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The Cretaceous geology of northeastern Arnhem Land, Northern Territory

A A Krassay

Record 1994/40

MINERALS AND LAND USE PROGRAM

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

The Cretaceous Geology of Northeastern Arnhem Land, Northern Territory

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ABSTRACT

Late Aptian to early Cenomanian strata were deposited in a large epeiric seaway which covered much of the northern Australian landmass during the Cretaceous. Siliciclastic sediments accumulated on a gently-sloping shelf which formed the western margin of the Carpentaria Basin. Cretaceous rocks which accumulated in the northwestern part of the seaway are preserved in northeastern Arnhem Land, and represent alluvial/coastal-plain and inner-shelf depositional environments. The rocks have been divided into 15 lithofacies, which are stacked to form 5 separate grain size cycles (facies successions). These rocks were previously named as the Mullaman Beds, but two new stratigraphic names (Walker River Formation and Yirrkala Formation) are proposed here.

Stratigraphic correlation is based on the vertical and lateral variation of facies successions and has resulted in the erection of a stratigraphic framework for the shelf succession. The shelf maintained a relatively similar configuration throughout the mid-Cretaceous with water depths rarely exceeding 50 m, and the seafloor was apparently within the influence of storm waves over much of the area. The shelf was storm- and wave-dominated, and most early-formed or fair-weather sedimentary structures were destroyed or extensively modified during episodic storms.

The composite sections and stratigraphic framework developed here are linked by regional correlations to biostratigraphically dated zones outside northeastern Arnhem Land to define the age of the shelf succession, and to facilitate stratigraphic ties to thick Cretaceous strata in the central Carpentaria Basin and Eromanga Basin.

1. INTRODUCTION

The mid-Cretaceous was a time of global high sea level (Haq *et al.*, 1988) as shown by the simultaneous formation of numerous large epeiric seaways throughout the world. Much of the Australian landmass was inundated during this period and a number of shallow epeiric seaways were formed. The largest of these occupied most of the Great Artesian Basin, which connected the Carpentaria, Eromanga and Surat Basins and covered an enormous area of inland Australia (Fig. 1).

The northwestern part of this large epeiric seaway covered what is now northeastern Arnhem Land in the Northern Territory. During mid-Cretaceous time a series of sedimentary sequences accumulated in this northwestern part of the seaway on a broad, shallow-marine shelf. After retreat of the sea in Late Cretaceous time the area was emergent and Cretaceous rocks were subjected to a lengthy period of erosion and weathering. The result of these processes is that the Cretaceous shelf succession is preserved as erosional remnants, in the form of mesas and plateaus, over an area of approximately 150,000 km^2 along the western and southwestern margins of the Gulf of Carpentaria.

Due to the nature of the outcrop, the distance between investigated localities varies between several hundred metres and tens of kilometres, and is in most cases several kilometres. Most shelf lithologies are exposed onshore in an outcrop belt about 150 km wide along the western margin of the Gulf of Carpentaria (Fig. 2), and consist mainly of sandstone, siltstone, and conglomerate with subordinate claystone. The Cretaceous shelf succession has not been formally subdivided and detailed lateral correlations between and within individual marginal shelf facies are difficult because erosion resulted in many incomplete sections and biostratigraphic data are limited. However, regional facies successions and the broad

FIG. 1

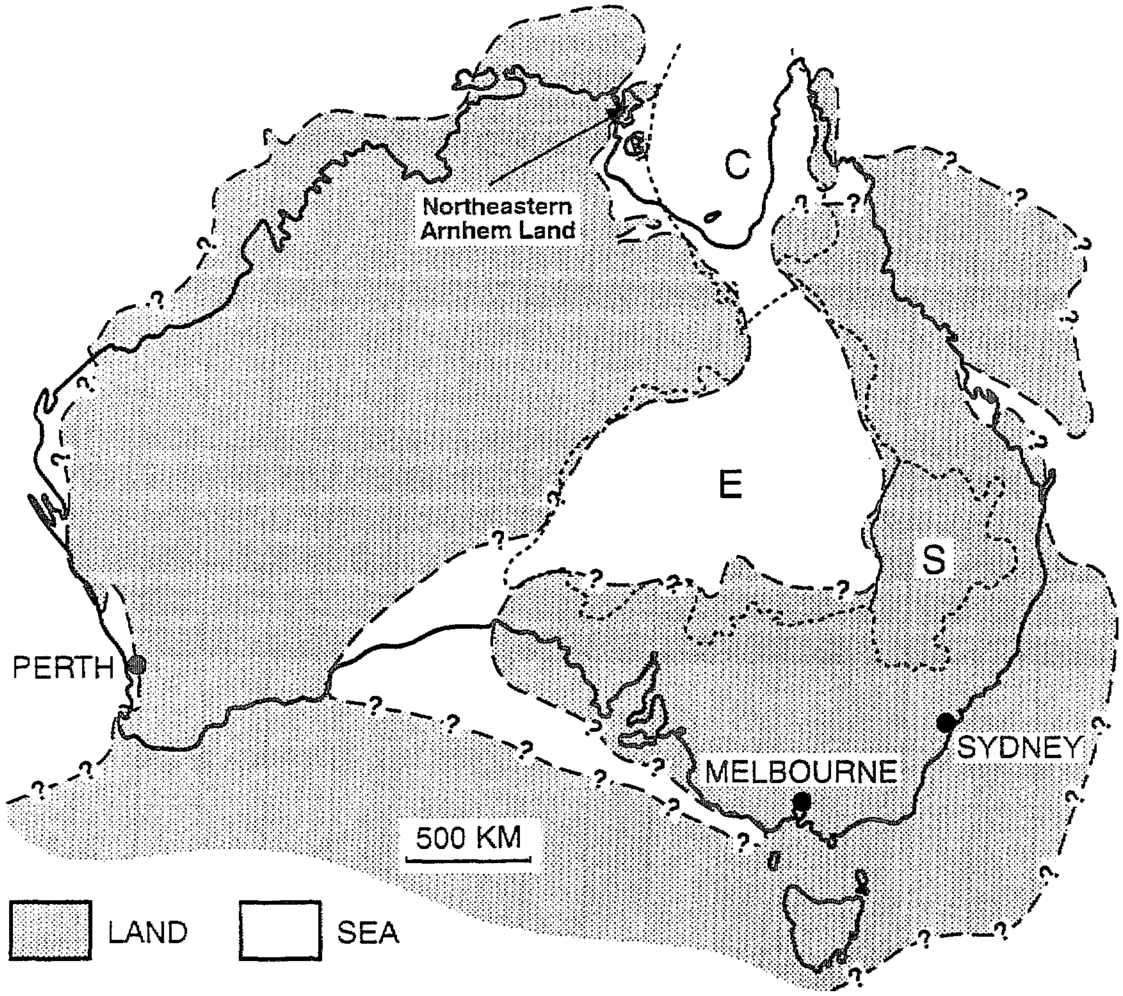


FIGURE 1. Late Albian palaeogeography of Australia. Outlines of Carpentaria (C), Eromanga (E), and Surat (S) Basins are shown by thin dashed lines. Late Albian regional shoreline is shown by bolder dashed lines. Dashed lines with question marks represent regions where shoreline position is uncertain. Modified after Frakes *et al.* (1987).

lithostratigraphic framework are known with confidence because the sediments are undeformed and flat-lying in most places.

The marginal shelf sediments discussed here have a thickness of 50 to 100m. Jurassic and Cretaceous strata in the Carpentaria Basin depocentre, 300 km to the east of the shelf (Fig. 3), have a maximum thickness of 1200 m (Smart *et al.*, 1980). The broad age equivalence of Cretaceous rocks in northeastern Arnhem Land and the Carpentaria Basin depocentre (offshore to the west of Weipa, Fig. 2) is known from regional stratigraphic studies (Skwarko, 1966; Morgan, 1980), and this correlation is refined in the present study. The broad stratigraphic equivalence of Cretaceous rocks in the two areas is also supported by lateral correlation using seismic data (*e.g.* Passmore *et al.*, 1992; Thomas *et al.*, 1992).

Cretaceous rocks are best exposed in two main zones within northeastern Arnhem Land, and are missing through erosion or are covered by alluvium between these two zones. The Arnhem Land Zone (ALZ) covers a large part of the ARNHEM BAY-GOVE 1:250,000 map sheet area, and the Bath and Parsons Ranges Zone (BPRZ) covers the central part of the BLUE MUD BAY 1:250,000 map sheet area. Discussion in this record focuses on the Cretaceous rocks in these two zones.

2. SCOPE AND PURPOSE

This record has been written in order to fully document the Cretaceous geology of northeastern Arnhem Land, in terms of lithology, sedimentology, relative age, detailed stratigraphy, depositional environments, and depositional systems. The material presented here is an expansion of that presented in the explanatory notes for the ARNHEM BAY-GOVE and BLUE MUD BAY 1:250,000 map sheets, and documents geological investigations of Cretaceous rocks undertaken as part of BMR (now AGSO) NGMA mapping activity in Arnhem Land in recent years.

The details of specific localities, sample sites and descriptions, and outcrop descriptions from field work in northeastern Arnhem Land are available under originator number 195 in the OZROX database within AGSO's NGMA database, and a summary table is presented in Appendix 1. Further details and additional data on the petrology, mineralogy, sedimentology, and sequence stratigraphy of Cretaceous rocks exposed along the entire western and southwestern margins of the Gulf of Carpentaria are presented as part of a much larger study of Cretaceous rocks in the eastern Northern Territory and northwest Queensland (Krassay, PhD thesis in prep.).

3. REGIONAL SETTING

The Jurassic to Cretaceous Carpentaria Basin is a classic example of a cratonic-interior basin, and is located within northern Queensland and the Northern Territory (Fig. 2). The Basin is essentially a north-south trending depression, the northernmost of three interconnected Jurassic-Cretaceous downwarps which formed the Great Artesian Basin. Marine connection was not maintained at all times, because the Euroka Arch (Fig. 2) occasionally barred full circulation between the Carpentaria and Eromanga Basins (Smart *et al.*, 1980). In general the Carpentaria Basin, closest to the northern marine connection with the open ocean, was affected greatly by marine circulation, fair-weather waves and tides, and storm processes, whereas generally lower energy levels characterised much of the southern portion of the epeiric seaway south of the Euroka Arch.

FIG. 2

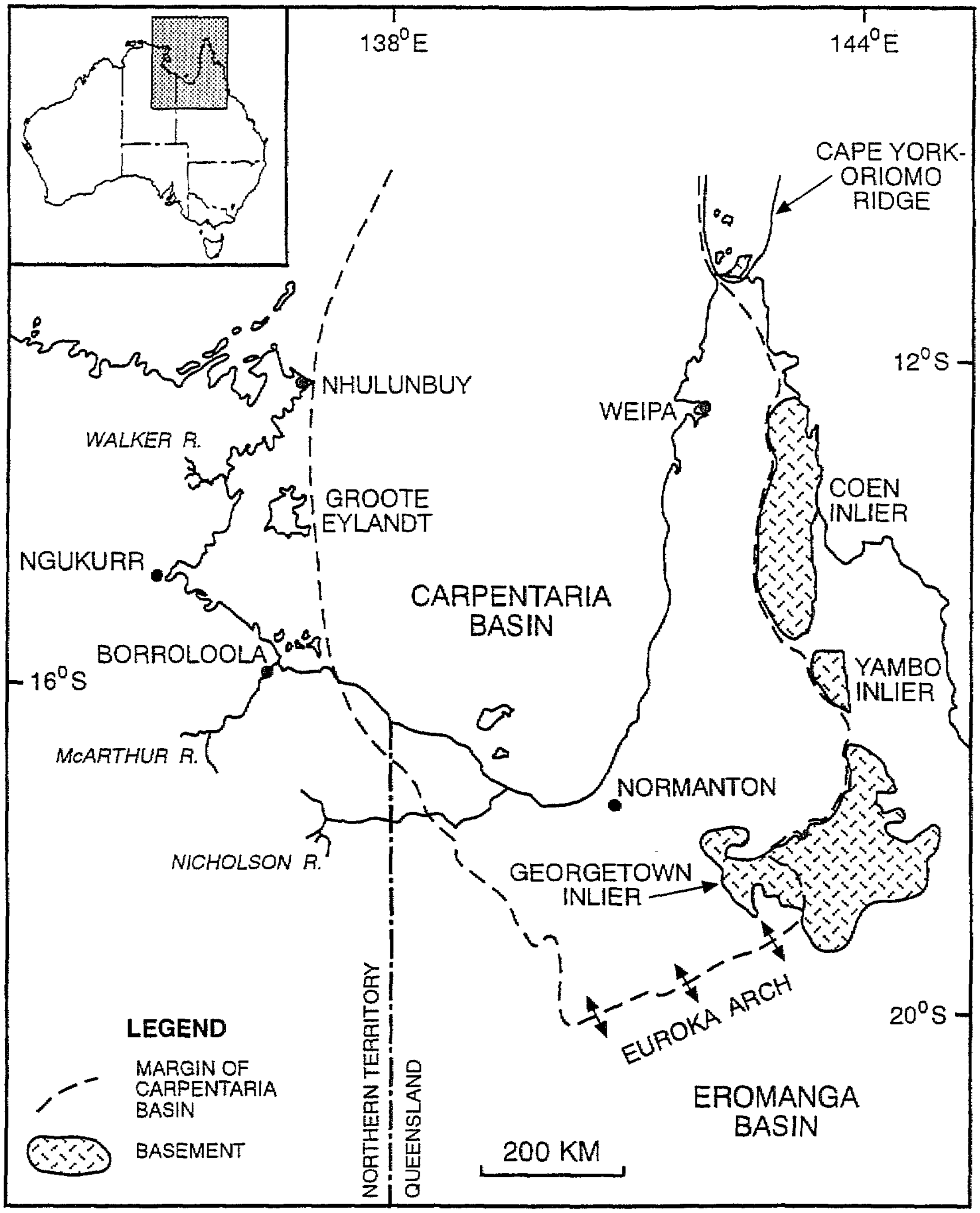


FIGURE 2. Geological setting of the Carpentaria Basin. The margin of the Carpentaria Basin as recognised by previous workers (*e.g.* Smart *et al.*, 1980) is shown by the dashed line. The Walker River and Yirrkala Formations (formerly Mullaman Beds) are exposed mostly to the west of this traditional boundary, but are still part of the Carpentaria Basin stratigraphy. Modified after Thomas *et al.* (1992).

The Carpentaria Basin has dimensions of about 1000 km north-south and 650 km east-west, covering an area of approximately 600,000 km^2 (Burgess, 1984). The margins of the basin closely follow the coastline of the present day Gulf of Carpentaria. The western margin of the Carpentaria Basin was a hingeline during Early Cretaceous subsidence (Smart *et al.*, 1980), and sediments eastward of this fault bounded margin were structurally undisturbed, except for gentle downwarping and minor movements along reactivated faults (Passmore, 1979). The eastern margin of the basin is bounded by Precambrian igneous rocks of the Coen, Yambo, and Georgetown Inliers, together with Carboniferous igneous rocks of the Cape York-Oriomo Ridge (Fig. 2).

To the north, the Carpentaria Basin is in probable lithologic continuity with the Papuan Basin over the Bramwell Arch, and with the Morehead Basin. Probable ties to the Laura, Styx, and Maryborough Basins occur in this region to the north of the Coen Inlier. To the south, over the Euroka Arch, the sediments are continuous into the Eromanga Basin (Fig. 2) (Smart *et al.*, 1980). There is little, if any, relationship between sedimentation in the Carpentaria Basin and the Bathurst Island / Money Shoals Basin to the west because the two sedimentary regimes were separated by an extensive structural barrier. Onshore, in the west, the Carpentaria Basin is flanked by Proterozoic rocks of the Arnhem and Mount Isa Inliers and the McArthur Basin, which the shelf succession overlies with angular unconformity. Post-Cretaceous rocks in the study area typically belong to the Cainozoic cover succession of the Karumba Basin, which is an epicratonic basin superimposed on the Mesozoic Carpentaria Basin (Smart *et al.*, 1980).

The main structural elements of the Carpentaria Basin were formed during pre-Jurassic movements before sediment accumulation (Passmore *et al.*, 1992). There is no evidence of structural movement in the basin in Jurassic time, and only minor structural movement occurred in Early Cretaceous time (Passmore *et al.*, 1992; 1993; Smart *et al.*, 1980). Such syn-depositional movements appear to have been limited in extent and influence and had only minor effects on deposition (Passmore, 1979). Structural activity in the Late Cretaceous and Tertiary produced only mild deformation within the Carpentaria Basin succession.

The broad stratigraphy of the Carpentaria Basin is known from eight onshore petroleum wells, several water bores and one offshore petroleum well, Duyken 1, but the current geological interpretation of the offshore area is based on extrapolation of geological knowledge from onshore, interpretation of marine seismic data, and integration of factual well-completion data from Duyken 1. Extrapolation from the onshore to the offshore can be made with confidence because the lack of structural disturbance within the basin allows confident correlation of reflectors (Burgess, 1984). The extension of the Eromanga Basin marine rock units into the Carpentaria Basin is based largely on lithological similarity, although some micropalaeontological control is available along the eastern margin (Burger, 1986; Morgan, 1980).

