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Bathymetric change during Early Cretaceous intracratonic marine transgression across the northeastern Eromanga Basin, Australia

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Bathymetric change is investigated within the transgressive phase of an extensive Early Cretaceous (Aptian-Albian) marine flooding of the Australian continent. Lithofacies and biofacies associations, found in nine outcrop sections and four continuously cored bore sections in the northeastern Eromanga Basin, are used to reconstruct depositional environments and to determine palaeobathymetry. Shoreface (*c.* 0–2 m water depth), transitional (*c.* <10 m), upper offshore (*c.* <50 m), and lower offshore (*c.* 50–100 m) facies are distinguished. Curves showing bathymetric changes are constructed for each stratigraphic section, and are placed in a time framework by biozones and compared across the region. Three depositional cycles are tentatively recognized during the transgressive phase. The first depositional cycle includes the Gilbert River Formation and the lower part of the Doncaster Member, and ranged from early Aptian (or late Barremian) to within the late Aptian. During maximum flooding, water depth was greatest in the southwest of the study area. Most sediment accumulation occurred under standstill conditions, and a fall in relative sea level occurred at the end of the cycle in all areas within the study region. The second cycle, during the later part of the late Aptian, includes the upper Doncaster Member and the Jones Valley Member. Most sediment accumulation occurred under fluctuating water depths, but a fall in relative sea level ends the cycle in all areas. The third depositional cycle includes the Ranmoor Member, and was represented by a significant late Early Albian transgressive pulse, recognized in age-equivalent formations from widely separated basins in Australia. At maximum flooding, the sea-floor was deepest in the northeast and shallowest in the southwest of the study area. The reversal in the direction of the bathymetric gradient between cycle 1 and cycle 3 in the region is probably related to tectonism along the eastern Australian margin. The apparent lack of correspondence between the Australian Albian record and the global sea-level curve suggests that continental-wide tectonism was an important influence in determining Australian sea levels during this time.
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KEY WORDS: Early Cretaceous; Aptian-Albian; marine transgression; palaeobathymetry; biofacies; lithofacies; foraminifera; biostratigraphy; intracratonic basin; Eromanga Basin.

1. Introduction

The northeastern Eromanga Basin contains a stratigraphic record of extensive marine flooding across the Australian continent during the Early Cretaceous (Figure 1). An estimated 60% of Australia's current land surface was inundated by the sea during the Aptian-Albian (Frakes *et al.*, 1987), signifying the largest marine flooding over the continent since the Cambrian-Ordovician (Veevers, 1990). This Cretaceous event approximately coincided with globally high sea levels, which resulted in the deposition of marine sedimentary rocks across much of the world's continental platforms (Haq *et al.*, 1988; Hallam, 1992). Flooding in the Eromanga Basin probably began during the Barremian and was followed by rapid regression during the Cenomanian (Frakes *et al.*, 1987; Figure 2). The marine flooding episode represents a depositional cycle of over 30 my, with peak flooding recognized during the late early Albian to early late Albian (Frakes *et al.*, 1987; Smith *et al.*, 1992; Haig & Lynch, 1993; Henderson, 1998). This paper charts the transgressive phase of the intracratonic flooding in the northeastern Eromanga Basin using an integrated lithofacies-biofacies approach.

The Eromanga Basin is a relatively undeformed intracratonic sedimentary basin covering about one million square kilometres of eastern Australia (Figure 1), and has a maximum thickness of 3 km at the basin depocentre (Passmore, 1989). It is a Jurassic-Cretaceous basin that unconformably overlies Palaeozoic-Triassic rocks of the Galilee and Cooper Basins (Senior *et al.*, 1978). Basement structural highs separate the Eromanga Basin from the adjacent Carpentaria and Surat Basins (Veevers, 1984;

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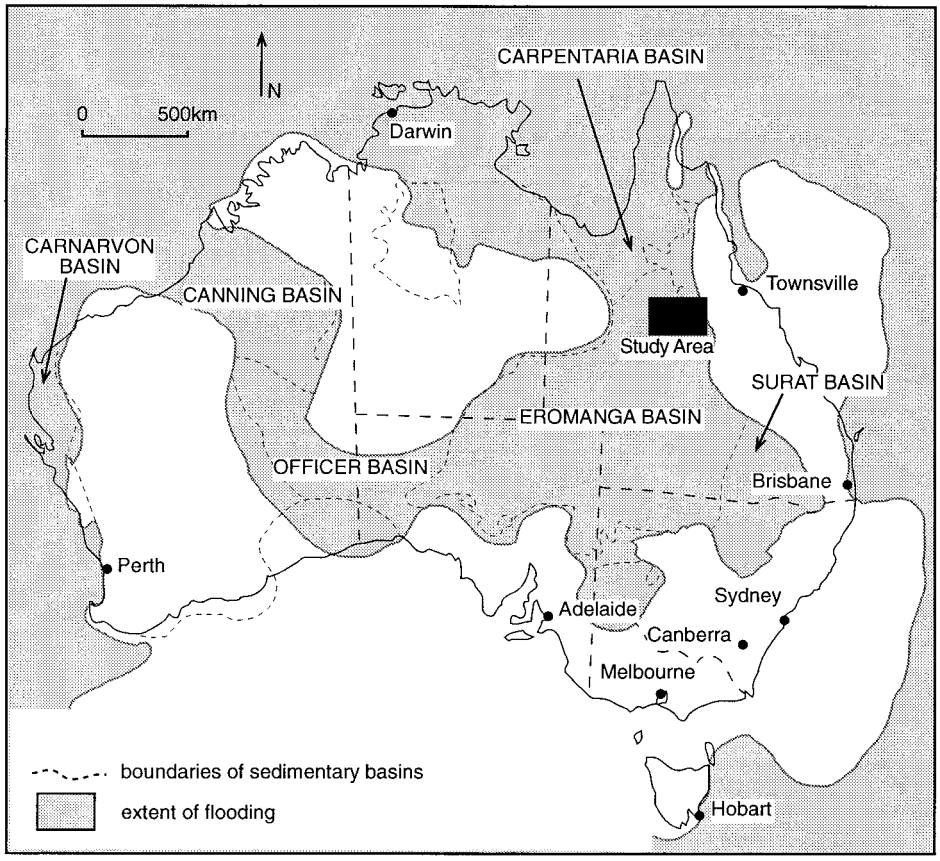


Figure 1. The extent of marine flooding of Australia during the Aptian is represented by the shaded area on the map (after Frakes *et al.*, 1987). The study area is marked in the northeastern Eromanga Basin.

Wiltshire, 1989; Krassay, 1994). Most of the Eromanga Basin succession consists of fluvial and lacustrine sediments; deposits of the mid-Cretaceous marine flooding are the only marine units represented in the basin. These marine deposits, preserved in sub-horizontal strata, are remarkably uniform over a wide area, and some formations are recognized throughout the basin and in the adjacent Carpentaria and Surat Basins (Exon & Senior, 1976; Senior *et al.*, 1978).

The Aptian-Albian seaway across Australia (Figure 1) was analogous to the Late Cretaceous Western Interior Seaway in North America. Both epeiric seas were located at high palaeolatitudes (in opposite hemispheres), and had restricted openings to the open ocean. Comparable lithofacies and marine biota suggest that similar physico-chemical conditions (distinct from the open ocean) existed within these shallow interior seas. The main lithofacies represented are shoreface sandstone, offshore organic-rich mudstone, and minor pelagic limestone (reflecting maximum marine flooding). The marine faunas are characterized generally by sparse benthic molluscan assemblages, provincial ammonites and belemnites, the *Ammobaculites* Association of benthic foraminifera (Haig, 1979a), and low diversity planktic foraminiferal assemblages present only during maximum flooding episodes.

In North America, much recent work has concentrated on sequence recognition along the western margin of the interior seaway, now exposed in the eastern flank of the Rocky Mountains orogenic belt. These studies have dealt mainly with sand facies of the marginal marine zone, and have developed 'ramp-setting' sea-level change models to explain the stratigraphic architecture (e.g., Nummedal & Molenaar, 1995; Hart & Plint, 1993). In contrast to the North American localities, in the topographically more subdued Eromanga Basin the marginal marine facies are poorly exposed and have been cored in very few boreholes. Some of the best Cretaceous marine outcrops in Australia occur along the Flinders River in the northeastern part of the Eromanga Basin, and these form the focus of the present study. However, the sections here are dominated by offshore mudstones; marginal-marine sands are encountered only

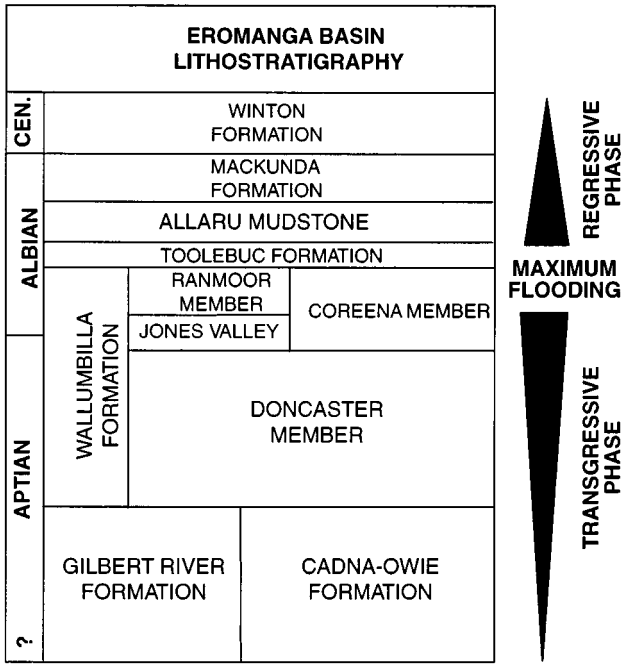


Figure 2. Lithostratigraphy of the Eromanga Basin (adapted from Haig & Lynch, 1993). The broad phases of the overall marine flooding event are indicated on the right.

in limited outcrop. Based on the stratigraphic sections presently available for study in the northeastern Eromanga Basin, it is not possible to fully test the ramp-setting sequence models developed in equivalent settings in North America.

The northeastern Eromanga Basin outcrop sections are dominated by mudstone facies that accumulated offshore of the marginal-marine zone. In terms of bed morphology and grain-size, these facies are monotonous; macrofossils are usually rare and bioturbation, although often present, is usually difficult to discriminate. Similar lithologies have received scant attention in sequence stratigraphic studies of the North American interior sea. The biogenic sand component of the mudstone, however, provides substantial information for bathymetric interpretation that is often overlooked by sedimentologists. The biogenic grains in the sand fractions of the Eromanga Basin mudstones are mainly foraminifera, but also include radiolaria, diatoms, ostracods, sponge spicules, echinoid debris, and molluscan shell fragments.

The primary aim of this study is to chart bathymetric change in the dominantly mudstone successions available in the northeastern Eromanga Basin, through an analysis of the biofacies and lithofacies. The depositional setting poses the following questions. (1) Was the Aptian to mid Albian marine transgression gradual or was it punctuated by changes? (2) Is there evidence of cyclic patterns of bathymetric change and can these be correlated across the study area and further? (3) Were the preserved offshore mudstones mainly deposited during periods of bathymetric change or standstill? (4) Does a record of decreasing bathymetry in the offshore mudstones reflect relative sea-level fall throughout the epeiric sea or just the local progradation of shore-line facies?

2. Study area and methods

The study area is located at the northeastern margin of the basin, near the town of Hughenden (Figure 3). Nine stratigraphic sections were measured at rock outcrops exposed by the Flinders River drainage system. Here the marine rocks form river cliffs capped by resistant Tertiary basalt and sandstone. The outcrop data is supplemented by information from four continuously cored bore sections located in the Hughenden region (Figure 3).

Micropalaeontological analysis of rock samples involved disaggregation in boiling water and wet-sieving through 2 mm, 150 μm, and 63 μm meshes. Smear slides of the calcareous mudstones were made in order to detect the presence of nannofossils. The main microfossils found in the sand-fraction residues were foraminifera and these were systematically picked from the 150 μm–2 mm fractions. The 63–150 μm sediment fractions were scanned to detect the presence of small species not found in the coarser sediment residue. Foraminiferal species were identified following the taxonomy outlined by Haig (1980, 1982) and Haig & Lynch (1993). Selected species are illustrated on Figures 4–6. Because of the low diversity and low abundance of many of the foraminiferal assemblages, species occurrences are recorded as 'abundant' (>20 specimens recovered), common (10–20 specimens), and rare (<10 specimens), rather than as percentages. All microfossils are housed in the micropalaeontological collection of the Department of Geology & Geophysics, The University of Western Australia.

The information obtained from stratigraphic logging and the micropalaeontological analyses formed the basis of recognition of 12 lithofacies (Table 1) and 9 biofacies (Table 2). Lithofacies were distinguished on the basis of rock-type, texture, bedding and sedimentary structures related to particular depositional processes (following interpretations made elsewhere by Amorosi, 1995; Bhattacharya, 1993; Donovan, 1993; Heckel, 1972; Hocking *et al.*, 1987; Krassay, 1994; Leithold, 1994; McCubbin, 1982; Reineck & Singh, 1980; Reinson, 1984; and Savrda, 1995). The

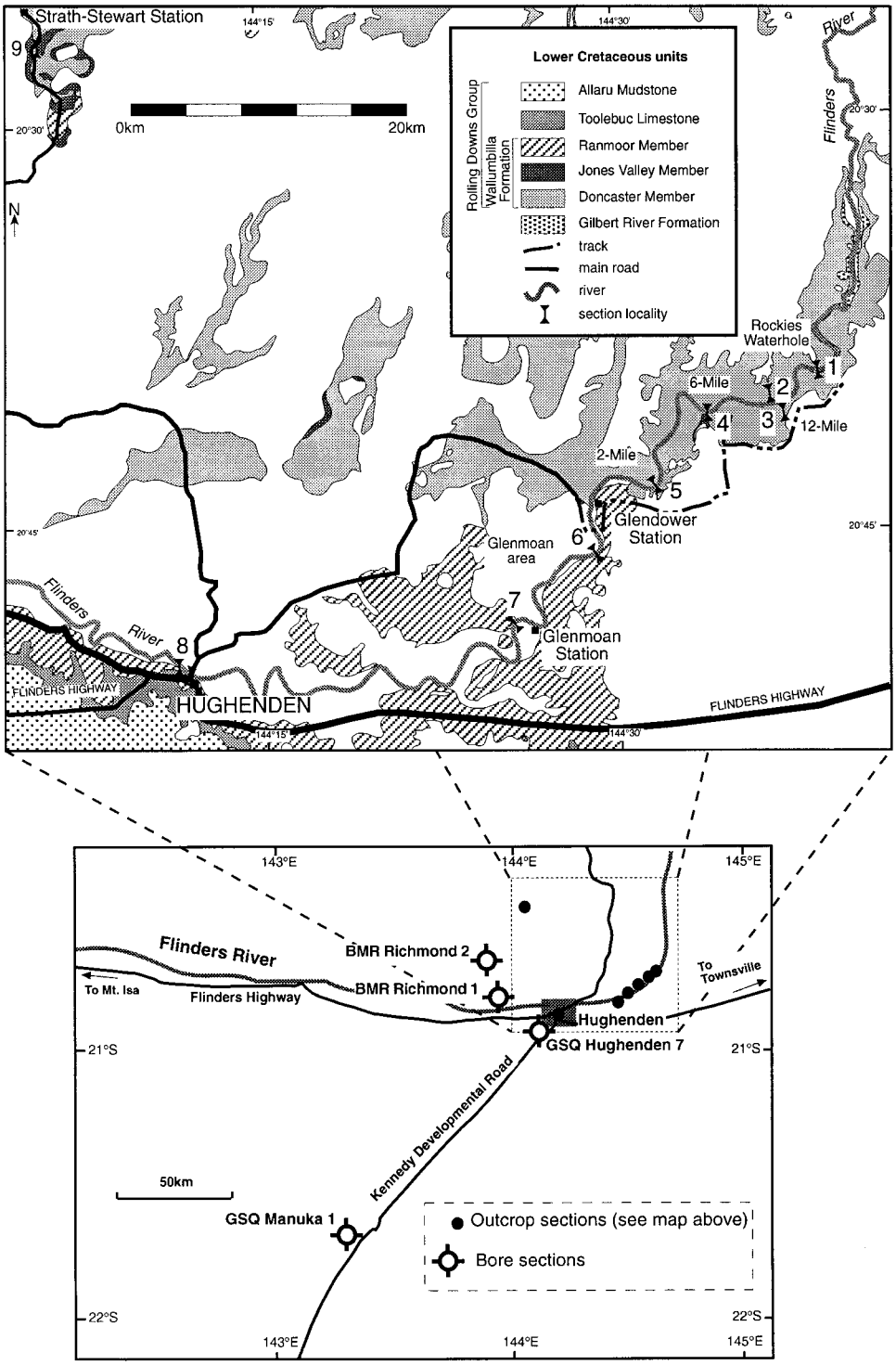


Figure 3. Geological map of the study area (adapted from the Hughenden 1:250 000 sheet SF 55-1; Vine & Paine, 1974). The distribution of the main lithostratigraphic units is shown in the enlarged map of the outcrop area, along with the location of outcrop sections 1–9. The lower map shows the location of drill-holes situated basinward of the outcrop sections.

biofacies were recognized on the basis of dominant foraminiferal species and the associated biotic components in the sediment. Palaeoenvironmental interpretation of the foraminiferal biofacies was based on analogy to modern distribution patterns. Modern patterns are influenced by light intensity, water

salinity, water temperature, the nature of substrate, water pH, water eH, and water depth (e.g., Reiss & Hottinger, 1984; Fuchs & Schreiber, 1988; Murray, 1991). Conditions in the upper part of the water column are reflected by planktic foraminifera, whereas sea-floor conditions are indicated by benthic forms. The interpretations of the biofacies are based upon the following observations: (1) the benthic species associations (e.g., Sliter & Baker, 1972; Haig, 1979a; Sikora & Olsson, 1991; Koutsoukos & Hart, 1990) (2) dominant genera (e.g., Murray, 1991); (3) diversity of benthic assemblages (e.g., Murray, 1973; 1991); (4) percentage of planktic tests in the total foraminiferal assemblage (Murray, 1976). In addition to modern analogues, the estimated depth ranges of agglutinated foraminifera within the Cretaceous Western Interior Basin, USA, were considered in the interpretation (following Haynes, 1981). The environmental interpretations based on foraminifera were supplemented by information derived from other microfossil groups and macrofossils found in the studied rocks.

Bathymetric trends are interpreted from changes in facies through the stratigraphic succession (see Section 3 below). Based on information obtained from the facies analysis, a model for deposition within the northeastern Eromanga Basin was constructed (Figure 7). The model places the facies in an idealised shallowing upward succession, and suggests a bathymetric zonation from the offshore zone to the foreshore zone (following the terminology of Reading, 1978). The bathymetric changes are placed in a chronostratigraphic framework using the biozonations outlined on Table 3.

3. Description of sections

3.1. Outcrop section 1

Section 1 at the Rockies Waterhole is the designated type-section of the Doncaster Member of the Wallumbilla Formation (Vine & Paine, 1974). The entire Doncaster Member is not exposed in the type-section (Figures 8, 9), since a further 30 m crops out downstream. The Gilbert River Formation, exposed at the base of the Rockies section, unconformably overlies Jurassic sandstones.

Lithology. An erosional surface on well-indurated quartz sandstone marks the base of the Rockies section, and is overlain by a thin (20 cm thick), red-brown, clast-supported conglomerate (Figures 9, 10). The conglomerate is laterally extensive with a planar base, and is composed of rounded clasts of mainly quartz (90% of clasts) and indurated mudstone (10% of clasts). The quartz clasts resemble pebbles distributed within the coarse-grained, planar cross-bedded, quartz sandstones, of probable Jurassic age, beneath the erosional surface.

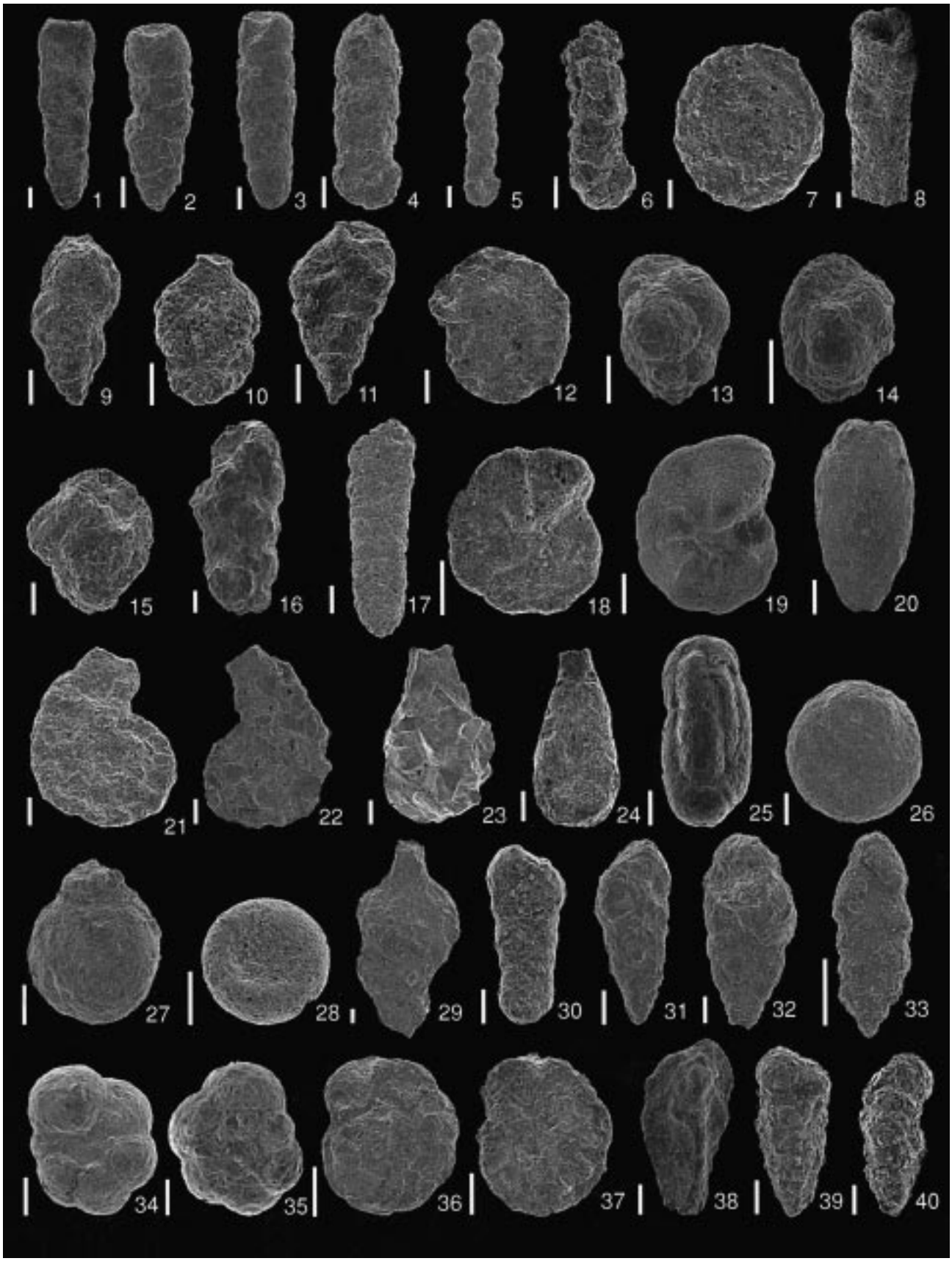
Muddy quartz sandstone conformably overlies the conglomerate (Figures 9, 10) and is quartz-rich (72% of sand grains), poorly sorted, and supported by a muddy matrix. Quartz grains are commonly polygonal, mainly monocrystalline (90% of quartz grains), angular, and have rare embayments. Interbedded with the muddy quartz sandstones are thin, indurated, black mudstones which contain framboidal and pyritohedral pyrite. Both mudstones and muddy quartz sandstones are extensively bioturbated by branching, horizontal burrows attributed to the ichnogenus *Thalassinoides* (Figure 11). Ellipsoidal mud-clasts, ranging to 3 cm long and 1 cm wide, are a feature of the youngest muddy quartz sandstone unit.

Pyritic, blue-grey mudstone overlies the youngest muddy quartz sandstone, and is the main rock-type in the section (Figures 8, 9). The mudstone is friable and contains small-scale mottling indicative of bioturbation. Between 3 and 10 m up the section are a number of light-grey sandy mudstone beds, containing well-rounded, coarse quartz grains (up to 5 mm), and *Thalassinoides* burrows. Glaucony-rich, fine-grained muddy sandstones punctuate the blue-grey mudstone between 20 and 37 m (Figures 8, 9). Some horizons (e.g., 26.5–28 m) are particularly glaucony-rich (>50%). Many of the glaucony beds contain a high proportion of angular quartz, mostly rounded glaucony grains, and are barren of foraminifera.

Calcareous nodules are common within the blue-grey mudstones and glaucony-rich horizons (Figures 8, 9). The nodules vary in size and shape, from 10 cm diameter spheres, to metre-long egg-shaped nodules. They are composed of a carbonate cement and muddy matrix, with minor quartz and glaucony, and can form distinctive horizons (e.g., 16.5 m up the section). The nodules are often formed around fossil nuclei.

