALE SOUTH 1
9	AAR ROLLESTON 11	22	GSQ TAROOM 12-12A	35	PPC DURABILLA 1
10	AAR ROLLESTON 3	23	AAO GRAFTON RANGE 1	36	AAR WARRAWA 1
11	AAR ROLLESTON 12	24	AAO YANALAH 1	37	AAR WIDARA 1
12	AAR ROLLESTON 8	25	ASP BINDAROO EAST 1	38	SOC BOGONG 1
13	AAR ROLLESTON 6	26	AAO ARBROATH 1		

Figure 1: Distribution of major sedimentary basins and location of petroleum wells and stratigraphic bores.

The Mesozoic stratigraphic coverage includes:

- The lower part of the Permian-Triassic transition in AAR Springton 2 (Filatoff & Price, 1991) and the upper part of the transition in the Peat wells (Price, 1996c, d);
- The lower Rewan Group in APN Back Creek 1 and 2, GSQ Eddystone 1, and the Redcap Block (Price, 1993a; 1994a, b);
- The mid-upper Rewan Group and Clematis Group palynofloral succession (de Jersey, 1968, 1970a);
- The Showgrounds Sandstone to Snake Creek Mudstone/Moolayember Formation transition

in APN Back Creek 1 and 2 , GSQ Taroom 12, ASP Bindaroo East 1, SSL Fairfield North 1, ASP Tarrawonga North 1, and the Redcap Block (Price, 1994a, b; 1995a; 1996b);

- The Moolayember Formation in AGL Champagne Creek 1 (Price, 1994c);

- The latest Triassic-Early Jurassic Precipice Sandstone-Evergreen Formation-basal Hutton Sandstone succession in GSQ Taroom 12, GSQ Eddystone 1, ASP Bindaroo East 1, SSL Fairfield North 1, ASP Tarrawonga North 1, AAO Grafton Range 12, AAR Avondale 1, AAR Avondale South 1 and AAO Yanalah 4 (Filatoff, 1982, 1984a, 1984b; Filatoff & Price, 1984; Price, 1994a, 1994b, 1995a, 1996b);

- The Jurassic Surat Basin succession in AAR Avondale 1, AAR Avondale South 1, AAR Warrawa 1, AAR Widara 1 and AAO Yanalah 4 (Filatoff, 1982, 1983, 1984a, 1984b; Filatoff & Price, 1981, 1984, 1985);

Species-distribution and abundance lists and group-abundance and diversity charts for the Mesozoic sections of the Bowen and Surat Basins, which have been considered in the present review, are included in the cited reports.

STUDY METHODOLOGY

The palynofloral assemblages were obtained from the unoxidized +20µm fraction and from the +10-20µm and +20µm floats of 1.65 specific-gravity, separated, oxidised fractions. Species lists were established from examination of these fractions; the relative abundance of the palynomorphs identified was derived from counts of between 200 and 3,000. These statistical data resolved only the dominant and major subordinate taxa and gave an indication of changes in relative abundance of the 'morphological' and 'phylogenetic' groups of species together with species diversity within these groups. Minor components noted in initial species distribution records were often not recordeed in the counts.

Changes in palynomorph populations are thought to reflect a complex interplay between the influences of the depositional system and regional climatic change upon the geographic distribution and the evolution of the flora. Comprehension of these factors is essential to application the palynostratigraphic subdivision.

The organic facies studies described in individual well studies (but not discussed in any detail in this review) were conducted on the +20µm and the total recovered unoxidized organic fractions. Estimates of the proportions of the various kerogen groups were established and are considered to be reflection of the depositional conditions.

BIOSTRATIGRAPHIC PHILOSOPHY

OBJECTIVES OF PALYNOSTRATIGRAPHIC SUBDIVISION

The objective of the biostratigraphic subdivision defined herein is to provide ‘time lines’ (albeit approximations) for correlation of well sections and an understanding of depositional history. In most well sections, where there is an adequate suite of samples, emphasis is placed upon defining the boundaries between biostratigraphic units to give the required ‘time-line’ datum. A chronostratigraphical unit, by definition, is bounded by isochronous surfaces, which delimit the same interval of time throughout the unit’s lateral extent. Biostratigraphical units, however, need not be bounded by isochronous surfaces, as they define the stratigraphical limits (both vertically and areally) of biological associations or entities. These associations are the product of both biological evolution (time significant) and the constraints on their geographic and vertical distribution caused by environmental variation and the migration of parent plants from their sites of genesis (of no time significance).

It is worth noting that not all biostratigraphical units are directed towards time correlation. For example, they may be used to define the extent of an organic facies (such as a hydrocarbon source rock) or a particular depositional environment. Thus, for a biostratigraphical unit to have a chronostratigraphical function, the factors influencing the distribution of the biological entities used to define a biostratigraphic unit must be determined, and those that are not of time significance taken into account. The distribution of index forms, therefore, must be considered in the context of associated palynofloral assemblages and lithofacies.

To realise the objective of defining biostratigraphical boundaries that approximate time lines, at least on a local or intra-basinal scale, several features have been considered desirable and have been given emphasis in definition of the palynostratigraphical units defined below:

1. Definition of a boundary is based upon a single taxon, where that taxon is morphologically distinct, with resilient preservation characteristics and has been shown to be nearly ubiquitous within the zone. Additionally, where correlations (inter-basinal, continental, or global) are attempted over considerable distances, migration of the organism should be considered.
2. The distribution of the index form in the various contemporaneous palynofloral assemblages, and the interrelationships of these assemblages with the lithofacies need to be established. The species may not be widely distributed in some associations and, thus some palynostratigraphic units, and may only be relied on as a chrono-stratigraphic marker in particular assemblages and facies.
3. The oldest occurrence of a taxon is preferred to its extinction, as the time of extinction can be obscured by reworking or the persistence of relict floras in isolated areas. This criterion presumes that uncontaminated samples (core and sidewall cores, but NOT ditch cuttings) are available. Where cuttings are used (with the attendant problems of down hole contamination), extinctions of taxa become more significant for biostratigraphic correlation.
4. Emphasis is given to recognising the progenitors and successors of the selected index taxon. Utilisation of members of a lineage or complex is considered to have a stronger time significance by selecting a particular point in the morphological evolution of the index taxon (Runnegar & McClung, 1975; Price, 1983; Price & Filatoff, 1990), provided speciation' is not a result of polyploidy (Price & Filatoff, 1990).

By definition, these units are Interval Zones and their boundaries are biohorizons, each being defined (in most cases) upon the first appearance of a specified taxon (Hedberg, 1976; Salvador, 1994). The application of the units, however, is not of rigid, uncompromising mapping of the first occurrence of a designated taxon, but must be tempered by the palynologist's assessment of the significance of the logged first occurrence within a particular well section. This assessment is not easily defined, but is influenced by the yield, preservation, diversity and the associated taxa (particularly other phylogenetically related species), both in the assemblage being considered and those from preceding and succeeding samples. This is not to say that the presence of an index taxon will be assumed in a poorly preserved or restricted assemblage, but rather that the particular sample will not be taken as an indicator of the position of the palynostratigraphic unit in question.

Thus, the application of the proposed units is best suited to a sequence of samples which are free from contamination and in which the preservation is at least fair. If applied to isolated or unrelated samples (such as outcrop samples) or to a sparsely sampled section, the result is commonly best regarded as being broadly defined and thought of as being 'no older than' the designated unit.

Some biostratigraphers consider that the problems of erratic distribution of index forms (due to migration, environment and preservation factors) are sufficient to lessen the effectiveness of Interval Zones and Biohorizons, and opt for Assemblage Zones or Oppel Zones. Assemblage Zones (defined upon an association and abundance of forms) and Oppel Zones (defined by the co-occurrence of several forms) perhaps give some security by being less susceptible to the vagaries of facies influences upon a single form as their boundaries are defined upon multiple 'events'. However, their boundaries are transitional and somewhat subjective.

Additionally, the individual index taxa are still subject to facies influences and the abundance or association of the defining forms that characterise an Assemblage Zone are as much a reflection of regional environmental factors (climate, marine transgression) as the evolution of the flora. These regional environmental conditions can commence earlier or persist longer in differing parts of the basin. Certain palynomorph associations or assemblages may parallel a particular lithofacies and, as such, an Assemblage Zone may be as time transgressive as a single taxon biohorizon.

It is believed that the facies and preservation problems, which are common to all biostratigraphic units, can be ameliorated by tempering the observed palynomorph distribution data, and taking into account the nature and preservational state of the assemblage. The reliability of an Interval Zone can be improved further by employing, as index taxa, members of evolutionary significant, morphological lineages and complexes (Runnegar & McClung 1975, Price & Filatoff, 1990). This is facilitated by using an adequate sequence of samples and ranking the palynostratigraphic units and associated biohorizons according to their regional significance in a hierarchical scheme. It is emphasised, therefore, that care should be taken to avoid making a palynostratigraphic assignment by merely logging the down-hole oldest or youngest occurrence (depending on zone definition) of the index forms.

PALYNOMORPH TAXONOMY

An account of the philosophy taken in the selection of index forms has been outlined by Price (1983), Filatoff & Price (1988b) and Price & Filatoff (1990). In this approach, increments of variation are assigned Form Species, Subspecies or Variety status, contrast to grouping the full range of variation within a taxon centred on a single type specimen. The Form Species and varieties are grouped into 'complexes' as a means of defining lineages and recognising any biostratigraphically significant variants within the continuum of morphological variation that characterises these complexes.

Hughes (1970) noted the problems of using the accepted taxonomic conventions for biostratigraphic applications. He recognised the need to better define biostratigraphically useful variation, but proposed that the range of variation within a form-species population at successive stratigraphic levels be defined and given taxonomic status ('biorecord'), as opposed to the traditional single type-specimen approach. It is considered, however, that Hughes' concepts differs significantly from the widely accepted palynomorph taxonomic conventions and would be time consuming to establish and apply, in comparison to the 'incremental' approach adopted in this study.

The taxonomic nomenclature used herein therefore reflects this 'incremental' approach and differs from the classical palynological nomenclatures that have aimed at placing such variation within a single morphological entity centred on a single type specimen. As a consequence, this approach has resulted in a high proportion of 'informal' taxa, as many of these represent 'increments' of variation within established taxa and lack published descriptions. Additionally, the formally described taxa are often used with very narrow morphologic limits and may not include the range of forms assigned by other workers to a nominated taxon.

It is acknowledged that the range of variation represented by a number of such taxa may be included within the range of morphological variation represented in fructifications of an individual plant or an individual sporangium. This may reflect various phases in the ontogeny of the spores and sporangia within a cone or various phases in the degradation of the spore(Balme, 1995). It is perhaps worth considering in the context of biostratigraphic application, the possibility that the range represented in one plant taxon may not be as extensive as another related plant even though the latter may include some of the same dispersed spore varaints. Thus while such spore morphologcal variation may be known to be represented in a single sporangium, the extene of the variation may change with time.

While it is recognised that this splitting has resulted in considerable taxonomic 'inflation', the use of computer sorting and presentation lessens the problem in terms of practical application. All the taxonomic entities (both published and informal) used in this study are described in a comprehensive photographically illustrated card index of type and reference specimens held by APG Consultants so that stability in the informal taxonomy is maintained. An attempt will be made to publish the biostratigraphically significant taxa at a later date if resources for the project can be provided.

BIOSTRATIGRAPHIC NOMENCLATURE

The alpha-numerical nomenclature which has been adopted here is based on that of Price & others (1985). It is hierarchical in structure, with the numerical value increasing from oldest to youngest within each geological period. The first three letters give the geographic region (A = Australia), the palynomorph group used to define the unit (P = pollen and spores, D = dinoflagellate), and the adopted geological age (for example P = Permian, T = Triassic, K = Cretaceous). The numerals that follow give the ranking of the subunits and their relative stratigraphic position and should be regarded as decimal increments. The first-order subunits (the first numeral) represent the broad subdivisions which can be applied to approximately 90% of samples after a brief examination. In general, they correspond to the major units of previous palynostratigraphical schemes.

The second-order subunits (second numeral) correspond more or less to the subzones of the earlier nomenclature. These subzones are more difficult to apply and so only some 60% of samples may be assigned to this level in the hierarchy. The third and fourth order subunits (third and fourth numerals) are for the more subtle or speculative subdivisions which may have only local application. The order of appearance of the index forms defining these low ranking subunits may differ from basin to basin (because of migration or environmental constraints) or may prove to be mis-stated with the benefit of further work.

It should be noted that in a hierarchical biostratigraphic scheme, a major unit is defined by the presence of any of the lower-ranked, subunit, index forms. Thus, even if the major-unit index form is absent in a given sample, the major unit can be recognised by the subunit index forms. For example, Unit APT5 can be established by the presence of *Polycingulatisporites mooniensis, Retitriletes rosewoodensis, Perinopollenites elatoides, Zebrasporites interscriptus* or *Retitriletes austroclavatidites*, even if *Polycingulatisporites crenulatus* (the nominated APT5 index form) is absent. In this respect, hierarchical interval zones have the same 'security' of several index forms, as has an Oppel Zone or Assemblage Zone, but have the potential of greater biostratigraphic resolution.

The 'International Stratigraphical Guide' (Hedberg, 1976; Salvadore, 1994) perhaps frowns upon such numerical nomenclatures, preferring to sanction a convention which takes the form of the name of the defining fossil or, where that name has been used for another biostratigraphical unit, the name of some other form species. It is considered, however, that the numerical nomenclature adopted here has several practical advantages in terms of its application to the hydrocarbon and coal exploration industry:

1. The numerical sequence indicates the relative stratigraphical position, circumventing the need to know the stratigraphical order of appearance of the index forms, a convenience for explorationists with non-biostratigraphic specialisations.
2. The units are amenable to computer data processing.
3. The 'alpha-numerical' codes are concise and thus suitable for inclusion on geological cross-sections and logs.
4. This nomenclature avoids the complications which arise from taxonomic revisions of the index or naming fossil and similarities of the specific epithet. For example, the *Minutosaccus crenulatus* Zone, the *Polycingulatisporites crenulatus* Zone and the *Playfordiaspora crenulata* Zone are all 'formal' palynostratigraphic units from different levels within the Australian Triassic. These become confusing when the zone name is contracted to the specific epithet ('the *crenulatus* Zone') only. Additionally, nomenclatural changes to the nominate index form can make the zone name inappropriate in terms of the current taxonomic usage. For example, Reiser & Williams (1969) named the basal Surat Basin palynostratigraphic unit the *Classopollis classoides* Zone, but the nominated species is variously referred to as *Classopollis classoides, Corollina torosa* or *Classopollis chateaunovi*; and their *Tsugaepollenites dampieri* Zone has faired no better (*Tsugaepollenites dampieri, Callialasporites dampieri, Zonalapollenites dampieri* or *Applanopsis dampieri*).

The particular alpha-numeric format adopted is used to minimise confusion with the previous alpha-numerical codes such as those of Evans (1962; 1966a, b).

PRESENTATION CONVENTIONS

In applying the proposed nomenclature, the following conventions have been used to indicate the levels of confidence and limits of biostratigraphical resolution applied to individual samples:

1. Where a sample only can be assigned broadly and the subunits cannot be resolved, only the higher order units will be indicated (for example APK1, meaning that APK11, APK121 or APK122 could not be recognised).
2. If the sample can be defined only within a range, the lower and upper limits will be given (for example, APK21-APK1).
3. If the sample can be assigned to either of two adjacent subzones, it will be given as a range (for example APK21-APK122).
4. If a sample can be defined within a range in which assignment to a particular subzone is favoured, but not proved, then the designation is given as a biostratigraphic range in which the assemblage can be confidently assigned followed by a qualifier ('probably', '?' = 'possibly', 'tentatively',) and the favoured unit (for example APK21-APK1; ?APK121).
5. An attempt will be made to give a zonal range for a sampled horizon rather than use the expressions 'no older than' or 'no younger than'. In the case of cuttings, or where reworking is suspected, such assignments may not be avoidable and, when used, the expressions may be abbreviated to 'N.O.T.' or 'N.Y.T.' in such instances.

APPLIED BIOSTRATIGRAPHY

PERMIAN

Previous Studies

The Permian palynostratigraphic subdivision that has been applied to the Bowen Basin is an amalgamation adopted from units initially established by Evans (1969), Paten (1969) and Price (1973, 1976, 1983). A review of the pre-1983 biostratigraphies is given by Price (1983). The palynomorph zonation took on its present alpha-numerical nomenclature in 1985 (Price & others, 1985), with a subsequent update being published by Draper & others (1990). The latter version is further updated here in the light of the Denison Trough data (Filatoff & Price, 1991; Price, 1994d) and data from the Perth Basin (Backhouse, 1991), Canning Basin (Foster & Waterhouse, 1988), Galilee Basin (Jones & Truswell 1992) and Cooper Basin (Wood, unpublished data). The revised palynostratigraphical nomenclature and relationships to the lithostratigraphy are presented below.

Unit APP1

Unit APP1 is defined as the interval between the oldest occurrence of Striatiti (Protohaploxypinus spp.) and Pseudoreticulatispora pseudoreticulata (Figure 2). In terms of the pre-1985 nomenclature, it corresponds to Stage 2 (in the usage of Paten, 1969; Price, 1973, 1976, 1983; and Norvick, 1974, 1981) and C2-P1b (Evans, 1962, 1966b). It should be noted that other workers (for example Powis, 1984; Kemp & others, 1977) have a different interpretation of Stage 2, regarding it as being slightly younger, with both Stage 1 and Stage 2 of their usage being included in Stage 2 in the sense of Paten (1969) [see Price, 1983; Jones & Truswell, 1992].

Unit APP1, although well represented in the lower parts of the Cooper and Galilee Basins, is almost absent from the Bowen Basin region (Figures 3, 4). It has been reported from only the 'pre-Reids Dome beds Volcanics' in AFO Comet 1 and probably in the pre-Jurassic of AAR Warrawa 1 and PPC Durabilla 1 (Filatoff & Price, 1981). It is possible that some of the deeper parts of the Reids Dome beds may be as

AGES	PRE - 1985 USAGE		1990 NOMENCLATURE (Filatoff & Price, 1990; Draper & others, 1990)			CURRENT NOMENCLATURE (Filatoff & Price, 1991; Price, 1994)			
TRIASSIC	Tr1b		APT1			APT1			
LATE PERMIAN	Tr1a		APP6			APP6			
	upper stage 5		APP5	5.0.3		APP5			5006
									5005
									5004
		U5a		5.0.2	5.0.2.2				5003
									5002
				5.0.1	5.0.2.1				5001
	lower stage 5	L5c	APP4	4.3		APP4	43	432	
								431	
EARLY PERMIAN		L5b		4.2			42		
		L5a		4.1			41		
	stage 4	U4b	APP3	3.3	3.3.2	APP3	33	332	3322
									3321
					3.3.1			331	
		U4a		3.2			32	322	
								321	3214
									3213
									3212
									3211
		L4		3.1			31		3102
									3101
	stage 3	3b	APP2	2.2		APP2	22	222	2222
									2221
								221	
		3a		2.1			21	212	
								211	
	stage 2		APP1	1.2		APP1	12	122	
								121	1212
									1211
LATE CARBON-IFEROUS				1.1			11		
	stage 1		APL4	4.2		APL4	42		
				4.1			41		

INDEX FORMS

- *Lunatisporites pellucidus* (sp. 92)
- *Triplexisporites playfordii* (sp. 805)
- *Lycopodiumsporites* "*crassus*" (sp.1083)
- *Micrhystridium evansii* Acme Zone ("P3c horizon")
- *Microreticulatisporites bitriangularis* "*bireticularus*" (sp. 1079)
- *Dulhuntyispora stellata radians* (sp. 312) — Consistent *A. villosus* *
- *Dulhuntyispora spongia* (sp. 277 & 309) — *Dulhuntyispora spongia*
- *Dulhuntyispora* (large forms) (sp. 1141, 313 & 308)
- *Dulhuntyispora parvitholus* (sp. 339) — *Dulhuntyispora granulata*
- *Dulhuntyispora* sp. cf. *D. parvitholus* (sp. 298)
- *Dulhuntyispora dulhuntyi* (sp. 6)
- *Didecitriletes ericianus* (sp. 7)
- *Dulhuntyispora granulata*
- *Lopadiospora vermithola* (sp. 205)
- *Lopadiospora pannosus* (sp. 1379)
- *Acanthotriletes villosus* (sp. 5)
- *Acanthotriletes* "*baculatus*" (sp. 251)
- *Granulatisporites* sp. cf. *M. indica* (sp. 4)
- *Propinquispora praetholus* (sp. 206)
- *Granulatisporites trisinus* "*subtlis*" (sp. 3781)
- *Praecolpatites sinuosus* "*corona*" (sp. 21)
- *Granulatisporites trisinus* "*microsubtlis*" (sp. 4549)
- *Phaselisporites cicatricosus* (sp. 63) — *Praecolpatites* spp.
- *Granulatisporites* "*parvus*" (sp. 4610)
- *Gondisporites ewingtonensis* (sp. 4569)
- *Granulatisporites trisinus* (sp. 671)
- *Striatopodocarpites fusus* (sp. 1181)
- *Pseudoreticulatispora pseudoreticulata* (sp. 1595)
- *Pseudoreticulatispora confluens* (sp. 194)
- *Granulatisporites micronodosus* (sp. 46)
- *Granulatisporites tentula* (sp. 276)
- *Protohaploxypinus* spp.
- *Diatomozonotriletes birkheadensis* (sp. 1612)
- *Potonieisporites* spp.

* APP4 forms, including *A villosus, P. cicatricosus*

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Figure 2: Permian palynostratigraphic nomenclature.

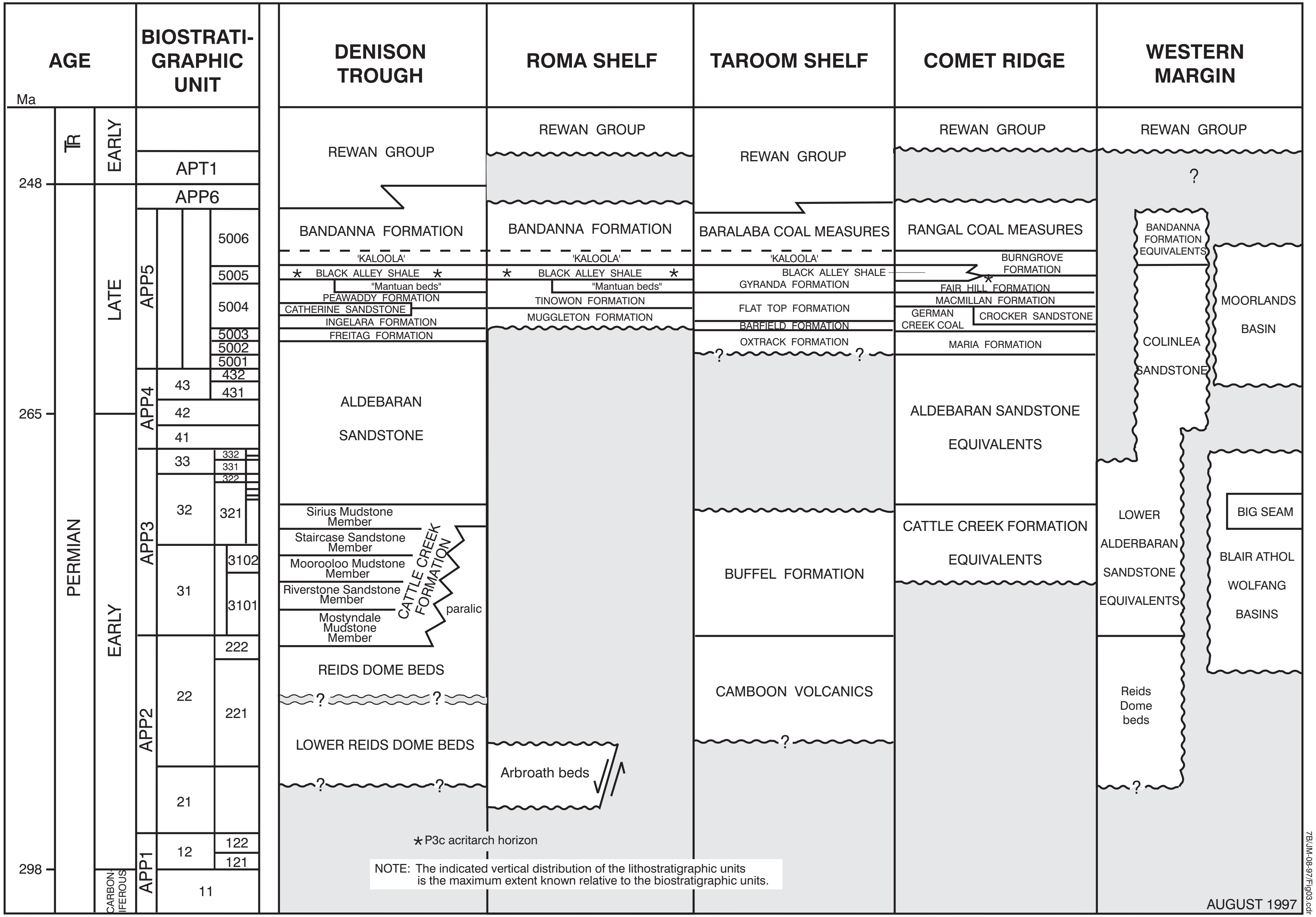

Figure 3: Permian stratigraphy - Bowen Basin

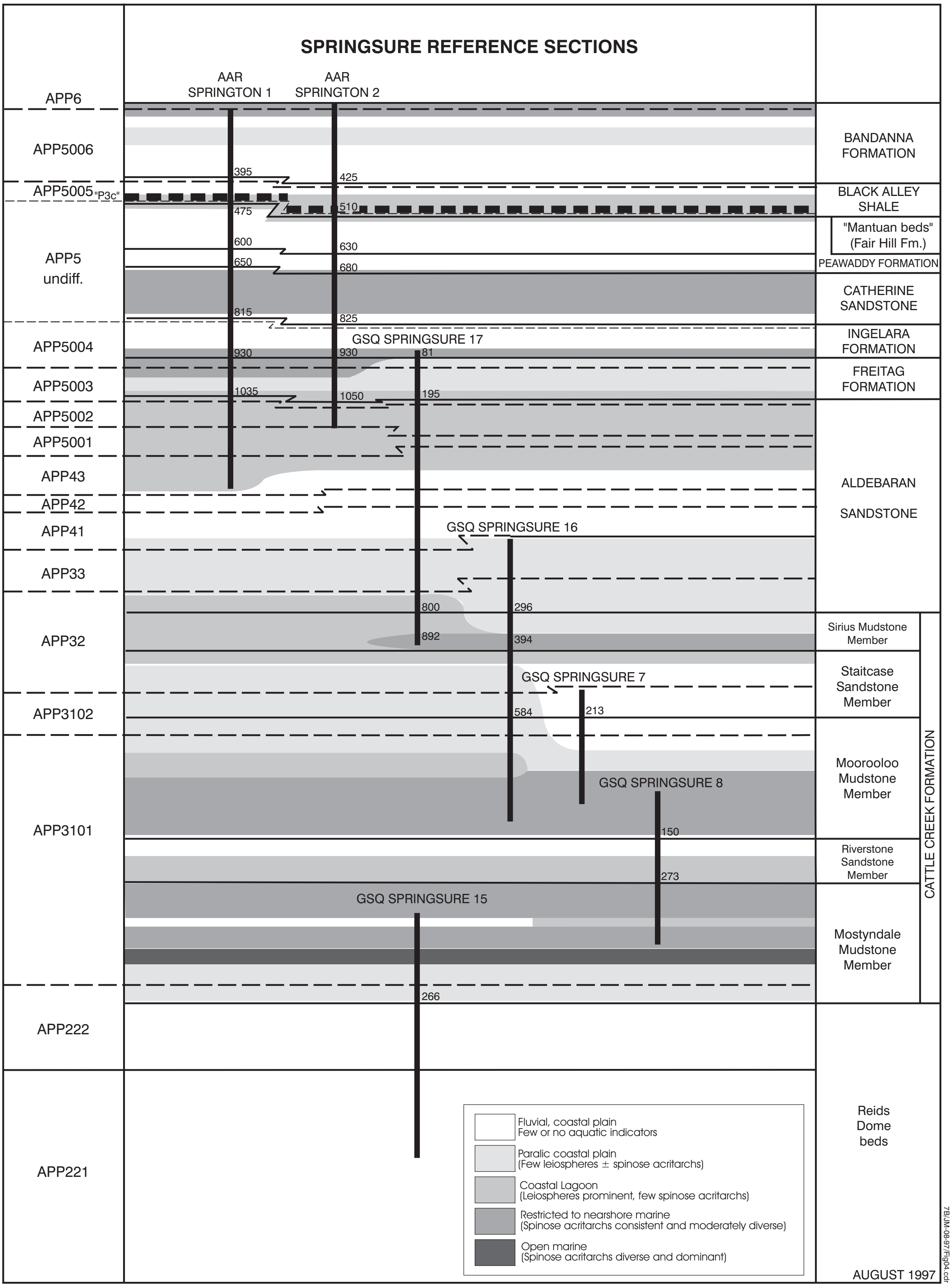

Figure 4: Springsure reference sections

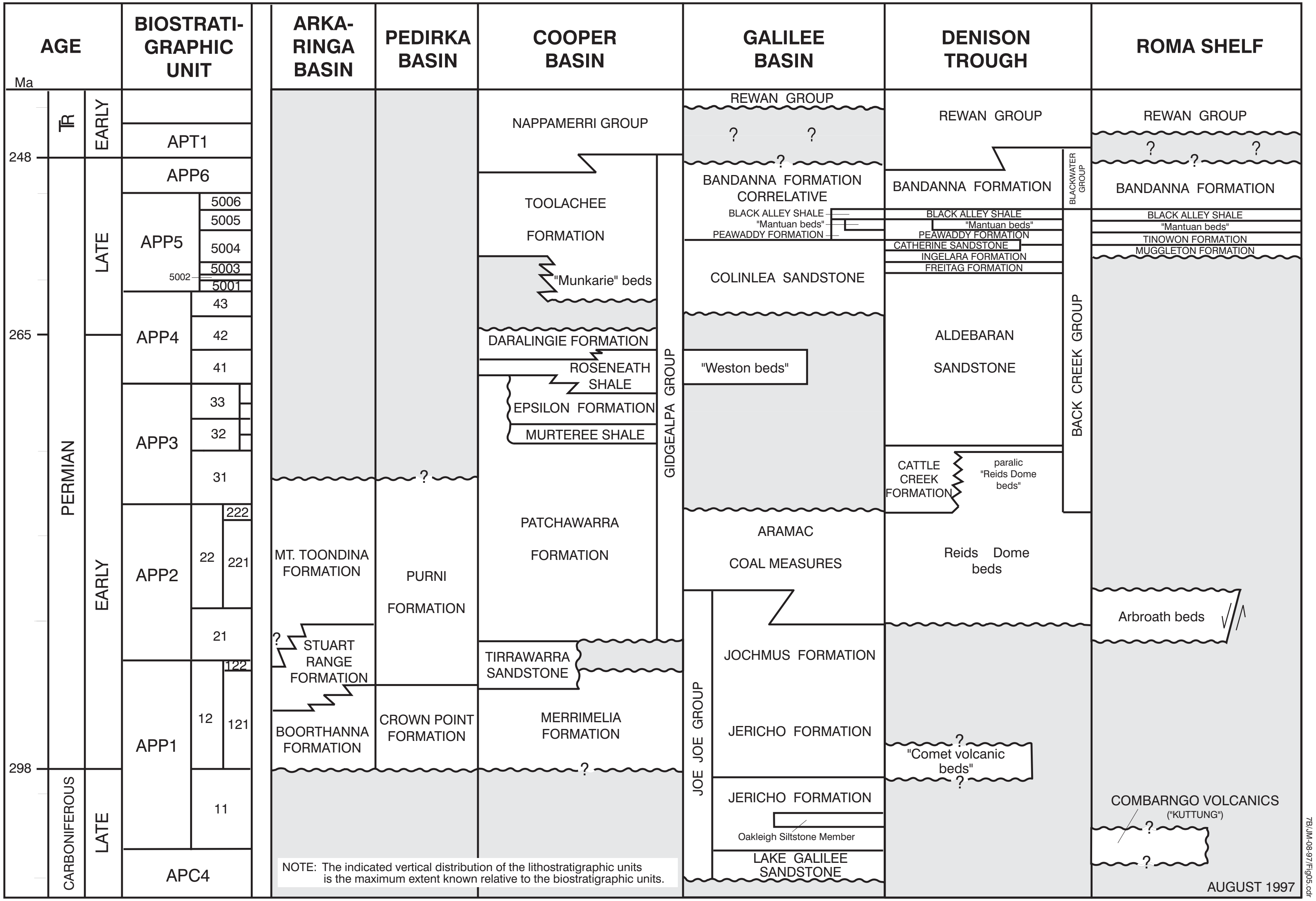

Figure 5: Permian inter-basinal stratigraphy

old as APP1, but, because of their high thermal maturity, they have failed to yield palynofloras.

Unit APP1 palynofloras typically include an abundance of monosaccate pollen and laevigate trilete spores (*Calamospora* spp., *Punctatisporites* spp., *Retusotriletes* spp.) and the initial phase of diversification of cheilocardoid spores (including *Microbaculispora tentula*, *Granulatisporites micronodosus* and *Pseudoreticulatispora confluens*) is represented.

Unit APP2

The oldest occurrence of *Pseudoreticulatispora pseudoreticulata* and *Phaselisporites cicatricosus* define respectively the base and top of unit APP2 (Figure 2). As such, the unit corresponds to Stage 3 as interpreted by Paten (1969) and Price (1973, 1976, 1983) and approximates unit P1b and the lower part of P1a of Evans (1962; see Price, 1983). Unit APP2 can be subdivided by the successive appearances of *Striatopodocarpites* spp, *Granulatisporites trisinus* and *Gondisporites ewingtonensis* (Figure 2). The *Striatopodocarpites fusus* biohorizon was defined by Backhouse (1991) in the Collie Basin of southern Western Australia and is untested in central and eastern Australia, but, on present data, has promise, although a broarder concept of *Striatopodocarpites* spp. (including *S. fusus* and *S. cancellatus*) is preferred here. *Gondisporites ewingtonensis* , the other marker from Backhouse's Collie study (although not specifically used by him), has proven to be reliable in the Patchawarra Formation of the Cooper Basin (Wood, unpublished data) and is present at a similar stratigraphic level (top of the Reids Dome beds and basal Cattle Creek Formation) in GSQ Springsure 8 and GSQ Springsure 15 (Filatoff & Price, 1991).

A basal APP21 assemblage was recovered in SOC Bogong 1 (Price, 1982b, 1983), being characterised by an association of Late Carboniferous forms such as *Verrucosisporites aspratilis, Cristatisporites* sp. 890 and *Pseudoreticulatispora confluens* (sp. 194), together with the APP2 index, *Pseudoreticulatispora pseudoreticulata,* and an abundance of monosaccate pollen. This association corresponds to the upper part of unit P1a of Evans' (1962, 1966b) nomenclature and is widely distributed in the Galilee Basin. The older forms characteristic of P1a, however, have been found to persist higher in the section, albeit as isolated specimens, into APP3 and APP4, (Filatoff & Price, 1991); monosaccate pollen may be prominent (although very rarely dominant) in some assemblages from APP3 and APP4. Thus, the recognition of these P1a associations as a basal subunit of APP21 should be applied with caution. The Arbroath Trough (a similar down-faulted inlier of Early Permian section as in SOC Bogong 1) includes APP21 strata at its base and extends up into APP22 in AAO Arbroath 1, CSR Cuscus 1 and AAR Avalon 1 (see Figures 3, 4; Price, 1987; Price & Filatoff, 1986, 1989). The base of the section in AAO Arbroath 1 is perhaps slightly younger than that in SOC Bogong 1 as, with the exception of *Pseudoreticulatispora confluens* , P1a forms were not recorded in the Arbroath wells.

Unit APP2 is represented in the axial regions of the Bowen Basin (Denison Trough, Taroom Trough), probably representing the initiation of sedimentation. There is little palynological data for the earliest of these sedimentary rocks, as they are mostly over-mature giving few, if any, identifiable palynomorphs. APP21 palynofloras have not been proved to be present unequivocally, but their occurrence is suspected in the Reids Dome beds in the Emerald-Capella region.

The upper part of unit APP22 is represented in the Reids Dome beds and in the basal marine facies of the Cattle Creek Formation in GSQ Springsure 15 (Figure 4). In most other parts of the Bowen Basin, this facies is thinner and lies wholly within APP3, with the APP2-APP3 boundary being within the Reids Dome beds (Figures 3, 4).

The assemblages recovered from unit APP221 (GSQ Springsure 15, 457.1m-657m) were dominated by non-striate bisaccate pollen (mostly *Scheuringipollenites*), with striate bisaccate pollen subordinate, but marginally more abundant than the monosaccate pollen. Spores were subordinate to pollen, with apiculate and cheilocardoid forms (ferns) being more frequent than lycopod spores, which form only a minor constituent of the total palynoflora. Aquatic forms were all but absent.

Evans' (1962, 1966b) P1-P2 boundary in the Bowen Basin was based upon the lowest occurrence of spinose acritarchs and was generally assumed to be an approximately synchronous event in the Denison Trough. The occurrence of spinose acritarchs below APP3 and in APP2 assemblages in GSQ Springsure 15 indicate that Evans' (1962, 1966b) 'P2'– marine facies of the Cattle Creek Formation is diachronous, with the lower Cattle Creek Formation and the upper (' paralic') Reids

Dome beds being lateral equivalents. Indeed, in some areas in the southern part of the Denison Trough (AGL Yoothapinna 1; Filatoff & Price, 1990a), the marine facies of the Cattle Creek Formation is thin and grades into a transitional paralic coal-measures section within APP32 at the top of the Reids Dome beds.

In the Springsure reference section (Figure 4), a marked change in the floras occurs in the lower half of unit APP222. This corresponds to a change in lithology from silty mudstone to interbedded coals, shales and sands. Pollen are still dominant, but spores are prominent. *Scheuringipollenites* (non-striate bisaccate pollen) remains the most frequent form, with monosaccate pollen as a major subordinate component, being commonly more frequent than striate pollen. Spores are dominated by cheilocardoids (mostly small, proximally laevigate, apiculate forms), with lycopod spores being minor, but more frequent than in unit APP221. Non-marine algal forms are a minor, but persistent feature of this palynoflora. Upper APP222 palynofloras are similar to those of APP221, except that spinose and non-spinose acritarchs are present. Gross changes in the palynoflora within APP222 seem to reflect changes in lithology and depositional setting. The lower APP222 flora is associated with interbedded coals, sands and shales of the Reids Dome beds, and the upper APP222 flora corresponds to the initial marine phase of the basal Cattle Creek Formation. The spore-rich palynoflora of the upper Reids Dome beds is perhaps best represented by the assemblage in GSQ Springsure 15 at 381.04m (Filatoff & Price, 1991). As this assemblage was recovered from a carbonaceous mudstone within a coal seam, it may represent a specialised flora of the Reid Dome peat bogs.

Unit APP3

APP3 is defined by the oldest occurrence of *Phaselisporites cicatricosus* at its base and *Dulhuntyispora granulata* at its top (Figure 2). The unit is more or less equivalent to Stage 4 as interpreted by Evans (1969), Paten (1969) and Price (1976, 1983). Recently, Filatoff & Price (1991) and Draper & others (1990) restricted the morphological limits of *P. cicatricosus* (sp. 64) to include only those forms with a dominantly cicatricose sculpture, and assigned dominantly apiculate or verrucate-apiculate forms to *P. hamatus* (sp. 63). Prior to this, Price (1976, 1983) included this full morphological range within *P. cicatricosus* thus, in the Bowen and Cooper Basins, the APP2-APP3 or Stage 3-Stage 4 boundary may have been picked somewhat lower. It is believed that redefinition of *P. cicatricosus* (sp. 64) will give a more reliable biohorizon, as earlier representatives of the *Phaselisporites* complex are somewhat patchy in their distribution in the section below the first appearance of this morphological entity.

The relationship of unit APP3 with the earlier 'P' units of Evans' (1962, 1966b) nomenclature is blurred and varies over the extent of the Basins. As noted above, the P1-P2 boundary (based on spinose acritarch distribution) appears to be diachronous, lying between the top of APP22 and the base of APP321. The top of unit APP3 falls within P3b, with the APP31-APP32 boundary more or less corresponding to the P3a-P3b boundary (depending upon the morphological limits accepted for *P. sinuosus*).

In this study, APP3 has been subdivided into 10 subunits (Figure 2). The second order subunits (APP31, APP32, APP33) were established by Paten (1969) and Price (1976, 1983) and have been widely applied to the Australian Permian. Discrimination of the APP31-APP32 boundary, based upon the oldest occurrence of *Praecolpatites sinuosus* (sp. 21), requires some caution. Several morphological variants can be recognised, including a large (~100-120mm), robust, somewhat asymmetrical fusiform variant with sharply defined folds (*P. sinuosus* form 21; Price, 1983, Plate 16, Figures 7-12, 14), a smaller flaccid oval form (*P. sinuosus* form 798; Foster, 1976, Plate 8, Figure 1; Foster, 1979, Plate 37, Figure 17; Gilby & Foster, 1988, Plate 7, Figure 30), and a moderately sized (~80mm) rigid form, with a rectangular amb (*P. sinuosus* form 3780; Foster, 1975, Plate 37, Figures 15, 16).

Although Balme & Hennelly's (1956) initial circumscription of *P. sinuosus* referred only to form 21 and form 3780, later usage (in terms of defining the base of upper stage 4 or APP3.2) broadened the definition of *P. sinuosus* to include these other forms (Foster, 1976, 1979; Price, 1983). Recent studies in the Bowen, Cooper and Arckaringa Basins (Gilby & Foster, 1988; Filatoff & Price, 1991) indicate a downward extension of *P. sinuosus sensu lato* into palynofloras, which, on other floral characteristics, would be regarded as APP2. These significantly older occurrences of *P. sinuosus sensu lato* below the appearances of the APP31 index (*Phaselisporites cicatricosus*) are referable to *P. sinuosus* form 798 or another diminutive form, *P. "minuta"* form 4912 . However, the often quoted occurrences of *P.*

sinuosus in the Reids Dome beds, as noted by Rigby & Hekel (1977), are probably representative of folded monosaccate pollen remnants. On present data, *P. sinuosus* form 3780 first appears at about the oldest occurrence of *Phaselisporites cicatricosus*, with *Praecolpatites sinuosus* form 21 occurring somewhat higher in the section. The latter form appears to be a reliable marker in terms of defining the APP31-APP32 boundary and was adopted by Filatoff & Price (1990b, 1991) and Price (1994d).

The base of unit APP33 is picked on the basis of the oldest occurrence of *Acanthotriletes villosus* (sp.5)(Figure 2)]. Baculate forms, including *A. 'baculatus'* (sp. 251), are excluded from the morphological limits applied to this species. The third- and fourth-order units of APP33 are newly established and, particularly with respect to the fourth-order units, tentative.

Unit AAP3 is widely represented in the Bowen, Cooper and Sydney Basins. In the Denison Trough, the unit spans the Cattle Creek Formation, extending into the 'paralic' upper Reids Dome beds below, and into the marine-influenced, lower Aldebaran Sandstone above. In this study, the unit is represented in the upper part of GSQ Springsure 15 (above 209m), the lower part of GSQ Springsure 17 (below 601m), and in the GSQ Springsure 7, 8 and 16 (Filatoff & Price, 1991).

In the Springsure reference sections (Figure 4), unit APP31 spans all but the lowest 60m of the Mostyndale Mudstone Member (GSQ Springsure 8, 15), Riverstone Sandstone Member (GSQ Springsure 8), Moorooloo Mudstone Member (GSQ Springsure 7, 8, 16) and basal Staircase Sandstone Member (Filatoff & Price, 1991). The palynofloras from the mudstone members were monotonous, with low species diversity and a dominance of wind-dispersed saccate pollen (greater than 75%, commonly 90%, of the land-plant flora; mostly *Scheuringipollenites*). Spinose acritarchs are persistent (commonly frequent and occasionally subdominant), with brackish water leiospheres being prominent only below the Staircase Sandstone Member and in the upper Moorooloo Mudstone Member.

In contrast, the palynofloras of the Riverstone Sandstone Member are dominated by spores (mostly *Punctatisporites, Retusotriletes*); and monosaccate pollen, although subordinate to non-striate bisaccate pollen, are more abundant than striate bisaccate pollen. In many respects, the palynoflora of the Moorooloo Mudstone Member is reminiscent of APP2 palynofloras, perhaps representing a relic, specialised, distributary-channel levee flora. Aquatic forms include rare leiospheres, with almost no spinose acritarchs, suggesting less marine influence than associated with the mudstone units.

The specialised floras of the Riverstone Sandstone Member and the bland, wind-dispersed pollen floras of the Mostyndale Mudstone Member are difficult to assign on an individual sample basis, as the index forms are somewhat erratic in occurrence. This illustrates the importance of an adequate sample cover so an overall reliable biostratigraphic assignment can be made. The Moorooloo Mudstone Member is of similar palynofloral character to the Mostyndale Mudstone Member, but index forms are more persistently present.

The bland, wind-blown, pollen-dominated palynoflora of the lower Cattle Creek Formation in the Springsure region closes with an association embracing abundant leiospheres, perhaps signifying a change in depositional environment. At about 646m in GSQ Springsure 16, the character of the land-plant flora changes, with spores being more diverse and abundant. Gymnosperm pollen, although displaying greater diversity comprise a lower portion of the assemblages (less than 75% of the land-plant forms). Leiospheres are a minor but persistent component, while spinose acritarchs progressively reduce and disappear up section. This floral pattern, which is established in the upper, sandy siltstone of the Moorooloo Mudstone Member, persists through the Staircase Sandstone Member, Sirius Mudstone Member and into the lower Aldebaran Sandstone (690m in GSQ Springsure 17; Filatoff & Price, 1991), representing units APP3102, APP32 and APP33.

The uniformity of these floras suggests a stable, nearshore marine environment, passing upwards into non-marine conditions. In this region, this suggests that the upper Cattle Creek Formation-lower Aldebaran Sandstone succession is a single depositional entity.

To the north west of the Springsure region, in the Blair Athol and Wolfang Sub Basins, Unit APP3 is represented with APP332 associations at the top, spanning down through APP32 with the thick coal intervals into APP31and probably APP22 at the base of the sequence (Filatoff and Price 1990b). As with the Moorooloo Mudstone and Mostyndale Mudstone Members of the Cattle Creek Formation in the Springsure region, the lower APP3 palynofloras in these Bowen Basin sections are difficult to assign, as they are dominated by saccate pollen and have sparse, restricted spore associations.

In the Springsure reference sections (Figure 4), the Cattle Creek Formation spans the lower part of APP32, APP31 and the upper part of APP222, but in some sections in the southern Denison Trough [AAR Yellowbank 1 (Price, 1993b); AGL Yoothapinna 1 (Filatoff & Price, 1990a)], the Cattle Creek Formation is thinner and confined to APP32, with the upper part of the Reids Dome beds lying within APP3102 and perhaps the lower limits of APP32. Thus, as noted above, the upper Reids Dome beds coal measures and the marine-influenced lower Cattle Creek Formation section are facies equivalents. The Blair Athol and Wolfang palynofloras lack the marine indicators of the Cattle Creek Formation. Therefore, as with the southern Denison Trough, it seems that the Cattle Creek-lower Aldebaran marine transgression did not reach the Blair Athol and Wolfang Sub-basin.

Unit APP4

Unit APP4 is recognised by the interval between the oldest occurrence of *Dulhuntyispora granulata* and *Dulhuntyispora parvitholus* (Figure 2). As such, it corresponds to lower Stage 5 in the sense of Paten (1969) and Price (1973, 1976, 1983), and to the upper part of P3a of Evans' (1962,1966b) nomenclature. The subunits of APP4 are widely applicable, being recognised (where the Permian section is complete) in the main depocentres of the Bowen, Gunnedah, Cooper, and Canning Basins. In many Australian basins, including the Bowen, Galilee, Cooper and Canning Basins, there is a major period of non-deposition in which APP4 and the lower part of APP5 (APP5001-APP5003) are not preserved in marginal areas away from the major depocentres.

In a recent study of the Collie Basin, Backhouse (1990) recorded a different order of appearance of the APP4 subunit index forms, with *Dulhuntyispora dulhuntyi* extending below the ranges of *D. granulata* and *Didecitriletes ericianus*. Since the order of appearance of *Dulhuntyispora granulata, Didecitriletes ericianus,* and *Dulhuntyispora dulhuntyi* holds for the Canning Basin, as well as the Cooper and Bowen Basins, this discrepancy in the Collie Basin is puzzling and unexpected in terms of Price's (1983) lineage interpretation of *Dulhuntyispora*. A recent re-examination by the present author of one of the Collie Basin assemblages, in which *D. dulhuntyi* occurs below *D. ericianus* (Bore MH5 at 208.3m), determined that it comprised a spore-dominated association, which included a prominence of *Balmeospora lordii* (and *Bipartitisporis "cyclopsii"* sp 769; both representative of the *Bipartitisporis* complex and similar in morphology to microspores from some extant water ferns of the Marsileaceae) , *Granulatisporites trisinus, Dulhuntyispora dulhuntyi* forms 4686 and 3648, together with *Acanthotriletes villosus* and *Lundbladispora iphilegna*. The association is unlike palynofloras from APP4 in the Bowen, Cooper and Gunnedah Basins, but is similar to some 'specialised' associations from APP5004 to APP5006, where *Dulhuntyispora parvitholus* is patchy in its distribution.

A further twist to the lineage hypothesis was noted in the Springsure material with some variations of *D. granulata* (for example form 4536), in which the grana are difficult to resolve, although the irregular radial ridges are readily observed, giving a form approaching (and generally difficult to distinguish from) *D. inornata* var. *'antiquus'* sp. 306. This suggests that *D. inornata var. 'antiquus'* has a different progenitor and arises slightly earlier than previously suspected.

The assemblages assigned to APP4 in GSQ Springsure 17 were confined to the mid Aldebaran Sandstone (Figure 4). Their assignment to APP41 and APP42 represented a continuation of the trend started in APP33, in which the gross proportions of land-plant palynofloral elements remained fairly stable. One oddity, recorded initially in the Springsure reference sections, was a trend of increasing proportion of monosaccate pollen, such that they were commonly more frequent than striate bisaccate pollen and (in unit APP43) approached the abundance of non-striate bisaccate pollen. Similar trends have been recorded in the Gunnedah Basin (Price, 1997a) and in the Cooper Basin (Price 1996c) in APP42 - APP43 section. Aquatic forms were restricted to a minor proportion of leiospheres; and spinose acritarchs were absent.

Throughout units APP32-APP42, the cheilocardoid component evolved, giving an increase in morphological diversity (Price, 1983; Price & Filatoff, 1991), but their relative

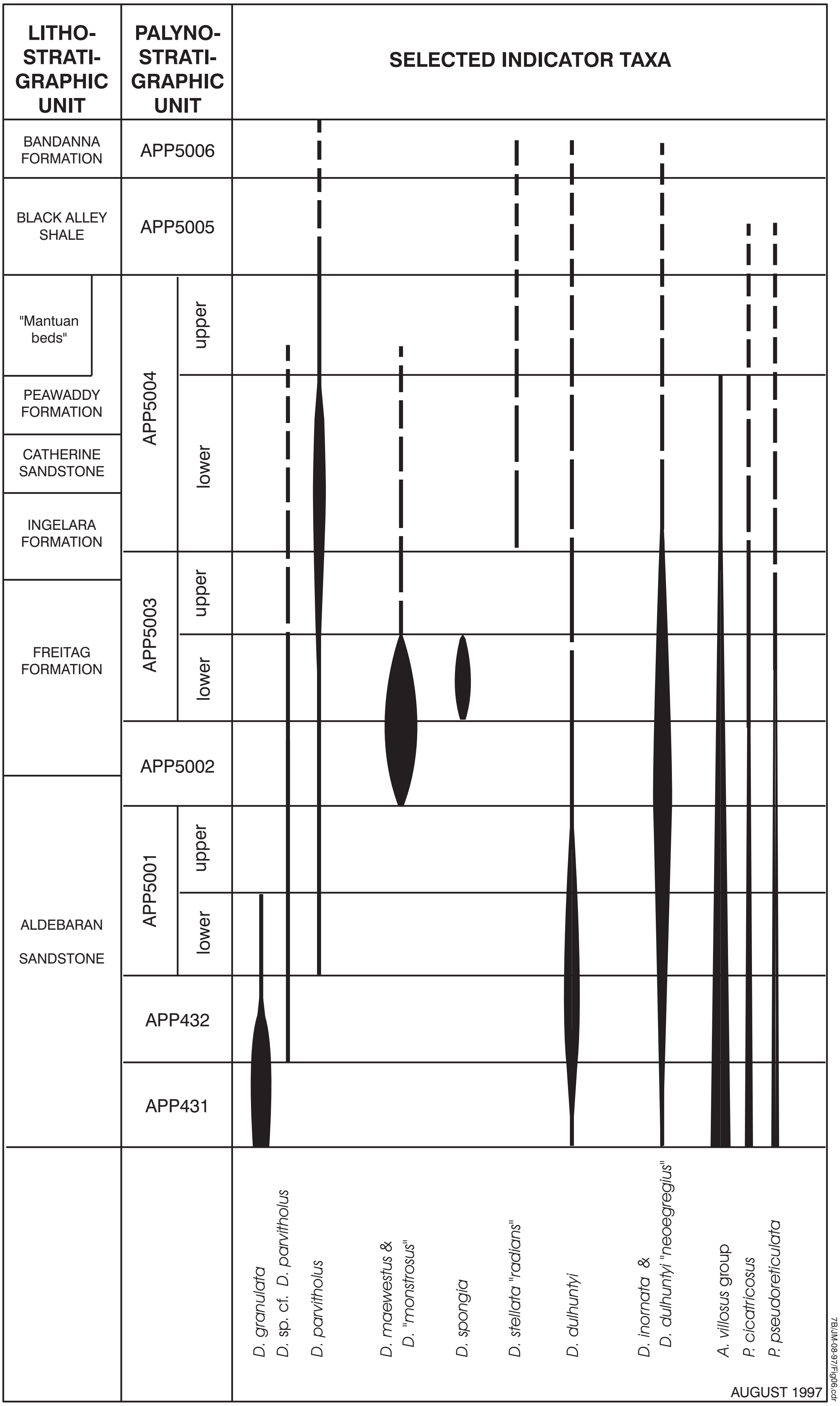

Figure 6: Stratigraphic distribution of selected Late Permian indicator taxa.

abundance in the palynofloras remained fairly constant. In units APP43-APP5003, the morphological diversity of the cheilocardoids increased further, together with their abundance, so that they became the major spore group. At the top of APP43 in the Springsure and Rolleston areas, there was a return to prominence of non-spinose acritarchs (mostly leiospheres), which persisted into unit APP5. In the southern Denison Trough, there is commonly a sharp contrast between APP43 and APP5 palynofloras (perhaps suggesting a depositional break). However, in GSQ Springsure 17 and AAR Springton 1 and 2, this boundary is transitional, with the trends established in unit APP43 continuing into APP5.