Sedimentation within the Carpentaria Basin commenced in the Jurassic with the accumulation of fluvial sands in a series of basement depressions. As a result of gentle sagging and high relative sea levels, sedimentation became more widespread during the Cretaceous and a thick sequence of non-marine grading to marine clastics accumulated over the entire basin. Most of the basin fill is interpreted to have been derived directly from adjacent Precambrian and Palaeozoic highstanding terrains (Doutch, 1976; Smart *et al.*, 1980). A summary of the stratigraphy of the Carpentaria Basin is presented in Fig. 4, and readers are referred to Doutch (1976), Passmore (1979), and Smart *et al.* (1980) for further detail.

FIG. 3

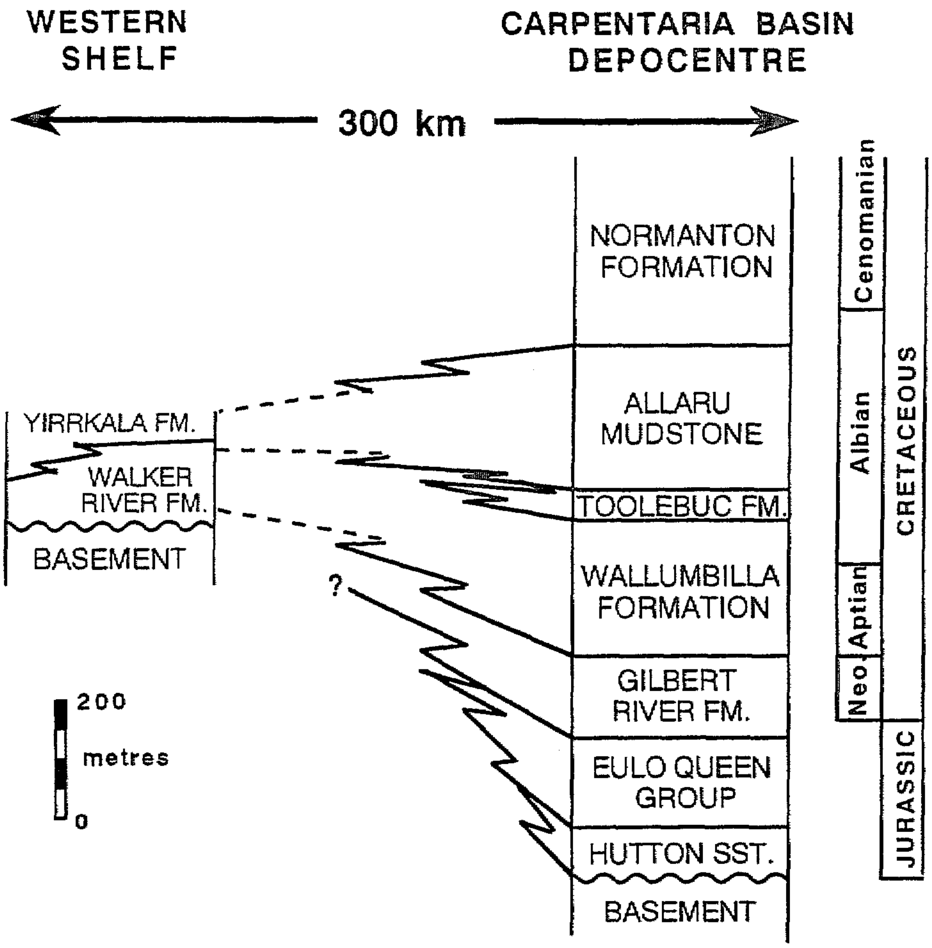


FIGURE 3. Schematic diagram showing thicknesses and stratigraphic relationships of the Walker River and Yirrkala Formations (formerly Mullaman Beds) and the Carpentaria Basin depocentre sequence. Modified after Krassay (1994).

FIG. 4

CARPENTARIA BASIN STRATIGRAPHY

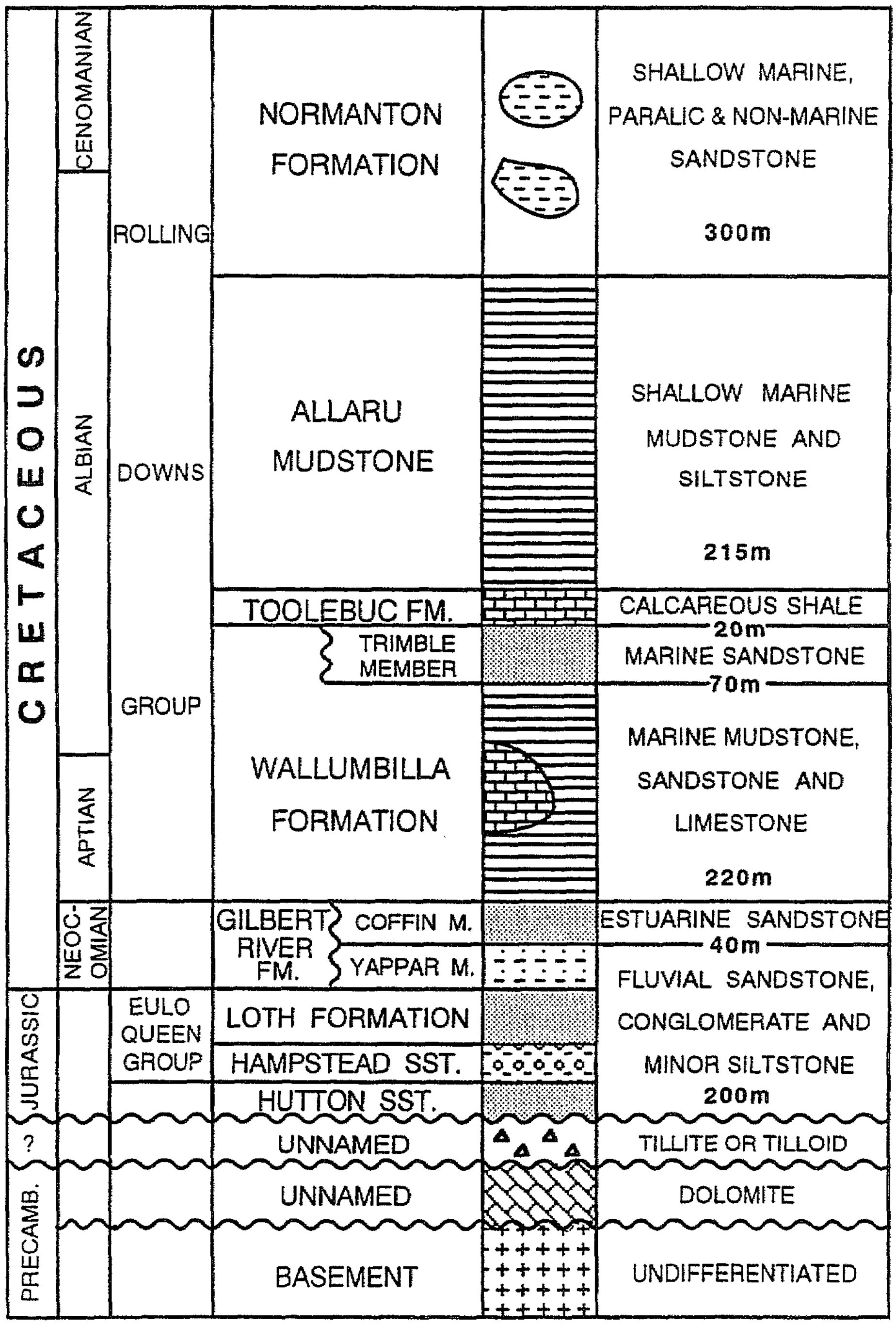


FIGURE 4. Stratigraphic column for the central Carpentaria Basin with thicknesses of major formations shown in metres. Modified after Burgess (1984).

4. PREVIOUS WORK

The stratigraphy and palaeontology of Cretaceous rocks of northern and central Australia has been the focus of numerous local and regional studies. In many of these studies the Carpentaria, Eromanga, and Surat Basins have been collectively studied as one large basin, the "Great Artesian Basin" of Day (1969). Far fewer studies have concentrated on the Carpentaria Basin, and only one provided any detail on the stratigraphy and palaeontology of onshore Cretaceous rocks of the western and southwestern margins of the Gulf of Carpentaria, *i.e.* Skwarko (1966).

Noakes (1949) proposed that all Cretaceous sediments from Darwin and other coastal areas in the Northern Territory be placed in his Mullaman Group. Geologists from the Bureau of Mineral Resources (BMR) later down-graded this term to Mullaman Beds in line with the Australian code of stratigraphic nomenclature (Skwarko, 1966). Hughes (1978) attempted to redefine the established stratigraphy of the term Mullaman Beds after suggesting ties to the Petrel Formation and the Darwin Member of the Bathurst Island Formation.

Skwarko (1966) examined the palaeontology, and to a lesser extent the stratigraphy, of the Mullaman Beds as the basis of his Ph.D thesis. His study is the only detailed one concerning the Mullaman Beds, except for local studies by geologists from mineral exploration companies. Skwarko's (1966) study was based primarily on invertebrate palaeontology and resulted in a division of Cretaceous sediments into two groups; the generally marine "Coastal Belt" and the generally non-marine "Inland Belt" (Fig. 5). The rocks discussed here are roughly equivalent in position to rocks of his Coastal Belt, in which Skwarko (1966) recognised 7 units that form a composite section. The basal unit (1) is interpreted as a lacustrine sandstone, which is overlain by a stacked series of fossiliferous marine siltstones and sandstones (units 3 through 6); these are overlain by conglomerate and marine sandstone and siltstone (unit 7). In northeastern Arnhem Land only rocks equivalent to Skwarko's units 1, 2, and 3 are exposed.

Skwarko's (1966) biostratigraphic age determinations suggested a Neocomian age for units 1 through 3, a Neocomian to Aptian age for unit 4, an Aptian age for units 5 and 6, and an Albian age for unit 7. These age determinations have now been superseded (see below), and the age of the shelf succession has been redefined as Aptian to early Cenomanian.

5. NEW STRATIGRAPHIC NAMES

Onshore marine and nonmarine rocks on the western shelf of the Carpentaria Basin have long been termed the Mullaman Beds (Skwarko, 1966). However, the use of the name Mullaman Beds has been discouraged (Hughes, 1978), due to the recognised stratigraphic inadequacy of the term in its original form, where it was used to describe most Mesozoic rocks, not only those of proven Cretaceous age, in the northeastern Northern Territory. On the basis of the more detailed study reported herein, two new names are proposed to replace the term Mullaman Beds for Cretaceous rocks distributed onshore along the western and southwestern margins of the Gulf of Carpentaria.

The Walker River Formation (new name) is proposed to encompass moderately to well sorted, typically cross-bedded, fossiliferous, fine- to coarse-grained quartz sandstone interbedded with laminated clayey siltstone and chert granule and pebble conglomerate. The Yirrkala Formation (new name) is proposed to encompass poorly sorted, fine- to very coarse-grained, large-scale crossbedded matrix-poor quartz sandstone with dispered chert pebbles and rare plant fossils. Distinction between the Yirrkala Formation and Walker River

FIG. 5

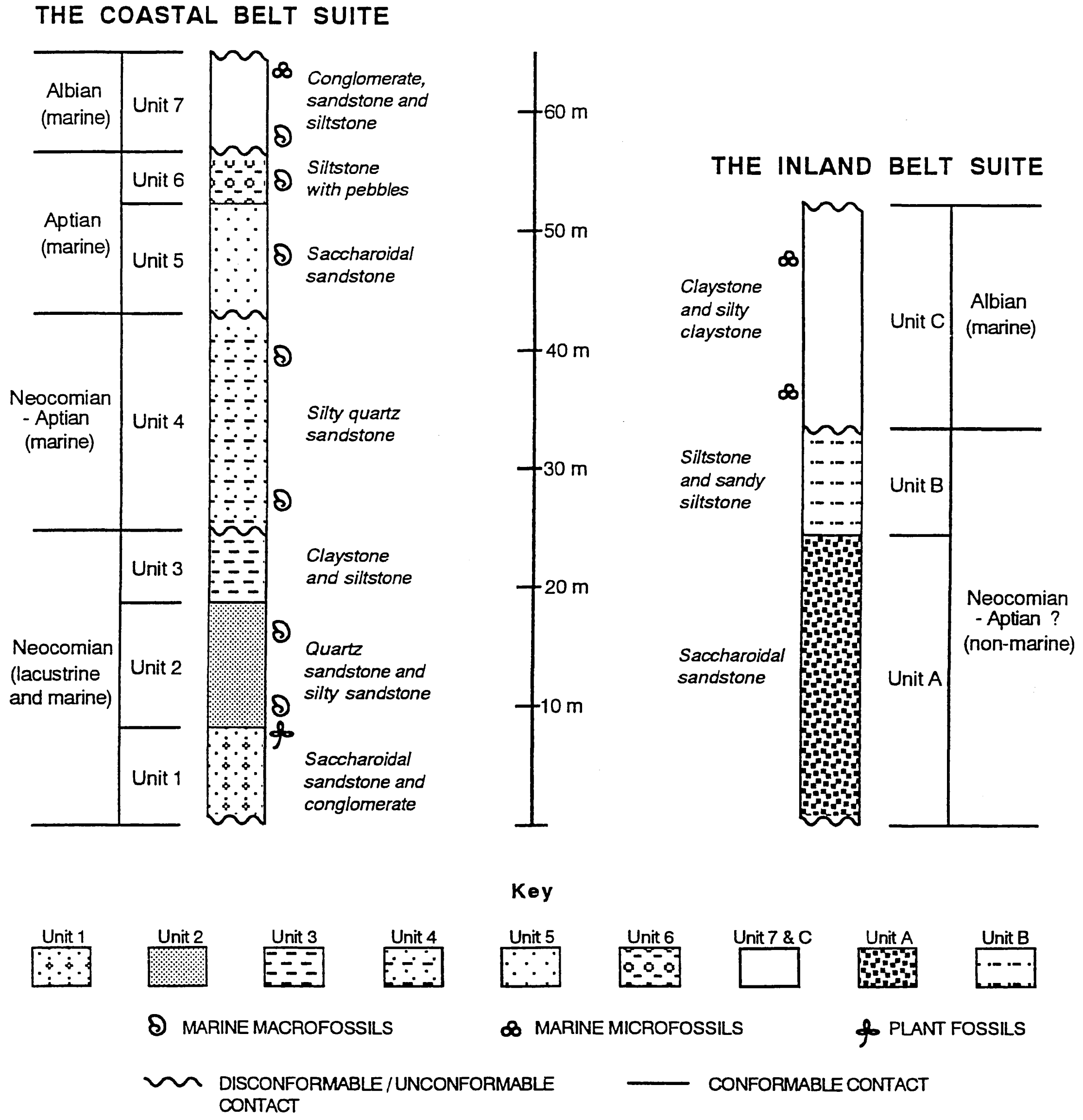


FIGURE 5. Skwarko's stratigraphic scheme for the Mullaman Beds. Modified from Skwarko (1966).

Formation (respectively) is based broadly on the following characteristics; plant fossils vs. marine shelly fossils, high degree vs. low degree of sorting within single beds, lithologically homogeneous vs. heterogeneous, coarse sand vs. fine-medium sand, pale coloured vs. mid to dark coloured (iron-staining), large or very-large scale crossbedding vs. mid to small-scale crossbedding, and low vs. high proportion of clay. Refer to the stratigraphic definitions below for further distinctive features of each unit on an outcrop-scale. Typical outcrops of each formation are illustrated in Plates 1a and 1b.

5.1 WALKER RIVER FORMATION

(new definition: A.A. Krassay)

DERIVATION OF NAME

From the Walker River, in the west-central part of the BLUE MUD BAY 1:250,000 Sheet. The headwaters of the river occur at approximately 13^0 20' S, 135^0 22' E, and the river enters the Gulf of Carpentaria at 13^0 35' 30" S, 135^0 50' 00" E.