Above 44 m in the Rockies Section is a quartz sandstone (Figures 8, 9). Initial sandstone beds are medium-grained, bioturbated by *Thalassinoides*-type burrows, and contain small mud-clasts (ranging to 2 cm in diameter). The unit is well-sorted, and consists mainly of monocrystalline quartz (83%) grains, with syntaxial quartz overgrowths. Volcanic (1.2%) and sedimentary (2.6%) lithic fragments are minor but significant components of the rock, along with alkali feldspar (3.6%) and plagioclase (0.4%).

Planar bedding (10–15 cm^5 thick) is well developed within the quartz sandstone at 45–46 m above the base of the section, whereas trough cross-bedding and


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lenticular mudclasts (10 cm in length) are present between 46 and 46.5 m (Figure 9). Poorly exposed and highly weathered white mudstone overlies the quartz sandstone.

Palaeontology. Plant remains are preserved in basal units of outcrop section 1 (Figure 9). The youngest muddy quartz sandstone unit (at 3 m) is resistant to erosion, and forms a platform on the river bed. Impressions of two types of fossil wood are exposed on this surface: segmented branches of the plant division Sphenophyta (Figure 12), and non-segmented branches. A mould of an ammonite, with closely spaced ribs, is preserved on the muddy quartz sandstone bed surface.

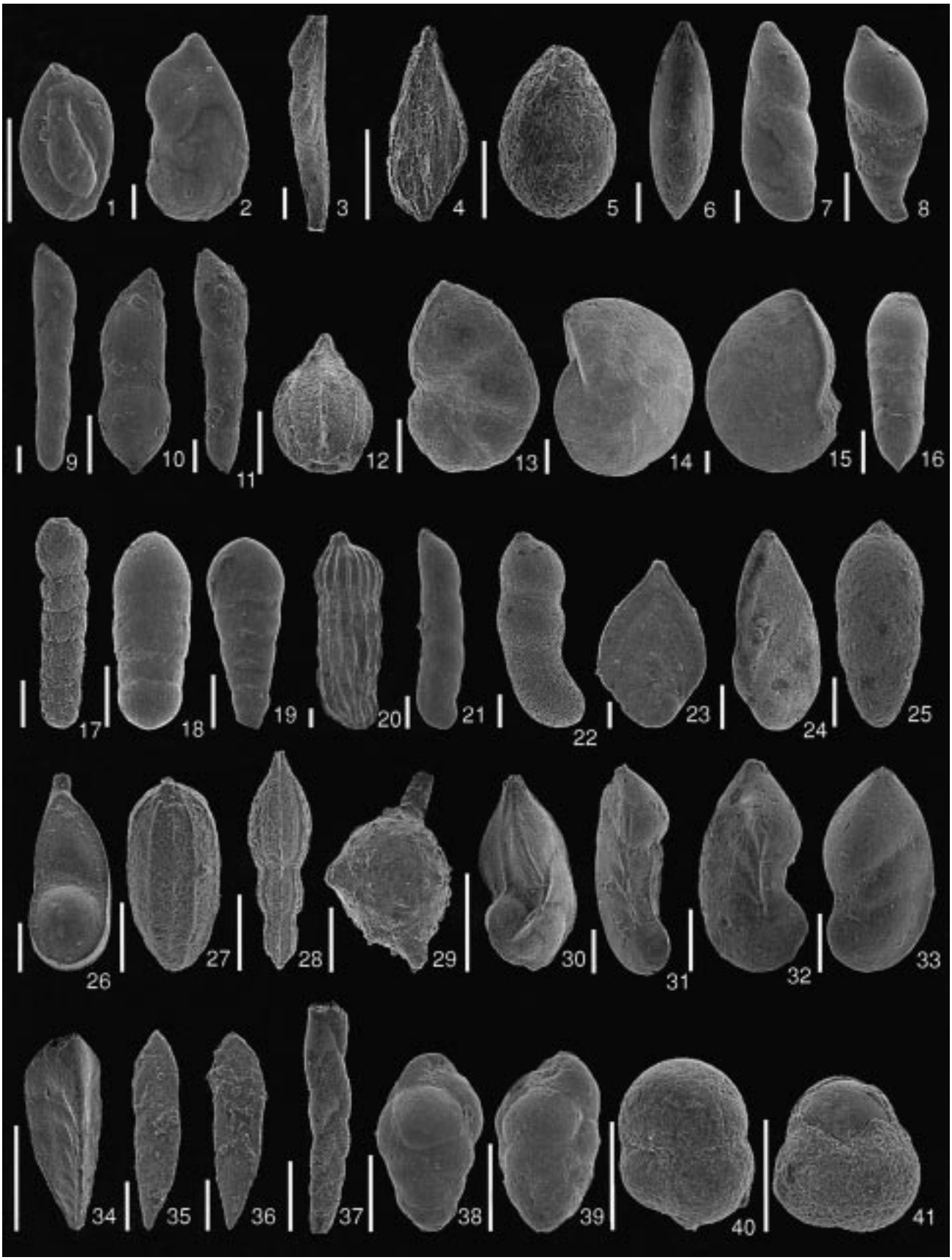
Large logs of permineralized fossil wood, up to 30 cm in diameter, are weathering from a sandy mudstone unit 9 m up the section (Figures 8, 9). Much of this wood contains club-shaped centimetre-thick borings of the ichnogenus *Teredolites*.

Marine invertebrate macrofossils are generally preserved within, or eroded from calcareous nodules, as noted by Day (1974). Ammonites (e.g., *Australiceras jackii*), bivalves (e.g., *Maccoyella barklyi*), and decapod crustaceans resembling ?*Glyphaea* are the most numerous fossils (Figure 9), although generally macrofossils are rare within the section and many of Day's (1974) collection sites yielded only one individual. The belemnites *Peratobelus oxys* and *P. sellheimi* are present in both blue-grey mudstones and glaucony-rich horizons.

Sharks' teeth, sponge spicules, and foraminifera occur in the mudstones of section 1 (Figure 9). Foraminiferal assemblages from the mudstones consist solely of siliceous and usually deflated agglutinated forms, and are generally of low abundance and diversity with no more than 12 species found at any of the sampled beds (Table 4). Two species dominate most samples: *Trochammina minuta* and *Cribrostomoides* sp. Only the foraminiferal assemblage from the uppermost mudstone at 47m shows evidence of test bleaching due to weathering of the rock; the lower assemblages include specimens which retain the brown organic lining of the test and show no evidence of being affected by weathering processes.

Facies and bathymetric trends. The conglomerate deposit (Cm lithofacies) exposed at the base of the section was derived from erosion of underlying fluvial sedimentary rocks in a high-energy setting. The planar, and laterally extensive nature of the deposit suggests a marine origin, similar to pebble lag horizons formed during the early stages of marine transgression (Bhattacharya, 1993; Donovon, 1993; Leithold, 1994). A shallow-foreshore to upper-shoreface marine setting is interpreted for lithofacies Cm (Figure 7). Within 0.25 m of the base of the section a change occurs from lithofacies Cm through Sc to M containing biofacies 1 (Figure 9, Table 1). This is interpreted to reflect a deepening from a foreshore to a lower shoreface to upper transitional environment (Figure 7), which was the deepest water setting reached during deposition of Section 1. Coarse muddy quartz sandstone (lithofacies Sc) containing large-scale *Thalassinoides* burrows (Figure 11) reappears above the initial mud facies (at 1 m above base of section)

Figure 4. Selected agglutinated benthic foraminifera. Taxonomy follows Haig (1981, with revisions by Haig & Lynch 1993). All bar scales=0.1 mm. 1–3, *Aaptotoichus pitmani* (Crespin, 1953); 1, megalospheric test from outcrop section 4, 10/10/94-15; 2, microspheric test from Manuka 1, 608.98 m; 3, megalospheric test from Manuka 1, 608.98 m. 4–6 *Ammobaculites humei* Nauss, 1947; 4, 5 from Manuka 1, 619.82 m; 6 from outcrop section 8, 11/6/96-1. 7, *Ammodiscus rotalarius* Loeblich & Tappan, 1949; from outcrop section 3, 5/6/96-3. 8, *Bathysiphon* sp; from outcrop section 1, 4/6/96-1. 9, 10 *Bimonilina engeninensis* (Ludbrook, 1966); 9, microspheric test from outcrop section 4, 10/10/94-19; 10, megalospheric tests from outcrop section 4, 10/10/94-19. 11, *Bimonilina variana* Eicher, 1960; microspheric test from outcrop section 9, 10/6/96-1. 12, *Cribrostomoides* sp. from outcrop section 1, 8/10/94-5. 13–15. *Eomarssonella crespinae* (Ludbrook, 1966); 13, 14 from Manuka 1, 569.95 m; 15 from outcrop section 6, 12/10/94-13. 16, *Gaudryinopsis enodis* (Crespin, 1963) from Manuka 1, 727.18 m. 17, *Gaudryinopsis filiformis* (Berthelin, 1880) from outcrop section 6, 12/10/94-13. 18, 19, *Haplophragmoides minor* Nauss, 1947; 18 from outcrop section 4, 10/10/94-1; 19 from outcrop section 4, 7/6/96-1. 20, *Hippocrepina barksdalei* (Tappan, 1957) from Hughenden 7, 82.99 m. 21, 22, *Kutsevella implanus* (Crespin, 1963); 21 from outcrop section 9, 10/6/96-1; 22, from Manuka 1, 608.98 m. 23 *Lagenammina alexanderi* (Loeblich & Tappan, 1950) from outcrop section 4, 10/10/94-1. 24, *Lagenammina lagenoides* (Crespin, 1953) from outcrop section 4, 10/10/94-13. 25, *Miliammina ischnia* Tappan, 1957 from outcrop section 5, 12/10/94-3. 26, 27, *Placentammina lathrami* (Tappan, 1960), different specimens from Hughenden 7, 99.53 m. 28, *Psammosphaera laevigata* White, 1928 from outcrop section 9, 10/6/96-1. 29, *Reophax geniculatus* Ludbrook, 1966 from Manuka 1, 569.95 m. 30, *Spiroplectammina edgelli* Crespin, 1953 from outcrop section 4, 10/10/94-3. 31, *Textulariopsis cushmani* Crespin, 1944 from Manuka 1, 724.45 m. 32, *Textulariopsis wilgunyaensis* Crespin, 1963 from Manuka 1, 591.77 m. 33, *Textulariopsis* sp. from Manuka 1, 541.02 m. 34, 35, *Trochammina minuta* Crespin, 1953, umbilical and spiral views of same specimen from outcrop section 1, 3/6/96-7. 36, 37, *Trochammina* sp. A; 36 from Manuka 1, 724.45 m; 37 from outcrop section 4, 10/10/94-3. 38, *Verneuilinoides howchini* (Crespin, 1953) from outcrop section 6, 12/10/94-14. 39, 40, *Verneuilinoides neocomiensis* (Myatliuk, 1939); 39 from Hughenden 7, 35.77 m; 40 from outcrop section 8, 11/6/96-1.


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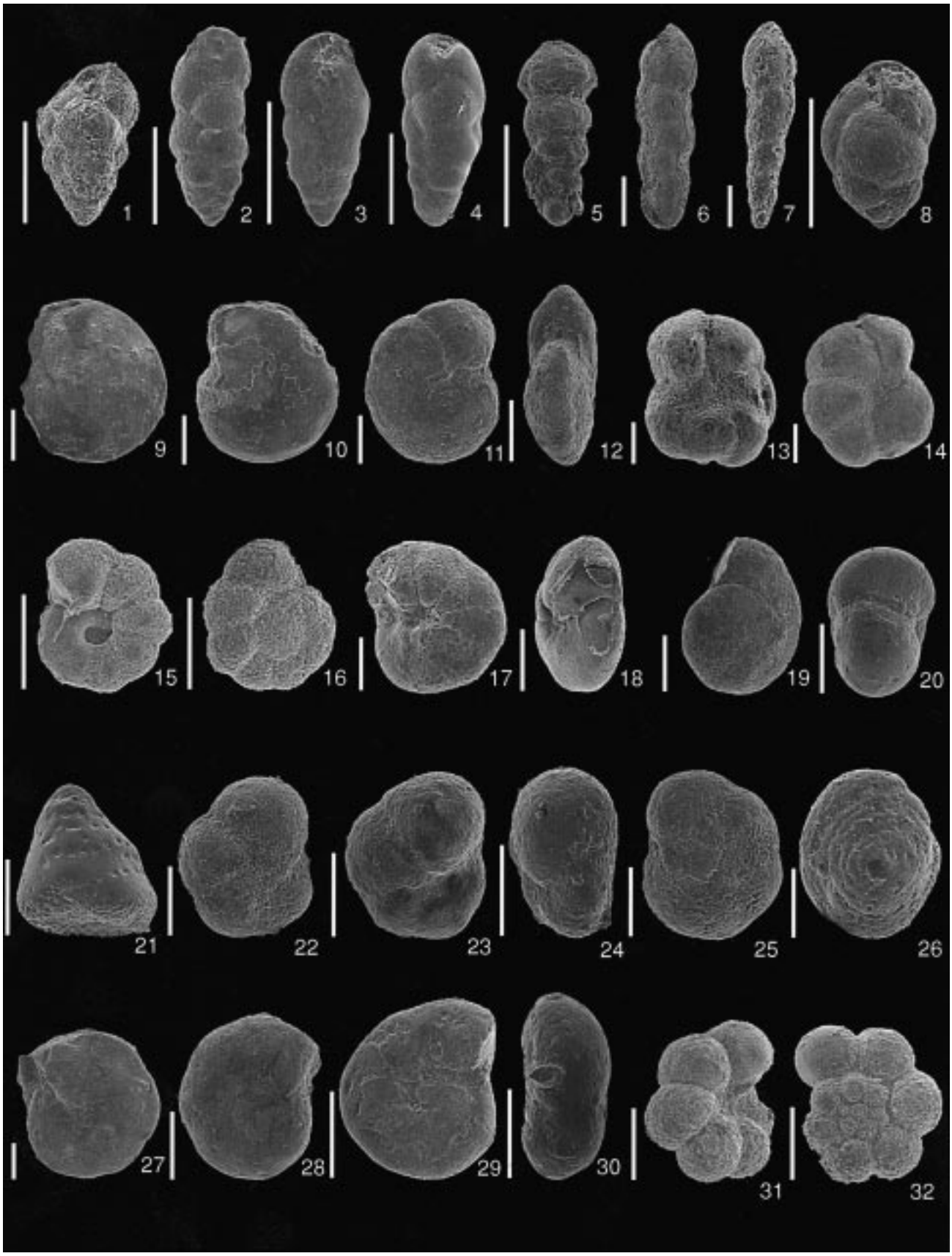
signifying a return to very shallow, probably middle-shoreface conditions. Within the next 4–5 m of section, facies pass from Sc to Ms to M containing biofacies 1, reflecting a deepening to the lower shoreface or transitional environment. The overlying sandy mudstone (Ms facies), between 8–10 m above base of section, indicates a shallowing to the shoreface, and was followed immediately by mud deposition in slightly deeper water.

The shoreface to transitional cycles evidenced in the lower 10 m of section 1, gave way to relatively uniform mudstone deposition (M lithofacies with biofacies 1) in the lower shoreface to upper transitional zone (Figure 9) punctuated by a number of levels of glauconitic-quartz sand accumulation (Sg lithofacies). Over 30 m of sediment accumulated in this shallow-water setting. Glaucony-rich sandstones may be indicators of slow sedimentation rates (Heckel, 1972; Amorosi, 1995), but also may be transported or reworked and concentrated in, for example, storm deposits. The abundance of quartz in the Sg lithofacies of section 1 suggests that these sand deposits (each about 1–2 m thick) may be the result of reworking by storm waves in the lower shoreface to upper transitional environment. However, no sedimentary structures indicative of storm deposition occur in the beds.

The Smc, Sxm, and Sxc lithofacies recognized at the top of section 1 (Figure 9) record a slight shallowing from the site of mud deposition to the middle to upper shoreface zone. The Smc sandstone is a mature sediment indicating rapid deposition and high-energy transportion. Ripple laminations within interbedded mudstones are lower flow-regime structures formed by currents or shoaling waves during lower-energy deposition. Bioturbation by *Thalassinoides* in Smc suggests deposition in the middle to upper shoreface. Lithofacies Spm contains planar beds of medium to coarse-grained quartz sandstone with occasional rip-up clasts. The sediment is well sorted, and submature to mature. These features represent upper flow regime conditions, developed by currents and shoaling waves, and indicative of the upper shoreface to foreshore depositional environment (Reineck & Singh, 1980; Reinson, 1984). Facies Sxc, at the top of the upper sandstone unit in section 1, contains small-scale, trough cross laminations formed by lower to upper flow regime migration of current ripples, which are indicative of a middle to upper shoreface setting (Hocking *et al.*, 1987; McCubbin, 1982).

Section 1 contains a bathymetric signature of initial trangressive/regressive cycles within a shallow and narrow bathymetric range, perhaps related to changes in sand influx. The main portion (>30 m) of the section accumulated in the lower shoreface to upper transitional zone. This standstill situation implies that a balance existed for a considerable time between sedimentation, sea-level rise and any subsidence in the area. An influx of sand in prograding shoreface to foreshore facies completes the depositional record evidenced in the section.

Figure 5. Selected porcellaneous (1) and hyaline (2–41) benthic foraminifera. Orders represented include Miliolida (1), Lagenida (2–34), and Buliminida (35–41). Taxonomy follows Haig (1982) and Haig & Lynch (1993). All bar scales = 0.1 mm. 1, *Miliolinella australiana* Scheibnerová, 1976 from Manuka 1, 591.77 m. 2, *Astacolus howchini* Ludbrook, 1966 from Manuka 1, 660.32 m. 3, *Citharina* cf. *petila* Eicher & Worstell, 1970 from outcrop section 6, 12/10/94-12. 4 *Citharina tyelea* Ludbrook, 1966 from outcrop section 5, 12/10/94-6. 5, *Globulina lacrima* (Reuss, 1845) from outcrop section 6, 12/10/94-9. 6, *Globulina prisca* (Reuss, 1863) from outcrop section 4, 7/6/96-1. 7, 8, *Hemirobulina hamulus* (Chapman, 1894), both specimens from Manuka 1, 586.81 m. 9, *Laevidentalina hamiltonensis* (Ludbrook, 1966) from Manuka 1, 586.81 m. 10, *Laevidentalina* cf. *oligostegia* (Reuss, 1845) from Manuka 1, 586.81 m. 11, *Laevidentalina praecommunis* (Tappan, 1960) from Hughenden 7, 38.14 m. 12, *Lagena* sp. from outcrop section 6, 12/6/96-3. 13, *Lenticulina kiwania* Ludbrook, 1966 from outcrop section 5, 12/10/94-5. 14, *Lenticulina* gr. *gaultina* (Berthelin, 1880) from outcrop section 5, 12/10/94-6. 15, *Lenticulina warregoensis* Crespin, 1944, from Hughenden 7, 168.29 m. 16, *Lingulina buddencanyonensis* Dailey, 1970, from Manuka 1, 586.81 m. 17, 18, *Lingulonodosaria nodosaria* (Reuss, 1863); 17 from outcrop section 6, 12/10/94-9; 18, from Manuka 1, 670.61 m. 19, *Lingulonodosaria* cf. *nodosaria* (Reuss, 1863) from Manuka 1, 660.32 m. 20, *Marginulina innaminckae* Ludbrook, 1966 from Hughenden 7, 82.99 m. 21, *Marginulinopsis arimensis* Ludbrook, 1966 from Manuka 1, 586.81 m. 22, *Marginulinopsis pristipellis* Ludbrook, 1966 from outcrop section 6, 12/10/94-9. 23, *Palmula* sp. from Hughenden 7, 38.14 m. 24, *Planularia* sp. cf. *P. strombecki* (Reuss, 1863) from outcrop section 4, 7/6/96-1. 25, *Pseudonodosaria humilis* (Roemer, 1841) from Manuka 1, 586.81 m. 26, *Psilocitharella recta* (Reuss, 1863) from Manuka 1, 586.81 m. 27, *Pyramidulina obscura* (Reuss, 1845) from Manuka 1, 586.81 m. 28, *Pyramidulina sceptrum* (Reuss, 1863) from outcrop section 6, 12/10/94-11. 29, *Ramulina* sp. from Hughenden 7, 35.77 m. 30–32, *Saracenaria ninbella* Ludbrook, 1966; 30 from outcrop section 6, 12/6/96-3; 31 and 32 from Hughenden 7, 38.14 m. 33, *Saracenaria planiuscula* (Reuss, 1863) from Manuka 1, 591.77 m. 34, *Tristix perelongatum* (Ludbrook, 1966) from outcrop section 5, 12/10/94-4. 35–37, *Coryphostoma* sp. A; 35 and 36 from Hughenden 7, 28.72 m; 37 from outcrop section 5, 12/10/94-4. 38, 39, *Eurycheilstoma*? *hergottensis* (Ludbrook, 1966), both specimens from Manuka 1, 709.42 m. 40, 41, *Eurycheilstoma*? *moorei* Haig, 1982; 40, umbilical view; 41, spiral view; both specimens from Hughenden 7, 82.99 m.


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Age and lithostratigraphic correlation. The low diversity foraminiferal assemblages found in mud facies in the lower 33 m contain no species diagnostic of an established foraminiferal zone. Above 33 m the assemblages are indicative of the *Aaptotoichus pitmani* Zone of late Aptian age. Ammonites of the late Aptian Roma Fauna are known from above 16 m. The age of the lower strata in the section (below 16 m) is uncertain.

The predominantly mudstone section above 3 m is the type section of the Doncaster Member of the Wallumbilla Formation. Vine & Paine (1974) correlated the basal sandstone and interbedded mudstone unit (0–3 m) with the Gilbert River Formation.

3.2. Outcrop sections 2 and 3

Sections 2 and 3 at the Twelve-Mile locality on Glendower Station, are both 5.5 m thick (Figure 13), and contain exposures of the quartz sandstone and overlying mudstones which crop out at the top of section 1. Both the quartz sandstone and the mudstone belong to the Doncaster Member of the Wallumbilla Formation.

Lithology. The sections consist of lower and upper quartz sandstone units, separated by an erosional surface (Figures 13, 14). The lower unit is a medium-grained quartz sandstone interbedded with thin black mudstone layers (5–10 cm thick). The black mudstones contain flecks of carbonaceous material and fine-grained sand laminations. Medium-grained quartz sandstone beds are interbedded with the mudstones and contain asymmetric ripples. The quartz sandstone is bioturbated by random mud-filled burrows 3–4 cm long and 2 mm in diameter. Low-angle trough cross-beds are features of both Twelve-Mile sections (Figures 13, 14). The trough cross-beds are truncated by an erosional surface, above which is the upper coarse-grained quartz sandstone unit. The rock is texturally distinct from the underlying quartz sandstone, being porous, poorly consolidated, very well sorted, and consisting of coarse (modal 1.5 mm) subrounded to well-rounded, spherical grains. Quartz (71%) is the main mineralogical component, although chert (0.7%) and volcanolithic fragments (3%) are also present. Nearly 40% of the quartz is polycrystalline. The lower 0.75 m of the coarse unit contains large (15–20 cm) mud clasts. Weakly developed horizontal-subhorizontal bedding is evident above these mud clasts, and *Thalassinoides* burrows are a feature of the top 1 m of outcrop. Pyritic blue-grey mudstone overlies the coarse-grained sandstone (Figure 13).

Palaeontology. Both lower and upper quartz sandstones are unfossiliferous. Black mudstones immediately below the sand-dominated unit in section 3 yield low-diversity and low-abundance siliceous agglutinated faunas, consisting mainly of *Cribrostomoides* sp., *Trochammina minuta*, and *Aaptotoichus pitmani* (sample 5/6/96-2, Table 4). Overlying the sandstone units is mudstone that contains calcareous nodules with rare decapod crustaceans. The mudstone has a foraminiferal assemblage dominated by *Cribrostomoides* sp. and *Trochammina minuta*, and also contains *Ammobaculites humei*, *Psammosphaera laevigata*, *Bathysiphon* sp.,

Figure 6. Selected hyaline benthic foraminifera (1–30) and planktic foraminifera (31, 32). Among the benthic foraminifera, the orders Buliminida (1–8), Robertinida (9, 10), and Rotaliida (11–30) are represented. Taxonomy follows Haig (1982) and Haig & Lynch (1993). All bar scales = 0.1 mm. 1, 2, *Neobulimina albertensis* (Stelck & Wall, 1954); 1 from outcrop section 5, 12/10/94-7; 2 from Hughenden 7, 48.37 m. 3, 4, *Neobulimina kareelensis* (Ludbrook, 1966); different specimens from Manuka 1, 598.84 m. 5, *Orthokarstenia*? *calcarata* (Berthelin, 1880) from Hughenden 7, 28.72 m. 6, 7, *Pleurostomella reussi* Berthelin, 1880; 6, megalospheric test from outcrop section 12/10/94-9; 7, microspheric test from outcrop section 6, 12/10/94-9. 8, *Turrilina* sp. from Hughenden 7, 57.37 m. 9, 10, *Epistomina chapmani* ten Dam, 1948; 9, spiral view; 10, umbilical view; both specimens from Manuka 1, 586.81 m. 11, 12, *Berthelina intermedia* (Berthelin, 1880); 11, umbilical view; 12, peripheral view; both specimens from Manuka 1, 586.81 m. 13, 14, *Bilingulogavelinella australis* Scheibnerová, 1971; opposite sides of test from outcrop section 4, 7/6/96-1. 15, 16, *Gavelinella dakotensis* (Fox, 1954); umbilical and spiral views of test from outcrop section 6, 12/6/96-2. 17–19, *Gyroidina* sp; 17, umbilical view, from outcrop section 5, 12/10/94-4; 18, 19, peripheral and spiral views of test from outcrop section 5, 12/10/94-4. 20, *Gyroidinoides* cf. *infracretaceus* (Morozova, 1948), peripheral view, from Hughenden 7, 136.49 m. 21, *Hergottella jonesi* (Howchin, 1895); lateral view, from Manuka 1, 660.32 m. 22–24, *Lingulogavelinella*? *innaminckae* (Ludbrook, 1966); 22, view of oral side; 23, view of aboral side; 24, peripheral view; all specimens from Manuka 1, 586.81 m. 25, *Lingulogavelinella*? *santoodnae* (Ludbrook, 1966), view of oral side, from Hughenden 7, 82.99 m. 26, *Patellinoides tilchus* (Ludbrook, 1966), spiral view, from Hughenden 7, 82.99 m. 27, *Pseudogavelinella*? *impedita* (Ludbrook, 1966), umbilical view, from Hughenden 7, 136.49 m. 28–30, *Pseudogavelinella*? sp. A; 28, spiral view, from Manuka 1, 650.76 m; 29, umbilical view, from Manuka 1, 642.11 m; 30, peripheral view, from Manuka 1, 650.76 m. 31, 32, *Hedbergella planispira* (Tappan, 1940); umbilical and spiral views of test from outcrop section 6, 12/10/94-12.