Unit APP5

The successive appearances of *Dulhuntyispora parvitholus* and *Triplexisporites playfordii* define the lower and upper limits of APP5 (Figure 2), which is the equivalent of upper Stage 5 of Paten (1969) and Price (1973, 1976, 1983). Unit APP5 encompasses P3b-P4 of Evans (1962, 1966b), although the top of P4 was recognised by a marked change in floral composition (to unit Tr1a or younger floras), while the APP5-APP6 boundary lies within what would have been regarded as a P4 palynoflora.

The subdivision of Unit APP5 has proved elusive, reflecting the stability of the palynoflora in which most forms established in APP4 (albeit sporadically) span the interval, with few new forms evolving. Evans' (1962, 1966b) subdivisions, represented by P3b, P3c, P3d and P4, reflected changes in the acritarch flora. Of these, P3c (the *Micrhystridium evansii* Acme Zone) is extremely reliable, but is confined to the Denison Trough and Springsure Shelf (Evans, 1962, 1966b; Price, 1983). The P3b-P4 boundary represents the highest occurrence of spinose acritarchs and, as such, reflects the change from marginal marine to coal-measures deposition. This event now is regarded as being diachronous on a basin-wide scale (McClung, 1981; Price, 1983).

In the Denison Trough, the coal measures of the Bandanna Formation may be somewhat paralic, as sparse spinose associations fade in and out of the post-P3c section, occurring sporadically to the top of the Bandanna Formation-Rewan Group, APP6 transition and into the lower Rewan Group. For example, sparse associations have been recovered in AAR Rolleston 11 and AAR Springton 1 and 2 from the Bandanna Formation; de Jersey (1979) has recorded spinose acritarchs from the Bandanna Formation-Rewan Group transition and the lower Rewan Group in both GSQ Springsure 1 and GSQ Taroom 8. It is also of interest to note that similar sparse spinose acritarch associations have been recovered from the lower Rewan Group in CON Namarah 2 and 3, suggesting that paralic coastal-plain conditions may have persisted into the braded-stream dominated depositional systems of the Early Triassic (Price, 1994b).

Price (1973, 1976) defined a basal assemblage of APP5 ('lower stage 5a'), representing the cryptogam-rich uppermost Aldebaran Sandstone and Freitag Formation palynofloras, which include a consistent occurrence of APP3-APP4 forms (*Acanthotriletes villosus, Phaselisporites cicatricosus* and *Pseudoreticulatispora pseudoreticulata*), and in the Canning Basin, a distinctive suite of large *Dulhuntyispora* occurs. However, the unit was difficult to delineate with precision, as the upper boundary was defined on assemblage criteria, and the extinction of the APP3 and APP4 forms was blurred by their sporadic occurrence (perhaps, in part, being reworked) in the pollen-dominated association from the upper part of APP5.

The thin overlap between the range of *D. parvitholus* and *D. granulata* observed in the Canning Basin was represented rarely in the Denison Trough (observed only in the Springsure reference sections and AAR Rolleston 11), suggesting a hiatus between APP4 and APP5 in most of the Denison Trough areas, as shown on Price's (1973, 1983) cross-sections.

In 1983, Price attempted to subdivide upper Stage 5 (APP5) on the basis of interval zones ('upper 5a', 'upper 5b', 'upper 5c'), using the oldest occurrences of *Microreticulatisporites bitriangularis* (then thought to occur only within and above the Mantuan bed) and the oldest occurrence of *Dulhuntyispora stellata sensu lato* (within the Ingelara Formation). Subsequent work indicated that *M. bitriangularis sensu lato* extends down into some of the sandstones assigned to the uppermost Aldebaran Sandstone and Freitag Formation facies of the southern Denison Trough (Price & others, 1985; Filatoff & Price 1990b, 1991; Price, 1992, 1994d).

Dulhuntyispora stellata, in terms of its biostratigraphic application, has been used in a broad sense, including at least two variants, *D.*

stellata var. 'radians' sp. 312 (centred on *D. stellata*; Price, 1983, Plate 12, Figures 4, 5, 7) and *D. stellata var. 'reticulata'* sp. 3789 (*D. stellata*; McLoughlin, 1988, Plate 2, Figure 12). This latter variant includes extreme forms of *D. dulhuntyi var. 'egregius', D. dulhuntyi var. 'neoegregius'* and *D. inornata var. 'elegans'*, which extend down into the upper Aldebaran Sandstone.

In response to these problems, Price & others (1985) subdivided the PP5 section within the Denison Trough-Springsure Shelf region only on the basis of the 'P3c' (*Micrhystridium evansii* Acme Zone) datum, abandoning the upper Stage 5 interval subzones of Price (1983). More recently, Filatoff & Price (1990b, 1991) and Draper & others (1990) re-introduced an interval-zone subdivision of APP5 in an attempt to resolve the Late Permian sections of the western Comet Ridge and Capella Block (northwestern Bowen Basin). In these studies, a four-fold subdivision of APP5 was based upon the oldest occurrence of *M. bitriangularis sensu lato*, *D. 'pickeringiae' sp.* 1141 and *D. stellata* sp. 312(Draper & others, 1990, Figure 2b). Its application, however, was difficult, because of the short stratigraphic range of *D. 'pickeringiae'* (making it difficult to distinguish section immediately above its range from section immediately below); and because of the problems of identifying the older representatives of *M. bitriangularis sensu lato* in poorly preserved palynofloras.

As the stratigraphic relationships of these thin, bore sections in the north-western Bowen Basin were not known, and as the distribution of some of the nominated index forms and the larger *Dulhuntyispora* species was not well established in the thicker Denison Trough succession, the subdivision required further revision. For example, the morphological limits of *M. bitriangularis* had been interpreted fairly broadly, including forms with weak folds (*M. 'subtilis'*) and others with limited proximal reticulum development (*M. 'monoreticulatus'*). There appear to be a morphological lineage (from a small, thin, angular variety resembling *Leiotriletes directus* to *M. explicita,* to *M. 'subtilis'*, to *M. monoreticulatus* and to *M. bitriangularis*), which requires further taxonomic circumscription and stratigraphic resolution.

As the Springsure reference-section study provided further data on the distribution of APP5 index taxa in the context of detailed stratigraphic control, further modification of the subunits was facilitated. The appearance of *Lycopodiumsporites 'crassus'*, a distinctive, thick-walled, reticulate form, defines the base of subunit APP5006 (Figure 2). *M. bitriangularis* sp. 1079, used to define the base of APP5005, represent the youngest and the most distinctive of the morphological entities of the *Microreticulatisporites* lineage (Figure 2). This contrasts with the broader interpretation of *M. bitriangularis* used in Draper & others (1990).

A better appreciation of the stratigraphic distribution of lower APP5 *Dulhuntyispora* forms was afforded by the relatively thick upper Aldebaran Sandstone section preserved in the Springton-Springsure and the Rolleston-Dunellen sections described by Filatoff & Price, (1991) and Price (1994d). These species have been used to subdivide lower APP5 palynofloras. Price (1983) regarded the large, coarse representatives of *Dulhuntyispora* as being limited to the lower part of upper Stage 5 in the Canning Basin, having recorded only a few, isolated specimens in the Bowen Basin. In the Springsure-Springton region, the APP4-APP5 transition seems to be more complete than to the south, with the precursor of *D. parvitholus* (*D. sp. cf. D. parvitholus* 298) being present, and overlap occurring in the stratigraphic ranges of *D. granulata* and *D. parvitholus*. Additionally, the diversity of the larger forms of *Dulhuntyispora* in units APP5002-APP5003 in the upper Aldebaran Sandstone-basal Freitag Formation succession of the Springton-Rolleston-Dunellen area (and also in the Moorlands Basin; Filatoff & Price, 1990b) is considered to represent section not widely or completely preserved in the southern Denison Trough.

Contrary to Archbold & Dickins' (1991) interpretation of the palynological record, *Dulhuntyispora* sp. are consistently and widely represented in all non-marine and near-shore marine shale facies from lower APP5 and APP4, provided that the embracing sedimentary rocks are neither 'over-mature' nor facies (sandstones) not conducive to palynomorph preservation. Their consistency is well supported in the Springsure reference sections and the Rolleston-Dunellen studies. Certain forms of *Dulhuntyispora*, like many fossil species, become erratic in their distribution towards the top of their range (extinction), and are also scarce at their level of appearance. Thus, their sparsity in APP5004-APP6 and APP41-APP42 palynofloras is to be expected.

A source of confusion with regard to their biostratigraphic distribution may involve instances of where lower APP5 (APP5001-APP5003) and or APP4 floras are missing (due to erosion or non-deposition), such that APP5004-APP5006 palynofloras rest directly on APP32 or older section. As noted by Price (1983, page 158), this is a common situation on the flanks and basement highs of the Cooper, Galilee and Bowen Basins, and is the case in Foster's (1982a) Mundubbera study. Additionally, palynostratigraphic interpretation in these circumstance can be difficult, particularly if preservation is marginal or there is an inadequate sequence of samples. It is worth noting that in the Gloucester Trough study quoted by Archbold & Dickins (1991), McMinn (1987) notes "poor preservation due to excessive thermal alterations (the coals have a high bituminous rank) has made identification of many specimens difficult and the illustration of some palynomorph taxa impossible". With better preserved samples from the Gloucester Trough, Helby & others (1986) recovered one of the index forms thought to be missing by McMinn (1987). Similarly, Wood's (1983) study of GSQ Springsure 19 involved poorly preserved material, but, nonetheless, resolved the presence of Units APP5 and APP4 by virtue of an adequate suite of samples.

The trend of increasing abundance and diversity of the cheilocardoid spores, noted in APP43, continued in the lower APP5 (APP5001-APP5003) palynofloras from the Springton-Springsure and Rolleston-Dunellen section, with *Didecitriletes*, *Granulatisporites* and *Acanthotriletes villosus* groups being well represented. Within APP5001, monosaccate pollen again decline (relative to older palynofloras), while striate bisaccate pollen become more prominent to the point where they can dominate the gymnosperm component within APP5003 and above. The lower part of APP5001 is characterised by the occurrence of both *D. granulata* and *D. parvitholus* (albeit as rare components), together with a prominence of *D. dulhuntyi 'densus'* and *D. Inornata* (Figures 2, 6). In the upper part of APP5001 (Figures 2, 6), *D. parvitholus* becomes a notable component, but *D. granulata* is absent; and *D. dulhuntyi* becomes abundant and morphologically diverse, with *Microreticulatisporites 'subtilis'* making its first appearance.

Unit APP5002 reflects a continued increase in the morphological diversity of the larger forms of *Dulhuntyispora*, with the appearance of several coarsely ornamented types: *D. maewestus*, *D. 'pickeringiae*' and *D. 'monstrous'* (Figures 2, 6). *Didecitriletes* and *Acanthotriletes villosus* groups are prominent, but the *Granulatisporites trisinus* group is less common than lower in the section. The pinnacle of diversity of *Dulhuntyispora* is reached in the lower part of unit APP5003, where *D. spongia var 'queenslandii*' is present. However, the distinction between the APP5002 and the lower APP5003 is subtle, particularly if preservation is adverse. In the upper part of APP5003, the diversity of the large and robust forms of *Dulhuntyispora* declines, but *D. dulhuntyi var.'neoegregius'* and *D. parvitholus* are consistent (if not prominent) components. Moreover, *Didecitriletes* are prominent and morphologically diverse; and *Microreticulatisporites 'subtilis'* and *M. 'monoreticulatus'* are consistent elements.

The distinction between upper APP5001 and upper APP5003 palynofloras can be difficult to sustain if the intervening APP5002 and lower APP5003 associations are not recovered. However, the prominence of *D. parvitholus* in the APP5003 palynofloras may be a guide to their recognition.

In Unit APP5004, the larger representatives of *Dulhuntyispora* are sporadic in their occurrence and are represented by *D. inornata var. 'elegans'*, *D. dulhuntyi var. 'neoegregius'*, *D. Dulhuntyi var. egregius* and *D. Stellata* (Figure 6). *Didecitriletes* remains prominent and morphologically diverse, while *Dulhuntyispora parvitholus* is conspicuous only in the lower half of APP5004. The *Acanthotriletes villosus* group declines and is near absent within the upper part of the unit (Figure 6).

Within APP5005, the cheilocardoids are a minor component, mostly represented by small, baculate-clavate forms and *Leiotriletes;* and *Dulhuntyispora parvitholus* and *Didecitriletes* become somewhat intermittent in their occurrence, although either may be prominent in isolated 'specialised' assemblages assigned to APP5005 and APP5006. In the Toolachee Formation of the Cooper Basin, most APP5 palynofloras conform with APP5004-APP5006 (Figure 5). However, a restricted association recovered from the basal part of Toolachee Formation in some areas is difficult to relate to basal APP5 or upper APP43 assemblages in the Denison Trough (Price & Wood, 1994). In this context, the rather bland saccate-pollen dominated associations, which lack specific spore index taxa that characterise the Late Permian upper APP5003 to APP5006 coal measures, may be recovered as low as APP43. Again, it is emphasised that an adequate suite of samples is the key to the resolution of many of these sections.

Within APP5004, the land-plant palynoflora becomes stable in terms of its gross character. Saccate pollen are dominant and represented by a diversity and prominence of striate forms, with monosaccate pollen being all but absent and non-striate bisaccates generally subordinate to the Striatiti. This pattern of saccate-pollen distribution persists throughout the upper part of APP5004, APP5005 and APP5006, although, at the base of Unit APP5006 in the lower shale section (equivalent of the Kaloola Member of the Rangal Coal Measures) of the Bandanna Formation (Figure 3), non-striate bisaccate pollen are dominant over the Striatiti. The spore component of palynofloras in the upper part of APP5004 and above generally lacks diversity of the cheilocardoids, which characterise lower APP5 palynofloras; and *Osmundacidites* spp. are more prominent.

The uniformity and blandness of these palynofloras, in terms of the cryptogams (especially assemblages from the upper part of APP5004, representing the Catherine Sandstone, Peawaddy Formation and Mantuan sands and the equivalent section of the Comet Ridge and Springsure Shelf), renders them difficult to assign to anything but APP5. Their placement in APP5004 drives from their relative positioning between the appearances of *D. stellata* sp. 312 and *Microreticulatisporites bitriangularis* sp. 1079, respectively in assemblages above and below.

In the Springton and Warrinilla sections (Filatoff & Price, 1991; Price, 1994b), the prominence of leiospheres established in Unit APP43 persists into Unit APP5003, spanning the upper Aldebaran Sandstone and lower half of the Freitag Formation. Spinose acritarchs are intermittent in occurrence towards the top of the Aldebaran Sandstone in Unit APP5002, and become persistent to prominent at the base of the Ingelara Formation, more or less at the top of Unit APP5003 or within the basal part of APP5004.

The transition in the aquatic flora from only leiospheres to leiospheres and intermittent spinose acritarchs to mostly spinose acritarchs suggests that the upper Aldebaran Sandstone, Freitag Formation and Ingelara Formation represent a transgressive phase, with the depositional setting changing from a coastal plain to near-shore marine conditions, with a maximum marine influence in the basal Ingelara Formation.

Spinose acritarchs are persistent in palynofloras from the lower Ingelara Formation and Catherine Sandstone, attesting to their marine origin, although the absence of such forms (or aquatic forms as a whole) in the upper Ingelara Formation and Peawaddy Formation (including the lower 'Mantuan' sand) is difficult to interpret in the Springton sections.

Leiospheres become prominent in the upper part of the Peawaddy Formation (mid 'Mantuan' sand), presaging the pulse of spinose acritarchs of the *Micrhystridium evansii* Acme Zone ('P3c' horizon) in the upper 'Mantuan' sand and coquinite or basal Black Alley Shale (Price, 1976, 1983). This represents the last of the widespread marine events, although restricted to the central western Bowen Basin. Intermittent spinose-acritarch occurrences persist to the top of APP6, indicating that paralic, coastal-plain conditions throughout the deposition of the Late Permian coal measures.

THE PERMIAN-TRIASSIC TRANSITION

Previous Studies

Palynofloras from the Permian-Triassic transition in the Bowen Basin have been described by de Jersey (1970a, 1979), Foster (1979, 1982b), Price (1982, 1983, 1994b, 1995a) and Filatoff & Price (1991); and from other Australian basins by Hennelly (1958), Evans (1966a, b), Helby (1971, 1972, 1973), Balme (1963, 1964, 1989), Balme & Helby (1973) and Price (1972a,b, 1982a, 1983). The transition embraces Unit Tr1a of Evans' (1966a) nomenclature, although this author did not record the full extent of the palynofloral transition. However, in terms of its application in the Bowen Basin, Unit Tr1a [in the sense of Paten (1969), Price (1973, 1976, 1982a, 1983) and de Jersey's (1979)and the *Triplexisporites playfordii-Lunatisporites pellucidus* Interval Zone] are equivalent to, and includes, the entire Permian-Triassic transition. Helby's (1971, 1973) '*Protohaploxypinus reticulatus*' (= *P. microcorpus*) Assemblage in the Sydney Basin and Price's (1972a,b; 1982a) '*Paravittatina*' and '*P. reticulatus*' Assemblages in the Cooper Basin are also representative of the transition.

Helby (1971, 1972, 1973) recognised two associations ('A' and 'B') or zonules ('lower' and 'upper') in his *Protohaploxypinus microcorpus* Assemblage. Foster (1982b), in describing the transition in the eastern Bowen Basin, also recognised two associations within the equivalent interval, designating them as the *Playfordiaspora crenulata* Zone and the *Protohaploxypinus microcorpus* Zone. However, as the palynofloral expression of the transition differs from area to area and there is no clearly defined boundary between the two associations, Helby's hierarchical concept is preferred. As such, the *Playfordiaspora cancellosus* (=*P. crenulata*) association (APP601) and the *Protohaploxypinus microcorpus* association (APP602) are considered as subunits of the *P. microcorpus* Assemblage (APP6).

Unit APP6

Unit APP6 is defined as the interval between the oldest occurrences of *Triplexisporites playfordii* and *Lunatisporites pellucidus* (Figures 2 and 7). It encompasses the transition from the Striatites palynofloras of the Permian to the *Falcisporites* palynofloras of the Triassic . The character of these transitional palynofloras differs from area to area, but *Densoisporites* spp. and *Lundbladispora* spp. (including *L. rallus, L. springsurensis*), *Polypodiisporites mutabilis, Triplexisporites playfordii, Playfordiaspora crenulata*, *Apiculatisporis hennellyi, Triquitrites proratus, Waltzispora strictura, Limatulasporites fossulatus, L. junior* and *Indospora* spp. make their appearance or become consistent representatives of the palynoflora at about this level. Bisaccate pollen (*Falcisporite*s spp., *Vitreisporites signatus, Protohaploxypinus microcorpus*), lycopods (*Densoisporites spp., Lundbladispora spp*.) and some of the newly established fern taxa (listed above) are locally abundant.

The fully established APP6 assemblages contrast sharply with the *Scheuringipollenites-Protohaploxypinus limpidus-P. amplus*-cheilocardoid associations of APP5, although there is a gradation between the two palynofloras, which occurs at the top of APP5 ('upper APP5006') and the base of APP6 (APP601). The APP601 associations retain the saccate-pollen and cheilocardoid spore character of APP5, although the associations within APP5 can be very restricted in some samples. APP602 associations are variable with local abundances of several of the newly established taxa, but they lack the *P. limpidus-Scheuringipollenites* pollen component, and cheilocardoid spores are restricted to intermittent occurrences (sometimes in notable numbers) of almost only *Dulhuntyispora parvitholus* and small *Didecitriletes* spp. The variability of the APP602 assemblages perhaps reflects the establishment of specialised floras in the more demanding habitats associated with the Rewan Group, contrasting with the more uniform environment of the extensive peat bogs and swamps of the Late Permian coal measures.

While APP6 floras of Western Australia typically include an abundance of small spinose acritarchs (Balme, 1968; Balme & Helby, 1973), it is usual for such forms to be present in Bowen-Basin APP6 assemblages only in sparse, very restricted, intermittent associations. The meagre spinose-acritarch association recorded in AAR Springton 2 at the top of the Bandanna Formation is typical of such occurrences (Filatoff & Price, 1991).

Spinose acritarchs are absent entirely from APP6 palynofloras of the Cooper Basin, but the distinctive pollen *Weylandites lucifer* (='*Paravittatina*') is a conspicuous component in the early (APP601) part of the transition (Price, 1972a,b, 1983). This form is all but absent in equivalent Bowen-Basin palynofloras.

Unit APP6 is not always preserved in the Bowen Basin (Figure 3, 4), often being lost within the unconformity between the Bandanna Formation and the Rewan Group (or younger sediments), or is represented in organically lean, arenaceous sedimentary rocks (Price, 1994b).

Where present in the Denison Trough region of the Bowen Basin, Unit APP6 is almost entirely confined to the coal measures of the Bandanna Formation, perhaps just extending into the base of the Rewan Group. The unit lies within the basal Rewan Group in the north-western area of the basin (de Jersey, 1979), and in the south-east, it occurs mostly within the basal Rewan Group, but also extends down into the uppermost grey shales of the Baralaba Coal Measures (Foster, 1979, 1982b).

The lithological change from the grey shales of the Blackwater Group to the red and green shales and sandstones of the Rewan Group seems gradational where the section is complete. The palynological evidence suggests that the onset of Rewan Group sedimentation occurred at slightly different times in various parts of the basin.

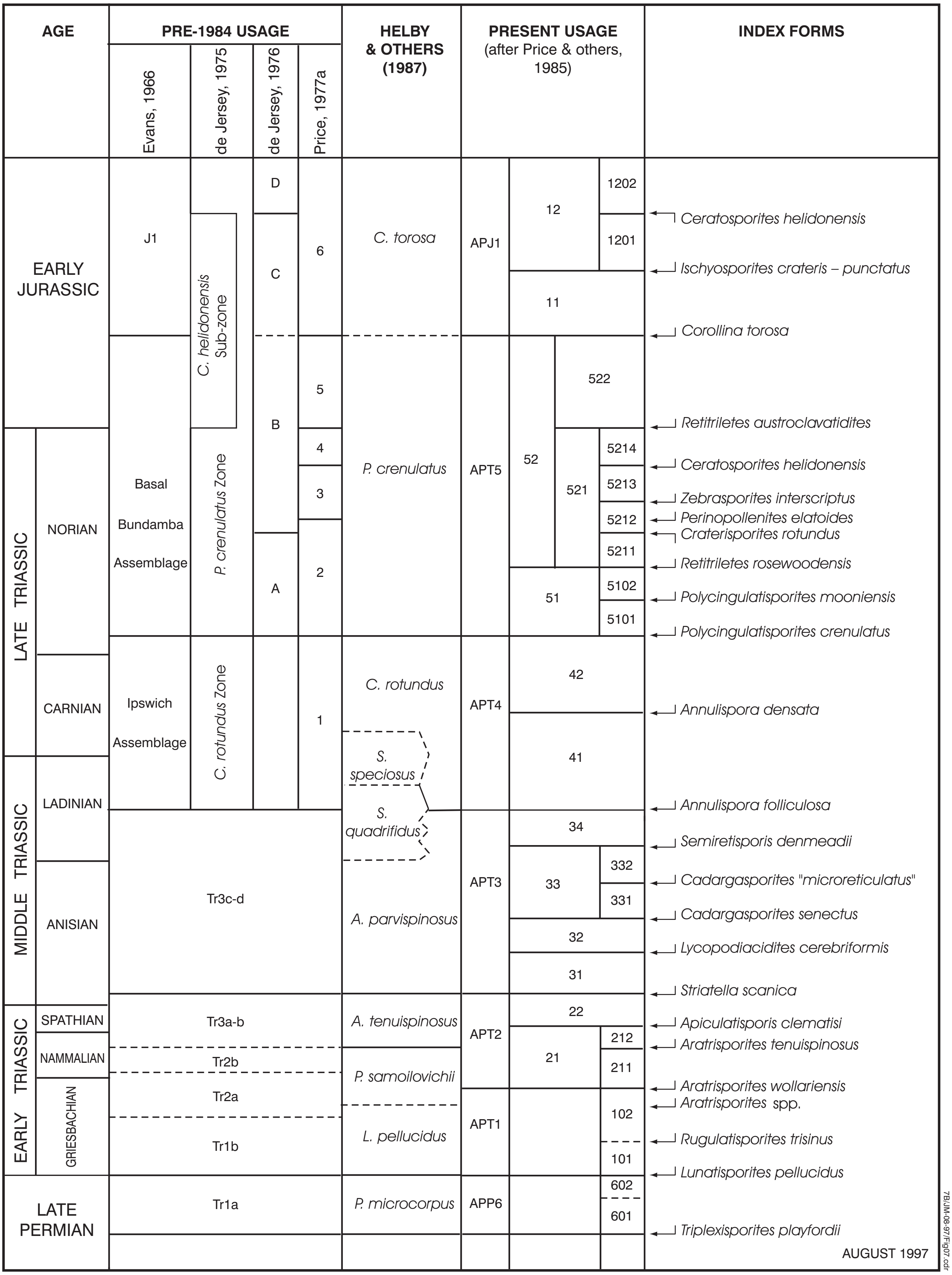

Figure 7: Triassic Palynostratigraphy

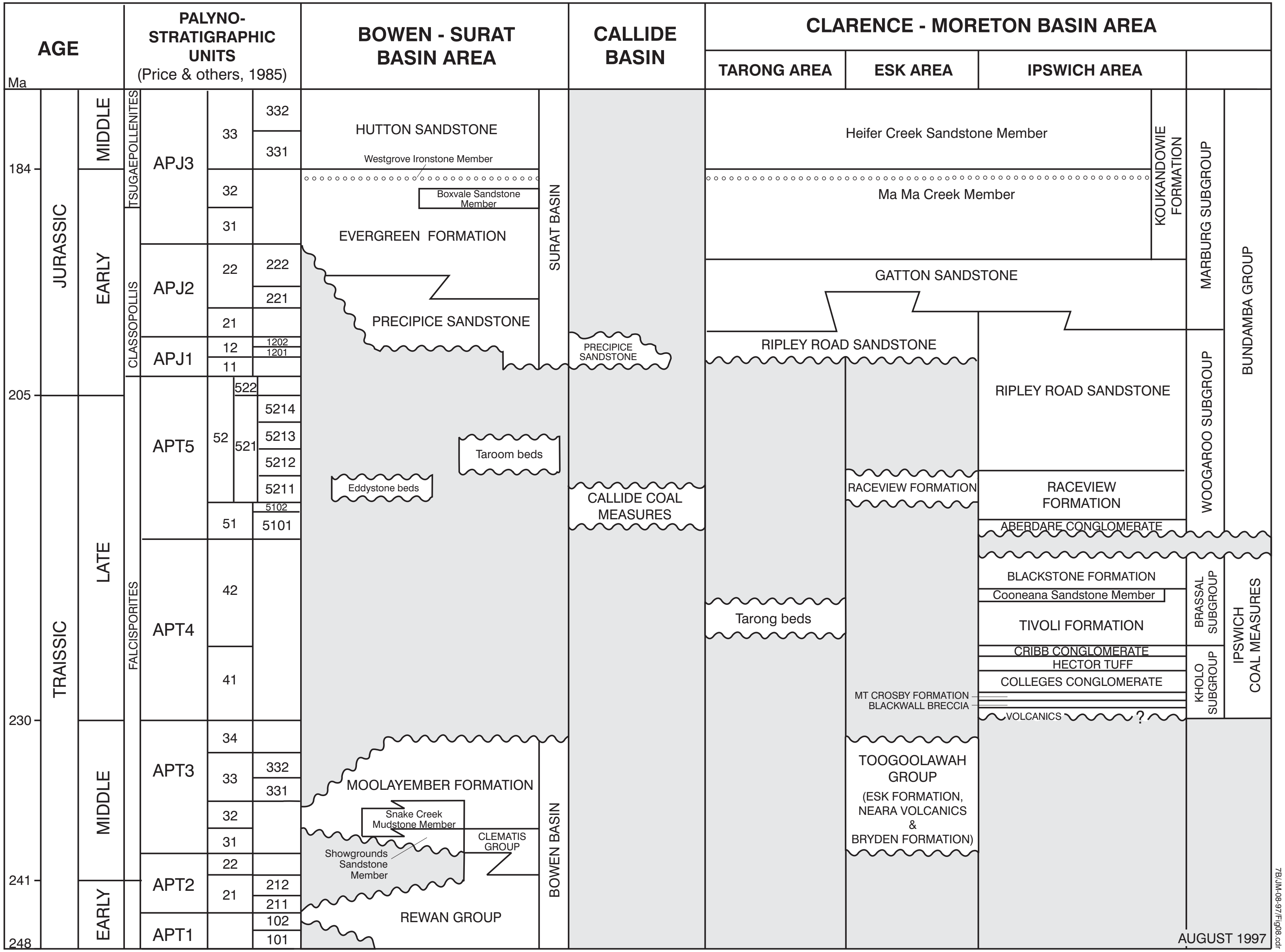

Figure 8: TRIASSIC LITHOSTRATIGRAPHY

MESOZOIC

Earlier Palynostratigraphic Subdivisions

The palynostratigraphic subdivision of the Triassic and Jurassic described in this study is based upon the units established in earlier studies of this part of the section in eastern and central Australia. These units include the four 'Zones' proposed by the founding palynological studies of the Bowen-Surat section in the early 1960s by the BMR and GSQ (for example, Evans, 1960). Balme (1964) introduced a pan-Australian palynostratigraphic subdivision of the Palaeozoic and Mesozoic, recognising successive 'microfloras' based upon gross changes in the palynofloral succession. Evans (1966a) introduced a more detailed palynostratigraphic subdivision of the Mesozoic, which, with various modifications, served as the basis for correlation in the Great Australian Basin region.

The present nomenclature was initially proposed by Price & others (1985) to update Evans' (1966a) units. Helby & others (1987) introduced a refined palynostratigraphy of the Mesozoic, drawing upon both spore-pollen and dinoflagellate distributions. Their spore-pollen units retain the basic framework of Balme's (1964) 'microfloras'. Although pan-Australian in scope, the scheme of Helby & others (1987) is most frequently applied to marine-influenced sections in western and northern Australia. The retention of the nomenclature of Price & others (1985) for the Great Australian Basin reflects the need for continuity with the earlier studies and a total dependence upon spore-pollen based units in these predominantly non-marine sequences.

Relationships between the various palynostratigraphic schemes and the present nomenclature are shown in Figure 7.

Early and Middle Triassic; Units Apt1-Apt3

Previous Bowen Basin Studies

The palynostratigraphic subdivision of the Early-Middle Triassic sections in the Denison Trough and on the Roma Shelf regions of the Bowen Basin are poorly understood. Almost all of the palynological studies in the area have been limited to brief examinations aimed at distinguishing the Jurassic from the Triassic or the Triassic from the Permian.

Palynological studies aimed at providing broad age relationships and palynomorph taxonomy of the Bowen Basin Triassic have been conducted mostly by the GSQ in the late 1960s to early 1980s, based upon stratigraphic drilling in the northern Denison Trough, Comet Ridge and eastern Mimosa Syncline regions. These studies, and their relationships to the present biostratigraphic nomenclature, are outlined below:

- de Jersey, 1979 (Bandanna Formation and lower Rewan Group; Taroom and Springsure areas); APP5006-APT201.
- Foster, 1982 (Bandanna Formation and lower Rewan Group; Taroom, Springsure and Baralaba areas); APP5006-APT1.
- de Jersey, 1970a (Bandanna Formation to top Rewan Group; Baralaba area); APP5006-APT202.
- de Jersey, 1968 (uppermost Rewan Group, Clematis Group and basal Moolayember Formation; Baralaba area); APT202-APT32.
- de Jersey & Hamilton, 1967 (Moolayember Formation; Baralaba area); APT31-APT34.
- de Jersey & Hamilton, 1969 (Clematis Group, lower Moolayember Formation ('Wandoan' Fm); Roma Shelf area); APT202-APT33.
- de Jersey, 1972); APT32-APT33.
- de Jersey & Raine, 1990 (New Zealand with comparisons to east Australia); APT2-APJ1.
- Playford & others, 1982 (Moolayember Formation; Taroom area); APT33.
- Price, 1982a (Mesozoic Surat and Eromanga Basin regions); APP6-APK6.

The GSQ palynological coverage of the Permian-Triassic transition and lower Rewan Group provides close sample data over a number of sections. The coverage of the mid to upper Rewan Group and Clematis Group is more limited. With the exception of Foster (1982b), who revised Helby's (1971, 1973) Sydney Basin nomenclature, these studies did not offer a biostratigraphic subdivision of the Early-Middle Triassic, although the age relationships of the formations in these groups were reviewed.

Evans (1966a) published a palynostratigraphic subdivision of the Triassic, based on data mostly from the Sydney and Bowen Basins. His units (Tr1a - Tr3d) were widely applied, but, being based upon gross assemblage criteria, they were better suited to regional overviews than detailed well-to-well correlations. A comparison of Evans' units with the present nomenclature is given in Figure 7.

A comprehensive study resolving the palynostratigraphy and facies relationships of the equivalent Sydney Basin section was conducted by Helby (1971, 1973). Some of these data were used by Evans (1966a) as a basis for his subdivision. Helby (1971, 1973) published a synthesis of the Sydney Basin palynology, defining a series of assemblage zones. The precise application of Helby's units in the Bowen Basin, however, was difficult because of the facies dependence of the assemblages, particularly in the Early Triassic. Moreover, time equivalent assemblages in the Bowen Basin differed in composition with respect to the prominence of some species in the Sydney Basin.

The Early and Middle Triassic nomenclature adopted here has its origins in Evans' (1966a) units, with modifications based upon data from GSQ Bowen Basin studies and Helby's (1971, 1973) Sydney Basin investigations. Price (1982a) presented a revised biostratigraphy, of the subdivision retaining Evans' nomenclature. These were further revised by Price & others (1985) and Draper & others (1990) and additional refinements have come from the studies of de Jersey & Raine (1990; New Zealand), Mc Minn (1993; Gunnedah Basin) and Price (1994a, 1994b, 1994c, 1995, 1996b; Bowen Basin).

The revised, low-order subunits of APT1 and APT2 should be regarded as being somewhat speculative, requiring confirmation in more complete sections spanning the Rewan Group to Clematis Group interval. The application of these zones in the Early and Middle Triassic is difficult, as many of the taxa seem facies sensitive, and this aspect of their distribution is poorly understood. Other taxa such as *Guttatisporites vischerii, G. grandis, Clavatisporites conspicuus, Apiculatisporis clematisi, Foveosporites mimosae, Limatulasporites 'dejerseyi', Polypodiisporites ipsviciensis, Lycopodiacidites cerebriformis 'minor'* and *Callialasporites 'moolayemberensis'* may prove useful in advancing the resolution of the section once their distribution is better understood.

Unit APT1 (Early Triassic)

Unit APT1 is defined as the interval between the oldest appearance of *Lunatisporites pellucidus* and the introduction of *Aratrisporites wollariensis* (Figure 7). The adoption of *Aratrisporites wollariensis* (the earliest of the distinctly spinose forms) for the APT1-APT2 boundary marker is favoured instead of *Aratrisporites* spp., mainly because small, non-spinose *Aratrisporites* have been observed sporadically low in the Rewan Group succession, and diminutive (? aborted) *Lundbladispora* spp. can be difficult to distinguish in certain compressions from *Aratrisporites*. It should be noted that *Rugulatisporites trisinus* was found to range lower than had been recorded previously (Price & others, 1985; Draper & others, 1990), extending down into APT1 and now proving to be a useful marker in this unit (Figure 7).

The palynofloras assigned to APT101 have some of the character of the older APP602 assemblages (in comprising notable *Protohaploxypinus microcorpus* with almost no cheilocardoids), but *Lunatisporites pellucidus* is present. Similar palynofloras are described by de Jersey (1970a, 1979) from the basal 50-100m of the Rewan Group. In southern part of the Roma Shelf area, APT101 palynofloras are confined to the lower part of the Rewan Group, extending up some 10m from the base of this lithostratigraphic unit (Price, 1994b).

Unit APT102 witnesses a change in the character of the palynoflora to an association in which the broadly taeniate, striate pollen (*Protohaploxypinus jacobii*, *Lunatisporites* spp. and *Protohaploxypinus samoilovichii*) are more prominent; and *Rugulatisporites trisinus* and *Limatulasporites 'dejerseyi'* make their appearance (Figure 7). *Aratrisporites* may be intermittently present, but *A. wollariensis* is absent. In the Roma Shelf area, this palynoflora (APT102) extents upwards from within the basal lithological subunit of the Rewan to approximately 30m from the base of the Rewan Group. In the Baralaba region, where the Rewan Group is considerably thicker, de Jersey (1970) recovered similar palynofloras from the lower 1000m or so of the unit, while, in the Taroom area, the equivalent section spaned an approximate 300m interval upwards from about

100m above the base of the group (de Jersey, 1979).

Unit APT2

Unit APT2 is defined by the successive appearances of *Aratrisporites wollariensis* and *Striatella scanica* (Figure 7). As noted above, *Rugulatisporites trisinus*, previously used to subdivide APT2 (Price & others, 1985; Draper & others, 1990), was found to range consistently down into APT1 palynofloras, extending below the first appearance of *A. wollariensis*. The oldest occurrences of *A. tenuispinosus* and *A. clematisi* are used to subdivide Unit APT2 (Figure 7). This unit spans the transition from palynofloras with a prominence of striate bisaccate pollen to those in which *Falcisporites* dominate, *Aratrisporites* spp. are usually common, and striates are extremely rare, if not absent.

There have been few studies of palynofloras from the upper Rewan Group and lower Showgrounds Sandstone in the upper part of the succeeding Clematis Group in the western Bowen Basin (Denison Trough and Roma Shelf areas); and, to date, these mostly have failed to yield definitive assemblages. Thus, little can be indicated on direct palynological evidence as to the time span of APT2, although it is considerable and probably includes a major unconformity (Figure 8). The APT102, broadly taeniate, saccate-pollen palynofloras from the Rewan Group contrast sharply with the APT3 *Falcisporites*-*Aratrisporites* associations of the Showgrounds Sandstone. To the east, these *Falcisporites*-dominated, striate-deficient APT3 assemblages extend from the top third (upper 800m or so) of the Rewan Group in the Baralaba area, through the Clematis Group to the top of the Moolayember Formation.

Thus, on the basis of the relative thickness of the upper Rewan Group and lower Clematis Group sections represented in the western area compared to the Mimosa Syncline, it seems likely that a substantial unconformity is present. For example, in the Roma region, the lower Rewan Group with APT1 and APT2 palynofloras is some 50-100m thick and represents no more than the lower third (1000m) of the Rewan Group in the Mimosa Syncline, leaving at least the upper two thirds of the Rewan Group and the Clematis Group from the Mimosa Syncline (some 3000m of section) to be accommodated in less than 50m of section (below the first APT3 palynofloras of the Showgrounds Sandstone and above the last of the APT102 or APT201 floras of the Rewan Group) in the Roma Shelf area.

The APT22 index form (*Apiculatisporis clematisi*) makes its appearance in the upper Rewan Group within *Falcisporites-Aratrisporites* assemblages (Figures 7, 8). Its precise position is somewhat uncertain, as there are few stratigraphic sections studied palynologically in this part of the succession.

Unit APT3 (Middle Triassic)

Unit APT3 is defined by the oldest occurrence of *Striatella scanica* at its base and by the introduction of *Annulispora folliculosa* at its upper limit (Figure 7). Care needs to taken be in restricting the circumscription of *A. folliculosa*, as some distally annulate forms occur in APT3 palynofloras of the Moolayember Formation, but these types lack the distinctive proximal features of *Annulispora*. Additionally, *Striatella scanica* can be somewhat fickle in its distribution; and, thus, reliance must be placed on high sample density and the presence of the other APT3 marker species used to subdivide the unit (*Lycopodiacidites cerebriformis*, *Cadargasporites senectus, C. 'microreticulatus'* and *Semiretisporis denmeadii*; see Figure 7).

The Showgrounds Sandstone in the Roma Shelf region typically yields impoverished palynofloras, which, although sparse, represent assemblages which are no older than APT202 and are most probably as young as APT3. In the southern Bowen Basin, de Jersey & Hamilton (1969) recorded the APT31 index form (*Striatella scanica*) ranging down into the upper Clematis Group, including the Showgrounds Sandstone.

Unit APT32, defined at its base by the first appearance of *Lycopodiacidites cerebriformis* (Figure 7), commences near the top of the Showgrounds Sandstone/Clematis Group (Figures 7, 8). The transition from the Showgrounds Sandstone through the Snake Creek Mudstone Member of the Moolayember Formation to the base of the succeeding Moolayember Formation is not accompanied by a change in the gross character of the palynoflora, suggesting that the Showgrounds Sandstone and Moolayember Formation may be conformable. Additionally, it is probable that the transition of the Showgrounds Sandstone to the Moolayember Formation (including the Snake Creek Mudstone Member) may be diachronous with respect of the APT31-APT32 and APT32-APT33 boundaries. This suggests that these units have a facies relationship with each other. In the south-eastern part of the Roma Shelf area (Redcap area), the palynoflora from the upper part of the Snake Creek Mudstone Member is assignable to unit APT331, which, in other parts of the basin, is associated with the Moolayember Formation immediately above the Snake Creek Mudstone Member.

Moreover, in the north-west in APN Back Creek 2 (Price 1994a, 1995), the Showgrounds Sandstone-Moolayember Formation boundary lies within APT31, with the APT31-APT32 boundary being located towards the base of the Moolayember Formation and the APT32-APT33 boundary lying at the top of the attenuated Moolayember Formation section preserved therein. Further, if facies relationships do exist between the Showgrounds Sandstone, Snake Creek Mudstone and Moolayember Formation, then there may be some justification for considering the Showgrounds Sandstone as a subunit of the Moolayember Formation, rather than the Clematis Group.

Subdivision of APT3 in the Moolayember Formation is commonly difficult, as spores are subordinate to the absolute dominance of bisaccate pollen (*Falcisporites*). Palynofloras assigned to this unit are also known from the Esk Trough, which underlies the western Clarence-Moreton Basin. These Esk Trough palynofloras appear to span a similar biostratigraphic interval as the Moolayember Formation assemblages, but are equally as difficult to subdivide palynologically.

The APT34 index form (*Semiretisporis denmeadii*) is known from the uppermost part of the Moolayember Formation, where the formation is fully developed (Figure 7, 8). The transition from APT3 to APT4 has not been recognised in a conformable succession in Middle Triassic strata underlying the Surat and Clarence-Moreton Basins, as there is a marked unconformity, with APT3 section being overlain by APJ1 or APT5. In the Eromanga Basin, it is possible that some of the sections from which APT4 palynofloras have been recovered may be conformable with the APT3 interval of the upper Nappamerri Group (Powis, 1989).

The Western Australian and eastern Indonesian, Middle Triassic Onslow Microflora differs in its assemblage characteristics and includes taxa not generally seen in the eastern Australian Ipswich Microflora (Dolby & Balme, 1976; Helby & others, 1987). Some of the APT3 palynofloras from the Cooper and Galilee Basins include elements of the Western Australian Onslow Microflora as minor constituents (de Jersey & McKellar, 1980; Helby & others, 1987).

LATE TRIASSIC

Previous Studies and Nomenclature

Late Triassic palynofloras, although not widely distributed in eastern Australia, have been extensively studied, reflecting the importance of these sections in terms of their coal deposits. The most extensive of these are those from the Ipswich and Clarence-Moreton Basins, where a number of fully cored stratigraphic bores have been studied comprehensively during the 1960s and 1970s. Some of the more significant studies include those of:

- de Jersey, 1962 (Ipswich Coal Measures); APT4.
- de Jersey, 1970c (Tarong Coal Measures); APT4.
- de Jersey, 1971a (lower Ipswich Coal Measures); APT4.
- de Jersey, 1972 (Esk Formation and basal Bundamba Group); APT3 and APT5.
- de Jersey, 1971d (lower Bundamba Group); APT5-APJ3.
- de Jersey, 1975 (biostratigraphic review of the Ipswich and Clarence-Moreton Basins); APT4-APJ3.
- de Jersey, 1976 (biostratigraphic review of the basal Bundamba Group); APT5-APJ2.
- de Jersey, 1970b (upper Ipswich Coal Measures and basal Bundamba Group); APT4 and APT5.
- Price 1977a (Tarong, Ipswich and Clarence-Moreton Basin); APT4-APJ2.
- Price, 1982a (Surat and Eromanga Basin regions); APP6-APK6.
- Stevens, 1981 (Callide Coal Measures and Precipice Sandstone); APT5-APJ2.

The Late Triassic palynofloras are known from isolated sections underlying the Eromanga Basin (Price, 1982a; Filatoff, 1986; Powis, 1989) and have been described by Playford &

Dettmann (1965) from the Leigh Creek Coal Measures (South Australia). In Western Australia and eastern Indonesia (Timor Gap, Seram), the Late Triassic is more extensive, but the palynofloras are very different in character (Dolby & Balme, 1976; Helby & others, 1987). Occasional elements of the West Australia Onslow Microflora have been recorded in the eastern Australian Ipswich Microflora (de Jersey & McKellar, 1980; Helby & others, 1987).

Evans (1966a, page 60) alluded to the Ipswich and basal Bundamba palynofloras, regarding them as being "represented at least in part by the major unconformity between the Moolayember Formation and the Precipice Sandstone", but did not include them in his palynostratigraphic subdivision, indicating that the Moolayember Tr3c-d unit followed the J1 Precipice assemblage. A formal subdivision of the Late Triassic was proposed by de Jersey (1975) and an informal subdivision of the latest Triassic-Early Jurassic basal Bundamba Group was presented by de Jersey (1976).

This latter subdivision was slightly modified and used by Burger (1994a) for correlation within the Clarence-Moreton Basin of northern New South Wales. Price (1977a) presented an informal palynostratigraphic subdivision based on Ipswich-Clarence-Moreton Basin sections. Price & others (1985) introduced a subdivision, which was based upon the earlier nomenclatures of de Jersey (1975, 1976) and Price (1977a). This forms the basis of the scheme presented herein, together with some revision from Day & Price, (1985, 1986) and Price, (1995, 1997b).

Unit APT4

The spore association of APT4 assemblages from the Ipswich Coal Measures differs markedly from the APT3 palynofloras of the Esk and Moolayember Formations, although it is still dominated by *Falcisporites*, and has common *Polypodiisporites* and consistently occurring *Aratrisporites*. A series of distinctive forms including *Annulispora folliculosa, A. densata, A. microannulata, Anapiculatisporites pristidentatus, Craterisporites rotundus* and *Lycospora pallida* make their appearance. It should be noted that a diminutive *variety Pustulatisporites blackstonensis* occurs rarely through the APT3 palynofloras of the Moolayember Formation (Bowen Basin) and the Tinchoo Formation (Cooper Basin).

There is some tentative evidence from the Triassic successions in the Cooper and Pedirka Basins that *Annulispora folliculosa* is the earliest appearing of these newly introduced APT4 taxa, perhaps alluding to a continuity of section between APT3 and APT4 in this region. However, in the Clarence-Moreton Basin region, the *Anapiculatisporites pristidentatus-P. blackstonensis-C. rotundus* complex makes an abrupt entry, together with *Annulispora folliculosa* at the base of the Ipswich Coal Measures. Higher in the section, within the Tivoli Formation (Ipswich Basin) and within the Tarong beds (Tarong Basin), *Annulispora microannulata, A. densata* and *Lycospora pallida* appear. Several sections from the Triassic underlying the western Eromanga Basin have been assigned to APT4. These sections have yielded *Falcisporites* associations, which include one or other of *Annulispora densata, A. folliculosa* or *L. pallida*, but lack *Craterisporites rotundus.*

Unit APT5

Unit APT5 includes the transition from the typical *Falcisporites-Polypodiisporites* associations of the Middle and Late Triassic to the *Corollina*-dominated palynofloras of the Early Jurassic. The appearance of the *Polycingulatisporites crenulatus* and *P. mooniensis* represents the lower part of APT5 (Figure 7). The APT51 and APT5211 assemblages retain much of the Ipswich APT4 characteristics, including the presence of *Pustulatisporites blackstonensis, Craterisporites rotundus* and *Semiretisporis antiquus*. In using the presence of these older elements of the Ipswich Coal Measure in an APT5 association to infer an APT51 or APT5211 age, care must be taken to establish that they are endemic and not reworked from APT4 strata. The successive introduction of *Retitriletes rosewoodensis, Zebrasporites interscriptus, Ceratosporites helidonensis* and *Retitriletes austroclavatidites* serve to subdivide APT5 (Figure 7).

Unit APT5 is well represented in the Clarence-Moreton Basin (de Jersey, 1975, 1976; Burger 1994a,b; Price, 1997b), but is rarely recovered from the Surat Basin region where it has been recognised only in the Callide Coal Measures (de Jersey, 1974; Stevens, 1981) and in the Denison Trough region in GSQ Eddystone 1 and GSQ Taroom 12 (McKellar, 1978a, Price, 1995a)[See Figure 8). The Callide palynofloras, while including the APT5 and APT5211 marker species of *P. crenulatus, P. mooniemsis* and *R. rosewoodensis*, retain the older APT4 forms of *C. rotundus* and *P. blackstonensis* (de Jersey, 1974)

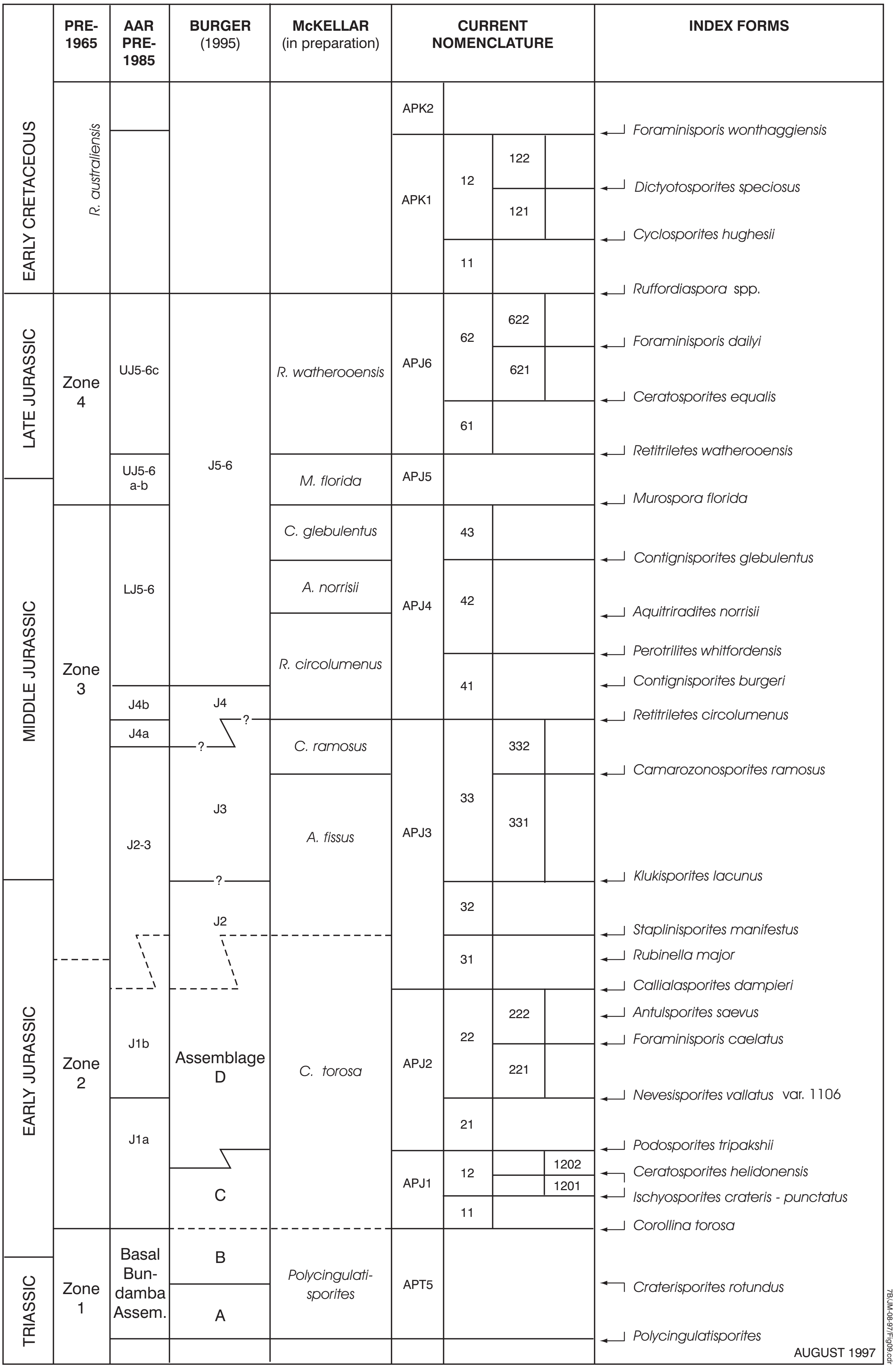

Figure 9: Jurassic palynostratigraphic units.

and thus are representative of the older part of APT5 (APT51-APT5211).

The restricted palynofloras recovered from the base of the Callide coal section recovered by Stevens, 1981 have been interpreted as representing APT4 but it is probable that they are impoverished APT5 associations. The GSQ Eddystone 1 APT5 palynoflora is similar to the Callide association and assignable to APT5211 (McKellar, 1978a, Price, 1995a). In the Eromanga Basin region, *Falcisporites* palynofloras including *Craterisporites rotundus, Polycingulatisporites crenulatus* and *Retitriletes rosewoodensis* have been recovered (Price, 1982a), indicating that sediments of similar age to the Callide and Eddystone APT5211 sections are represented. The GSQ Taroom 12 APT5 associations are marginally younger (Price, 1995a), as they lack APT4 elements, but include *Zebrasporites interscriptus*, thus representing the APT5213 palynoflora.

The lower APT5 palynofloras (APT51-APT5212) retain the Triassic characteristic of dominant *Falcisporites* and notable *Polypodiisporites*. Higher in the section, cheirolepidiacean pollen (*Classopollis/Corollina*) make their appearance and progressively assume prominence. Also, Triassic bisaccate pollen (*Falcisporites*) give way to the bisaccate pollen (*Alisporites lowoodensis, Podocarpidites* and *Piceaepollenites*) typical of the Jurassic. Although the upper part of the transition (APT5214 and APT522) has not been recorded in the Surat Basin, it is present in the eastern Clarence-Moreton Basin.