DISTRIBUTION

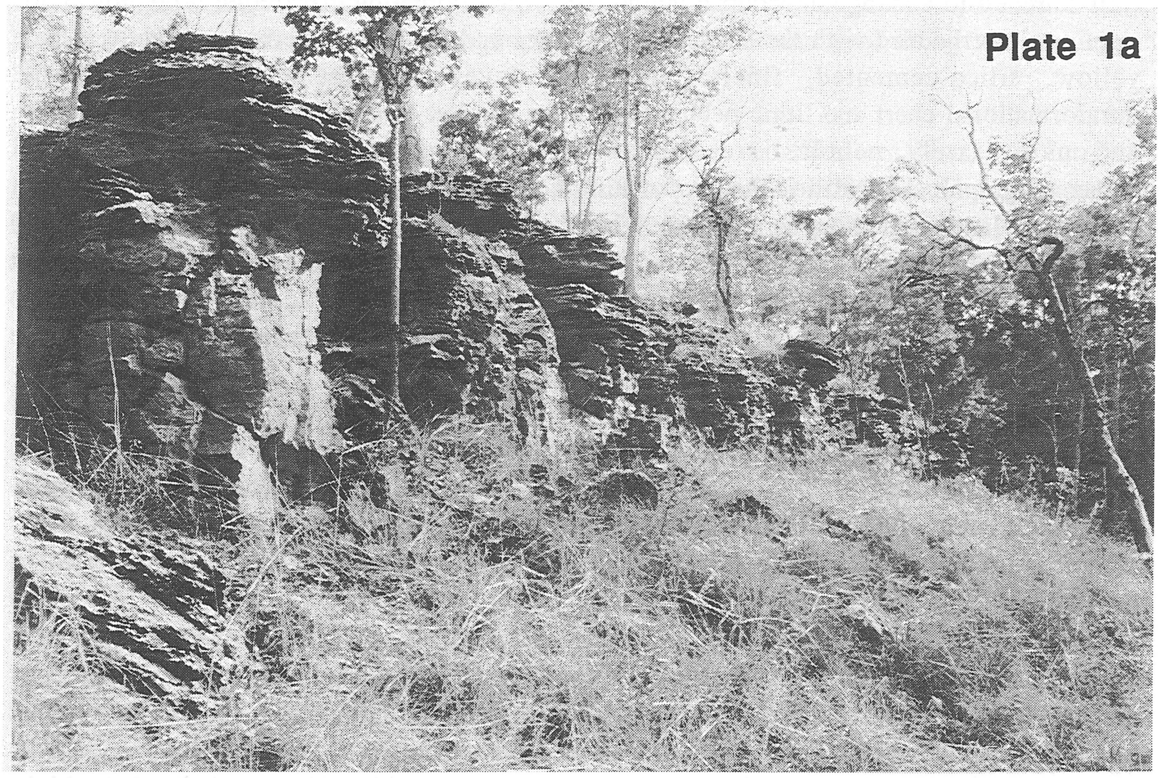
The unit is extensively distributed along the western and south-western margins of the Gulf of Carpentaria, mostly within the Northern Territory but also within far northwestern Queensland. The unit is preserved as erosional remnants in the form of mesas, plateaus and low-lying rubbly hills occupying a broad zone up to 150 km inland from the present Gulf coastline. The erosional remnants commonly form outliers resting directly on Proterozoic rocks of the McArthur Basin. The area encompassed by this unit is in the order of 120,000 km^2, but the western and southern margins of the outcrop belt are relatively poorly defined, as the unit tends to thin in these directions. The main outcrop belt lies east of about 134^0 30' E, west of 138^0 50' E, south of 12^0 05' S, and north of about 18^0 55' S. The outcrop belt covers a large part of the eastern Northern Territory along the margin of the Gulf of Carpentaria, and occupies all or part of sixteen 1:250,000 Sheet areas.

TYPE SECTION

23 m of sandstone and silty sandstone, thinly interbedded with clayey siltstone and thin intraformational chert pebble conglomerate, forming a tiered cliff exposure at the edge of a large dissected Cretaceous plateau, about 5 km southwest of the northern arm of the Walker River, at 13^0 34' 07" S, 135^0 29' 25" E in the BLUE MUD BAY 1:250,000 sheet area in northeastern Arnhem Land. The base is identified by a normally-graded, clast-supported chert cobble conglomerate, unconformably overlying laminated, shallowly-dipping Proterozoic siltstone. The top is the flat top of the erosional landform (plateau) which forms the outcrop, the upper surface of which is densely vegetated.

REFERENCE SECTION

Reference sections exist along the edge of dissected plateaus and large mesas in the areas surrounding the Walker River, within the boundaries of what was a large palaeoembayment in Cretaceous time between latitudes 13^0 21' S and 13^0 40' S, and longitudes 135^0 23' E and 135^0 31' E. Good reference sections also exist along the entire length of the outcrop belt of this marine shelfal formation, and the lithological character of the unit changes in response to facies changes away from the palaeoshoreline. For completeness, the locations of three reference sections are included here, covering proximal, intermediate, and distal (palaeogeographical) depositional settings of the unit. In order (proximal to distal) their locations are; 13^0 25' 51" S, 135^0 26' 54" E on the BLUE MUD BAY 1:250,000 Sheet, 15^0 36' 45" S, 135^0 36' 30" E on the MOUNT YOUNG 1:250,000 Sheet, and 17^0 14' 00" S, 135^0 38' 30" E on the WALLHALLOW 1:250,000 Sheet.



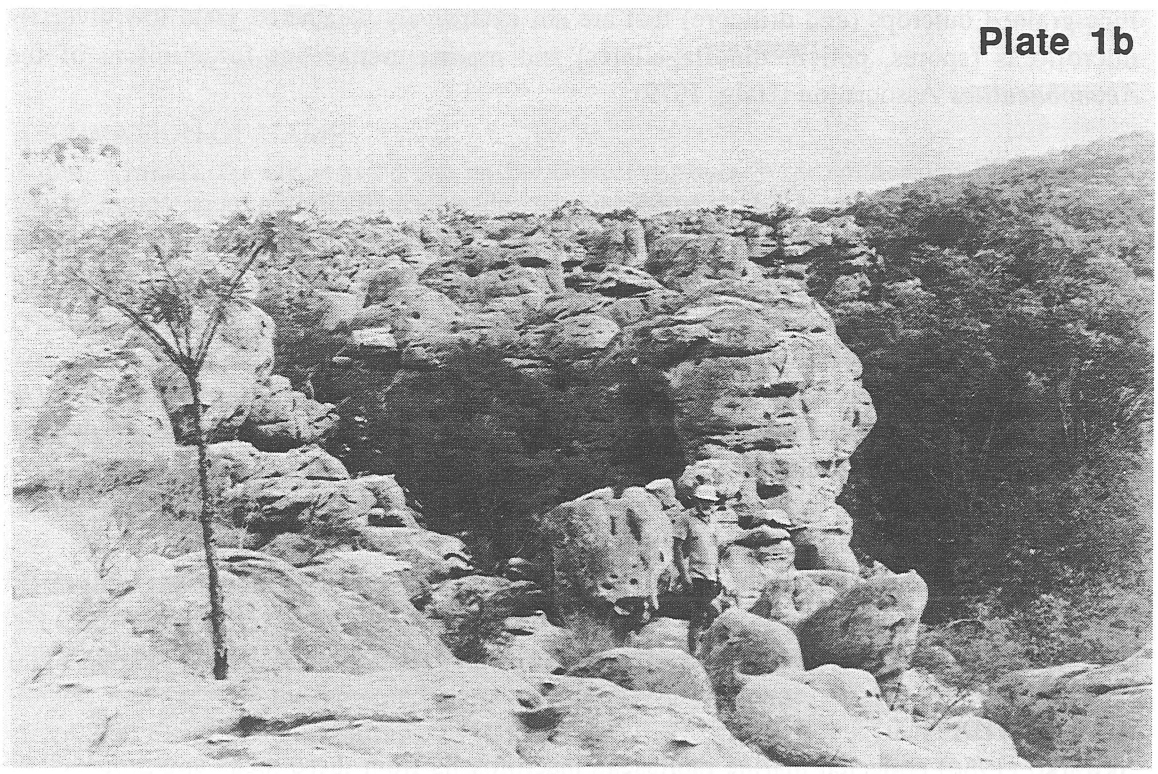


Plate 1a. General outcrop view of the Walker River Formation in the Bath and Parsons Ranges Zone, section 173. Thickness of rock ledge in foreground is about 5 m.

Plate 1b. General outcrop view of the Yirrkala Formation in the Bath and Parsons Ranges Zone, section 37. Note person at centre right for scale.

LITHOLOGY

The bulk of the unit is weathered sandstone: white to dark orange, moderately to well sorted, well rounded to subangular, coarse/medium- to fine-grained quartz arenite with iron-oxide staining. Interbedded with the sandstone are flaser and lenticular interbeds of white to pale yellow, silica-cemented, finely laminated clayey siltstone. Thin, sharp-based intraformational chert and lithic pebble lags occur parallel or slightly discordant to bedding, and more rarely pebbles are concentrated into metre-wide lenses. In distal palaeogeographical localities the proportion of sandstone is less, and the bulk of the unit consists of laminated siltstone with sandy interbeds. The unit forms both fining-upward and coarsening-upward grain size cycles, typically 5 to 10 m-thick. Where the base of the unit is exposed, it consists of a thick, normally graded, chert cobble to pebble conglomerate which grades up into marine sandstones containing molluscan macrofossils and marine trace fossils.

Sedimentary structures within this heterolithic unit include hummocky cross-stratification, planar cross-bedding (0.25 to 2 m), wave and current ripples, gravelly ripples, ripple-lamination, convolute lamination, slump structures, gutters and gutter casts and other complex erosional scours and tool marks, graded beds, coquinas, and various styles of lamination.

The unit contains abundant to rare, moderately to poorly preserved specimens of molluscan macrofossils, mainly bivalves, but also rare ammonites and belemnites. Rare stratigraphic intervals have segmented plant fossils mixed with the molluscan fossils. Marine trace fossils of the *Skolithos* and *Cruziana* ichnofacies are common, and are characteristic of the high-energy shallow-marine depositional environment of the unit (Pemberton *et al.*, 1992). Fine-grained outcrops (and drillcore) that are not extensively weathered yield low-diversity microfloras (spores, pollen, dinoflagellates) and marine arenaceous foraminifera of the *Ammobaculites* Association (Haig, 1979).

THICKNESS

Range 2 to 38 m in outcrop. At least 55m in the subsurface (B. Bolton, pers. comm., 1982; D. Sands, pers. comm., 1979). Construction of composite sections indicates that the overall maximum thickness of the unit in outcrop is greater than 70 m.

PALAEOENVIRONMENT

The unit generally represents high-energy deposition in the foreshore to offshore shallow-marine zone. Some interbedded stratigraphic intervals represent distal deltaic to deltaic-marine depositional environments.

RELATIONSHIPS AND BOUNDARY CRITERIA

In outcrop and subsurface the unit overlies older Cretaceous nonmarine units with disconformity, or Lower Proterozoic sedimentary rocks with angular unconformity. The unconformity surface is marked by a prominent chert cobble conglomerate in most places.

AGE & EVIDENCE

Skwarko (1966) collected marine molluscan macrofossils from these rocks and proposed an age range of Neocomian to Aptian, with rare Albian aged rocks. However, these biostratigraphic age determinations have now been refined (Krassay, 1994), and the age of the unit is considered as late Aptian to early Cenomanian. Palynomorphs in the lower part of this unit, in US Steel drillholes near Numbulwar, belong to the *Coptospora paradoxa* spore-pollen Zone and the *Canninginopsis denticulata* microplankton Zone and, give an age of middle Albian (N. Alley, pers. comm., 1991). Correlative outcrops contain arenaceous foraminifera belonging to the *Riyadhella crespinae* Zone, which give an age range of late early Albian to late Albian for the lower to middle part of the unit (D. Haig, pers. comm., 1991). Arenaceous foraminifera belonging to the *Bigenerina pitmani* Zone in rocks from the lowest exposed stratigraphic interval of the unit give an age of late Aptian (D. Haig, pers. comm., 1991).

Preliminary results from recent drilling in the onshore northeastern Northern Territory, south and west of the Yiyintyi Range on the MOUNT YOUNG 1:250,000 Sheet, suggest that the base of this unit may be as old as early Aptian (M. Warne, pers. comm., 1994). On the basis of correlation to dated stratigraphic intervals on Groote Eylandt, the upper part of this unit is considered to be early Cenomanian in age. The full age range of the unit is likely to be Aptian to Cenomanian.

REMARKS
This unit occupies a large part of Skwarko's (1966) 'coastal belt', and was previously placed within the Mullaman Beds. In terms of Skwarko's (1966) informal stratigraphic nomenclature, this unit is equivalent in part to Skwarko's 'units 2-7', and possibly also to 'unit B and C' of his 'inland belt'.

Skwarko's (1966) informal stratigraphic nomenclature is now superseded, and usage of his informal names ('belts' and 'units') should be discontinued. Further mapping is likely to extend the known westward limit of the Walker River Formation, and an aim of such mapping should be to replace the old terminology (Mullaman Beds, and Skwarko's informal terminology) on the basis of the new stratigraphic definition proposed here.

5.2 YIRRKALA FORMATION

(new definition: A.A. Krassay)

DERIVATION OF NAME
From, Yirrkala, the old mission site on the Gove Peninsula in far northeastern Arnhem Land, at 12^0 15' 05" S, 136^0 53' 20" E in the ARNHEM BAY-GOVE 1:250,000 sheet area.

DISTRIBUTION
The unit occurs in two main areas. Firstly, as a broad semi-continuous low-lying plateau in the northeastern part of the ARNHEM BAY-GOVE 1:250,000 Sheet area, between Melville Bay and Wanyamera Point, and Arnhem Bay and Dalywoi Bay. The exposed area of this plateau (now partly dissected) is about 1500 km^2. The greatest thickness and extent of the Yirrkala Formation occurs on the ARNHEM BAY-GOVE 1:250,000 Sheet, in an area within about 50km to the southwest of Nhulunbuy.

Secondly, the unit occurs as thinner, patchy palaeovalley fill and terraced deposits in the elevated parts of high-standing basement ranges. The unit has been recognised on the upper flanks of the Mitchell Range and Parsons Range on the BLUE MUD BAY 1:250,000 Sheet, and also in the elevated parts of the Yiyintyi Range on the MOUNT YOUNG 1:250,000 Sheet at about latitude 15^0 25' S.

TYPE SECTION
50 m of white sandstone exposed along the banks and to the sides of 'Tiger Creek', at approximately 13^0 31' 30" S, 135^0 14' 50" E on the eastern flank of the Parsons Range on the BLUE MUD BAY 1:250,000 Sheet. The base is identified by a chert cobble and pebble conglomeratic lag, mantling a well developed angular unconformity on the Palaeoproterozoic Parsons Range Group. The top is the uppermost part of the sequence of

flat-lying Cretaceous rocks which overlie shallowly to moderately dipping Proterozoic rocks of the Parsons Range.

REFERENCE SECTION

Reference sections exist along Wonga Creek, about 40km southwest of Nhulunbuy, on the ARNHEM BAY-GOVE 1:250,000 Sheet, from approximately 12^0 26' 00" S, 136^0 34' 00" E to 12^0 29' 30" S, 136^0 39' 00" E. Here, the thickness of the unit varies from a few metres to over 15 m, with an average thickness of 8 to 10 m. In the Wonga Creek area the unit is incised into older marine rocks of the Walker River Formation, and the amount of fluvial incision decreases towards the modern coastline.

LITHOLOGY

Sandstone: white to pale grey, poorly to moderately sorted, fine- to very coarse-grained: Massive to thickly planar bedded, with large-scale trough cross-bedding with set thicknesses up to 2 m at the base, and planar cross-bedding in the middle and upper parts with rare dispersed rounded pebble-sized chert clasts. Commonly forms fining-upward grain-size cycles, with chert pebble lags overlying local base-of-channel scours. Upper, finer-grained parts of the unit (or sub-cycles within the unit) contain rare, moderately to poorly preserved, external moulds of segmented plant fossils on upper bedding surfaces.

THICKNESS

Range 5 to 50 m: typically 8 to 15 m in outcrop, but probably much thicker in the subsurface, as shown in drill logs for 3 stratigraphic drillholes in the area surrounding Nhulunbuy (Dodson, 1967).

PALAEOENVIRONMENT

The unit generally represents high-energy fluvial deposition in channels, and coarse-grained nonmarine valley fills. Most outcrops conform to sandy bedform, channel, and gravel bar architectural elements in Miall's (1985) classification of fluvial deposits.

RELATIONSHIPS AND BOUNDARY CRITERIA

In outcrop, the unit overlies older Cretaceous marine units with disconformity or Lower Proterozoic sedimentary rocks with angular unconformity. In the subsurface the unit overlies Proterozoic metasediments and granites with nonconformity (Dodson, 1967).

AGE & EVIDENCE

Plant macrofloras are relatively poorly preserved and consist of long-ranging forms, which may only be considered as Late Mesozoic in age (Skwarko, 1966, p. 32). For a full list of plant fossils, that have been previously collected from this unit, refer to Skwarko (1966, p. 32). The unit is correlated with the nonmarine sequence in three stratigraphic drillholes near Nhulunbuy; siltstone interbedded with the arkosic sandstones in drillhole D.D.H. 2 at 64 m depth has been dated by palynology as late Albian (Evans, in Dodson, 1967). Furthermore, on the basis of regional lithostratigraphic correlations outcrops of the unit in the Wonga Creek area, about 40 km southwest of Nhulunbuy, disconformably overlie marine Cretaceous rocks of Albian age. The likely age of the unit in most places is Albian or younger (up to Cenomanian).