Table 1. List of lithofacies defined from outcrop sections 1–9, and applied to drill holes BMR Richmond 1, BMR Richmond 2, GSQ Hughenden 7, and GSQ Manuka 1. The interpretation of sedimentary processes follows interpretations made elsewhere by Amorosi (1995); Bhattacharya (1993), Donovan (1993), Heckel (1972), Hocking *et al.* (1987), Krassay (1994), Leithold (1994), McCubbin (1982), Reineck & Singh (1980), Reinson (1984) and Savrda (1995). Interpretation of the depositional environment of the lithofacies is shown in Figure 7.

Lithofacies	Code	Characteristics	Layer Thickness	Interpretation of Sedimentary Processes
conglomerate	Cm	poorly sorted; clast-supported; clasts mainly quartz (90%) of clasts; intraformational	20cm in outcrop; up to 8m in subsurface	upper flow regime erosion of underlying rocks
coarse quartz muddy sandstone	Sc	poorly sorted; muddy matrix; quartz rich (72% of grains); polygonal grains; bioturbated *(Thalassinoides)*; some rip up clasts	up to 2m in outcrop	limited transportation distance; moderate flow regime
massive, medium-coarse quartz sandstone	Smc	porous; well sorted; coarse, well rounded grains; bioturbated (*Thalassinoides);* some rip up mudclasts; some ripple lamination	up to 3m in outcrop	rapid deposition; high energy conditions; followed by low energy settling of fines from suspension
small-scale, cross-bedded, medium quartz sandstone	Sxm Sxc	small-scale trough cross laminae; medium to course-grained quartz sandstone	laminations cm-scale; bedsets up to 0.5m thick	lower-upper flow regime migration of small current ripples
planar bedded, medium quartz sandstone	Spm Spc	planar beds; medium to coarse-grained quartz arenite; some rip-up mud-clasts	laminations on mm scale; bedsets up to 20cm thick	upper flow regime plane-bed conditions caused by currents or shoaling waves
small-scale, cross-bedded, fine muddy quartz sandstone	Sxf	small-scale trough cross laminae; fine grained quartz muddy sandstone	laminations cm-scale; bedsets up to 0.5m thick	lower flow regime migration of small current ripples during storms
planar bedded, fine muddy quartz sandstone	Spf	planar beds; fine quartz muddy sandstone	laminations cm-scale, bedsets up to m thick	upper flow regime plane-bed conditions caused by storm currents
massive, bioturbated, fine muddy quartz sandstone	Smf	fine-grained quartz muddy sandstone, with no indication of bedding, occasionally bioturbated by *Thalassinoides*	20cm-1m	bioturbation and reworking, original rapid deposition
glaucony-rich sandstone, sandy mudstone	Sg	glaucony-rich (up to 60%); bioturbated; minor angular quartz; glaucony grains rounded	1-2m	authigenic growth of glaucony; low rates of sedimentation, some glaucony current transported
sandy mudstone	Ms	mudstone with 5mm rounded quartz grains; bioturbated *(Thalassinoides)*	units up to 5m thick	bioturbation and reworking of sediment, deposition from intermittent high energy regime, and settling from suspension
mudstone	M	blue-grey to black; pyritic; carbonaceous; planar laminated, bioturbated or massive; some areas slightly sandy	laminae on mm-scale; bioturbated and massive mudstone 10's of metres thick	settling from suspension; reducing benthic conditions.
calcareous mudstone	Mc	blue-grey to black; pyritic; carbonaceous and calcareous in parts; planar laminated, bioturbated or massive; some areas slightly sandy	laminae on mm-scale; bioturbated and massive mudstone 10's of metres thick	settling from suspension; reducing benthic conditions.

Table 2. List of biofacies (1–9) describing the composition of the foraminiferal fauna, the dominant foraminiferal species, associated microfossils, associated lithofacies, and an interpretation of depositional environment (see also Figure 7 for this interpretation). Interpretation of the biofacies is based on the models presented by Sliter & Baker (1972), Murray (1973, 1976, 1991), Haig (1979s), Haynes (1981), Koutsoukos & Hart (1990), and Sikora & Olsson (1991).

Biofacies	General features of foraminiferal assemblage	Dominant species	Associated biota	Associated lithofacies	Environment
1	low diversity benthic assemblage of organic-walled siliceous agglutinated foraminifera	usually abundant *Trochammina minuta*	occasional sponge spicules	M; usually with abundant quartz in the >150μm sand fraction	transitional-lower shoreface
2	moderate diversity benthic assemblage of organic-walled siliceous agglutinated foraminifera	usually abundant *Ammobaculites humei*, and/or *Aaptotoichus pitmani*, *Bathysiphon* sp., *Cribrostomoides nonioninoides*, *Eomarssonella crespinae*, *Kutsevella implanus*, *Reophax geniculatus*	occasional diatoms, radiolaria, ostracods, echinoderm debris, scolecodonts, fish bone and teeth	M; usually with common to abundant quartz in the 63-150μm sand fraction	transitional
3	moderate diversity benthic assemblage of organic-walled siliceous agglutinated foraminifera accompanied by rare to common calcareous hyaline foraminifera	same as for Biofacies 2	ostracods, echinoderm debris, diatoms, fish bone and teeth, radiolarians, scolecodonts	M; in some places rare to common quartz in 63-150μm sand fraction	upper offshore
4	high diversity benthic assemblage of organic-walled siliceous agglutinated foraminifera accompanied by abundant calcareous hyaline types	agglutinated spp. similar to Biofacies 2; abundant hyaline spp. inc. *Bilingulogavelinella australis*, *Eurycheilstoma ? hergottensis*, *Eurycheilostoma ? moorei*, *Gavelinella parvula*, *Globulina lacrima*, *Gyroidinoides infracretaceus*, *Laevidentalina hamiltonensis*	similar to Biofacies 3	M; very fine quartz common at some localities (in 63-150μm fraction).	mid offshore to upper offshore
5	similar to Biofacies 4, but with rare planktic foraminifera	similar to Biofacies 4	similar to Biofacies 3, but with more persistent occurrences	M	mid offshore
6	Abundant planktic foraminifera, together with a diverse benthic assemblage of siliceous agglutinated and calcareous hyaline types	planktic species dominated by *Hedbergella planispira* of small size (<0.25mm); agglutinated species similar to Biofacies 2; hyaline spp. include abundant *Berthelina intermedia*, *Coryphostoma* sp. A, *Epistomina chapmani*, *Gavelinella dakotensis*, *Gyroidina* sp.	similar to Biofacies 5	M	mid to lower offshore
7	Abundant planktic foraminifera, together with a low diversity benthic assemblage of mainly calcareous hyaline types	planktic species dominated by *Hedbergella planispira* of small size (<0.25mm); abundant benthic species include *Neobulimina albertensis*, *Gavelinella dakotensis*, *Gyroidina* sp.	radiolarians, diatoms, fish bone and teeth, mollusc fragments (including '*Inoceramus* prisms')	M	lower offshore
8	Abundant dwarf planktic foraminifera with very rare benthic foraminifera	minute *Hedbergella* (<0.1 mm)	similar to Biofacies 7, but less persistent	M	lower offshore with severe bottom-water anoxia
9	Abundant siliceous agglutinated foraminifera mainly of one species	minute *Textulariopsis* sp. A	fish debris, radiolaria, scolecodonts	M	lower offshore (based on stratigraphic position and adjacent facies) with moderately severe bottom-water anoxia

Ammodiscus rotalarius, *Lagenammina lagenoides*, *Haplophragmoides minor*, and *Verneuilinoides neocomiensis*.

Facies and bathymetric trends. The lower and upper mudstone units belong to biofacies 1, indicative of the lower shoreface to upper transitional zone. The sandstones include facies Smc, Spc, and Sxc reflecting middle to upper shoreface environments similar to those interpreted for the sandstone at the top of section 1.

Age and lithostratigraphic correlation. Sections 2 and 3 lie within the *Aaptotoichus pitmani* Zone of late Aptian age. The quartz sandstones are correlated with a similar unit of sandstones at the top of section 1. In both outcrop areas, the basal quartz sandstones are medium-grained and have similar bedding features. These medium-grained quartz sandstones are overlain by coarse-grained quartz sandstone, which is mostly massive, but has weakly developed cross or planar laminations. The regional significance of the erosion surfaces between upper and lower sandstone units observed in both sections is uncertain.

3.3. Outcrop section 4

This section, measured at the Six-Mile locality on Glendower Station, reveals the top 25 m of the Doncaster Member overlain by a thin, fine-grained quartz sandstone unit interpreted to represent the Jones Valley Member (Figures 15, 16). Calcareous mudstones of the Ranmoor Member are represented at the top of the section.

Lithology. Sulphidic black mudstone is the main lithology, interbedded with glaucony-rich fine-grained sandstone beds, and fossiliferous calcareous nodule horizons (Figures 15, 16). The stratigraphically highest bed containing glaucony (20–21 m) is extremely glaucony-rich, and contains minor angular quartz, plagioclase, and muscovite grains. The glaucony grains are mostly rounded. Glaucony-rich sedimentary dykes are derived from this greensand, and cut through the mudstone (Figure 15).

A thick (1 m) bed of fine-grained (0.075 mm modal), cross-laminated, muddy quartz sandstone occurs at the 25 m level. It consists of sub-rounded,

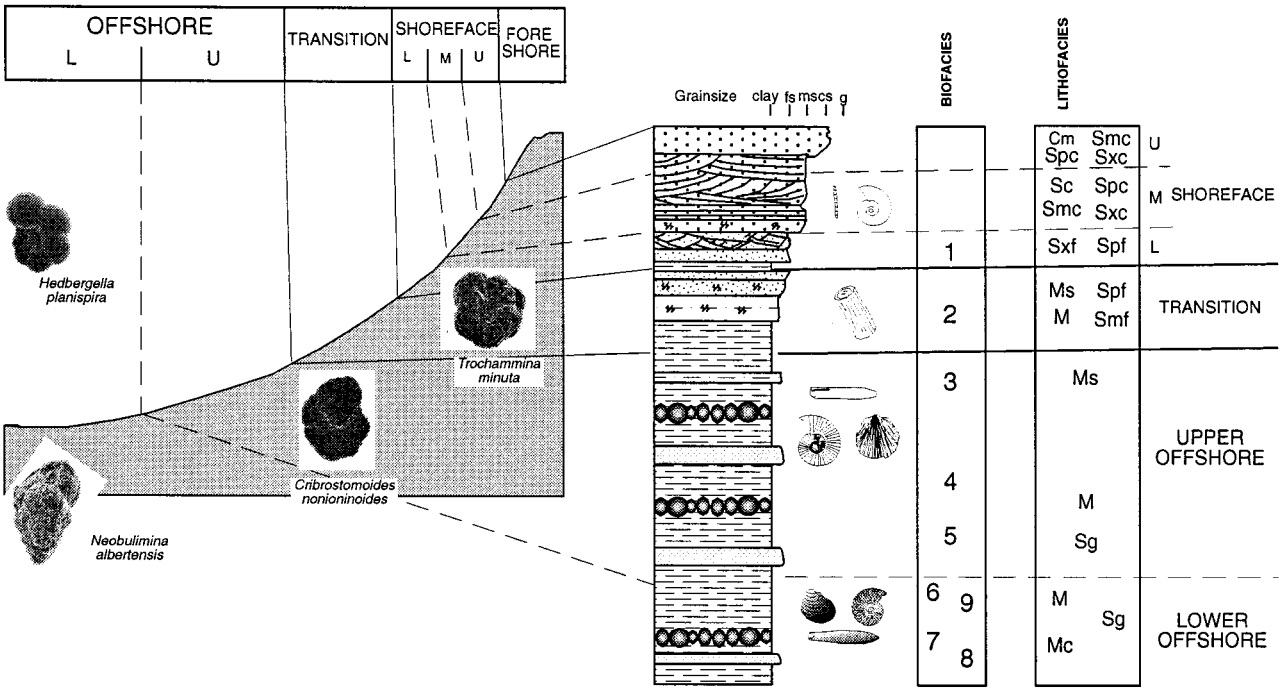


Figure 7. Depositional model for sedimentation in the northeastern Eromanga Basin. Bathymetric zones follow the terminology of Reading (1978). The characteristics of the biofacies and lithofacies are listed on Tables 1 and 2. A legend to the lithological units pictured is presented in Figure 13.

monocrystalline quartz with minor plagioclase (70% albite), and a large amount of carbonate cement. Overlying the muddy quartz sandstone unit is weathered, yellow-brown mudstone.

Palaeontology. Calcareous nodules in the black mudstones contain a macrofauna similar to that of Section 1, including crustaceans, the ammonite *Australiceras jackii*, and the bivalve *Maccoyella barklyi*. The bivalve *Cucullaea semistriata* was preserved as an internal mould within the black mudstone beneath the glaucony-rich marker bed. The belemnites, *Peratobelus oxys* and *P. sellheimi*, occur in both glaucony-rich horizons and calcareous nodules. Guards of the belemnite *Dimitobelus diptychus* occur in scree from the section overlying the fine-grained muddy quartz sandstone.

Table 3. Foraminiferal and macrofossil zonation for the northeastern Eromanga Basin. The foraminiferal zones are adapted from Haig & Lynch (1993), modified after Haig (1979b). The macrofaunal zones are based on the ammonite work of Whitehouse (1926).

STAGE	*AMMOBACULITES* BENTHIC ASSOCIATION	*HEDBERGELLA* PLANKTIC ASSOCIATION	MACROFAUNA
UPPER ALBIAN	*Eomarssonella crespinae* Zone	*Hedbergella delrioensis*	Tambo Fauna
		Zone of dwarf *Hedbergella*	
MIDDLE ALBIAN		*Hedbergella planispira* Zone	
LOWER ALBIAN	*E. crespinae - A. pitmani* Zone		
UPPER APTIAN	*Aaptotoichus pitmani* Zone	no planktics	Roma Fauna
LOWER APTIAN	*T. cushmani-A. pitmani* Zone		
	Textulariopsis cushmani Zone		

Diverse and abundant microfossils are found in the black mudstones, including diatoms, radiolaria, sharks' teeth, ostracods, and foraminifera (Figure 16). The foraminiferal fauna includes calcareous hyaline benthic forms that are more abundant in the lower part of the section (Table 4) and a more diverse assemblage of non-calcareous agglutinated species than occurs in the stratigraphically lower section 1.

Facies and bathymetric trends. The section below 25 m is mainly in mudstone facies with several <1-m-thick beds representative of Sg lithofacies.[14] The lower mudstone beds contain biofacies 3 and 4 indicative of mid to upper offshore environments. Above 12 m, biofacies 1 and 2–3 alternate, suggesting frequent changes in water depth within the upper offshore to

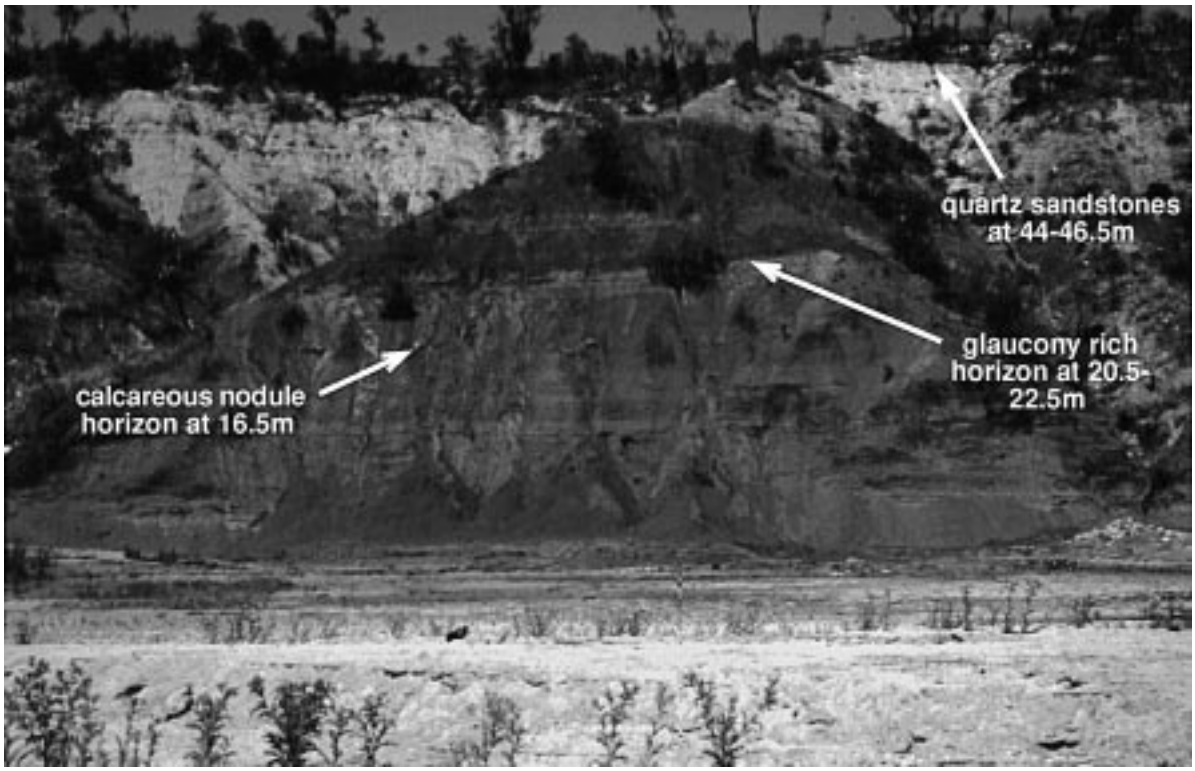


Figure 8. Photograph of outcrop section 1 from 3 m above the base, showing dominant blue-grey mudstone (lithofacies M), glaucony rich sandstone horizons (lithofacies Sg), calcareous nodule horizons, and quartz sandstones (lithofacies Spc, Smc, Sxc) near the top of the section. The quartz sandstones are overlain by weathered, white mudstone (lithofacies M) at the top of the cliff.

transitional range. Lithofacies Sxf appears at 25–26 m in the section. The fine grain size and cross-bedding in this sand facies indicate lower flow-regime migration of small current ripples probably within a lower shoreface environment.

Age and lithostratigraphic correlation. The entire section belongs within the *Aaptotoichus pitmani* Zone of late Aptian age. Mudstone at 2.2 m lies within the interval of overlap in ranges of *Eurycheilstoma*? *hergottensis* and *E*? *moorei*. Macrofossils belonging to the late Aptian Roma Fauna are present below 22 m. In scree of weathered mudstone at the top of the section, the presence of *Dimitobelus diptychus* is indicative of the Tambo Fauna of Albian age.

The base of section 4 is correlated to be 5 m above the quartz sandstone unit exposed in sections 1–3 (Figures 9, 13). Correlation was based on a poorly exposed section that was measured above the quartz sandstone at Twelve-Mile, and indicated a thickness of 25 m to a distinctive light-green glaucony horizon. This greensand was visually traced to the horizon that is exposed 20 m above the base of section 4 (Figure 16). Mudstones below 25 m are placed with the Doncaster Member, although this interval occurs stratigraphically above the type section of the member. The muddy quartz sandstone unit at 25–26 m is correlated to the Jones Valley Member; the overlying *Dimitobelus*-bearing mudstones are regarded as Ranmoor Member.

3.4. Outcrop section 5

Two stratigraphic sections were measured at Two-Mile (Figure 17). The basal section (5a) is stratigraphically equivalent to section 4 and contains the Doncaster, Jones Valley and Ranmoor Members of the Wallumbilla Formation. The second section (5b), above the greensand marker horizon, located 13–14 m above the base of section 5a, includes an additional 36 m of mudstone and encompasses parts of the Doncaster, Jones Valley and Ranmoor Members.

Lithology. The mudstones at the base of the section are equivalent to mudstones 7 m above the base of outcrop section 4, but include a fine-grained, quartz-rich, light-grey sandy mudstone at 1–2 m (Figure 17) that

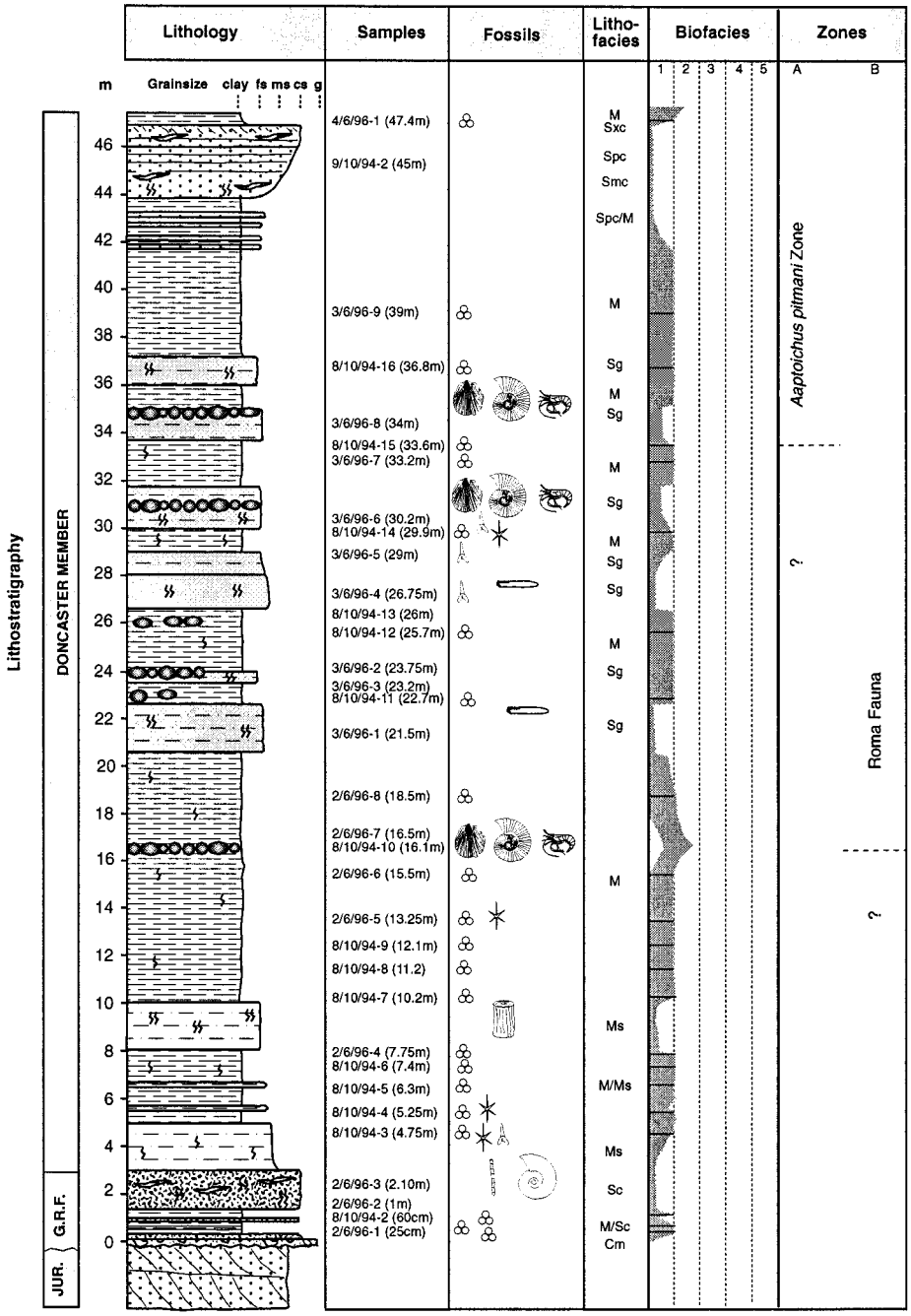


Figure 9. Outcrop section 1 (type section of the Doncaster Member, Wallumbilla Formation) showing lithostratigraphy, rock sample positions, fossil assemblage, lithofacies, biofacies, and biozones. Foraminiferal distributions from this section are shown on Table 4. The foraminiferal faunas obtained from samples in this section belong to Biofacies 1, corresponding to the lower shoreface-transitional bathymetric zone as indicated on Table 2, and in the depositional model shown on Figure 7. G.R.F. = Gilbert River Formation.

is not represented in section 4. Pyritic blue-grey mudstones are the primary rock type, and contain jarosite and gypsum as secondary minerals along weathered surfaces. Glaucony-filled sedimentary dykes are present through the section, as are fossiliferous calcareous nodule horizons. As in section 4, three glaucony-rich beds are present. Smooth, rounded, black, argillaceous pebbles occur at the base of the main greensand marker beds at 13.5 m (Figure 17). A thin (1 m) bed of muddy quartz

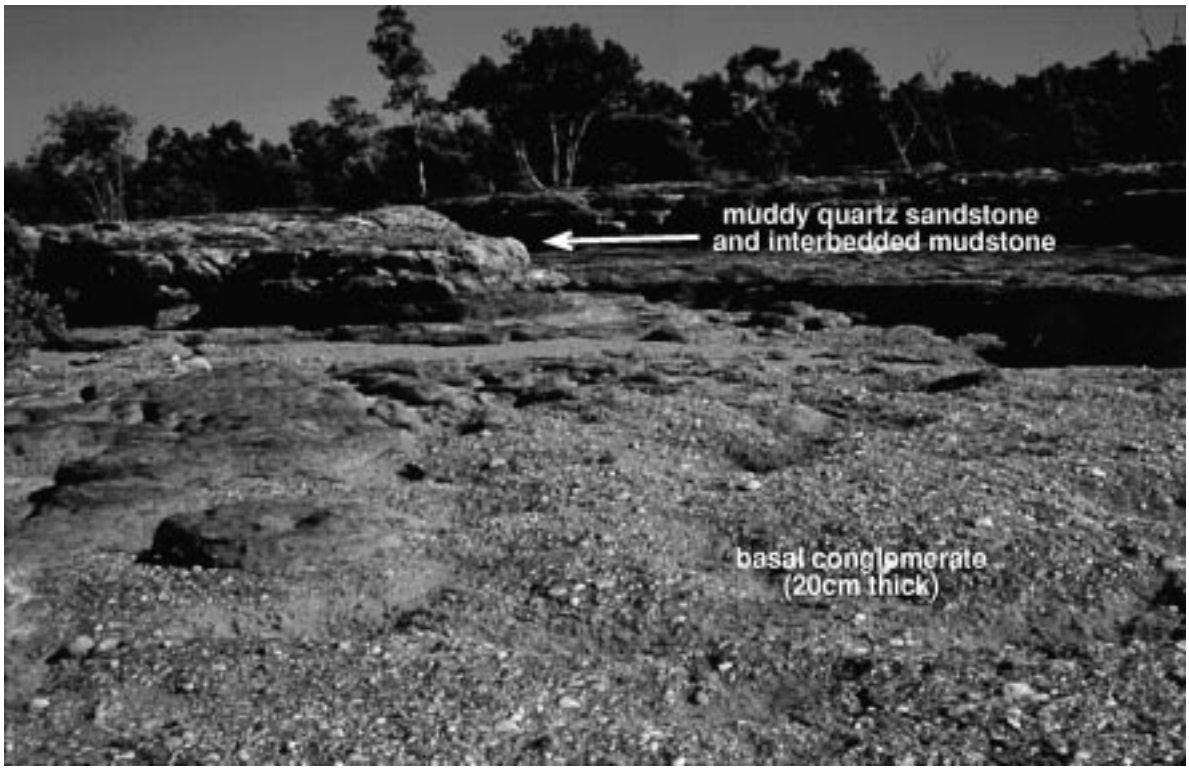


Figure 10. The conglomerate (lithofacies Cm) at the base of section 1, overlain by coarse muddy quartz sandstone (lithofacies Sc) and interbedded mudstone (lithofacies M). The conglomerate is about 20 cm thick, clast-supported, and laterally extensive with a planar base.