JURASSIC

Previous Investigations

Palynostratigraphic subdivision of the Early Jurassic Surat Basin section and differentiation of the Triassic Showgrounds Sandstone from the Jurassic Precipice Sandstone in the early 1960s represented one of the earliest applications of palynology in petroleum exploration in eastern Australia. These early studies conducted by BMR and GSQ palynologists (for example, Evans, 1960) resulted in a four-fold subdivision (Zones 1-4 ; Figure 9) of the Middle Triassic-Early Jurassic section of the Surat Basin. Since then, the Jurassic succession of the Surat and Clarence-Moreton Basins has continued to be closely studied, as has the equivalent section in other Australian basins. Some of the more significant studies influencing the Surat Basin palynostratigraphic subdivision are listed below:

- Balme, 1957 (Western Australia); APJ1-APK2.
- Backhouse, 1988 (Perth Basin); APJ5-APK6.
- de Jersey, 1960a,b (Walloon Coal Measures, Clarence-Moreton Basin); APJ4.
- de Jersey, 1963 (Marburg Formation, Clarence-Moreton Basin); APJ3-APJ4.
- de Jersey, 1971c (Bundamba Group, Clarence-Moreton Basin); APT5-APJ3.
- de Jersey, 1971b (Bundamba Group, Clarence-Moreton Basin); APJ1-APJ3.
- de Jersey, 1975 (Ipswich and Clarence-Moreton Basins); APT3-APJ3.
- de Jersey, 1976 (Bundamba Group, Clarence-Moreton Basin); APT5-APJ3.
- de Jersey & Paten, 1964 (lower Surat Basin section); APJ1-APJ3.
- Evans, 1960 (Surat Basin); APT3 and APT1-APJ5.
- Evans, 1966a (Australian Mesozoic); APP6-APK6.
- Filatoff, 1975 (Perth Basin); APJ1-APJ6.
- Filatoff, 1984b (Surat Basin); APT3 & APJ2-APK3.
- Filatoff, 1986 (western Eromanga Basin); APT4-APT5 and APJ2-APK3
- Filatoff & Price, 1981 (Surat Basin); APJ1-APK1.
- Filatoff & Price, 1984 (Surat Basin); APT3 & APJ2-APJ4.
- Filatoff & Price, 1985 (Eromanga Basin); APJ2-APK2.
- Helby & others, 1987 (Australian Mesozoic)
- Hodgson, 1964 (Showgrounds Sandstone and Precipice Sandstone); APT3 & APJ1-APJ3.
- McKellar, 1974 (Surat Basin); APJ2-APJ4.

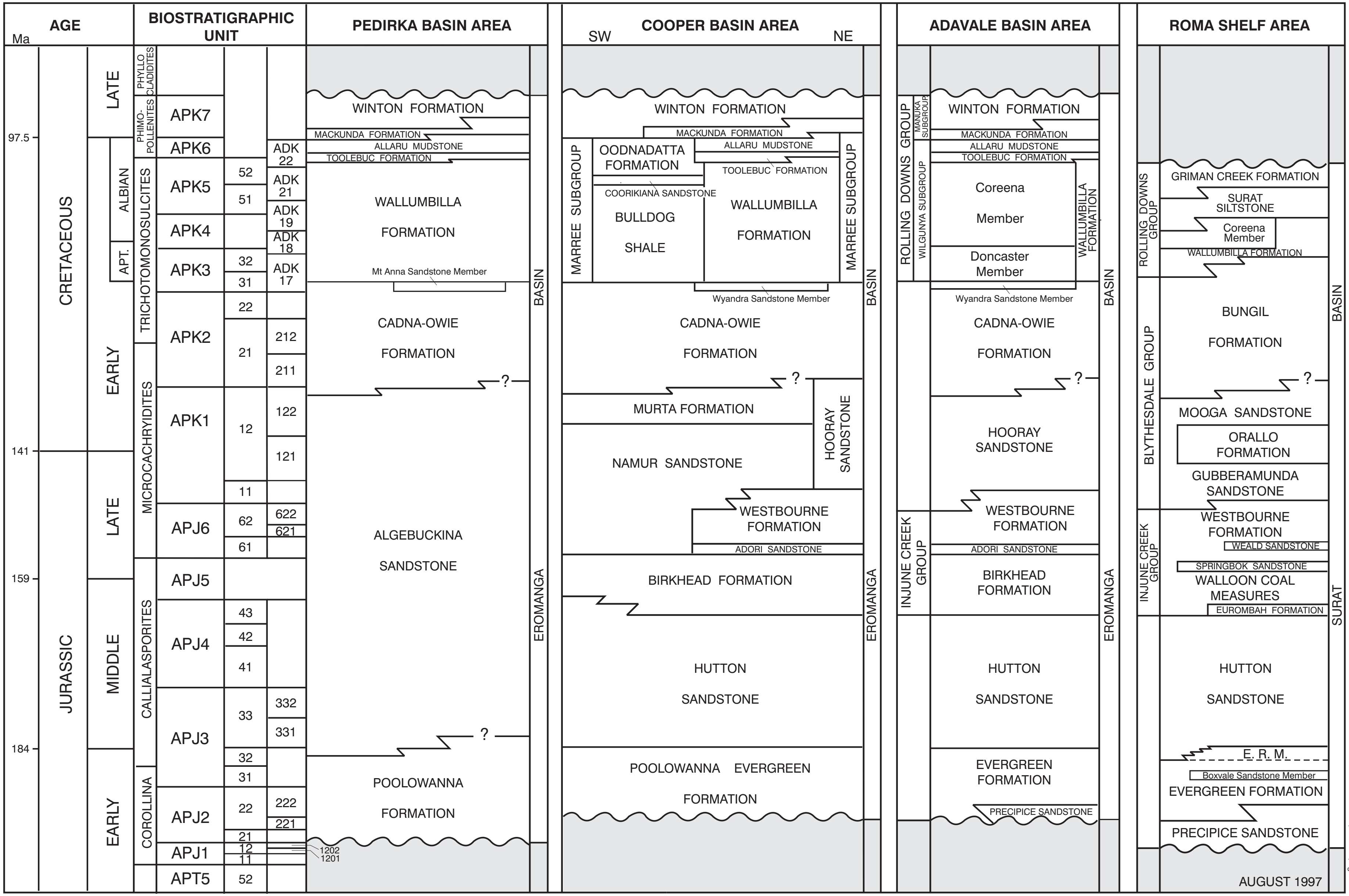

Figure 10: Jurassic Cretaceous lithostratigraphy - southern Great Australian Basin

- McKellar, 1978 (lower Surat Basin Section); APT5-APJ3.
- McKellar, 1981. (Bundamba Group, Clarence-Moreton Basin); APJ1-APJ4.
- McKellar, 1994 (Surat Basin Section); APT5-APJ6.
- McKellar, in prep (Surat Basin Section); APT5-APJ6.
- Paten, 1966 (Bundamba Group, Clarence-Moreton Basin); APT5-APJ3.
- Paten, 1967a,b (lower Surat Basin section); APJ1-APJ3.
- Price, 1982a (Mesozoic Surat & Eromanga Basin regions); APP6-APK6.
- Price, 1995, 1996b (lower Surat Basin sections); APT5-APJ3.
- Price, 1997b (lower Clarence-Moreton Basin section); APT5-APJ3.
- Price & others, 1985 (Mesozoic, Surat and Eromanga Basin Regions); APP6-APK6.
- Reiser & Williams, 1969 (lower Surat Basin section); APJ1-APJ3.

Evans (1966a) proposed a subdivision of the Jurassic (J1-J6), which, in the Surat and Eromanga Basins, was widely adopted and applied (in variously modified forms) during the late 1960s, 1970s and early 1980s. Paten (1966) recognised a subdivision of the lowest Jurassic unit, J1 (J1a and J1b), which was formally defined by Reiser & Williams (1969). De Jersey (1975, 1976) proposed a palynostratigraphic subdivision of that part of the section (Figure 7). Evans' (1966a) units were modified and applied by various workers in different ways (compare Price, 1977b or 1982a with Burger & Senior, 1979). Price & others (1985) thus proposed the present 'APJ' unit nomenclature to avoid confusion between the various versions of the Evans' scheme; and the 1985 units, with modifications based on data from Price, (1995, 1996b, 1997), form the basis of the present subdivision. As recently as 1994, Burger (1994a,b) retained the use of a modified version of the Evans' 'J' units which, like the 'APJ' units of this study, differ markedly from the original definitions given by Evans (1966a). McKellar (1994, in preparation), supported by a comprehensive taxonomic review of the Surat Basin palynology has defined a series of zones to subdivide the Jurassic sequence. The relationships of these various units are indicated in Figure 9.

Unit APJ1

Cheirolepidiacean pollen are established at the base of Unit APJ1, with the strongly infra-rugulate to striate variety of *Corollina torosa* making its appearance (Figures 7, 9). The upper limit of APJ1 is at the oldest occurrence of the trisaccate pollen, *Podosporites tripakshii* (Figure 9)and embraces the initiation of the *Ischyosporites-Klukisporites* complex. The top of APT1201 is taken as the highest consistent occurrence of *Ceratosporites helidonensis*; however, it should be noted that McKellar (1981c) recorded single specimens of *C. helidonensis* in several APJ222- APJ31 associations. The APJ1-APJ2 spore association of the Precipice Sandstone-lower Evergreen Formation, in addition to the ubiquitous Jurassic taxa (*Osmundacidites* spp., *Cyathidites* spp.), includes a diversity of sphagnaceous spores, *Anapiculatisporites dawsonensis*, *Cadargasporites* spp. and *Camarozonosporites rudis*. As noted above, the saccate pollen component is largely represented by *Alisporites lowoodensis*, *Podocarpidites* spp. and *Piceaepollenites* spp. and differs from Triassic palynofloras in that *Falcisporites* are all but absent. Inaperturate pollen, including early representatives of *Callialasporites* and *Araucariacites fissus* also become consistent components. In the Surat basin, the oldest Jurassic sedimentary rocks were considered to be assignable to Unit APJ1. They are characterised by a dominance of *Corollina*, the presence of *Ischyosporites*, and the absence of *Ceratosporites helidonensis*. As such, they are assignable to Unit APJ1202 . Only in GSQ Taroom 12 has APJ1 as old as APJ1201 been recognised and, in many areas, APJ1 is not represented at all, with the oldest Precipice Sandstone being associated with APJ2. Braided-stream deposits of the Precipice Sandstone did not commence at the same time over the entire Surat Basin with the initial deposition being confined to lows on the eroded Late Triassic surface. The full span of APJ1 is represented in parts of the Clarence-Moreton Basin (de Jersey, 1971b, c, 1973, 1975, 1976; Burger, 1994a, b).

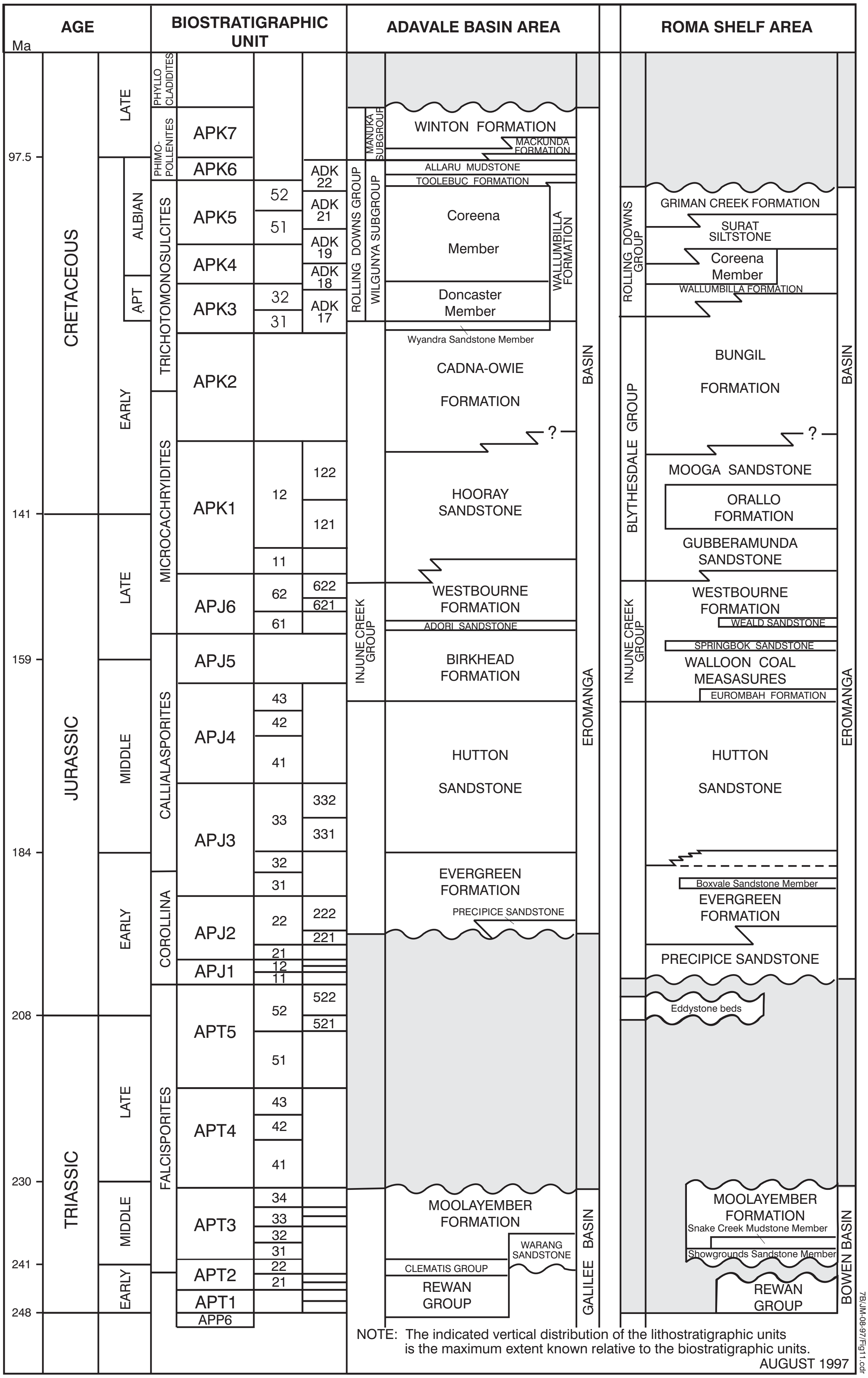

Figure 11: Mesozoic stratigraphy - central and eastern Great Austalian Basin

Unit APJ2

*Corollin*a remain the dominant form in APJ2 palynofloras, with inaperturate pollen becoming more prominent. The spore association remains similar to that in APJ1 in the Surat Basin, although lycopod forms (including *Retitriletes, Kekryphalospora* and the first of the *Dictyotosporites*) tend to be more prominent. It is worth noting that, in equivalent palynofloras from the western Eromanga Basin, spores are represented by a scant, bland filicalean association lacking sphagnaceous spores, but in which *Striatella* and *Ischyosporites surangulus* are notable [the 'lower Poolowanna' association (Filatoff, 1986)].

Unit APJ2, which at its base is defined by the incoming of *Podosporites tripakshii*, extends up to the first consistent occurrence of *Callialasporites* spp. and to the appearance of *C. dampieri* (Figure 9). As several species of *Callialasporites* (including *C. turbatus*) occur intermittently in APJ2 palynofloras, the incoming of the genus *Callialasporites* as a whole is not regarded as a reliable criterion to define the APJ2-APJ3 boundary. *C. dampieri (sensu lato*) has been reported from strata which, on all other criteria, would be regarded as APJ1, APJ2 or even older (McKellar, 1978; Helby, 1977). However, in terms of the palynostratigraphic nomenclature adopted in this study, it should be noted that an unusually smooth form of *Callialasporites* (*C. 'helbyi*' sp. 4768), which, in addition to being associated with the morphologically diverse *C. dampieri*-*C. trilobatus* complex within the Cretaceous, has been recovered in isolation from as low as the Middle Triassic Moolayember Formation in the Bowen Basin (Price, 1994a) and its equivalents in Western Australia (Helby, 1977), as well as from the APJ2 section of the Surat Basin (McKellar, 1978; Price, 1996a and this study). This form is distinguished by a wide to moderate separation of its exoexine, with few (if any) radial folds, a circular corpus and the absence of tight convoluted folds or vesicles on the exoexine over the corpus (Helby, 1977, Pl. 18, figs 10-15; McKellar, 1978a, specimen from 79.73m in GSQ Eddystone 1). Moreover, *C. turbatus, C. segmentatus* and a small form, *C. minus* 1230, (morphologically intermediate between *C. dampieri* and *C. segmentatus*) occur intermittently in APJ2 palynofloras; early variants with no equatorial exine separation are consistent, but rare members of the basal Surat Basin section.

The APJ2-APJ3 boundary may have been positioned a little lower in the section (within APJ222 of the present interpretation) in some earlier studies (Filatoff & Price, 1984; Filatoff, 1984a, b), as some of the above-cited forms of *Callialasporites* were accepted as being indicative of APJ3. The exclusion of *C. 'helbyi'* and *C. minus* from the morphological range of *C. dampieri* seems to provide a more reliable biostratigraphic datum in comparison with the J1-J2 boundary of Evans (1966a) and the base of the *Tsugaepollenites segmentatus*-*T. dampieri* Zone of Reiser & Williams (1969).

Nevesisporites vallatus, which is used as an indicator of APJ22, is restricted to forms with proximal sculpture comprising rugulae that are radially arranged with respect to the centre of each contact face. Varieties displaying grana with no or limited radial arrangement on the proximal contact surfaces have been recorded as low as the Rewan Group in APT102 palynofloras. Moreover, the identification of *Foraminisporis caelatus*, the other index form within APJ2 (Figure 9), also has some attendant difficulties. A distinction must be made between strongly ornamented varieties of *Anapiculatisporites dawsonensis*, which have similar distal ornament as the proximal surface of *F. caelatus*. In some APJ22 palynofacies, in which *A. dawsonensis* is all but absent and *F. caelatus* also is extremely sporadic, the APJ221-APJ222 subdivision should be applied with caution. Additionally, the subunits of APJ2 have proved difficult or impossible to apply in the *Striatella-Ischyosporites* 'lower Poolowanna' associations of the western Eromanga Basin, as the index forms are very intermittent in their distribution in this palynofacies.

Unit APJ3

The base of unit APJ3 is recognised by the oldest consistent occurrence of *Callialasporites* spp. and the first appearance of *C. dampieri* (used in the sense discussed above). The top of the unit is defined by the incoming of *Retitriletes circolumenus* (Figure 9). In the Surat Basin, the interval spans the upper Evergreen Formation (from about the Boxvale Sandstone Member) to the middle of the Hutton Sandstone (Figures 10, 11). *Corollina*, although still abundant near the base of APJ3, decline within the lower part of the biounit (within APJ31), from about 25-40% or more of palynoflora (as in APJ2) to less than 20%, commonly with a slight to modest inflection in the abundance trend at or about the top of the Boxvale Sandstone. Within APJ33, *Corollina*

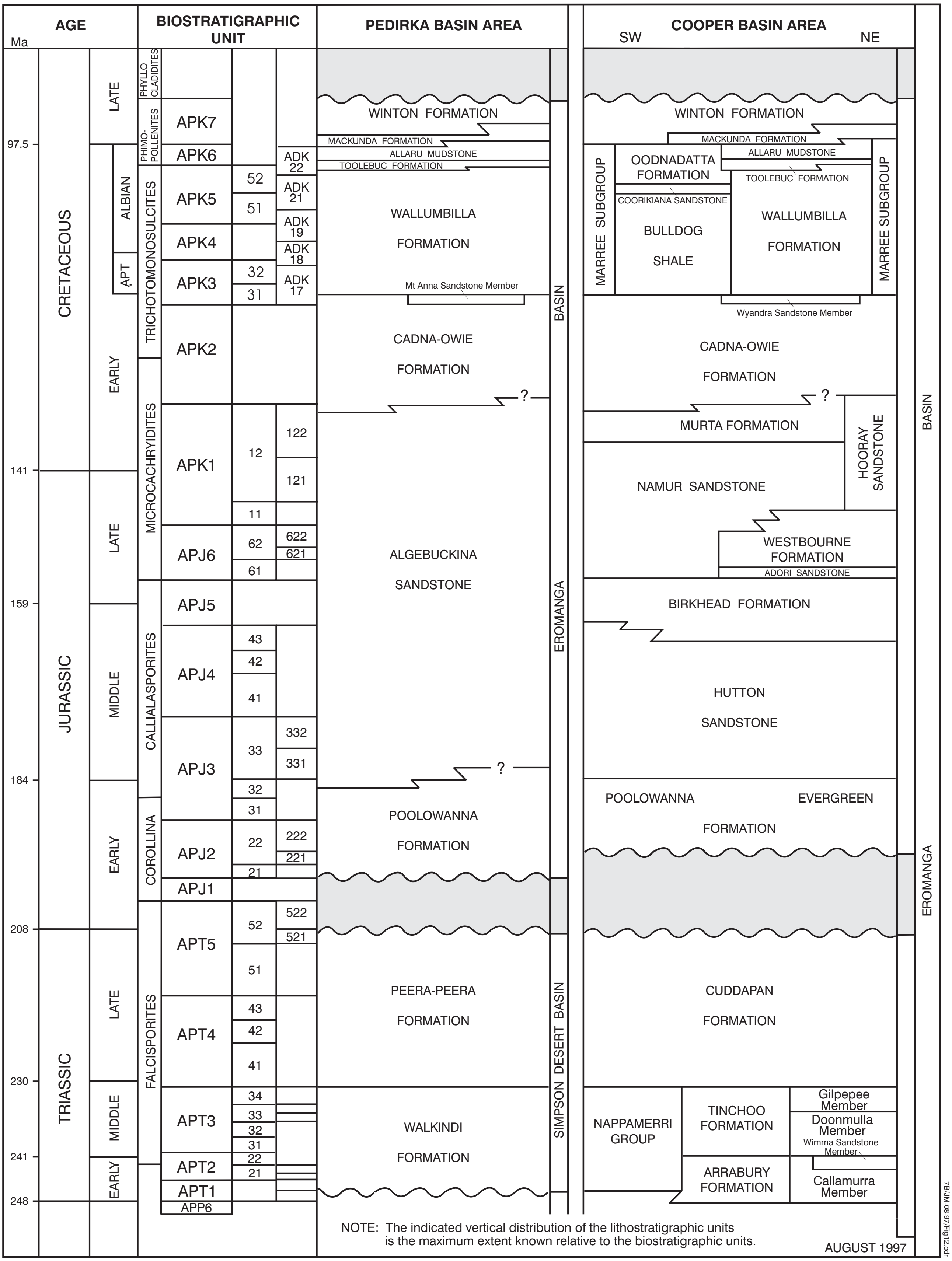

Figure 12: Mesozoic stratigraphy — western Great Australian Basin

generally represent 1-2% of the palynoflora. Inaperturate pollen (mostly *Araucariacites fissus* and *Perinopollenites elatoides*, with *Callialasporites* becoming more conspicuous up-section) and the saccate-pollen groups established in APJ1 become the dominant elements.

The spore associations of the lower part of APJ3 are somewhat variable, with two distinct associations being recognised. One is a rather sparse association, this being the 'upper Poolowanna' association of Filatoff (1986), in which *Striatella* (including the *Contignisporites*-like *S. 'transitorius'*, *S. balmei* and *S. jurassica*), the *Ischyosporites crateris-Trilobosporites antiquus* complex, and *Foveogleicheniidites 'jurassica'* are notable. It is characteristic of the Poolowanna Formation in the western Eromanga Basin and occurs in parts of the Boxvale Sandstone Member (upper Evergreen Formation). The second association, the 'upper Evergreen' association of Filatoff (1986), is more typical of the Surat Basin and is characterised by a diverse, more 'balanced' spore association in which *Foveosporites multifoveolatus-Sestrosporites pseudoalveolatus* and *Staplinisporites manifestus* make their appearance.

Spinose acritarchs associated with APJ31 and APJ32 palynofloras in the Surat Basin have been recorded from the Boxvale Sandstone Member and succeeding strata of the upper Evergreen Formation on the Roma Shelf. Evans (1963, 1966a) first reported these assemblages, but Paten (1966, 1967a,b) explored their stratigraphic potential, recognising two associations. Of these, the lower (Assemblage A), which was characterised by large *Micrhystridium* and *Veryhachium*, is associated with the Boxvale Sandstone Member, but has limited geographic distribution. The upper assemblage (Assemblage B), which was defined by sparse associations of small *Multiplicisphaeridium* and *Veryhachium*, is more widely distributed within the upper Evergreen Formation above the Westgrove Ironstone Member.

However, the Assemblage B acritarch acme is variable in thickness (up to 15m in AAO Trafford Park 1; Paten, 1967b), and it seems probable that it is not a single or continuous horizon. These assemblages of variable abundance seem to represent multiple occurrences of over intervals of varying thickness. They may occur at any level within the upper Evergreen Formation. Paten (1966, 1968) was able to trace the upper Evergreen spinose-acritarch association to the east into the Clarence-Moreton and Nambour Basins; and Price (1977b) recovered a sparse spinose-acritarch association from a similar level in the western Eromanga Basin.

The APJ31-APJ32 boundary is defined by the incoming of *Staplinisporites manifestus* (Figure 9) This form was considered by Price & Filatoff (1990) as being closely related to the APJ2 form, *S. caminus*, as the two taxa seem to represent end members of a cline, with the morphological limits used to circumscribe these taxa being somewhat arbitrary. In this and earlier studies of Price (1995a, 1996a), a distinction was made between the variants (*S. manifestus* var. *'laxus'* 4809) with well developed distal features, including closely spaced, branching, somewhat convoluted radial ridges, but with weakly developed proximal sculpture, which is boldly developed in *S. manifestus* var. *'strictus'* 621. The latter form seems to appear slightly higher in the section (within APJ32), but it should be noted that all three forms of *Staplinisporites* occur in APJ32 and APJ33 palynofloras as a very minor components, making APJ32 difficult to recognise. In the Surat Basin, Unit APJ32 encompasses the upper Boxvale Sandstone Member, upper Evergreen Formation and lowermost Hutton Sandstone.

It should be noted that Playford & Dettmann (1996) were sceptical of the lineage proposed by Price & Filatoff (1990) between *S. caminus*, *Coronatispora* and *Sestrosporites,* believing the taxa to be representative of two different plant phyla. It is acknowledged that there are marked morphological difference between the oldest end member (*S. caminus*) and the *Sestrosporites* and *Coronatispora* of the Cretaceous. However, it is believed that the continuity of morphological variation displayed between *Staplinisporites, Coronatispora* and *Sestrosporites* throughout the Jurassic and into the Cretaceous offers compelling evidence of their phylogenetic affinities particularly as Playford & Dettmann (1996) conclude that there are no consistent morphological features that differentiate proximal aperturate trilete bryophyte spores from similarly constructed lycopod spores.

The upper part of Unit APJ3 (APJ33) extends into the Hutton Sandstone and is recognised by the occurrence of *Klukisporites lacunus* within the *Ischyosporites-Klukisporites* complex; and *Camarozonosporites ramosus* makes its appearance within APJ33, defining the base of

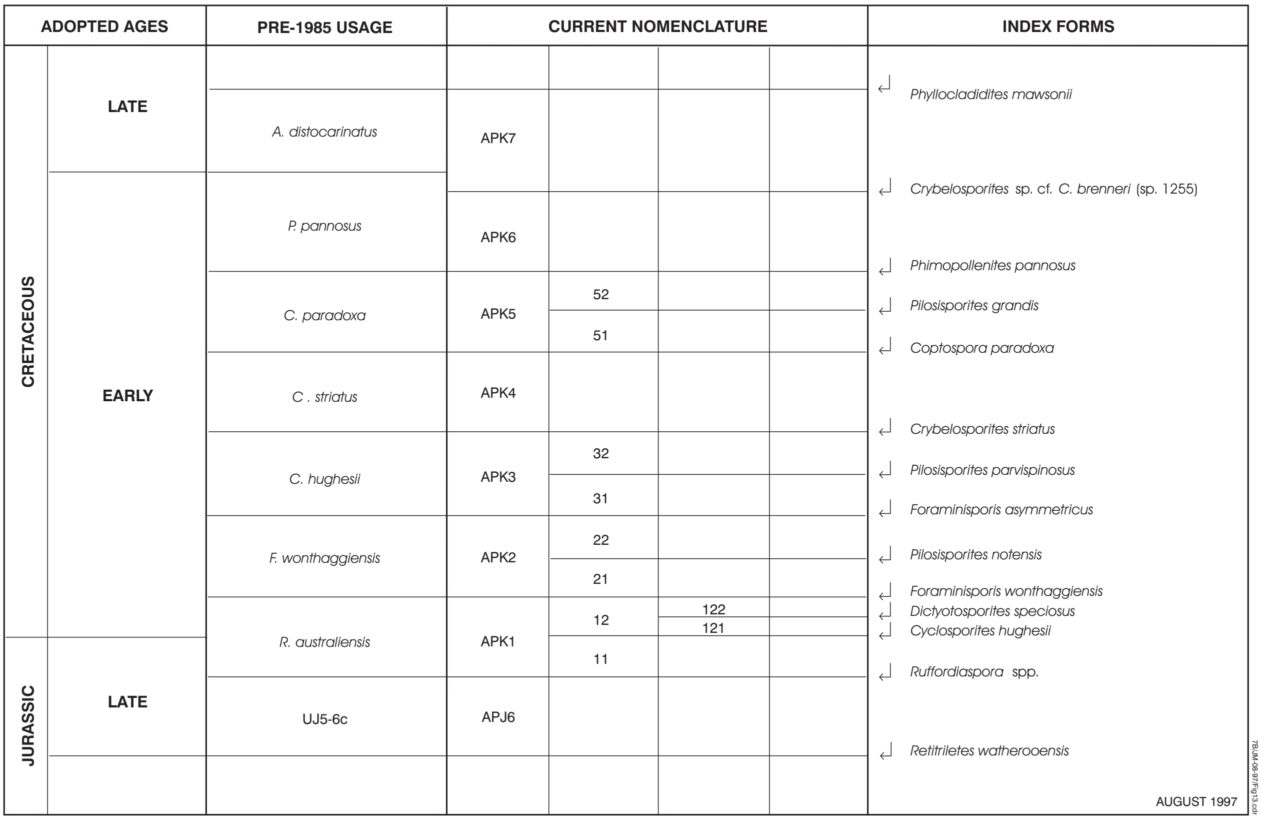

Figure 13: Early Cretaceous spore-pollen.

unit APJ332 (Figure 9). In the *Ischyosporites-Klukisporites* complex, as with the *Staplinisporites* complex, there is a continuum of morphological variation, and the morphological limits of *K. lacunus* are difficult to define.

In this study, the more triangular variant was assigned to *K. 'seramensis'* sp. 403 and was not regarded as being indicative of APJ33. In the Surat Basin, APJ331 is mostly confined to the lower Hutton Sandstone, but may extend into the upper Evergreen Formation where it is thickly developed (Figures 10, 11). Log correlation indicates that the upper Evergreen Formation and lower Hutton Sandstone have a facies relationship and this is supported by the position of the APJ32-APJ331 boundary.

Unit APJ4

Unit APJ4 is recognised by the successive appearances of *Retitriletes circolumenus* and *Murospora florida* (Figure 9). The lower APJ4 assemblages (APJ41 and APJ42), which are associated with the Hutton Sandstone, are similar to the APJ33 palynoflora, but several taxa are distinctive, including *Leptolepidites verrucatus, Dictyotosporites complex, Contignisporites burgeri* (the first of the true *Contignisporites*, contrasting with the *Contignisporites-like Striatella* of APJ2), *Perotrilites whitfordensis, Aequitriradites norrisii* and *Klukisporites scaberis* (and its variants); *Antulsporites saevus* has an acme at this stratigraphic level. Lycopods, including *Kekryphalospora parvireticulata*, are notable. The upper part of Unit APJ4 (APJ42-APJ43) is present in the upper Hutton Sandstone-lower Walloon Coal Measures and is characterised by the presence of the herpatician spores, *Aequitriradites norrisii* and *Perotrilites whitfordensis* (Figures 9-11). However, there is some possibility that these forms may be responding to the changed depositional environment and are not totally age dependant. For example, in GSQ Taroom 12, the upper Evergreen Formation shale facies included (albeit as sparse to isolated specimens) a *Perotrilites* similar to *P. whitfordensis* and a diminutive *Aequitriradites* similar to *A. norrisii*. These APJ42-APJ43 associations commonly include a prominence of the *Leptolepidites verrucatus-Camarozonosporites ramosus* complex representatives.

Unit APJ5

Unit APJ5 commences with the introduction of *Murospora florida* and concludes with the introduction of *Retitriletes watherooensis* (Figure 9). The identification of *M. florida* in the context of the APJ5 boundary requires some caution, as it is necessary to distinguish this species from *Matonisporites cooksoniae* and *M. crassiangulatus*. These three species form a complex, but the latter two (*M. cooksoniae* and *M. crassiangulatus*) extend lower in the section. For example, flat, robust, widely cingulate specimens of *M. crassiangulatus* occur within the basal Evergreen Formation (APJ221) and Boxvale Sandstone Member (APJ32) in GSQ Taroom 12. Early appearing representatives of the *Impardecispora-Concavissimisporites* complex occur in APJ5, but only in certain associations, and the full morphological development of the complex does not occur until higher in the section.

Unit APJ6

In many respects, Unit APJ6 represents the transition from the Jurassic inaperturate pollen associations (*Callialasporites* Palynoflora) to the Cretaceous trisaccate pollen associations (*Microcachryidites* Palynoflora). Unit APJ6 and its subunits are recognised by the successive appearance of *Retitriletes watherooensis, Ceratosporites equalis, Foraminisporis dailyi* and *Ruffordiaspora spp* (Figure 9). *Microcachryidites antarcticus* makes its appearance and, within APJ6 in the Eromanga Basin, podocarp pollen assume dominance over other saccate and inaperturate pollen; in the Otway Basin, the inaperturate pollen maintain their prominence into the APK1 section of the Casterton beds and the lowermost Crayfish Group (Price, 1992, 1996a). Unit APJ6 palynofloras are characterised by an abundance and diversity of lycopod spores (including *Dictyotosporites*), and *Gleicheniidites* assume a prominence in some sections.

THE CRETACEOUS

The palynostratigraphic subdivision of the Cretaceous is beyond the scope of this study, as it is not sampled in the Surat Basin as part of petroleum exploration investigations. The current version, which is based on Price & others (1985) derives dominantly from the Eromanga Basin section, with some modification from recent work in the Carpenteria Basin (Filatoff & Price, (1989) and the Otway Basin (Price, 1992, 1996a). It is shown in Figures 9 to 13 for completeness.

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VITRINITE REFLECTANCE DATA AND MATURATION IN THE SURAT BASIN AND SOUTHERN BOWEN BASIN, QUEENSLAND

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INTRODUCTION

The Geological Survey of Queensland's participation in the NGMA Sedimentary Basins of Eastern Australia (SBEA) Project included an assessment of the thermal history of the southern part of the Taroom Trough (Bowen Basin) and overlying Surat Basin (Figure 1).

An understanding of the thermal history of these basins is vital in understanding the timing of generation and migration of hydrocarbons from their contained source rocks. A common technique for assessing geothermal history is the assessment of maximum burial temperatures as defined by organic coalification, and measured by vitrinite reflectivity. The geothermal history of the Bowen Basin and Surat Basin in the study area has been delineated assuming increasing temperature with depth of burial and assuming a uniform temperature at the surface.

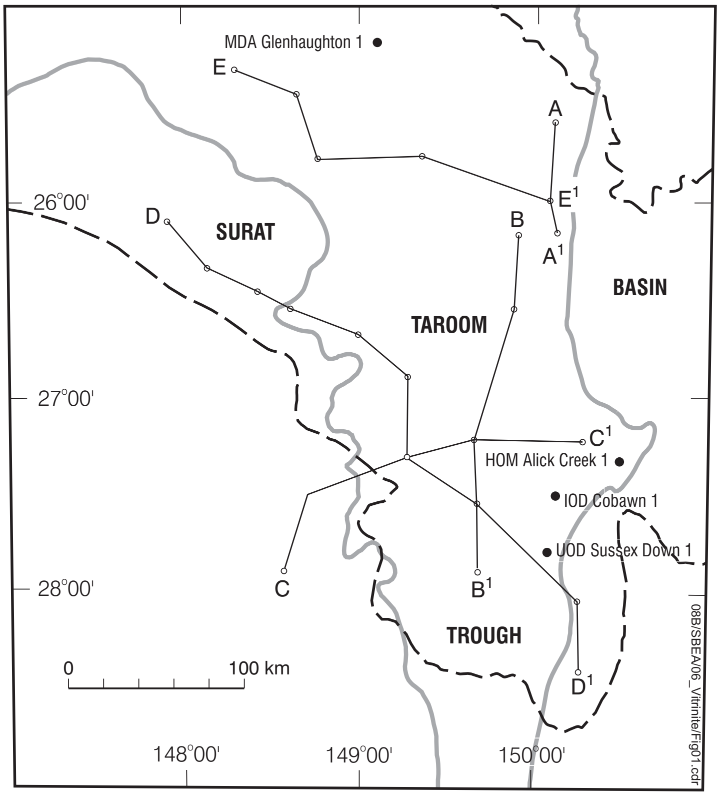

Figure 1: Map of the study area showing major cross-sections and some key reference wells mentioned in this study.

METHODOLOGY

Vitrinite reflectance determinations were made on samples from 150 petroleum exploration wells and stratigraphic bores that penetrated either or both of the Bowen Basin and Surat Basin. Of these, 103 yielded reflectance results that enabled a regression equation of reflectance versus depth to be calculated, 47 for the Bowen Basin, and 56 for the Surat Basin. Thirty of these holes yielded regression information for both basins. Values for selected formation boundaries and basin boundaries were extrapolated from the appropriate regression equations. The basic data for these wells and bores is held in a Department of Mines and Energy digital database, and is available for purchase on application.

STRATIGRAPHY AND REFLECTANCE

The stratigraphy of the basins has been recently revised (Green & others, this volume, Beeston & others, 1995; Beeston & Green, 1995) as part of the SBEA Project. Figure 2 indicates those horizons in the Bowen Basin relevant to this reflectance summary.

Reflectance results were obtained from most formations in the basins (Figure 3) and trends demonstrated compatability with the 'increase in reflectance-with -burial' model. Higher readings in the Baralaba Coal Measures and the Flat Top/Barfield Formations are a result of selective sampling of coal seams intersected in petroleum wells on The western (MPA Glenhaughton 1) and eastern (DOD Cockatoo Creek I, DOD Burunga 1) margins respectively.

Cross-sections (Figures 4-8) have been used to assess the regional variations in vitrinite reflectance across the study area.

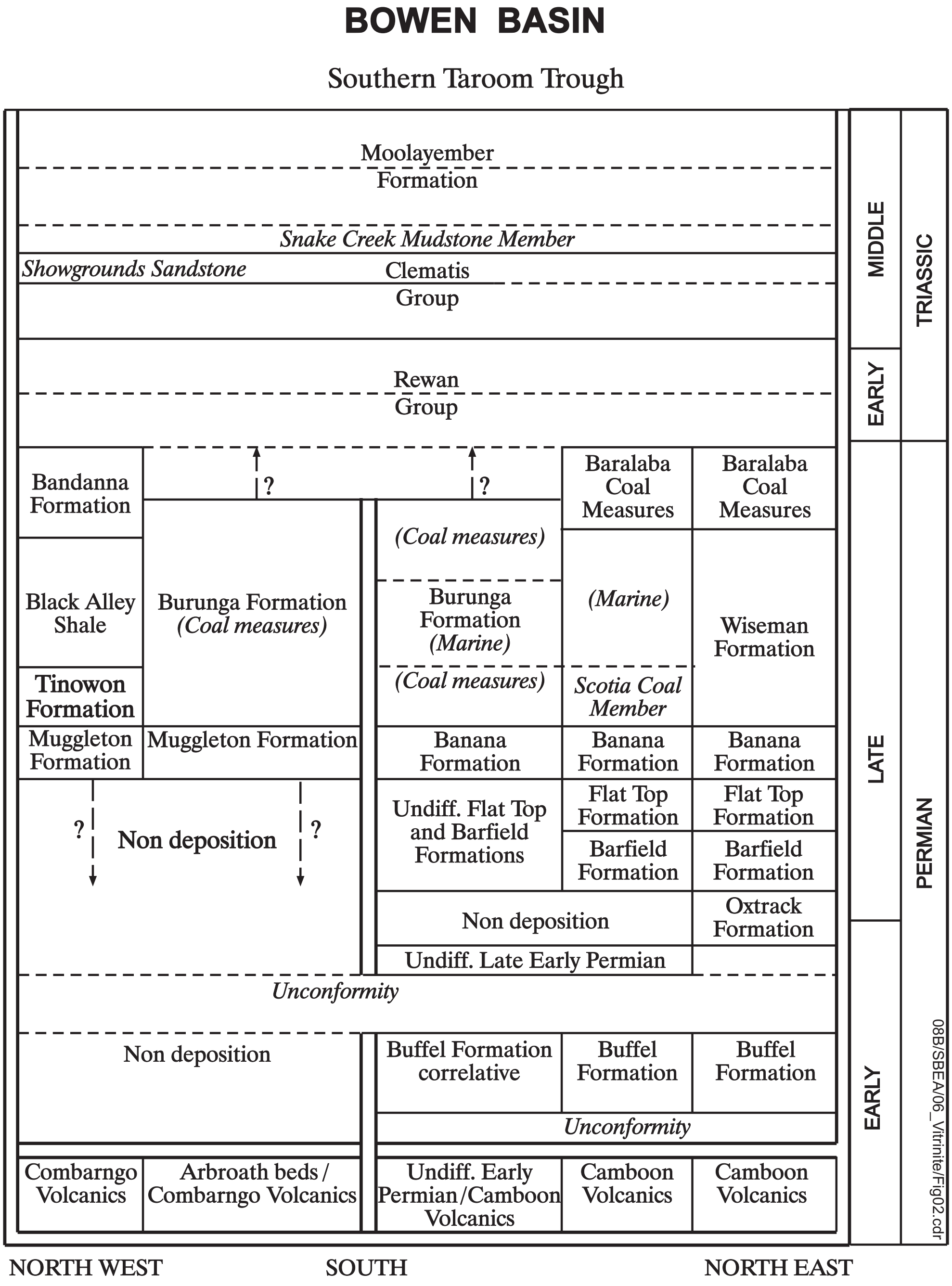

Figure 2: Stratigraphy of the southern Taroom Trough showing levels studied for reflectivity.

Isoreflectance contour maps have been prepared for the top of the Banana Formation, the top of the Burunga Formation and its equivalents, the top of the Baralaba Coal Measures and their equivalents, the top of the Bowen Basin (from data in the Bowen Basin), the base of the Surat Basin (from data in the Surat Basin), and the top of the Walloon Coal Measures. These horizons were selected as they correspond to either major coal intervals, regional unconformities or major regional sequence boundaries. All isoreflectance maps have been produced from data extrapolated from depth-reflectance profiles.

RANK LEVELS IN THE BOWEN BASIN

The Buffel Formation

Only one reflectance value (0.91 %) was obtained from the Buffel Formation. This was from a coal in HOM Alick Creek 1 which was drilled on the eastern flank of the Bowen Basin.

Barfield Formation/Flat Top Formation

Reflectance values (n = 12) from the Barfield Formation/Flat Top Formation interval range from 0.93-1.71%, with an average of 1.52% (Table 1). These maximum values reflect the high rank attained in DOD Cockatoo Creek 1 and DOD Burunga 1 in the north-eastern part of the study area (Figures 1 and 3).

Reflectance values between 1.63 and 1.71 % have been measured on coals from the lowermost part of the Barfield Formation in DOD Burunga 1 and DOD Scotia 1, on the eastern flank of the Taroom Trough.

Reflectance values of 1.11 and 1.18% were obtained from coals in the Barfield Formation (Table 1) in DOD South Burunga 1.

Banana Formation and correlatives

Two results were measured on samples from the Banana Formation, 1.06% from COE Inglestone 1 in the south, and 1.08% from DOD Cockatoo Creek 1 in the north (Table 1).

Reflectance values from formations in proximity are from disseminated organic matter (DOM). In the east, coal occurs immediately above the Banana Formation, in the Scotia Member of the Burunga Formation.

In the west, coal in the Wallabella Coal Member of the overlying Tinowon Formation occurs up to 20m above the top of the formation.

Extrapolated reflectance values in the Banana Formation and its correlatives range from 0.70% on the 'Dndulla Nose' structure in the east and in the south, to >1.60% in the north in MPA Glenhaughton 1 (= 1.94%). The isoreflectance map for the top of the Banana Formation shows

TABLE 1: Reflectance data from the Bowen and Surat Basins

REFLECT ANCE	Lowest value	Average value	Highest value	number of reflectance results
SURAT BASIN				
Griman Creek Formation	0.40	0.40	0.40	1
Surat Formation	0.37	0.40	0.42	2
Wallumbilla Formation	0.38	0.42	0.50	8
Bungil Formation	0.32	0.45	0.56	22
Mooga Formation	0.31	0.46	0.52	12
Orallo Formation	0.30	0.47	0.61	37
Gubberamunda Formation	0.38	0.44	0.56	12
Westbourne Formation	0.44	0.52	0.61	35
Walloon Coal Measures	0.44	0.56	0.70	126
Hutton Sandstone	0.34	0.55	0.73	80
Evergreen Formation	0.45	0.63	0.90	91
Precipice Sandstone	0.31	0.56	0.82	34
			TOTAL = 460	
BOWEN BASIN				
Moolayember Formation	0.46	0.71	0.92	50
Clematis Group	0.54	0.74	0.84	20
Rewan Group	0.49	0.73	1.05	32
Bandanna Formation	0.44	0.82	1.67	77
Baralaba Coal Measures	0.63	0.85	1.26	31
Burunga Formation	0.66	0.84	1.09	49
Black Alley Shale/Tinowon Formation	0.52	0.77	0.98	13
Wiseman Formation	0.89	0.90	0.90	2
Banana Formation	1.06	1.07	1.08	2
Flat Top Formation/ Barfield Formation	0.93	1.52	1.71	12
			TOTAL = 288	

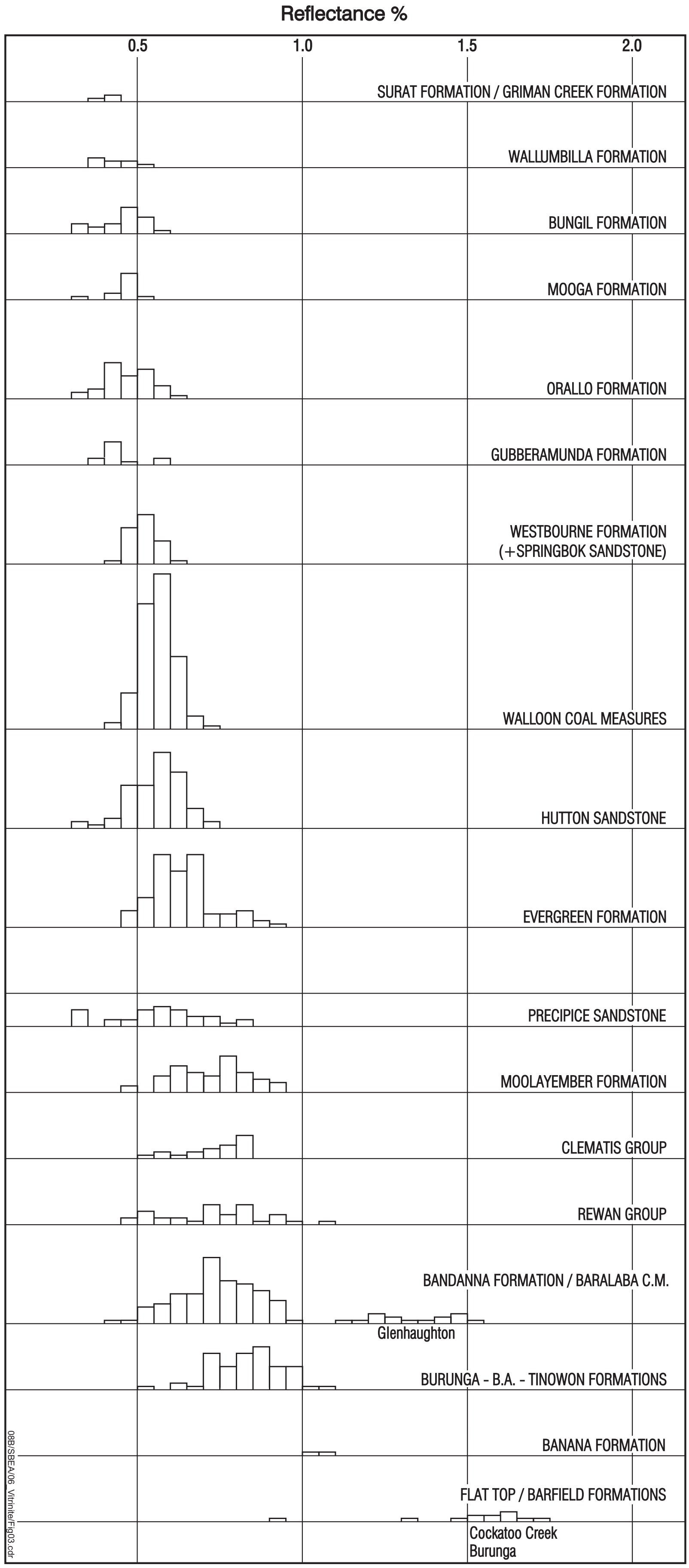

Figure 3: Graph showing the distribution of measured reflectances carried out on formations in the Bowen and Surat Basins.

values increasing from <0.7% in the very south to 0.8-0.9% on the western and eastern flanks, and>1.6% in the middle of the Trough (Figure 9). The increased values in the centre of the Taroom Trough are interpreted to result from the effects of Late Permian and Triassic subsidence due to the development of the Taroom Trough during that time.

Burunga Formation, Baralaba Coal Measures and Equivalents

Coal occurs throughout the Burunga Formation in the south, the Scotia Coal Member and overlying Baralaba Coal Measures in the north-east, and on the Roma Shelf, the Winnathoola Coal Member of the Black Alley Shale, and the Bandanna Formation. Vitrinite reflectance values range from 0.44-1.67%, with an average of 0.83% (n=172). Low values occur in the Denison Trough in the north-west, in the south, and on the 'Undulla Nose' in the east. Values exceed 1.6% at the northern end of the axis of the Taroom Trough in the study area (Table 1). The isoreflectance map for the top of the Burunga Formation and its equivalents shows the effects of development of the Taroom Trough, in particular the increased subsidence to the east of the Comet Ridge. Values> 1.0% were developed through this subsidence, which further south was confined to the centre of the Trough (Figure 10).The Baralaba Coal Measures are confined to the northern part of the study area. Reflectance values range from 0.6% in the east to 0.8% in the west, and exceed 1.4% in the Trough (Figure 11). This suggests that the depocentre was beginning to move further west during the early Triassic, but is probably related to the higher gradients in the west due to higher heat flows from the basement.

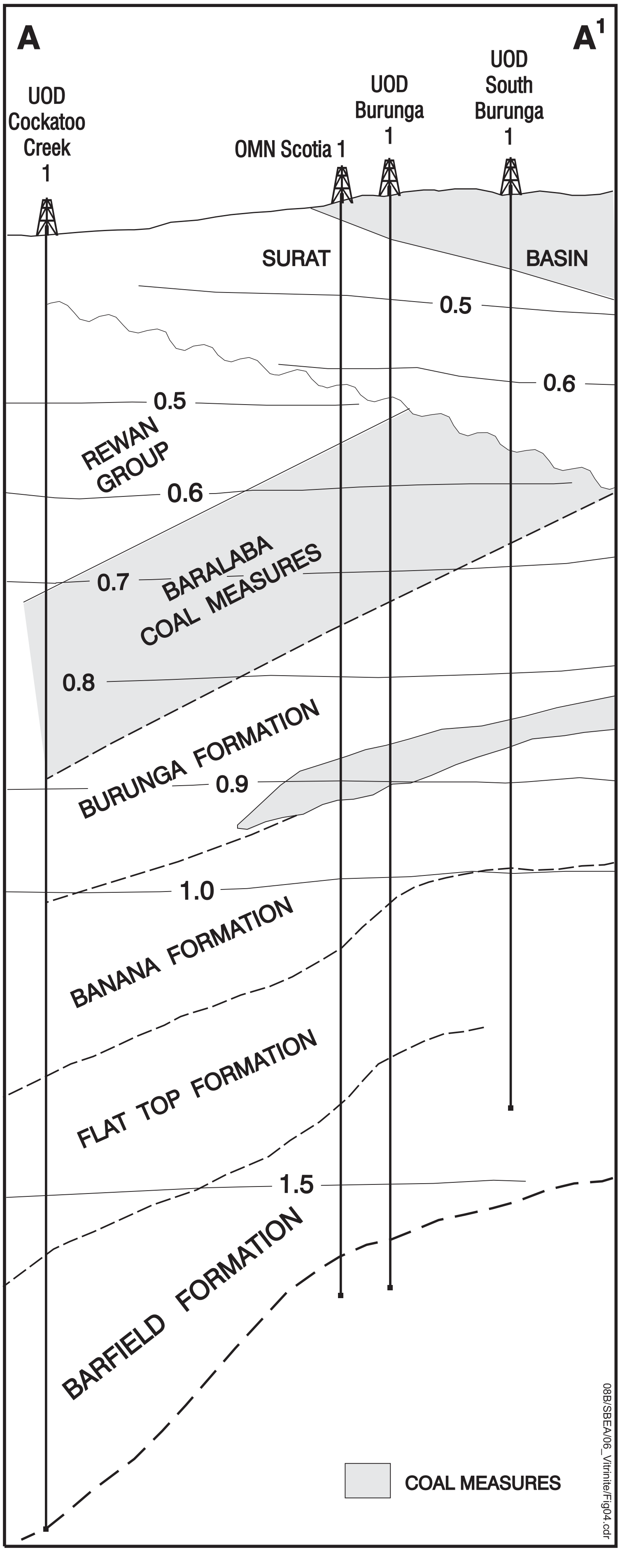

Figure 4. Cross-section showing reflectance '}ariance in the north-east.

Triassic strata

Reflectance values for the Triassic units in the Bowen Basin, obtained from 102 samples (Figure 3, Table 1) (Rewan Group, Clematis Group, Moolayember Formation) range between 0.46 and 1.05%, with an average of 0.72%. High values are located in the centre of the Trough in accordance with the greater depths of burial and hence higher temperatures.

Top of the Bowen Basin

The effect on reflectance, of the westerly migration of Triassic sedimentation resulting in the widespread deposition of the Clematis Group and Moolayember Formation, is less obvious. Uplift during the Middle Triassic caused erosion on the western, southern and eastern margins of the Trough. This is most noted on the eastern margin, where Permian sedimentary rocks subcrop beneath strata of the Surat Basin. Nevertheless, the isoreflectance map of the top of the Bowen Basin shows clearly that the highest reflectance values attained by Bowen Basin strata equate approximately with the axis of the present Taroom Trough. The effect of deeper burial in the northern region and around Cabawin (UOD Cabawin 1, UOD Sussex Downs 1) (Figure 12) is also apparent. Reflectance values are particularly high on the western margin over the Roma Shelf and further south, exceeding 0.8%.