REMARKS

In places this unit is similar to that described by Skwarko (1966) as 'unit 1' of his 'coastal belt' or 'unit A' of his 'inland belt', and is included within the Mullaman Beds.

The name Yirrkala Formation was initially proposed to describe nonmarine rocks in Arnhem Land, but it also applies to rocks distributed much farther to the south along the western margin of the Gulf of Carpentaria, south until the Northern Territory / Queensland border. It is anticipated that further mapping will almost certainly extend the known westward distribution of the unit.

6. LITHOFACIES

6.1 CONCEPTS AND DEFINITIONS

This record provides detailed descriptions of all facies in the onshore Carpentaria Basin in northeastern Arnhem Land. Along the entire western margin of the Gulf of Carpentaria, facies can be separated into two broad, interconnected groups (different to the two 'belts' of Skwarko, 1966) on the basis of their position relative to the regional palaeoshoreline. Facies in northeastern Arnhem Land generally represent proximal depositional environments of the alluvial and coastal plains, and the inner shallow-marine shelf. South of Arnhem Land along the Gulf of Carpentaria, facies generally represent outer to middle shelf positions and more basinal marine depositional environments.

A facies is defined as "a body of rock characterised by a particular combination of lithology, physical and biological structures that bestow an aspect ("facies") different from the bodies of rock above, below and laterally adjacent" (Walker, 1992, p. 2). Twenty facies have been recognised in the Walker River and Yirrkala Formations, fifteen of which occur in northeastern Arnhem Land. These were defined by features readily recognisable in the field, such as grain size, primary sedimentary structures, degree of bioturbation, colour, and the nature of bounding surfaces. Features of subordinate importance in facies division include petrography, geochemistry, and weathering or diagenetic effects.

The facies descriptions below are arranged as closely as possible according to grain size, coarsest first, with two common weathering horizons (ferricretes) in the area described last. The terminology for basic sedimentological parameters, *e.g.* grain size, sorting, roundness, and bedding, is based on the schemes presented in Pettijohn *et al.* (1987) and Tucker (1991). A summary of all facies descriptions and interpretations is presented in Table 1.

6.2 FACIES 1 - CHERT-COBBLE CONGLOMERATE AND COARSE SANDSTONE

This facies occurs in the BPRZ, south-southwest of Nhulunbuy. In many measured sections this facies forms the oldest Mesozoic unit in the region and overlies Proterozoic McArthur Basin units with an angular unconformity. The maximum thickness of the facies is 12.5 m, with an average thickness of 3 m. The conglomerate is normally graded, although this vertical trend is subtle. Other sedimentary structures are absent, except for very rare intervals with planar or trough cross-stratification in the upper part of the facies.

The conglomerate is clast-supported with a moderate to poor degree of sorting and clasts typically range from small pebbles to large cobbles, with rare boulders. Nearly all of the clasts comprise chert, silicified sandstone, and other lithologies typical of McArthur Basin basement rocks exposed in the BPRZ. Clasts are subrounded to rounded, with the clast shape being spherical to moderately elliptical. The matrix for the conglomerate is poorly sorted, subrounded to subangular, medium to coarse quartz sandstone. The basal part of this facies contains only a small amount of matrix, and the amount of matrix increases upward with decreasing clast size. Commonly the facies is heavily stained by red iron oxides or cemented by amorphous silica. Both body fossils and trace fossils are rare, although the matrix-rich upper part of the facies occasionally contains poorly preserved molds of molluscan fossils and *Thalassinoides* burrows.

TABLE 1. Cretaceous facies of northeastern Arnhem Land. Missing facies in the numbered sequence do not occur within northeastern Arnhem Land.

	FACIES DESCRIPTIONS
1	**Chert-cobble conglomerate and coarse sandstone**
3	**Lag**
5	**Cross-stratified and planar bedded pebbly sandstone**
6	**Plant-bearing pebbly sandstone**
7	**Trough cross-stratified coarse sandstone**
8	**Trough and swaley cross-stratified fossiliferous sandstone**
9	**Ferruginous lithic sandstone**
10	**Bioturbated clayey sandstone**
11	**Cross-stratified plant-bearing sandstone**
12	**Fossiliferous bioturbated clayey sandstone**
13	**Bioturbated silty sandstone**
14	**Hummocky cross-stratified sandstone**
15	**Thinly interbedded sandstone and siltstone**
21	**Intensely bioturbated siltstone**
22	**Silty claystone**
	INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS
1	**High-energy fluvial (valley fill)**
3	**Various (mostly marine deposits)**
5	**High- to moderate-energy fluvial**
6	**Fluvio-deltaic to estuarine**
7	**Fluvial (meandering stream system)**
8	**Middle to upper marine shoreface (rarely foreshore)**
9	**Fluvial (*e.g.* scour/channel fill) or marginal marine**
10	**Shallow marine (close to fair-weather wave base)**
11	**Brackish marine (*e.g.* foreshore to terrestrial-strandplain)**
12	**Restricted/sheltered marine (*e.g.* bays) to offshore marine**
13	**Lower shoreface to upper offshore marine**
14	**Shallow marine (between fair-weather and storm wave base)**
15	**Lower shoreface to upper offshore marine**
21	**Offshore shallow marine**
22	**Offshore shallow marine**

INTERPRETATION

This facies was produced after a long period of erosion and non-deposition associated with lowstand or falling sea level, and commonly unconformably overlies Proterozoic basement and grades up into Cretaceous fossiliferous sandstones. The conglomerate grades up into sandstones of the Walker River Formation and is considered here as a basal part of the formation, although the conglomerate may be equivalent in part to the Gilbert River Formation (**9.1**).

Clasts in the basal part of the facies show features typical of fluvial deposition in their sorting, shape and roundness. The lack of fossils and imbrication in the lower and middle parts of the facies indicates deposition under nonmarine (high-energy fluvial) conditions. The normally graded aspect of the facies indicates a gradual reduction in flow-strength, probably concurrent with initial transgression and the beginning of marine deposition. According to Miall's (1985; 1992) architectural element classification of fluvial deposits, this facies probably corresponds to element GB (gravel bars and bedforms) and associated minor SB (sandy bedforms) elements.

The conglomeratic basal and middle parts of this facies are very similar to deposits termed basin-margin conglomerates (formerly fanglomerates) by Miall (1992). Such sheet or tongue like bodies, bounded at the base by regional disconformities, represent valley-fill deposits formed at times of low base level.

6.3 FACIES 3 - LAG

Conglomeratic and shelly lags are common in the Walker River Formation overlying regional discontinuites (unconformities, sequence boundaries, disconformities), and within individual marine facies successions (intraformational lags). Similar lags related to high-energy fluvial processes also exist in the Yirrkala Formation. Lags also occur in the top part of coarsening- and shoaling-upwards facies successions (upper lags) beneath marine flooding surfaces which define parasequence boundaries. Lags occur on all parts of the shelf, but are in greatest abundance in areas where marine deposition occurred between the upper shoreface and offshore transition zone within the influence of storm waves.

Basal lags in individual facies and facies successions are typically 0.2 to 0.75 m thick, with a maximum thickness of 2 m. Basal lags contain numerous components, may be weakly normally graded, and display subtle erosive reactivation surfaces defined by laterally continuous variations in clast size. Most basal lags are polymict clast-supported conglomerates, with a medium to fine sand matrix. Maximum observed clast size is 26 cm, though nearly all clasts fall within the pebble size range. Pebbles are mostly well-sorted, well-rounded and composed of quartzite, chert and other lithologies typical of McArthur Basin basement rocks exposed in northeastern Arnhem Land.

Rarely, basal lags are composed of shelly fossils, which are highly fragmented and chemically altered; only a diagenetic 'ghost' fabric is present. These factors limit precise taxonomic assignments, although most shelly lags are composed of low-diversity molluscan faunas. Shelly lags at the base of facies or event beds are thin (0.25 to 5 cm thick), may be graded, and tend to be laterally discontinuous over tens of metres. They are composed of well-sorted, densely packed layers of granular shell debris (fragments < 0.5 cm) in a matrix of quartz silt and sand, and may form amalgamated beds up to 10 cm thick.

Intraformational conglomeratic lags are common within the Walker River Formation, particularly in facies 15. Here, the lags are thin (0.5 to 3 cm), laterally continuous and crudely graded. The basal surface is erosional and the upper surface is commonly sharp and irregular. Clasts are matrix-supported and range from granule to mid-pebble size (maximum is 4 cm), with many clasts being small pebbles (Plate 2a). Clasts are moderately-sorted, well-rounded and composed of the same rock types as basal lags. Very rarely these intraformational conglomerates contain a few molluscan shell fragments.

Upper lags also form discontinuous lenses or pods, which are commonly associated with HCS beds and coarser-grained cross-stratified sandstone (facies 8 and 14). These lags have

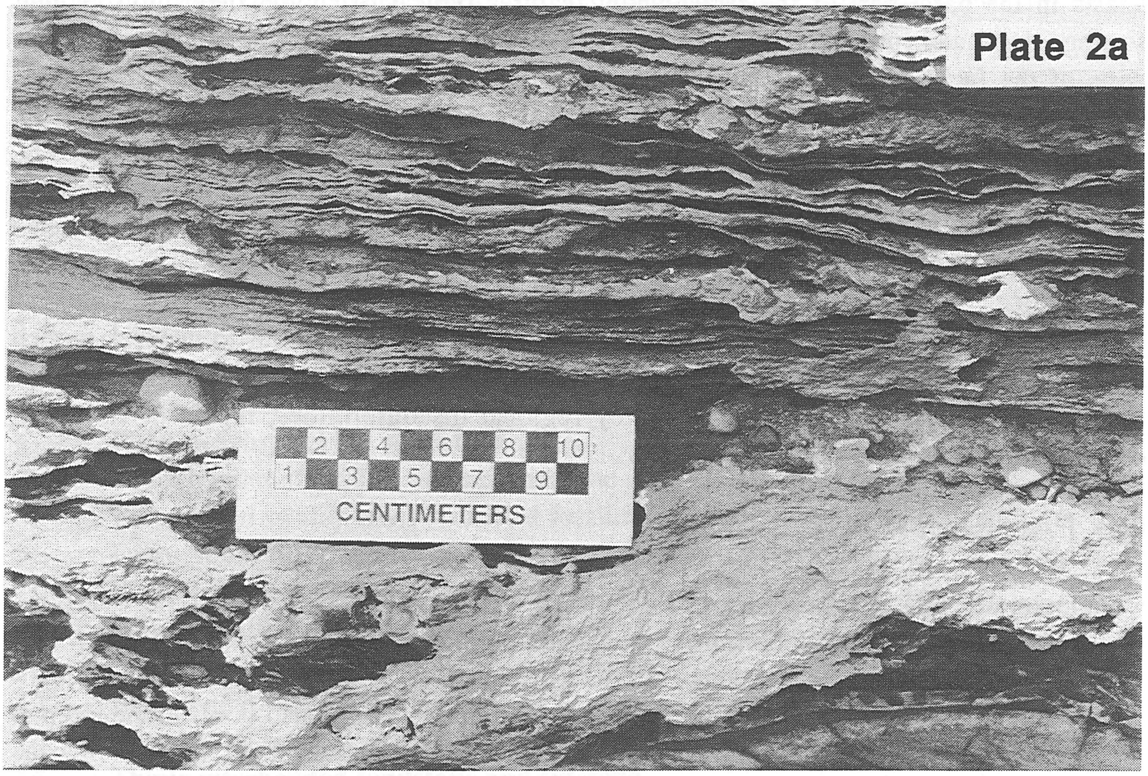


Plate 2a. Thinly interbedded rocks of facies 15, facies succession 2. Note the general wavy lamination and the thin matrix-supported intraformational pebble lag (facies 3) parallel to the top of the scale bar. Bath and Parsons Ranges Zone, section 154.

Plate 2b. Segmented plant fossil, external mould of a log, within poorly sorted coarse-grained quartz arenite of facies 6, facies succession 7. Bath and Parsons Ranges Zone, section 208-210.

a smooth, undulating or locally-erosional contact on HCS sandstone, and are confined to asymmetrical lenses up to 60 cm thick and 2 m long. Lags are clast-supported conglomerates, with well-sorted and well-rounded clasts composed of chert and quartzite. The maximum clast size is 6 cm and most clasts are middle-sized pebbles. Lags are crudely graded and may grade upward into coarse sandstone over a few centimetres.

Concentrations of shelly fossils form similar lags, but they are thin (< 2 cm thick), laterally discontinuous (< 1 m long), and less common. In some places they overlie large scale hummocky cross-stratified beds with an undulating contact, and only occur in large swales in the top surface of the underlying bed. These lags may be densely or loosely packed, and generally include well-sorted shell material, consisting of both whole valves and large fragments of broken valves. Occasionally they form shell pavements where disarticulated bivalves, both convex-up and convex-down, are stacked to form thin (< 5 cm) beds. Fossils within these swales do not show preferred orientation. Bioturbation is rare or absent in all lags, and only occurs in the finer-grained top of some graded lags, where *Arenicolites*, *Skolithos*, and rare *Thalassinoides* burrows have penetrated the matrix-rich part of the lag from above.

INTERPRETATION

Most lags within the the Walker River and Yirrkala Formations were formed in relation to changes in relative sea level during various stages of sequence development. Therefore, discussion and interpretation of the formation of all types of lags, including fluvial lags, is presented here with broad reference to sequence stratigraphic principles.

The formation of thin *basal lags* can be envisaged as occurring by one of three main processes:

1) by erosion in a fully subaerial setting following a major fall in relative sea level, in which case coarse-grained material would be transported across the shelf by incising streams;
2) by regional wave scouring in an open marine setting where a minor lowering of sea level results in wave erosion of the underlying marine substrate. Clasts incorporated in the lags could be derived both from erosion of underlying units, and from offshore-directed transport of coarse-grained shoreface conglomerate; and
3) by a combination of the first two processes; where initial erosion and lag formation is due to subaerial exposure during lowstand, and is followed by submarine (wave) erosion during transgression.

Thin basal conglomeratic lags were most likely formed by the third process, where a fall of relative sea level was followed immediately by a steady rise. Importantly, the coarse clastic component which accumulated during lowstand would remain on the unconformity as a transgressive lag and the transgressing shoreface would remove all(?) traces of subaerial exposure, *i.e.* soil, coal, desiccation cracks. Wadsworth and Walker (1991, p. 1517-1518) state that in this scenario "a shoreface would be expected to form at the point of maximum lowstand of sea level, before the transgression began". This is exactly what occurs within the Walker River Formation, where coarse-grained lowstand shoreface deposits occur on the distal part of the shelf, south of Arnhem Land.

In the ALZ, mineralised and brecciated horizons occur at the base of fining-upward rocks of facies succession 5. These mineralised and brecciated layers are regionally extensive and are similar in stratigraphic level to 'normal' conglomeratic lags at the base of similar successions in other areas. However, they are interpreted to have formed entirely by submarine erosion, and their fragments contain ferromanganese marine(?) cement. Possibly they represent marine hardgrounds at omission surfaces which were brecciated in situ by increased wave scour caused by minor falls in relative sea level, and were then passively filled-in by clayey sand during ensuing transgression.

In view of the interpreted low gradient of the shelf (Krassay, 1994), the most likely process for the development of *intraformational lags* is 'normal' marine transport and erosion on the shelf during stillstand or stable periods of sea level. The position of these lags within facies successions and their composition and lateral extent suggests that storm waves were occasionally capable of eroding the seafloor without a relative fall in sea level. Some thin intraformational lags contain only one major type, or size, of clast or skeletal material and probably represent true, single-event storm layers. This interpretation is supported by the normal grading of these beds, their upward change in stratification, and their association with small-scale HCS and interference wave-ripples, suggesting deposition of progressively finer sediment towards the top of the bed as flow strength waned (Krassay, 1994).

The process envisaged for widespread formation of numerous thin, laterally semi-continuous pebble lags *within* facies successions of the Walker River Formation has been described by Plint and Norris (1991). For a setting in the Alberta Foreland Basin similar to the Carpentaria Basin, Plint and Norris (1991) suggest that erosion by storm waves concentrated intraclasts, and moved chert pebbles several tens of kilometres out to sea in water that was only 10 to 20 m deep. This model is supported by the evidence for storm-deposition and/or reworking within intraformational lags of the Walker River Formation.

Upper lags tend to be thinner and less laterally continuous than basal lags or coquinas. Discontinuous lenses and pods of conglomerate at the tops of coarsening-upward facies successions are closely associated with HCS beds. Indeed, in many places their local distribution appears to be restricted to swales and erosional hollows in the underlying HCS beds. This suggests that after formation of HCS beds during waning storm conditions, the flow was probably incapable of moving pebbles significant distances, but was still able to concentrate pebbles in local topographic lows, *i.e.* the swales and hollows of the underlying HCS beds.