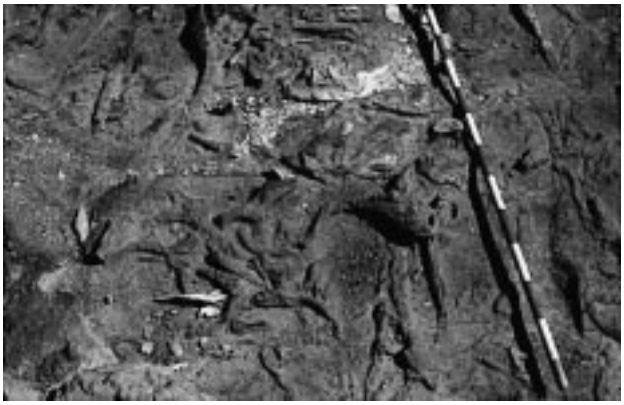


Figure 11. Horizontal, branching, feeding burrows exposed in a weathered, muddy quartz sandstone (lithofacies Sc), 1.5 m above the base of outcrop section 1. These burrows are assigned to the ichnogenus *Thalassinoides*, indicative of shallow marine depositional conditions. They are approximately 2 cm in diameter. The Jacob Staff is divided into 10 cm increments.



Figure 12. Mould of a sphenophyte branch preserved on a muddy quartz sandstone (lithofacies Sc) bedding surface, 3 m from the base of outcrop section 1. The geological pick next to the branch is 32 cm long. Over 50 fossil branches were observed on this bedding surface, as well as an ammonite mould.

sandstone is present at 17.5–18.5 m, and is correlated to similar rock units in sections 4 and 9. Above the muddy quartz sandstone is blue-grey mudstone weathering to a brown-yellow colour, and partly laminated (Figure 17). It also contains minor glaucony and pyrite (evident from grains in >150 μm washed sediment fraction). The mudstones are slightly calcareous, which may be the factor influencing weathering colour.

Palaeontology. A major faunal change occurs across the muddy quartz sandstone at 17.5–18.5 m in section 5a.

Table 4. Relative abundance of foraminiferal species in samples from outcrop sections 1–9. Sample horizons are recorded in the stratigraphic sections in Figures 9–20. Biofacies assignments are based on the criteria outlined in Table 2 and, together with lithofacies, are interpreted to reflect bathymetric changes within the basin as shown in Figure 7. A=>20 specimens, C=10–20 specimens, R=<10 specimens.

	SECTION 1																						S	3	SECTION 4																			SECTION 5						SECTION 6									7	8	9
Foraminiferal Species	2/6/96-1	8/10/94-2	2/6/96-2	8/10/94-3	8/10/94-4	8/10/94-5	8/10/94-6	2/6/96-4	8/10/94-7	8/10/94-8	8/10/94-9	2/6/96-5	2/6/96-6	2/6/96-8	8/10/94-11	8/10/94-12	8/10/94-14	3/6/96-7	8/10/94-15	8/10/94-16	3/6/96-9	4/6/96-1	5/6/96-2	5/6/96-3	10/10/94-1	DH640-646	10/10/94-3	10/10/94-5	7/6/96-1	10/10/94-7	7/6/96-4	10/10/94-9	10/10/94-10	7/6/96-8	10/10/94-12	7/6/96-2	7/6/96-3	10/10/94-13	10/10/94-14	10/10/94-15	10/10/94-16	10/10/94-18	10/10/94-19	12/10/94-2	12/10/94-3	12/10/94-4	12/10/94-5	12/10/94-6	12/10/94-7	12/6/96-1	12/6/96-3	12/10/94-9	12/10/94-11	12/10/94-12	12/10/94-13	12/6/96-2	12/10/94-14	DH667/668	12/6/96-4	11/6/96-1	10/6/96-1
Siliceous Agglutinated Forms																																																													
Aaptotoichus pitmani																			R	C	A		A							R	A	R	C			A	A	A		A	A		A	C	C																R
Ammobaculites humei	R	R		C	R	C	R	C		R				R	R				R	R	R	A	R	A	C	C	R	R	R	R	A		R	R	R	C	C	A	R	A	R	R	C	A	C			R	R			C			R	C		A		A	R
Ammodiscus rotalarius		R		R	R	R		R					R	R		R	R	R	R			R		A	R	C	R		R		R							R						R	R															R	
Bathysiphon sp.	A	R		R		R	R		R						R			R				A		A	R	R	R	C	C	R	R				R	R	R	C		A	R	R	A	C	R			R	R			R			R		R	R			A
Bimonilina engeninensis	R	R		R	R	A	A	A	C	R			R	A	R		R	C	R	R		R	R	R	R	R	C	R	R		C	R				A	C	R		R			A	R							R										C
Bimonilina variana	C	R				R										R					R	R					R				R																														A
Cribrostomoides sp.	A	C		R	A	A	A	A	C	C	R	C	A	A	C	R	R	A	A	A	A	A	A	A	A		C	C	A	R	A	R	R		A	A	C	A		A	C		R	C	C			R		R		C			A	R		C		A	A
Eomarssonella crespinae																																												R	C									R	A					C	
Evolutinella sp.																																																R		R	R			R	C	R	R	C		R	
Gaudryinopsis filiformis																																																							R						
Haplophragmoides minor				R		R										R		R				R	R	R	R	R	C	R	R				R					R		R			R	R											R				R		
Haplophragmoides sp.																																																							C		R			C	
Kutsevella implanus	R			R																		C	R	R		R	R	R		R	R	R				A	A	A		A	R	R	C	A																	A
Lagenammina alexanderi																									R	R					R							R		R			R	C																	
Lagenammina lagenoides				R		R	R															A		C	R	R	C	R	R	R	R		R		R	R		R		R	R	R	C	R	R							R									A
Miliammina ischnia																										R																			R													R			
Placentammina lathrami																			R											R					R																										
Psammosphaera laevigata	R	R			R	R	R		R						R			R	R	R		R		R	C	R	R			R			R		R	R	R	R		R		R	R	R										R				R			C
Psammosphaera sp.																																																		A	R	A	C		A		A				
Reophax geniculatus																																						C						R																	
Spiroplectammina edgelli																									R	R	R	R	R																	R															
Textulariopsis sp.																											R								R							R																			
Trochammina minuta	A	A	C	A	A	A	C	C	R	R	R	A	A	A	R	R	A	A	C	A	A	A	A	A	C	C	R	R	R	C	A	C	C		A	A	A	A		A	C		R	R				R	R												
Trochammina sp. A	R	R		R	R			R		R							R										R													R					R																
Trochammina sp.								C																																																					
Verneuilinoides howchini	R	R															R									A	R	R		R																		R	R		R	R		A	R	A	C	C		C	
Verneuilinoides neocomiensis			R	R																		C		R	R	R									R		R	C		R															R				R	C	
Hyaline calcareous: Lagenida																																																													
Astacolus howchini																										R																																			
Astacolus scitula																																																													
Citharina cf. *petila*																																														R						R		R	R			C			
Citharina tyelea																																																R										R			
Citharina yardinnensis																																																										R			
Frondicularia ungeri																													R																													R			
Globulina lacrima																										R			R																							R						R			
Globulina prisca																													R																													R			
Laevidentalina hamiltonensis																										C		R	R						R			R										R						R							
Laevidentalina cf. *oligostegia*																																														R					R		R	R				R			
Lagena sp.																																																													
Lenticulina kiwania																																														R	R									R					
Lenticulina gr. *gaultina*																																														R		R						R				R			
Lenticulina gr. *warregoensis*																									R	R		R	R				R					R								R	R	R				R								R	
Lingulonodosaria malanila																																																										C			
Lingulonodosaria nodosaria																										R																										R						R			
Marginulinopsis arimensis																										R																																			
Marginulinopsis cephalotes																										R																				R						R			R						
Marginulinopsis pristipellis																																																				R									
Marginulinopsis cf. *robusta*																																														R															
Planularia cf. *strombecki*																										R			R																																
Psilocitharella recta																																																										R			
Pyramidulina cf. *flexocarinata*																																														R	R					R						C			
Pyramidulina obscura																																														R															
Pyramidulina sceptrum																																																					R								
Ramulina sp.																										R																				R					R	R		C				R			
Saracenaria bronnii																																																R													
Saracenaria ninbella																																																			R			C		R		A			
Saracenaria planiuscula																										C												R																				R			
Tristix perelongatum																										R																				R	R											R			
Hyaline calcareous: Buliminida																																																													
Coryphostoma sp. A.																																														R						R						R			
Eurycheilostoma? hergottensis																										A																																			
Eurycheilostoma? moorei																										C																																			
Neobulimina albertensis																																																A	C	A	R	A	C	R		C	R	A		R	
Pleurostomella reussi																																														R						R						R			
Hyaline calcareous: Rotaliida																																																													
Berthelina intermedia																												R										R								R	R														
Bilingulogavelinella australis																									R	A			R																																
Gavelinella dakotensis																																														R		R	R	R	A	A	R	C		R		A			
Gyroidina sp.																																														A	R		R	A	C	R	R	A	R	R		R		R	
Gyroidinoides infracretaceus																										A							R																												
Gyroidinoides sp.																																																										A			
Lingulogavelinella cf. *albiensis*																										A																																			
Lingulogavelinella innaminckae																																																										R			
Lingulogavelinella santoodnae																									R	R			R																																
Patellinoides tilchus																																																													
Pseudogavelinella? impedita																										R																																			
Pseudogavelinella? sp. A																										R																																			
Hyaline calcareous: Globigerinida																																																													
Hedbergella planispira																																														A		A	A	A	A	A	A	A		A		A			
Biofacies	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	?	1	1	1	1	1	1	1	1	3	4	2	3	3	1	1	1	3	?	2	1	1	3	?	1	1	?	2	2	2	7	4	6	6	6	6	6	6	6	5	6	5	6	?	3	2

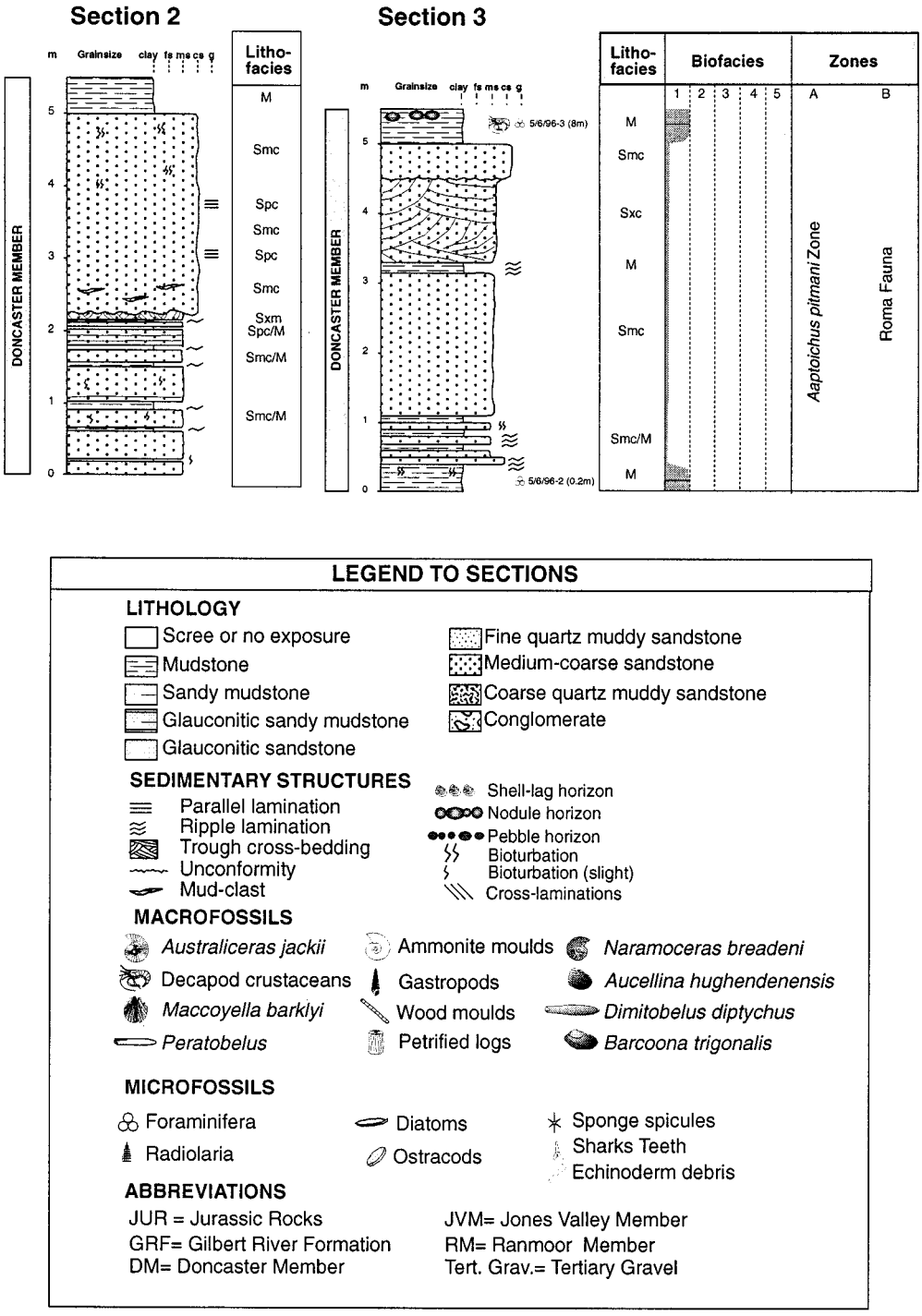


Figure 13. Outcrop sections 2 and 3 showing lithostratigraphy, rock sample positions, fossil assemblage, lithofacies, biofacies, and biozones. The quartz sandstones in these sections correlate to the quartz sandstones at the top of section 1. Mudstone samples collected above and below the quartz sandstones in section 3 contain foraminiferal faunas, shown on Table 4. Biofacies and lithofacies indicate deposition within a shoreface to transitional depositional environment. Also presented is a legend to the fills and symbols used on stratigraphic columns throughout this paper.

Below the muddy quartz sandstone, belemnites of the genus *Peratobelus* are preserved, as well as bivalves within the calcareous nodule horizons (Figure 17). The light-grey sandy-mudstone horizon, at 1 to 2 m above the base of the section, contains wood that has been bored by *Teredolites*.

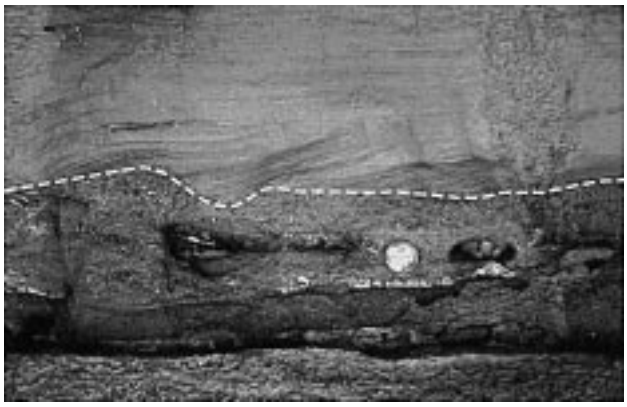


Figure 14. Photograph showing low angle trough cross bedding in medium-grained quartz sandstone (lithofacies Sxm), 2.3 m from the base of outcrop section 2. An erosional surface (indicated by the white dashed line) truncates the cross bedding, and separates the medium-grained quartz sandstone from overlying coarse-grained quartz sandstone (lithofacies Smc). Mud-clasts are present within the coarse-grained quartz sandstone.

Above the muddy quartz sandstone, the macrofauna is quite different (Figure 17). Cylindrical belemnite guards of the genus *Peratobelus* are replaced by clavate forms of the genus *Dimitobelus*. Large bivalves of genera such as *Maccoyella* are replaced by thin-shelled *Aucellina hughendenensis*, preserved as skeletal material and moulds in friable mudstone, rather than within calcareous nodules. Small (1–2 cm) ammonites, *Naramoceras breadeni*, are closely associated with *Aucellina* and are often found within the same horizon.

Major changes also occur in the microfossil assemblages across the muddy quartz sandstone horizon. The incidence of radiolaria and diatoms in the upper beds is high compared to the number found in the lower pyritic blue-grey mudstone (Figure 17). Above the muddy quartz sandstone, planktic foraminifera, mainly *Hedbergella planispira*, make their first appearance, associated with a high number of calcareous benthic species, such as *Gyroidina* sp., *Neobulimina albertensis*, and *Gavelinella dakotensis* (Table 4). Agglutinated genera associated with these calcareous species include *Ammobaculites humei*, *Bathysiphon* sp., and *Eomarssonella crespinae*. Calcareous nannofossils are associated with the beds containing planktic foraminifera and are not found in the lower sections.

Facies and bathymetric trends. The lithofacies developed in section 5a parallel those recognized in section 4. The sandy mudstone, indicative of the transitional zone, at 1–2 m in section 5a corresponds to a shallowing in facies recorded around 3 m in section 4. The planar-bedded fine muddy quartz sandstone lithofacies (Spf, Figure 17) is indicative of upper-flow regime plane-bed conditions, probably in a lower shoreface depositional environment. Section 5b contains evidence of a significant increase in bathymetry. Mudstone within 2 m above the quartz sandstone includes biofacies 2 of the transitional zone. Four metres higher in the section, calcareous mudstone contains biofacies 7 indicative of a lower offshore environment.

Age and lithostratigraphic correlation. Beds below 14 m in section 5a contain a Roma Fauna of late Aptian age. Section 5b contains a Tambo Fauna, which is of early Albian age according to Day (1969, 1974). The basal mudstones sampled in section 5b, located 7–8 m above the glaucony marker bed, contain agglutinated foraminifera that belong to the *Aaptotoichus pitmani–Eomarssonella crespinae* Zone of probable earliest Albian age. The interval from 12 to 26 m in section 5b contains planktic foraminifera belonging to the *Hedbergella planispira* Zone, which is known from lower to middle Albian in Australia. Sample 12/10/94-4 contains calcareous nannofossils including *Sollasites falklandensis* and *Rhagodiscus angustus* which, when combined with the absence of *Tranolithus phacelosus*, indicate the upper part of coccolith zone CC8a. This suggests a late early Albian age for the sample, and agrees with the foraminiferal zonation.

These sections can be correlated directly to section 4 using the glaucony-rich marker horizon. In section 5a the glaucony-rich horizon is located 13.5–14 m above the base (Figure 17), indicating that the basal mudstones of the section probably correlate to 7 m above the base of section 4 (Figure 16). This is consistent with the fossil assemblages. Mudstones beneath the muddy quartz sandstone horizon at 17.5–18.5 m are regarded as Doncaster Member, and the muddy quartz sandstone is correlated to a similar rock-unit in sections 4 and 9, as the Jones Valley Member. Calcareous mudstones overlying the muddy quartz sandstone unit are interpreted as belonging to the Ranmoor Member (based on similarities to section 6, the Ranmoor type section; Figure 18).

3.5. Outcrop sections 6 and 7

Section 6 (Figures 18, 19), north of Glenmoan homestead, is the type-section of the Ranmoor Member (Vine & Paine, 1974), but represents only a small segment of this lithostratigraphic unit. A second section (section 7), south of Glenmoan Homestead (Figures 18, 19), exposes a stratigraphically higher portion of the Ranmoor Member.

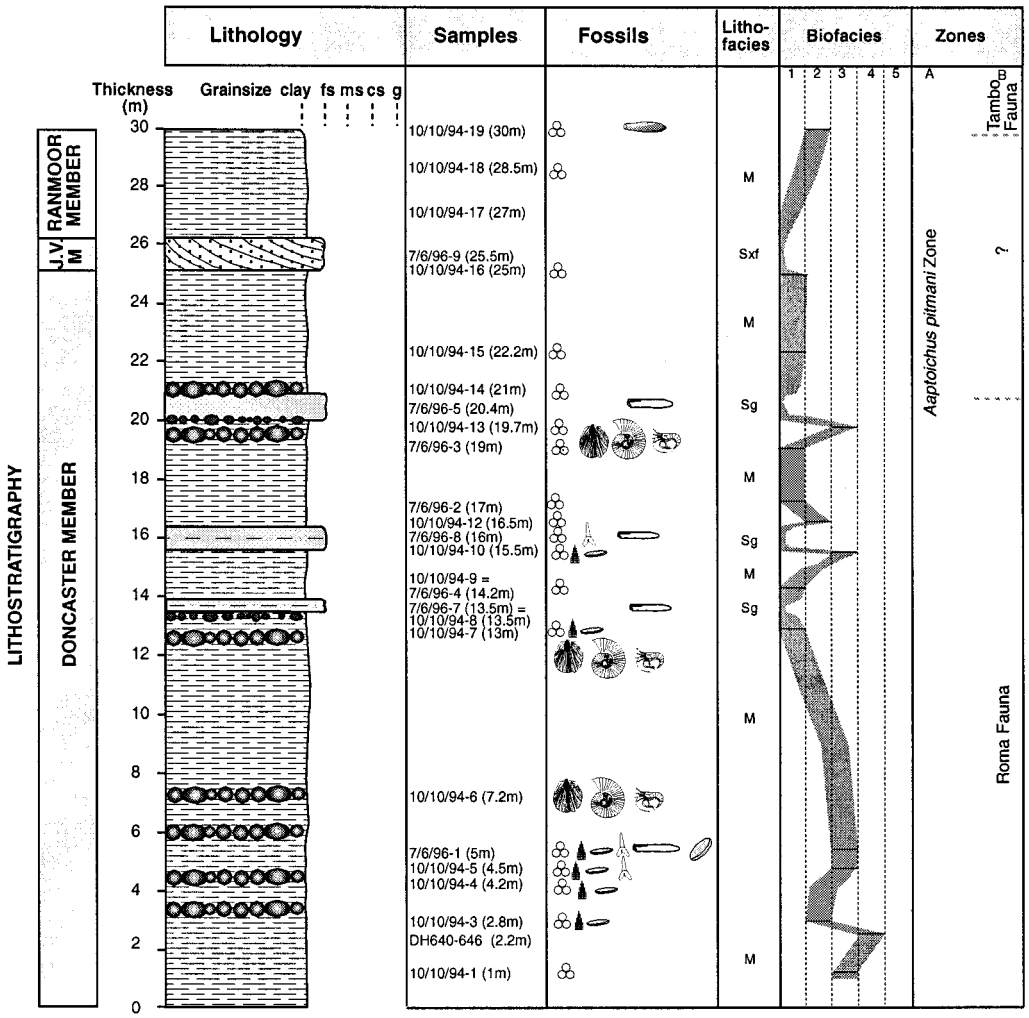


Figure 15. Section 4 showing lithostratigraphy, rock sample positions, fossil assemblage, lithofacies, biofacies, and biozones. The glaucony-rich horizon at 20–21 m is approximately 25 m above the top of the sandstone unit in outcrop section 1. The foraminiferal distributions of samples are shown in Table 1. The biofacies trends shown by the shaded curve reflect changes in bathymetry with biofacies 1 corresponding to the lower shoreface to transitional bathymetric zone, biofacies 2 representing the transitional zone, and biofacies 3 indicating an upper offshore depositional environment.