RANK LEVELS IN THE SURAT BASIN

Base of the Surat Basin

The base of the Surat Basin equates vith the base of the Precipice Sandstone over the central and North-eastern part of the Basin. In the west, south-west, and south it equates with the base of the Evergreen Formation, which

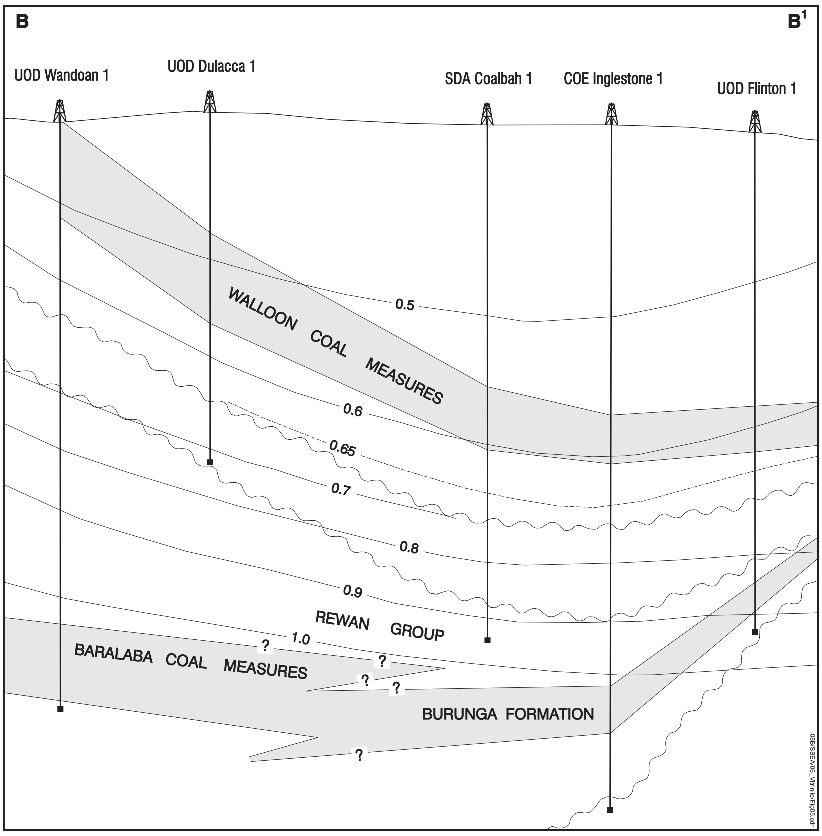

Figure 5: Cross-section showing reflectance variance from north to south.

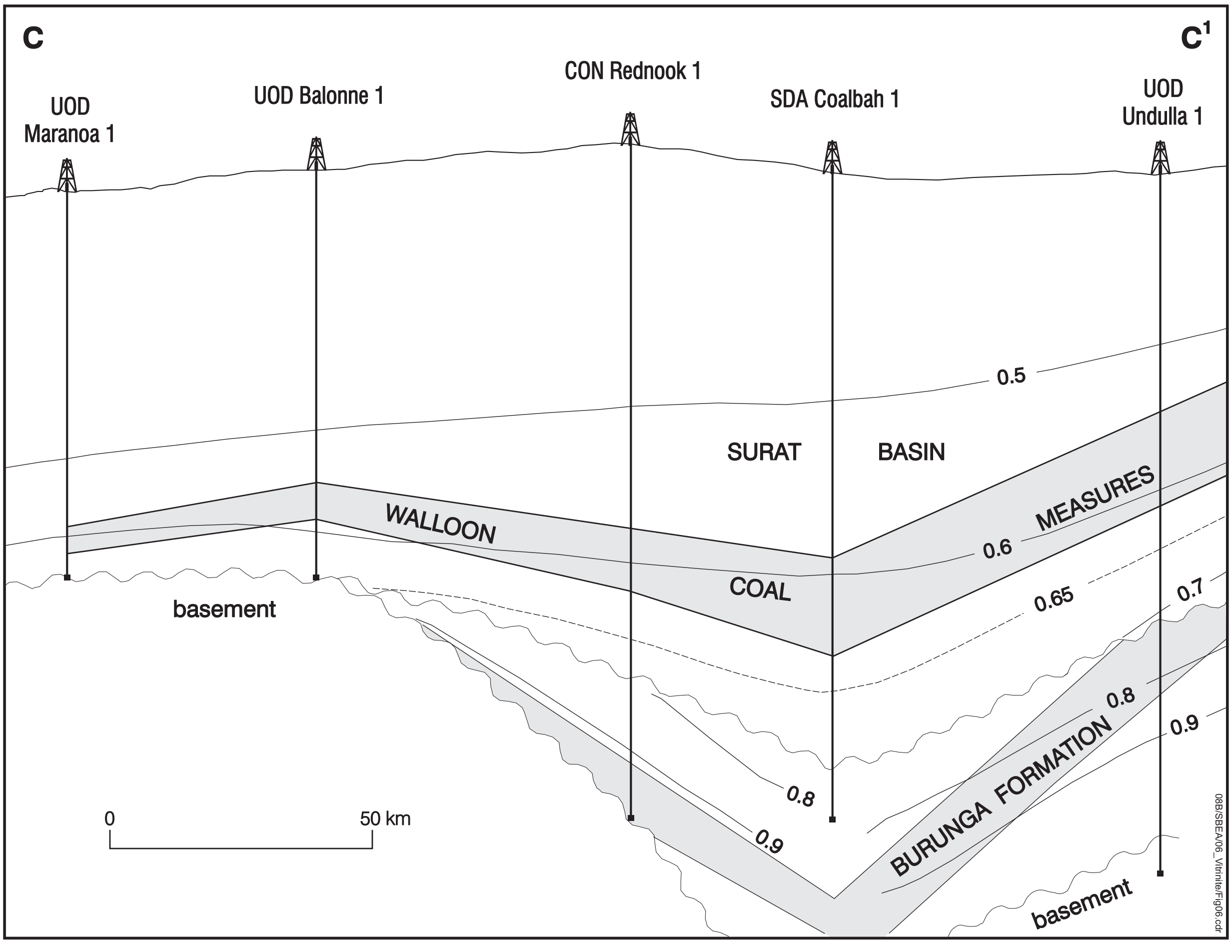

Figure 6: Cross-section showing reflectance varaincein the south, from west to east.

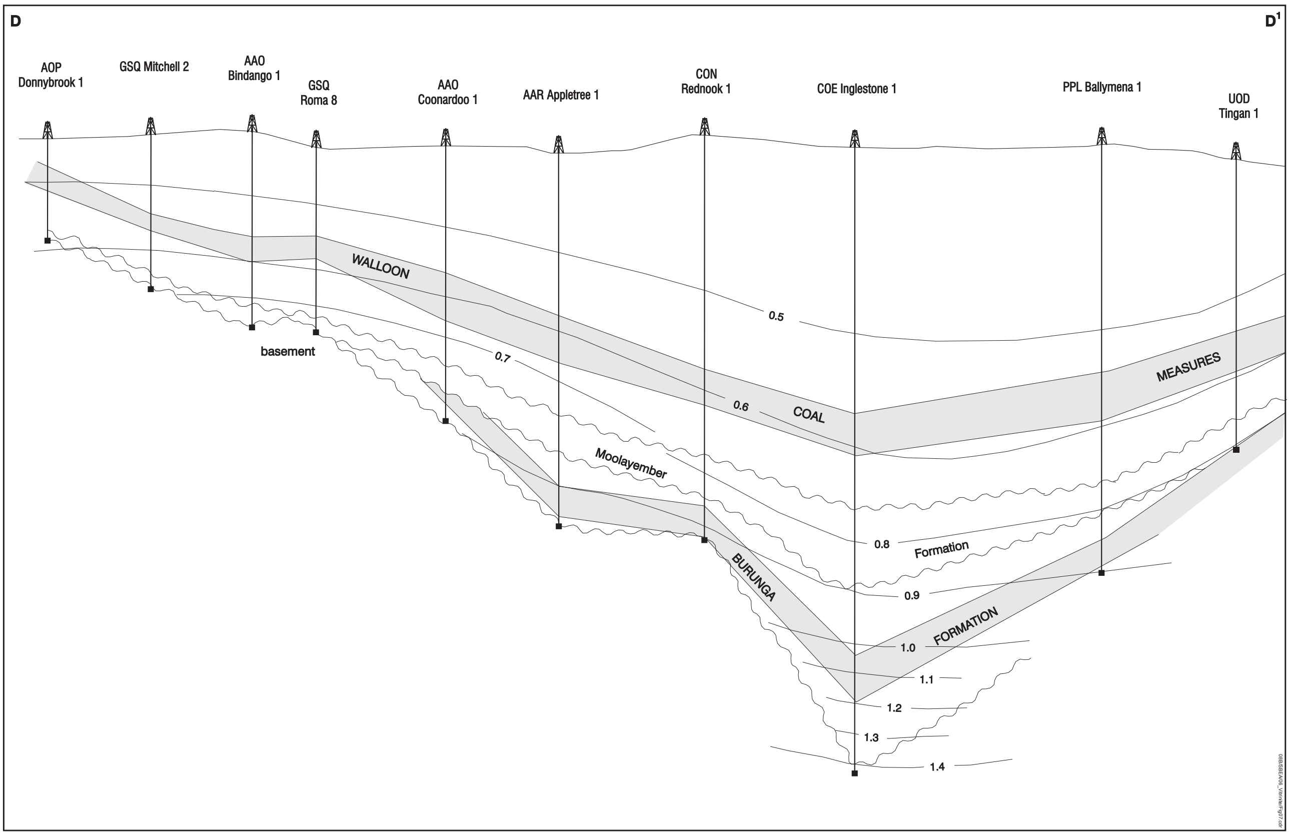

Figure 7: Cross-section showing reflectance variance in the west and south.

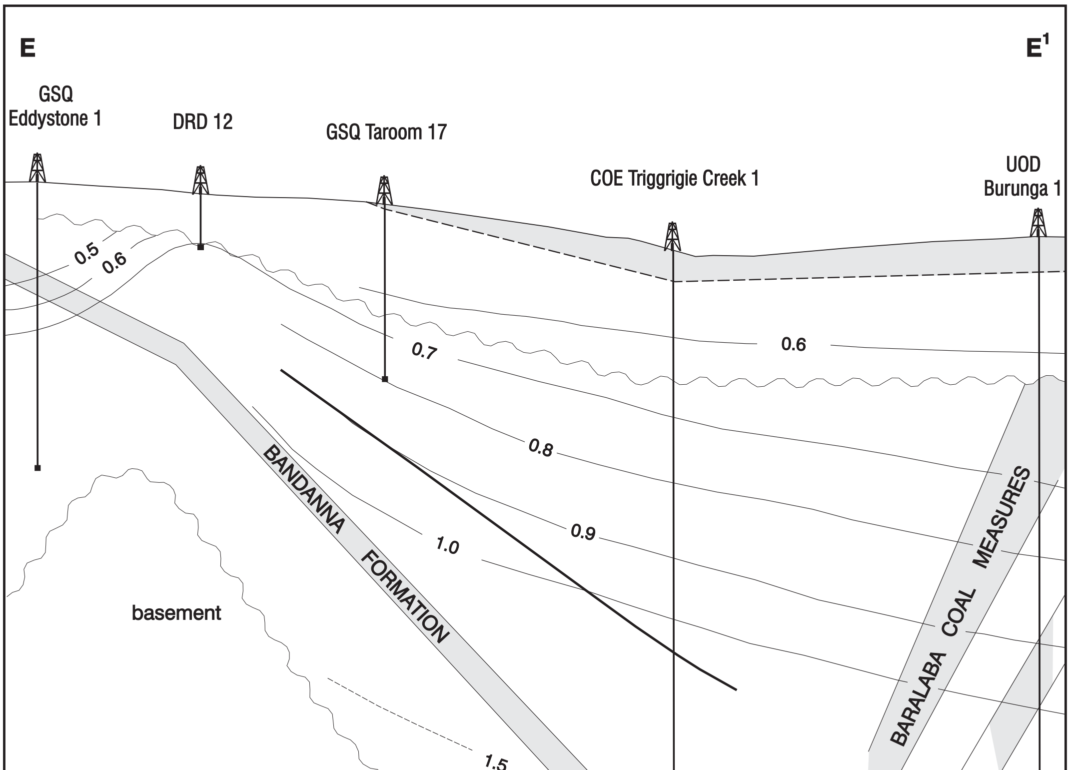

Figure 8: Cross-section showing reflectance variance in the north-west and north.

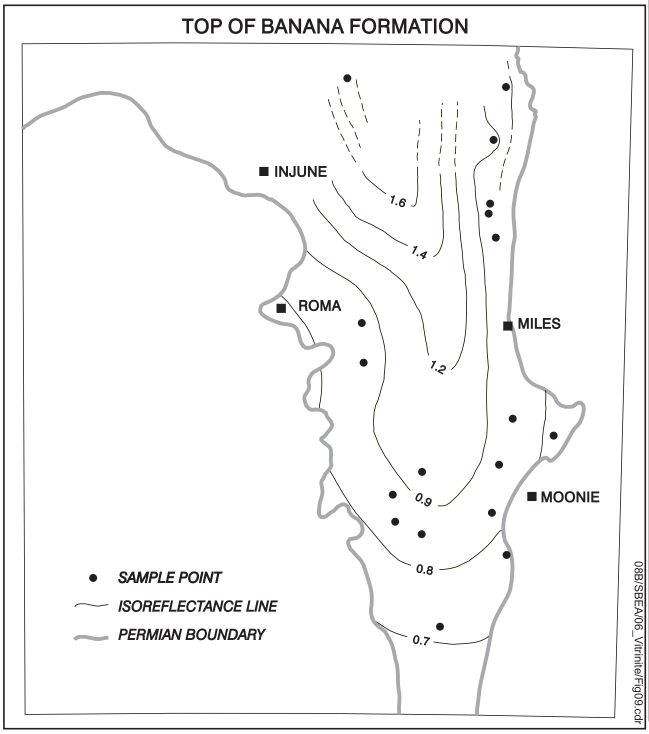

Figure 9: Isorefectance map for the top of the Banana Formation.

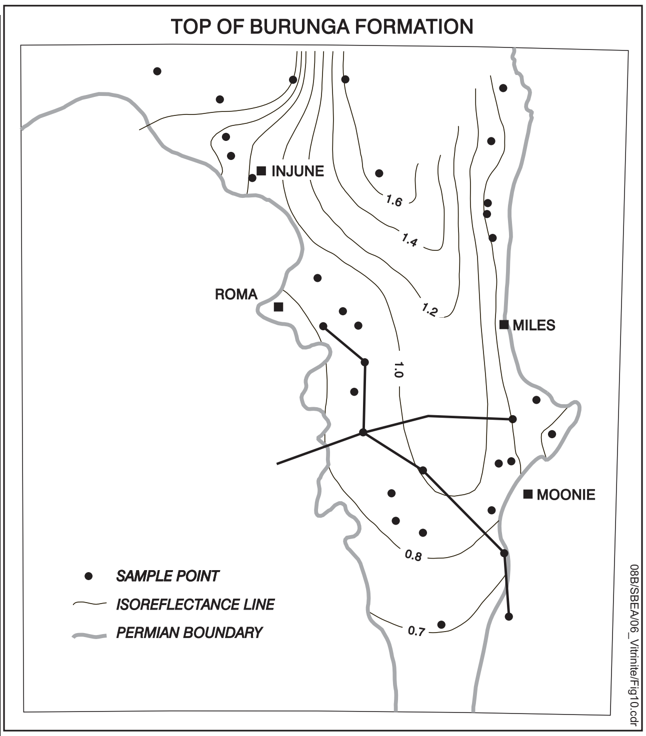

Figure 10: Isorefectance map for the top of the Burunga Formation/ Black Alley Shale.

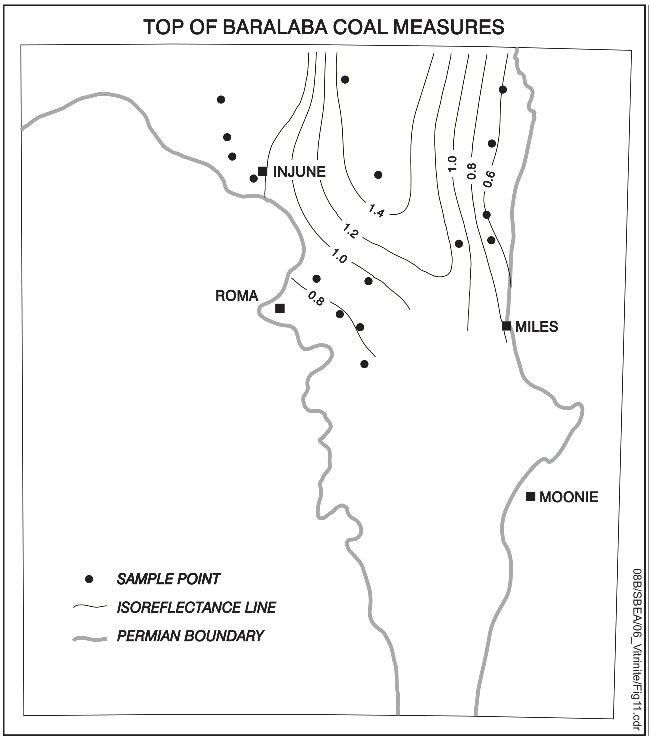

Figure 11: Isorefectance map for the top of the Baralaba Coal Measures/Bandanna Formation.

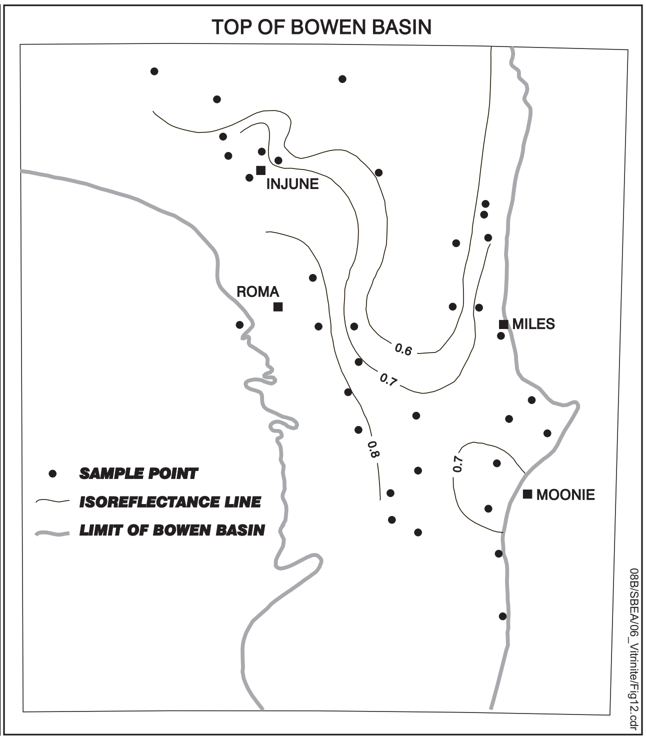

Figure 12: Isorefectance map for the top of the Bowen Basin. The map was derived from extrapolated results from depth-reflectance profiles in the Bowen Basin only.

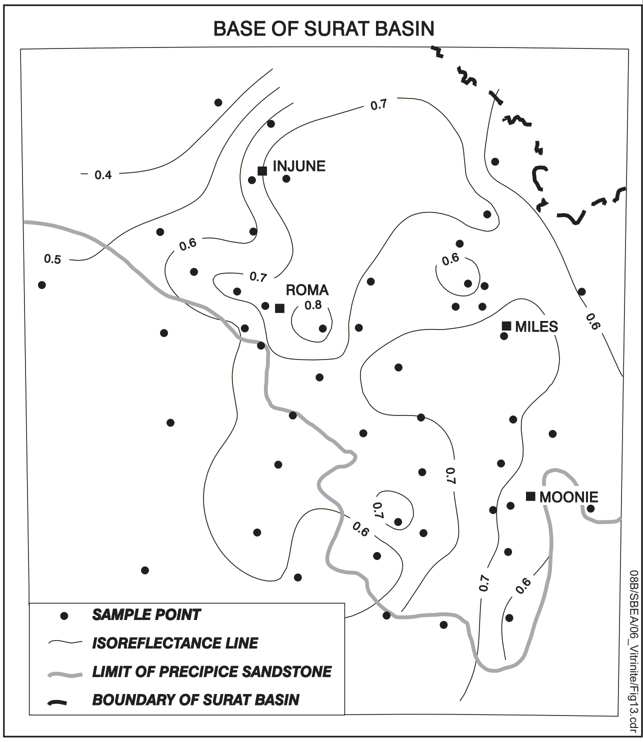

Figure 13: Isoreflectance map for the base of the Surat Basin.

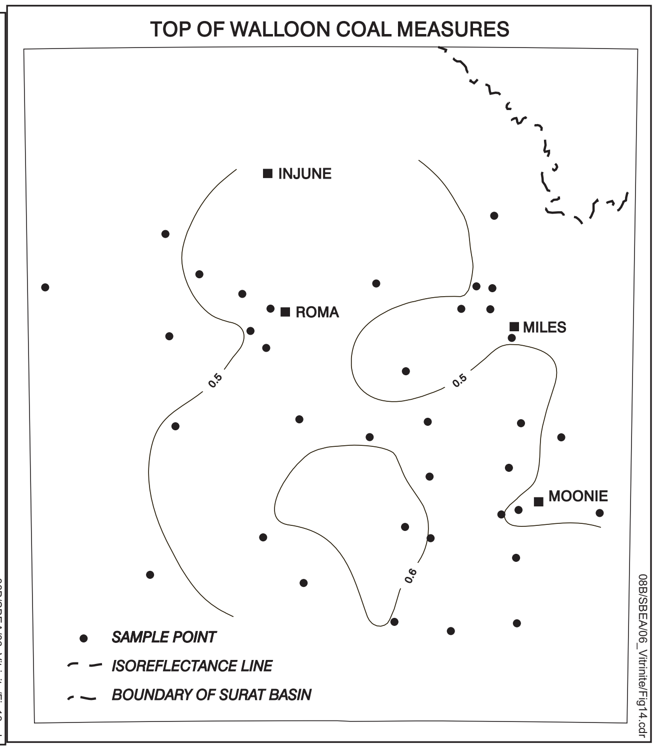

Figure 14: Isoreflectance map for the top of the Walloon Coal Measures.

transgressed to the south-west (Figure 13). Maximum reflectance levels occur in the northern and southern parts of the Taroom Trough, and across the Roma Shelf, increasing to >0.8%. Values decrease to the north-east, north-west, south-east, and particularly to the south-west.

This variation of reflectivity demonstrates that the main depositional effect of the Surat Basin was almost coincident with the underlying Taroom Trough. The high values associated with the Roma Shelf region are interpreted to be caused by granites present in the basement.

Precipice Sandstone – Hutton Sandstone interval

A total of 205 reflectance determinations was obtained from the Precipice Sandstone, the Evergreen Formation, and the Hutton Sandstone in the lower part of the Surat Basin. A maximum of 0.82% recorded from the Precipice Sandstone in the west of the Basin, and a minimum of 0.34% from the Hutton Sandstone in the north of the Basin.

Walloon Coal Measures

The middle section of the Surat Basin includes the Walloon Coal Measures. A total of 126 reflectance values was recorded from the formation, with a range from 0.44-0.70%. Reflectance values for the top of the Walloon Coal Measures vary from 0.4->0.6%. The lowest values are recorded from the west and the east, with a reflectance high occurring in the central-south.

The low range of reflectance values demonstrates regular subsidence over the Basin, with a late Cretaceous depocentre in the central-south (Figure 14). This late stage shift of depocentre has had minimal effect on the total rank variation in the Surat Basin, as demonstrated by the rank depocentre over the Taroom Trough for the base of the Basin.

Westbourne Formation – Griman Creek Formation interval

The Westbourne Formation, Gubberamunda Sandstone, Orallo Formation, Mooga Sandstone, Bungil Formation, Wallumbilla Formation, and Surat Siltstone/Griman Creek Formation in the upper section of the Surat Basin were also investigated.

A total of 129 determinations was made on these formations with a range from 0.30-0.61% (Table 1).

PALEOGEOTHERMAL GRADIENTS THROUGHOUT THE BOWEN BASIN

Deposition during the Early Permian in the southern Taroom Trough was confined to the north-east, with later onlap to the south and east.

Sedimentation became more widespread during the Late Permian with deposition occurring throughout the region of the southern Taroom Trough. During the Early Triassic, clastic and lacustrine deposition occurred in association with a major depocentre that developed in the northern part of the study area.

Isoreflectance lines for the Bowen Basin succession on a cross-section running north-south through the centre of the Taroom Trough show a deepening towards the south in rough parallelism with formations (Figure 5).

In the south, the reflectance lines are presently horizontal, whereas the formations show an abrupt shallowing. As the reflectance lines demonstrate the situation that was present at the time of maximum coalification, it is obvious that the formations shallowed out to the south at that time.

Major thinning of the Early Triassic strata (owing to a disconformity) occurs in the south, such that the overlying Clematis Group/ Moolayember Formation interval shows an overall increase in reflectance results when compared with the north.

Depth-reflectance profiles for the Bowen Basin strata in the north tend to conform with those in the overlying Surat Basin, whereas those in the south show a major jump from the Surat to the Bowen (Figures 15a,b).

The stratigraphy in an east to west cross-section over the southern Bowen Basin (Figure 6) demonstrates the major erosion of the Bowen Basin strata before burial beneath the Surat Basin. Isoreflectance lines in the Bowen Basin are conformable with burial in a north-south trending trough, with rank levels decreasing towards the shallower margins.

In the west, however, the isoreflectance lines tend to parallel the formations. This shows that the formations in this area were horizontal at maximum depth of burial, or that they have been affected by a higher heat-flow from the western basement rocks.

This is further demonstrated in Figure 7, a cross-section from the Roma Shelf in the north-west to the southern Bowen Basin. High geothermal gradients can be seen on the western side of the trough, not just in the Bowen Basin strata but also in the Surat Basin strata, shown by a rapid increase in depth-reflectance values (see also Figure 15). This has resulted in high-rank coals being presently at shallower depths on the western margin than either the centre of the Trough or on the eastern margin.

Such heating would probably have emanated from granites in the basement (Anderson & Koppe, 1976). Conversely, shallow sedimentary rocks overlying basement in the east show only minor effects from basement-induced heating. Higher ranks on the margins are also seen in the north, as shown on Figure 8.

Some of the distortion in the isoreflectance lines observed in the west of this section would also appear to be the result of uplift of the southern Comet Ridge during the Late Triassic. This is comparable with observations on the northern Comet Ridge (Beeston, 1981; 1986), where rank lines show higher values on the Ridge and to the east, than in the west.

RELATIONSHIP BETWEEN THE BOWEN AND SURAT BASINS

Top of Bowen Basin versus base of Surat Basin

The isoreflectance maps for the top of the Bowen Basin (as determined from depth-reflectance profiles in the Bowen Basin), and base of the Surat Basin (as determined from depth-reflectance profiles in the Surat Basin) show considerable differences (Figures 12 & 13). With regard to this relationship between extrapolated reflectance values, there are two main relationships that can be identified:

Type 1. Vitrinite reflectance values extrapolated to the base of the Surat Basin are **less than** *those extrapolated to the top of the Bowen Basin.*

Type 2. Vitrinite reflectance values extrapolated to the base of the Surat Basin are roughly **equivalent**

or greater than *those extrapolated to the top of the Bowen Basin.*

Type 1 situations are generally confined to the western and southern margins, and parts of the eastern margin of the Taroom Trough. These are areas, where uplift and erosion during the Late Triassic have brought high and medium rank Permian and Triassic sedimentary rocks near the surface and were covered by low-rank Surat Basin strata (Figures 4 & 5). This relationship is shown in depth-reflectance profiles in these areas (Figure 15 a-e).

Type 2 occurs in the central parts of the Trough and on the north-east margin. In these areas, high reflectance values in the Surat Basin have 'caught up' (and possibly overtaken) the residual reflectance values in the underlying Bowen Basin, such that the two depth-reflectance profiles coincide or show an 'overlap'(Figures 15f-h). Thus temperature gradients, following the deposition of the Surat Basin, 'over-rode' temperature limits previously experienced (Figure 15g-h).

The physical effects of such a 'second cooking' phase on the reflectivity of the contained coals is not clear, and it remains to be determined as to the impact of such a phenomenon on the potential 'late expulsion' of petroleum from the associated rocks. There are, therefore, two main scenarios for post-Surat Basin depositional coalification, taking into account the depth of Jurassic/Cretaceous burial and the low geothermal gradient during the Mesozoic, as follows:

1.Zero to low increase in coalification of Permian/Triassic coals on the margins of the Trough. Reflectance values of PermianTriassic strata on the margins of the Basin, are, generally, higher than any recorded from the overlying Surat Basin. This suggests that the underlying strata have not received any appreciable effect from coalification during the Mesozoic.

2.Moderate increase of coalification of Triassic strata in the middle of the Trough and in the north-east. Mainly in the centre of the Trough, and other areas where the Bowen Basin sediments have received minimal burial, were not dramatically eroded, and were covered with appreciable thicknesses of Surat Basin strata, there is a case for reactivated coalification to an appreciable depth into the Bowen Basin strata.

An alternative explanation for the apparent higher extrapolated values at the base of the Surat Basin in comparison with the top of the Bowen Basin. This explanation is based on the way the values were determined. The extrapolation of values from the different basins is dependant on the reflectance gradient in the particular basins. The reflectance value at the top of the Bowen Basin as calculated from Bowen Basin data is a reflection of the geothermal gradient and the extent of erosion that has affected that basin and likewise for the Surat Basin.

If the heating event in the Late Cretaceous / Early Tertiary was not of a magnitude capable of raising the level of maturity to values higher than those achieved in the Late Triassic, then the reflectance gradient in the Bowen Basin will reflect the earlier heating event. If the Late Cretaceous event was relatively minor, then the gradient in the Bowen Basin succession will reflect Late Triassic heating. Thus values in the Bowen Basin should always be equal to or greater than those in the Bowen Basin. Values calculated for the Surat Basin/Bowen Basin contact may very depending upon the gradients present in each basin. Only where the Late Cretaceous event is of a magnitude sufficient to increase vitrinite reflectivity through the upper part of the Bowen Basin will values at the contact be expected to be the same. Thus areas on the maps where reflectance values at the top of the Bowen Basin (Figure 12) are less than that at the base of the Surat Basin (Figure 13) are examples of variation in the gradients in the different basins.

BASIN DEVELOPMENT AND MATURATION

The isoreflectance contours for tops of formations in the southern Bowen Basin mirror the present-day structure of the southern Taroom Trough. Also, a common assumption has been that the formations were deposited in a geographic trough, with initial deposition in nearshore/deep water environments followed by extensive fluvial sedimentation. This geographic trough is assumed to have had the north-south orientation of the present-day Taroom Trough.

However, lithostratigraphic studies detailed elsewhere in this report (see also Beeston &

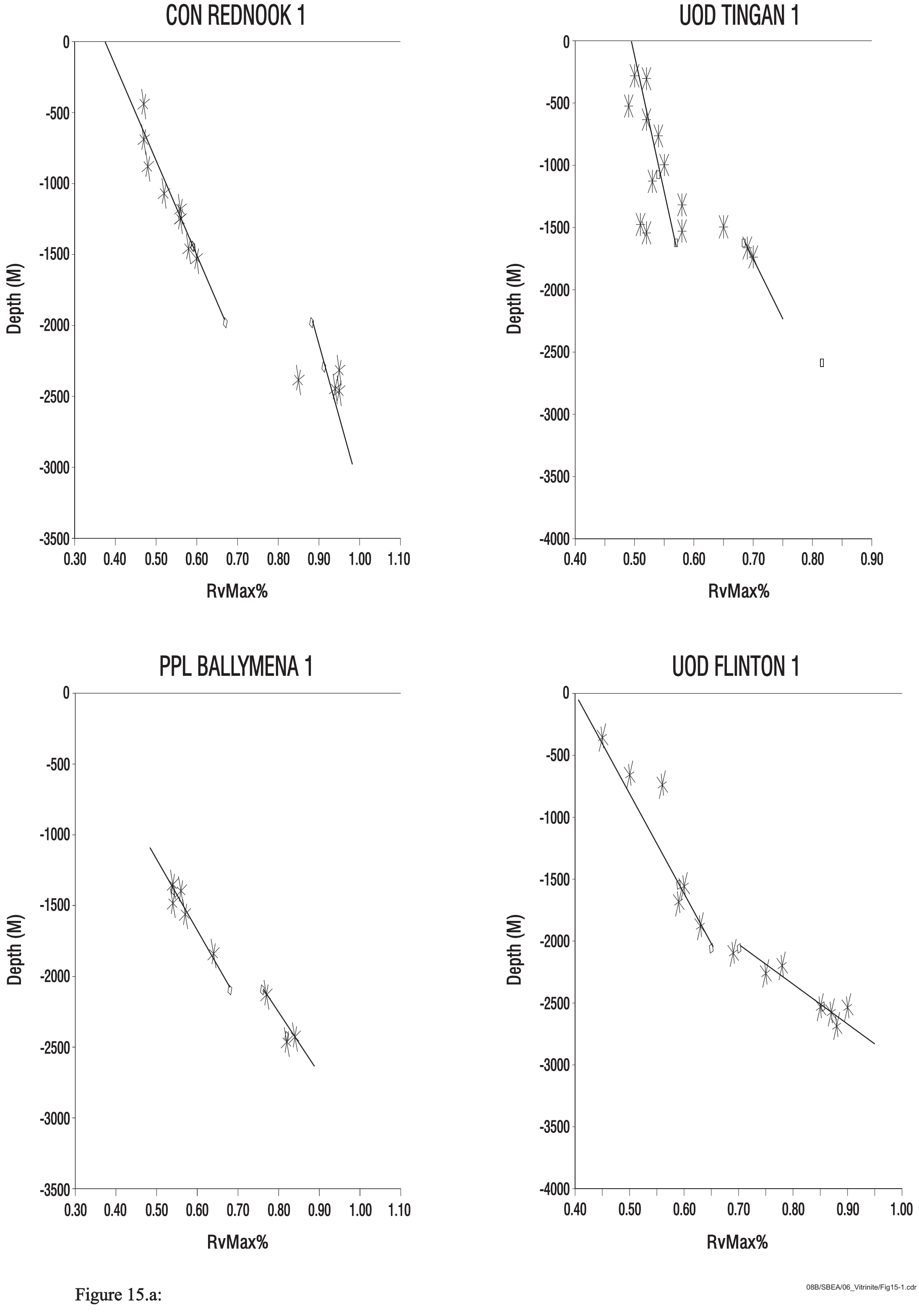

Figure 15-1: Depth-reflectance profiles, Bowen and Surat Basins.

others, 1995) indicate that major subsidence during the early Late Permian occurred in the north-east of the study area whereas little subsidence and deposition occurred elsewhere.

A major transgression during the middle Late Permian led to the widespread deposition of the Banana Formation/Muggleton Formation interval, but at the end of this time, the thickness of Late Permian strata throughout the study area in the southern Taroom Trough did not exceed 500m.

At the onset of post-Banana Formation sedimentation, only the coals in the Buffel Formation and those in the lower Barfield

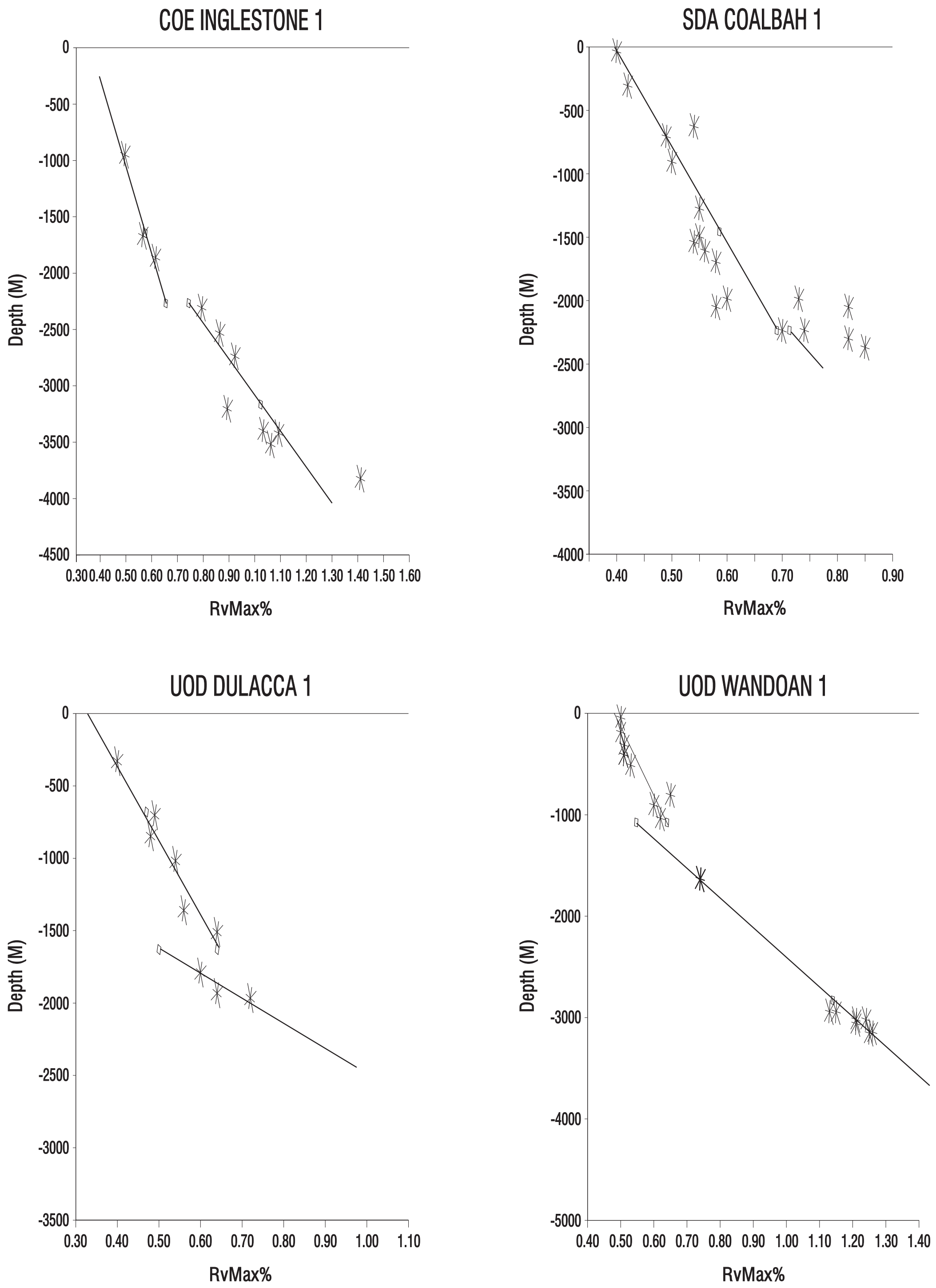

Figure 15.b:

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Figure 15-2: Depth-reflectance profiles, Bowen and Surat Basins.

Formation in the north-eastern part of the study area would have been buried to any appreciable depth, approximately 1700m. Based on the indicated geothermal gradient (from reflectance profiles) in holes in this area, the reflectance levels would have been about 1.0%. Any migration of petroleum generated from these lower coals during the Late Permian probably would have been to the west.

Coals in the Buffel Formation, Barfield Formation and Flat Top Formation in the north-eastern part of the study area, have reflectance values between 0.9 and 1.5%. Extrapolation suggests reflectance values > 2.00% will be present in these units in the axis of the Taroom Trough. Depth-reflectance profiles suggest that the levels of maturation for the formations were probably attained during the maximum accumulation of the Permian- Triassic units.

Therefore, any petroleum migration would have been controlled by the structural configuration of the Taroom Trough during that time. This timing of generation also applies to the coals in the north-east. Deposition of the Late Permian coal measures resulted in a further increase in the burial of the lower coal, approximately 900m, accompanied by a further increase in rank of about 0.3%, due to the increased depth of burial.

During the early Triassic, coals in the Scotia Member and Baralaba Coal Measures were buried beneath a thick pile of terrestrial strata which had a depocentre conforming largely with the present north-south configuration of the Taroom Trough. These coals exhibit reflectance values from 0.4-> 1.6%.

This period of maturation lasted only for a short time, before a major uplift of strata during the late Triassic and erosion in the early Jurassic. Thus, should migr.ation have occurred during the time of Permian- Triassic subsidence, then it can be assumed that migration trends would have been principally controlled by the emerging Trough shape, such that migration would be towards the Trough margins.

During the Middle Triassic, petroleum generation is most likely to have occurred in the north and central parts of the Taroom Trough when the Bowen Basin was most deeply buried. Hydrocarbons migrating from these areas then could have been trapped within the source or adjacent rocks, or along the westerly, easterly or southerly margins of the trough. Suitable reservoirs would have been confined to early Triassic strata, particularly sandstones in the Rewan Group.

The Bowen Basin was covered by the Surat Basin with the maximum depth of burial probably occurring in the Late Cretaceous. This increased burial is reflected in a wide spread thermal event that was the most significant influence for hydrocarbon generation (Raza & others, 1989). This is consistent with the character of the reflectance profiles in the southern part of the study area (Figure 15).

The additional hydrocarbons generated were sufficient to result in expulsion and migration into the overlying Triassic and Jurassic reservoirs particularly from the centre of the Trough. This is the major phase of hydrocarbon migration in the area. This timing is consistent with the timing of hydrocarbon generation and migration proposed by Boreham & others (1996).

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HYDROCARBON GENERATION POTENTIAL AND SOURCE ROCK DISTRIBUTION IN PERMIAN AND TRIASSIC ROCKS, SOUTHERN TAROOM TROUGH, QUEENSLAND

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INTRODUCTION

A regional source rock evaluation of the Permian and Triassic sedimentary rocks in the southern Taroom Trough, Bowen Basin has been undertaken as part of the National Geoscience Mapping Accord (NGMA) project: 'Sedimentary Basins of Eastern Australia'. The source rock evaluation was a joint Queensland Department of Minerals and Energy (QDME) and Australian Geological Survey Organisation (AGSO) project.

Results from Rock-Eval pyrolysis and TOC analyses have been used to determine the hydrocarbon source potential of the Permian and Triassic mudstones and coals in the southern Taroom Trough. The area of this evaluation is between latitudes 25°S and 29°S and longitudes 149°E and 151°E (Figure 1).

The Permian rocks in the southern Taroom Trough have long been attributed as a source for the oil, condensate and gas found in the Permian, Triassic and Jurassic reservoirs of the Bowen and Surat Basins. The aim of this evaluation was to show evidence that the Permian and also the Triassic rocks of the southern Taroom Trough are capable of producing hydrocarbons, as well as delineating areas that have produced hydrocarbons, the types of hydrocarbons produced, and in what quantities. Mudstones and coals from all the Permian formations and from the Triassic Moolayember Formation, including the Snake Creek Mudstone Member were sampled and analysed.

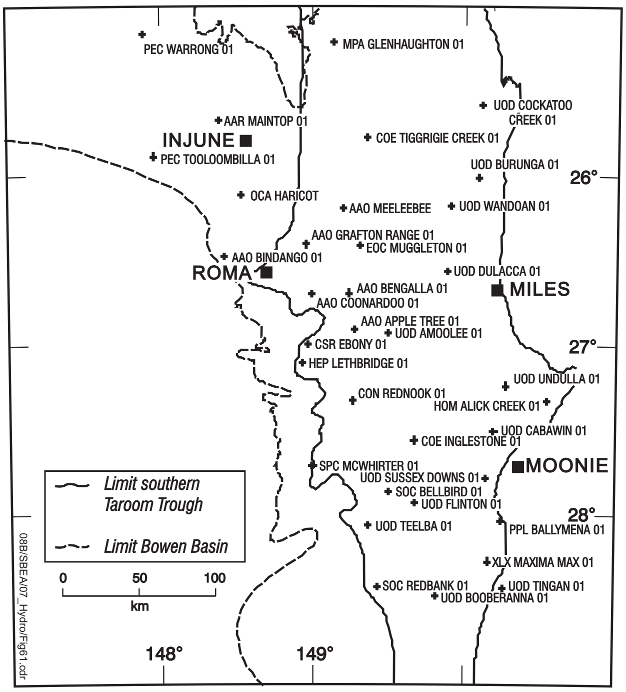

Figure 1. Well location map showing limits of the southern Taroom Trough and the Bowen Basin.

HYDROCARBON OCCURRENCES

Oil, condensate and gas occur in the southern Taroom Trough of the Bowen Basin and in the overlying Surat Basin. The first discovery of gas in Queensland was in a water bore drilled at Hospital Hill, Roma in 1900, and the first commercial discoveries were made at Timbury Hills and Pickanjinnie near Roma in 1960. The first commercial oil discovery in Australia was by Union Oil Development Corporation at Moonie in 1961, from the Surat Basin. Since the 1960's, exploration for oil and gas has taken place throughout the project area. The southern Taroom Trough and Surat Basin supply oil and gas to south-east Queensland through the Jackson-Moonie oil pipeline and the Roma-Brisbane gas pipeline. Gas is also supplied to Gladstone from Wallumbilla and the Denison Trough by the State Gas Pipeline.

The hydrocarbon occurrences in the southern Taroom Trough and overlying Surat Basin are shown in Figure 2. The hydrocarbons are found along the western and eastern edges of the Trough with the majority of the occurrences along the western edge. The largest oil field in the region is at Moonie in the south-east. The western edge of the Trough is characterised by the onlap of the Permian, Triassic and Early Jurassic sediments onto the basement rocks. The eastern edge is largely controlled by westward thrust faults. The hydrocarbons are found in fractured basement, Permian, Triassic and Jurassic reservoirs.

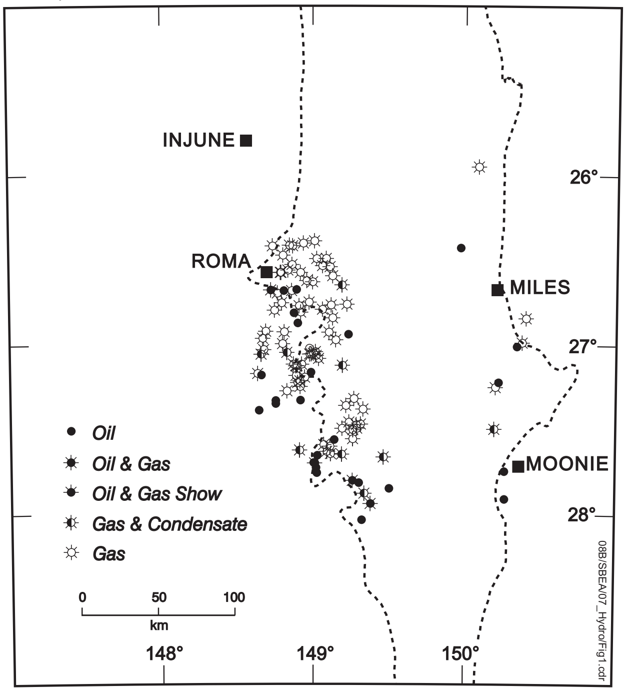

Figure 2. Hydrocarbon occurrences in the southern Taroom Trough and overlying Surat Basin.

Boreham (1994, 1995), measured the effective maturity of the oils on the western and eastern sides of the Trough and found a trend of decreasing maturity away from the axis of the Trough. This inferred that generation has occurred in the deeper parts of the Trough and over a wide maturity range. The initially generated oil has migrated the furthest to fill Jurassic reservoirs whereas a more mature oil is reservoired closer to the axis of the Trough.

This process involves considerable migration pathway lengths with movement direction of the hydrocarbons up-dip and up faults until a good seal is met. The main reservoirs in the region are the Middle Triassic Showgrounds Sandstone of the Bowen Basin and the Early Jurassic Precipice Sandstone of the Surat Basin. Hydrocarbons are also found in sandstone horizons of the Permian and other Triassic and Jurassic formations.

Most of the oil and condensate occurrences are between latitudes 27°S and 28°S; gas is dominant over the Roma Shelf and further north. Korsch (personal communication) suggest that there were two main periods of deep burial, Late Triassic and Late Cretaceous. During the Late Triassic burial event, the oil-prone source rocks in the north of the project area would have been buried deep enough to have generated oil and condensate but not deep enough for the generation of gas. During the same Late Triassic event, the oil-prone source rocks in the south would not have been buried deep enough to have begun generation of hydrocarbons. Subsequent uplift and erosion or breaking of the seals would have allowed any hydrocarbons that may have been generated in the Late Triassic to escape. The Late Cretaceous burial event was sufficient to generate hydrocarbons in both the northern and southern parts of the Trough.

Oil, condensate and gas would have been generated in the south but in the north, the source rocks had only a remaining potential for gas generation. This Late Cretaceous generation event accounts for the present-day hydrocarbon occurrences and explains why oil and condensate are associated with gas in the south and gas is present in the north. An alternative but less likely explanation for the distribution of hydrocarbons is that the source rocks are mainly gas-prone in the north and liquids-prone in the south.

PREVIOUS GEOCHEMICAL INVESTIGATIONS

In the last 15 years, several organic geochemistry investigations into the origin of the hydrocarbons in the southern Taroom Trough have been performed using modern analytical techniques (Thomas & others, 1982; Hawkins & others, 1992; Boreham, 1994, 1995).

Thomas & others (1982) used Rock-Eval pyrolysis analyses, vitrinite reflectance measurements and maceral analysis on samples from 17 wells to assess their source potential, and used extracts for oil/source correlations. They concluded that the Walloon Coal Measures was thermally immature, the Evergreen Formation was early mature and that the Moolayember Formation was in the oil generation zone in the north. The Permian was considered to be the main source of the hydrocarbons. They did not specify which Permian formations generated hydrocarbons and did not describe the source richness, or whether gas, oil or condensate was generated. They suggested that the onset of significant oil generation only occurred when organic maturity levels with vitrinite reflectance values between 0.7 to 0.8 had been reached.

Hawkins & others (1992) examined selected source rocks and oil samples from 17 wells in the southern Taroom Trough. They concluded that the Permian Blackwater Group was the most favourable source rock interval with restricted potential in the Permian Back Creek Group and the Triassic Moolayember Formation. The Blackwater Group was considered a potential oil source with the Back Creek Group generally gas prone. The Moolayember Formation was oil prone but was mostly immature for oil generation. In their evaluation they used 0.7% Ro as the beginning of oil generation.

Boreham (1994, 1995), in an analysis of over 80 gas, condensate and oil samples and 130 core samples, used a combination of biomarker and carbon isotope signatures to constrain the source for the oil and gas to the Permian rocks. A localised and very minor Triassic contribution was also recognised. Using the chemical maturity parameters based on MPI-1 for liquids and $^{13}C/^{12}C$ ratio for gases, a calculated vitrinite reflectance (Rc) was obtained which allowed for an extrapolation to the maturity of the source at the time of primary migration. The effective maturity for the oils and condensates falls between 0.65% and 1.05% Rc and for the gases between 1.05% and 1.4% Rc.

METHODS

SAMPLING

Cuttings samples were used for the source rock analyses because they provide the only consistent representative record of all rock units within the study area. Sidewall cores and conventional cores were not included as their availability could only provide spot samples resulting in an incomplete regional picture.

However, cores were used in a complimentary oil-to-source rock correlation study (Boreham, 1994, 1995).The samples collected were composite cuttings samples with the maximum sample interval at 50m. An equal amount of cuttings (5 grams) was taken from each bag (typically covering a 3m or 10ft depth interval) for the composite samples. The percentages of mudstone, siltstone, sandstone and coal were estimated visually for each composite sample. In some wells, individual coal horizons were sampled.

The main disadvantage using cuttings is the possibility of contamination from cavings of material from higher up the hole. To this end, Rock Eval and TOC analysis on the cores (Boreham, 1994, 1995) proved to be essential in 'calibrating' and testing the integrity of the cuttings data. The pyrolysis results from identified contaminated samples due to cavings have been removed from the data set.

Contamination from oil-based drilling muds has been identified in some samples from two wells; COE Tiggrigie Creek 1 and UOD Wandoan 1. The results from these contaminated mudrock samples also were not used in the interpretations.

Prior to analysis using Rock-Eval pyrolysis, the mudstones, siltstones and coals were separated from the composite cuttings samples by hand-picking, and analysed individually. Similar analytical results were obtained for the mudstones and siltstones and hereafter both rock types were collectively referred to as 'mudstone'. After contaminated samples were removed from the data set there were valid analyses for over 330 mudstone and 170 coal samples.

STRATIGRAPHIC CONTROL

Stratigraphic control on the sampling of the Bowen Basin units was maintained using the stratigraphy given in Beeston & Green (1995). The 34 petroleum wells which intersected this basin in the network of lithostratigraphic correlation lines were sampled. The location of these wells is shown in Figure 1.

The Permian rocks were divided into four informal 'groups', the "Flat Top", "Banana", "Burunga" and "Baralaba".

The "Flat Top" group consists of the Buffel Formation, Barfield Formation, Flat Top Formation and the undifferentiated Back Creek Group. The Buffel Formation comprises marine deposited mudstones, sandstones and limestones. The Flat Top Formation, Barfield Formation and undifferentiated Back Creek Group comprise marine deposited sandstones and mudstones and deltaic deposited coals and associated mudstones and sandstones.

The "Banana" group comprises the Banana Formation and the Muggleton Formation which are mainly a marine mudstone succession.

The "Burunga" group comprises the Burunga Formation (including the Scotia Coal Member), the Wiseman Formation, the Tinowon Formation and the Black Alley Shale. This group represents a mixed fluvial, fluvial-deltaic and marine succession of coals, sandstones and mudstones and is characterised by the presence of tuffs and marine fossils.

The "Baralaba" group comprises the Baralaba Coal Measures and the Bandanna Formation. These are terrestrial coals, mudstones and sandstones which lack marine fossils. Tuffs are present near the bottom of these formations.

The Triassic units sampled were the Moolayember Formation, including the Snake Creek Mudstone Member at its base.

MASS BALANCE APPROACH

Cooles & others (1986) quantified petroleum potential in terms of petroleum generated and expelled. The insoluble organic matter within the rock, termed kerogen, is defined in three simplified types. Labile kerogen is capable of producing oil and gas, refractory kerogen generates dominantly gas while inert kerogen has no hydrocarbon generative potential. To represent petroleum generation, a simple algebraic scheme, based on organic carbon mass-balance was devised (Figure 3).