Some conglomerate lenses pass upwards into HCS beds or cross-bedded medium- to coarse-grained sandstone. This provides further evidence that the concentration of pebbles into discontinuous lenses in upper lags was not the result of long-term reworking due to a relative fall in sea level, but more likely was the result of reworking during peak and waning storm-stages or possibly between storms in regions with strong bottom currents. Similar interstratified lenses of conglomeratic lag and shelly lag associated with HCS beds, high-angle cross-stratified pebbly sandstone, and coarse-grained megaripples have been described in other storm-influenced shallow marine successions (Brenchley, 1985; Craft and Bridge, 1987; Dott and Bourgeois, 1982; Leckie, 1988; Nottvedt and Kreisa, 1987).

6.4 FACIES 5 - CROSS-STRATIFIED AND PLANAR BEDDED PEBBLY SANDSTONE

This facies occurs in association with facies 1, 6, and 7 in northeastern Arnhem Land, and typically is a few metres thick. The facies is composed of moderately to well sorted, subrounded, medium quartz sandstone and dispersed clasts. Clasts are poorly sorted, up to 10 cm in diameter, and are composed of chert and silicified sedimentary lithologies. The number of clasts decreases upward with a corresponding increase in the degree of sorting.

The base of the facies is typically conglomeratic and contains little matrix. Clasts at the base of the facies have the same composition as clasts dispersed throughout the facies, but are up to small cobble size. Trough cross-stratification with sets up to 1.2 m thick occur in coarse-grained parts of the facies. Finer-grained parts of the facies are planar bedded and contain high-angle planar cross-stratification with set thicknesses between 40 and 60 cm. In places the facies contains abundant segmented plant fossils and appears to be slightly bioturbated.

INTERPRETATION

This facies represents a fluvial depositional environment. Indicators of fluvial deposition include the relatively coarse grain size, the occurrence of these rocks within fining-upward facies successions, the poor degree of sorting, irregular conglomeratic intervals, the lack of marine fossils, and the lack of pervasive bioturbation. The scale and style of cross-stratification and the isolated, lenticular geometry of the outcrops also point to a fluvial origin. This facies corresponds well to facies Gm, Gt, Gp, St, Sp, and Sh of Miall (1985; 1992), which are grouped under GB (gravel bars) and CH (channel) architectural elements.

Coarser-grained parts of the facies represent a high-energy fluvial regime, possibly reflecting deposition in braided streams. Finer-grained intervals exhibit planar cross-stratification, and may reflect a decrease in energy in the fluvial system to meandering streams. The lack of any fine-grained (overbank or swamp) sediments may indicate that fine-grained material was held in suspension, and bypassed this region as it was transported out on to the marine shelf or to the basin centre. Alternatively, the lack of fine-grained facies may be due to their poor preservation potential because fine-grained facies were eroded during lateral accretion and fluvial reworking, or simply due to minimal fluvial aggradation due to a lack of accommodation space.

6.5 FACIES 6 - PLANT-BEARING PEBBLY SANDSTONE

This facies is restricted to the region surrounding, and enclosed by, the Bath, Parsons and Mitchell Ranges in northeastern Arnhem Land. It is particularly well exposed on the eastern side of the Parsons Range, where the facies is up to 50 m thick, unconformably overlies Lower Proterozoic McArthur Basin sediments, and constitutes a large part of the Yirrkala Formation.

Facies 6 is composed of thickly planar bedded, moderately to poorly sorted, rounded, clean, friable, coarse to medium quartz sandstone. The facies commonly occurs in fining-upward facies successions, contains little matrix and is only rarely stained by iron oxides. The base of this facies is typically a lag up to 0.5 m thick, which comprises a monomict, matrix-supported, poorly sorted, rounded to subrounded, quartzite pebble conglomerate. Some exposures display granule to large pebble sized, subrounded to rounded chert clasts. Rarely these clasts are confined to poorly defined zones or form the foresets of high-angle cross-stratification, which have set thicknesses up to 1.3 m. Trough cross-stratification commonly occurs in the coarse-grained part of the facies, and finer-grained parts may display asymmetrical current ripples (wavelength 8 to 10 cm; height 1 to 1.5 cm) and rarer intervals with bipolar (herringbone) cross-stratification.

The facies is typically not bioturbated but contains numerous segmented plant fossils on some bedding surfaces, and very rare unidentified trace fossils. The largest of these plant fossils are manganese-stained external moulds of logs up to 48 cm long and 9 cm wide (Plate 2b). Other fossils include seed pods, twigs, stems, and rare leaves.

INTERPRETATION

The depositional environment of this facies is probl ic. Most likely this facies was deposited in a fluvio-deltaic to estuarine setting, a gh it is difficult to distinguish between the products of these depositional settings.

The bulk of the facies reflects deposition adjacent to topographically-high Proterozoic ridges. Local mapping shows that most sand and clasts were derived directly from erosion of Proterozoic sedimentary basement lithologies. Many of the Proterozoic lithologies in the hinterland have mature to supermature textures. Therefore, erosion and redeposition of this material has resulted in Cretaceous units with normal fluvial-estuarine characteristics including poor sorting and coarse grain size, but an anomalous degree of roundness inherited from the basement. Even though the grains in this facies are rounded, they have probably only been transported a short distance during Cretaceous deposition.

This facies contains the fluvial Se, Sl, Sp and St facies of Miall (1985; 1992) and probably LA and SB architectural elements, which typify deposition in sandy meandering, stream systems. Here, palaeocurrent analysis of individual fining-upward sandbodies show dominantly uni-directional flow, although there is marked variation between units. The lack of bioturbation, the large scale cross-stratification with coarse foresets, and the presence of rare plant fossils also supports an interpretation of a fluvial depositional environment.

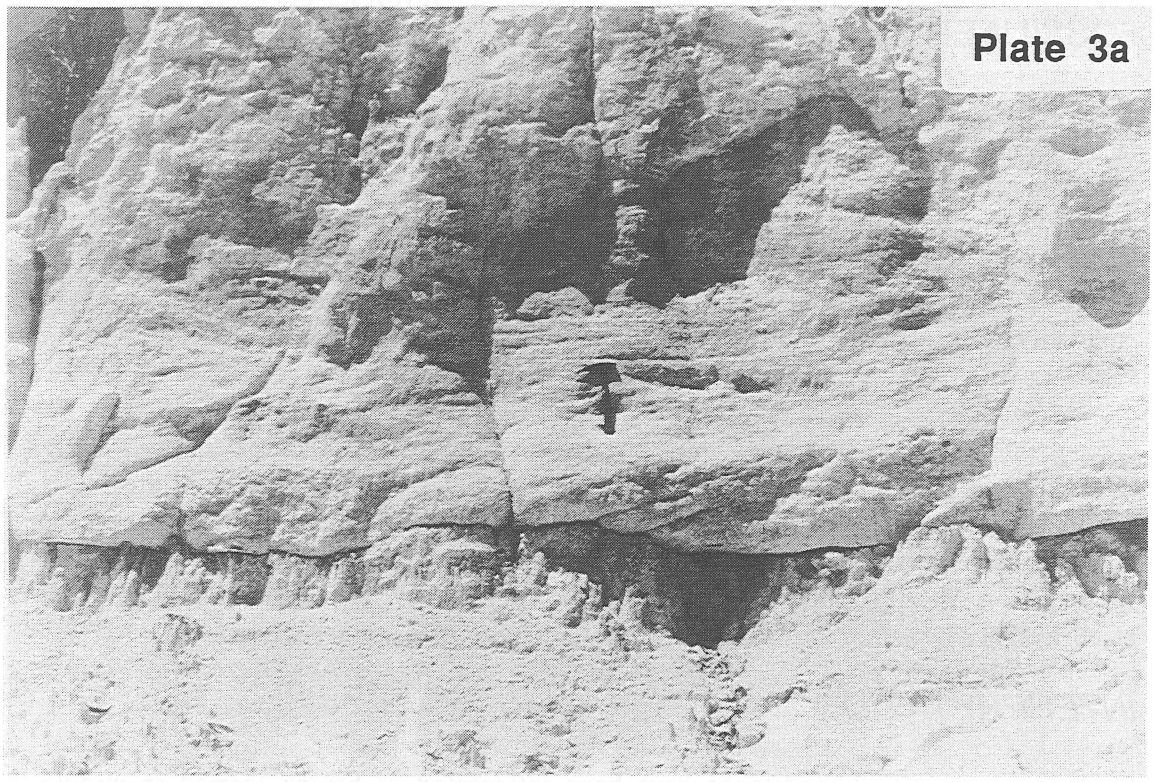
6.6 FACIES 7 - TROUGH CROSS-STRATIFIED COARSE SANDSTONE

This facies occurs in the ALZ and has a maximum thickness of 15 m. Typically facies 7 is unconformable on underlying marine units (*e.g.* facies 22), and is possibly a facies equivalent of facies 6 in the BPRZ. The facies consists of massive clayey, rounded, moderately sorted, very coarse- to fine-grained quartz sandstone, and is incorporated in fining-upward facies successions. Sedimentary structures include large-scale trough cross-stratification with set thicknesses up to 2 m (Plate 3a), and high-angle planar cross-stratification. The base of this facies is commonly erosional and features erosional cut out of underlying lithologies, rip-up clasts and rare erosional lags. The sandstone is friable and contains a large amount of pale orange to white clay matrix, and is highly stained or partially cemented by iron oxide in places. Body and trace fossils were not observed. The degree of weathering is typically high and in incipient lateritisation is apparent in places.

INTERPRETATION

Facies 7 has a lenticular or channel-like geometry and displays lateral accretion surfaces, which clearly indicate deposition in a sandy fluvial system, probably in meandering rivers. In some places the erosional base to this facies can be seen to cut out up to 10 m of underlying marine facies over a lateral distance of 90 m (Plates 3a and 3b). The nature of the erosional surface is highly irregular and suggests channel formation (with point bars) in a meandering pattern.

The poor sorting, coarse grain size, and the large scale trough cross-stratification suggest deposition in bedload or mixed-load streams. The lack of significant bioturbation and fossils also points to a nonmarine origin for this facies. The bulk of the facies corresponds to Miall's (1985; 1992) St and Sp facies, which reflect lower flow regime fluvial deposition in the form of dunes, bars or sand waves. These stacked facies form LA (lateral accretion macroform), SB (sandy bedform), and CH (channel) architectural elements (Miall, 1992).



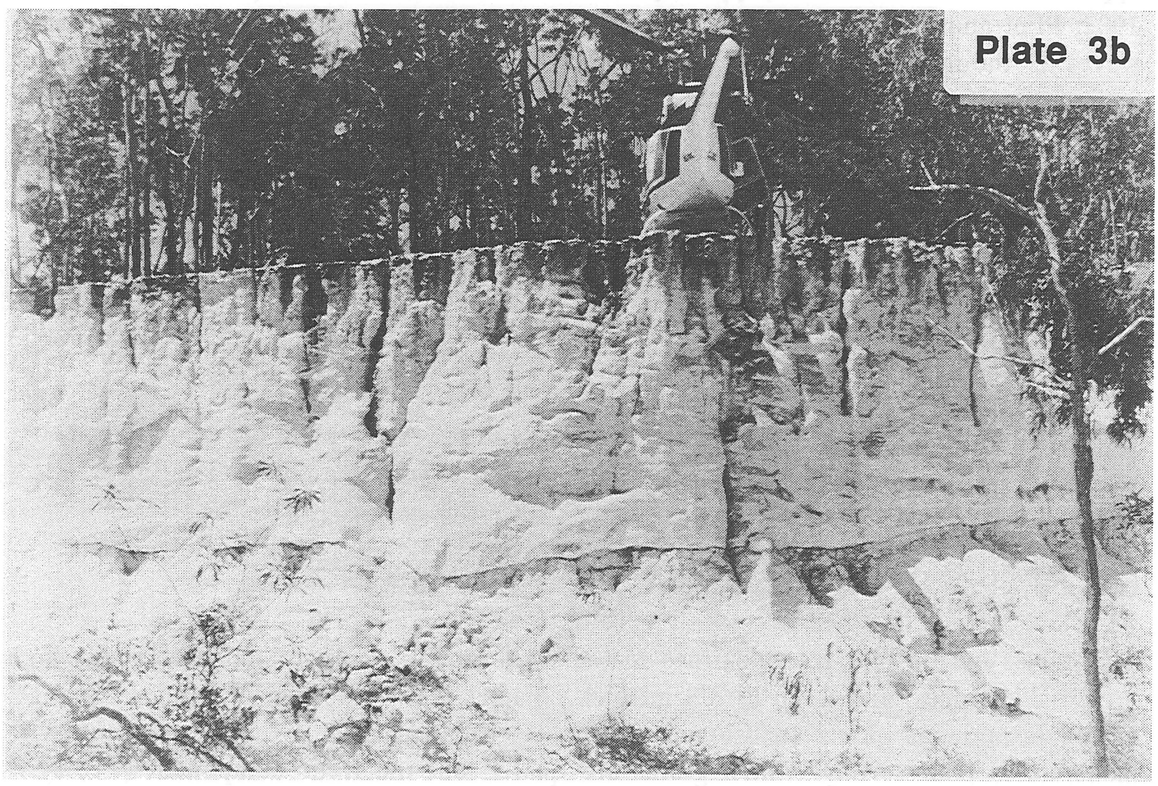


Plate 3a. Large-scale trough crossbedded sandstone of facies succession 7 (Yirrkala Formation) incised into fine-grained marine claystone of facies succession 5 (Walker River Formation). The erosional contact marks a regional unconformity and a sequence boundary (see plate 3b). Arnhem Land Zone, section 7. Hammer is 32.5 cm long.

Plate 3b. Outcrop-scale view of the erosional contact between the Yirrkala Formation (top) and the Walker River Formation (bottom). Note the irregular amount of erosional incision along the unconformity. Arnhem Land Zone, section 7. Helicopter for scale.

6.7 FACIES 8 - TROUGH AND SWALEY CROSS-STRATIFIED FOSSILIFEROUS SANDSTONE

This facies is well exposed in the ALZ and is commonly associated with coarse-grained facies (1 or 13). In places it is overlain by fluvial to marginal marine facies. Facies 8 occurs in proximal localities and consists of pale clayey, massive or thickly planar bedded quartz sandstone. Grains are typically well sorted, well rounded, and have a very coarse to medium sand size. The base of the facies is very coarse and displays small- to mid-scale trough cross-stratification; as grain size decreases internal stratification changes progressively to high-angle planar cross-stratificaton, and further to small scale trough and swaley cross-stratification (SCS) (Plate 4a).

Finer-grained parts of the facies show flat lamination and asymmetrical ripples, and rare coarse foresets with granule to very small pebble sized clasts. XRD analysis of this facies in proximal locations shows a mature composition of quartz with a kaolinite matrix containing minor muscovite/illite. Body fossils include trigonids, ammonites and bivalves. Bioturbation is apparently pervasive, but the lack of lithological contrast makes identification of specific forms difficult, although *Skolithos* was recognised.

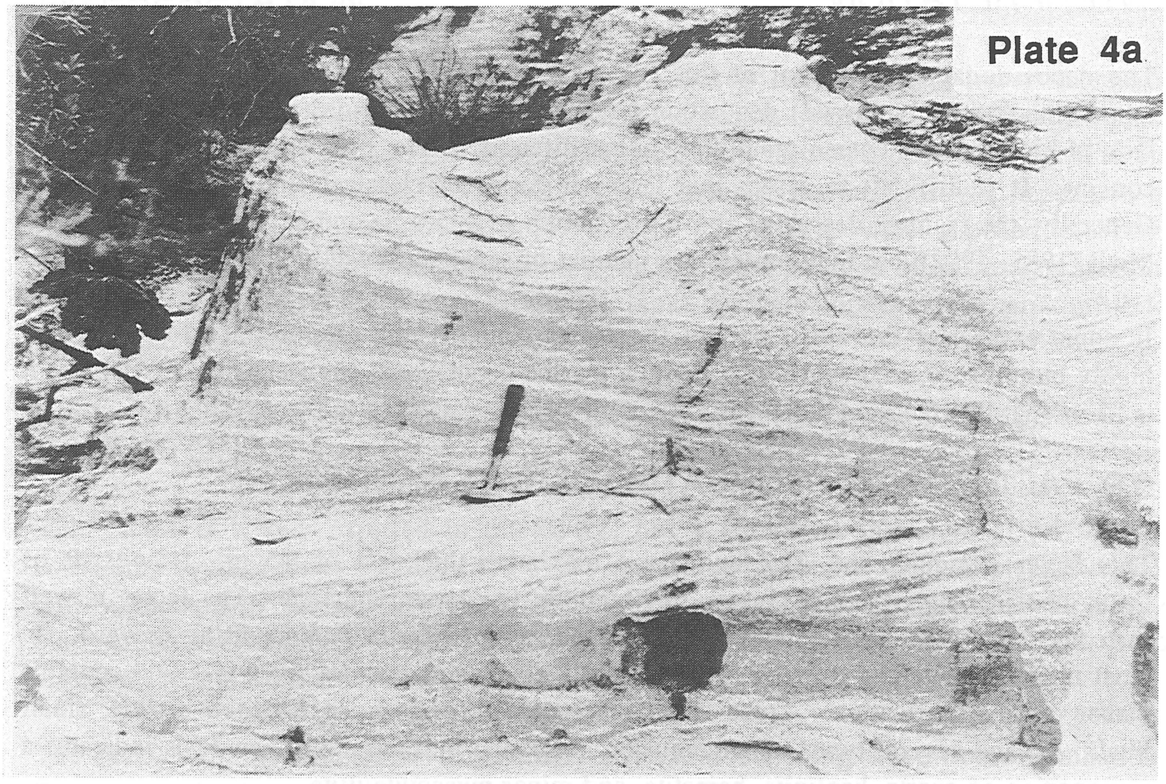
INTERPRETATION

Swaley cross-stratified sandstones have been interpreted as having formed in middle to upper shoreface environments, typically in about 5 to 10 m of water (Leckie and Walker, 1982; Plint and Norris, 1991). In this setting, reworking by both storm and fair-weather waves is thought to prevent the accumulation of mud, resulting in a very unstable environment inhabited by only a few well adapted infaunal organisms of the *Skolithos* ichnofacies. In some exposures of facies 8 flat lamination (formed by swash and/or backswash) is present and an even shallower (foreshore) depositional setting is inferred. The small- to mid-scale trough and high-angle cross-stratification in the coarser sand-sized intervals are characteristic of a high-energy upper shoreface position. Further, the high energy conditions of the middle shoreface to foreshore depositional environments are apparent from the low abundance and low diversity of trace fossils, which reflect the instability of the habitat.