Lithology. The main lithology in the Glenmoan area is calcareous mudstone, which has an oily feel and is black when fresh, and yellow brown when weathered. As in section 5, the mudstones also contain glaucony and rare pyrite. Interbedded with the mudstones are fine-grained muddy quartz sandstones with carbonate cement and sub-rounded to sub-angular, non-spherical quartz grains. The quartz grains are mono-crystalline, and many have undulous extinction. Glaucony, plagioclase, and muscovite are minor components. Soft-sediment slump structures caused by sediment loading during burial are developed at the base of the muddy quartz sandstones (Figure 18). Evidence of *Thalassinoides* burrowing occurs in scree from section 7 (Figure 18).

Calcareous nodules are rarer in the calcareous mudstones than in the stratigraphically lower pyritic mudstones of the Doncaster Member, an observation also made for sections 5a and 5b. In addition to being fewer in number, the nodules are orange-brown with internal, black, moss-like dendrites of manganese oxide.

Palaeontology. As noted in section 5, a different macrofossil fauna and mode of preservation is present in the Ranmoor Member, compared to the underlying Doncaster Member. The bivalve *Aucellina hughendenensis* and small (1–2 cm diameter) ammonites of the species *Naramoceras breadeni* are the most abundant macrofossils (Figure 18). Belemnite guards

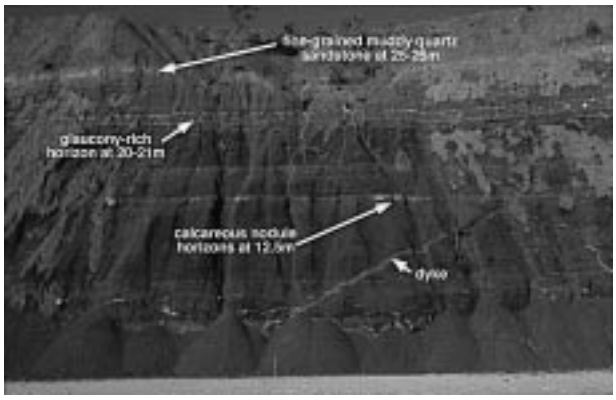


Figure 16. Photograph of Section 4, showing dominant mudstone lithology (lithofacies M), calcareous nodule horizons, and glaucony-rich marker bed (lithofacies Sg). The thin (1 m) fine-grained muddy quartz sandstone horizon (lithofacies Sxf) correlated with the Jones Valley Member, is evident as a light band 25–26 m above the base of the section. The light-green band cross-cutting the dark-grey mudstone at an angle is a glaucony-rich sedimentary dyke. The Jacob Staff at the base of the section is 1 m long.

belonging to *Dimitobelus diptychus* were found in scree at the base of section 6 (Figure 18).

Foraminiferal assemblages from section 6 samples (Table 4) are commonly composed of calcareous hyaline and siliceous agglutinated benthic forms, along with large numbers of the planktic foraminifera *Hedbergella planispira*. Significant siliceous agglutinated benthic forms include *Verneuilinoides howchini* and *Evolutinella* sp., whereas *Gyroidina* sp., *Gavelinella dakotensis*, and *Neobulimina albertensis* are important calcareous hyaline forms. Other associated microfossils in the Glenmoan samples include radiolaria, diatoms, and rare sharks teeth (Figure 18).

Facies and bathymetric trends. The main lithofacies represented in section 6 is calcareous mudstone associated with biofacies 5–6, indicative of mid to lower offshore environments. Thin sands at 5m (Spf lithofacies) and at 6, 9.5, and 10.2 m (Smf lithofacies) may represent intermittent shallowing episodes or influxes of quartz sand possibly associated with storm events. Section 7 includes a greater sand content than in section 6. Interbedded mudstones at 0.5 m in section 7 contain a sparse agglutinated foraminiferal assemblage suggestive of biofacies 1 or 2. The presence of *Thalassinoides* burrows in at least one of the sand beds, the probable occurrence of biofacies 1/2, and the absence of the molluscan macrofauna that is common in section 6, suggest that section 7 was deposited in shoreface to transitional environments, at considerably shallower depths than reflected by lower beds in section 6.

Age and lithostratigraphic correlation. The molluscan fauna (including ammonites) of section 6 is typical of the Tambo Fauna of early Albian age (Day 1969, 1974). Planktic foraminifera in this interval belong to the *Hedbergella planispira* Zone known from the Australian late early to middle Albian. On the basis of a similar fossil assemblage, the type Ranmoor Member (section 6, Figure 18) can be correlated with an 11-m-thick interval, commencing at 12 m above the top greensand horizon in section 5 (Figure 17). Correlation of section 7 (Figure 18) is less clear, but projection of the greensand marker horizon of section 5 places section 7 about 5 m above the top of section 5b. Both sections in the Glenmoan area represent the Ranmoor Member.

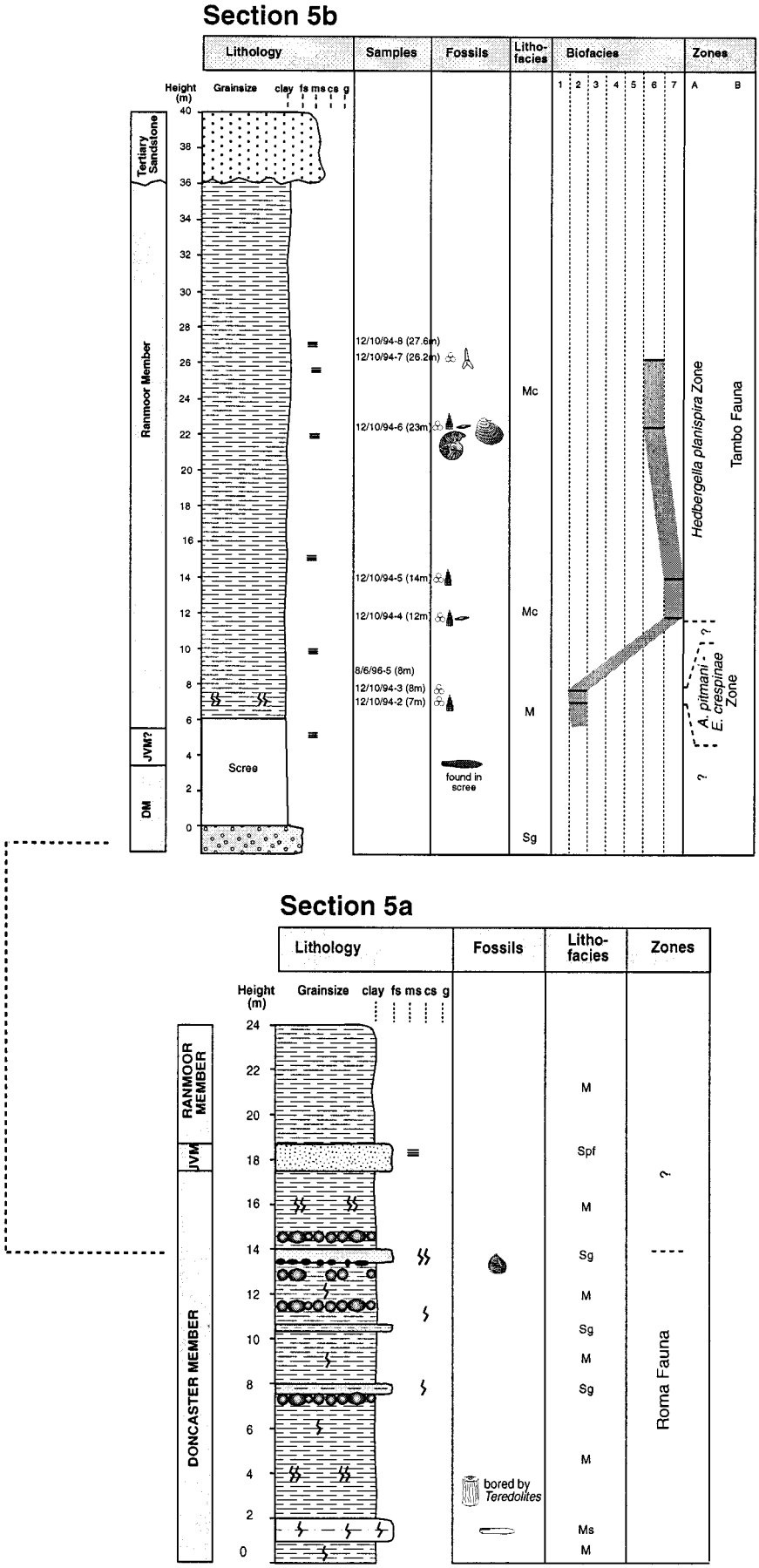
3.6. Outcrop section 8

This section, in the Hughenden town area (Figure 18), is the youngest part of the Lower Cretaceous stratigraphy studied at outcrop, but it is poorly exposed and extremely weathered. The lithostratigraphic unit represented is the Ranmoor Member, at a level just below the contact with the overlying Toolebuc Formation.

Lithology. The section consists of yellow-brown mudstone, with a silty mudstone interbed (1 m thick). Orange-yellow calcareous nodules are present, but are unfossiliferous (Figure 18).

Palaeontology. The basal beds of the section contain shelly material of the bivalve *Aucellina hughendenensis* (Figure 18). Decapod crustacean remains, and two broken specimens of the ammonite *Beaudanticeras flindersi*, were collected from scree at the base of the section.

Figure 17. Outcrop sections 5a and b showing lithostratigraphy, rock sample positions, fossil assemblage, lithofacies, biofacies, and biozones. The glaucony-rich horizon at 13.5–14 m above the base of section 5a correlates to the unit 20–21 m above the base of section 4. Correlation of sections 5a and 5b is based on tracing the glaucony-rich marker bed. The foraminiferal assemblages of samples from section 5b are shown on Table 1. The biofacies trends in section 5b reflect a deepening from the transitional environment (biofacies 2) to the lower offshore bathymetric zone (biofacies 6 and 7).


Section 5b
Lithology
Samples
Fossils
Litho-facies
Biofacies
Zones
Height (m)
Grainsize
clay fs ms cs g
Tertiary Sandstone
Rannoor Member
JVM?
DM
Scree
12/10/94-8 (27.6m)
12/10/94-7 (26.2m)
12/10/94-6 (23m)
12/10/94-5 (14m)
12/10/94-4 (12m)
8/6/96-5 (8m)
12/10/94-3 (8m)
12/10/94-2 (7m)
found in scree
Mc
Mc
M
Sg
Hedbergella planispira Zone
Tambo Fauna
A. pitmani
E. crespinae
Zone
Section 5a
Lithology
Fossils
Litho-facies
Zones
Height (m)
Grainsize
clay fs ms cs g
RANMOOR MEMBER
JVM
DONCASTER MEMBER
bored by Teredolites
M
Spf
M
Sg
M
Sg
M
Sg
M
Ms
M
Roma Fauna

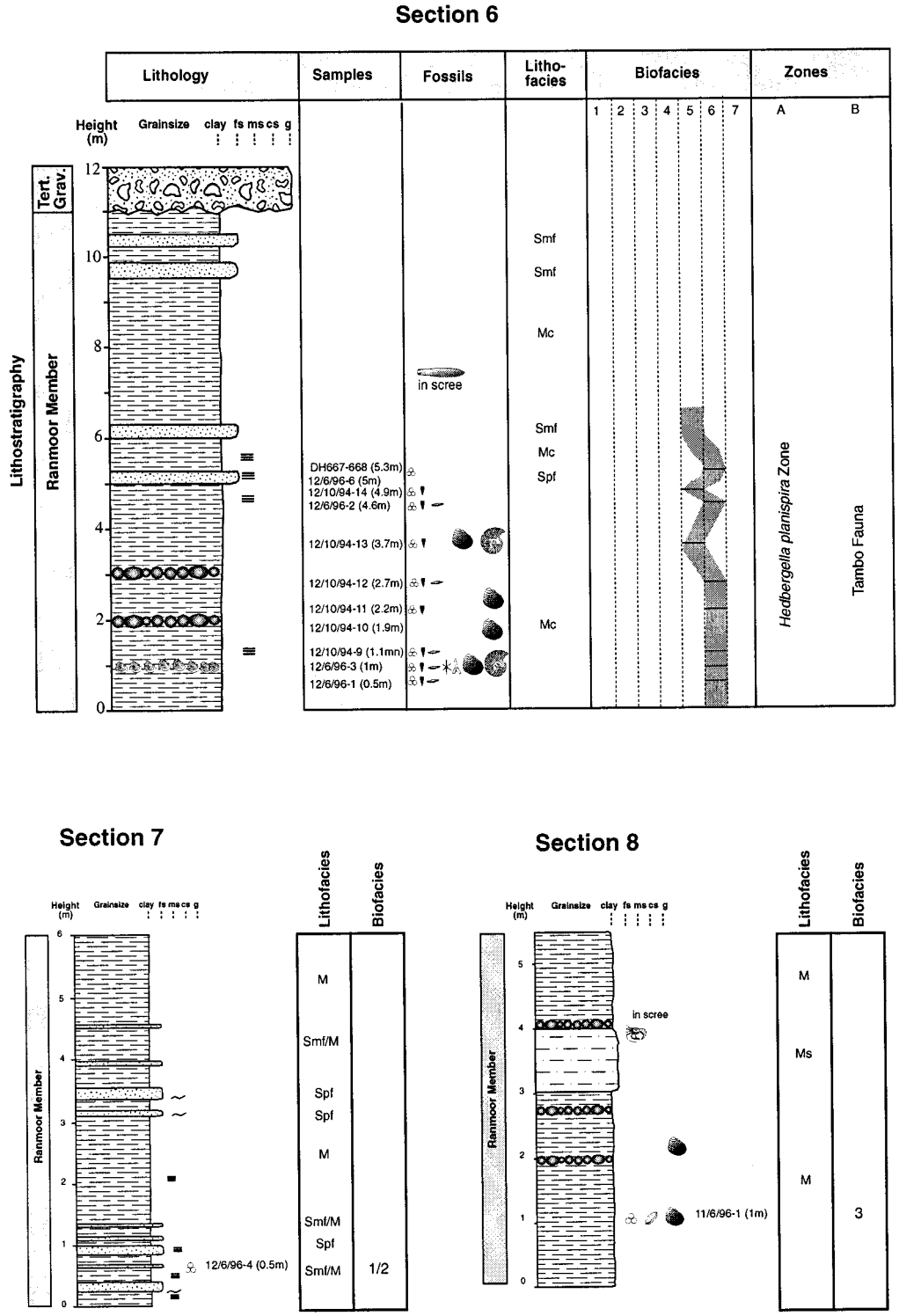


Figure 18. Outcrop sections 6, 7, and 8 showing lithostratigraphy, rock sample positions, fossil assemblage, lithofacies, biofacies and biozones. Table 1 lists foraminiferal distributions for the samples. Biofacies 5 and 6 in section 6 were deposited in upper to lower offshore depositional environments (see Figure 7 and Table 2). Shallower settings are indicated for sections 7 and 8, although dissolution of calcareous forms may have affected biofacies assignments.

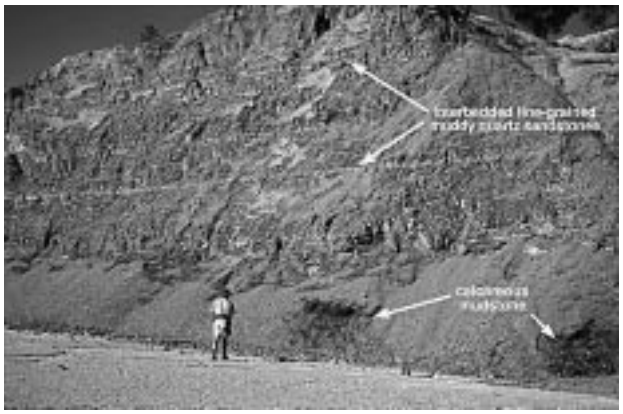


Figure 19. Photograph of outcrop section 6. The dominant lithology is a black calcareous mudstone (lithofacies Mc), which weathers yellow-brown. Thin, fine-grained muddy quartz sandstone horizons (lithofacies Spf/Smf) are interbedded with the calcareous mudstone. These may represent storm-derived deposits.

The microfossil sample collected 1 m up the section, yielded a siliceous agglutinated fauna of *Cribrostomoides* sp., *Ammobaculites humei*, *Eomarssonella crespinae*, *Verneuilinoides neocomiensis*, and *V. howchini* (Table 4). The presence of rare calcareous forms, *Lenticulina* gr. *gaultina*, *Neobulimina albertensis*, and *Gyroidina* sp. is evidence that weathering has not dissolved calcareous components of the fauna.

Facies and bathymetric trends. The section is mainly of mudstone facies (M) containing biofacies 3, indicative of the upper offshore zone.

Age and lithostratigraphic correlation. The presence of *Beaudanticeras* is diagnostic of the Tambo Fauna of Albian age (Day, 1969). The benthic foraminiferal assemblage belongs to the *Eomarssonella crespinae* Zone of the Australian Albian.

Section 8 represents part of the Ranmoor Member, and is regarded as stratigraphically younger than the Ranmoor Member exposed at Glenmoan and Two-Mile. Close proximity of section 8 to outcrops of the Toolebuc Formation (Figure 3) suggests that it is the upper part of the member, close to the contact with the overlying Toolebuc Formation.

3.7. Outcrop section 9

This section (Figure 20), on Strath-Stewart station, is the designated type-section of the Jones Valley Member (Vine & Paine, 1974). The section is located some 45 km north of Hughenden, and about 50–60 km northwest of sections 1–6 (Figure 3). The muddy quartz sandstone that is characteristic of the Jones Valley Member is thicker (6 m thick) than at localities on the Flinders River at Six-Mile and Two-Mile (sections 4 and 5a). The Jones Valley Member overlies pyritic black mudstones of the Doncaster Member.

Lithology. The basal unit in the measured section (Figure 19), attributed to the uppermost Doncaster Member, is a thick (10 m), black sulphidic mudstone which is mostly finely bioturbated, but also contains fine (2 mm thick) silty laminations (at 3 m above base of section). Calcareous nodule horizons (at 1, 2, and 7.5 m) are unfossiliferous. The black mudstone is overlain by fine-grained muddy quartz sandstone, composed of undulous, monocrystalline quartz and glaucony within a muddy matrix. Grains are subangular-subrounded and have low sphericity. The unit texturally and compositionally resembles the 1-m-thick muddy quartz sandstone bed in section 4 (Figure 9), but lacks a carbonate cement. Parallel laminations persist throughout most of the unit, although low-angle, trough cross-laminations occur at certain levels. The top of the muddy quartz sandstone in this area forms an eroded plateau, and its passage to the overlying Ranmoor Member is not preserved.

Palaeontology. A sparse macrofauna was obtained from the Strath-Stewart section (Figure 20). The basal black mudstones of the upper Doncaster Member contain belemnite guards (*Peratobelus oxys*), and moulds of small high trochospiral gastropods (about 4 mm in length). The muddy quartz sandstone unit contains bivalves, possibly ?*Barcoona trigonalis*, and trace fossils of unknown affinity. Bivalves have been recorded previously from the Strath-Stewart section (Vine & Paine, 1974). A foraminiferal assemblage composed entirely of agglutinated species was obtained from the basal black mudstone (Table 4). The assemblage is dominated by forms such as *Cribrostomoides* sp., *Bathysiphon* sp., *Lagenammina lagenoides*, and *Kutsevella implanus*.

Facies and bathymetric trends. The basal mudstone unit (lithofacies M) is associated with biofacies 2 suggesting a transitional depositional environment. The sands of the type Jones Valley Member include Smf, Sxf, and Spf lithofacies indicating shoreface to foreshore depositional settings.

Age and lithostratigraphic correlation. The basal mudstones (at 0.7 m in the measured section) belong to

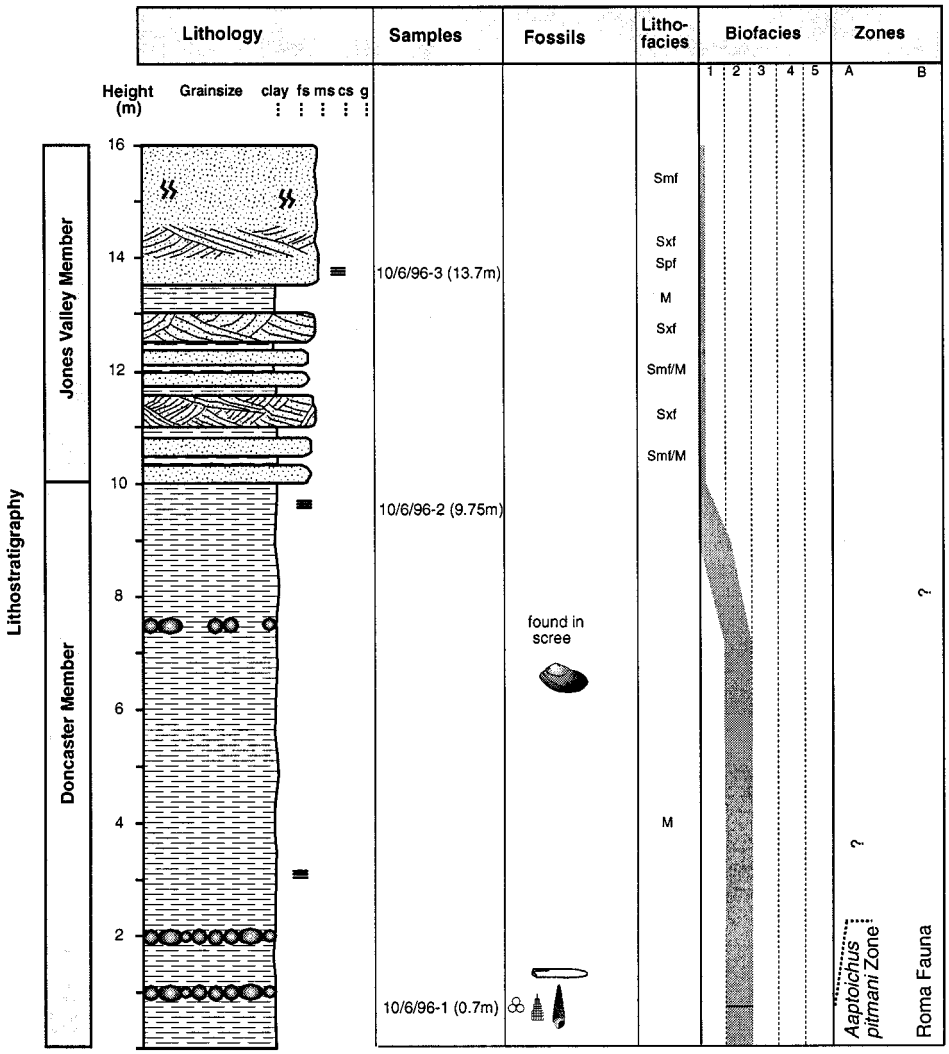


Figure 20. Outcrop section 9 (type section of the Jones Valley Member, Wallumbilla Formation) showing lithostratigraphy, rock sample positions, fossil assemblage, lithofacies, biofacies, and biozones. The results of foraminiferal analysis are shown on Table 1. Biofacies 2 is associated with mudstones at the base of the section and indicates a transitional depositional environment, whereas fine-grained muddy quartz sandstones at the top of the section suggest a shallowing to a shoreface setting.

the *Aaptotoichus pitmani* Zone of benthic foraminifera, of late Aptian age. These mudstones contain a Roma Fauna characteristic of the Australian upper Aptian. No age diagnostic fossils were recovered from the Jones Valley Member. The muddy quartz sandstone forming the type section of the member is correlated to the thin (1 m) muddy quartz sandstone unit outcropping 25–26 m above the base of section 4 (Figure 15), and 17.5–18.5 m above the base of section 5a (Figure 17). The underlying black mudstones are characteristic of the Doncaster Member, and foraminiferal faunas are similar in composition to those in the mudstones in section 4.

3.8. BMR Richmond 1 borehole

Richmond 1 stratigraphic hole was drilled by the Australian Bureau of Mineral Resources 27 km west-north-west of Hughenden (Vine & Galloway, 1969; Figure 3). The hole started near the top of the Ranmoor Member in this area (55 km west of the Ranmoor type section), and was continuously cored from 24 m to 85 m.