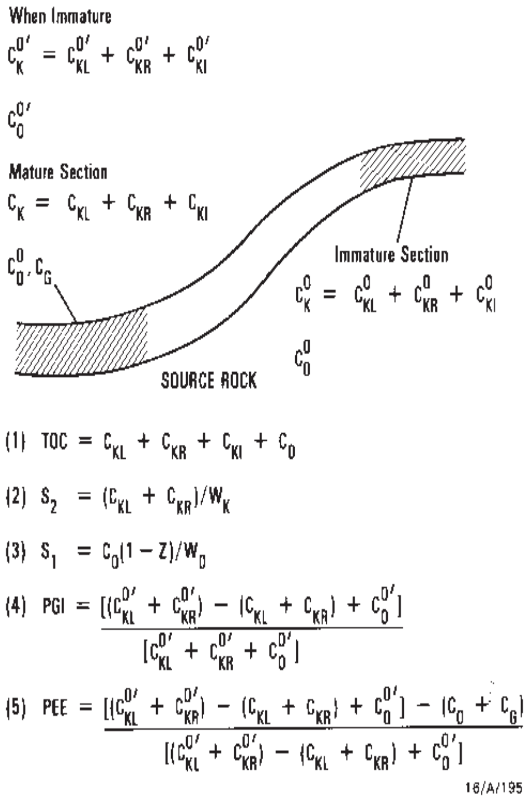

Figure 3. Algebraic scheme used to calculate amounts of hydrocarbons generated and expelled (Cooles et al, 1986). C_K = mass concentration of carbon in kerogen; C_{KL}= mass concentration of carbon in labile kerogen; C_{KR} = mass concentration of carbon in refractory kerogen; C_{KI} = mass concentration of carbon in inert kerogen; C_O = mass concentration of carbon in oil; C_G = mass concentration of carbon in gas; TOC = total organic carbon; S_2 = pyrolysable hydrocarbons from Rock Eval analysis; S_1 = free hydrocarbons from Rock Eval analysis; W_K = proportion of C in kerogen; W_O = proportion of C in oil; Z = correction for loss of light hydrocarbons. PGI = Petroleum Generation Index. PEE = Petroleum Expulsion Efficiency.

A carbon deficit in a mature source rock compared with its immature analogue, implies that carbon has been lost by migration from the source rock. The carbon content of an immature source rock is divided between free-oil carbon, reactive carbon (labile plus refractory kerogen) and inert carbon. The free oil content can be determined from either Rock Eval S1 or from solvent extractable organic matter and corrected for heavy-end and light-end hydrocarbon losses, respectively (Cooles & others, 1986). The reactive carbon is determined from Rock Eval S2, and the inert carbon is the difference between TOC content and the sum of the free oil carbon and reactive carbon. A similar proportioning of carbon is done for the mature correlative. However, to compare the mature and immature source rocks, it is assumed that there is a common starting point for both and that there is no loss or additions to the inert carbon content as the source rock follows its evolutionary path of maturation.

Certainly this latter fundamental assumption is not true in laboratory pyrolysis experiments where coking and char formation occur. However, these experiments probably over-estimate similar processes at geological temperatures (Boreham & Powell, 1994 and references therein).

As sedimentary rocks have variable TOC contents, the inert carbon content in the mature analogue is normalised to the inert carbon content of the immature analogue. Applying this normalisation factor to correct free-oil and reactive carbon in the mature analogue enables a calculation of the Petroleum Generation Index (PGI) and the Petroleum Expulsion Efficiency (PEE), which are defined as follows:

$$PGI = \frac{\textit{Petroleum generated} + \textit{Initial petroleum}}{\textit{Total petroleum potential}}$$

$$PEE = \frac{\textit{Petroleum expelled}}{\textit{Petroleum generated} + \textit{Initial petroleum}}$$

PGI defines the proportion of the total petroleum potential (free oil plus reactive kerogen in the immature rock) that has been generated from the source rock at various stages of maturity. PEE is a measure of the extent of expulsion and relates to the difference between the calculated amount of petroleum that is liberated at a PGI value and the amount of petroleum actually retained in the source rock.

CALIBRATION OF HYDROGEN INDEX WITH PETROLEUM COMPOSITION

Rock Eval analysis indicates the hydrocarbon potential of the organic matter, but it gives little insights into the petroleum composition and gas-to-oil ratios (Boreham & Powell, 1994 and references therein). This information can be obtained in more detail using pyrolysis-gas chromatography (Boreham & Powell, 1994). Figure 4 shows the pyrolysate composition, in terms of fractions of C_1-C_5 total hydrocarbons,

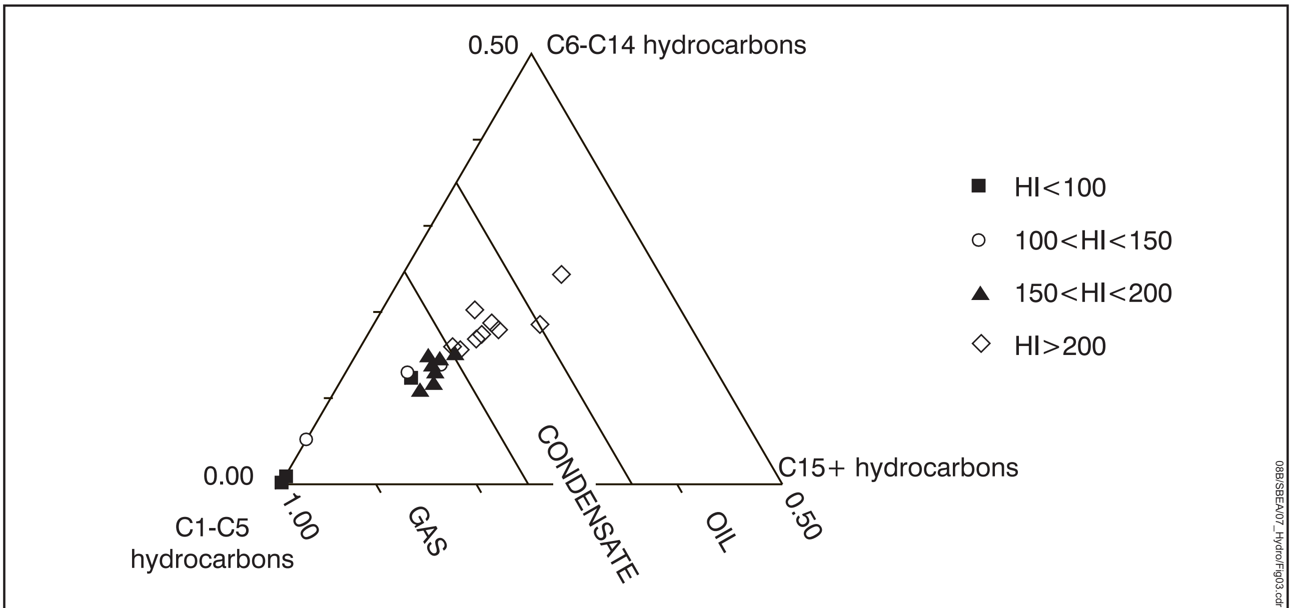

Figure 4. Pyrolysate composition, from pyrolysis-gas chromatography, for Bowen Basin coals with different HIs, with their inferred petroleum product.

C_6-C_{14} *n*-alkanes and C_{15+} *n*-alkanes for various Bowen Basin coals with different hydrocarbon generation potentials (HI's). Superimposed on the triangular plot is the inferred petroleum product that would be generated from the organic matter under natural conditions. The 'cut off' lines are based mainly on results from northern hemisphere rock types. A recalibration may be necessary for Australian rocks with terrestrial organic matter. However, there is a general trend to higher gas content with decreasing HI's. For this investigation the following standards were applied:

- HI>200mg hydrocarbons /gTOC; potential to generate oil
- 150<HI<200mg hydrocarbons /gTOC; potential to generate condensate/wet gas
- 100<HI<150mg hydrocarbons /gTOC; potential to generate gas with minor condensate
- HI<100mg hydrocarbons /gTOC; minor to no gas potential.

In the application of these standards it should be realised that the fields are defined from a limited data set and that for different types of organic matter the composition of the generated hydrocarbons can be different although they may have the same HI values. Furthermore, during the maturation process

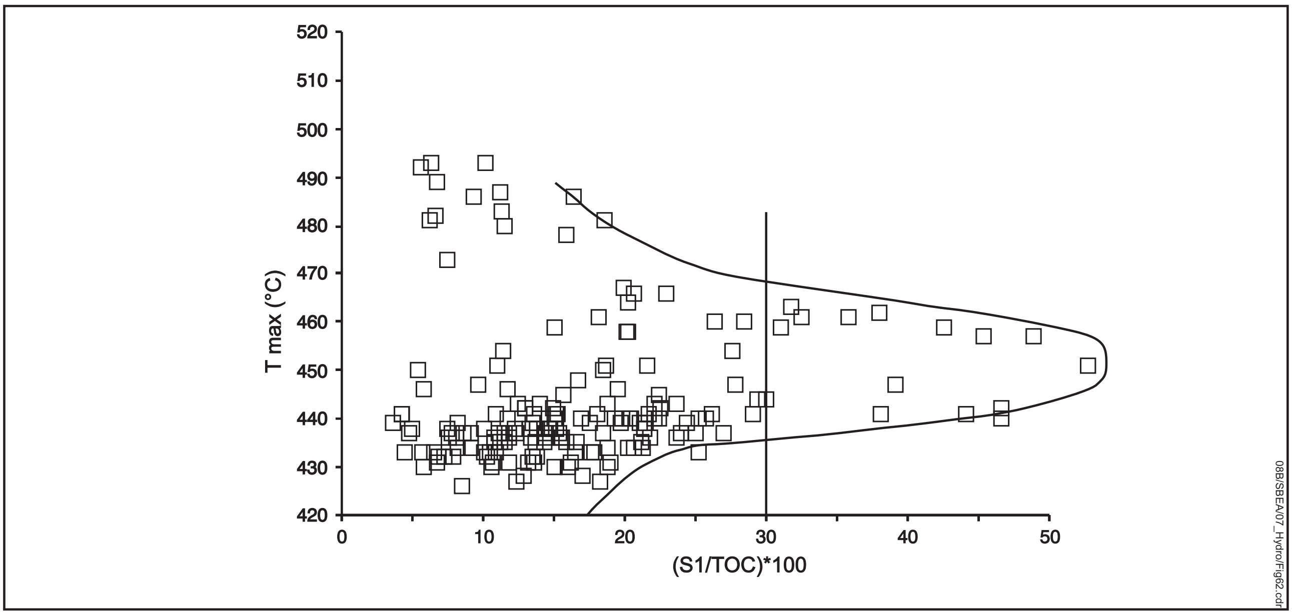

Figure 5. Effective oil window for coals in the southern Taroom Trough is between Tmax 440°C and 470°C.

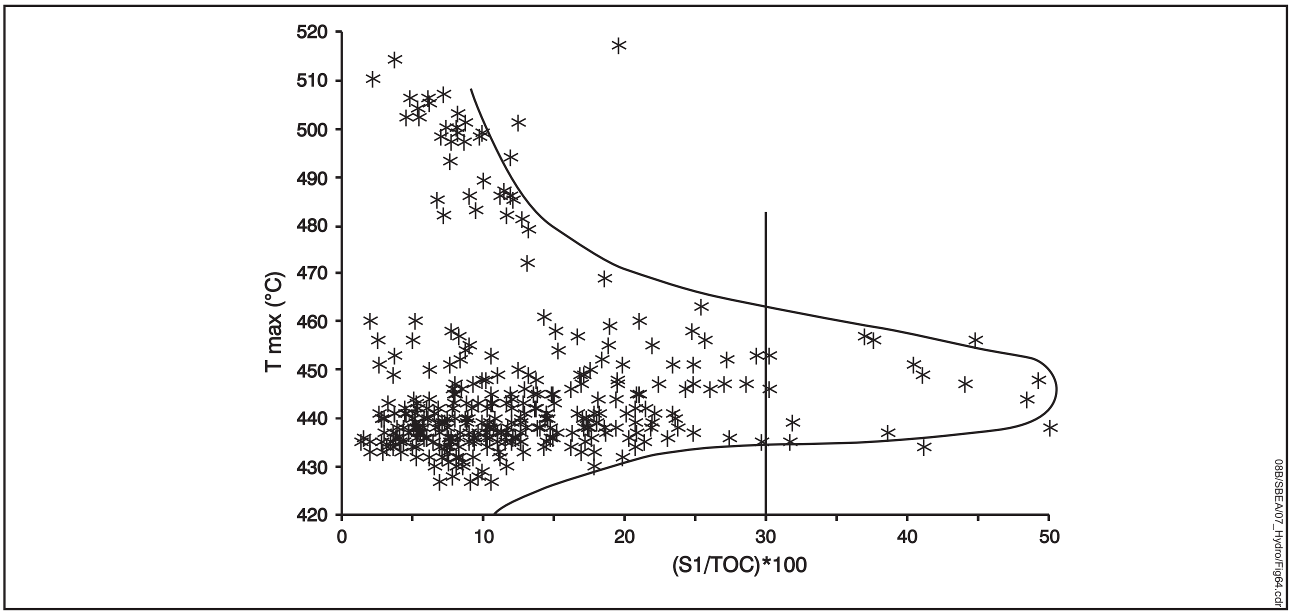

Figure 6. Effective oil window for mudstones in the southern Taroom Trough is between Tmax 435°C and 465°C.

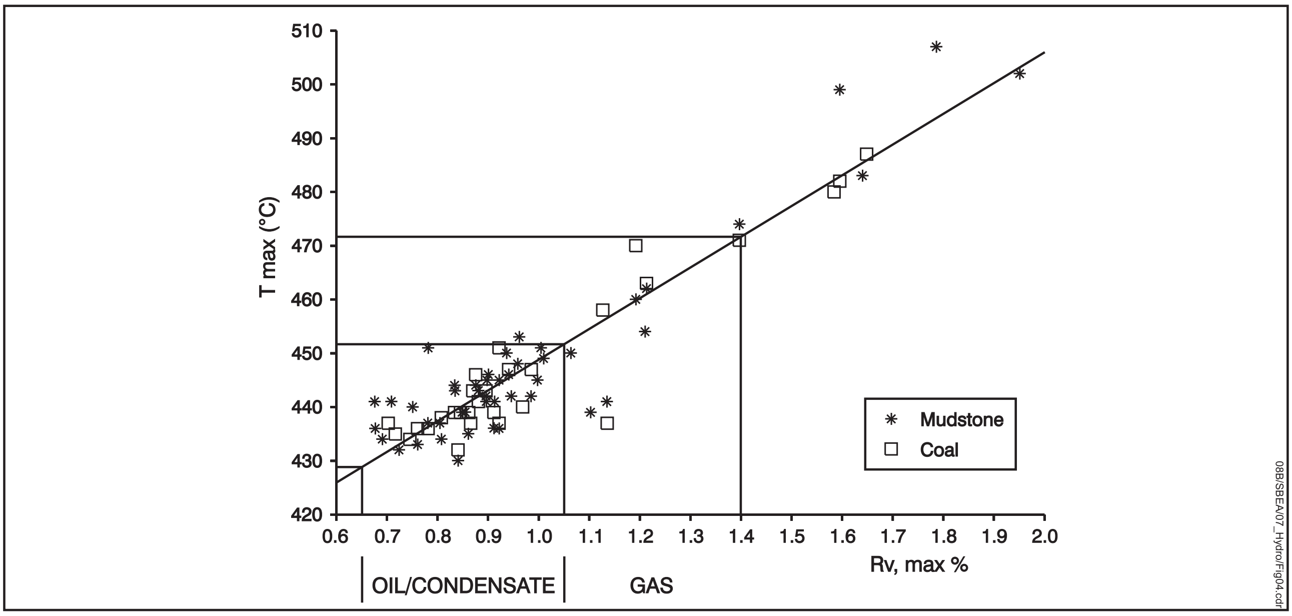

Figure 7: Average Tmax versus Rv,max for the mudstones and coals for each Permian group sampled in the southern Taroom Trough.

the compositions of the evolved hydrocarbons will change (Boreham & Powell, 1994 and references therein). The change can be gradual or abrupt at certain maturity levels so that the 'cut off' maturities used to define the end of liquids and beginning of gas generation in the subsequent discussions should be taken as only approximate.

CALIBRATION OF MATURITY PARAMETERS

Using extract yield and Tmax data from core material, and the good linear relationship between Tmax and Rv,max for the Rangal Coal Measures, Boreham (1994) was able to show that the 'oil window' occurred between Tmax of 440°C and 470°C, with Rv,max of 0.7% to 1.3%. These maturity ranges for oil generation are similar to those proposed previously for organic matter in the Taroom Trough (Thomas & others, 1982; Hawkins & others, 1992).

These relationships are further supported from the plots in Figures 5 and 6. Using a cut-off value of 30mg hydrocarbons/gTOC for 100°S1/TOC, which indicates petroleum generation and primary migration, the effective oil window for the coals is between a Tmax of 440°C to 470°C. Boreham (1994) used the same cut-off value using solvent extracts. For the mudstones, the Tmax range is offset to lower values by a few degrees compared with the coals which may reflect the higher mobility of liquids in the former.

Figure 7 shows the plot of average Tmax values against the measured or extrapolated Rv,max at the average depth for each Permian group. For Tmax >445°C, there exists a strong linear relationship. However, for Tmax<445°C a linear correlation with Rv,max is less certain. Here an increase in Rv,max corresponds to no or little change in Tmax. Thus it is not possible to pinpoint the onset of petroleum generation with any degree of certainty, from this style of data alone.

RESULTS

Figure 8 shows the TOC frequency plot for all the mudstones. Values with TOC>1.0% can be considered to have good source potential if there is good quality kerogen, and values with TOC>2% are considered to have a very good source potential. The plot shows most TOC values fall within the 0.5% to 2.0% range indicating a source potential from fair to good. The Moolayember Formation and 'Burunga' group have their highest TOC frequencies in

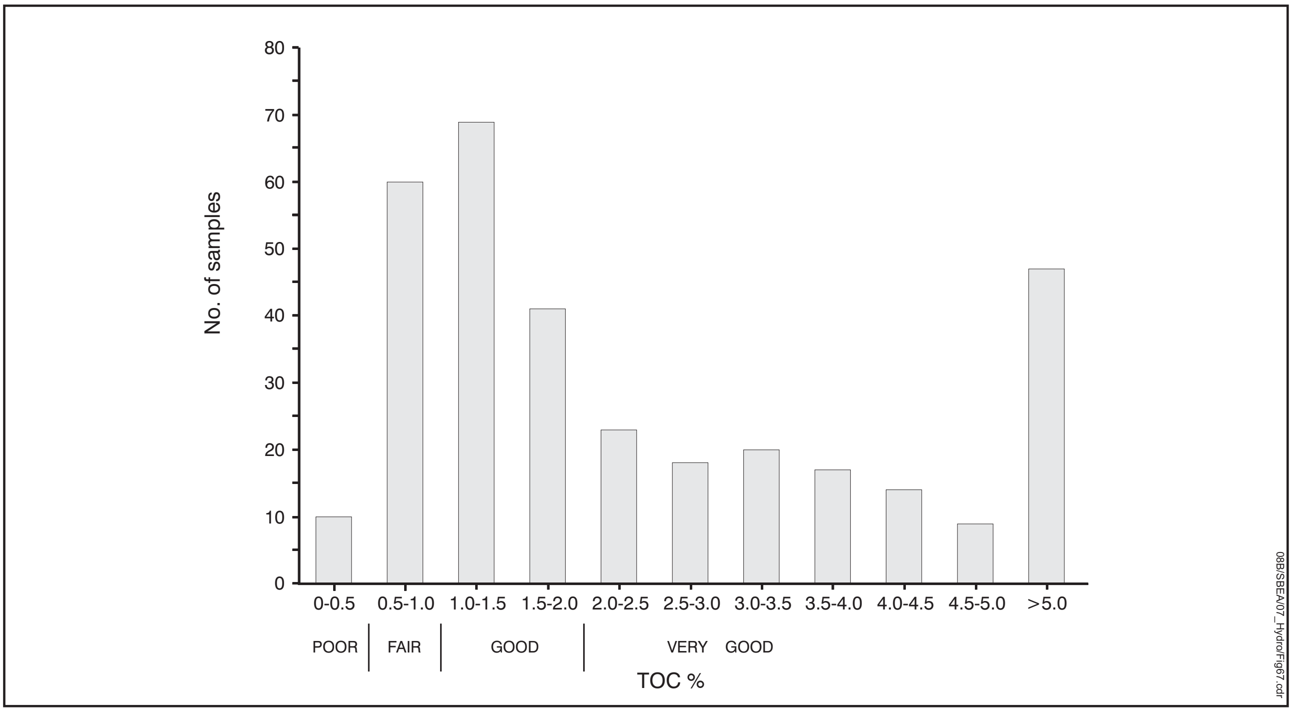

Figure 8: Frequency plot, TOC% for mudstone samples.

the range 0.5% to 2.5%, indicating a fair to very good source potential. The 'Baralaba' and 'Banana' groups have a lesser source potential ranging from fair to good, with the highest TOC frequencies from 0.5% to 1.5%. The relatively small number of samples taken from the "Flat Top" group makes interpretation of a frequency plot more difficult. The highest frequency of TOC values falls in the 0.5% to 2.0% range but there are a number of samples with TOC values up to 4.5%. Pyrolysis results for samples with less than 0.5% TOC and Tmax values from samples with low S2 values (generally less than 0.15mg HC/g rock) were not used.

Tmax versus depth cross plots were produced for each well to identify contaminated samples due to cavings. Those samples that had Tmax values significantly lower than the rest for a particular well were considered to be contaminated. Hydrogen Index versus depth cross plots were also used to identify contaminated samples. The samples with Hydrogen Index values significantly higher or lower than the other values for the same well were interpreted to be contaminated.

In each well, average Rock-Eval pyrolysis results were calculated for each of the formations sampled. The results were calculated as proportional averages dependent on the thickness sampled. The formula used is shown as follows:

$$\textit{Average value} = \frac{\textit{Sum of (analytical result} \times \textit{sampled mudrock thickness)}}{\textit{Total sampled thickness}}$$

Carbon mass balance calculations were performed to calculate the proportion of petroleum that has been generated with the PGI and PEE being determined. This technique is only possible if there exists a wide range of maturities and an immature analog for each unit.

Effective thicknesses for the mudstones and coals for the Permian 'groups' have been calculated using the observed percentages of the rock type multiplied by the sampled depth range. For these groups of samples it was found that the Rock-Eval pyrolysis results did not significantly differ between the mudstones and the siltstones. Hence the effective thicknesses for the mudstones and siltstones are referred to as mudstone thicknesses.

Source rock quality and maturity as well as generation and expulsion for the various groups and units are as follows:

'FLAT TOP' GROUP

Source Rock Quality and Maturity

The 'Flat Top' group has two potential source rocks, mudstones and coals. A plot of the HI versus Tmax values for both rock types

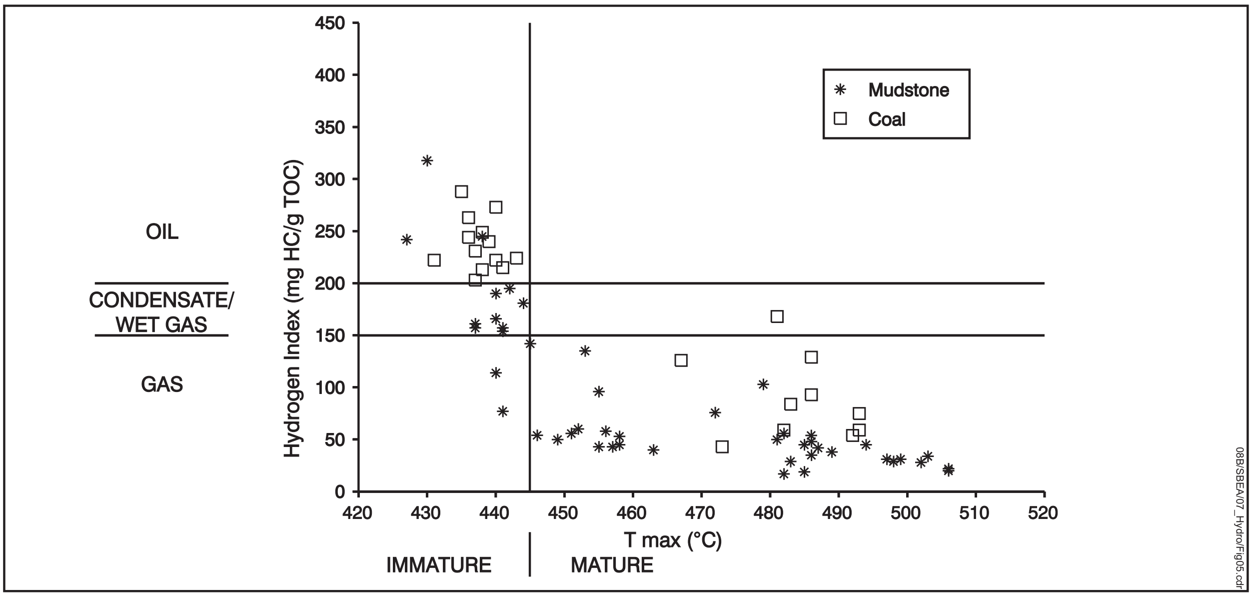

Figure 9: HI versus Tmax plot for mudstones and coals in the 'Flat Top' group.

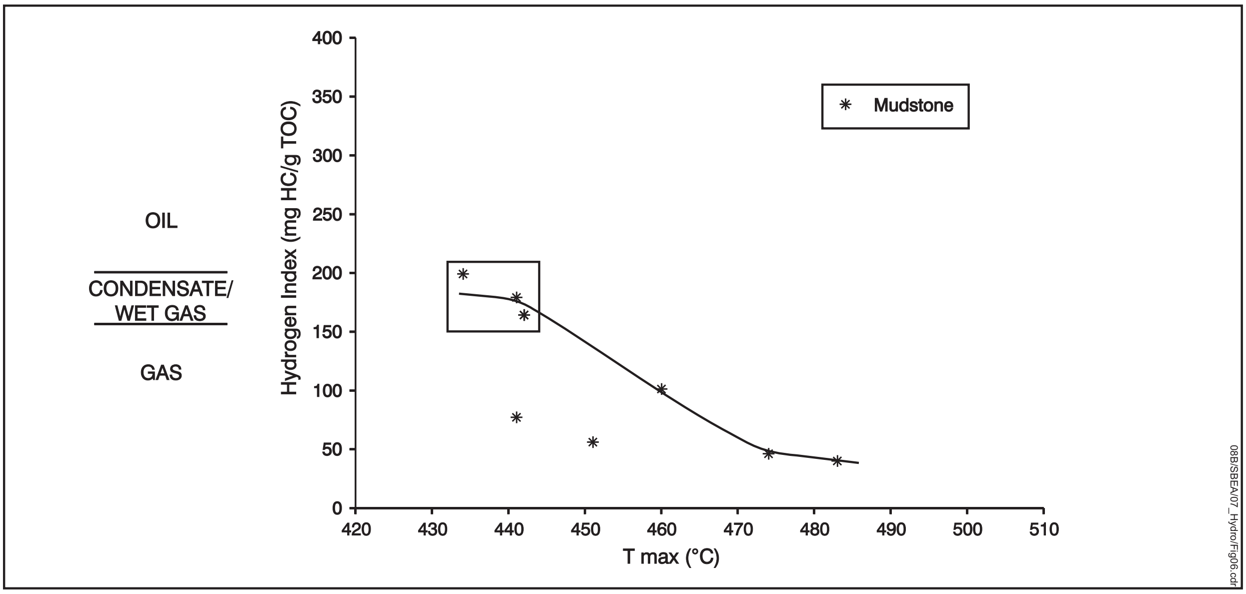

Figure 10: Average HI versus average Tmax values for the mudstones from each well intersecting the 'Flat Top' group.

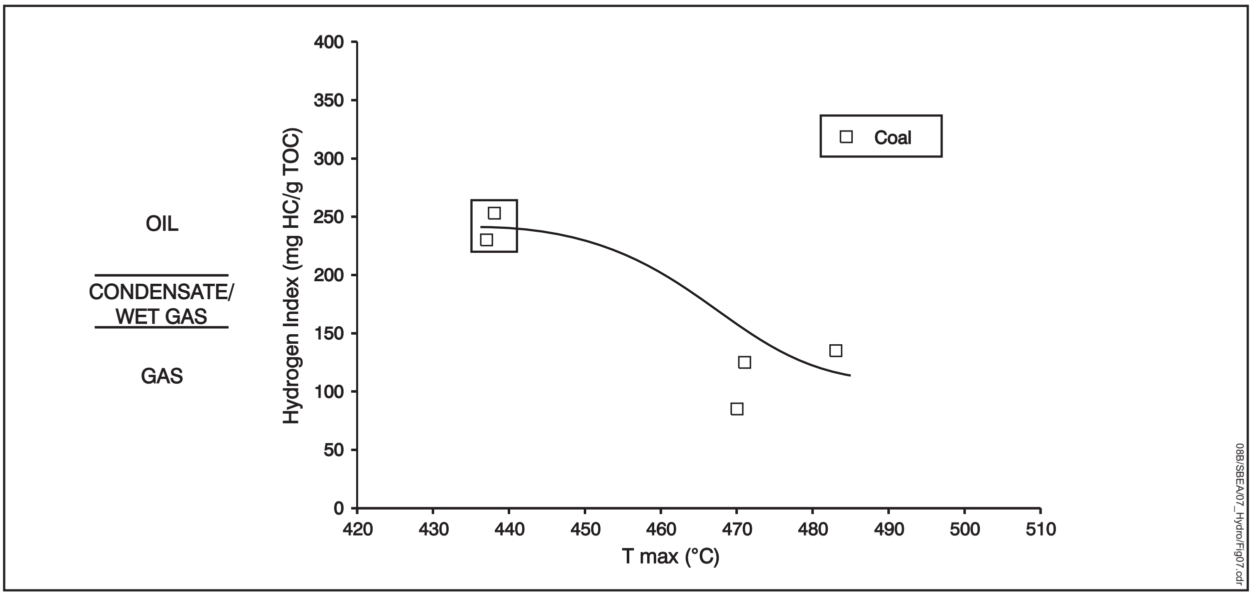

Figure 11: Average HI versus average Tmax values for the coals from each well intersecting the 'Flat Top' group.

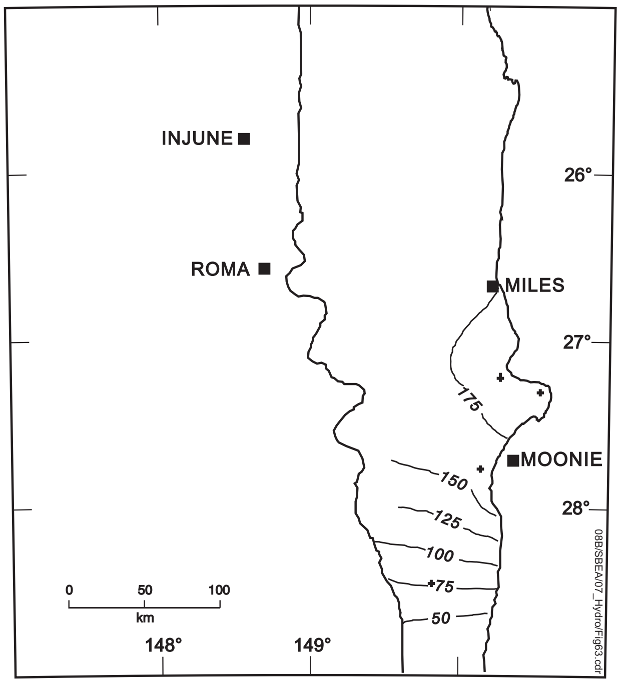

Figure 12: Initial HI values for mudstones *in the 'Flat Top' group.*

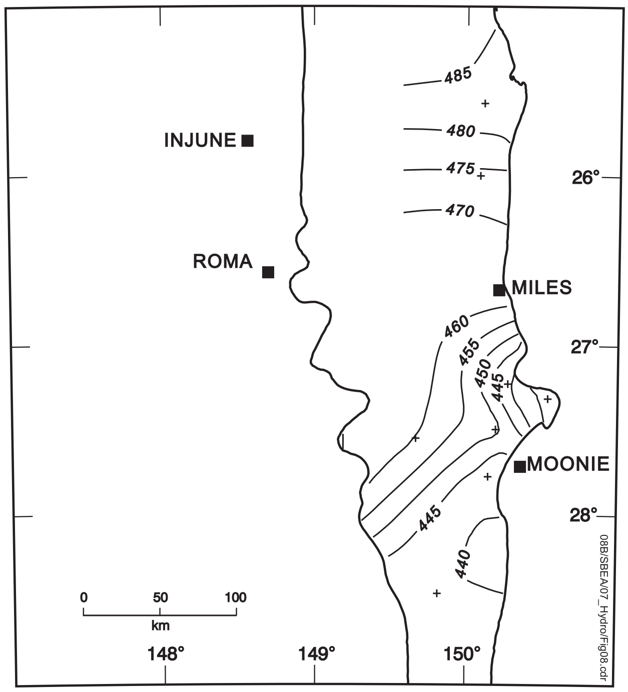

Figure 13. Tmax values for mudstones in the 'Flat Top' group.

(Figure 9), characterises the source potential of this unit. Both rock types show a trend to higher Hydrogen Index (HI) values for Tmax<445°C and low HI's for Tmax>445°C. Thus, at approximately Tmax 445°C there is a downwards inflection of the hydrocarbon evolution curve joining the maximum HI values over the full Tmax range. The onset of hydrocarbon generation is interpreted where the decrease in HI begins and continues, as Tmax increases. However, the exact maturity level where hydrocarbon generation begins may be slightly lower because HI can increase at the onset of petroleum generation for Type III kerogen due to preferential generation of heteroatom compounds (Boreham & Powell, 1994 and references therein). To compare present source qualities, only those samples that have not started generation of hydrocarbons can be used.

The HI values for samples with Tmax less than 445°C are mostly in the 150 to 300mg HC/g TOC range which indicates gas to liquids potential. One mudstone sample from HOM Alick Creek 1 has a HI greater than 300mg HC/g TOC suggesting that there are isolated patches of better liquids source potential. For the same Tmax values, the coals generally have higher HI values than the mudstones.

Average HI and Tmax values for the mudstones from each well were calculated and plotted in Figure 10. One well, UOD Booberanna 1 had a lower HI value (HI<100mg HC/g TOC) than the

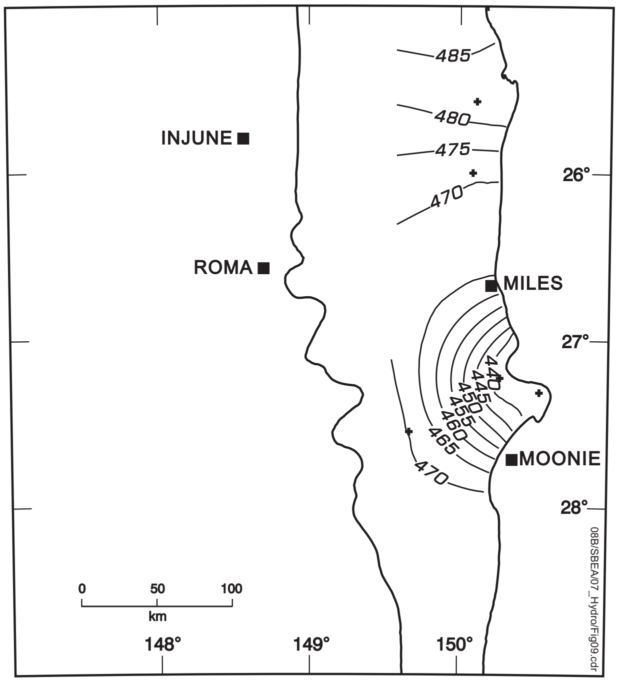

Figure 14: Tmax values for coals in the 'Flat Top' group.

average trend for the immature wells and the data from the well was not included in the mass balance calculations. The lower HI value for this well may be due to reworking and oxidation of the organic matter. The immature wells are HOM Alick Creek 1, UOD Undulla 1 and UOD Sussex Downs 1. The wells that have begun generation are UOD Cabawin 1, COE

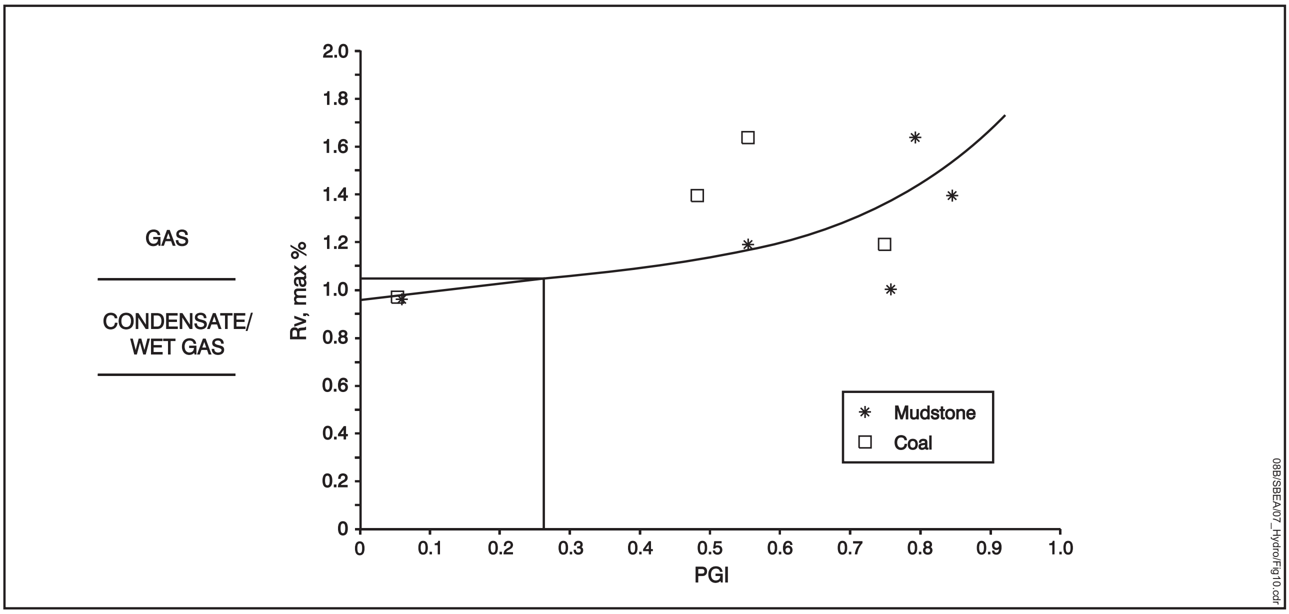

Figure 15. PGI versus Rv,max plot for mudstones and coals in the 'Flat Top' group.

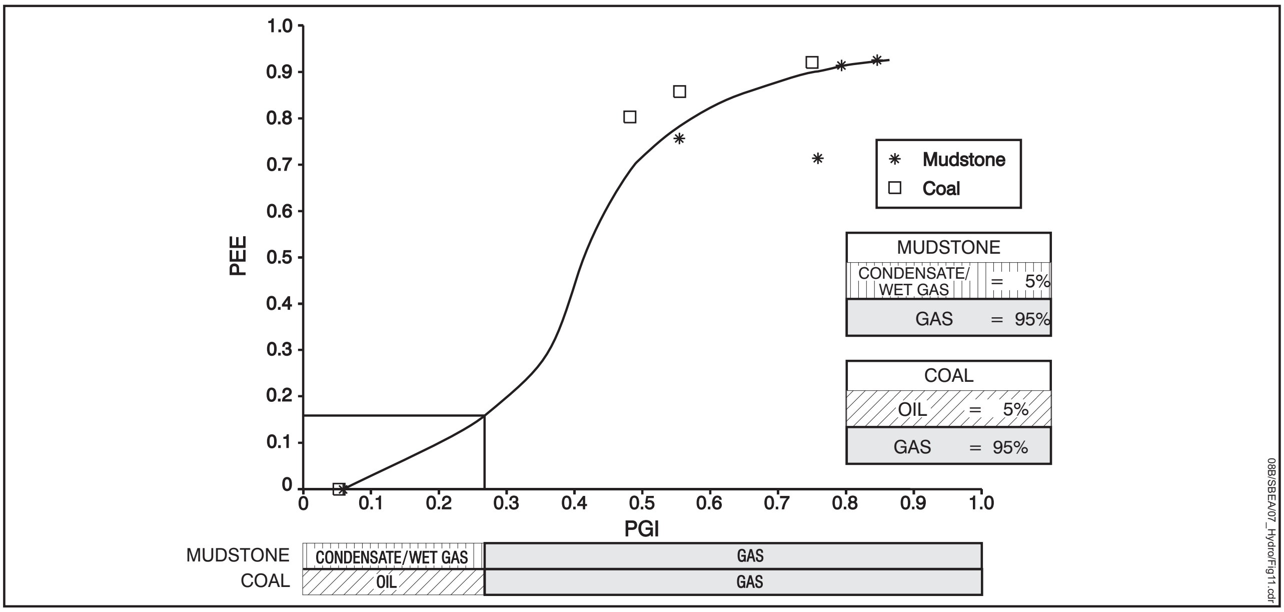

Figure 16. PGI versus PEE plot for mudstones and coals in the 'Flat Top' group.

Inglestone 1, UOD Burunga 1 and UOD Cockatoo Creek 1. The mudstones in the 'Flat Top' group have a potential for generation of condensate/wet gas.

The average HI and Tmax values for the coals are presented on a separate plot (Figure 11). For this group, the immature wells are UOD Undulla 1 and HOM Alick Creek 1. The wells that have begun generation are COE Inglestone 1, UOD Burunga 1 and UOD Cockatoo Creek 1. The coals in the 'Flat Top' group have potential for oil production.

To evaluate the original source quality of the mudstones, (before any generation has taken place which results in a decrease in HI), an initial HI map (HI_{init}) was produced. The HI_{init} map was drawn using HI values from wells that have Tmax values less than 445°C. The HI_{init} map for the mudstones shows a trend of increasing HI_{init} values from the south to the Undulla Nose region (Figure 12). However the number of data points available is very limited due to the small number of wells with average Tmax values less than 445°C. Due to the lack of data points, a HI_{init} map could not be produced for the coals.

The Tmax map for the mudstones shows low values of less than 445°C in the south and in the Undulla region whereas Tmax values increase towards the centre of the Trough and to the north (Figure 13). Tmax values

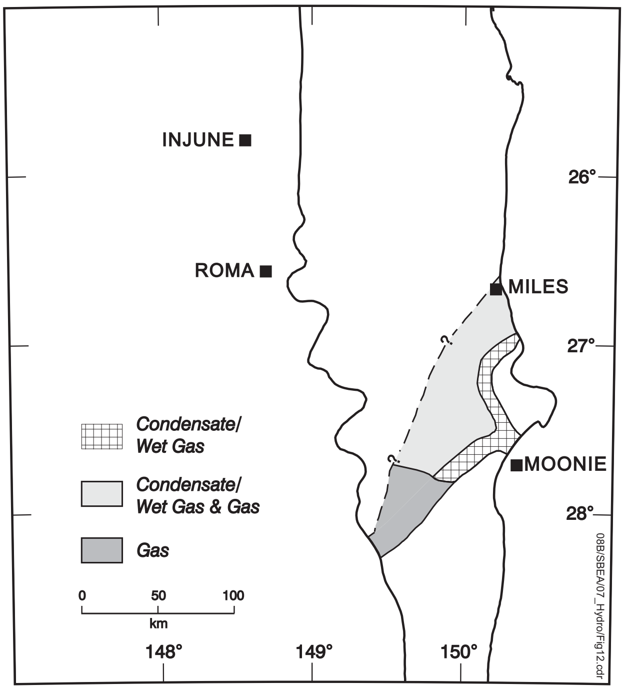

Figure 17: Hydrocarbon generation areas for the mudstones in the 'Flat Top' group.

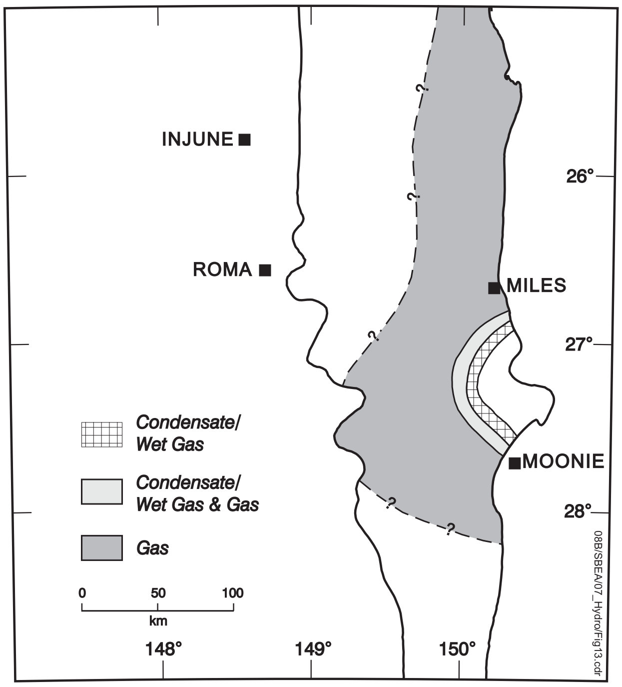

Figure 18: Hydrocarbon generation areas for the coals in the 'Flat Top' group.

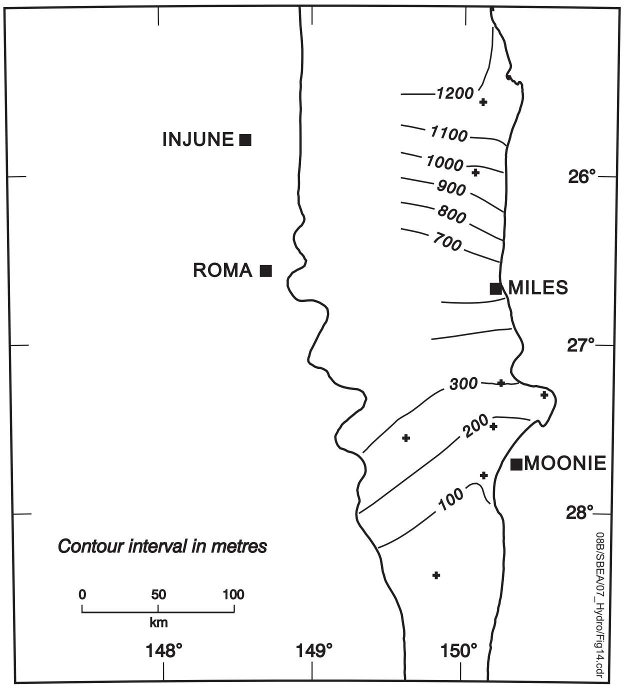

Figure 19: Effective thickness for the mudstones in the 'Flat Top' group.

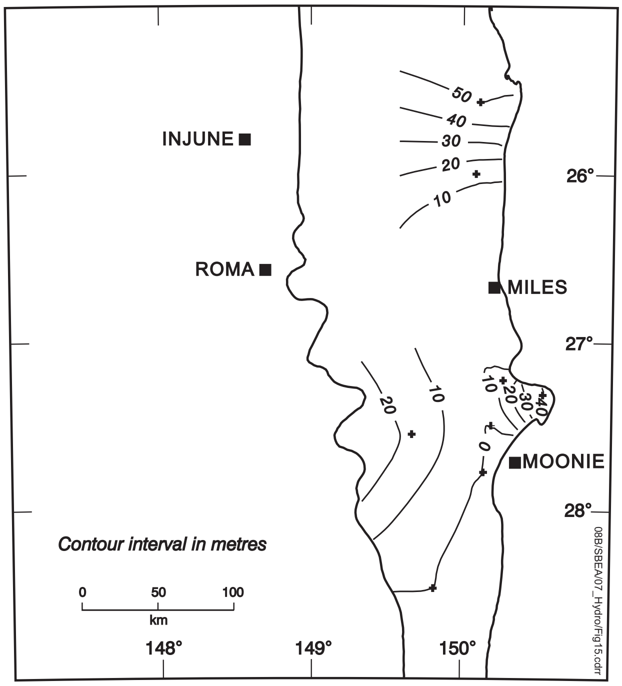

Figure 20: Effective thickness for the coals in the 'Flat Top' group.

exceeding 445°C (beginning of hydrocarbon generation) are in the central and northern areas of the Trough.

The Tmax map for the coals shows values similar to the mudstones except for the southern parts of the Trough where there are no coals (Figure 14).

The areas that have the highest potential to generate hydrocarbons are the thermally immature areas. The coals in the Undulla region have a potential for oil generation but are thermally immature. The same immaturity situation occurs with the mudstones in this area, which are capable of producing condensate.

Generation and Expulsion

The PGI versus Rv,max plot for the mudstones and coals (Figure 15) indicates that the onset of generation given at PGI of 0.1 is equivalent to Rv,max of 0.9-1.0% (Tmax = 445°C). At the completion of generation of condensate/wet gas at Rv,max of 1.05% (Tmax = 450°C) the PGI has reached 0.25.

The coals and mudstones from each well display a wide range of PGI values for the same reflectance value. In UOD Burunga 1 and UOD Cockatoo Creek 1 the mudstones have higher PGI values than the coals but the reverse is the case for COE Inglestone 1. The wide spread of data may be attributable to the heterogeneous environments of this group which consists of lower delta plain coal deposits and marine mudstones. The environment of deposition and manner of preservation would have influenced the type of organic matter and quality.

The PGI versus PEE plot shows a slow increase in expulsion efficiencies up to a PGI of 0.25. From a PGI of 0.35 to 0.5, the PEE increases rapidly from 0.25 to 0.75. From thereafter, the PEE curve flattens off to reach a maximum of 0.95 (Figure 16).

Oil/condensate/wet gas is generated up to a PGI of 0.25. At this point the PEE is at 0.15. Thus the maximum amount of petroleum that can be generated and expelled from the mudstones or coals is 5% of the hydrocarbon potential. Beyond a PGI of 0.25 (Tmax >450°C) mainly gas is generated. It is the generation of gas that accounts for the rapid increase in expulsion efficiencies from 0.25 to 0.75, as mentioned previously. Liquids trapped in the pores and fractures of the rocks at the higher maturity would be readily expelled due to a more efficient gas mobilisation mechanism.

Hydrocarbon generation area maps for the mudstones and coals (Figures 17 & 18) both show nearly concentric zones of condensate/wet gas generation in the central/eastern parts of the Trough with gas generation further to the west and north. The hydrocarbon generation areas map for the mudstones (Figure 17) is incomplete due to the absence of any Hi_{init} data above 27°S latitude. As mentioned previously, the coals and mudstones in the Undulla region are a potential source for oil and condensate respectively, but are thermally immature (Tmax<445°C) and hence petroleum generation has not commenced.

The effective thickness map of mudstones in the 'Flat Top' group shows a consistent trend of increasing thickness from the south of the Trough to the north where thicknesses reach 1200m (Figure 19). Thicknesses in the condensate generation zone range from 100m to over 300m.

The effective thickness map of the coals shows coal is absent in the south. Effective coal thicknesses of about 40m occur in HOM Alick Creek 1 (Figure 20). However, this coal is in the thermally immature Undulla region and has not produced any hydrocarbons. The areas where condensate has been generated have effective coal thicknesses from zero to 10m. The areas in the north-east with thicknesses of coal up to 50m, have contributed to the production of hydrocarbons.

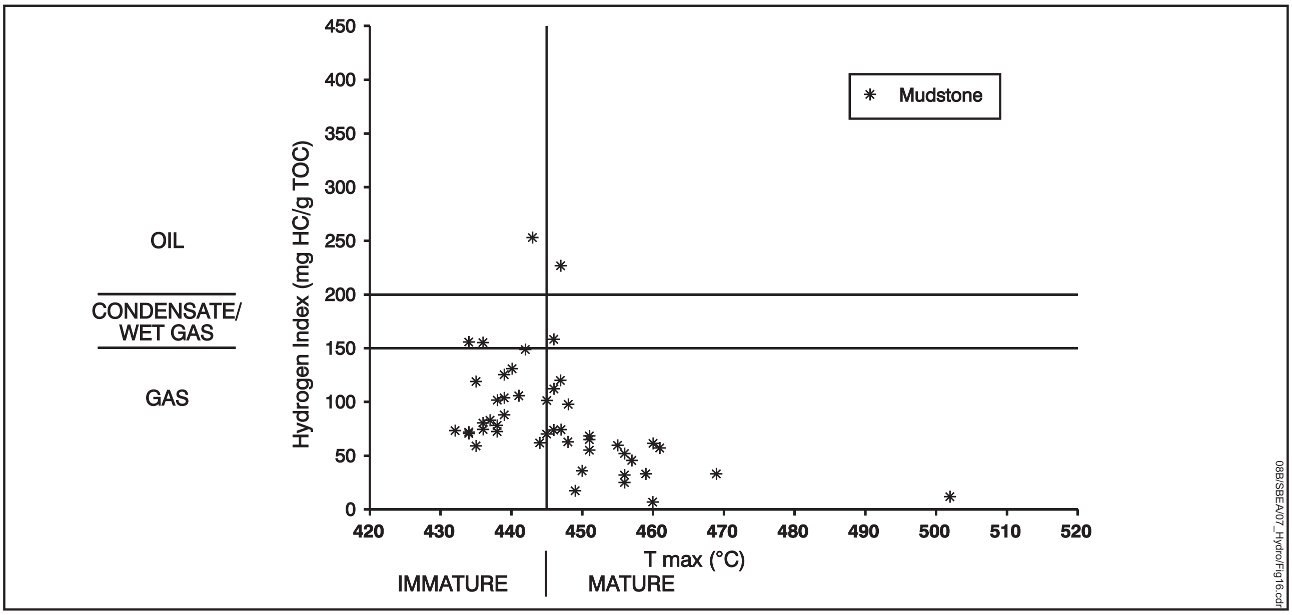

Figure 21: HI versus Tmax plot for mudstones in the 'Banana' group.

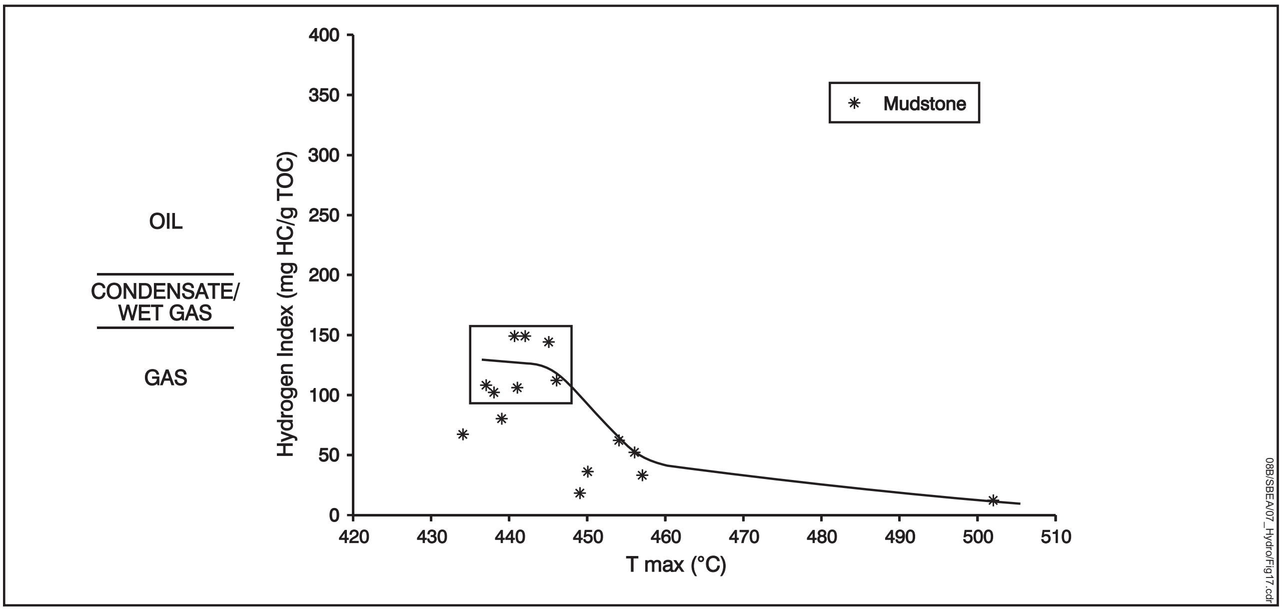

Figure 22. Average HI versus average Tmax values for the mudstones from each well intersecting the 'Banana' group.