The amount of matrix is high in proximal localities in the ALZ. Here the amount of matrix decreases down-section, and the matrix is interpreted to have formed by lateritisation and soil-forming processes rather than by primary deposition.

6.8 FACIES 9 - FERRUGINOUS LITHIC SANDSTONE

This facies occurs in a few localities in the ALZ on the flanks of topographically-high Proterozoic ridges, and is up to 8.8 m thick. Facies 9 is composed of massive, orange, friable ferruginous quartz sandstone. Grains are rounded, medium to coarse sand with moderate to poor sorting. Most grains are quartz, but the lithic component (<10%) is higher than that of other coarse-grained facies. Dispersed pebble-sized ferruginous, lithic clasts sometimes occur near the base of this facies, and the matrix is a pale clay with a small amount of ferruginous or manganiferous cement. Sedimentary structures are absent except for traces of planar cross-stratification in coarser-grained intervals of the facies, and the amount of bioturbation is insignificant.



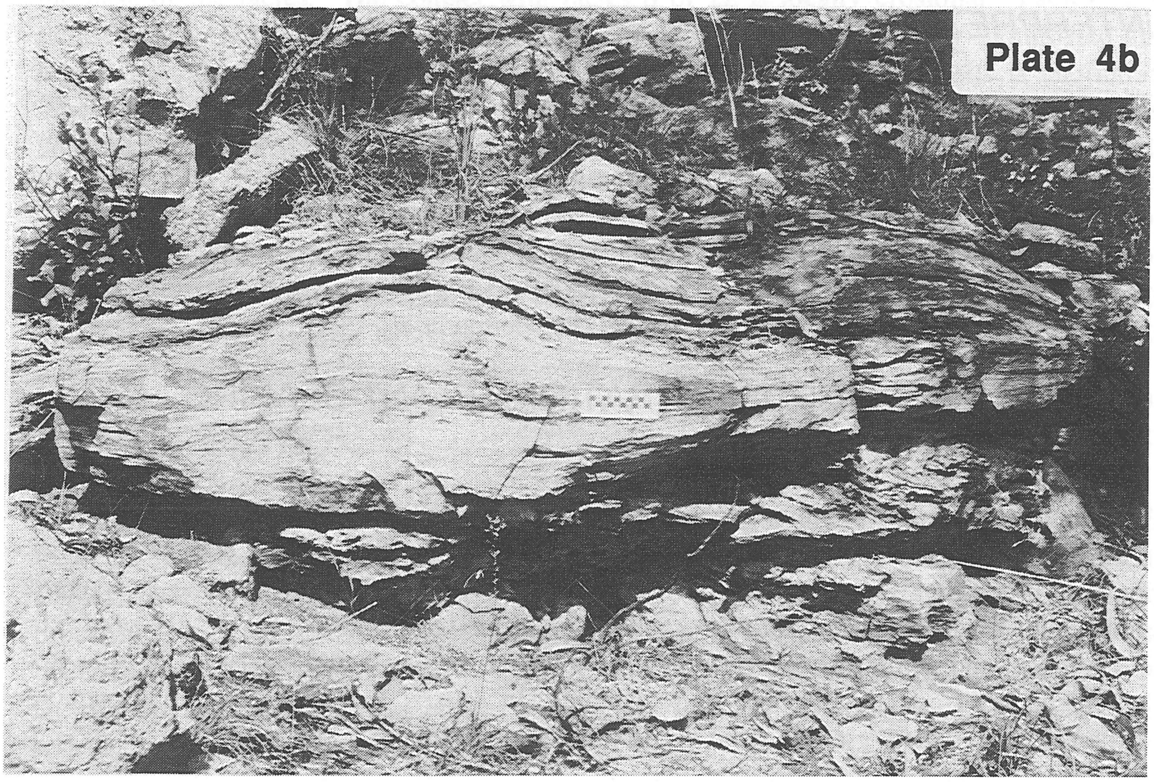


Plate 4a. Trough- and swaley- cross-stratified coarse-grained sandstone of the middle to upper shoreface. Facies 8, facies succession 5, Arnhem Land Zone, section 7. Hammer is 32.5 cm long.

Plate 4b. Large-scale hummocky cross-stratified fine-grained sandstone to coarse siltstone of facies 14, facies succession 2. Bath and Parsons Ranges Zone, section 148. White scale bar at centre right is 12 cm long.

INTERPRETATION

The depositional environment of this facies is not readily interpreted. Indicators of a nonmarine (probably fluvial) depositional environment in the northern region include the lack of bioturbation, coarse grain size, unfossiliferous nature, poor sorting, and high lithic content. It is difficult to assess this facies in terms of classical fluvial facies analysis. Generally, the features described above are similar to facies Se and Ss (scour fill facies) of Miall (1985; 1992), but may represent a number of separate fluvial architectural elements.

In some exposures the upper part of the facies contains rare marine trace fossils and is highly bioturbated; suggestive of a shallow marine depositional environment. Elsewhere, it is likely that this facies is dominantly fluvial in origin, especially in the ALZ.

6.9 FACIES 10 - BIOTURBATED CLAYEY SANDSTONE

This facies occurs in the ALZ and has a maximum thickness of 8.5 m. It consists of ferruginous, orange, friable, clayey, fine-medium to coarse sandstone. The facies is well sorted and moderately to intensely bioturbated, with bioturbation increasing upward. In most facies successions this facies has a gently coarsening-upward grain size and contains planar cross-stratification. Trace fossils include *Thalassinoides*, *Rhizocorallium*, small *Skolithos*, and several types of unidentified horizontal burrows. XRD analysis indicates a composition of quartz, kaolinite, hematite, and minor muscovite/illite.

INTERPRETATION

The coarse grain size, pervasive bioturbation, typically coarsening-upward character, and presence of marine trace fossils clearly indicate that this facies was deposited in a shallow-marine environment. The rarity of wave-generated features suggests that deposition occurred close to, or possibly beneath fair-weather wave base in a low to moderate energy environment. The presence of *Skolithos* burrows indicates that the environment was aerobic to dysaerobic and probably involved an unstable, sandy substrate which was only suitable for a low diversity, opportunistic ichnofacies (Pemberton *et al.*, 1992).

6.10 FACIES 11 - CROSS-STRATIFIED PLANT-BEARING SANDSTONE

This facies occurs in nearshore zones, especially in the BPRZ, and is commonly associated with facies 8 and 15. The maximum thickness is 9 m and the average thickness is 3 m. Facies 11 is composed of massive to very thickly planar bedded medium to fine quartz sandstone. Grains are subrounded to rounded, moderately to well sorted, and the sandstone is texturally and compositionally mature. Commonly the weathered sandstone is cemented by silica, but fresh samples are quite friable. In several localities the facies contains dispersed subrounded, granule sized clasts of cherty siltstone or quartz.

This facies displays planar cross-stratification with set thicknesses of 25 to 40 cm and is moderately bioturbated in most intervals. The foresets of some cross strata are defined by granule sized clasts. Rarely, poorly preserved asymmetrical current ripples and molluscan macrofossil impressions and trace fossils are evident in fine-grained parts of the facies. The most distinctive feature of the facies is the high abundance of plant fossils, including small segmented wood stems, 'fern-like' structures and seed pods. The plant fossils typically occur in the upper part of the facies and are rather poorly preserved as external moulds on silica-cemented bedding surfaces.

INTERPRETATION

This facies is very similar to facies 8 except that it is coarser, has a lower degree of bioturbation, has far fewer marine macrofossils, and has an abundance of segmented plant fossils in finer-grained parts of the facies. This facies may also be a facies equivalent to the upper part of facies 6. Facies 11 probably reflects brackish marine to fluvial deposition in the terrestrial-strandplain to foreshore, and is particularly well exposed close to topographically-high Proterozoic ridges. It is interpreted that much of the coarse material and plant debris was derived from fluvial input and erosion in close proximity to Proterozoic basement terrains.

6.11 FACIES 12 - FOSSILIFEROUS BIOTURBATED CLAYEY SANDSTONE

This facies is widely exposed in the BPRZ, has a maximum thickness of 14 m, and commonly overlies facies 8 or 22. The facies consists of massive to medium planar bedded, clayey, moderately sorted, subrounded, fine to fine-medium quartz sandstone with a silty clay matrix. In proximal locations the facies is slightly conglomeratic, containing dispersed clasts of chert and silicified fine-grained sandstone up to 1.5 cm in diameter.

The facies exhibits a range of sedimentary structures including wave-ripple lamination, flasers, rare flat lamination, escape burrows, dewatering structures, and very rare HCS near the base of the facies. The contact with facies 8 or 22 is locally erosional. Facies 12 is mottled, slightly friable, generally uncemented, and is invariably intensely bioturbated and highly fossiliferous. In some places the abundance and diversity of fossils is enormous, much greater than in other facies. Macrofossils include ammonites, trigonids, bivalves, unidentified vertebrate bone fragments, and a large range of segmented plant fossils. Trace fossils include *Rhizocorallium*, *Planolites*, *Arenicolites*, *Teredolites*, *Skolithos*, and possibly *Ophiomorpha*.

XRD analysis indicates that all samples of this facies are composed of quartz, kaolinite, and minor muscovite/illite and hematite. Petrological analysis shows that much of the clay in this facies was derived from the weathering of microcline(?) feldspar.

INTERPRETATION

The general lack of wave-generated sedimentary structures, the fining-upward grain size trend in many exposures, and the well preserved nature of many of the marine macrofossils suggest that this facies was deposited in a relatively quiet marine environment. Facies 12 probably reflects deposition in sheltered shallow-marine regions such as large bays. The trace fossils belong to the *Cruziana* ichnofacies, which is considered to be characteristic of an offshore shelf environment between storm and fair-weather wave base, or a shallower restricted marine setting (Pemberton and Frey, 1984).

In places intense bioturbation has destroyed the primary sedimentary fabric, and sedimentary structures are not preserved. This suggests that the seafloor was well oxygenated and able to sustain an abundant and diverse biota. In several places the abundance and diversity of preserved marine macrofossils is great, and finer-grained parts of the facies display delicate bivalve fossils, which are preserved with the two valves still joined. The delicate preservation of these fossils argues against significant transport, whilst the fossil abundance suggests local dense communities of living organisms.

6.12 FACIES 13 - BIOTURBATED SILTY SANDSTONE

This facies occurs on the eastern side of a palaeoembayment along the western margin of the Bath Range in the BPRZ. The facies has a maximum thickness of 5.5 m and only occurs where the basal Mesozoic chert conglomerate (facies 1) is missing.

The facies can be divided into several slightly different units, depending on position relative to the palaeoshoreline, but has an overall fining upward character in most facies successions. Lithologically it consists of slightly friable white to pale yellow, well to moderately sorted, subrounded to subangular, silica cemented, fine sandstone to coarse siltstone. The matrix is a pale, fine-grained clay with minor staining by iron oxides. The base of the facies has thick planar bedding, which changes upward to medium scale planar cross-stratification, to herring-bone cross-stratification, and finally to flat lamination, slump structures, and ripple lamination. Weathered exposures contain dark coloured limonite concretions up to 12 cm in diameter. Elsewhere, pale coloured, early-formed sedimentary concretions are occasionally present in the upper part of the facies.

The facies is moderately to intensely bioturbated throughout and contains numerous macrofossils including bivalves, trigonids, and scaphopods. Rare exposures display segmented plant fossils. In several cases the upper bioturbated bedding surface is highly cemented and was probably a firmground or a hardground. Trace fossils include *Planolites*, *Skolithos*, *Rhizocorallium*, *Palaeophycus*, *Thalassinoides*, and rare *Diplocraterion*.

INTERPRETATION

This facies represents marine deposition under a regime of increasing water depth in the lower shoreface to upper offshore region, as shown by an upward decrease in grain size and change in stratification. The coarser-grained base of the facies shows evidence of wave activity in the form of planar cross-stratification. The finer-grained top of the facies, with its trace fossil assemblage and fine lamination, indicates quieter marine deposition below fair-weather wave base. The facies is thoroughly bioturbated and contains abundant marine macrofossils and trace fossils of a mixed *Cruziana* and *Skolithos* assemblage. In the northern region the facies is interpreted as a distal facies equivalent of facies 9.

Concretions in the upper part of the facies suggest slow deposition in an intermediate to distal marine setting, possibly related to condensed sedimentation during highstand of relative sea level (*e.g.* Van Wagoner *et al.*, 1990). The high degree of bioturbation suggests that the water column was oxygenated and conducive to biological activity.

6.13 FACIES 14 - HUMMOCKY CROSS-STRATIFIED SANDSTONE

Hummocky sandy beds occur on the shelf in localities close to the interpreted palaeoshoreline, and are commonly associated with facies 3, 8, and 15. The facies is composed of fine sandstone to coarse siltstone exhibiting well preserved, small to large scale hummocky cross-stratification (HCS) (Plate 4b). Commonly HCS beds are 20 to 80 cm thick with individual sets 5 to 30 cm thick, but may form thicker amalgamated beds. Set wavelengths range from 0.75 to 6 m, with most HCS having a wavelength of 1 to 2 m. HCS beds contain parallel laminae which dip at angles of 5^0 to 12^0 in random directions. Reactivation surfaces between individual fine sandstone (HCS) beds are common and are highlighted by truncation of internal lamination. Laminae thickness increases towards the hummock crest in a characteristic hummock and swale pattern in three-dimensional view.

Flat lamination and low-angle lamination are commonly associated with HCS beds. The inclined low-angle (typically less than 5^0) cross-bedding surfaces have wavy or irregular bases, and in some outcrops it appears that cross-bedding grades laterally over tens of metres into small scale HCS. The tops of thick HCS beds or low-angle cross-bedded layers may have symmetrical ripples with a wavelength of 5 to 10 cm and an amplitude of 0.5 to 2 cm. The finer-grained tops of HCS beds occasionally display interference wave-ripples of a similar scale, and in some outcrops the interference ripples grade into symmetrical ripples along a single bed. Rarely, coarser-grained parts of the facies contain megaripples (*sensu* Leckie, 1988) with a maximum wavelength of 1.2 m and a maximum amplitude of 10 cm.

Event beds (up to 25 cm thick) with a thin granule or shelly base, normal grading, and a fine-grained rippled top are occasionally recognisable amidst amalgamated hummocky beds. Event beds are sometimes separated from HCS beds and other tempestites by a millimetre- to centimetre-thick bioturbated siltstone layer. The base of these graded beds display thin lags, small gutters and gutter casts, and complex erosional scours. Larger sand-filled gutters (up to 40 cm wide and 0.8 m long) tend not to be attached to any laterally continuous sandy bed, but are enclosed within siltstone. Commonly individual centimetre- to decimetre-thick sandy beds and event beds have abrupt lateral pinch-outs, or rapid lateral decreases in thickness. Rare sedimentary structures in this facies include dewatering structures and small scale trough-cross-stratification in medium- to coarse-grained parts of the facies. Trace fossils include *Skolithos*, *Diplocraterion*, and rare *Thalassinoides*.

INTERPRETATION

Facies 14 shows the most compelling evidence for storm-influenced shallow-marine sedimentation on the shelf. Storm features include HCS, event beds, megaripples, intra-formational lags, lateral pinch-out of beds, and wave-ripples on the tops of graded beds.