Lithology. The borehole penetrated a mainly mudstone section and bottomed in a glaucony-rich muddy unit between 80–85 m (Figure 21). The mudstone

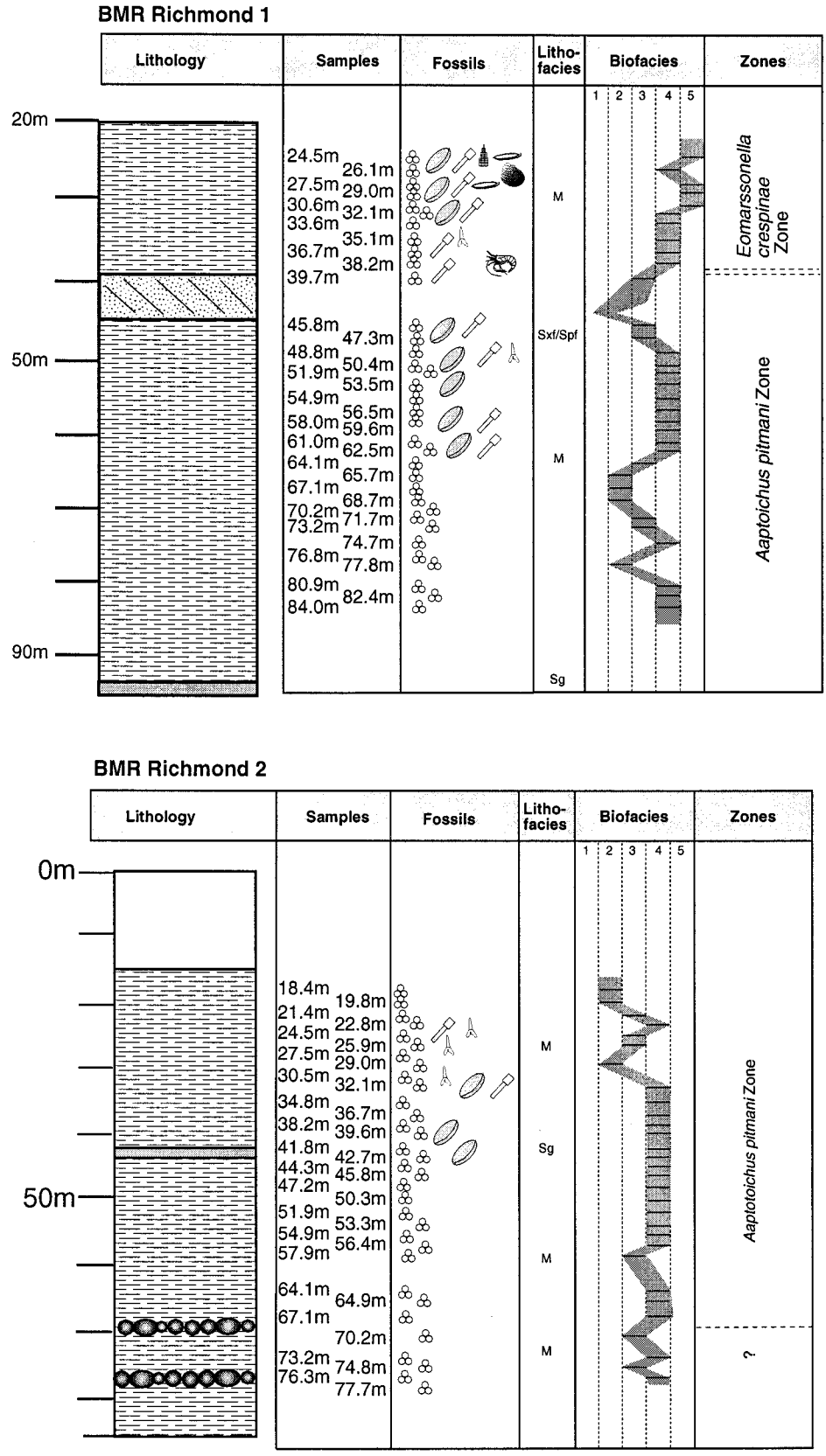


Figure 21. BMR Richmond 1 and BMR Richmond 2 stratigraphic columns showing sample positions, fossil assemblage, lithofacies, biofacies and biozones. Deposition during *A. pitmani* Zone-times fluctuated between the transitional and upper offshore zones (biofacies 2–4). A sandstone between 39–45 m in Richmond 1 indicates a shallowing, above which there is a return to upper offshore deposition (biofacies 4 and 5).

Table 5. Relative abundance of foraminiferal species in samples from BMR Richmond 1 borehole. Sample horizons are recorded in Figure 21. Biofacies assignments are based on the criteria outlined in Table 2, and together with lithofacies are interpreted to reflect bathymetric changes within the basin as shown in Figure 7. A=>20 specimens, C=10–20 specimens, R=<10 specimens.

Foraminiferal species	84.0m	82.4m	80.9m	77.8m	76.3m	74.7m	73.2m	71.7m	70.2m	68.7m	67.1m	65.7m	64.1m	62.5m	61.0m	59.6m	58.0m	56.5m	54.9m	53.5m	51.9m	50.4m	48.8m	47.3m	45.8m	39.7m	38.2m	36.7m	35.1m	33.6m	32.1m	30.6m	29.0m	27.5m	26.1m	24.5m
Siliceous Agglutinated Forms																																				
Aaptotoichus pitmani	C	R		R	R	R	R	A		R	R	R	R	C		R	R	R	R	C	R	C	C	A	C	C										
Ammobaculites humei	R		C				R	C	R	C	A	C	R	R	A	R	A	A	R	R	R	C	A				A	R	R	A		A	A	C	A	A	A
Ammodiscus rotalarius			R	R					R		R				R			R	R								R	R	R							
Bathysiphon sp.	A						R	R	A	A	R	C	R	R		C	A	C	C	R	R	C	C	R	R	R										
Bimonilina engeninensis	R		R		R			R		R	R		R	C			R	C		R		R	C	R			R	R	R				A	A	R	
Cribrostomoides sp.				R																									R							
Eomarssonella crespinae																											A	A	A		A	A	R	A	A	R
Haplophragmoides minor									R	C	R				R		R		R	R								R								
Hippocrepina barkesdalei							R									R																				
Kutsevella implanus	R	R		R	R			A			R	R	R	A	R		R	A	R	R	R	C	C	R		R	R	R			R	R	R	R	R	C
Lagenammina alexanderi																																C		R		R
Lagenammina lagenoides	R		R		R		R	R	R		C	R		R	R		C	A	R	A	R	R	C	R				R							
Placentammina lathrami														R															R							
Psammosphaera laevigata							R		R	R	R				R		R	C	R	R	R	R	C				R		R							
Reophax geniculatus			R	R				R		R	C	C	R	R	A		R	C	R	R	R	C	C	R	R	R	R		R	R						
Spiroplectammina edgelli																											C	R	R		C	C		C	R	A
Textulariopsis wilgunyaensis																																			R	R
Trochammina minuta	R		R								R				R			R										R	R					R		
Verneuilinoides howchini	R	R	R		R							R															R	R	R		R		R		R	
Verneuilinoides neocomiensis	C		R				R				R	R			R		R	R	R			R	R						A							
Porcellaneous: Miliolida																																				
Miliolinella australiana																		A		R	R	R	R				R									
Hyaline calcitic: Lagenida																																				
Astacolus howchini																R						R	R		R				R							C
Bojarkaella sp. A																											R									
Citharina sp. C																																				R
Globulina lacrima	R		A			R								R			R	A	R				R				A	C	A		A	A	C	A	A	A
Hemirobulina hamulus																		R		R																
Hemirobulina inaequalis																	R																			
Laevidentalina hamiltonensis	R		C											R		R	R	C					R			R	R	R	R		R	C		C	R	A
Laevidentalina praecommunis	R																											R	R		R					
Lenticulina gr. *warregoensis*	C		A											R	R	R		R		R		R				R	A	C	R		A	A	C	A	A	A
Lingulina buddencanyonensis																							R									R		R		
Lingulonodosaria cf. *nodosaria*	R		R												R		R	R	R	R		R				R	R			R			R	C	C
Marginulina innaminckae			R																																	
Marginulinopsis arimensis	R		R											R				R									R	R	R	R	R		R	R	C
Marginulinopsis cephalotes			R											R				C		R	R		R					R		R					
Oolina sp.																																	R			
Planularia cf. *strombecki*	R		R																												R		R	R	C
Pseudonodosaria humilis	R																R	C	R	R		R			R	R						R	C	R	R
Pyramidulina cf. *flexocarinata*			R														R		R							C	R	R		R	R	R	R	R	R
Pyramidulina obscura	R																	R																		
Ramulina sp.	R													R	R			R																		
Saracenaria bononiensis	R		R										R	R			R	R					R				R		R		R	R			C	C
Saracenaria bronnii																		R																		R
Saracenaria ninbella																																				
Saracenaria planiuscula			R											R														R	R							R
Tristix perelongatum			R											R					R								R	R	R		R	R		R	R	C
Hyaline calcitic: Buliminida																																				
Coryphostoma sp. A																												R				R				R
Eurycheilostoma? hergottensis	C		A			R																														
Eurycheilostoma? moorei	R		A											A	R	R	A	A	R	R							A	A	A							
Neobulimina kareelensis														R	R	R		C		R		R	R				C	A	A		A	A	A	A	A	A
Hyaline aragonitic: Robertinida																																				
Epistomina chapmani															C			R										R							R
Hyaline calcitic: Rotaliida																																				
Bilingulogavelinella australis	C		A												R																					
Gavelinella parvula																							A	R	C											R
Gyroidinoides infracretaceus	R		A											R	R	R	R	A	R	C	R	R	R				R	R			A	C	R	C	C	C
Lingulogavelinella cf. *albiensis*	C		A												R												A	C	R	R						
Lingulogavelinella santoodnae																											A	A	A	R	A	R	R	A	A	A
Paralabamina sp. A	R					R									R			R									R	C							R	
Patellinoides tilchus			R															R									R	R								
Pseudogavelinella? impedita		R	R				R							R	R		R	A	R	R	R			R												
Pseudogavelinella? sp. A	R		A																																	
Hyaline calcitic: Globigerinida																																				
Hedbergella sp.																																R	R	R		R
Biofacies	4	4	4	2	2	4	3	3	2	2	2	2	3	4	4	4	4	4	4	4	4	4	4	3	3	3	4	4	4	4	4	5	5	5	4	5

succession is interrupted at 39.6–44.8 m by a parallel-laminated very fine-grained quartz-sandstone/siltstone with calcareous cement, minor glaucony, and lithic fragments. Above this unit, the mudstone is slightly more calcareous than the mudstone below 45 m.

Palaeontology. The biogenic component of the sand fractions of mudstone samples from the core consists mainly of foraminifera (Table 5). Also present in the interval from 24–64 m, are ostracods, echinoderm debris (e.g., echinoid spines and plates, isocrinoid columnal plates), fish teeth and bone, decapod crustacean carapace fragments, diatoms, radiolaria, and mollusc debris (Figure 21).

The mudstone interval from 45–85 m contains a macrofossil assemblage consisting of *Lingula* cf. *subovalis, Maccoyella subangularis*?, *Maccoyella corblensis,* and *Pseudavicula anomala* (Day in Vine & Galloway, 1969). The calcareous mudstones above 39 m contain the macrofossils *Aucellina hughendenensis* and *Aconoceras* sp. (Day in Vine & Galloway, 1969).

Facies and bathymetric trends. The interval from 45–85 m lies in mudstone (M lithofacies) associated with biofacies 2, 3 and 4. The alternations of these biofacies shown in Figure 21 suggest that the environment changed several times within the transitional to upper offshore range. The fine sandstone at 39–45 m represents lithofacies Sxf-Spf of the shoreface zone. Biofacies 4 and 5 are associated with slightly calcareous mudstone above 39 m, suggesting a middle to upper offshore environment for this part of the section.

Age and lithostratigraphic correlation. The molluscan assemblage from 45–85 m is typical of the late Aptian Roma Fauna. The macrofauna in the upper mudstone unit above 39 m contains a Tambo Fauna of Albian age. Based on benthic foraminifera, the section below 39 m belongs to the *Aaptotoichus pitmani* Zone of late Aptian age. The section from 84–74 m lies within the zone of overlap of *Eurycheilstoma*? *hergottensis* and *E*? *moorei*. The interval above 38.2 m belongs to the *Eomarssonella crespinae* Zone of Albian age.

The basal glaucony-rich horizons (Sg) and dark-grey mudstones (M) below 45 m represent the Doncaster Member, Wallumbilla Formation, as confirmed by the *A. pitmani* Zone in this interval. The cross-laminated, fine-grained quartz-sandstone between 39 and 45 m is correlated with the Jones Valley Member, Wallumbilla Formation, The calcareous mudstones (Mc), change in biofacies, and *E. crespinae* Zone above 39 m are indicative of the Ranmoor Member.

3.9. BMR Richmond 2 borehole

BMR Richmond 2 was drilled by the Australian Bureau of Mineral Resources as a stratigraphic hole located 40 km NW of Hughenden (Figure 3). The lithostratigraphy was described by Vine & Galloway (1969). The hole was started at the base of the Jones Valley Member (30 km southwest of its type section), and was continuously cored from 18–79 m (Figure 21).

Lithology. The cored section, as described by Vine & Galloway (1969), consists of dark grey mudstone interbedded with thin glaucony-rich beds. Calcareous nodules were the probable cause of drilling difficulties at 65 and 71 m, and there was poor recovery of core from these depths.

Palaeontology. Moderately diverse assemblages of benthic foraminifera occur throughout the section (Table 6). Ostracods, echinoderm debris, and fish bone and teeth are present in the sand fractions of the mudstone above 43 m. A study of the macrofossil assemblage by Day (in Vine & Galloway, 1969) indicated the presence of *Lingula* cf. *subovalis, Nuculana randsi, Maccoyella subangularis, Pseudavicula anomala, Peratobelus oxys,* and *Tatella maranoana*.

Facies and bathymetric trends. Much of the section below 32 m includes mudstone with a relatively uniform microfauna belonging to biofacies 4 or 3. During most of the deposition of the mudstone section from 78–32 m, standstill conditions apparently existed within the middle to upper offshore zone. The interval between 32 and 18 m contains mudstone with biofacies varying from 2 to 4, suggesting conditions fluctuating in a shallower depositional range than that represented in the underlying beds.

Age and lithostratigraphic correlation. The foraminiferal assemblages indicate that the interval between 67 and 18 m belongs to the *Aaptotoichus pitmani* Zone of late Aptian age, with the overlap in ranges of *Eurycheilostoma*? *hergottensis* and *E*? *moorei* occurring between 67 and 32 m. The molluscs are typical of the late Aptian Roma Fauna.

Dark grey mudstones (lithofacies M) containing glaucony-rich (lithofacies Sg) and calcareous nodule horizons are characteristic of the Doncaster Member, Wallumbilla Formation. This interpretation is confirmed by the presence of the Roma Fauna and the

Table 6. Relative abundance of foraminiferal species in samples from BMR Richmond 2 borehole. Sample horizons are recorded in Figure 21. Biofacies assignments are based on the criteria outlined in Table 2, and together with lithofacies are interpreted to reflect bathymetric changes within the basin as shown in Figure 7. A=>20 specimens, C=10–20 specimens, R=<10 specimens.

Foraminiferal species	77.7m	76.3m	74.8m	73.2m	70.2m	67.1m	64.9m	64.1m	57.9m	56.4m	54.9m	53.3m	51.9m	50.3m	48.8m	47.2m	45.6m	44.3m	42.7m	41.1m	39.6m	38.2m	36.7m	34.8m	32.1m	30.5m	29.0m	27.5m	25.9m	24.5m	22.8m	21.4m	19.8m	18.4m
Siliceous Agglutinated Forms																																		
Aaptotoichus pitmani								R	C												C	R	R	C	R	R	A		C	C	C	R	R	R
Ammobaculites humei		R	C		R	R	R	R		R	R			R					R	A	R	C	R	R	R		R		A	A	A	R	R	R
Ammodiscus rotalarius		R	R													R				R		R		R										
Bathysiphon sp.		R	C	R			R				R			R		R				C	A			R				R	A	A	C	R		R
Bimonilina engeninensis		R	C	A		R	R	R						R	R					R							R	R	R					
Cribrostomoides sp.									R													R		R						R	R	R	R	R
Flabellammina alexanderi																													R	R				
Haplophragmoides minor																											R	R	R	R	R			
Hippocrepina barksdalei			R	R																														
Kutsevella implanus		R	R	C	C			C		R		R							R	R	R	R	R	C	C	R	R		C	C	A	C	C	A
Lagenammina alexanderi								R												R														
Lagenammina lagenoides		R												R		R		R	R	R							R	R	R	R	C			R
Placentammina lathrami																				R										R				
Psammosphaera laevigata		R																	R	R									R					
Reophax geniculatus		R	A	R	R	R	R			C		R										R	R	R	R			R	A	C	A	C	R	C
Spiroplectammina edgelli																				R														
Trochammina minuta		R	C	C			R	R		R				R					R	R			R		R					A			R	R
Verneuilinoides howchini					R									R						R	R	R	R											
Verneuilinoides neocomiensis														C					C	R							R		R	C				
Hyaline calcitic: Lagenida																																		
Astacolus howchini	R	R	R	C	R	R	R			R	R	R	R	R		R			R	R	R	R										R		
Globulina lacrima		R		C		R	C	R			R		R						R	R					A					R				
Laevidentalina hamiltonensis			R			R	C	C		R			R			R			R	R	R	R			C					R				
Laevidentalina praecommunis										R										R														
Lenticulina gr. *warregoensis*		R	R	C	R		C	R	R	C		R		A	R	R	R	R	R	A	C	R	R	R	C					R				
Lingulina buddencanyonensis										R																								
Lingulonodosaria cf. *nodosaria*							R	R		R										R	R	R			R									
Marginulina subcretacea				R																														
Marginulinopsis arimensis				R						R						R				R	R	R			R									
Marginulinopsis australis			R																															
Marginulinopsis cephalotes							R	R								R	R								R									
Marginulinopsis pristipellis																					R													
Planularia cf. *strombecki*				R													R																	
Pseudonodosaria humilis		R						R													R				R									
Pyramidulina cf. *flexocarinata*							R	R									R		R	R	R													
Saracenaria bononiensis											R										R													
Saracenaria planiscula				R			R			R				R		R				C	R													
Hyaline calcitic: Buliminida																																		
Eurycheilostoma? hergottensis		C	R	R		R	A	C		A		R	R	A		R	A	C	A	C	A				A									
Eurycheilostoma? moorei						R	A	C						C			R	R	R		C				A									
Hyaline aragonitic: Robertinida																																		
Epistomina chapmani																			R															
Hyaline calcitic: Rotaliida																																		
Bilingulogavelinella australis																			R	R	C			R										
Gyroidinoides infracretaceus										R		R	R	A		R	A	C	A	A					A					R	R			
Hergottella jonesi										R											R													
Lingulogavelinella cf. *albiensis*												C	R	A			R	R	A	A	A	R		R	R									
Paralabamina sp.							A	R																	R									
Patellinoides tilchus				R			R	R		R						R				R	R				R									
Pseudogavelinella? impedita																			R										R	R	C	R		
Pseudogavelinella? sp. A										C			R						R		R				R									
Biofacies	?	4	3	4	3	4	4	4	3	4	3	4	4	4	?	4	4	4	4	4	4	4	4	4	4	?	2	?	3	3	4	3	2	2

A. pitmani Zone. The biofacies succession found at 18–32 m below the top of the hole (and therefore 18–32 m below base of Jones Valley Member) corresponds to that observed at 65–80 m in Richmond 1 (i.e., at 20–35 m below base of Jones Valley Member in this hole).

3.10. GSQ Hughenden 7 borehole

Hughenden 7 stratigraphic hole was located 3 km southwest of Hughenden (Figure 3). It was drilled by the Queensland Department of Mines (Balfe, 1979) to a total depth of 829 m. Cretaceous strata

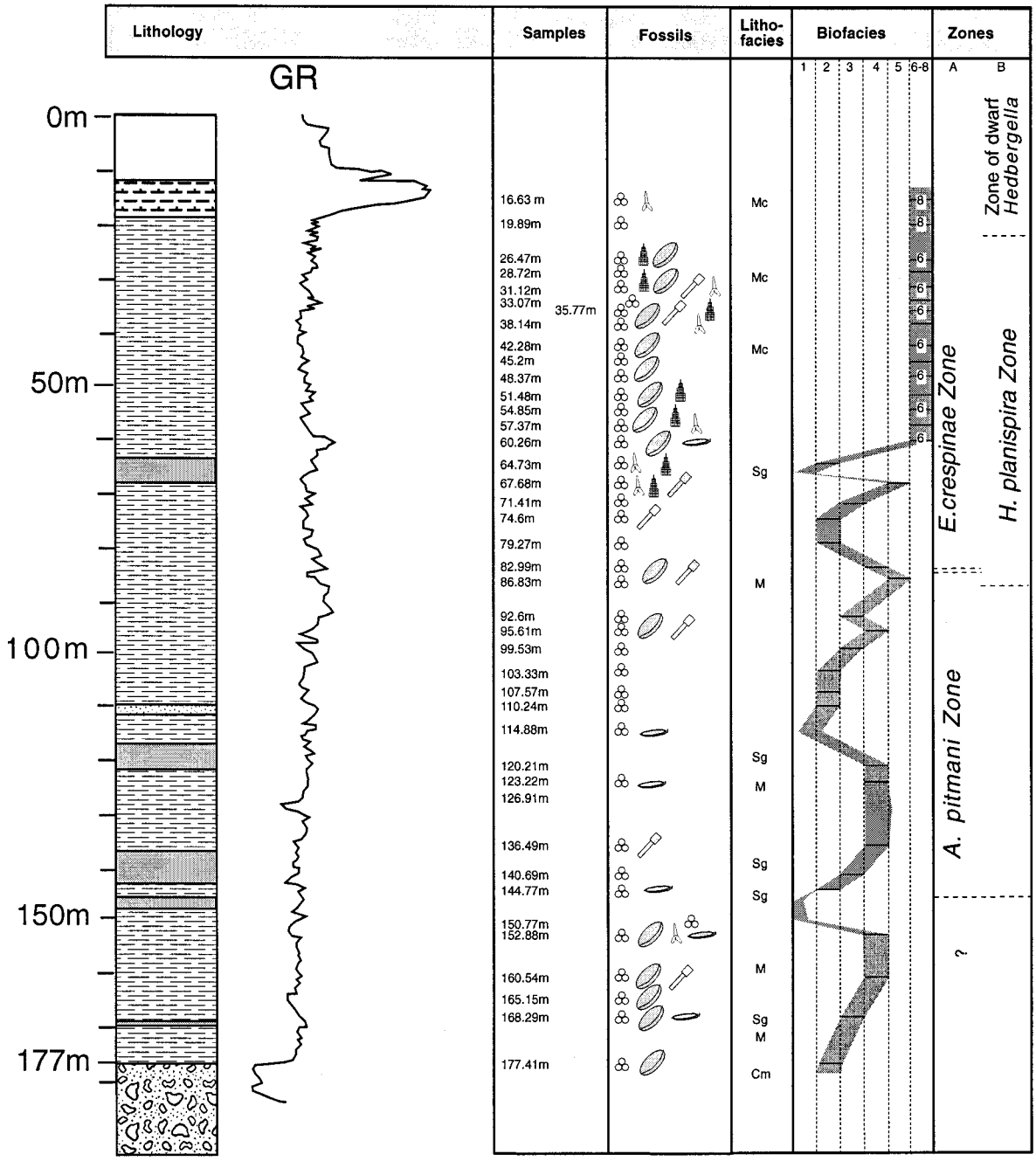


Figure 22. GSQ Hughenden 7 showing lithology, gamma response, sample positions, fossil assemblage, lithofacies, biofacies and biozones. The biofacies indicate a similar deepening as recorded in the outcrop sections in the *E. crespinae* Zone.

were penetrated from the surface (top Toolebuc Formation) to 193 m, and were continuously cored below 14 m. A stratigraphic log of the Cretaceous interval is shown in Figure 22.

Lithology. Basal units at 193–177 m consist of poorly sorted brown-grey conglomerate, with milky-quartz pebbles, interbedded with coarse-grained, off-white, quartz sandstone. The low gamma-response of the coarse-grained sediments contrasts with the high response of overlying dark-grey mudstones and dark-green glaucony-rich beds. A cross-laminated, fine-grained quartz-sandstone is present at 113–114 m. At 64–68 m a distinctive light-green glaucony-rich sandstone is present. Calcareous grey-black mudstones overlie the glaucony-rich sandstone. A gradual

Table 7. Relative abundance of foraminiferal species in samples from GSQ Hughenden 7 borehole. Sample horizons are recorded in Figure 22. Biofacies assignments are based on the criteria outlined in Table 2, and together with lithofacies are interpreted to reflect bathymetric changes within the basin as shown in Figure 7. A=>20 specimens, C=10–20 specimens, R=<10 specimens.