'BANANA' GROUP

Source Rock Quality and Maturity

Mudstone is the only potential source rock as coals do not occur in the 'Banana' group. The HI v Tmax plot shows that the immature mudstones have HI values mostly less than 150mg HC/g TOC and are dominantly gas prone (Figure 21). The beginning of hydrocarbon generation is interpreted to be at Tmax of 445°C.

Five samples with HI values in the 150-250mg HC/g TOC range indicate there are some mudstones with limited liquids potential. These higher HI values are from UOD Sussex Downs 1, UOD Undulla 1 and HOM Alick Creek 1.

The average HI and Tmax values for the 'Banana' group for each well are plotted in Figure 22. The source quality for the 'Banana' ranges from very poor (HI <100mg HC/g TOC), to gas-prone (HI <150mg HC/g TOC). For the carbon mass balance calculations, seven wells (UOD Undulla 1, UOD Teelba 1, UOD Sussex

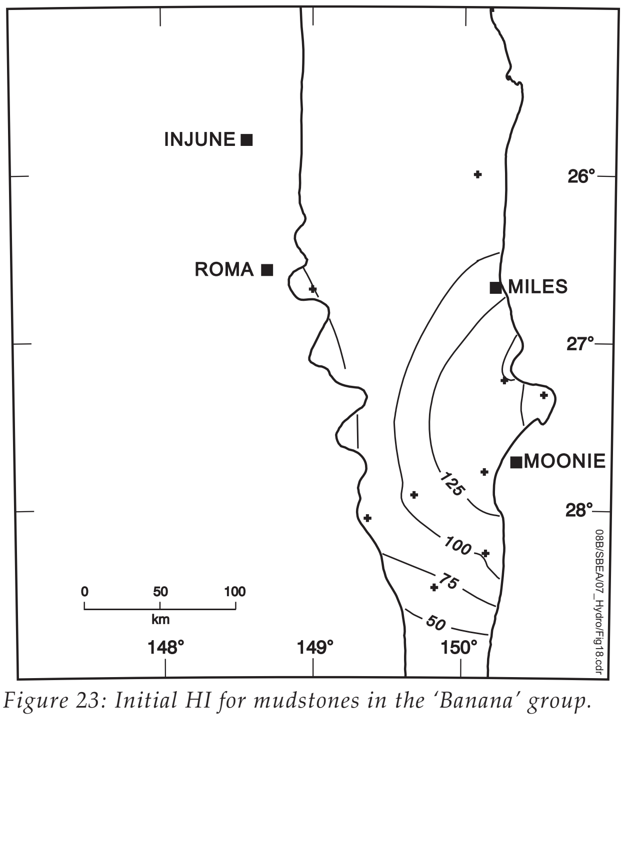

Figure 23: Initial HI for mudstones in the 'Banana' group.

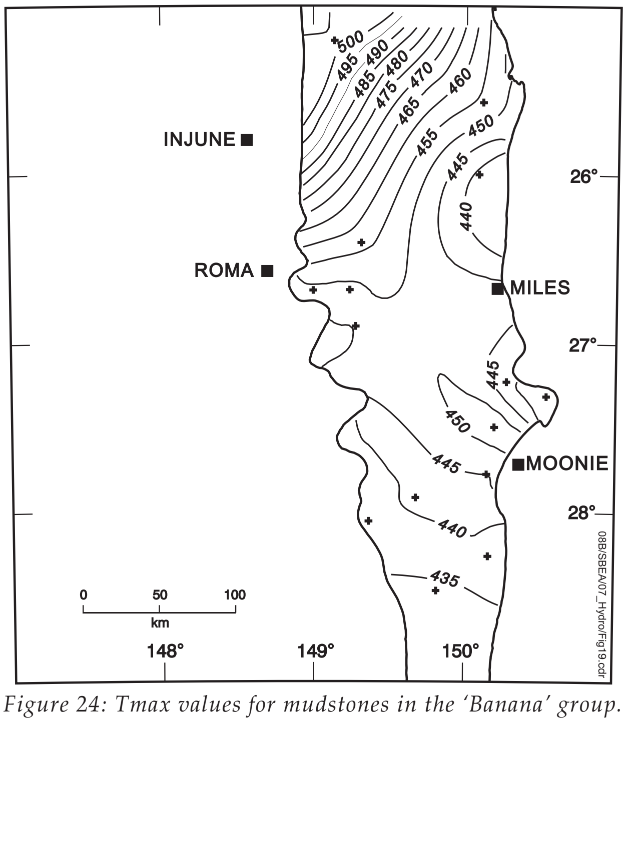

Figure 24: Tmax values for mudstones in the 'Banana' group.

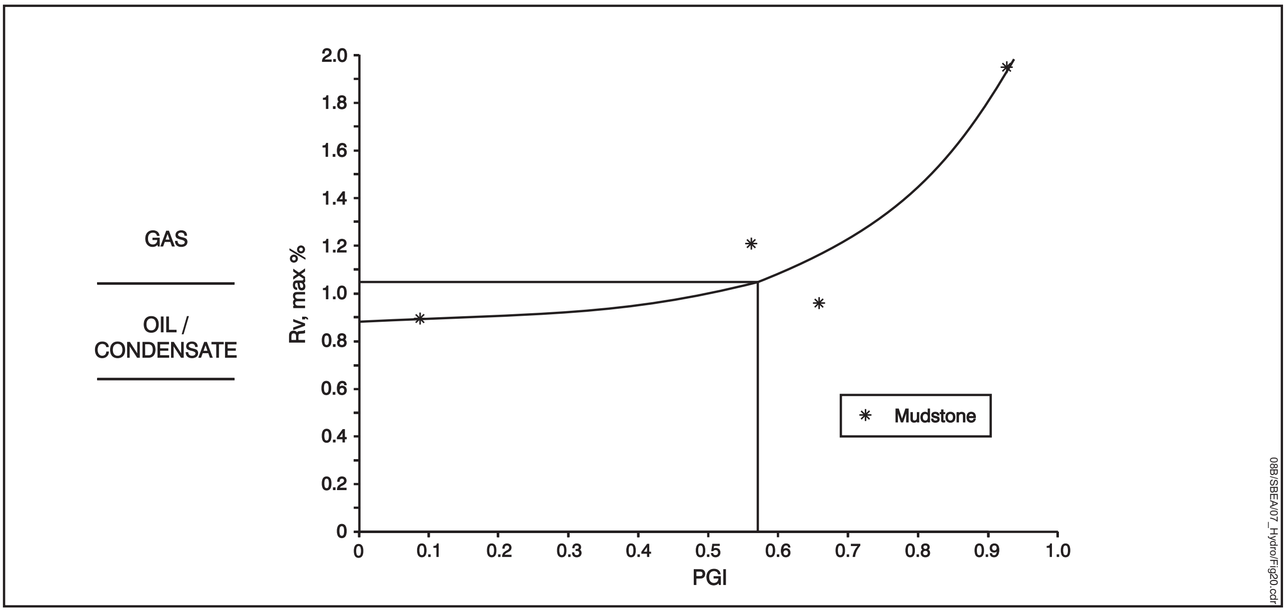

Figure 25: PGI versus Rv,max plot for the mudstones in the 'Banana' group.

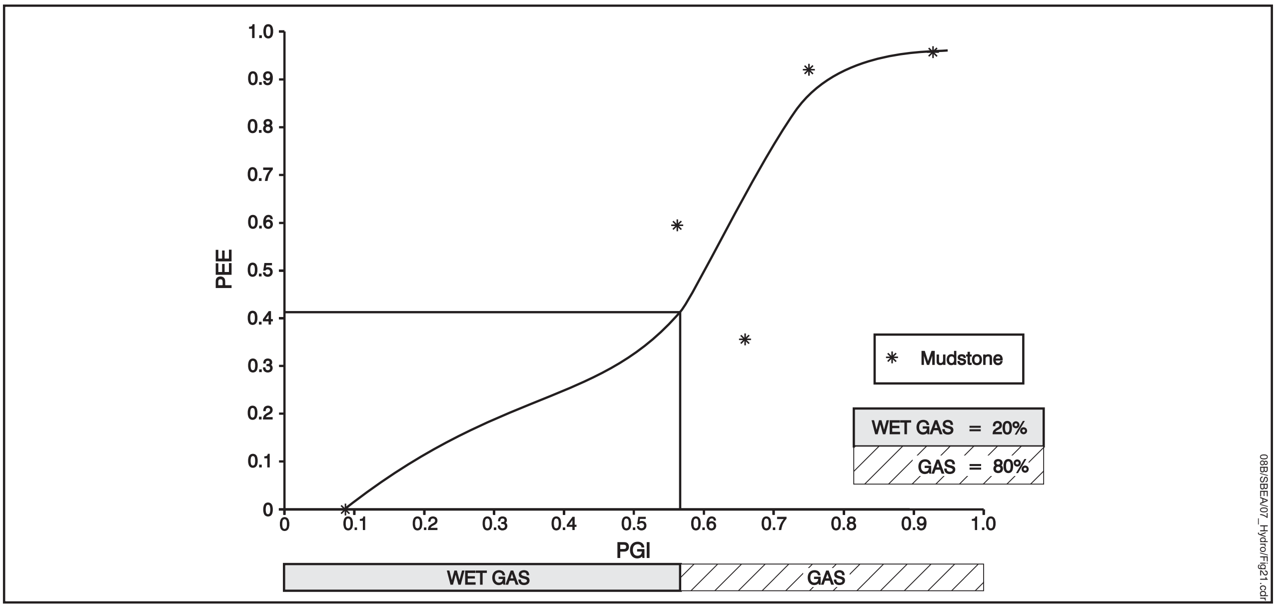

Figure 26: PGI versus PEE plot for the mudstones in the 'Banana' group.

Downs 1, HOM Alick Creek 1, XLX Maxima Max 1, UOD Flinton 1 and AAO Coonardoo 1) were selected as representing the immature analogues with HI's between 100 and 150mg HC/g TOC. Two wells, UOD Booberanna 1 and UOD Burunga 1, were not included in this immature group as their HI values were considerably lower, being less than 100mg HC/g TOC. This is probably due to extensive reworking and oxidation of the organic matter leading to little source potential.

Two wells in the mature range, AAO Apple Tree 1 and AAO Bengalla 1, were also not included in the mass balance calculations as it was considered that the organic material is of poorer source quality. Wells that have produced hydrocarbons are UOD Cockatoo Creek 1, UOD Cabawin 1, EOC Muggleton 1 and MPA Glenhaughton 1.

The initial source quality is gauged by using the HI values from wells where Tmax is less than 445°C. The HI_{init} contour map (Figure 23) shows a consistent trend of increasing source quality towards the east. The contour lines run nearly north-south, parallel to the depositional axis of the Taroom Trough. Only in areas around UOD Undulla 1 and HOM Alick Creek 1 does the source quality exceed HI_{init} of 150mg HC/g TOC.

The average Tmax values for the 'Banana' group have been contoured over the project area (Figure 24). Areas with Tmax <445°C are immature for hydrocarbon generation and expulsion. These immature areas fall within the

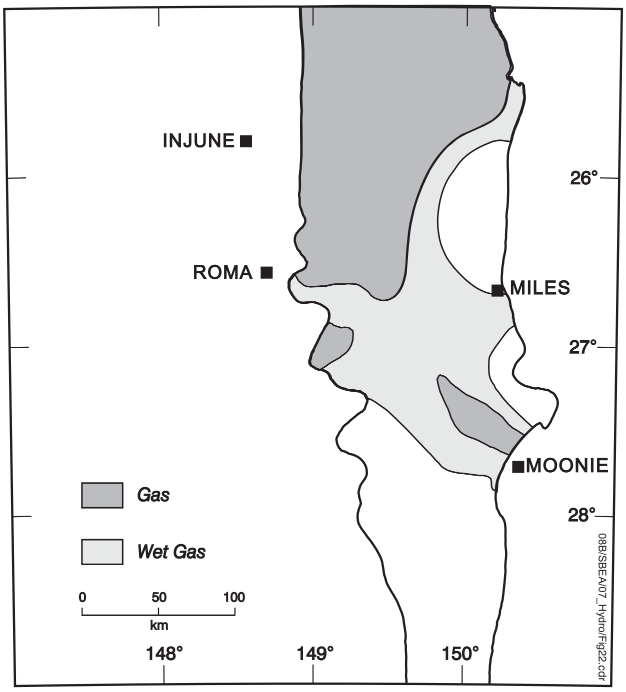

Figure 27: Hydrocarbon generation areas for the mudstones in the 'Banana' group.

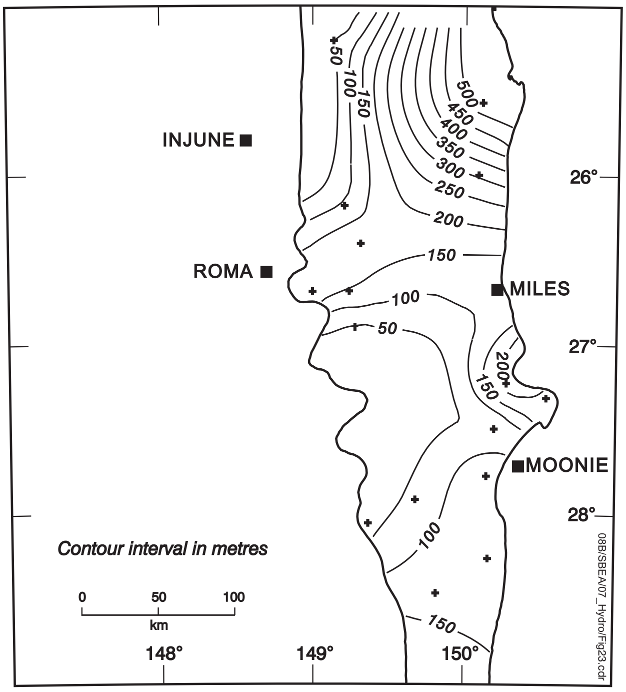

Figure 28: Effective thickness for the mudstones in the 'Banana' group.

southern parts of the Trough, in the Undulla region and near UOD Burunga 1, in the north-east. Significant hydrocarbon generation occurs between a Tmax range of 445°C and 450°C. This range occurs within the central parts of the Trough. The northern regions are where Tmax exceeds 450°C. These areas have reached maturity for gas generation. Overall there is a trend of increasing maturity from the south to the north.

Generation and Expulsion

Initial hydrocarbon generation would be wet gas/condensate from Tmax 445°C to 450°C as the HI values are less than 150mg HC/g TOC. The bulk of the generation of gas would continue for Tmax in excess of 450°C. A plot of PGI versus Rv,max (Figure 25) was used to determine at what maturation level wet gas/condensate generation begins and what fraction of the hydrocarbon potential is generated. The onset of wet gas/condensate generation taken at PGI of 0.1 occurs at Rv,max of 0.9%; which is equivalent to Tmax of 445°C. Wet gas is generated up to Rv,max of 1.05% after which dry gas is generated. This occurs at PGI of 0.55. Over one-half of the hydrocarbon generation potential occurs over a narrow effective Rv,max range and between Tmax of 445°C and 450°C (Figure 25).

The PGI versus PEE plot shows at a PGI of 0.55 there is a moderate PEE of 0.4 (Figure 26). Thus, at Tmax of 450°C, 20% of the hydrocarbon potential has been expelled as wet gas. This PEE is higher than that for the "Flat Top" group (PEE = 0.15) over the same maturity range, presumably due to the more efficient expulsion of a phase with a higher gas/liquids ratio.

Over a small PGI increase from 0.55 to 0.70 there is a corresponding large increase in expulsion efficiencies from PEE of 0.4 to 0.8. This rapid increase in expulsion efficiency is attributed to the generation of gas which involves a large volume increase and the expulsion efficiencies rapidly increase. The expulsion efficiencies plateau out at 95% as the remaining gas is generated at higher maturities.

The hydrocarbon generation area map shows gas generation in the north, wet gas generation in the centre and no hydrocarbon generation in the south of the Trough (Figure 27).

The effective thickness map for the mudstones shows the thinnest sections (<50m) are on the western side of the Trough and there is an increase in thickness towards the eastern side with thicknesses up to 200m (Figure 28). In the north-east of the Trough, thicknesses rapidly increase to 300m and 500m around UOD Cockatoo Creek 1 and UOD Burunga 1.

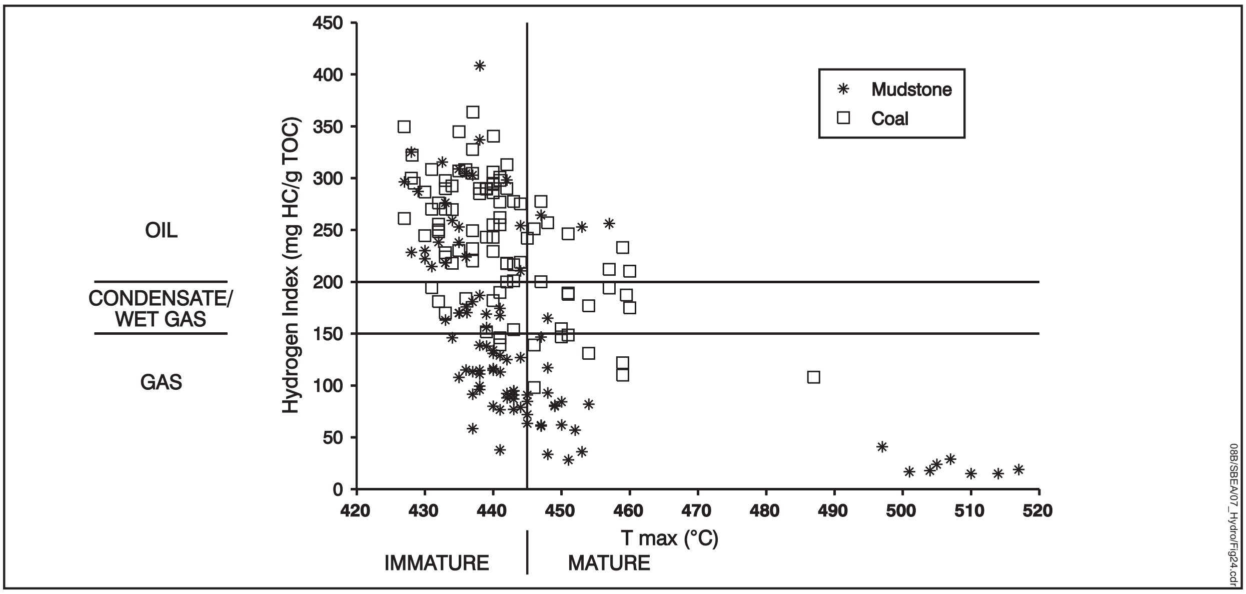

Figure 29: HI versus Tmax plot for mudstones and coals in the 'Burunga' group.

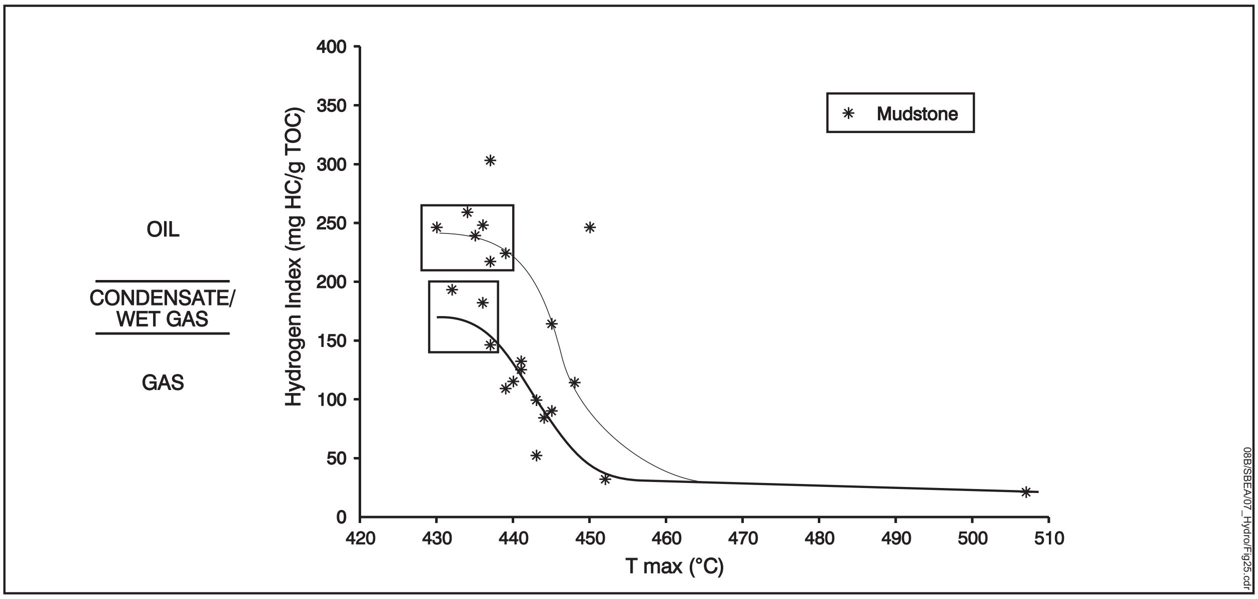

Figure 30: Average HI versus average Tmax values for the mudstones from each well intersecting the 'Burunga' group.

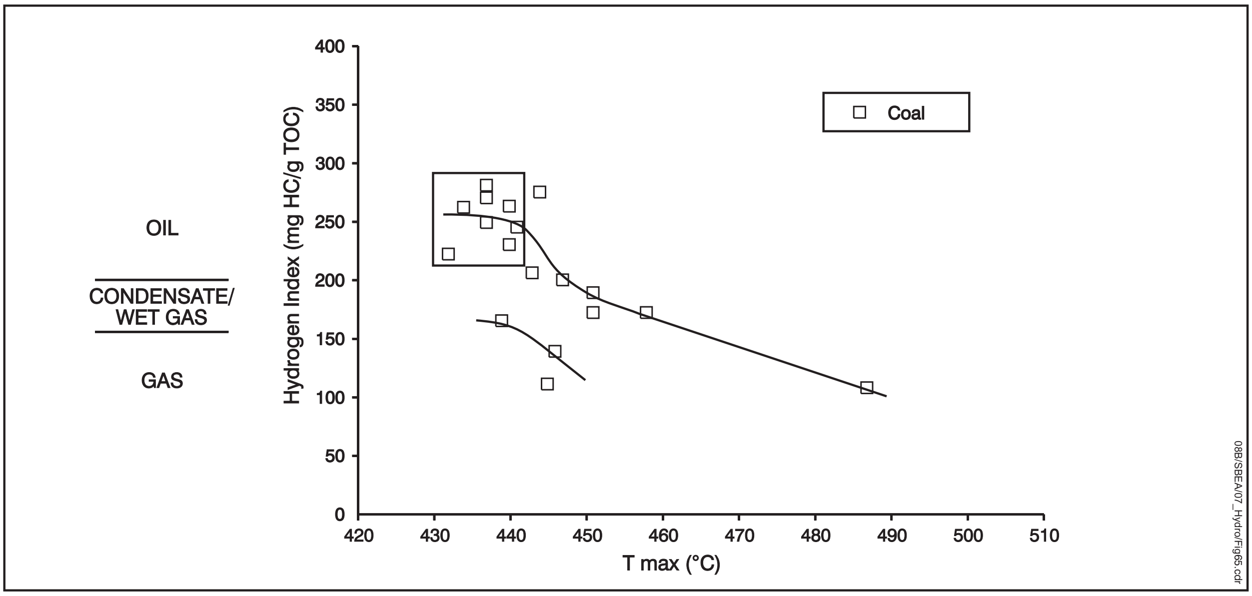

Figure 31: Average HI versus average Tmax values for the coals from each well intersecting the 'Burunga' group.

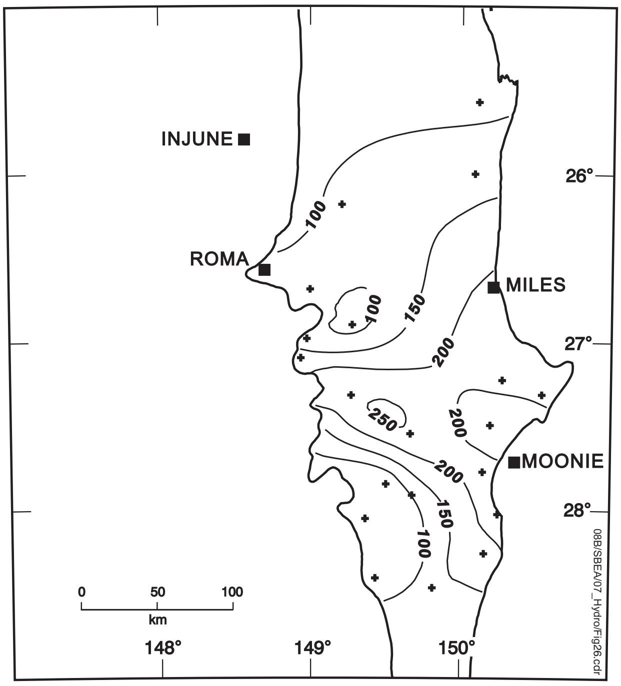

Figure 32: Initial HI values for mudstones in the 'Burunga' group.

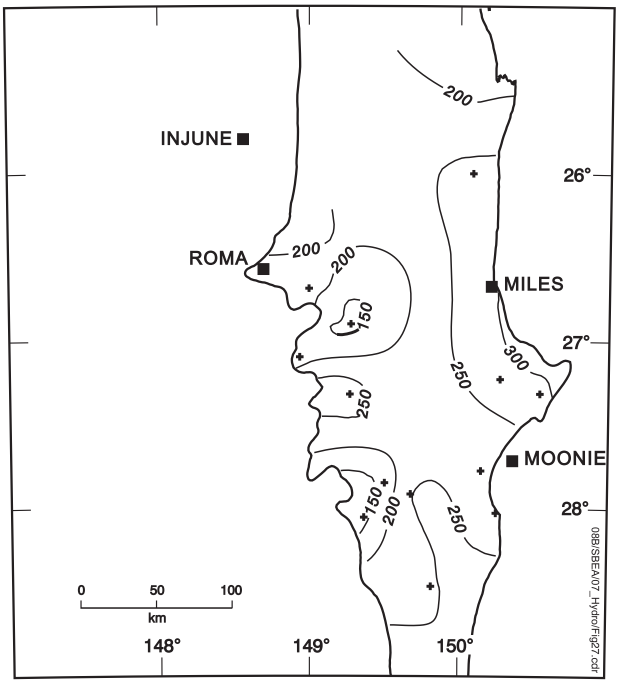

Figure 33: Initial HI values for coals in the 'Burunga' group.

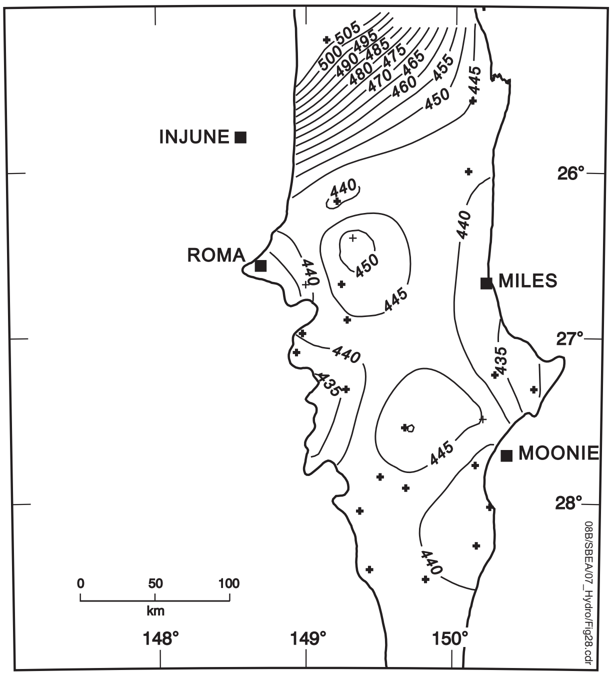

Figure 34: Tmax values for mudstones in the 'Burunga' group.

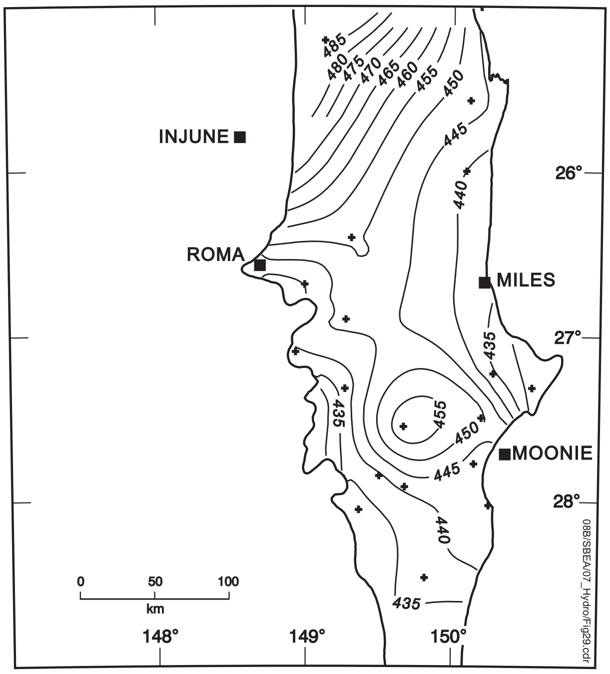

Figure 35: Tmax values for coals in the 'Burunga' group.

'BURUNGA' GROUP

Source Rock Quality and Maturation

In the 'Burunga' group, the HI values for both the coals and mudstones range up to 400mg HC/g TOC (Figure 29). These values indicate that the 'Burunga' group mudstones and coals have the potential to generate liquids.

Generally, the liquids generation potential for the 'Burunga' is higher than that for the 'Banana' and 'Flat Top' groups. The coals have an oil and condensate generation potential whereas the mudstones with a wider range of HI values than the coals, can produce oil, condensate and gas.

The mudstones and coals both show two source quality types, oil and condensate/wet gas (Figures 30 & 31). The source rocks with the potential to produce oil have HI values greater

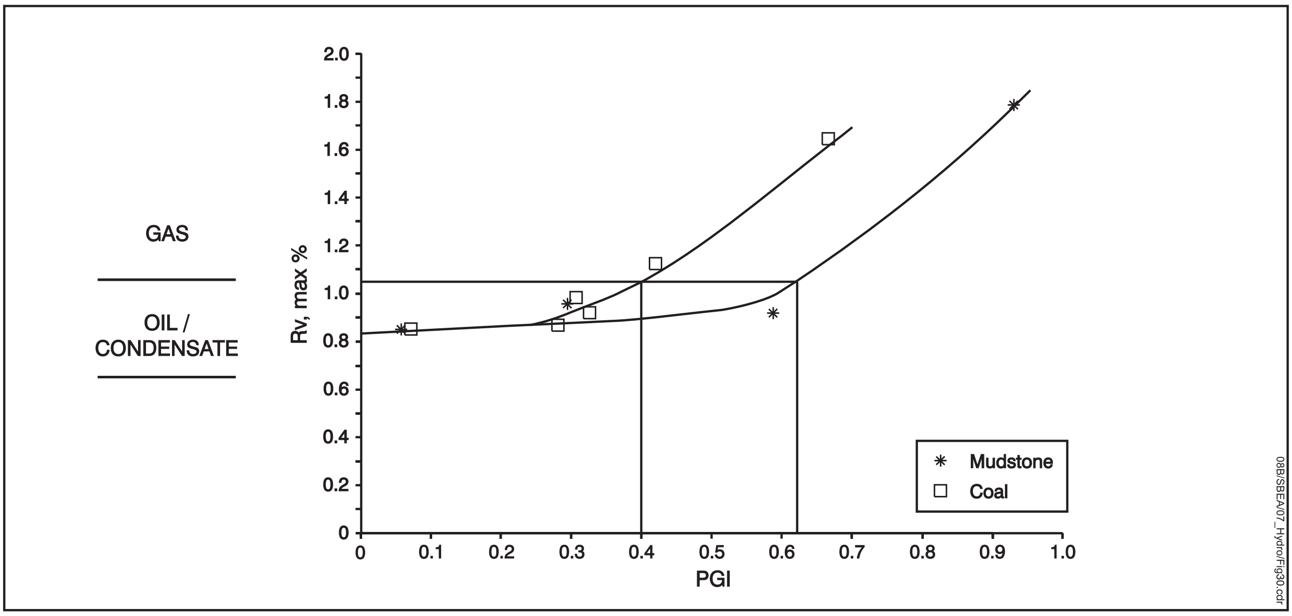

Figure 36: PGI versus Rv,max plot for the oil potential mudstones and coals in the 'Burunga' group.

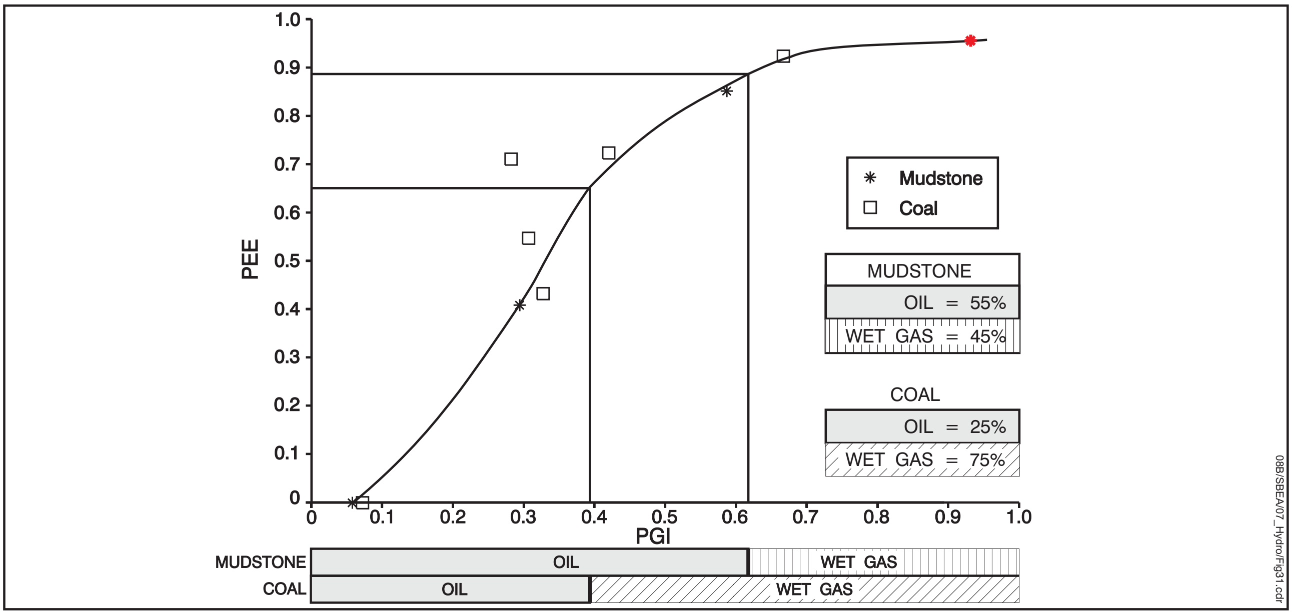

Figure 37: PGI versus PEE plot for the oil potential mudstones and coals in the 'Burunga' group.

than 200mg HC/g TOC and the source rocks with the potential to produce condensate/wet gas have HI values in the range 150-200mg HC/g TOC. Onset of generation and expulsion is at 440°C. For each rock type, there are two populations of data reflecting two distinct organic matter types; one for oil and the other for condensate/wet gas. Each follows a unique evolution curve for petroleum generation.

For the coals that have a potential to generate condensate/wet gas, only 3 data points are available over a narrow Tmax range making interpretations difficult (Figure 31). Also, there are no data points for the mudstones between Tmax of 455°C and 507°C the coals between 455°C and 487°C.

The wells with mudstones that have the potential to produce oil and that have not started generation are, PPL Ballymena 1, CSR Ebony 1, HEP Lethbridge 1, CON Rednook 1, UOD Sussex Downs 1, UOD Teelba 1 and UOD Undulla 1. The wells that have commenced generation of oil from the mudstones are UOD Cabawin 1, AAO Bengalla 1, COE Inglestone 1 and MPA Glenhaughton 1.

The immature oil-prone coals are from HOM Alick Creek 1, PPL Ballymena 1, UOD Booberanna 1, AAO Coonardoo 1, UOD Flinton 1, CON Rednook 1, UOD Burunga 1 and UOD Undulla 1. Coals that have produced oil are from UOD Sussex Downs 1, HEP Lethbridge 1, UOD Cockatoo Creek 1, UOD Cabawin 1, EOC

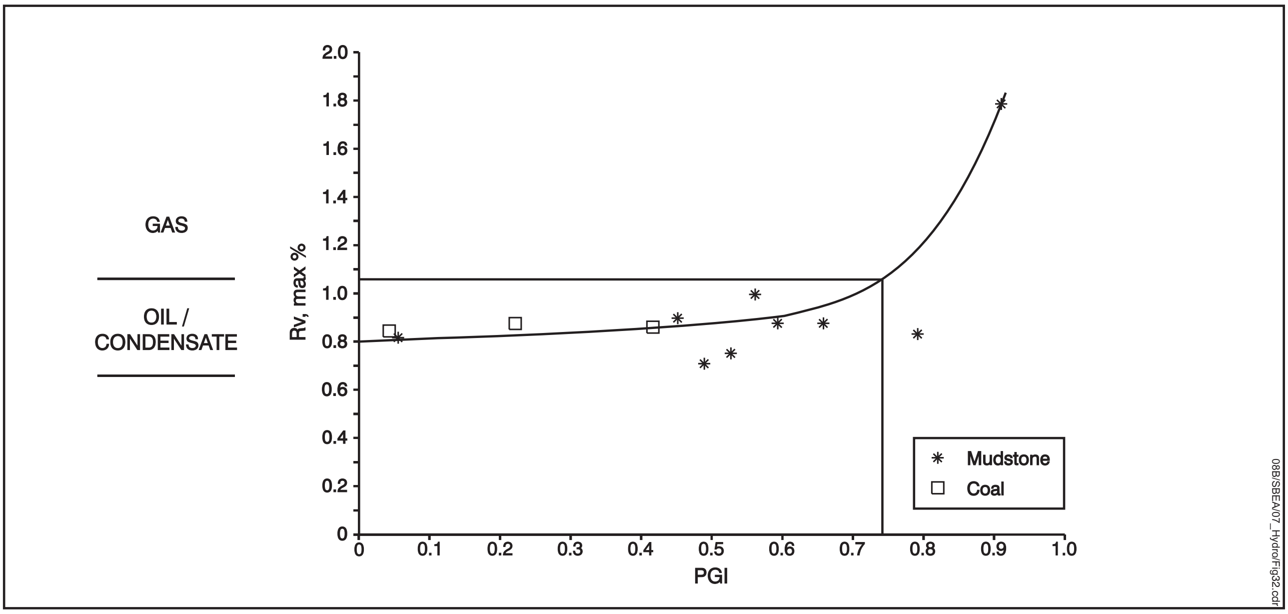

Figure 38: PGI versus Rv,max plot for the condensate/gas potential mudstones and coals in the 'Burunga' group.

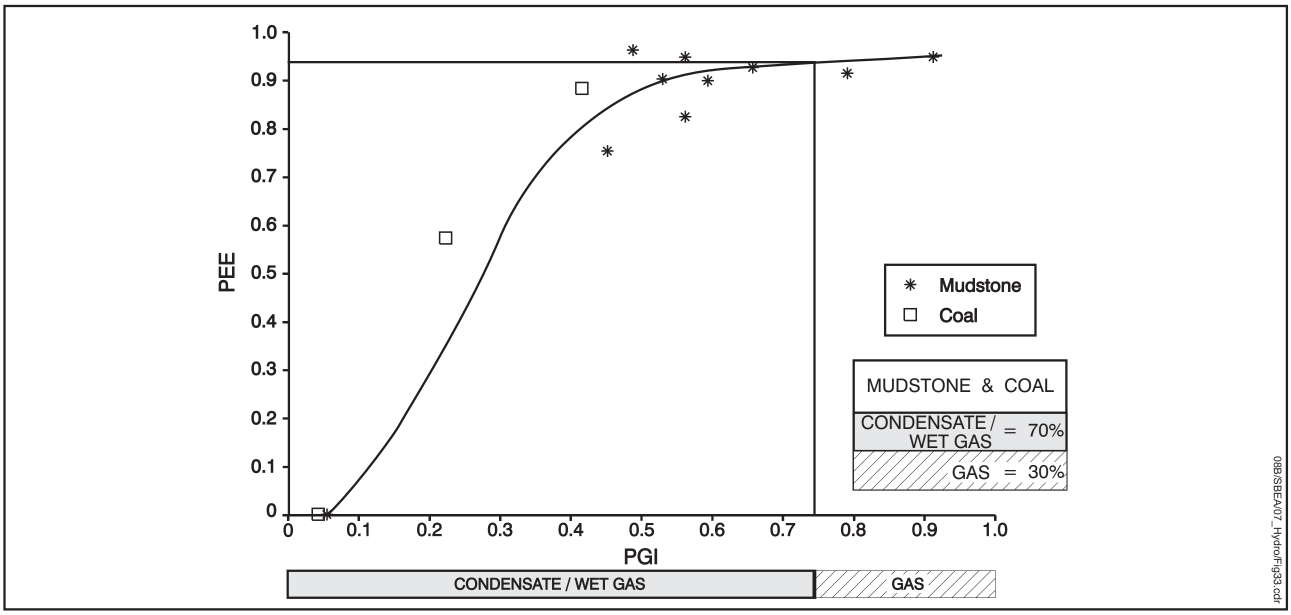

Figure 39: PGI versus PEE plot for the condensate/gas potential mudstones and coals in the 'Burunga' group.

Muggleton 1, COE Inglestone 1 and MPA Glenhaughton 1.

The immature mudstones from HOM Alick Creek 1, XLX Maxima Max 1 and AAO Coonardoo 1 and the immature coals in SOC Bellbird 1 fall within the condensate/wet gas potential field. Wells that have begun generation of condensate/wet gas from the mudstones in the 'Burunga' group are UOD Burunga 1, UOD Booberanna 1, SOC Redbank 1, AAO Meeleebee 1, UOD Flinton 1, UOD Cockatoo Creek 1, AAO Apple Tree 1, SOC Bellbird 1, UOD Muggleton 1 and MPA Glenhaughton 1. The coals that have produced condensate/wet gas are from AAO Apple Tree 1 and UOD Teelba 1.

The mudstones from the 'Burunga' group display a gradual increase in source quality from HI_{init}<100mg HC/g TOC in the north, to HI_{init}>200mg HC/g TOC at 27°S in the south (Figure 32). This high source quality continues in an east - west band across the Trough. Further to the south and south-west the HI values decrease to less than 50mg HC/g TOC. The coals display less HI_{init} variation than the mudstones but follow the same general trends (Figure 33).

The thermal maturity of the mudstones and coals (Figures 34 & 35, respectively), is low on the eastern and western margins but increases towards the axis of the Trough. This increase in maturity is mostly a result of increase in depth of burial.

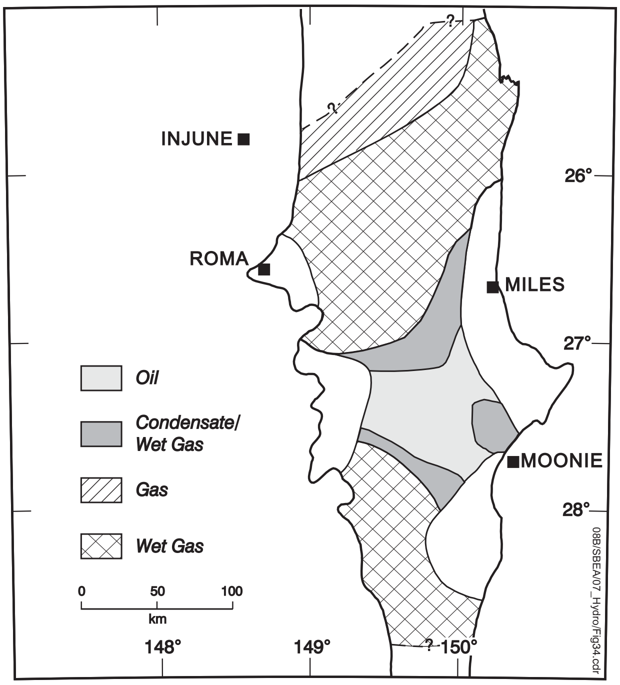

Figure 40: Hydrocarbon generation areas for the mudstones in the 'Burunga' group.

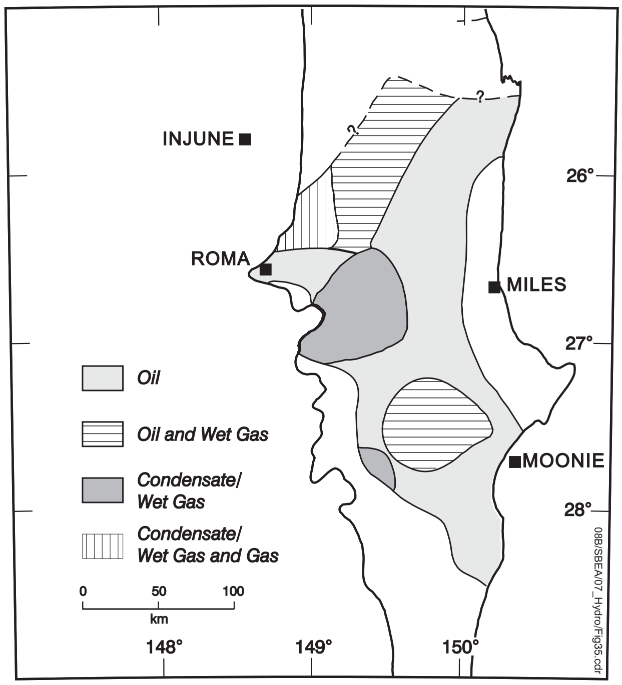

Figure 41: Hydrocarbon generation areas for the coals in the 'Burunga' group.

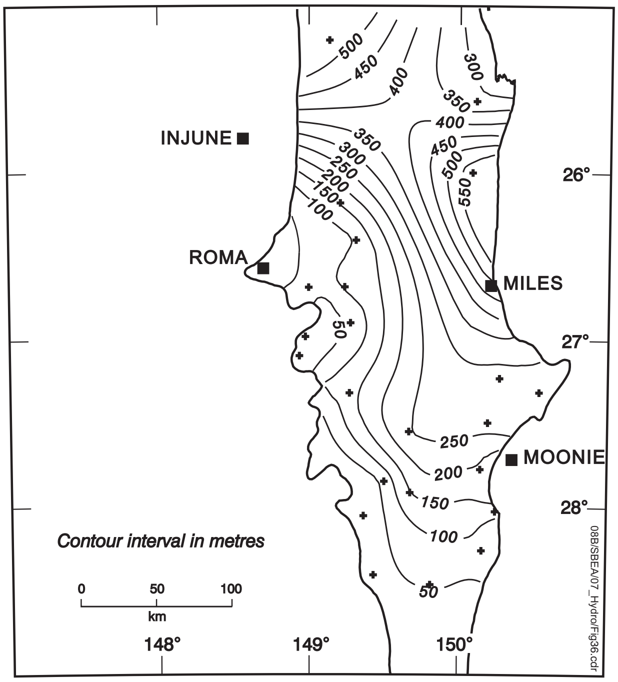

Figure 42: Effective thickness for the mudstones in the 'Burunga' group.

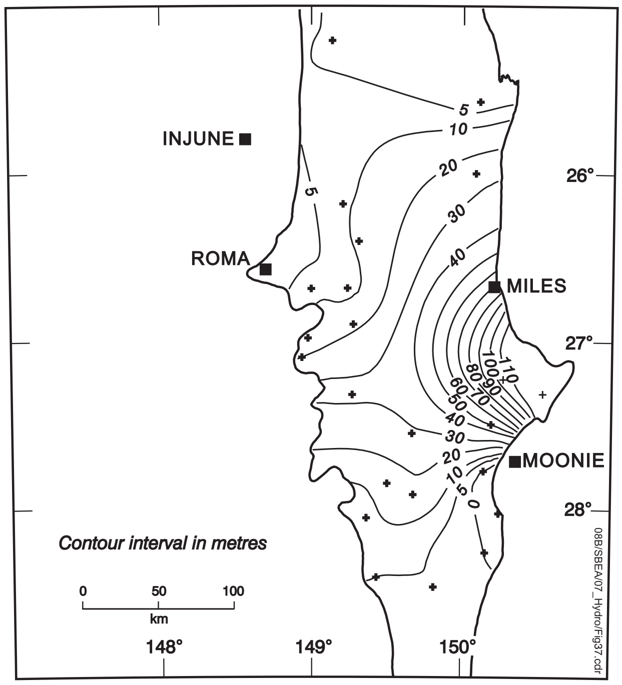

Figure 43: Effective thickness for the coals in the 'Burunga' group.

Generation and Expulsion

Oil potential samples:

The generation trends for the coals and mudstones (Figure 36) show that oil generation begins at Rv,max of 0.85% up to Rv,max of 1.05% (equivalent to Tmax of 450°C). Generation beyond Rv,max of 1.05% continues as mainly gas generation. For the coals, oil is generated up to PGI of 0.4 and for the mudstones, oil is generated up to PGI of 0.6. Thus the mudstones have a higher liquids generation potential.

For the coals, oil is generated to PGI of 0.4 at which stage 65% of the oil has been expelled (Figure 37). Thus 25% of the hydrocarbon potential of the coals is expelled as oil. At higher maturities (Rv,max>1.05%), the expulsion efficiency increases markedly as gas generation commences.

Oil expulsion from the mudstones is more efficient than from the coals. At the end of oil generation, (PGI of 0.6 for the mudstones), 90% of the generated liquids has been expelled. The mudstones have 1.5 times the potential to generate oil and over twice the potential to expel oil than the coals. This may be explained by greater mobility of a lighter oil or a higher gas/oil ratio in the petroleum generated from the organic matter in the mudstones.

Condensate/wet gas potential samples:

Similar condensate/wet gas generation trends exist for the coals and mudstones (Figure 38) although there is no data available for the coals at higher PGI values. Condensate/wet gas is generated up to PGI = 0.75 with initial condensate/wet gas generation starting at Rv,max = 0.8% (Tmax of approximately 440°C) up to Rv,max 1.05% (Tmax of 450°C). Beyond Rv,max of 1.05% there is generation of gas.

There is 90% expulsion of condensate/wet gas at 0.75 PGI resulting in 70% expulsion from the coals and mudstones (Figure 39). The PEE's for the two rock types are similar to those observed for the oil-prone mudstones above, suggesting only minor compositional differences between hydrocarbons generated from these rock types. The remaining 30% of the hydrocarbon potential is generated as gas with expulsion efficiencies over 90%.

The generation areas for the mudstones and coals in the 'Burunga' group are shown in Figures 40 & 41. Areas that have generated oil have HI_{init}>200mg HC/g TOC and Tmax>440°C. The mudstones that have generated oil are located mainly between latitudes 27°S and 28°S in the central parts of the Trough (Figure 40). There are no areas where the mudstones have generated oil to their full potential as Tmax has not reached 450°C in the central parts of the Trough; (the oil generation range is from Tmax 440°C to 450°C).

Condensate/wet gas generation from the mudstones has occurred in linear zones to the north, east and south of the oil areas. These areas fulfil the criteria of HI_{init} = 150-200mg HC/g TOC and Tmax>440°C. As is the case with the oil generation areas, the potential of the mudstones to produce condensate/wet gas has not been fully realised as Tmax in these areas has not exceeded 450°C.

The mudstones in the remaining areas in the southern Taroom Trough have generated gas. There has been limited wet gas generation in the areas where HI_{init}<150mg HC/g TOC and Tmax = 440-450°C. These areas are located to the north and south of the condensate generation areas. Greater quantities of gas have been generated in the northern parts of the Trough where HI_{init}<150mg HC/g TOC and Tmax>450°C.

The oil generation areas for the coals cover a much larger area than that by the mudstones (Figure 41). As well there are two areas in the central part of the Trough where oil generation is complete and gas generation has commenced. This area has HI_{init}>200mg HC/g TOC and Tmax>450°C.

Condensate/wet gas generation from the coals has occurred in areas to the west of the oil generation zones. To the north-west, there are two smaller areas where there has been complete generation of the condensate/wet gas followed by generation of gas from the coals. These areas have HI_{init} = 150-200mg HC/g TOC and Tmax>450°C.

Although the mudstones have the potential for high oil production, the oil generation areas are limited in areal extent compared with those for the coals. This restriction in area could be due to the limited well control or the absence of data from wells in the axis of the Trough where HI_{init} may have exceeded 200mg HC/g TOC.

The area of oil generation from the coals covers a substantial portion of the southern Taroom Trough (Figure 41). Therefore it is the coals rather than the mudstones in the 'Burunga' group that have made a greater contribution to the generation of oil in the southern Taroom Trough.

The effective thickness of the mudstones shows a rapid increase from the southern and western parts of the Trough to the north and north-east where thicknesses exceeding 500m occur (Figure 42). The oil generation areas have effective mudstone thicknesses ranging from 200m to 300m. The condensate generation areas have a wide range of effective thicknesses from 100m to 500m. The lesser thicknesses are in the south and west.

The effective thickness of the coals in the 'Burunga' group increases from the north, south and west from <5m to >110m in the area around Miles (Figure 43). To the south of Miles near UOD Sussex Downs 1, PPL Ballymena 1 and UOD Tingan 1, coal is effectively absent in the 'Burunga' group. The thickness of coal that has generated oil ranges from <5m to 100m. Condensate generation occurs in areas where the coal thickness ranges from <5m to 30m.

'BARALABA' GROUP

Source Rock Quality and Maturity

The 'Baralaba' group, the youngest of the informal Permian subdivisions, contains mudstone and coal as potential source rocks. The 'Baralaba' group differs from the three underlying groups in that it is restricted to the area north of latitude 27°S. The Baralaba Coal Measures and the Bandanna Formation, which constitute the 'Baralaba' group on the eastern and western sides respectively of the Trough, both have similar oil and condensate/wet gas potentials.

The 'Baralaba' group has a potential for oil, condensate and gas generation (Figure 44). The potential to source oil is not as good as the 'Burunga' group because HI values are lower, the highest being just in excess of 250mg HC/g TOC.