HCS has been reported from a large number of localities in a variety of shallow-marine environments, from the tidal flat to the inner shelf (Dott and Bourgeois, 1982), and is generally considered to have formed from oscillatory-dominant combined flow during the waning stages of storms (Nottvedt and Kreisa, 1987; Duke *et al.*, 1991). It has also been postulated that some variation of HCS may form in fluvially-dominated environments (Cotter and Graham, 1991). In storm-dominated facies successions of the Walker River Formation in northeastern Arnhem Land, the close spatial association of hummocky cross-stratified sandstone with marine shelly and conglomerate lags (facies 3) and offshore siltstone (facies 21 and 22) suggests a purely marine origin for HCS beds of facies 14. HCS beds occur to the northwest (shoreward) of offshore siltstone and to the southeast (seaward) of swaley cross-stratified shoreface sandstone (facies 8). This suggests that HCS beds were deposited below fair-weather wave base in the transitional zone between the middle to lower shoreface and storm wave base.

Associated with the HCS facies of the Walker River Formation are individual beds with abrupt lateral pinch-out, hummocky sandy event beds with a thin laminated or rippled silt-sized drape, sand-filled erosional gutters and megaripples; all of these features are typical of storm-dominated environments (Brenchley, 1985; Jennette and Pryor, 1993; Kreisa, 1980; Leckie, 1988). Lenticular micro-hummocky sandy beds occur where preservation of HCS bedforms is not complete, or where the amount of available sand was low. The intense nature of the bioturbation within the fine-grained tops of beds in facies 14 suggests low sedimentation rates and high rates of biological turnover between storms (*e.g.* Wheatcroft, 1990), and such stratigraphically-restricted intense bioturbation is a general characteristic of storm deposits (Dott and Bourgeois, 1982). Occasionally burrows can be seen to completely penetrate thin storm beds from above; this is typical of colonisation after episodic storms (Pemberton *et al.*, 1992).

6.14 FACIES 15 - THINLY INTERBEDDED SANDSTONE AND SILTSTONE

This facies is well exposed in the BPRZ and in the ALZ. The maximum thickness is 13 m and the facies is often associated with facies 3, 14, 21, and 22. Facies 15 is composed of centimetre- to millimetre-thick ripple laminated interbeds of clayey siltstone and coarser-grained rocks (Plate 2a), including sandstone, intraformational conglomerate, and fossiliferous sandstone.

In northern localities the sand content is great and interbeds tend to be 1.5 to 5 cm thick, but rare decimetre-scale interbeds are present. Sandstone- and siltstone-dominated intervals have a typical thickness of 0.5 to 2 m. Within each of these intervals the two units are thinly interbedded. The sandstone is composed of moderately sorted, rounded quartz grains with a pale coloured, very fine-grained clay matrix. Lithic grains are rare but granule to small pebble sized siliceous clasts sometimes occur near the base of the facies. The bases of thicker interbeds display load casts, scour and tool marks and thin lags, whilst the tops of beds have low-amplitude, straight-crested or interference wave ripples in places (wavelength 5 to 8 cm; amplitude 2 to 3 cm). Internal stratification comprises ripple cross-lamination with 1 to 2 cm-thick sets and erosional bases. Other prominent features are discrete lags with erosional bases and sharp tops, and rare gutter casts up to 20 cm wide, 25 cm thick and 50 cm long. Planar cross-stratification and small scale trough cross-stratification with set thicknesses of 8 to 15 cm occur locally where sandstone is medium-grained.

The tops of some siltstone interbeds contain symmetrical or asymmetrical current ripples with wavelengths of 8 to 10 cm and amplitudes of 0.5 to 1 cm, and spherical concretions up to 6 cm in diameter and 4 cm in height. XRD analysis of the siltstone identified quartz, kaolinite, hematite, and minor muscovite/illite as the components. Similar to other facies, feldspar is rare or absent. Lenticular sandy ripples (up to 17 cm long and 3 cm in height) with internal ripple cross-lamination are present in the middle part of the facies, and typically form semi-continuous layers where sets of ripples are partly separated by fine-grained drapes. Smaller sandy ripples or micro-hummocky bedforms are completely enclosed by clayey siltstone in finer-grained parts of the facies. Body fossils are rare within this facies, and are limited to fragmented, unidentified molluscan shells. The amount of bioturbation increases upward and well preserved trace fossils, including *Thalassinoides*, *Diplocraterion*, and rarer *Rhizocorallium* and *Planolites* occur at the contacts between interbeds.

INTERPRETATION

This heterolithic facies represents marine deposition in water depths between storm and fair-weather wave base in the lower shoreface to upper offshore zone. The facies shows a range of storm-generated wave and current features, which indicate that normal, quieter sedimentation was overprinted by episodic storm deposition.

Vertical changes in sedimentary structures and grain size within this facies indicate changes in wave and current energy. Relatively low energy sedimentation is indicated by lenticular ripples isolated in clayey siltstone (linsen), sets of ripple-laminated very fine-grained sandstone separated by clayey siltstone drapes (flasers), and amalgamated units of ripple-laminated sandstone with finer-grained drapes were deposited in higher-energy settings.

Load casts overlying reactivation surfaces at the base of interbeds indicate that deposition of beds was rapid, whilst thin lags suggest at least minor erosion of underlying facies.

Lenticular micro-hummocky cross-stratified beds and planar cross-stratified intervals with coarse-grained foresets attest to occasional vigorous storm currents, which were able to scour the sediment surface in deeper water. These structures are smaller and less continuous than those of facies 14. The trace fossil assemblage belongs to the *Cruziana* ichnofacies and is very similar to ichnofacies described in similar rocks of the Cretaceous Interior Seaway of North America (Pemberton and Frey, 1984; Pemberton *et al.*, 1992). Although burrows are common in facies 15, physical reworking of the sediment was the dominant process. The lack of pervasive bioturbation and the preservation of delicately laminated beds indicates that the infauna were unable to completely homogenise the sediment between storms.

6.15 FACIES 21 - INTENSELY BIOTURBATED SILTSTONE

This facies occurs throughout the field area, but is particularly well exposed in the BPRZ. Facies 21 commonly has a thickness of only a few metres and is typically associated with facies 15. Facies 21 consists of extremely bioturbated siltstone with few preserved sedimentary structures. Where bioturbation is less intense, flat lamination is the most common internal stratification; rare silty graded beds (< 1 cm thick), and convolute lamination are present. The top of the facies in proximal exposures contains very rare starved sandy ripples and micro-hummocky lenticular beds, but these are much smaller and less common than similar structures in facies 15. The degree of bioturbation is so intense locally that identification of individual trace fossils is difficult. However, rare *Planolites*, *Zoophycos*, and *Arenicolites* burrows are present, whilst the dominant trace fossil is small (1 to 2 mm diameter), silt-filled *Chondrites* burrows. Body fossils were not observed.

INTERPRETATION

This marine facies was deposited in distal regions that were generally beyond the influence of storm waves. The overall lack of wave-formed sedimentary structures suggests deposition beneath storm wave base, in deeper water than most marine facies (*e.g.* facies 8, 12, 13, 14, and 15).

Rocks of facies 21 are interpreted as largely the product of suspension settling of fine-grained clastic material in an offshore or transitional zone during periods of fair-weather. Fine-grained pelagic sedimentation was intermittently overprinted by coarser-grained sedimentation during large storms. The action of storms during accumulation of this facies was weaker than that affecting other facies, due to greater water depth and distance from the palaeoshoreline. The presence of very rare starved sandy ripples and micro-hummocky lenticular beds indicates disturbance of the seafloor by occasional vigorous storm currents, or deposition of thin tempestites in a distal setting. Convolute lamination within siltstone in slightly coarser-grained parts of the facies suggests rapid deposition by settling of suspended material after episodic storms.

The intense nature of the bioturbation (*Cruziana* ichnofacies) is a distinctive feature of this facies, and the presence of such abundant infauna suggests deposition under mostly aerobic to slightly dysaerobic conditions in the lower offshore zone (Pemberton *et al.*, 1992). However, the dark colour of much of the facies suggests at least intermittent deposition in dysaerobic to anaerobic bottom waters. The relative abundance of *Chondrites* burrows in most exposures also supports the interpretation of intermittently dysaerobic to anaerobic bottom waters, because the *Chondrites* ichnogenera has a relatively high tolerance to depressed oxygen levels (Ekdale and Mason, 1988). These apparent changes in bottom water oxygenation may have been enhanced or caused by vigorous circulation during and after large storms.

6.16 FACIES 22 - SILTY CLAYSTONE

This is an important facies for regional correlation and occurs at numerous localities in the BPRZ, and at a few localities in the ALZ. Facies 22 is typically 1.5 to 2 m thick with a maximum thickness of 4 m, and is commonly associated with facies 15 and 21.

In proximal localities facies 22 consists of clayey fine siltstone, and in intermediate to distal localities the facies consists of silty claystone. The facies is usually massive, and internal stratification such as flat lamination is poorly preserved due to intense bioturbation. Many exposures of this facies display irregular, discontinuous streaks or small lenses, usually less than 5 cm in diameter, where fine sand to fine granule sized grains are concentrated without a large amount of clay matrix. These streaks or lenses are sometimes stained or cemented by iron oxide and have a distinctive purple to dark red colour. Coarser-grained parts of the facies contain small scale HCS and wave-ripple lamination. XRD analysis shows the facies comprises quartz, kaolinite, and minor muscovite/illite. Facies 22 has not yielded macro- or micro-fossils, and the degree of bioturbation is typically so intense that most trace fossils have been obliterated. However, the basal part of the facies contains *Rhizocorallium* and *Planolites* burrows and the upper bedding surface forms a *Skolithos* burrowed hardground in some localities.

INTERPRETATION

Pervasive homogenisation by a burrowing infauna has destroyed most evidence of primary sedimentary structures in this facies. However, the rare HCS and wave-ripple lamination suggest that sedimentation was partly controlled by episodic storms. It seems likely from the fine grain size, trace fossils, and the high degree of bioturbation that this facies was deposited in an open-marine setting in well oxygenated bottom waters. The general lack of wave-formed sedimentary structures suggests that deposition occurred in the offshore zone beneath fair-weather wave base.

The light colour of the facies and the high degree of silicification indicate that this facies has undergone intense weathering and chemical diagenesis. The presence of pods and stringers of sand to small granule sized clasts possibly suggest selective bioturbation and concentration of coarse-grained storm-transported debris by abundant infauna.

6.17 FERRICRETE 1

Ferruginised or lateritic plateaus and tablelands are well exposed throughout northeastern Arnhem Land. Ferricretes are the most common component of these landforms, but in places true laterites are present and show a distinctive vertically-zoned deep weathering profile. Ferruginisation of sandstone at Cape Arnhem (about 10 km east from the nearest outcrop of ferricrete 1, and 5 to 10 km southeast of the nearest known bauxite deposit) has been tentatively dated as Late Cretaceous (M. Idnurm, pers. comm., 1994). Moreover, other lateritic profiles or ferricretes are considered to be Cretaceous in age by correlation (Bardossy and Aleva, 1990) because they are directly related to Cretaceous rocks of the Yirrkala Formation (their parent lithology). However, many of these ferricretes and other weathered zones probably formed in Tertiary time. The development of ferricrete partly depends on the nature of the underlying parent material, and in this sense the presence of ferricrete, ferruginous hardpans or other resistant duricrusts as a cap overlying particular Cretaceous facies can be useful for correlation on a local scale.

This unit is the more common of the two ferricretes recognised in northeastern Arnhem Land during this study and consists of lithic and ferruginised clasts set in a matrix of ferruginous clay, silt and sand. It has a maximum thickness of 5 m. The clasts are granule to mid-cobble size, poorly sorted and rounded to subrounded. Clasts are composed of ferruginised sandstone and other unidentifiable, highly weathered lithic fragments. The matrix is very poorly sorted and highly variable in composition; the main matrix type is subrounded, poorly sorted, argillaceous, ferruginous, coarse to fine quartz sand. In places the unit is cemented or intensely stained by iron oxides and manganese oxides with a porous, mottled texture, which resembles a fine boxwork. Primary sedimentary structures are absent.

INTERPRETATION

Ferricrete 1 represents a ferricrete or ferruginous hardpan, and it appears that parts of the horizon have been brecciated by mechanical surface weathering and short-distance (in the order of metres) lateral transport before the fragments were again cemented by iron oxides.

The ages of initial ferruginisation and subsequent reworking and cementation associated with this unit are difficult to assess from this regional study. Indeed, it is likely that this ferricrete is not associated with any particular geomorphic surface or event, but rather occurs where conditions were suitable for iron accumulation and hardening (*e.g.* Pain and Ollier, 1992). In places the base of the unit exhibits a brown/purple mottled 'boxwork' texture which is characteristic of deep weathering and ferruginisation in humid climates (Bardossy and Aleva, 1990). This weathering profile shows varying degrees of mechanical reworking and chemical reconstitution. It appears to occur in lower lying regions than the overlying weathered horizon (ferricrete 2), and in many places ferricrete 1 is found in gradational contact with the underlying Yirrkala Formation.

6.18 FERRICRETE 2

This unit also occurs in the northern part of the ALZ, but is not as widely exposed as ferricrete 1. It has a maximum thickness of 5 m and consists of massive or pisolitic, strongly cemented ferruginous sandstone or lithic debris. Where cementation is less intense, concentrically zoned pisoliths with a poor to moderate degree of sorting are preserved. The matrix is commonly iron-oxide stained, clayey, lithic, quartz sand of variable grain size. The unit varies in colour from brick red to a blackish-red, depending mainly on the type and amount of cement. In rare exposures the facies has a ferromanganese or manganese oxide cement. Sedimentary structures are absent, but weathering features are present, including solution pipes and soil pisoliths.

INTERPRETATION

This unit is considered to be a residual weathering profile and forms a duricrust in most exposures. In most areas it can be classified as a ferricrete, although to the north superficially similar landforms form true bauxites, and are currently being mined in the vicinity of Nhulunbuy in the northeastern corner of Arnhem Land.

7. FACIES SUCCESSIONS (lithofacies stacking patterns)

This section is designed to incorporate the detailed facies descriptions of the previous section with vertical facies stacking patterns to describe facies successions that occur over the entire study area. Correlation of these facies successions (**8**) forms the basis for interpretation of local and semi-regional depositional environments, and allows construction of composite sections for Cretaceous rocks in northeastern Arnhem Land. Information concerning the distribution and nature of facies successions is then combined with correlations using specific marker horizons and biostratigraphy (extrapolated from regions to the south) to create a regional lithostratigraphic framework.

The vertical facies successions described below are based on observations of repeated and systematic facies relationships in outcrop and core, not only from northeastern Arnhem Land, but along the entire western and southwestern margins of the Gulf of Carpentaria in the eastern Northern Territory and northwest Queensland. Facies successions described below represent distinct two-dimensional lithofacies assemblages. Mapping and correlation of facies successions adds the third dimension, and indicates that some facies successions tend to occur together while others are mutually exclusive.

Most facies successions on the Carpentaria Basin shelf are less than 10 m thick and are commonly bounded by discontinuities, such as marine flooding surfaces, transgressive surfaces of erosion, and sharp based channels (regressive surfaces of erosion). The contacts between facies within a succession are typically gradational, although local erosion and minor surfaces of reactivation are common. Repeated vertical stacking of thin discontinuity-bounded successions on the Carpentaria Basin shelf has resulted in a stratigraphically and sedimentologically complex sequence which exhibits multiple facies changes.

Eight distinct facies successions have been recognised in the Walker River and Yirrkala Formations (only five of these occur in northeastern Arnhem Land), and they follow three basic patterns: 1) coarsening-upward or (sandier-upward) successions; 2) fining-upward successions; and 3) irregular successions (Table 2). The interpretive titles of the successions are discussed in the individual descriptions below. Measured sections showing typical outcrop examples of each facies succession and their important variations are illustrated in stratigraphic correlation diagrams (**8**), and symbols used in the measured sections are shown in Fig. 6.

7.1 DEFINITION AND CONCEPTS

Most workers dealing with the stratigraphic and sedimentological analysis of siliciclastic strata by outcrop, divide a sedimentary package into a number of lithofacies, which are largely descriptive and have only a brief environmental interpretation assigned to them. One then looks for repeated vertical and lateral patterns of organisation in these facies, and defines these patterns by documenting facies trends. In this study, facies successions are used to document the main variations within the Cretaceous rocks of northeastern Arnhem Land (Fig. 7).