Foraminiferal species	177.41m	168.29m	165.15m	160.54m	152.88m	150.33m	144.77m	140.69m	136.49m	126.91m	123.22m	120.21m	114.88m	110.24m	107.57m	103.33m	99.53m	95.61m	92.6m	86.83m	82.99m	79.27m	74.6m	71.41m	67.68m	64.73m	60.26m	57.37m	54.85m	51.48m	48.37m	45.2m	42.28m	38.14m	35.77m	33.07m	31.12m	28.72m	26.47m	19.89m	16.63m
Siliceous Agglutinated Forms																																										
Aaptotoichus pitmani							C	R			R		R		A	R	C	A	C	R																						
Ammobaculites humei	A	C		R	R	R	C		R		R			R	R	R	C	C	R		A	A	C	A	A	A	A	C	R	A	C	C	A	A	A	A	C	C	C		
Ammodiscus rotalarius						R	R		R					R		R		R	R		C	R		R								C		R	R	R		R		
Bathysiphon sp.	C	R		R	R		R		R					A	C		C	A	R	R													R								
Bimonilina engeninensis	C	C		R		R	R	R	R		R		R	R	R	R	R	R	R	R	R	R	C	C																	
Cribrostomoides sp.	A	A		C	C	R	C	C	A		R	R	R	C	A	R	R	C	R		A	C	R	C	C	R	A	C		R	C	C	A	A	C	C	C	C	A		
Eomarssonella crespinae																					R	A	A	A	C	C	C	R	R	R	R	C		R	C	R	A	R		
Gaudryinopsis filiformis																																R		C							
Haplophragmoides minor														R																					R		R				
Haplophragmoides sp. D																																R	R	R	R	R	A	A	A		
Hippocrepina barksdalei		R																	R		R																				
Kutsevella implanus							C				R			R	A	C	A	A	C	R	R	R	R	R	R																	
Lagenammina alexanderi														R										R				R				R		R		R					
Lagenammina lagenoides														R	R		R	R	R	R					R																
Miliammina ischnia				R							R										R										C		R			R	R			
Placentammina lathrami							R							R			R				R																				
Psammosphaera laevigata	R							R				R		R		R	R						R	R	R		R		R	R	R			R			R	R		
Reophax geniculatus	R						C								C		R	R	R		R	R	R	R	A			R			R		R	R	R		R			
Spiroplectammina edgelli									R												R	R		R	R	A		R	R			R	C	A	C		R	A		
Textulariopsis sp. A									R									R																						
Trochammina minuta	C	R		R		R		R	R			R	R		C		R																							
Trochammina sp. A															R																										
Verneuilinoides howchini	R																							R	R	C	A					R		R	C	R	R			
Verneuilinoides neocomiensis							R		C				R	C	R	R	A	R		R				R	C	R			R	R	R	C		R	C	C				
Porcellaneous: Miliolida																																									
Miliolinella australiana																					R																				
Hyaline calcitic: Lagenida																																									
Astacolus howchini									R															R									R							R	
Citharina tyelea																																	R		R		R	R	R		
Dentalina angusticostata																								R																	
Globulina lacrima			R	R													R	R		C																			R	R	
Globulina prisca																			R																						
Hemirobulina hamulus																		R									R				R		R		R					
Laevidentalina hamiltonensis		R		R	R												R	R		R				R					R											
Laevidentalina praecommunis																				R								R				R	R		R					
Lenticulina cf. *warregoensis*		R		R	R			R	R		R	R				R	A		R	C			C		R	R														
Lenticulina cf. *gaultina*																								R							R	C	C	C	C	C	C	R	C	
Lingulina buddencanyonensis																																								R	
Lingulonodosaria cf. *nodosaria*																					R										R	R	R		R	R		R		
Marginulina innaminckae																					R			R																
Marginulina tilchae																											R						R							
Marginulinopsis arimensis	R																	R		R																				
Oolina sp.																								R							R				R					
Palmula sp.																																R	R	R						
Pseudonodosaria humilis																		R		R													R							
Pyramidulina cf. *flexocarinata*																					R							R	R		R		R	R		R	R		
Pyramidulina obscura																																			R					
Pyramidulina sceptrum																																	R	R			R			
Ramulina sp.																								R	R									R	R			R		
Saracenaria cf. *bononiensis*																		R												R										
Saracenaria ninbella																																	C	C	C					
Saracenaria planiuscula				R														R		C				R							R	R			R	R	R	R		
Tristix perelongatum																				R											R			R	R		R			
Hyaline calcitic: Buliminida																																									
Coryphostoma sp. A																				R											R		A	C	C		C	R	A	
Eouvigerina cf. *nagappai*																																						R	R		
Eurycheilostoma? hergottensis			C	R					R			R																													
Eurycheilostoma? moorei			R	R					R									R		A																					
Neobulimina albertensis																							R			A	A	R	C	A	R	A	C	R			A			
Neobulimina kareelensis																		R		C																					
Orthokarstenia? calcarata																																							R		
Turrilina sp.																												R	R	R		R								
Hyaline aragonitic: Robertinida																																									
Epistomina chapmani																										C		A	A	C	A	A	A	R		C	R		
Reinholdella claytonensis																																									
Hyaline calcitic: Rotaliida																																									
Berthelina intermedia																									A								R		R		A			
Bilingulogavelinella australis									A		R							C																						
Gavelinella dakotensis																				C						C								R		C	C		
Gavelinella oodnadattensis																																			R		R			
Gyroidina sp.																											R	R		R		R	R							
Gyroidinoides infracretaceus									A								C	R	R	R			R	R		R		R			R	A	A	A		A	A	A	
Lingulogavelinella cf. *albiensis*									C		R						R																							
Lingulogavelinella cf. *indica*																																	R	R						
Lingulogavelinella innaminckae																																			R					
Lingulogavelinella santoodnae																				R	A										C				R	C	A		
Paralabamina sp.																		R																						
Patellinoides tilchus			R																		R										R	R							
Pseudogavelinella? impedita									R									A																						
Pseudogavelinella? sp. A											R																													
Valvulinoides sp.																												R										A	A	
Hyaline calcitic: Globigerinida																																									
Hedbergella spp. (dwarf forms)																																								R	A
Hedbergella planispira																				R						A	A	C	A	A	A	A	A	A	A	R	C	A	A	
Biofacies	2	3	?	4	4	?	2	3	4	?	4	4	?	2	2	2	3	4	3	5	4	2	2	3	4	2	6	6	6	6	6	6	6	6	6	6	6	6	6	8	8

decrease in radioactivity distinguishes these mudstones from the underlying non-calcareous types. A gamma-ray peak at 21 m coincides with an increase in carbonate content and abundant shell and fish debris.

Palaeontology. Foraminifera are the most common biogenic components of the sand fractions of the mudstones (Table 7). Benthic foraminifera occur throughout the Cretaceous section. Planktic foraminifera are rare at 86.83 m and abundant and persistent only above 64 m. Ostracods, diatoms, echinoderm debris, and fish bones and teeth have scattered occurrences through the section, whereas radiolaria are most conspicuous above 68 m (Figure 22). Burger (1982) recorded palynomorphs (spores, pollen, dinoflagellates) of variable preservation from the bore section.

Facies and bathymetric trends. The basal conglomerate (Cm) and associated sandstone (Smc) with low gamma response represent an upper shoreface depositional setting. The lower part of the mudstone succession, from 177–160 m, contains a succession of biofacies (2 to 4) which suggests a progressive increase in water depths from transitional to middle offshore environments. On the basis of changing biofacies, a shallowing-deepening cycle within the middle offshore to lower transitional bathymetric range is suggested between 152 and 136 m, followed by middle offshore deposition until 120 m. From 120–110 m a shallowing to the transitional zone is indicated. Changing biofacies between 110 and 64 m suggest an overall increase in water depth punctuated by shallowing episodes. The calcareous mudstone facies above 64 m contains biofacies 5–8 indicative of lower offshore conditions.

Age and lithostratigraphic correlation. Based on benthic foraminifera, the section from 161–87 m belongs to the *Aaptotoichus pitmani* Zone of late Aptian age, with overlap in ranges of *Eurycheilstoma*? *hergottensis* and *E*? *moorei* found in the interval between 161 and 120 m. The interval above 83 m belongs to the *Eomarssonella crespinae* Zone of Albian age. Below 161 m no zonal indices occur. The *Hedbergella planispira* Zone, of late early to middle Albian age is present from 61–26 m. The interval from 20–16 m belongs to the Zone of dwarf *Hedbergella* of late middle to early late Albian age in the Australian interior basins.

According to Burger's (1982) palynostratigraphy, the interval from 174–120 m belongs to the spore-pollen *Osmundacidites dubius* Zone and the dinoflagellate *Odontochitina operculata* Zone. Samples from 111–77 m are within the spore-pollen *Crybelosporites striatus* Zone, and the interval from 66–29 m belongs to the *Coptospora paradoxa* Zone. The dinoflagellate *Pseudoceratium turneri* Zone includes samples from 111–34 m, with the samples from 111–86 m belonging to subzone A and samples from 77–66 m belonging to part of subzone B. Because of poor dinoflagellate preservation above 66 m, Burger (1982) was unsure of the position of the subzone B–C boundary within the *P. turneri* Zone of Hughenden 7.

The basal sandstone unit is correlated to the Gilbert River Formation. At the top of the hole (down to 20 m), calcareous mudstones with abundant shelly layers, an extreme radioactivity peak, and planktic foraminifera characteristic of the Zone of dwarf *Hedbergella*, are placed in the Toolebuc Formation. The intervening mudstone succession between 20 and 177 m is included in the Wallumbilla Formation. Subdivision of the Wallumbilla Formation is difficult in this section. The presence of the *Aaptotoichus pitmani* Zone between 177 and 86 m correlates most of this interval with the Doncaster Member. The blue to dark grey mudstones with highly uniform radioactivity and interbedded glaucony-rich units (Sg) are characteristic of the Doncaster Member in its type section (outcrop section 1) and in outcrop sections 4 and 5a. The calcareous mudstones of the *Hedbergella planispira* Zone correspond to those of the type Ranmoor Member (outcrop section 6). Based on the foraminiferal zonation the section between 83 and 64 m, belonging to the *Eomarssonella crespinae* Zone, correlates with the lower Ranmoor Member in outcrop section 5b. However, no unit equivalent to the Jones Valley Member is present in the uppermost *A. pitmani* Zone. Burger (1982) suggested that the interval between 110 and 122 m may be the Jones Valley Member. This level lies well below the top of the *A. pitmani* Zone (between 87 and 83 m), and well below the boundary between dinoflagellate subzones A and B of the *Pseudoceratium turneri* Zone (between 86 and 77 m). In Richmond 1, Morgan (1980b, 1984) equated the boundary between the Jones Valley Member and the Ranmoor Member to the subzone A–B boundary, and suggested that the Jones Valley Member belonged to the upper part of subzone A.

3.11. GSQ Manuka 1 borehole

Manuka 1 was drilled by the Queensland Department of Mines as a stratigraphic hole located 140 km southwest of Hughenden (Figure 3). The Cretaceous succession was continuously cored from 17–782 m (Winton Formation down-sequence to Cadna-owie Formation; Figure 2), and was described by Balfe (1978). The interval of interest for this study is from

Table 8. Relative abundance of foraminiferal species in samples from GSQ Manuka 1 borehole. Sample horizons are recorded in Figure 23. Biofacies assignments are based on the criteria outlined in Table 2, and together with lithofacies are interpreted to reflect bathymetric changes within the basin as shown in Figure 7. A=>20 specimens, C=10–20 specimens, R=<10 specimens.

Foraminiferal species	727.18 m	724.45 m	720.11 m	715.04 m	709.42 m	700.43 m	690.73 m	680.73 m	670.61 m	660.32 m	650.76 m	642.10 m	628.57 m	619.82 m	608.98 m	598.84 m	591.77 m	586.81 m	580.65 m	569.95 m	561.06 m	549.51 m	541.02 m	536.21 m	532.35 m	519.83 m
Siliceous Agglutinated Forms																										
Aaptotoichus pitmani											R			C	A	A										
Ammobaculites humei	R			R	R				R		C	R	C	C	A	R	A	C	A	A	A	A	R			
Ammodiscus rotalarius									R		R			R	C		C	R		R		R				
Bathysiphon sp.											A	R	R		A	R	R			R	R	C				
Bimonilina engeninensis		R	C	A	R			R	C		R		C	R	A	R	R	R	R	R	R					
Cribrostomoides sp.		R		R					C		C	A	A	R	C	R	R	R	A	A	C	A				
Eomarssonella crespinae																R	A	A	A	A	R	A	R			
Gaudryinopsis enodis	R																									
Gaudryinopsis filiformis																		R		R						
Haplophragmoides minor											R		R	R	C											
Haplophragmoides sp. D																		R		C		C				
Hippocrepina barksdalei									R									R								
Kutsevella implanus				R	R						R	R	C	R	A	C	A	R	R	R	R					
Lagenammina alexanderi													R		C	C										
Lagenammina lagenoides													R		A											
Miliammina ischnia		R												R				R	R							
Placentammina lathrami													R		R	R		R	R							
Psammosphaera laevigata					R				R				R			R		R	R	R	R	R	R			
Reophax geniculatus	C	R	R	R					R		R		C	A	A	R	C	R	C	C	R	C				
Spiroplectammina edgelli																		R	R	R	R	R				
Textulariopsis cushmani	R	A																								
Textulariopsis wilgunyaensis																	R									
Textulariopsis sp. A																				R		A				
Trochammina minuta	R	A	R	A					R	A	A	C	R							R	R	R				
Trochammina sp. A		A													R				R							
Verneuilinoides howchini											C							R	R	A	R	R				
Verneuilinoides neocomiensis	R	A			R				R	A	A	R	R	A			R					A				
Porcellaneous: Miliolida																										
Miliolinella australiana																	C									
Hyaline calcitic: Lagenida																										
Astacolus howchini									R								R									
Citharina sp. C																		R								
Globulina lacrima			R		R		R		A	R							R	A		R						
Hemirobulina hamulus																		R								
Laevidentalina hamiltonensis					R				R	R	R					R	R	C		R						
Laevidentalina cf. *oliqostegia*																		R								
Laevidentalina praecommunis																		R								
Lenticulina qr. *warreqoensis*			R	R	R				C	R	R	C	A		R	R	R	A	R							
Lingulina buddencanyonensis																		R								
Lingulonodosaria cf. *nodosaria*									R	R	R		R				R	R								
Lingulonodosaria nodosaria					R				R				R					R								
Marginulina tilchae																	R	R								
Marginulinopsis arimensis				R					R			R	R				R	R								
Marginulinopsis cephalotes																		R								
Planularia cf. *strombecki*													C				R									
Pseudonodosaria humilis													R		R			R								
Psilocitharella recta																		R								
Pyramidulina cf. *flexocarinata*									R									R								
Pyramidulina obscura																		R								
Saracenaria planiuscula			R	R	R		R		R			R	R				R	R								
Tricarinella excavata													R													
Tristix perelongatum																		R								
Hyaline calcitic: Buliminida																										
Eurycheilostoma? hergottensis			A	A	A		C	R	A	C	R	A	R													
Eurycheilostoma? moorei								R	A	A	R	A	R													
Neobulimina albertensis																								A	R	
Neobulimina kareelensis																A	A	A								
Hyaline aragonitic: Robertinida																										
Epistomina chapmani																		C								
Hyaline calcitic: Rotaliida																										
Berthelina intermedia																		A								
Bilingulogavelinella australis											R	R														
Gavelinella dakotensis																A	R	R							R	
Gyroidina sp.																									R	
Gyroidinoides infracretaceus									R		C	A	A		R	R		C		R						
Hergottella jonesi										R																
Linguloqavelinella cf. *albiensis*											C	R														
Lingulogavelinella innaminckae																		C		R						
Lingulogavelinella santoodnae																		A								
Paralabamina sp.										R		A						?								
Pateliinoides tilchus									R		R							R								
Pseudogavelinella? impedita											R		R													
Pseudogavelinella? sp. A								R	R	R	A	R														
Hyaline calcitic: Globigerinida																										
Hedbergella spp. (dwarf forms)																								R	A	A
Biofacies	1	1	4	4	4	?	4	4	4	4	4	4	4	2	3	4	4	4	3	3	2	2	9	7	8	8

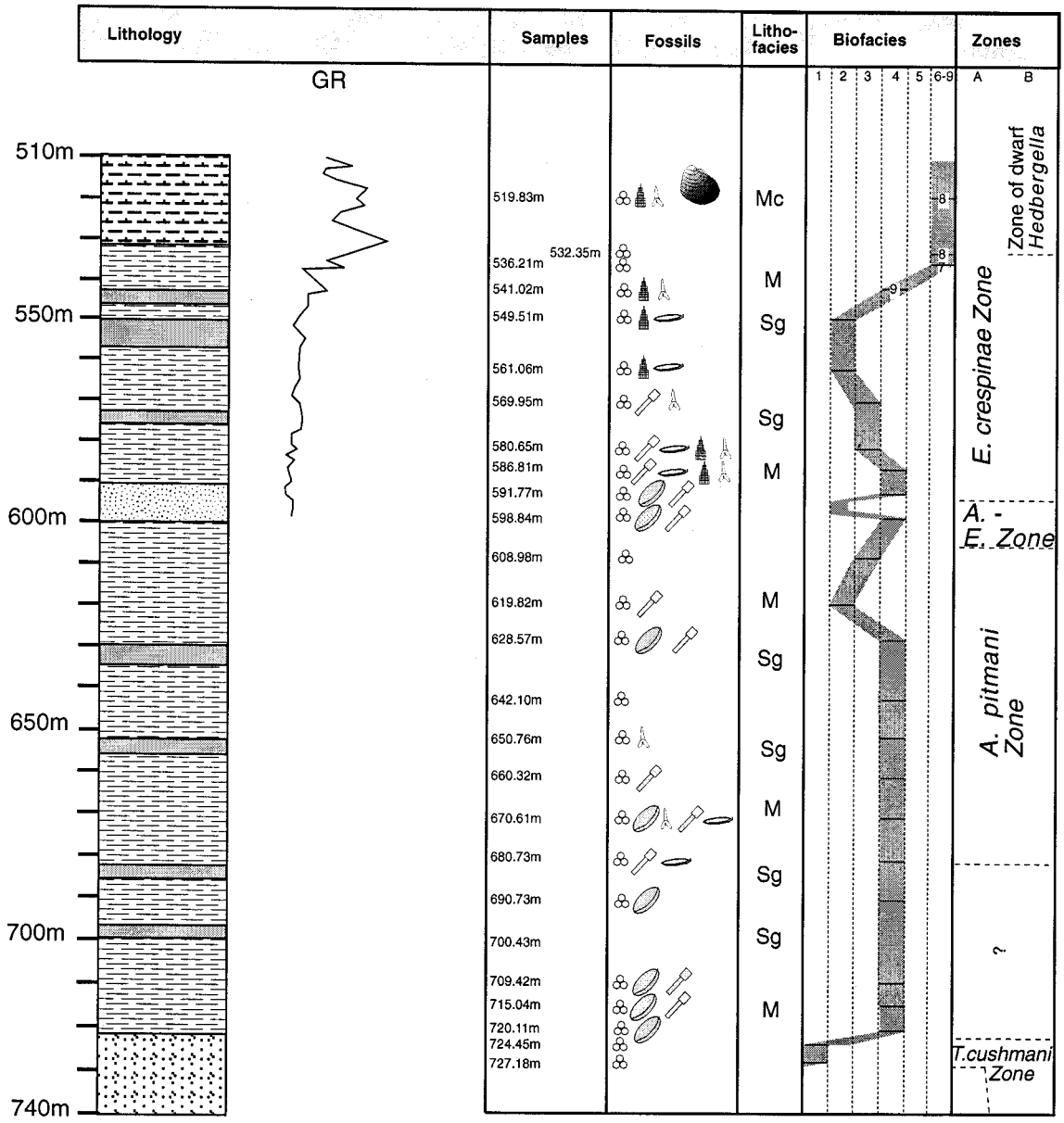


Figure 23. GSQ Manuka 1 showing lithology, gamma response, sample positions, fossil assemblage, lithofacies, biofacies and biozones. Standstill conditions in an upper offshore setting are recorded throughout much of the *A. pitmani* Zone. The deepening to lower offshore conditions during *E. crespinae* Zone-times recorded in the Hughenden 7 and outcrop sections is not evident until the very highest part of the zone.

510 m (top of Toolebuc Formation) to shales within the upper 14 m of the Cadna-owie Formation at 725–739 m (Figure 22). Balfe (1978) interpreted the Cadna-owie Formation below 739 m to be of non-marine, probably fluvial facies.

Lithology. The basal unit (725–739 m depth) consists of sandstones and very minor sandy mudstone. The sandstones are light grey to cream, fine to coarse-grained, fair to well sorted and quartz dominated. Overlying these quartz sandstones are dark grey, pyritic mudstones (725–555 m). The mudstone contains grey to green, glaucony-rich muddy sandstones. Between 544 and 510 m the mudstones are dark and calcareous with common shell layers between 532 and 510 m.

Palaeontology. Foraminifera are the most common sand-size biogenic components of the mudstones (Table 8). Benthic foraminifera are present through-

out the studied section between 727 and 532 m. Planktic foraminifera are present only in the calcareous mudstone unit (rare at 536.21 m, and abundant in higher samples). Other biogenic components include ostracods, echinoderm debris, diatoms, fish teeth and bone, and radiolaria (Figure 23). Shell layers in the calcareous mudstone section (532–510 m) are composed of *Inoceramus* and *Aucellina*.

Facies and bathymetric trends. The basal unit from 739–725 m includes deposits of lithofacies Smc, Sc, and minor Ms indicative of shoreface environments. The presence of biofacies 1 in sandy mudstones in this interval supports the interpretation of a shoreface setting. In the following 5 m of mudstone deposition, an environmental shift from shoreface to middle to upper offshore water depths took place (as evidenced by a biofacies change from 1 to 4; Figure 23). The section from 720–628 m remained in the middle to upper offshore zone. Glauconitic sandy units in this section probably do not signify any change in bathymetry. Mudstone facies at 619 m are associated with biofacies 2 of the transitional zone, and followed by progressively deeper-water biofacies (3 then 4) in the interval from 619–591 m. Progressive shallowing to the transitional zone is evidenced by biofacies (4 to 2) developed in mudstone between 586 and 549 m. From 549–532 m, water depths increased to the lower offshore zone with decreasing levels of dissolved oxygen in the bottom waters.

Age and lithostratigraphic correlation. Based on benthic foraminifera, the *Textulariopsis cushmani* Zone is present from 727–724 m. This is the oldest foraminiferal zone known in the Eromanga Basin and is believed to range from within the ?Barremian to the lower Aptian. The *Aaptotoichus pitmani* Zone of late Aptian age is recognized between 680 and 608 m, based on the lowest appearance of *Eurycheilostoma*? *moorei* at 680 m and the highest appearance of *A. pitmani* at 608 m in the absence of *Eomarssonella crespinae*. This zone includes an interval of overlap in the ranges of *Eurycheilostoma*? *hergottensis* and *E*? *moorei* between 680 and 628 m. Mudstone at 598.84 m belongs to the *Aaptotoichus pitmani–Eomarssonella crespinae* Concurrent-Range Zone. The *Eomarssonella crespinae* Zone of Albian age is recorded above this level. Calcareous mudstones at the top of the studied section, belong to the planktic foraminiferal Zone of dwarf *Hedbergella* of late middle to early late Albian age in this region.

The following lithostratigraphic subdivision of the studied section was made by Balfe (1978): Toolebuc Formation, 510–544 m; Wallumbilla Formation, 544–725 m; and Cadna-Owie Formation, 725–758 m. Based on the foraminiferal zonation, the section of Wallumbilla Formation from 725–608 m correlates with the Doncaster Member as defined in outcrop sections 1, 4 and 5a. The interval from 598–544 m corresponds in age to the type Ranmoor Member (outcrop section 6), but the mudstones in Manuka 1 are much less calcareous and contain shallower water biofacies.

4. Correlation of sections

In order to compare bathymetric trends across the region, the sections must be correlated with the greatest possible precision. This is difficult in interior basins because of the fairly monotonous nature of basinal lithofacies, and the peculiarities of the biota associated with restricted water conditions (e.g., abnormal salinities and abnormal bottom-water dissolved-oxygen levels). The vertical and palaeogeographical distribution of fossils within the basin is more a result of environmental conditions within the epicontinental sea than a product of age-diagnostic evolution. Open-ocean communication would have been limited in the silled interior sea, especially during times of low sea level.

The studied stratigraphic succession includes outcrop sections near the basin margin, and subsurface sections further into the basin (Figure 3). Lithostratigraphic subdivision of the offshore mudstone succession is difficult, and units such as the Jones Valley Member separating the Doncaster and Ranmoor Members in the marginal outcrop sections cannot be differentiated in the basinal sections.

The highest resolution means of correlation between the basinal subsurface sections and the more marginal outcrop sections is provided by foraminifera assigned to Haig's (1979b; revised by Haig & Lynch, 1993) zonation. This zonation (Table 3) is based on the stratigraphic ranges of species that belong to Haig's (1979a) epicontinental benthic *Ammobaculites* Association, and planktic *Hedbergella* Association. For the shallow water biofacies (*Ammobaculites australis* and *Lingulogavelinella albiensis* biofacies of Haig, 1979b; biofacies 1–5 of the present study), the zonation was based on the ranges of benthic species within their preferred biofacies, and zonal index species were chosen among the siliceous agglutinated foraminifera. Partial range zones are bounded by concurrent range zones in the benthic zonation. For the deeper water biofacies (*Neobulimina albertensis* biofacies of Haig, 1979b; biofacies 6–8 of present study), the planktic zonation was used. In the studied sections, the full

foraminiferal zonation could not be recognized across the region; intervals of uncertain zonal attribution are present. Palynomorphs (dinoflagellates, spores and pollen) provide a broad zonation of the borehole sections (Morgan, 1980a, b; Burger, 1982), but outcrop samples processed during the present study yielded very poorly preserved palynomorph assemblages.