The mudstones (Figure 45) and coals (Figure 46) can be subdivided into oil and condensate/gas

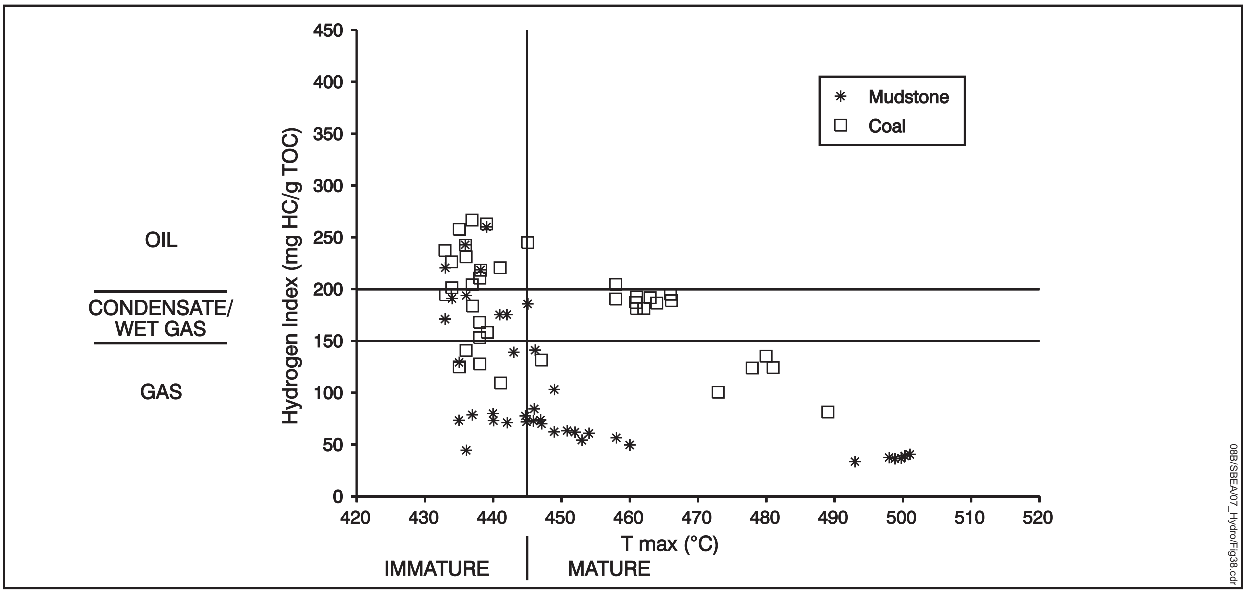

Figure 44: HI versus Tmax plot for mudstones and coals in the 'Baralaba' group.

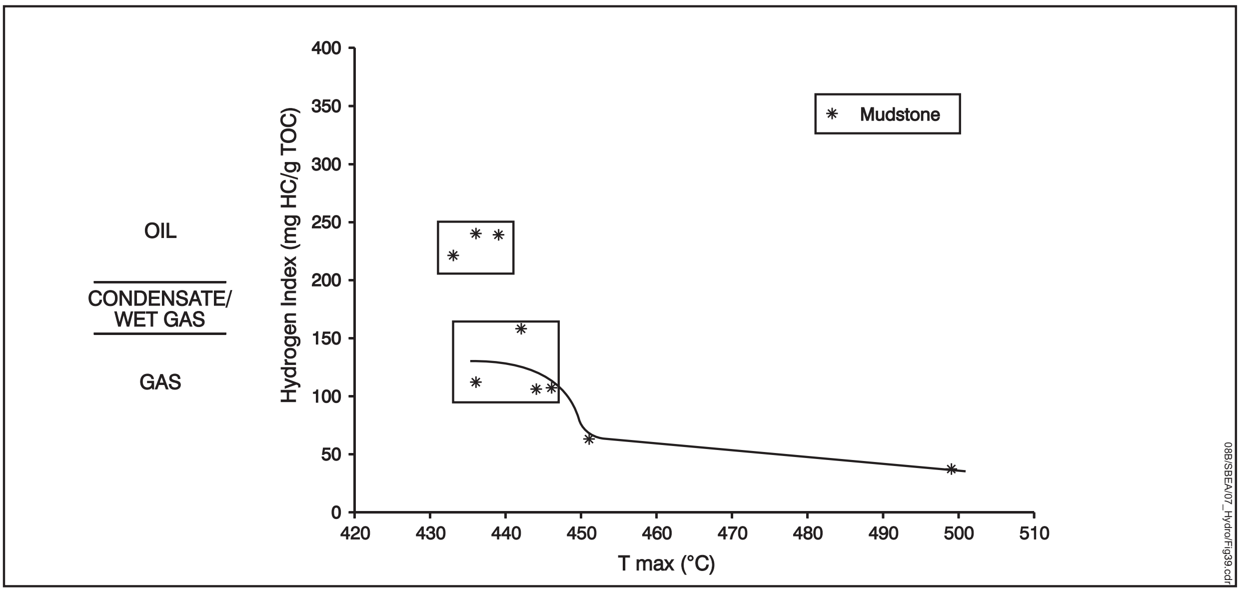

Figure 45: Average HI versus average Tmax values for the mudstones from each well intersecting the 'Baralaba' group.

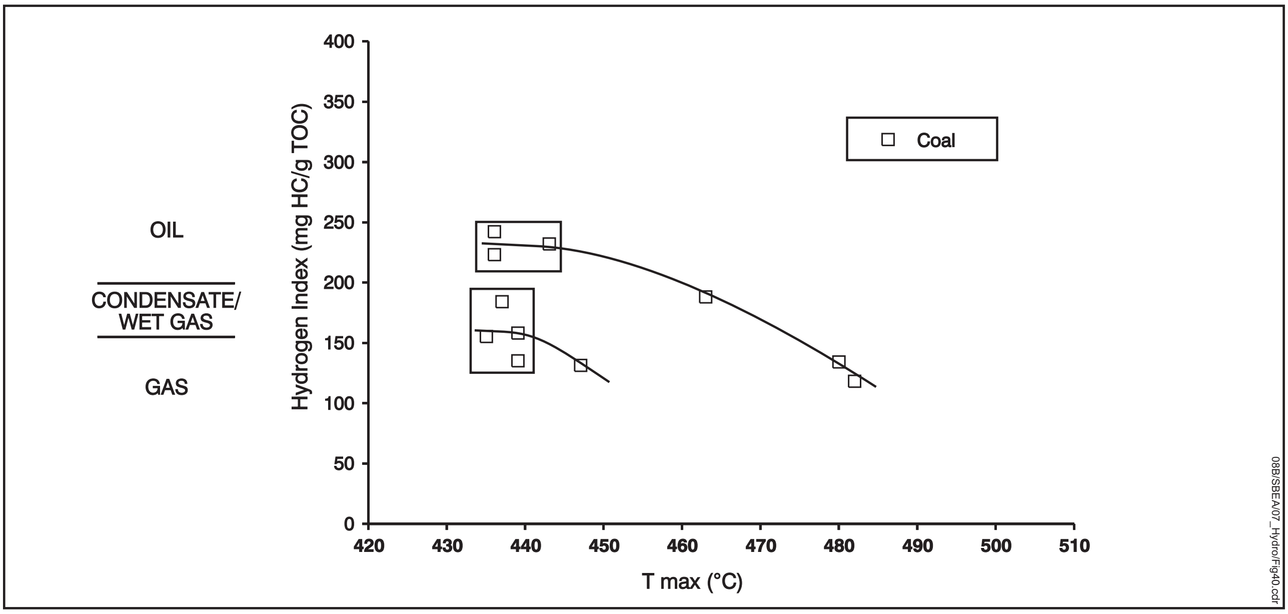

Figure 46: Average HI versus average Tmax values for the coals from each well intersecting the 'Baralaba' group.

groups. Onset of generation is in the 440°C to 445°C range. Most samples are thermally immature and there are only a few with higher maturities. For the oil-prone mudstones, (Figure 45), there is no data available for mature samples and for the condensate/gas-prone mudstones, only two higher maturity data points are available. For the condensate/gas-prone coals there is only one higher maturity data point (Figure 46).

The immature oil-prone mudstones are from AAO Coonardoo 1, AAO Grafton Range 1, and AAO Meeleebee 1. The corresponding coals are from AAO Bengalla 1, UOD Cockatoo Creek 1 and AAO Meeleebee 1. Coals that have generated oils are from UOD Wandoan 1, COE Tiggrigie Creek 1 and MPA Glenhaughton 1.

The immature condensate/wet gas-prone mudstones are from AAO Apple Tree 1, AAO Bengalla 1, UOD Burunga 1 and EOC Muggleton 1. UOD Cockatoo Creek 1 and MPA Glenhaughton 1 have begun generation of condensate/wet gas. The immature condensate/wet gas-prone coals are from AAO Apple Tree 1, UOD Burunga 1, AAO Coonardoo 1, and AAO Grafton Range 1. The coals in EOC Muggleton 1 have generated condensate/wet gas.

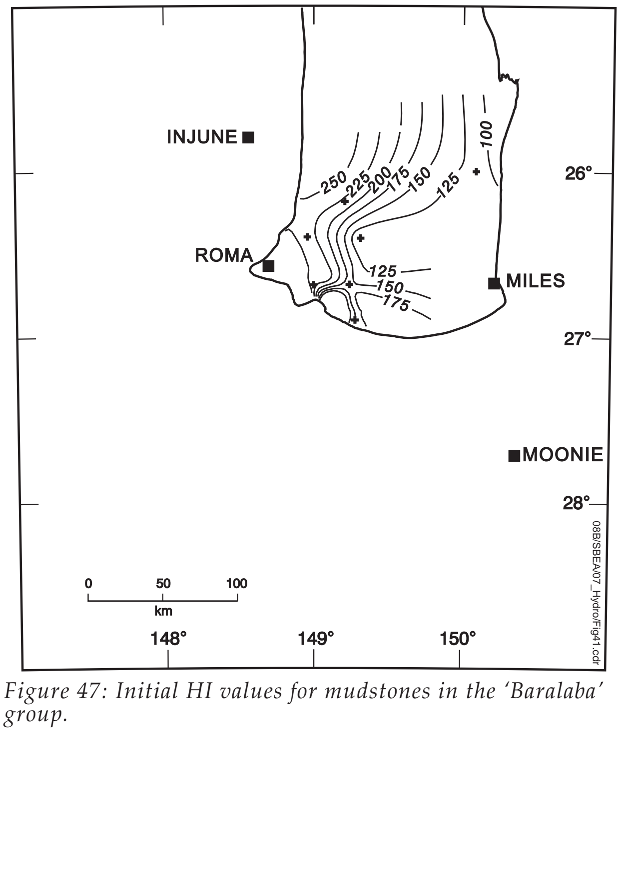

Figure 47: Initial HI values for mudstones in the 'Baralaba' group.

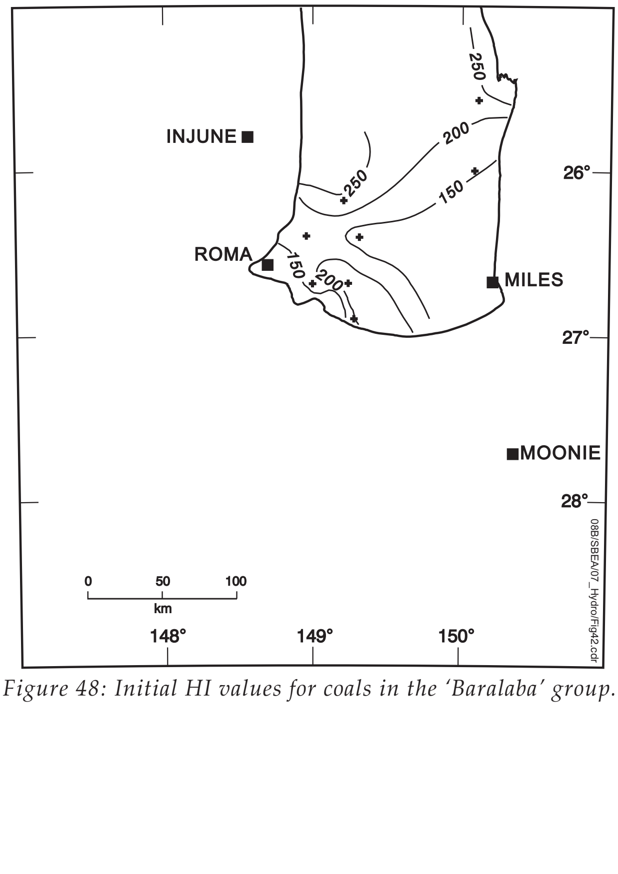

Figure 48: Initial HI values for coals in the 'Baralaba' group.

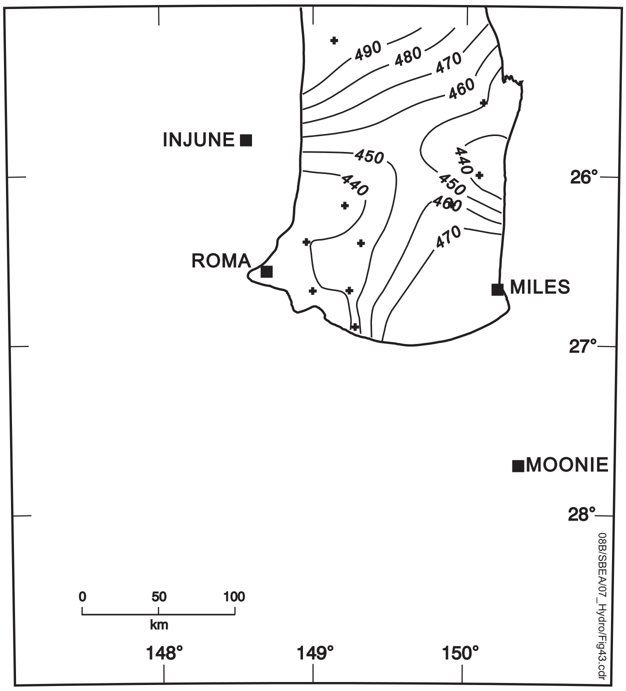

Figure 49: Tmax values for mudstones in the 'Baralaba' group.

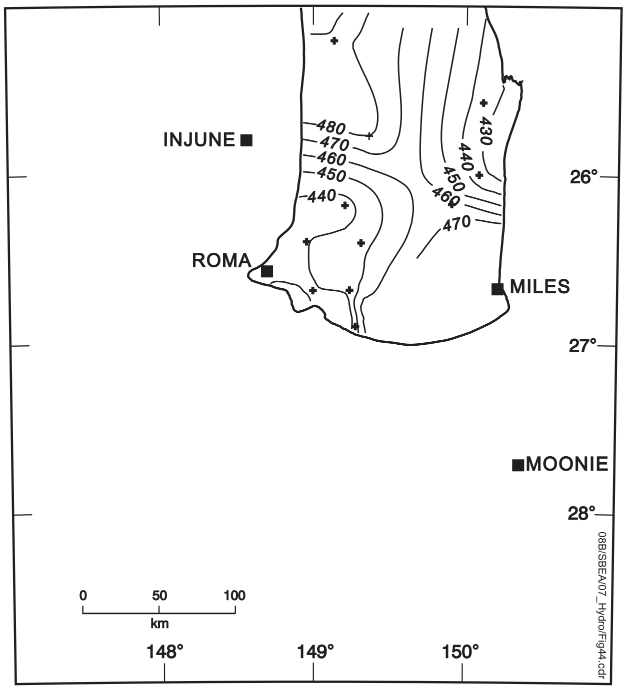

Figure 50: Tmax values for coals in the 'Baralaba' group.

The HI_{init} of the mudstones increases in values from 100mg HC/g TOC in the east to over 250mg HC/g TOC in the west (Figure 47). The coals do not display the same trend, instead there are low values (<150mg HC/g TOC) in the south-east and south-west with generally increasing values to the north (>250mg HC/g TOC) (Figure 48). This is unusual as in the underlying three "groups" there is normally a similar trend between the mudstones and the coals.

The Tmax values for the mudstones and coals (Figures 49 & 50) increase towards the axis of the Trough. This increase reflects a greater depth of burial. Also, there is also increasing maturity towards the north-west, particularly to the east of Injune. Areas that have not begun generation, with Tmax less than 440°C, occur in the south-west and south-east of the Trough.

Generation and Expulsion

For wells with the potential to produce oil (Figure 51) there is no data for mudstones with PGI values more than 0.1, but there are sufficient coal samples to draw a generation curve. The coals generate oil up to Rv,max of 1.05% with a PGI of 0.2. On the PEE v PGI plot

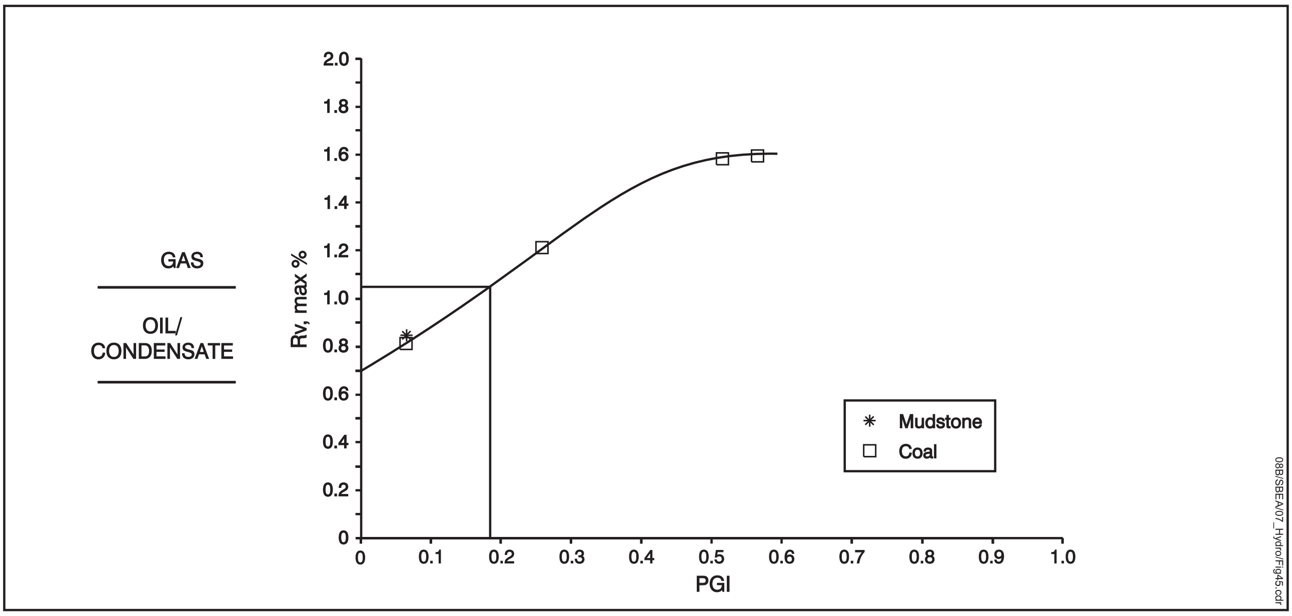

Figure 51: PGI versus Rv,max plot for the oil potential mudstones and coals in the 'Baralaba' group.

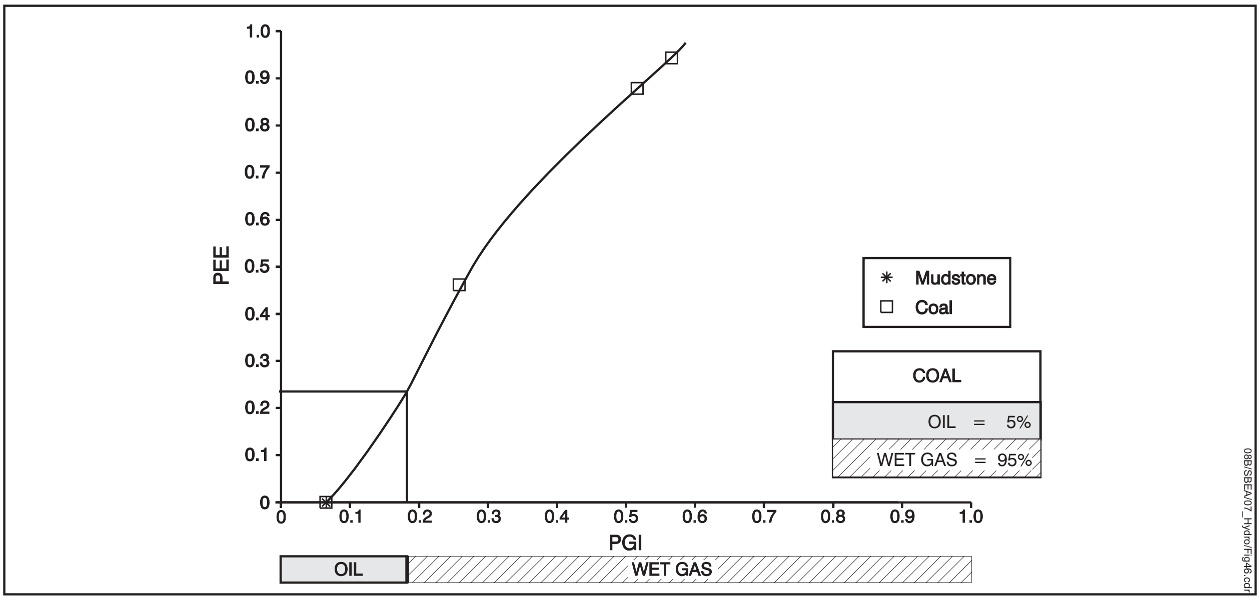

Figure 52: PGI versus PEE plot for oil potential mudstones and coals in the 'Baralaba' group.

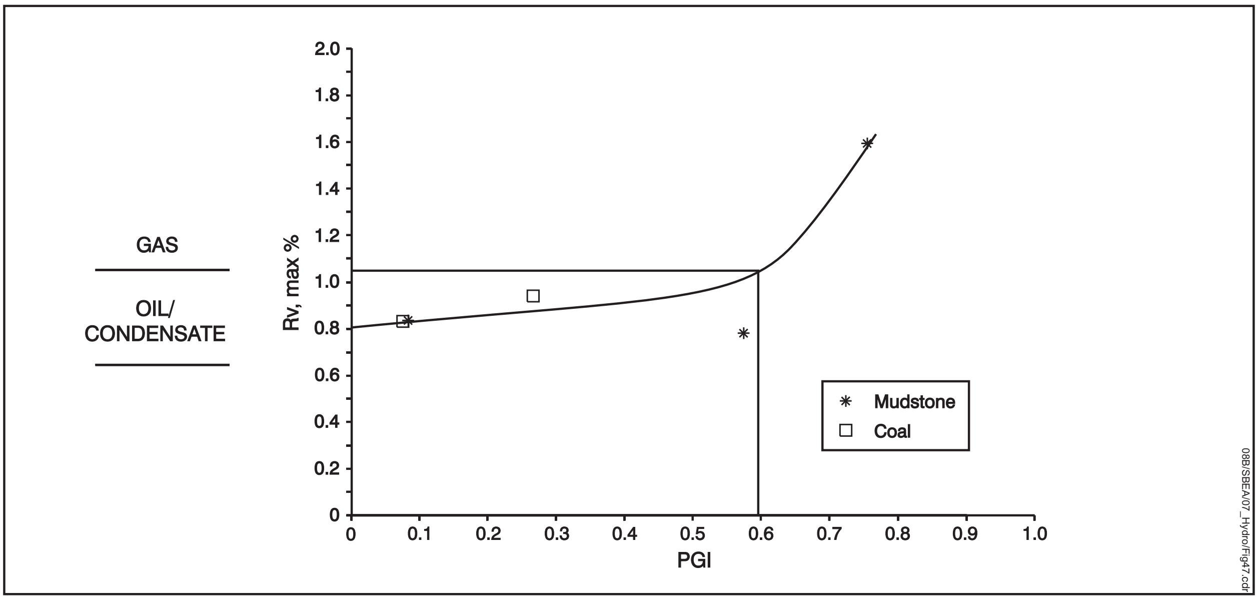

Figure 53: PGI versus Rv,max plot for condensate/gas potential mudstones and coals in the 'Baralaba' group.

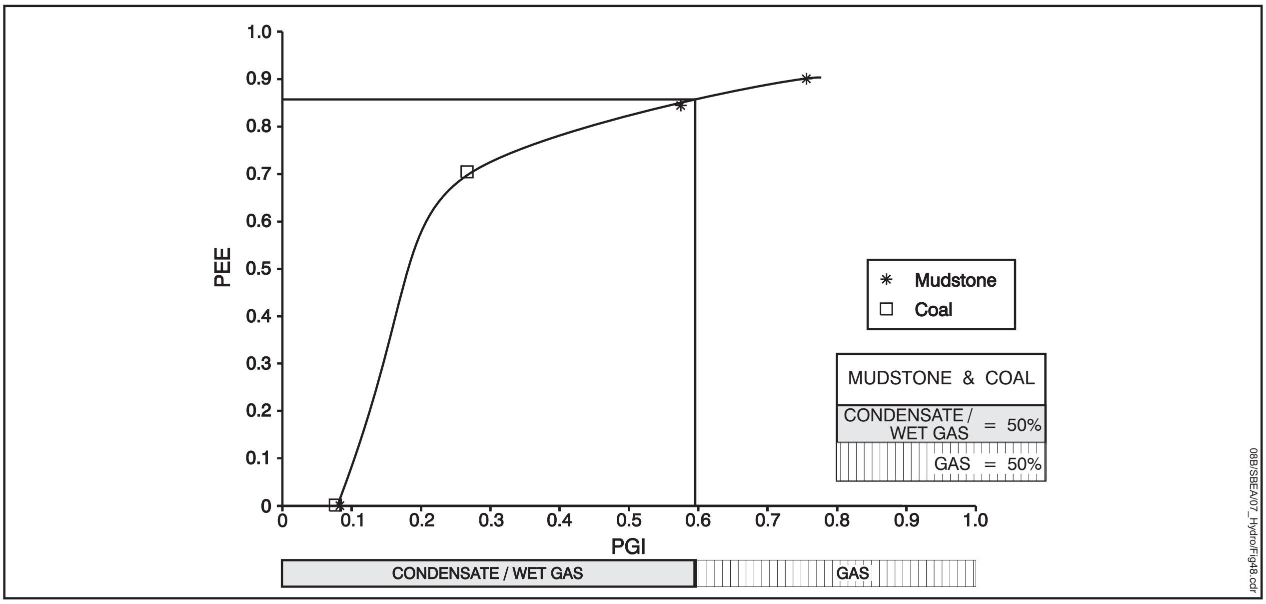

Figure 54: PGI versus PEE plot for the condensate/gas potential mudstones and coals in the 'Baralaba' group.

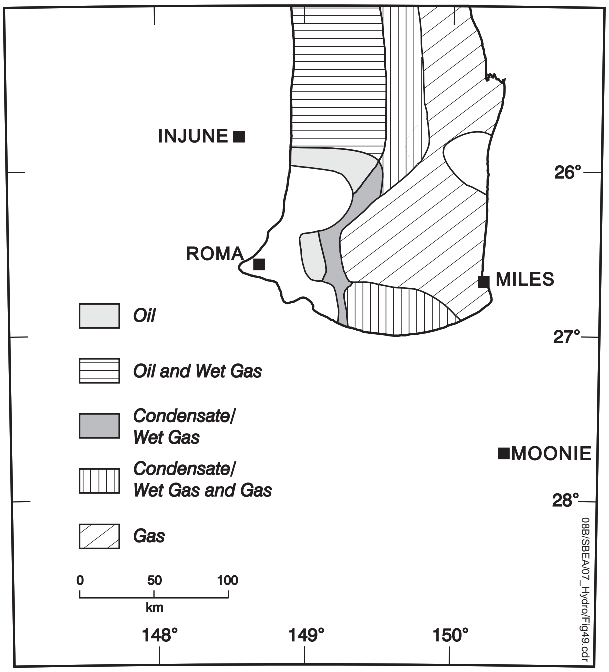

Figure 55: Hydrocarbon generation areas for the mudstones in the 'Baralaba' group.

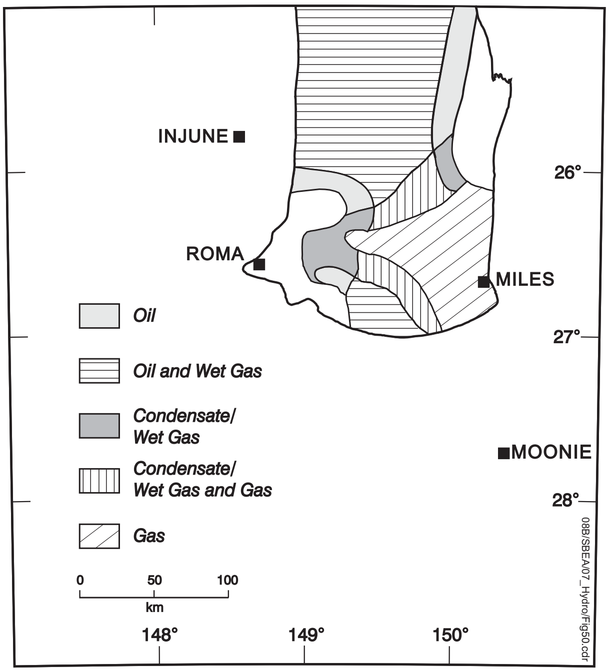

Figure 56: Hydrocarbon generation areas for the coals in the 'Baralaba' group.

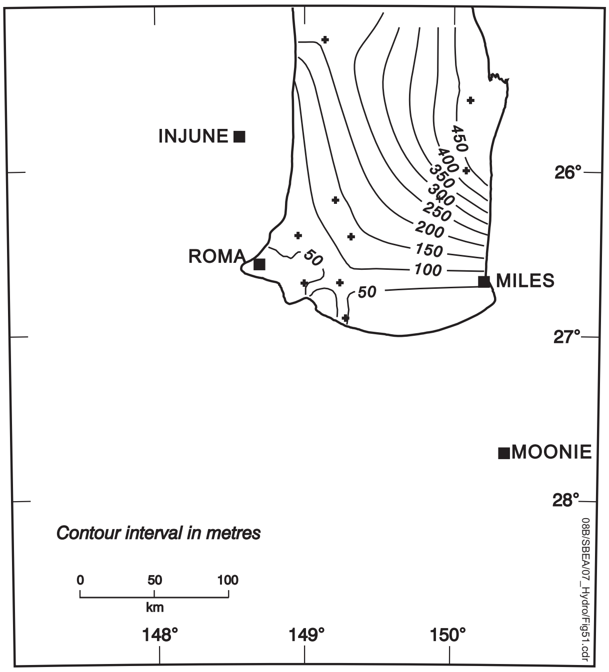

Figure 57: Effective thickness for the mudstones in the 'Baralaba' group.

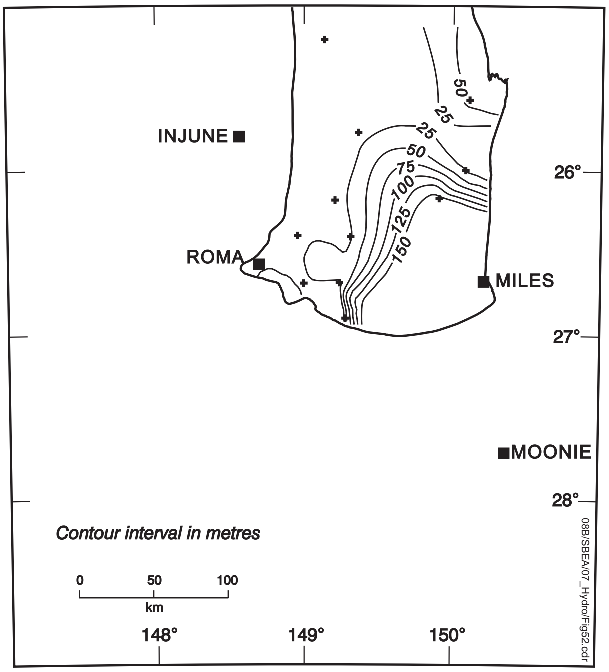

Figure 58: Effective thickness for the coals in the 'Baralaba' group.

there is a PEE expulsion value of 0.25 at PGI of 0.2 (Figure 52). This results in a maximum of 5% expulsion of oil from the coals, a value similar to that for the 'Flat Top' group coals.

The 'Baralaba' (and 'Flat Top') group coals have one-fifth the ability to generate and expel oil over the initial 'oil window' compared with the 'Burunga' group coals. This difference may be caused by a more waxy product being generated from the 'Baralaba' coals or be due to some difference in the physical properties of the 'Baralaba' and 'Burunga' coals. If the mudstones vary to the same extent as the coals, then the mudstones in the 'Baralaba' can be expected to expel one-fifth the oil to that of the 'Burunga' group. That is, 10% oil is capable of being expelled from the mudstones in the

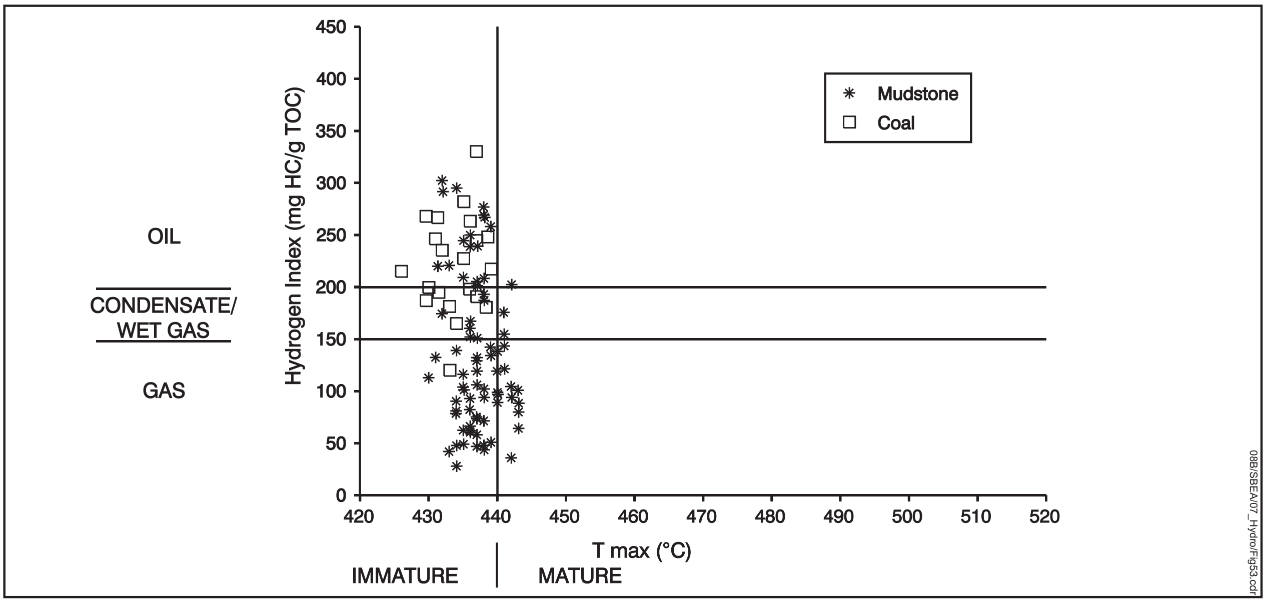

Figure 59: HI versus Tmax plot for mudstones and coals in the Moolayember Formation.

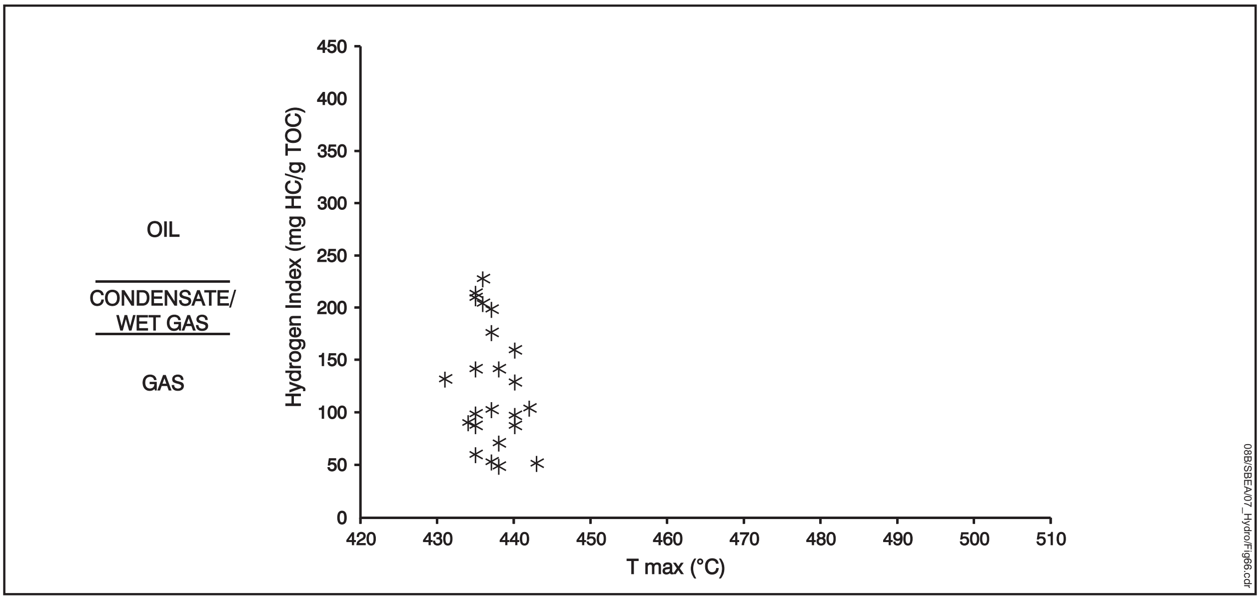

Figure 60: Average HI versus average Tmax values for the mudstones for each well intersecting the Moolayember Formation.

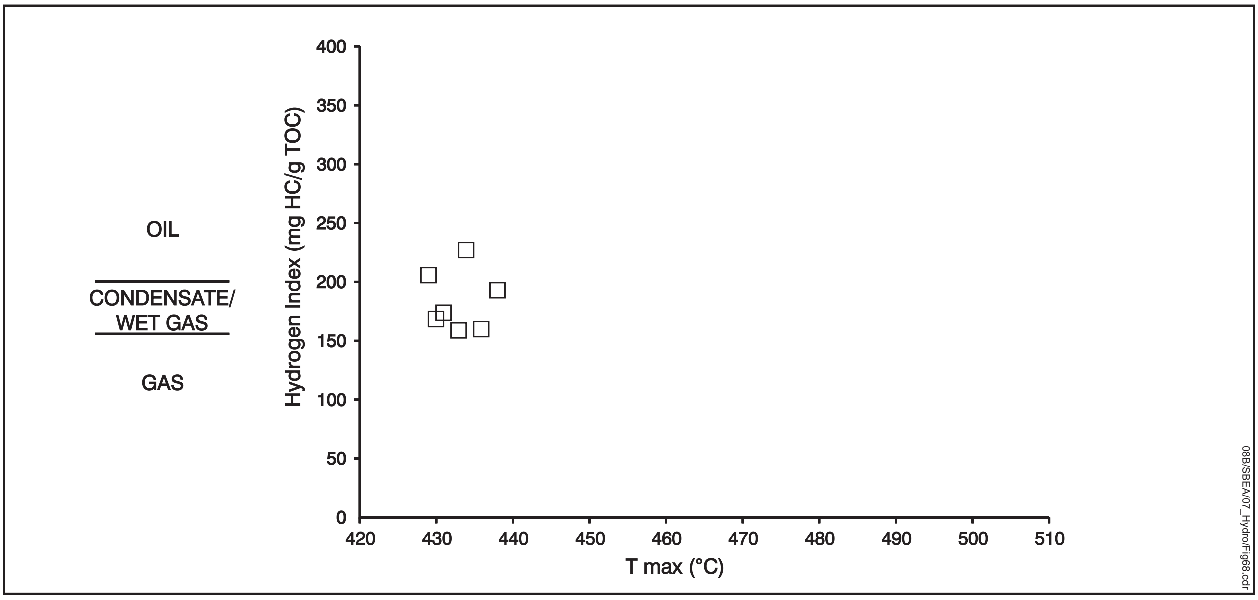

Figure 61: Average HI versus average Tmax values for the coals for each well intersecting the Moolayember Formation.

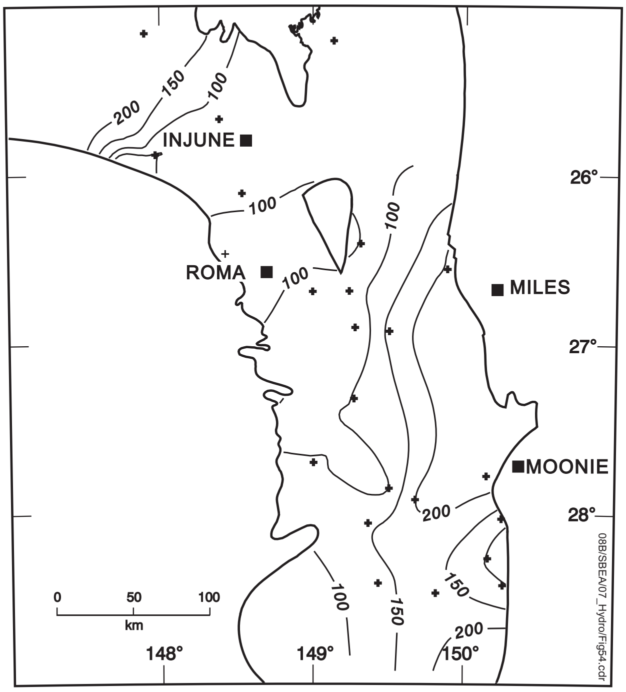

Figure 62: HI values for mudstones in the Moolayember Formation..

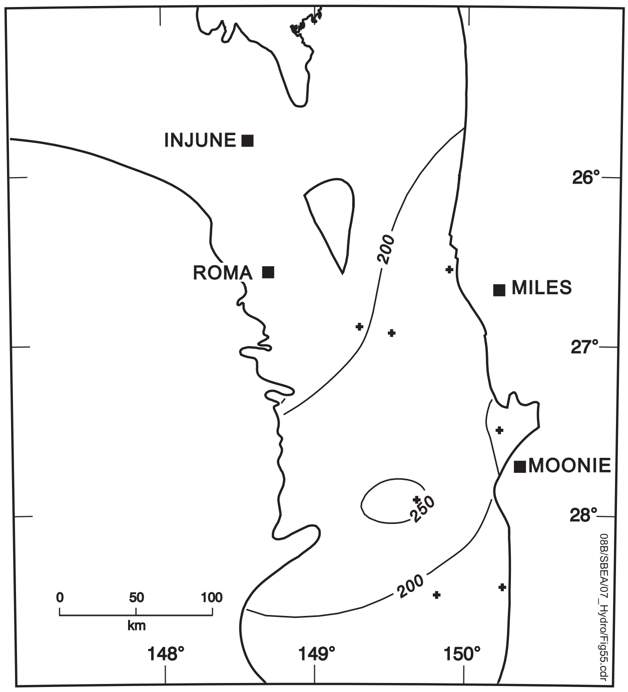

Figure 63: HI values for coals in the Moolayember Formation.

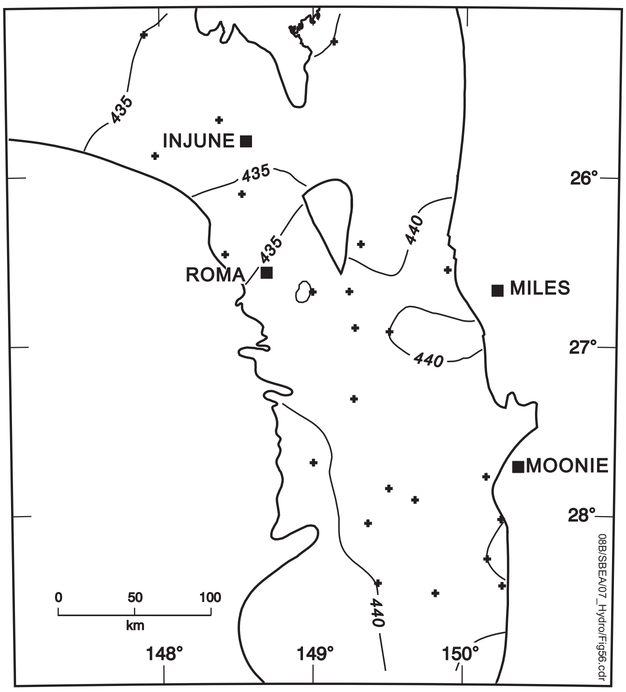

Figure 64: Tmax values for mudstones in the Moolayember Formation.

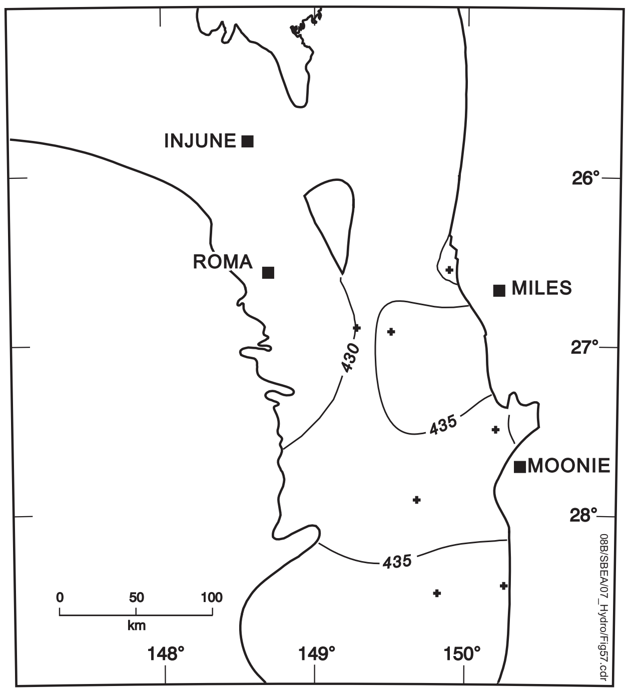

Figure 65: Tmax values for coals in the Moolayember Formation.

'Baralaba' group. The remaining 90% would be generated as gas.

The condensate/wet gas-prone coals and mudstones are shown on the Rv,max v PGI plot (Figure 53). Generation of liquid petroleum occurs up to PGI = 0.6. The coals and mudstones have similar generation trends.

Initial generation of liquids occurs at, or before Rv,max = 0.85% and Tmax of 440°C. There is a high expulsion rate of 85% at PGI = 0.6 so that 50% condensate/wet gas is expelled from the mudstones and coals (Figure 54). The remaining 50% potential is generated and expelled as gas when Tmax exceeds 450°C.

For the mudstones there is an area of non generation in the south-west (Figure 55). To the north and east of this area there are regions of oil generation where HI_{init}>200mg HC/g TOC and Tmax is between 440°C and 450°C and of oil and gas generation where HI_{init}>200mg HC/g TOC and Tmax>450°C. In a zone to the east, condensate/wet gas generation occurs where HI_{init} is between 150– 200mg HC/g TOC and Tmax is between 440°C and 450°C. Mainly gas generation occurs when the Tmax exceeds 450°C. On the eastern side of the Trough only gas has been produced as HI_{init} values are less than 150mg HC/g TOC.

The generation areas for the coals are similar to those for the mudstones except that the oil generation areas occupy almost one-half the total area of the 'Baralaba' group (Figure 56). The south-west corner is an area of non-generation and to the north, north-east and south-east of this area are areas of oil generation where HI_{init} > 200mg HC/g TOC and Tmax>440°C. Between the gas generation area in the south-east quadrant where HI_{init} <150mg HC/g TOC, and the oil generation areas, are condensate/wet gas generation areas (where HI_{init} is between 150 to 200mg HC/g TOC). Oil, condensate and gas generation occurs in the northern and central regions and gas generation in the south-eastern quadrant.

The effective thickness of the mudstones increases from less than 50m in the south-west to over 450m in the north-east (Figure 57). The areas that have generated oil have the thinnest effective mudstones thicknesses ranging from 50m to 300m. The effective thicknesses for the condensates/wet gas increases to a range between 50m to 400m. The mudstones with solely gas potential have the greatest effective thicknesses.

The effective thickness of the coals is generally less than 25m (Figure 58). The exceptions are UOD Wandoan 1 in the south-east, with a calculated 161m of coal and UOD Cockatoo Creek 1 in the north-east, with a calculated thickness of 56m of coal.

MOOLAYEMBER FORMATION

Source Rock Quality and Maturity

The Moolayember Formation has the potential to generate oil, condensate and gas (Figure 59), because the HI values range from <50mg HC/g TOC to greater than 300mg HC/g TOC. There were no samples with a Tmax>445°C indicating that the Moolayember Formation is immature to marginally mature for hydrocarbon generation. The Moolayember Formation may have reached higher maturities in the central parts of the Trough where burial has been deeper.

The average HI and Tmax values for the mudstones and coals for each well (Figures 60 & 61) show the coals have a potential for generating oil and condensate/wet gas and the mudstones have a wider potential ranging from gas to oil.

The source quality of the mudstones and coals is given by the HI contour maps (Figures 62 & 63). The HI values used are present-day and these are equivalent to the HI_{init} values given in the other 'groups' as little or no generation of hydrocarbons has occurred. The mudstones have generally low values of 50 to 100mg HC/g TOC on the western side of the Trough with higher values up to 200mg HC/g TOC on the eastern margin and in the north-west.

The HI for the coals shows a fairly even range of values around 200mg HC/g TOC (Figure 63). The coals in the Moolayember Formation are located in the eastern half of the Trough south of latitude 26°S.

The Tmax of the mudstones shows an almost even Tmax range around 440°C with only slightly lower values to 435°C in the north-west (Figure 64). The Tmax values for the coals are more limited with only a small variation around 435°C (Figure 65).

Generation and Expulsion

From the available data the Moolayember Formation is interpreted to be mainly immature with only very limited liquids generation which is in accord with the results of Boreham (1994; 1995). As such, no meaningful mass balance calculations could be performed.

SNAKE CREEK MUDSTONE MEMBER

Source Rock Quality and Maturity

The source quality of the mudstones of the Snake Creek Mudstone Member at the bottom

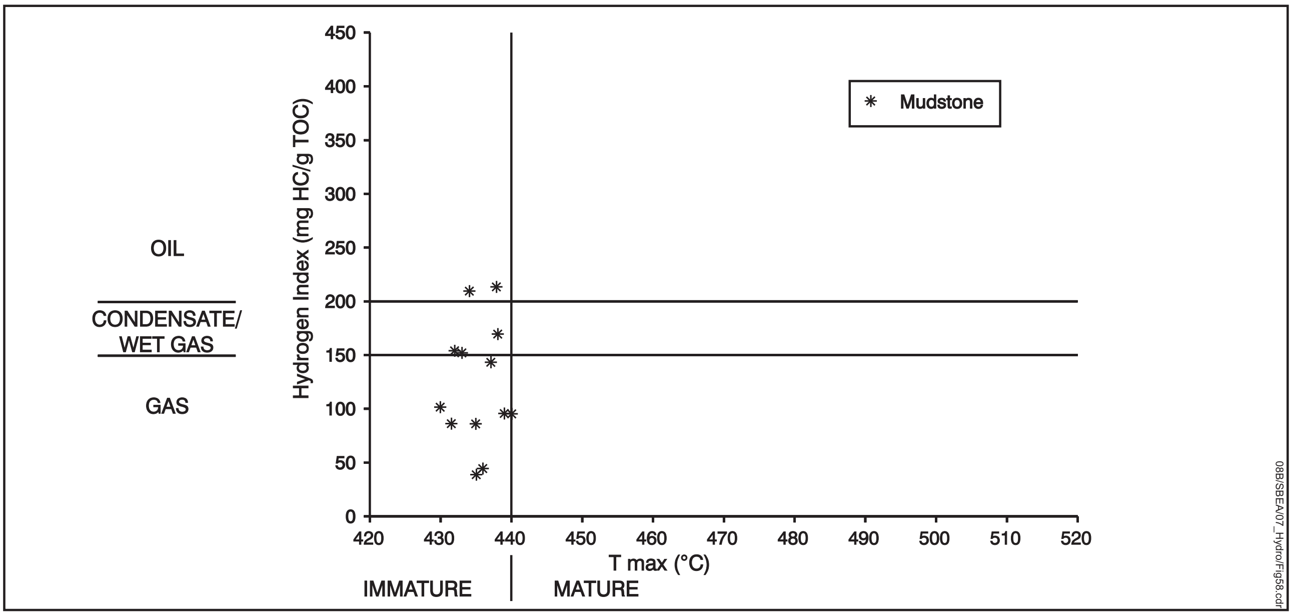

Figure 66: HI versus Tmax for mudstones in the Snake Creek Mudstone Member.

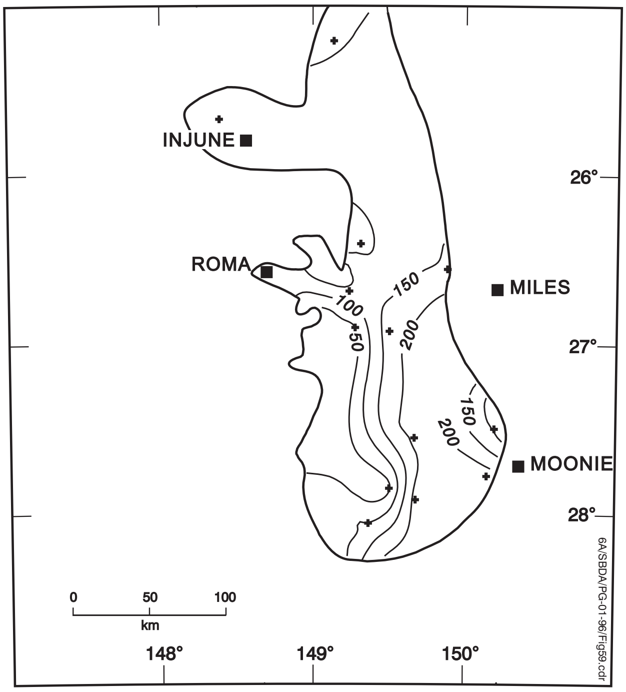

Figure 67: HI values for mudstones in the Snake Creek Mudstone Member.

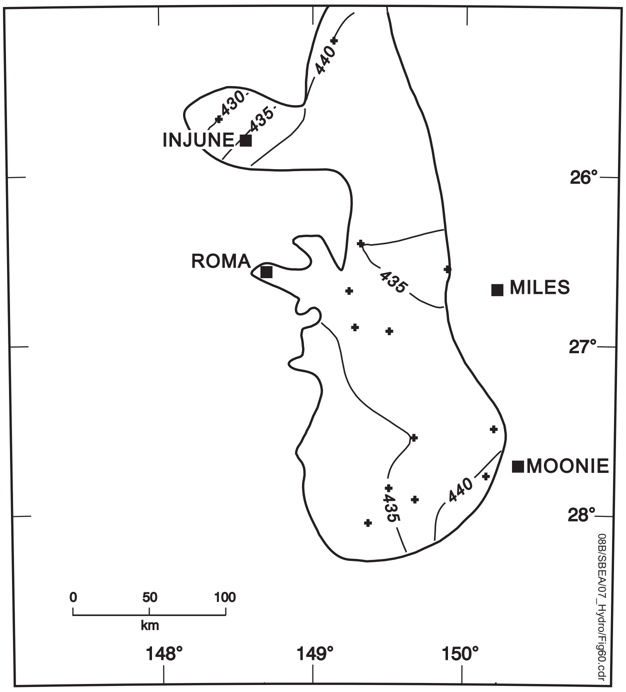

Figure 68: Tmax values for mudstones in the Snake Creek Mudstone Member.

of the Moolayember Formation is limited to condensate and gas with HI values mostly less than 200mg HC/g TOC (Figure 66). As for the Moolayember Formation, the mudstones are immature with most Tmax values less than 440°C.