Correlation of sections across the region is shown on Figure 24. Four 'correlation lines' are plotted on the diagram, separating the stratigraphic succession into four 'correlation intervals'. Correlation line 1 is the base of the Cretaceous marine succession. Although clearly trangressive, the flooding was probably synchronous in terms of geological time because of the subdued relief of the continental interior (all marine sections overlie slightly older sheet-like fluvial units). Palynostratigraphic correlations of borehole sections in the region suggest that this level was probably within the early Aptian, but may have been as old as late Barremian. Correlation line 2 is marked by the last occurrence up-section of *Eurycheilostoma*? *hergottensis*. This calcareous hyaline species found in biofacies 3–5, evolved into *E*? *moorei* within the lower part of the *Aaptotoichus pitmani* Zone, and persisted with its descendant species for some time before disappearing during the late Aptian (Haig, 1979b, 1982). *Eurycheilostoma*? *moorei* ranges into the Albian. In studied sections the highest occurrence of *E*? *hergottensis* is invariably associated with a change from middle-upper offshore facies (the preferred habitat of the *Eurycheilostoma*? species) to transitional facies where these forms are absent. *Eurycheilostoma*? *hergottensis* is absent where biofacies 3–5 reappears higher in the sections. Correlation line 2, therefore, probably only broadly approximates a time level within the late Aptian. Correlation line 3 is defined by the lowest occurrence of *Eomarssonella crespinae* associated with or just above the highest occurrence of *Aaptotoichus pitmani*. These siliceous agglutinated species occur over a biofacies 2–6 range. Proximity to the very narrow zone of overlap of these species (*Aaptotoichus pitmani–Eomarssonella crespinae* Zone of Haig, 1979b; Haig & Lynch, 1993) suggests that this correlation closely follows a time level within the earliest Albian. Correlation line 4 is marked by the first appearance of dwarf planktic *Hedbergella*, and the distinctive Toolebuc facies which characterised lower offshore basinal facies during the late middle to early late Albian.

Correlation interval 1, mainly of early to late Aptian age, thickens into the basin from 50 m in the Flinders River outcrop sections 1 and 4; greater than 47 m in Richmond 2; 73 m in Hughenden 7; to 111 m in Manuka 1. Correlation interval 2, of late Aptian age, remains fairly uniform in thickness across the region: 28 m in the Flinders River outcrop sections 4 and 5a,b; 36 m in Richmond 1; 32 m in Richmond 2; 33 m in Hughenden 7; 20 m in Manuka 1. Correlation interval 3, of early to probable middle Albian age, is greater than 30 m thick in the Flinders River area (outcrop sections 5b–8); 38 m in Richmond 1; 67 m in Hughenden 7; and 67 m in Manuka 1. Correlation interval 4, of late middle to early late Albian age, is about 20 m thick in Hughenden 7 and 26 m thick in Manuka 1.

5. Bathymetric trends

Bathymetry is compared across each of the correlation intervals identified in Section 4 above. Figure 24 shows the correlation of sections and bathymetric trends from which the lateral and time variations in water depth discussed below are interpreted.

In correlation interval 1, the basal sandstones and the lower few metres of mudstone record the initial transgressive phase of the marine incursion. This is recognized in an inshore situation in outcrop section 1 where water depths deepen to the lower shoreface–upper transitional zone; and in the more basinal situations (Hughenden 7 and Manuka 1) where bathymetry reaches the middle to upper offshore zone.

The initial transgressive pulse is followed by standstill conditions during most of the deposition of correlation interval 1. In the basinal setting (e.g., Manuka 1), standstill occurs at middle to upper offshore depths. In the marginal setting (e.g., outcrop section 1), standstill occurs in upper transitional to lower shoreface environments. Towards the top of the interval in the marginal setting (as seen in outcrop sections 1–4), shoreface to foreshore sand facies prograde over the transitional to lower shoreface muds. The sand facies are followed by deepening to the middle to upper offshore zone and accumulation of mud. This episode is not recognized in basinal sections (Manuka 1 or Hughenden 7) where offshore facies persist. This is possibly because the bathymetric range involved in changing the shallow-water facies is of an order less than would affect the deeper water offshore facies.

Correlation interval 2 contains evidence of changing bathymetry in both marginal and basinal sections. An initial shallowing to the transitional zone marks all sections of this interval. In basinal sections (e.g., Richmond 1, Hughenden 7, and Manuka 1), deepening to the middle to upper offshore zone follows the initial shallowing. In contrast, in the marginal setting of outcrop section 4, water depths fluctuate within the

transitional to lower shoreface zone. In the upper part of this interval, shoreface to foreshore sands prograde across the transitional to lower shoreface muds in the marginal parts of the basin (e.g., outcrop sections 4, 5a, 9). The sands form the Jones Valley Member that apparently thins rapidly into the basin. In the basinal sections, the Jones Valley episode may be represented by minor shallowing evidenced just below the top of correlation interval 2.

Correlation interval 3 contains one of the most marked changes in bathymetry and fauna that is recognized in the Australian interior basins and also in widely separated basins at the continental margin (e.g., Laura, Papuan, and Carnarvon Basins; Haig & Lynch, 1993; Haig *et al.*, 1996). The change, occurring during the late early Albian, involved the appearance of normal salinity open-marine benthic foraminiferal faunas in the marginal basins (*Marssonella* Association of Haig, 1979a) replacing the restricted-marine *Ammobaculites* Association, and brought calcareous microplankton (planktic foraminifera and nannofossils) into the interior seas for the first time.

In the Hughenden area, the bathymetric change within correlation interval 3 is most pronounced in the eastern sections (outcrop sections 5b and 6, and Hughenden 7) where water depth increased from the lower shoreface-transitional zone to the lower offshore zone. In Richmond 1, to the west of these sections, the change in bathymetry was more restricted, with water depth increasing from the lower shoreface-transitional zone to the middle-upper offshore zone. In contrast to these sections, water depths in the southwest of the study area at Manuka 1 showed an initial increase to the middle-upper offshore zone, followed by 35 m of mud deposition during shallowing to the transitional to upper shoreface zone. The upper 10 m of the interval in Manuka 1 was apparently deposited during rising water depths to the middle-upper offshore zone. In all sections, benthic foraminifera more characteristic of the *Marssonella* Association appear for the first time in the *Ammobaculites*-Association assemblages. These species include *Coryphostoma* sp. 1, *Berthelina intermedia*, *Psilocitharella recta*, *Eouvigerina* cf. *nagappai*, and *Pleurostomella reussi*.

Correlation unit 4 was deposited in the lower offshore zone under severe bottom-water anoxia. In the southwest of the study area at Manuka 1, this represented a bathymetric increase to lower offshore depths. In the central part of the region, in Hughenden 7, water depths probably did not change much from the underlying interval, but bottom water circulation became much more restricted with increasing anoxia on the sea floor.

In overview, the following are the most conspicuous features of the bathymetric trends interpreted for the studied stratigraphic succession. (1) Similarity of trends existed through the Aptian in all sections; but trends in the Albian were not as similar across the region. (2) During the earliest Albian all sections showed an increase in water depth. (3) During the early to late Aptian a bathymetric gradient existed across the region, from shallow transitional to shoreface environments in the northeast to middle-upper offshore depths in the southwest. (4) A reversal of the bathymetric gradient occurred during the early Albian with water depths deeper in the northeast (lower offshore zone) than in the southwest (middle-upper offshore zone).

In the above comparisons, the bathymetric differences have been discussed using a relative scale (from shoreface to lower offshore). Can the bathymetric changes be quantified? Three-dimensional stratigraphic architecture within the basin is insufficiently clear to assist in the assignment of numerical water depths from recognition of shifts in shoreline facies. The best method of obtaining some idea of the magnitude of water depths is to consider analogous present-day interior seas. The Gulf of Carpentaria between north Queensland and New Guinea represents an interior sag basin that is a descendant of the Cretaceous interior basins over the continent (as a continuation of the Carpentaria Basin). The Gulf of Carpentaria covers an area of over 0.5 million square kilometres and has a very low gradient sea floor with maximum water depths in the centre of about 60 m. The gulf is connected across very shallow water sills (<12 m deep) to the Pacific Ocean in the east and the Indian Ocean in the west. In terms of depositional conditions, the Cretaceous Eromanga sea may have had water depths similar to those of the present Gulf of Carpentaria. However, the latter lies in a tropical belt prone to summer monsoons, severe cyclones and dry winters. These climatic features contrast with the cold humid conditions at high latitudes experienced by the Cretaceous interior sea. The setting of the Eromanga sea was probably more like that found today in parts of the Baltic Sea, as suggested by Exon (1972).

In the shallow interior sea, the transition from sandy shoreface facies to muddy offshore facies is related to the depth of fair-weather wave base. Because of the restricted fetch of waves in the interior setting, effective wave base was probably not much deeper than 10 m. Severe storms would probably disturb the muds in the offshore zone, even in the deepest parts of an interior sea with a similar physiography to that of the Gulf of Carpentaria.

Based on the analogy of the Cretaceous foraminiferal assemblages with those of present-day seas, Haig (1979b), Haig & Lynch (1993), and Haig *et al.* (1996) suggested that faunas equivalent to biofacies 6–8 were representative of water depths between 50 and 100 m. Biofacies 1 contains genera of organic-walled siliceous agglutinated foraminifera that are typical of modern marginal-marine hyposaline marshes (usually 0–2 m water-depth range). The absence in any of the biofacies of agglutinated foraminifera with calcareous cement indicates that bottom waters were abnormal (slightly hyposaline and/or oxygen deficient) throughout the interior sea compared to the open ocean. The increase in abundance and diversity of calcareous hyaline benthic foraminifera from biofacies 3 to biofacies 6 suggests progressive deepening, probably in the 2–100 m range. The absence of planktic foraminifera in biofacies 3 and 4 and their rarity in biofacies 5, where benthic calcareous hyaline forms occur, suggest that water depths for these biofacies were less than 50 m.

In the study area, the lower offshore zone was probably at a water depth of 50–100m. The upper offshore zone probably extended from about 10 to 50 m water depth. The transitional zone was probably no deeper than 10 m, with the shoreface zone shallower than about 2 m.

6. Discussion

The correlations made above demonstrate that bathymetric changes can be traced across the region during particular time intervals. Parallel variations in water depth through time may reflect relative sea-level changes independent of sediment influx that were balanced between eustatic change and regional tectonic sag or uplift. The bathymetric trends also demonstrate that the trangressive phase of the Cretaceous marine incursion did not involve a uniform increase in bathymetry through time.

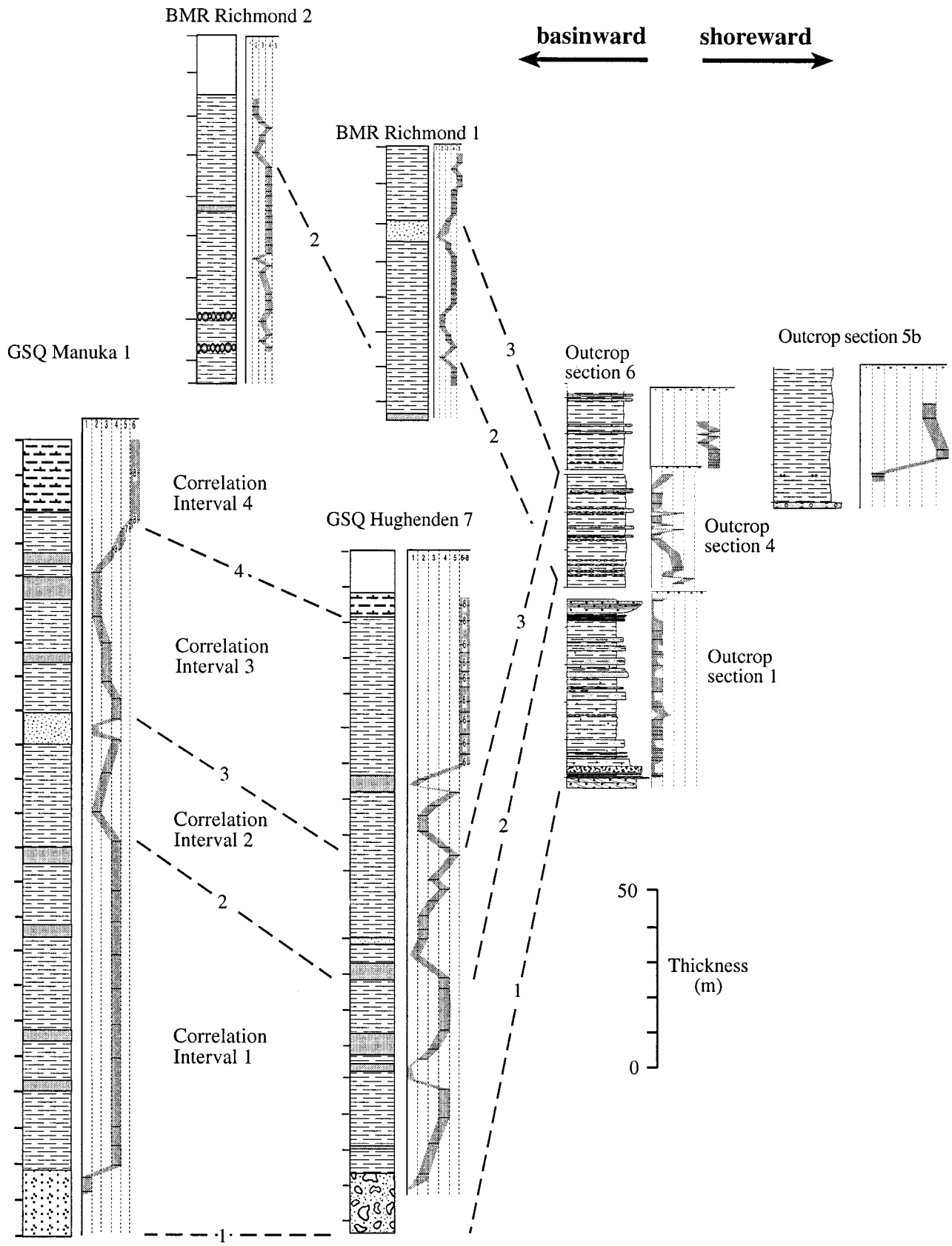
Relative sea level rose during the early Aptian and maintained standstill conditions until well into the late Aptian. During the standstill, as much as 90 m (compacted) of mud was deposited in the middle-upper offshore zone. At the basin margin, lithofacies changes were more conspicuous with periodic influx of quartz sand, and the total thickness of mainly muddy sediment that accumulated in the shoreface to transitional zone during an equivalent time was about 45 m (compacted).

During the latter part of the late Aptian relative sea level initially fell throughout the region, as indicated by parallel bathymetric trends, but in basinal areas then rose. The basinal deposits of this episode are thinner in the section considered most distant from the shore (viz., Manuka 1, 20 m compacted thickness) than the sections to the northeast (28–36 m compacted thickness). This is the reverse of the earlier depositional pattern, when a greater thickness accumulated at Manuka compared to the other sections. At the basin margins influxes of sediment (including a significant pulse of quartz sand forming the Jones Valley Member) kept water depths fluctuating mainly in the shoreface to transitional zone.

During the early Albian, all sections show an initial increase in water depth signifying a transgressive pulse across the region that was accompanied by many new faunal elements. A significant change in sea-floor gradients occurred during this time. During the Aptian, water depths were very shallow in the northeast and progressively deepened to the southwest. During the early Albian, a reversal in sea-floor bathymetric gradients occurred. A dramatic deepening to the lower offshore zone (50–100 m) took place in the northeast, whereas water depths in the southwest varied within the transitional to middle-upper offshore zone (2–50 m). Lower offshore conditions did not appear in the southwest until the late middle to early late Albian, marking the end of the transgressive phase of the continental marine incursion.

Haig & Lynch (1993) recognized that the late early to middle Albian lower offshore zone was confined to the eastern margin of the interior basins. They recognized it in the Ranmoor Member of the present study area; in the upper part of the Coreena Member in the Longreach area to the south; and in the Surat Siltstone of the Surat Basin in southern Queensland. They related the deepening event to units exposed in sedimentary basins north of the present area: the Woolena Claystone in the Laura Basin; undifferentiated Cretaceous deposits in the eastern Carpentaria Basin; and the lower Chim Formation and part of the Ieru Formation in the Papuan Basin.

The offshore zone during the early late to middle Albian was probably confined to a narrow strait in the Hughenden area. The following features suggest this. (1) A shallowing of facies is evidenced in outcrop section 8 (at Glenmoan, about 30 km east of Hughenden) at a level above the lower offshore facies, suggesting proximity to an eastern shore line. (2) The lower offshore facies persists through most of the Ranmoor Member in Hughenden 7. (3) Shallower, middle to upper offshore depths were maintained during this interval at Richmond 1 about 30 km northwest of Hughenden.


BMR Richmond 2
basinward
shoreward
BMR Richmond 1
GSQ Manuka 1
Outcrop section 6
Outcrop section 5b
Outcrop section 4
Outcrop section 1
GSQ Hughenden 7
Correlation Interval 4
Correlation Interval 3
Correlation Interval 2
Correlation Interval 1
4
3
2
1
50
0
Thickness (m)

The reversal in bathymetric gradients in the study area during the early Albian probably reflected tectonic sagging along the eastern margin of the basin, perhaps owing to tectonism along eastern Australia during this time. Veevers & Powell (1990) suggested that the eastern continental margin was a magmatic arc and convergent plate margin, and that activity associated with this may account for the discrepancy in maximum flooding between the Australian interior basins (during the Albian), and the global peak transgression during the Turonian.

Erosional unconformities and parasequence stacking patterns, the tools of sequence stratigraphic subdivision of marginal marine facies employed by workers in the Western Interior Basin of North America, cannot be recognized in the Eromanga Basin strata. Henderson (1998) also had problems in recognising these sea-level signatures within the mudstone-dominated Bathurst Island Group succession on the Money Shoals Platform in northern Australia. In our study we have interpreted bathymetric trends from biofacies-lithofacies analysis in an attempt to define sea-level cycles.

The transgressive phase of the marine incursion studied here probably had a duration of over 20 my. The duration of Cretaceous third-order sea-level cycles recognized on passive continental margins was about 1–3 my (Haq *et al.*, 1988). This cyclicity should be mirrored in an interior sea. Because we are dealing mainly with offshore facies and cannot recognize unconformities within the studied marine succession, we can only tentatively suggest where sequence boundaries may fall.

The oldest level where the interpreted water-depth curve falls in all sections (by equivalent depths) is in the upper Aptian, just above correlation line 2 shown on Figure 24. This relative sea-level fall may mark a sequence boundary in the basin. The next highest consistent decrease in bathymetry occurs at the Jones Valley Member level just below correlation line 3 (Figure 24), close to the Aptian-Albian boundary. Above this level, evidence is present of a significant transgressive pulse and the realignment of bathymetric gradients in the interior sea. The level represents a probable sequence boundary in the basin. The significance of the Toolebuc Formation in the sequence-stratigraphic subdivision is uncertain. The stratigraphic interval from the base of the marine succession (lower Aptian or uppermost Barremian) to the top of the Ranmoor Member (probably middle Albian) seems to include three sequences.

Previous work on cyclic sedimentation in the Eromanga Basin by Morgan (1980a) and Burger (1986) was based on palynomorph data, using the proportion of dinoflagellates to pollen and spores to estimate proximity to the coastline. Their relative sea-level curves were based on a broader sample spacing than we have used, and show only broad correspondence to the curves generated in our study.

Haig & Lynch (1993) recognized the third Eromanga cycle as a significant transgressive pulse across northeastern Australia. They traced the cycle from the Papuan Basin in the north (basal Chim Formation and Bawia Member of Ieru Formation) through the undifferentiated mudstones of the northern Carpentaria Basin, Woolena Claystone of the Laura Basin, Ranmoor Member of the north-eastern Eromanga Basin, upper Coreena Member of the central-eastern Eromanga Basin, to the Surat Siltstone of the Surat Basin in southern Queensland.

Labutis (1994) subdivided the Aptian to mid-Albian strata of the North West Shelf of Australia into five depositional sequences (OPERCULATA to DENTICULATA Sequences), but did not publish the full evidence for sequence recognition. His depositional sequences seem to correspond to dinoflagellate zones and were named after these. It would appear that the first Eromanga Basin cycle, which probably belongs to the dinoflagellate *Odontochitina operculata* Zone, correlates with the OPERCULATA Sequence; that the second cycle correlates with the DAVIDII Sequence (belonging to subzone A of the dinoflagellate *Pseudoceratium turneri* Zone=*Diconodinium davidii* Zone); and that the third correlates with the TETRACANTHA B Sequence (belonging to subzone B of the dinoflagellate *Pseudoceratium turneri* Zone=*Muderongia tetracantha* Zone).

Figure 24. Correlation of the outcrop sections with the basinward borehole sections. Correlation lines are defined by the following events: (1) the base of the marine succession, indicated by conglomerate (outcrop and Hughenden 7), or coarse sandstone and gravel (Manuka-1); (2) the last occurrence up-section of *Eurycheilostoma*? *hergottensis*; (3) the lowest occurrence of *Eomarssonella crespinae* associated with or just above the highest occurrence of *Aaptotoichus pitmani*; (4) the first appearance of dwarf planktic *Hedbergella*. These correlation lines define correlation intervals. Plotted alongside the stratigraphic columns are the biofacies trends shown as shaded curves. These reflect changes in bathymetry as indicated in the depositional model shown on Figure 7 and indicated on Table 2.

In the Southern Carnarvon Basin of Western Australia Mory & Yasin (1999) found a similar pattern of relative sea-level cycles to that described by Labutis (1994) and recognized by us in this study. In the Southern Carnarvon Basin the cycles were based on the foraminiferal bathymetric studies of Haig (in press) tied to the dinoflagellate zonal determinations of Backhouse (1999). The first Eromanga cycle correlates to the depositional sequence encompassing the Muderong Shale and its Windalia Sand Member (*Muderongia australis* to *Odontochtina operculata* Zones). The second cycle correlates to the Windalia Radiolarite sequence (*Diconodinium davidii* Zone). The third correlates to the depositional sequence represented by the lower Gearle Siltstone (as suggested by Haig *et al.*, 1996, on the basis of the planktic foraminiferal *Hedbergella planispira* Zone and the nannofossil CC8a Zone).

It seems probable that the sequences, which we have tentatively recognized in the northeastern Eromanga Basin, are also reflected on the distant western margin of the continent. This suggests that the dominant control on the relative changes in sea level may have been either eustatic changes or tectonism affecting the entire continent.

Haq *et al.* (1988) described a number of sequences of supposed global extent in the mid-Cretaceous. Two main supercycles (2nd order) were recorded in the Aptian/Albian, the Lower Zuni B-4 (LZB-4) and Upper Zuni A-1 (UZA-1). Within these supercycles were recognized a number of shorter duration cycles (3rd order). Within the Aptian LZB-4, two 3rd order cycles were defined (LZB-4.1 and LZB-4.2), which may correlate with the Aptian cycles recorded in the Eromanga Basin. However the resolution of our biostratigraphic correlation to the standard Aptian succession is not fine enough to confirm the sequence correlations. The three 3rd order sequences recognized by Haq *et al.* (1988) in the lower to middle Albian (UZA-1.1-1.3) appear to have no clear counterparts in the Eromanga succession. This Albian inconsistency suggests that broad-scale tectonism, such as described by Veevers & Powell (1990) and Gurnis *et al.* (1998), may have affected relative sea levels over Australia during the Albian.

7. Conclusions

The transgressive phase of the Cretaceous marine incursion across the northeastern Eromanga Basin is represented in the Gilbert River Formation, Wallumbilla Formation and Toolebuc Formation, and took place from the early Aptian (or late Barremian) to the late middle or early late Albian. Maximum flooding occurred from the late early Albian to early late Albian. The marine transgression did not involve a uniform increase in water depth. Three depositional cycles are tentatively recognized in the section below the Toolebuc Formation.

The first depositional cycle may include the Gilbert River Formation and the lower part of the Doncaster Member (including its type section), with thickness varying from 50–111 m. It ranged from early Aptian (or late Barremian) to within the late Aptian. Most sediment accumulation occurred under standstill conditions (45 m of compacted sandy mudstone in lower shoreface to transitional zone; 90 m of compacted mudstone in upper to middle offshore zone). A fall in relative sea level occurred at the end of the cycle in all areas within the study region. At the time of maximum flooding within the cycle, a sea-floor gradient existed that ranged from the shoreface to the transitional zone (perhaps 0–10 m water depth) in the northeast of the study area to the middle offshore zone (possibly around 50 m water depth) basinward to the southwest. The sequence correlates with at least part of the Muderong Shale (including the Windalia Sand Member) depositional sequence of the Carnarvon Basin in western Australia.

The second depositional sequence probably includes the upper Doncaster Member and the Jones Valley Member, with thickness varying from 20–36 m. This cycle included the later part of the late Aptian. Most sediment accumulation occurred under fluctuating water depths, but a fall in relative sea level ends the cycle in all areas. The sequence correlates with the Windalia Radiolarite sequence of the Carnarvon Basin in western Australia.

The third depositional sequence includes the Ranmoor Member, with thickness varying from 38–67 m. This cycle was represented by a significant transgressive pulse recognized in age-equivalent formations from the Papuan Basin in the north through the eastern Carpentaria Basin, Laura Basin and eastern Eromanga Basin to the Surat Basin in the south. In Western Australia, the equivalent sequence is represented by the lower part of the Gearle Siltstone. At the time of maximum flooding during this cycle, the sea-floor was deepest in the northeast (lower offshore zone, probably 50–100 m water depth) and shallowest in the southwest (middle offshore zone, less than 50 m water depth) of the study area. The reversal in the direction of the bathymetric gradient between cycle 1 and cycle 3 in the region is probably related to tectonism along the eastern Australian margin.

The correspondence in depositional cycles between the interior sea and the western continental margin suggests that changes in relative sea level over

Australia during the Aptian-Albian were influenced by continent-wide tectonism. The apparent lack of correspondence between the Australian Albian record and the global sea-level curve suggests that continent-wide tectonism was an important influence in determining Australian sea levels during this time.

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