The HI values indicate gas potential along the western sides of the Trough with HI values less than 150mg HC/g TOC (Figure 67). The Snake Creek Mudstone Member in eastern half of the Trough has a potential for producing condensate/wet gas.

The Tmax values have a fairly even range with no general trend (Figure 68).

Generation and Expulsion

From the available data, the Snake Creek Mudstone Member is interpreted to be mainly immature with limited generation. No mass balance calculations were attempted.

DISCUSSION

Previous workers have concluded that potential source rocks exist in both the Bowen and Surat Basins (Thomas & others, 1982; Hawkins & others, 1992). Boreham (1994, 1995) considers that the Surat Basin has not made a contribution towards reservoired liquids. Bulk geochemical parameters based on Rock Eval and TOC confirm liquid hydrocarbon potential in the Permian succession and the Triassic Moolayember Formation.

For the southern Taroom Trough, the coals and mudstones that were deposited in lower delta plain and near shore marine environments such as the 'Burunga' group are source rocks with the best potential for producing liquid hydrocarbons. The source rocks that were deposited in marine dominated environments, such as those from the 'Flat Top' and the 'Banana' groups, have minor liquids potential and are mainly a producer of gas. The source rocks from the fluvial, swamp and delta plain environments of the 'Baralaba' group, have a fair potential for liquid hydrocarbon generation. Depending on the maturities reached, gas is capable of being generated from the source rocks of all four 'groups'.

The question as to "what maturity levels can be used to define the petroleum generation history in the Bowen Basin?" has been addressed through a combination of geochemical and optical techniques. Using the evolution of HI and S1/TOC with Tmax, the onset of liquids generation occurs at Tmax = 440°C for the oil-prone coals and mudstones whereas those rocks with lower oil-producing potential begin hydrocarbon generation at slightly higher maturities, at Tmax = 445°C.

At higher maturities, HI continues to decrease in response to petroleum generation and the rate of decrease is reflected in the type of petroleum generated. The S1/TOC parameter maximises at about Tmax 450°C, seen as a significant maturity level where there is a change in the composition of the evolved hydrocarbons from liquids dominated below Tmax 450°C to gas above. This maturity (corresponding to Rv,max of 1.05%) separates the maturity levels of oils and condensates, from the reservoired gases (Boreham, 1994, 1995). Furthermore, the cumulative PGI's at this maturity level for the more oil-prone coals and mudstones are higher that those with lower hydrocarbon potential.

In the oil-prone rocks, there is a higher percentage of total hydrocarbon potential converted to free hydrocarbons (mainly oil) up to this maturity while for the latter, the bulk of the hydrocarbon potential (mainly gas) is converted from kerogen to free hydrocarbons at higher maturities.

Nevertheless, the efficiency of expulsion of the liquids depends on rock type and petroleum composition. Generally, mudstones have the same or higher PEEs compared with coals up to Rv,max 1.05% whereas the PEEs are high for both rock types at higher maturities in accord with high gas saturations. Thus, the decrease in the S1/TOC content above Tmax = 450°C is a result of more efficient expulsion of residual liquids or cracking of liquids to gas which is more readily expelled. At Tmax of 460-470°C, the S1/TOC falls below 30mg hydrocarbons which effectively defines the end of the 'oil window'.

There is a positive relationship between Tmax and Rv,max, for Tmax>445°C. However, at lower maturities the relationship is less certain where over a maturity range of Rv,max 0.6-0.85% there is little variation in Tmax. In part, this is due to limitations of the Rv,max values which have been extrapolated assuming linear increases in Rv,max with depth. Thus, there is a lower confidence level in assigning a Rv,max value to the onset of oil generation either directly from the vitrinite reflectance data or indirectly from its relationship with Tmax. Thomas & others (1982) used a vitrinite reflectance of 0.7% to 0.8% and Hawkins & others (1992) and Boreham (1994, 1995), used 0.7% Ro for the onset of oil generation. These values are slightly lower (0.1% Rv,max) compared with the results obtained in this investigation. The maturity values, Tmax and Rv,max, may indicate the point at which maximum generation of hydrocarbons occurs and may not be sensitive enough parameters to be able to measure the onset of hydrocarbon generation. This may account for the lower calculated maturity for the oils and gases and the higher maturities calculated for the source rocks.

The 'Flat Top' group is generally mature for petroleum generation with the central and eastern parts of the study area at approximately latitude 27°S within the 'liquid window', although there is a trend to lower maturities towards the basin margin. To the north, west and south, the rocks are in the 'gas window'. Coals have generated condensate in the centre at approximately latitude 27°S. However, the limited extent, thickness and inefficient expulsion preclude the coals from being a major contributor to present accumulations. However, the more extensive mudstones, that have undergone peak generation of gas in the central region could have provided an efficient gas drive for mobilising residual liquids within the 'Flat Top' group or those generated from younger 'groups'. Mudstone thicknesses increase northwards along the present eastern margin. Although these rocks are now past peak gas generation, they would have generated and expelled significant amounts of liquids and gases.

The 'Banana' group mudstones are a source for gas with minor light liquids generated in the central areas. To the south of latitude 28°S, the mudstones are immature. To the north-north-west, the rocks are overmature with generation of mainly highly mobile dry gas. A prospective pocket occurs in the far north-east where the mudstones are the thickest and show maturities for peak gas generation.

The 'Burunga' group coals and mudstones show the best liquid generation in the Permian succession with the coals having generated oil over most of the southern Taroom Trough. The mudstones have generated both oil and condensate/wet gas. Along the margins and in the south, the rocks are immature for liquids generation. The centre of the trough has reached peak liquid generation. Expulsion efficiencies are moderate to high over the 'oil window' for both coals and mudstones, with the mudstones having the greater efficiencies. Thus, the 'Burunga' group is considered to be the principle source for the liquid petroleum reservoired on both sides of the Trough.

The 'Baralaba' group mudstones and coals have liquids potential and are mature for petroleum generation except in the south-west, where the group is immature to marginally mature. Where the rocks show the highest liquids potential (south-west corner) they generally have inefficient maturity and thickness to be considered local sources for the reservoired petroleum. However in the centre of the Trough, they could have provided a contribution to the petroleum on the Roma Shelf.

The Moolayember Formation and the Snake Creek Mudstone Member contain coals and mudstones with some liquids producing potential. However, insufficient maturity over most of their extent precludes any significant contribution to petroleum accumulations.

CONCLUSIONS

The Permian Buffel Formation, Barfield Formation, Flat Top Formation and the undifferentiated Back Creek Group (collectively termed 'Flat Top' group) are predominantly a source for gas and minor liquids. The oil-prone mudstones and coals are restricted to an area that has not reached sufficient thermal maturity for oil generation. The liquids generation potential from the coals and mudstones is low, mainly due to poor source quality and limited expulsion from these source rocks. Gas has been the main product generated from this group. Condensate/wet gas generation occurs within the Tmax range 445-450°C. Gas is generated above Tmax of 450°C.

The Permian Banana Formation and the Muggleton Formation (termed the 'Banana' group) are predominantly a source for gas. The southern parts of the Trough are immature for gas but the generation potential increases northwards. Limited quantities of wet gas are generated in the Tmax range 445-450°C with most gas generated above 450°C.

The Permian Burunga Formation, including the Scotia Coal Member, Black Alley Shale, Tinowon Formation and the Wiseman Formation (termed 'Burunga' group) have the richest source potential. Coals and mudstones are the principal effective source for liquid petroleum accumulations in the southern Taroom Trough. The coals capable of generating and expelling oil extend across a significant area of the Trough whereas mudstones capable of generating and expelling oil are more limited in extent. Mudstones have a greater contribution to the condensate/wet gas accumulations. Oil and condensate/wet gas generation occurs within the Tmax range 440-450°C. Gas is generated when Tmax exceeds 450°C.

The Permian Baralaba Coal Measures and the Bandanna Formation (termed 'Baralaba' group) are a potential source for gas and minor liquids. The mudstones and coals capable of generating and expelling oil extend across almost half of the area covered by these formations. However, low expulsion efficiencies and limited source rock thicknesses reduce their significance as a source. The gas-dominated petroleum reserves on the Roma Shelf may have had a significant contribution from the 'Baralaba' group through medium to long range south-westerly migration from the more mature rocks. Oil and condensate/wet gas generation occurs within the Tmax range 440-450°C. Gas is generated above Tmax of 450°C.

The Triassic Moolayember Formation with the Snake Creek Mudstone Member are immature to marginally mature for generation of hydrocarbons. Only where Tmax has exceeded 440°C, has there been any generation of hydrocarbons.

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HYDROCARBON POTENTIAL AND FUTURE EXPLORATION STRATEGIES IN THE BOWEN BASIN AND OVERLYING SURAT BASIN, SOUTH-EAST QUEENSLAND

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(Geological Survey of Queensland)

INTRODUCTION

The results of the “Sedimentary Basins of Eastern Australia” Project provide information on the potential of the Bowen and Surat Basins in southern Queensland to contain hydrocarbon accumulations additional to those already known. This qualitative assessment of hydrocarbon potential is based on the major sequences identified in an earlier chapter (Hoffmann & others, this volume). The potential of each sequence is assessed on the basis of the interrelationships between the source, thermal history and knowledge on the stratigraphic distribution of reservoirs and seals throughout the study area and is summarised in Table 1. The assessment of the hydrocarbon potential and the development of the future exploration strategies are based on the ideas developed by Queensland Department of Mineral and Energy’s staff during the project.

The major element considered in this assessment of the hydrocarbon potential of the southern Taroom Trough was the influence that the depositional setting of the sequences had on source potential and reservoir distribution.

Traditionally, the southern Taroom Trough has been regarded as a structural trough being infilled from both the eastern and western sides. However, the results of this project show that throughout most of the Permian, no trough existed in the southern part of the study area. Rather, the Permian succession represents a series of four stacked transgressive system — highstand system tracts (TST–HST) deposited in a back-arc sea. Lowstand system tracts (LST) are not represented in this part of the Bowen Basin.

The development of the trough as a structural identity first occurred in the Early Triassic when it started to be filled with a thick succession of fluvial and lacustrine sediments. The recognition of this depositional setting assists in understanding reservoir development in this area and thus its hydrocarbon potential.

The lower part of the Surat Basin succession represents a stacked series of fluvial sequences. The alternation of sequences incorporating various parts of the LST–TST–HST fluvial sequence cycle greatly influenced the distribution of reservoirs and seals in the basin throughout the study area.

The Permian succession has been identified as having the best source potential (Carmichael & Boreham, this volume) and this influences the distribution of hydrocarbon accumulations in both the Bowen and Surat Basins. Accordingly, the areas assessed as having potential for the accumulation of hydrocarbons are shown relative to the extent of the Permian in the study area (Figures 1–10).

TABLE 1: POTENTIAL OF THE SURAT AND BOWEN BASINS

Sequence	Formations	Source Types	Reservoirs	Seals	Traps	Potential Reserves
SURAT BASIN						
L	Westbourne Formation	Nil	Poor	Good	Anticlinal	Nil potential due to absence from a source
	Springbok Sandstone	Nil	Good	Nil	Anticlinal	Limited potential due to distance from source
K	Walloon Coal Measures	Early methane generation	Some potential in lowermost parts	Good	Anticlinal	Coal seam methane only; no expulsion from source rocks
	Hutton Sandstone	Nil	Good	Nil	Anticlinal	Potential mainly in the east where leakage up faults has occurred
J	Evergreen Formation (Boxvale Sandstone Member)	Nil	Boxvale Sandstone Member; Basal sandstones on Roma Shelf	Good regional seals to Boxvale and basal sandstones	Anticlinal; ?stratigraphic on Roma Shelf	High prospectivity due to presence of good seal and reservoir; good potential on western margin where underlying seals are thinner
	Precipice Sandstone	Nil	Good	Nil	Anticlinal	High prospectivity due to proximity to source units in the Bowen Basin
	Late Triassic rocks	Nil	Good but limited extent	?Local seals	Anticlinal; ?stratigraphic	Limited potential due to extent but proximity to Triassic and Permian sources increases prospectivity
BOWEN BASIN						
I_{1-2}	Moolayember Formation	Possible source in deeper parts of the southern Taroom Trough	Poor, locally better in the west and north	Good seals, especially in the north	Anticlinal	Moderate potential for small discoveries on the southern Roma Shelf; moderate potential in the north due to local generation and better reservoir development
H_{1-2}	Snake Creek Mudstone Member, Clematis Group, Showgrounds Sandstone	Minor liquids generation in the central part	Good	Good regional seal	Anticlinal; stratigraphic in the west	Good on the Roma Shelf due to well developed seals and close proximity to source; isolated reservoirs elsewhere
G	Rewan Group	Nil	Basal sandstones; moderate in the west and some potential in the central part	Good regional seals in the upper part	Anticlinal	Moderate to good due to upper seals and reservoirs being adjacent to a better quality source in the south and south-west; significant undiscovered reserves possible
F	Black Alley Shale, Burunga Formation (marine + upper coal interval), Bandanna Formation, Baralaba Coal Measures, lower part of the Rewan Group	Mainly gas; minor liquids	Nil; coal seams	Local seals in the west; good regional seals in the east	Anticlinal; ?stratigraphic in the centre of the Trough	Coal seam methane potential good in shallower parts
E	Tinowon Formation, Scotia Coal Member, Burunga Formation (lower coal measures), Banana Formation, Muggleton Formation	Liquids	Better in the west; potential in the centre	Good internal seals	Anticlinal ; ?stratigraphic in the central parts of the Trough	Moderate potential; good reservoir prediction will be difficult
D	Flat Top Formation, Barfield Formation	Mainly gas	Better in the north-east; ?onlapping basal sandstones in the west	Good regional seals	Anticlinal; ?stratigraphic in the north-east	Moderate potential in the north-east in stratigraphic traps with a structural component
C	Undifferentiated Late–Early Permian, Oxtrack Formation	?	?	?	?	Unlikely to contain any major reserves due to restricted distribution and thinness
B	Buffel Formation and correlatives	Mainly gas	?Basal sandstones	Good seal	Anticlinal; ?stratigraphic	Poor potential due to lack of reservoir; gas only
A_{1-2}	Camboon Volcanics, Combarngo Volcanics, Arbroath beds, Undifferentiated Early Permian rocks	Mainly gas	Poor	Good seal	Anticlinal; ?stratigraphic	Some potential exists in fractured volcanic rocks but generally poor potential due to lack of porosity; gas only

SEQUENCE ASSESSMENTS

BASEMENT

Basement to the Surat and Bowen Basins on the Roma Shelf and western side of the Taroom Trough has reservoired hydrocarbons (Table 2). Since 1961, seven wells have flowed gas from drill stem tests of basement. In addition to gas, oil and condensate was recovered from AAO Dirinda 1 and AAO Pringle Downs 1 respectively. Several other wells in the Roma area have also recorded strong hydrocarbon shows from basement. Hydrocarbons have not been discovered in the basement to any other sedimentary basin in Queensland.

All gas flows have been from the Timbury Hills Formation. In five wells, Permian strata directly overlie the basement gas occurrence; the Middle Triassic Moolayember Formation and the Early Jurassic Evergreen Formation directly overlie the other two. The proximity of the Permian succession provides a ready source of hydrocarbons in these basement occurrences.

In five wells, hydrocarbons generated in the Permian would have migrated downwards directly into the fractures in the underlying basement. In the other two wells, some lateral migration must have occurred before vertical migration.

The possibility of finding commercial reserves of hydrocarbons in the basement to the Surat and Bowen Basins should never be ignored.

SUPERSEQUENCE A

Resource Assessment Rating: Poor to moderate

Supersequence A includes the Camboon Volcanics, Combarngo Volcanics and the Early Permian coal measures and related rocks. This sequence has limited potential to have been a source or have reservoired hydrocarbons. This assessment is based on the limited areal distribution and thinness of the sequence.

Table 2: Hydrocarbons in basement

Well	Location	Structural Setting	Stratigraphy (lower part) (m)	Relevant DST	Year
AAO Pickanjinnie 2	26°37'00" 149°08'00"	Roma Shelf	1416 Permian 1600 Timbury Hills Formation 1704 T.D.	DST 5 (1606–1671.5) Gas to surface @ 2100m^3/D	1961
AAO Dirinda 1	26°40'47" 148°40'32"	Roma Shelf	1106 Evergreen Formation 1208 Timbury Hills Formation 1309 T.D.	DST 2 (1209–1219m) Gas to surface @ 1030m^3/D 180m oil; DST 3 (1219–1230m) Gas to surface @ 200m^3/D	1964
AAO Pringle Downs 1	26°41'05" 148°43'00"	Roma Shelf	1185 Moolayember Formation 1188 Timbury Hills Formation 1222 T.D.	DST 1 (1184–122m) Gas to surface @ 96 300m^3/D, 1.5m condensate	1967
HPP Namara 1	27°22'50" 149°19'22"	Western Bowen Basin	2270 Permian 2346 Timbury Hills Formation 2383 T.D.	DST 5 (2336–2374m) Gas to surface @ 135 600m^3/D	1981
HEP Blackbutt 1	26°55''50" 149°05'47"	Southern Roma Shelf	1634 Permian 1732 Timbury Hills Formation 1792 T.D.	DST 3 (1734–1766m) Gas to surface @ 135 900m^3/D	1984
CON Namara 2	27°21'45" 149°16'43"	Western Bowen Basin	2304 Permian 2393 Timbury Hills Formation 2445 T.D.	DST 6 (2395–2445m) Gas to surface @ 226 000m^3/D, reduced to 62 000m^3/D	1987
BON East Glen 1	27°28'25" 149°16'43"	Western Bowen Basin	2146 Permian 2210 Timbury Hills Formation 2259 T.D.	DST 3 (2212–2259m) Gas to surface @ 8500m^3/D, reduced to 20m^3/D	1991

The presence of coals suggests that there are possible source rocks in the sequence. Although the maturation level of the sequence suggests that hydrocarbon generation has occurred, the coals are thin, not widely distributed and thus unlikely to have generated significant quantities of hydrocarbons.

The best reservoir potential of the sequence is related to fractured Camboon Volcanics. Fractured intervals of this unit have produced significant gas flows on test, especially in OMN Scotia 1 and UOD Burunga 1 in the northeastern part of the study area.

The depth of approximately 3000m to the Camboon Volcanics is however a mitigating factor regarding the exploitation of this potential resource. Nevertheless, the possible large reserves associated with the fractured volcanics, especially when on a large structure, make this a potential exploration target (Figure 1).

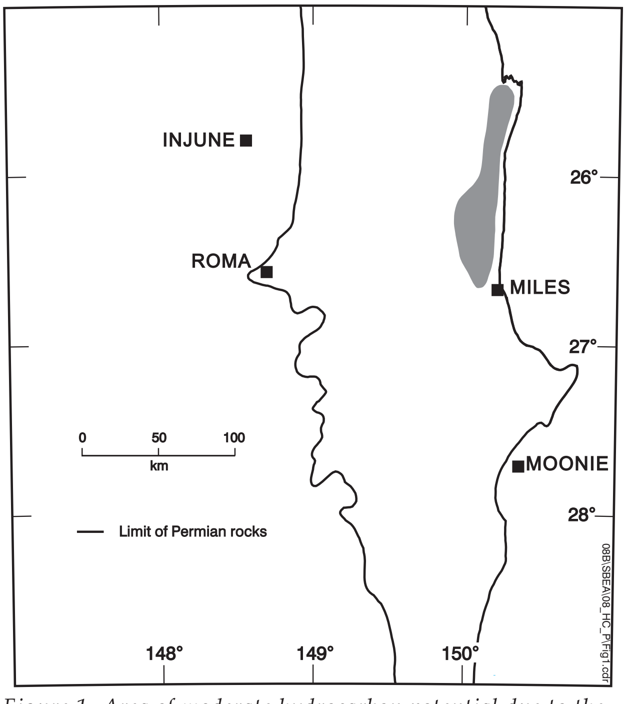

Figure 1: Area of moderate hydrocarbon potential due to the presence of large structures and fracture volcanic basement Supersequence A).

The gas in the Camboon Volcanics in the Scotia-Burunga area is unlikely to have been sourced from the Permian coal measures which are at least 1300m stratigraphically higher in the section. The source of the gas is likely to have been the overlying marine succession.

A flow of gas at 2600m^3/D and oil at 100BPD were obtained from a drill stem test of the fractured Combarngo Volcanics directly underlying the Showgrounds Sandstone in BON Taylor 1 in the western Surat and Bowen Basins. If the source of these hydrocarbons is the nearby Permian coal measures, then lateral migration and considerable downwards migration must have occurred. The interval tested (2064–2075m) is approximately 57m below the top of the volcanics in this well.

Although subsequently proved to be non-commercial, the possibility of finding other flows in the Combarngo Volcanics must not be ignored.

The reservoir quality of clastic rocks in the related Early Permian strata in both the Arbroath Trough and southern Taroom Trough is likely to be poor due to their volcanoclastic composition. The poor reservoir quality has significantly downgraded the potential of this sequence to contain conventionally trapped hydrocarbons.

The development of structural traps would have occurred from the late Early Permian compressional event to the present-day. Anticlines developed during the Early Permian event would be ideally situated to trap any subsequently generated hydrocarbons.

SEQUENCE B

Resource Assessment Rating: Poor to ?Moderate

The Buffel Formation and its correlatives are the major units present in Sequence B. The depositional setting for this sequence was mainly in a broad shallow sea landward of a volcanic arc. Fluvial conditions were associated with faults scarps in the south but shallow marine conditions predominated elsewhere. The level of thermal maturity associated with this sequence is sufficiently high for significant hydrocarbon generation to have occurred. There is insufficient data to assess the type of hydrocarbons that would have been produced, but gas is most likely.

The capability of the sequence to contain significant quantities of hydrocarbons is probably limited by poor reservoir quality. This is due to an abundance of volcanolithic grains in the sandstones. Also there is insufficient information to determine the distribution of the reservoir facies in this sequence in order to establish porosity trends.

Thick conglomeratic units and a higher percentage of sandstone are present in the basal part of the sequence in the south. This area is the most likely to contain suitable reservoirs, which increases its attractiveness for exploration.

There are no known major source intervals associated with this sequence. Sourcing of hydrocarbons, if not local, would require downward migration of gas and liquids generated higher in the section.

The type of trap most likely to be successful is anticlinal. The anticlines to be targeted are the early-formed structures associated with the late Early Permian compressional event. Those formed during this event would have been in existence to trap any hydrocarbons generated during the Triassic and Late Cretaceous.

High-risk types of traps are stratigraphic plays associated with pinch-outs along the western margin. Sedimentary facies along the western margin are poorly known and it is possible that better quality reservoirs may exist here due to regional facies variations and the presence of quartzose sandstones sourced from the west. These sandstones may have formed as a transgressive sandstone sheet or as deltas. Slightly higher energy conditions associated with these settings may have enhanced the porosity in these types of sandstones.

SEQUENCE C

Resource Assessment Rating: Poor

The Oxtrack Formation is the only lithostratigraphic unit in the sequence. This relatively thin formation (30–50m thick) is considered to be only locally developed and appears to be restricted to near outcrop. The potential of the sequence to have generated and trapped hydrocarbons is considered to be poor. If limestone units are present in the subsurface then the sequence could provide an excellent seal or reservoir. However, the current knowledge on the distribution and rock types present in the sequence in the subsurface significantly downgrades its resource potential.

SEQUENCE D

Resource Assessment Rating: Moderate

Sequence D includes the Barfield and Flat Top Formations and represents the first widespread development of marine conditions in the southern Taroom Trough. The development of these conditions was not simultaneous throughout the area. Marine conditions followed by fluvial or fluvio-deltaic conditions developed in the northern part of the basin, whereas in the southern part of the basin, a time of non-deposition followed by marine conditions existed.

The sequence has a high level of thermal maturity and is dominantly a source for gas. The major restriction on the hydrocarbon potential of the sequence is the development of suitable reservoirs.

Porosity is developed in the Flat Top Formation in the north-eastern part of the study area. A gas flow of 7075m^3/D from the Flat Top Formation in UOD Burunga 1 in this area indicates this is the most prospective part of this sequence (Figure 2). Traps present will have both structural and stratigraphic components. The stratigraphic component will be associated with the distribution of porosity

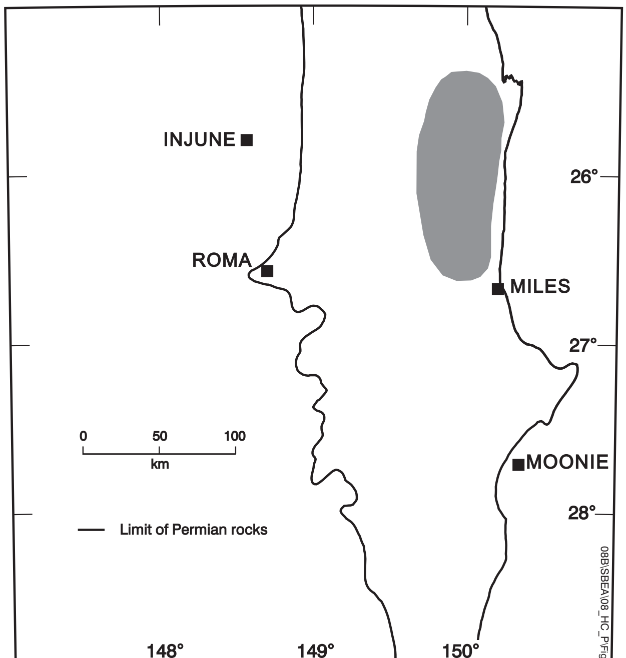

Figure 2: Area of moderate hydrocarbon potential associated with a known gas flow in the Flat Top Formation (Sequence D).

in a deltaic setting. However, the dominance of volcanoclastic material associated with this formation suggests that porosity development may be restricted. The key element in determining the prospectivity of the area is the original deltaic setting. The deltas associated with this sequence are likely to have been deposited mainly in a restricted sea and the potential for porosity enhancement due to reworking of the delta front may be limited. The major structural component preferred is anticlinal, and this will enhance the potential of any trap.

Basal sandstones are likely to be present in the south and south-west and would be associated with the onset of the transgression. However, the apparent rapid nature of the transgression associated with this sequence suggests that extensive regional development of reservoir quality sandstones is unlikely.

As discussed, the dominance of volcanolithic grains in the sandstones would also downgrade their potential. However, the gas flow in the Flat Top Formation in the north-eastern part of the study area is encouraging. This area is considered to have moderate potential.

SEQUENCE E

Resource Assessment Rating: Moderate

Sequence E comprises the marine Banana Formation, Scotia Coal Member and the lower coal interval of the Burunga Formation in the east and south and the Muggleton and Tinowon Formations in the west. The distribution of these formations reflects the complex facies variations associated with this sequence. The initial sedimentation reflects the development of extensive marine deposits followed by the widespread occurrence of coal. These coals are the earliest source rocks with a significant liquids generation potential. The maturation level associated with these coals suggests that significant liquids generation and expulsion have occurred.

The development of marine conditions has greatly influenced the potential of the lower part of Sequence E to contain hydrocarbons, particularly on the western margin. The presence of the deltaic, mostly quartzose Lorelle Sandstone Member of the Muggleton Formation greatly increases the prospectivity of the sequence in this region (Figure 3). In the eastern part of the basin, the Banana Formation is unlikely to produce major hydrocarbons owing to the dominance of mudstone and the absence of reservoir units.

The form of the deltas associated with the Lorelle Sandstone Member on the western margin is unknown. However, their deposition in a back-arc sea suggests that extensive reworking by ocean or wind-driven waves is unlikely. The deltas are probably fluvial dominated and contain elongate sandstone bodies associated with channels and distributary mouth bars.

The widespread presence of coals in the upper part of Sequence E reflects the extensive development of swamps. However, the lack of well-developed fluvial facies makes the recognition of potential reservoirs difficult. Also, the understanding in detail of the depositional setting of the coal measures is poorly known. Additional sedimentological investigations are required to delineate the depositional setting and, in particular, the controls on channel development and distribution. Any major stream development would be difficult to define and there is no apparent regional facies trends that would suggest the likely development of better reservoirs.

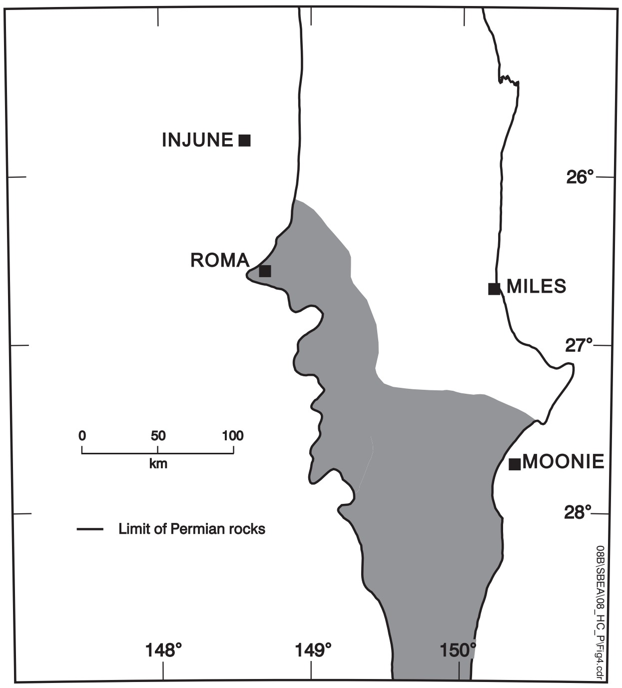

Figure 3: Area of moderate hydrocarbon associated with deltas of the Lorelle Sandstone Member (Muggleton Formation) and the excellent source potential of coals in the lower part of the Burunga Formation (Sequence E).

Although the sequence contains good source rocks, the ability to predict the occurrence of good reservoirs is the key factor in successful exploration for hydrocarbons in this sequence. Thus its potential can be rated as only moderate owing to the difficulties associated with reservoir prediction.

SEQUENCE F

Resource Assessment Rating: Poor to good

The lithostratigraphic units present in Sequence F include the marine and upper coal intervals of the Burunga Formation, the Baralaba Coal Measures and the lower part of the Rewan Group in the east and south and the Black Alley Shale and Bandanna Formation in the west. The depositional setting of the sequence reflects the final marine transgression and the establishment of fluvial and lacustrine conditions.

The cycle began with the development of widespread marine conditions and culminated in the development of extensive coal swamps. The coal measures were deposited in different settings, being fluvio-deltaic in the south and fluvial in the northern part of the study area. This change in setting reflects a northwards migration of coal depositional environments.

The early marine conditions were unsuitable for the development of significant reservoir facies in the lower part of the sequence. Reservoirs are only likely in the upper part of the sequence in association with channel sandstones deposited in association with coal swamps. The presence of abundant volcanogenic material, both primary and reworked, has been detrimental to reservoir quality. Therefore Sequence F is unlikely to contain significant quantities of hydrocarbons in conventional reservoirs.

Another problem associated with reservoir prediction is that the distribution of facies associated with this sequence is poorly known. The sequence stratigraphic model suggests that there was widespread development of coal swamps throughout the southern part of the study area during most of the deposition of this sequence. The depositional setting of the coal measures also varies from fluvio-deltaic in the south to fluvial in the north. The absence of a structural trough suggests that delta development was restricted to the eastern and western margins and the rivers feeding the deltas had an east-west orientation. A detailed reassessment of the depositional setting for the coal measures, especially those in the south, is needed to improve reservoir prediction.

The best reservoir potential exists in the lowermost part of the Rewan Group in the south. The lowermost part is a facies of the Baralaba Coal Measures and sediments were sourced from the south and west. Sediments supplied from these directions would have been derived from continental or granitic terranes and have a higher quartz content than those derived from the volcanic arc in the east. This would enhance reservoir quality. Better quality reservoirs therefore are likely to be present down-dip to the south (Figure 4).

The widespread distribution of thick shales in the upper part of the Rewan Group in the overlying sequence would act as a significant regional seal. Thus the lower part of the Rewan Group in Sequence F is ideally situated for the accumulation of hydrocarbons, being located stratigraphically above excellent source rocks (Burunga Formation) and capped by regional seals.

The source potential of the sequence is variable. The coal measures (Burunga Formation) deposited in the southern part of the area have the best liquids generation potential of all in the study area. The coal measures (Baralaba Coal Measures) in the north are mainly

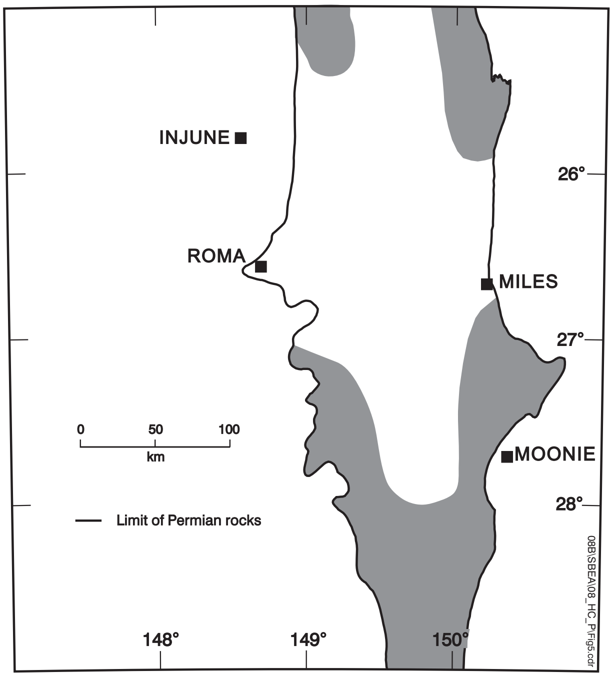

Figure 4: Areas of good hydrocarbon potential reflecting the quartz-rich sandstones in the lower Rewan Group and the coal seam methane potential of the Baralaba Coal Measures (Sequence F).

gas-prone and do not have as good a potential for hydrocarbon generation. This is related to the difference in depositional setting associated with the coal measures in the different parts of the study area.

The traps most likely to contain conventional hydrocarbons would be anticlinal, located in the southern part of the study area. This is supported by the number of significant hydrocarbon indications present in that basal part of the Rewan Group in this area.

The potential for coal seam methane production is also good especially for seams in the Baralaba Coal Measures (Figure 4). The seams in the formation are relatively thick and are thermally mature for the early generation of methane. The area rated "good" in the north of the study area reflects the recent coal seam methane discoveries.

SEQUENCE G

Resource Assessment Rating: Poor

Sequence G consists of most of the Rewan Group. The potential of this sequence to contain significant hydrocarbon reserves is considered poor. This rating is based on a perceived limited to non-existent source potential, and poor reservoir quality of the upper part of the Rewan Group.

In the southern part of the study area, Sequence G is stratigraphically near the best hydrocarbon generating sequence in the area and the abundant shales present in the upper part of the Rewan Group of Sequence G would form an excellent seal for the sandstones of Sequence F which comprise the lower part of the Group.

A systematic assessment of the hydrocarbon source potential of the Rewan Group was not undertaken as part of the Project. The source rock quality of the Rewan Group is generally considered to be poor due to most of its deposition in an oxidising fluvial setting. This setting resulted in the formation of red-beds, which is mostly devoid of organic matter. Nevertheless, continuous coring of the upper Rewan Group in GSQ Taroom 13, GSQ Taroom 14 and GSQ Baralaba 1 in the northern and north-eastern parts of the study area respectively, has shown that significant thicknesses of grey to black carbonaceous siltstones and mudstones are interbedded with the red-beds (Gray, 1984, 1985). The Rewan Group should not be disregarded completely as a source of hydrocarbons in the southern Taroom Trough.

SUPERSEQUENCE H

Resource Assessment Rating: Good

Supersequence H consists of the Clematis Group, Showgrounds Sandstone and the Snake Creek Mudstone of the overlying Moolayember Formation. The hydrocarbon potential of this supersequence is considered good. This rating is based on the excellent reservoir qualities associated with the Showgrounds Sandstone and Clematis Group and the ability of the Snake Creek Mudstone to act as a seal.

The distribution of the reservoirs in the Clematis Group is complex. The best reservoirs are associated with the Expedition Sandstone in the upper part of the Group. This formation forms a regionally continuous sandstone sheet throughout most of the study area and is thickest in the central and northern parts; it is porous in parts. The good quality of this reservoir is due to its braided-stream origin resulting in minimal clay being incorporated into the original stream channel deposits. However where the Expedition Sandstone is best developed in the central and northern parts of the study area, it is underlain by thick mudstones of Sequence G which act as a seal for any hydrocarbons generated in the Permian coal measures.

The Showgrounds Sandstone is the major reservoir on the Roma Shelf and western side of the Trough. Like the Expedition Sandstone, the Showgrounds Sandstone was also deposited in a fluvial setting. The coarse-grained nature of the formation suggests proximal sourcing of the quartz, the main component.

On the Roma Shelf and the western side of the Trough, the underlying Sequence G, which forms a seal to the hydrocarbon source of the underlying Permian coal measures, thins or is absent. This means that hydrocarbons generated in the coal measures can migrate upwards directly into the overlying sequence.

The Showgrounds Sandstone has long been recognised as being deposited by rivers that flowed eastwards between basement highs,

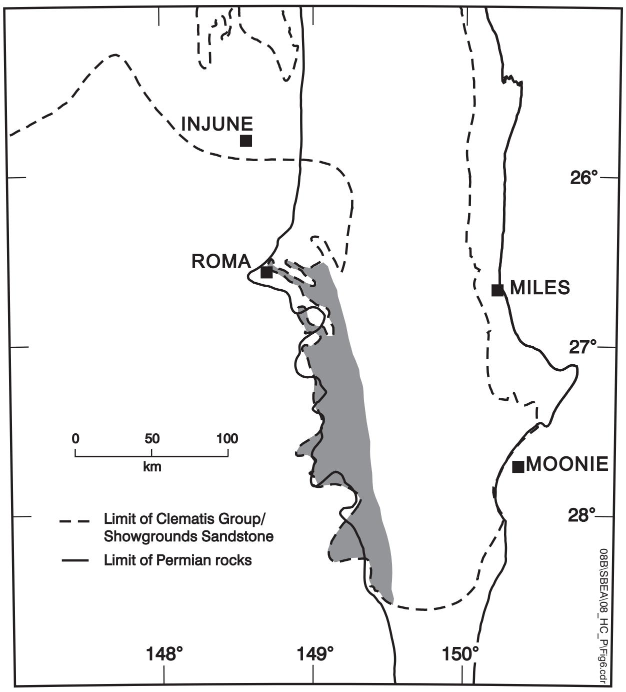

Figure 5: Area of good hydrocarbon potential reflecting the distribution of the Showgrounds Sandstone along the western margin (Sequence H).

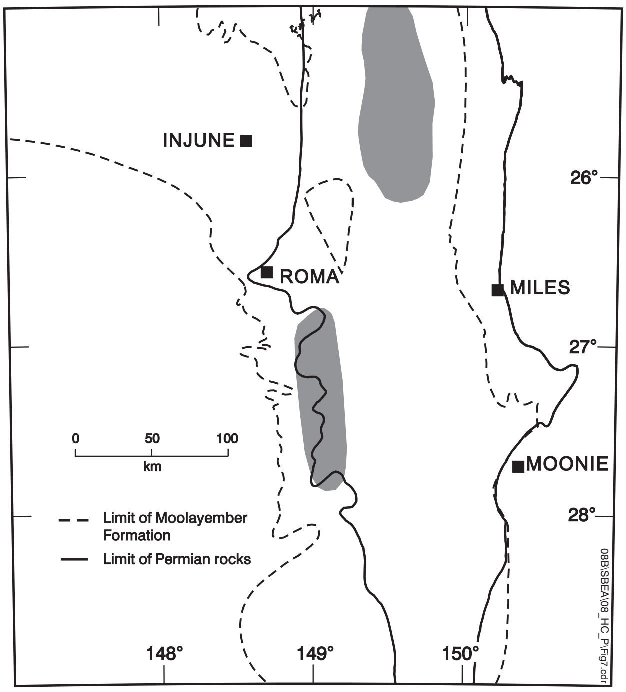

Figure 6: Area of moderate hydrocarbon potential reflecting local hydrocarbon generation and potential reservoir units in the north and known occurrences along the western margin (Sequence I)

with the best quality reservoirs associated with channel sandstones.

Thus exploration for hydrocarbons associated with the Showgrounds Sandstone needs to incorporate this distribution pattern for the reservoir facies. The positioning of exploration wells to intersect the top of any structure could result in missing the reservoir unit and penetrating basement.

Detailed source potential assessment has only been undertaken on the Snake Creek Mudstone Member of the Moolayember Formation. An assessment of this member suggests that only limited generation and expulsion of hydrocarbons has occurred and then only in the central parts of the Trough.

The best potential for Sequence H is on the Roma Shelf and the western side of the Trough where thinning of the underlying seals results in the sequence being closer to the underlying source units in the Permian sequences (Figure 5). Although highly explored, the possibility for further discoveries is considered excellent, but they are likely to be small.

SUPERSEQUENCE I

Resource Assessment Rating: Poor to moderate

Supersequence I comprises the Moolayember Formation above the Snake Creek Mudstone Member. The Moolayember Formation may be thermally mature for the generation of hydrocarbons in deeper parts of the Trough but no detailed source potential assessment has been undertaken.

The deposition of the Moolayember Formation in a fluvio-lacustrine setting and the formation of coals in the upper part suggests that the formation may have some source potential. Supersequence I is likely to be the main source of any Triassic contribution to hydrocarbons reservoired in the study area, although as discussed, the Rewan Group of Sequence G contains carbonaceous mudstones and siltstones which could have source potential in some areas.

The return to a volcanogenic source for the sequence results in a deterioration in reservoir quality, and the development of major reservoirs seems unlikely. The best reservoir development is likely to be in the northern part of the study area, although hydrocarbon production is obtained from the Moolayember Formation (Wandoan Formation) in several fields on the western side of the basin (Figure 6). The basal Moolayember Formation has produced gas at Kincora, Samari Plains, Carbean and in adjacent gas fields on the southern Roma Shelf.

Production from these fields suggests nearby sourcing and there is the possibility of future small discoveries in this area. These discoveries may reflect leaking and or thinning of the nearby Snake Creek Mudstone seal.

In the northern area, the formation is thick and contains numerous channel sandstones which have better developed reservoir characteristics than elsewhere. A gas flow of 2549–3087m3/D was obtained from two drill stem tests combined of the Moolayember Formation in COE Tiggrigie Creek 1 in this area.

This suggests that generation has occurred in the north when the sequence was buried under 3km of strata during the Middle to Late Triassic. Therefore early-formed structures will need to be targeted.

In the south, generation occurred in Late Cretaceous to Early Tertiary time and later-formed structures are prospective in the deeper parts of the basin.

The entrapment of hydrocarbons generated from the Permian coal measures is unlikely in Supersequence I, owing to the need for extensive vertical migration.

The presence of the Snake Creek Mudstone Member forming a regional seal in Sequence H immediately below, as well as mudstones of the Rewan Group in Sequence G, will generally have prevented the vertical migration of hydrocarbons. Only hydrocarbons generated from local sources will accumulate.

The northern part of the study area therefore is the only place where local generation and entrapment of hydrocarbons could have occurred within the supersequence. Thus Supersequence I is assessed as having only moderate potential, mainly in the northern part of the study area.

As discussed above, further small discoveries could also be made on the western side of the basin with vertical and lateral migration of hydrocarbons from a Permian source (Figure 6).

SEQUENCE J

Resource Assessment Rating: Good

Sequence J is the basal sequence of the Surat Basin and consists of Late Triassic rocks, the Precipice Sandstone and the Evergreen Formation. This sequence is one of the most important for the accumulation of commercial hydrocarbons where significant quantities are associated with good quality reservoirs in the Late Triassic rocks and the Precipice Sandstone.

Assessment of the geochemistry of the oil and gas accumulations in Sequence J has indicated that most are of Permian origin with only a minor contribution from the Triassic. Thus the Jurassic sequences do not generate hydrocarbons and all hydrocarbons present in these sequences are the result of migration.

The westerly thinning, and in some areas, the non-existence of the regional seals in the deeper parts of the southern Taroom Trough has enabled the vertical migration of hydrocarbons to occur. Thus the hydrocarbons present in this sequence have accumulated in the reservoirs associated with effective younger Jurassic seals.

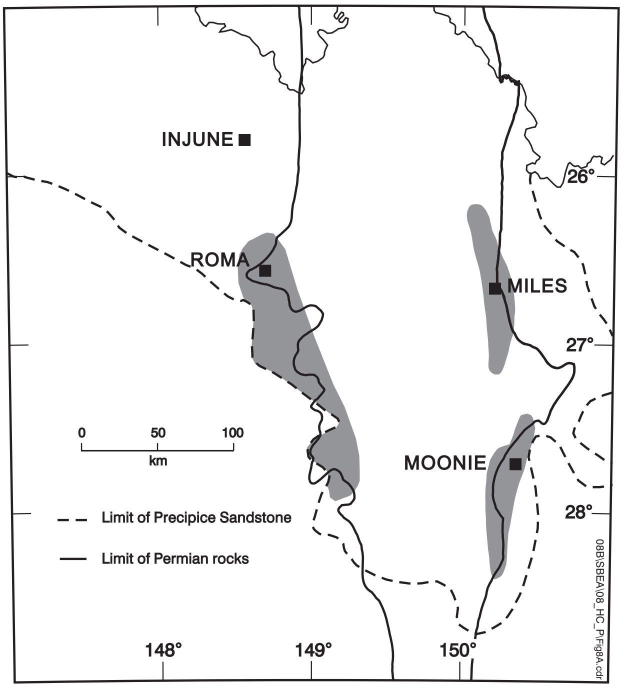

Figure 7: Areas of good hydrocarbon potential reflecting the distribution of the excellent reservoir units in the Precipice Sandstone. Moderate potential exists north of Moonie if fault leakage has occurred and competent seals are present (Lower Sequence J).

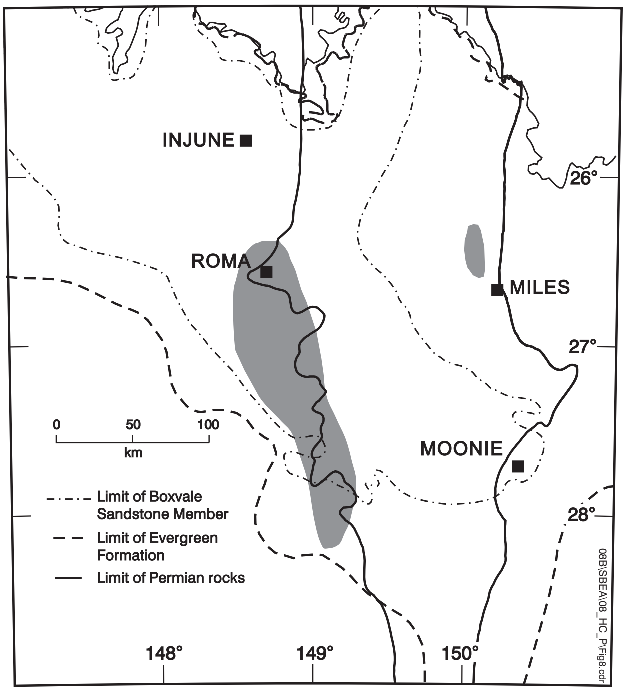

Figure 8: Areas of good hydrocarbon potential reflecting the distribution of the reservoirs at the base of the Evergreen Formation and the Boxvale Sandstone Member. The area to the north of Moonie reflects possible fault leakage from the underlying Permian units (Upper Sequence J).

The lowest unit in the sequence is the Late Triassic rocks. The distribution of this unit is virtually unknown and its effect on the distribution of hydrocarbons cannot be assessed. The Late Triassic rocks are probably much more extensive than presently known, particularly in the axial parts of the Trough.

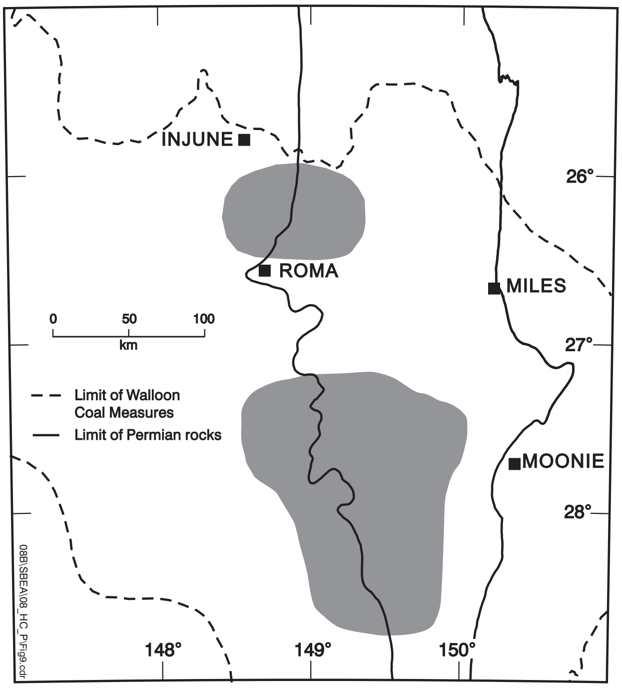

Figure 10: Area of coal seam methane potential based on the level of thermal maturity of the Walloon Coal Measures (Upper Sequence K).

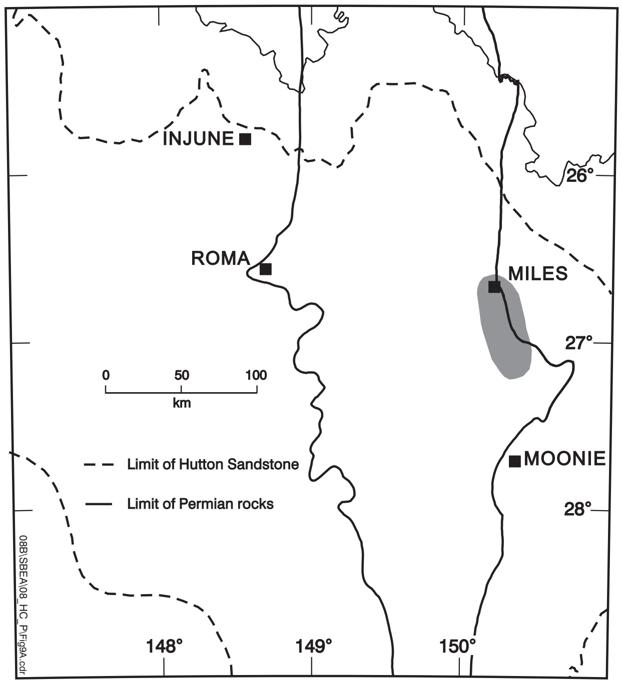

Figure 9: Areas of moderate hydrocarbon potential reflecting possible accumulations in the Hutton Sandstone associated with fault leakage (Lower Sequence K).

The overlying Precipice Sandstone blankets much of the area. Reservoir quality associated with this unit is excellent and the major control on the accumulation of hydrocarbons is trap integrity. If good seals are present then the Precipice Sandstone has excellent potential (Figure 7).

The overlying Evergreen Formation also contains significant quantities of hydrocarbons. The accumulations are restricted mainly to lower sandstone units and to the Boxvale Sandstone Member which occurs in the middle to upper part of the formation. The depositional setting of the latter as a deltaic deposit, influences reservoir distribution.

The development of lower sandstone reservoirs in the Evergreen Formation is a reflection of facies changes around the western margin of the Surat Basin. Overlying mudstones act as seals (Figure 8).

The major style of trap for Sequence J is anticlinal with the reservoirs acting as effective gathering systems for hydrocarbons leaking from the underlying (mainly Permian) units. Thus the prime areas to be targeted for exploration are where the underlying units, particularly the Early Triassic Rewan Group, are thinner or non-existent. Accordingly excellent potential exists for Sequence J along the western margin. However, the extensive exploration that has occurred in this area means that most of the large-scale anticlinal traps have already been drilled. Nevertheless, discoveries with smaller and more subtle traps are still likely.

Along the eastern margin of the Trough, several oil discoveries in addition to Moonie have been made in Sequence J. The potential for further discoveries exists in this area (Figure 8). Vertical migration of hydrocarbons along faults from a Permian source is required.

SEQUENCE K

Resource Assessment Rating: Poor to moderate

Sequence K consists of the Hutton Sandstone and the overlying Walloon Coal Measures. The Hutton Sandstone is a reservoir unit regionally, although in many areas the formation contains over 50 per cent interbedded siltstones and mudstones. Hydrocarbon accumulations in the Hutton Sandstone are present mainly along the eastern margin. The proven lack of generation from Jurassic units means that the underlying Bowen Basin contributes hydrocarbons to the Hutton Sandstone.

The amount of sealing associated with underlying Sequence J suggests that an additional mechanism to leakage around thin seals contributes to the accumulation of hydrocarbons in the Hutton Sandstone. These accumulations, stratigraphically so far removed from the Permian source, require fault leakage to be a major contributing factor (Figure 9).

Reservoir potential exists at the bottom of the Walloon Coal Measures, especially in the west where sublabile sandstones are present (Eurombah Formation of Swarbrick & others, 1973), compared with labile sandstones higher in the section. The generation potential of the Walloon Coal Measures is limited and the expulsion of hydrocarbons is unlikely to have occurred.

Although small accumulations of both gas and oil have been found in the Walloon Coal Measures, these are probably local occurrences and large-scale accumulations of liquid hydrocarbons are unlikely to be present. The presence of early-gas generation associated with the Walloon Coal Measures as well as the poor expulsion factors, suggest that the formation would be an excellent target for coal seam methane exploration.

The overall rating potential of the sequence is poor. Any hydrocarbon accumulations will probably be small and be located on the eastern side of the Trough in association with fault closure (Figure 10).

The coal seam methane potential of Sequence K in areas of higher maturity is worthy of further investigation.

SEQUENCE L

Resource Assessment Rating: Poor

Only the lowermost part of Sequence L which consists of the Springbok Sandstone and the overlying Westbourne Formation was considered as part of this assessment. The Springbok Sandstone is a regional unit with reservoir potential and the overlying Westbourne Formation a likely seal. The major migration mechanisms operating in the basin are lateral migration followed by vertical migration when the regional seal becomes too thin. Thus for significant hydrocarbons to occur in this sequence, long-distance migration of hydrocarbons from a lower source must occur. The general lack of hydrocarbons in the underlying Sequence K suggests that this is unlikely. The hydrocarbon potential of Sequence L is considered therefore to be poor.

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