A facies succession is defined as "a vertical succession of facies characterised by a progressive change in one or more parameters..." (Walker, 1992, p. 2). The concept of a facies succession implies that certain facies properties change in a specific direction (vertically and/or laterally); these properties might include the proportion of sand, the amount of bioturbation, or the grain size of the sand. It is implied that the facies are

FIG. 6

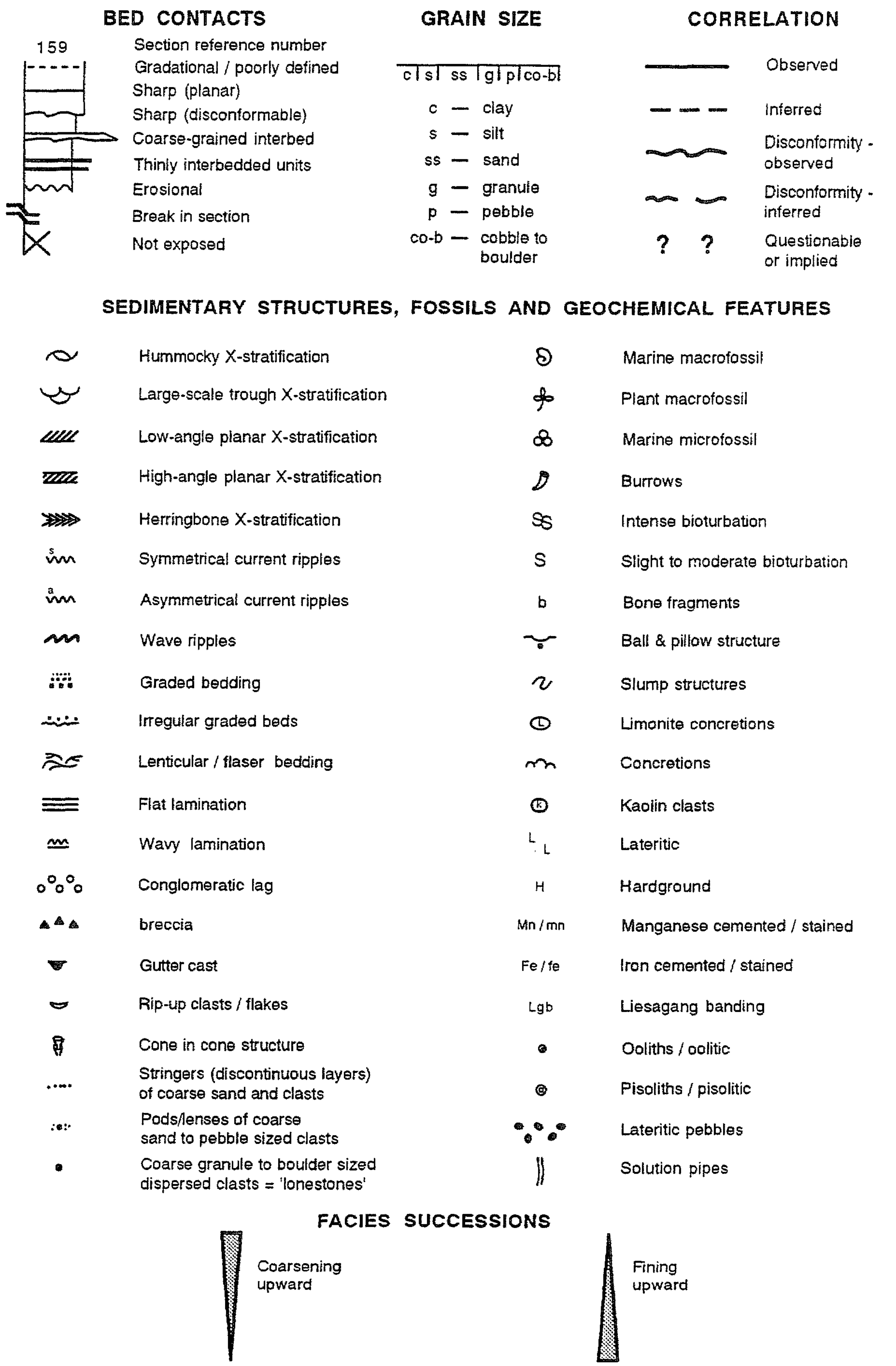


FIGURE 6. Symbols used in measured sections and composite sections of the Walker River Formation and Yirrkala Formation.

FIG. 7

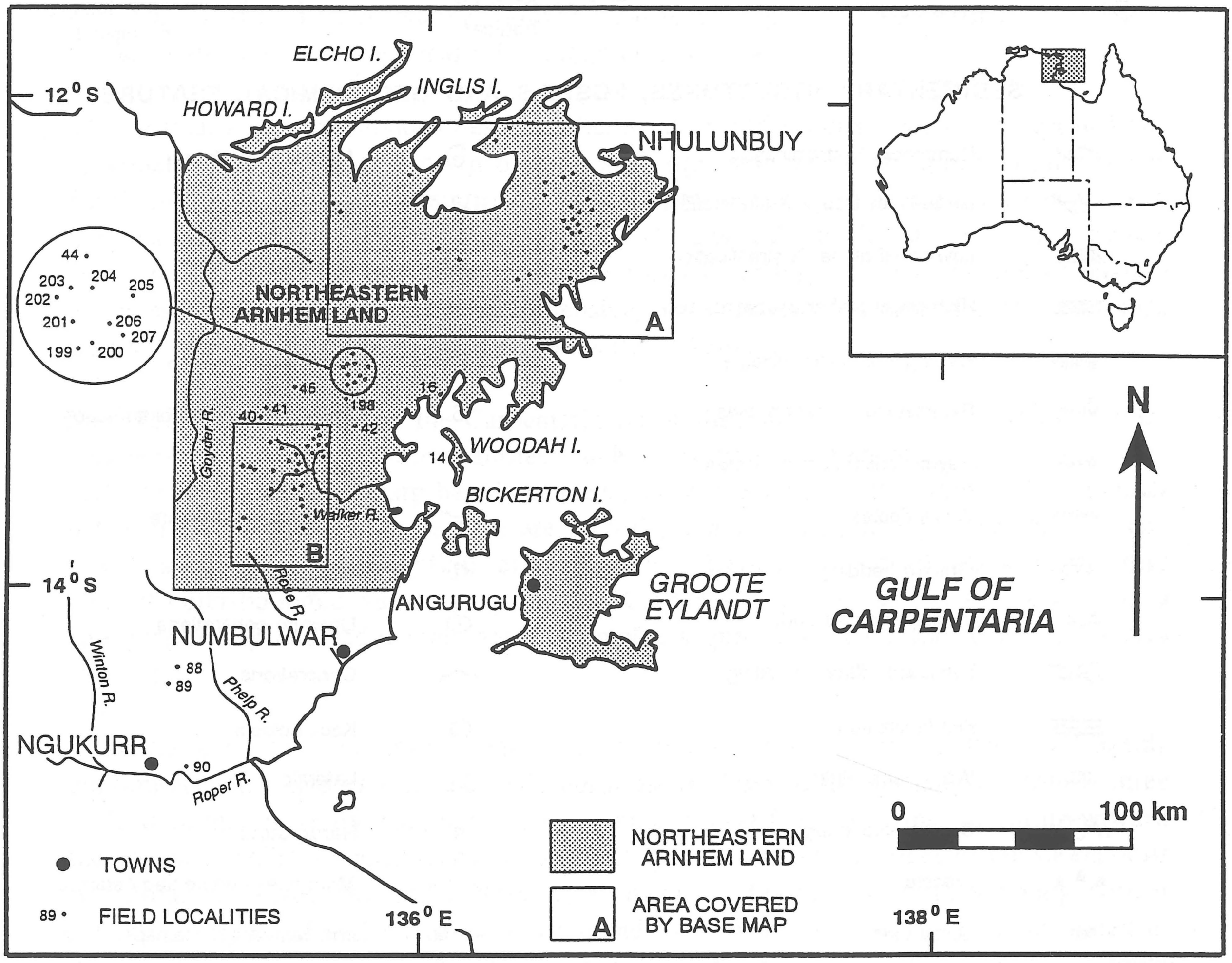


FIGURE 7. Location map for northeastern Arnhem Land. Numbers correspond to individual field localities. Base map A area corresponds to the Arnhem Land Zone (ALZ). Base map B area corresponds to the Bath and Parsons Ranges Zone (BPRZ). Numbers for field sites within the area covered by the base maps are presented on more detailed maps in Appendix 2 and Appendix 3.

genetically related inasmuch as particular sedimentological characteristics are progressively changing throughout the succession; for example, grain size might be gradually increasing, and there might be a change upward from dominantly biologically formed structures to physically formed ones.

TABLE 2. Cretaceous facies successions in northeastern Arnhem Land. Missing successions in the numbered sequence do not occur within northeastern Arnhem Land. WRF = Walker River Formation; YF = Yirrkala Formation.

	FACIES SUCCESSION	FACIES STACKING (from base to top of succession)
2	**Storm- (and wave-) dominated shoreface (typically prograding) (WRF)**	**coarsening-upward (22/21-13-12/15-14-8/3)**
5	**Storm- (and wave-) dominated shoreface (typically retrograding) (WRF)**	**fining-upward (3-8-12/15-14/13-21/22)**
6	**Paralic systems (estuarine and deltaic-marine) (WRF)**	**fining-upward (variable)**
7	**Fluvial channel fill (YF)**	**fining-upward (1/2-5-7/11-6)**
8	**Bay / lagoon (sheltered / restricted marine) (WRF)**	**irregular (10/12-13)**

7.2 COARSENING- (AND SANDIER-) UPWARD FACIES SUCCESSIONS

7.2.1 Facies Succession 2 - storm- (and wave-) dominated shoreface (typically prograding; Walker River Formation)

The northern part of the shelf is sand-dominated, and measured sections in these areas commonly consist of numerous coarsening-upward successions with thicknesses of 3 to 6 m. The base of succession 2 consists of fine-grained silty claystone (facies 22) or siltstone (facies 21), which commonly overlies coarse-grained marine sandstone of an underlying facies succession with a disconformable contact. The grain size increases upward as the basal facies grades smoothly upward into coarser siltstone of facies 13. The grain size continues to increase toward the top of the succession and silty sediments are gradationally overlain by fine-grained sandstone (facies 12), or interbedded sandstone and clayey siltstone (facies 15). These two facies form the bulk of succession 2.

The heterolithic facies (15) is commonly overlain by hummocky cross-stratified fine sandstone and coarse siltstone (facies 14), which is typically less than 2 m thick. The contact between facies 14 (if present) and facies 15 is sharp and commonly erosional on a small scale. The grain size increases rapidly upward from this part of the succession to medium-coarse sand (facies 8). The contact between facies 8 and facies 14 or 15 is locally erosional and the base of facies 8 sometimes displays a thin pebble to granule sized lag. The top of the succession is marked by a discontinuous conglomeratic lag or coquina (facies 3). Thus the basal and intermediate parts of succession 2 are smoothly coarsening-upward, and the upper part displays increasing grain size with one or two rapid 'jumps' across sharp contacts between facies.

The upward change in physical sedimentary structures is readily apparent in succession 2. The basal claystone and siltstone facies (22 and 21) are intensely bioturbated, but contain some preserved structures where biological reworking has been less intense; these include flat lamination, small scale wave-ripple lamination, and starved sandy ripples.

The middle part of succession 2 consists of facies 15 and sedimentary structures change upward from lenticular ripples isolated in clayey siltstone (linsen), through sets of ripple laminated, very fine-grained sandstone separated by clayey siltstone drapes (flasers), to amalgamated units of ripple laminated sandstone with rare finer-grained drapes and sand-filled gutters in the upper part of facies 15 (*e.g.* sections 149 and 178, **8.3.4**). In places intermediate parts of the succession consist of facies 13 and 12, and flat lamination and wave-ripple lamination change upward into very rare small-scale HCS, thin discontinuous pebble beds, and rare flaser bedding (*e.g.* sections 168 and 176, **8.3.4**). Fine sandstone and coarse siltstone (facies 14) overlying the intermediate part of the succession contain thick, amalgamated beds with hummocky cross-stratification. The top of the succession may contain coarser-grained intervals with megaripples and planar-, swaley-, and trough- cross-stratification. The fine-grained drapes of some of these coarse-grained beds contain current ripples and micro-hummocky cross-stratification. Lags at the top of succession 2 are unstratified and occur as discontinuous pods and lenses, which appear to have random shapes and orientation.

The degree of bioturbation is moderate to intense throughout the succession, with the most intense bioturbation at the base. The basal facies (21 and 22) do not contain any preserved macrofossils, but trace fossils such as *Thalassinoides*, *Diplocraterion*, *Rhizocorallium*, *Planolites* and *Arenicolites* are recognisable. In coarser-grained sections the intermediate part of the succession (facies 12 and 13) contains some macrofossils including bivalves, trigonids and rare scaphopods. Trace fossils here include *Planolites*, *Skolithos*, *Rhizocorallium*, *Palaeophycus*, *Thalassinoides*, and rare *Diplocraterion* and *Teichichnus*.

In finer-grained sections the amount of bioturbation increases upward in the interbedded part of the succession (facies 15), and well preserved trace fossils occur near the contacts of silty and sandy beds. The clayey siltstone beds invariably exhibit a higher degree of bioturbation than the sandy beds and contain the same trace fossils as the basal part of the succession. Hummocky cross-stratified beds are generally not bioturbated, except where their drapes consist of intensely bioturbated siltstone and claystone. The upper part of the succession (medium to coarse sandstone) contains rare body fossils including bivalves, trigonids and ammonites, and rare segmented plant fossils; bioturbation here is apparently pervasive, but the lack of lithological contrast makes identification of specific forms difficult. Lags at the top of succession 2 may contain rare molluscan macrofossils, but are not bioturbated.

Interpretation

Facies succession 2 is interpreted as the deposit of a typically prograding storm- and wave-dominated shoreface. The succession represents marine deposition under a regime of decreasing water depth, in the offshore to foreshore zone. Most examples of this succession contain both storm- and wave-generated structures. Whether a single example of this succession is storm- or wave-dominated depends largely on location relative to the palaeoshoreline and on the type of exposure. Fining-upward storm-, wave-, and combined storm- and wave-dominated successions have been grouped together here.

In coarser-grained examples of this succession individual beds are relatively thick and contacts between facies are distinct. This type of succession occurs in nearshore localities, where wave reworking of the sediment was a continual process. Under these conditions the succession is dominated by structures formed under fair-weather conditions, because most storm-generated features were subsequently obliterated by 'normal' wave reworking. Storm-generated features are present, but they are normally restricted to the lower (deeper water) parts of the succession. Finer-grained examples of this succession were deposited in slightly deeper water, commonly between fair-weather and storm wave base. Characteristic features here include interbedding of fine and coarse layers, large scale wave and current bedding (HCS) and scours (gutters), and normally graded beds. Storm-generated features dominate this type of the succession and are preserved due to the offshore shallow-marine location.

Facies 21 and 22 at the base of the succession show a high degree of bioturbation with numerous trace fossils of the *Cruziana* ichnofacies, and represent a marine environment with dysaerobic to aerobic bottom conditions. Bioturbation has obliterated any sedimentary structures, but the fine grain size of the facies suggests deposition in a relatively quiet marine setting in the offshore to lower shoreface zone. The interbedded facies (15) shows a range of features which indicate that normal, quieter sedimentation was overprinted by episodic storm deposition. Lenticular micro-hummocky beds, cross-stratified beds, ripple laminated beds, and gutters were sporadically formed in facies 15 by storms. The vertical changes in sedimentary structures and grain size within this facies indicate an upward increase in wave and current energy.

Sedimentary structures indicate that after deposition of the basal part of the succession, areas of offshore marine mudstone were first invaded episodically by HCS sandstones deposited during storms. As the shoreface aggraded and prograded the sediment surface built gradually upward, until it was affected by stronger wave energies, storm waves being the most energetic. With continued shallowing more and more storm events affected the beds, and more deposits were preserved, culminating in amalgamated HCS sandstones of the upper offshore to middle shoreface. Crossbedding is preserved in coarser sandstone of the upper shoreface. Discontinuous lags and coquinas are common near the top of the succession and testify to reworking of the upper part of the succession by large storm waves and currents. In proximal localities the upper half of the succession is dominated by cross-stratified medium to coarse sandstones, and HCS and other storm generated structures (*e.g.* gutters, graded beds, interference ripples) were not formed or preserved here.

With continued shallowing, the sea floor was affected by higher and higher energy processes and thick, amalgamated sandstone beds with hummocky cross-stratification were formed. The hummocky bedforms have a long wavelength and low amplitude and attest to the presence of large waves (Dott and Bourgeois, 1982; Duke *et al.*, 1991). Discontinuous lags at the top of the succession rarely contain any fine-grained sediment due to winnowing and reworking under maximum energy conditions during storms. At proximal localities more and more crossbedded d)osits were preserved as grain size increased upward, culminating in swaley cross-strat..ied (SCS) sandstones of the lower shoreface. However, well-preserved SCS is rare within the Walker River Formation. At some localities cross-stratification is overlain by flat lamination (produced by swash and backswash) characteristic of the beach.

Nonmarine facies with root traces or coal were not observed in succession 2. This suggests that the succession was not subaerially exposed, or that subsequent erosion of the nonmarine facies was common. The successions were probably only rarely emergent, because erosion is unlikely to have removed all traces of nonmarine facies at the top of succession 2 at all localities. Beach (foreshore) lamination is relatively rare and this indicates that the succession typically accumulated in water depths no shallower than the middle / upper shoreface.

7.3 FINING-UPWARD SUCCESSIONS

7.3.1 Facies Succession 5 - storm- (and wave-) dominated shoreface (typically retrograding; Walker River Formation)

Facies succession 5 occurs throughout the study area and exhibits a smooth, continuously fining-upward grain size trend. It has a maximum thickness of 7.5 m and an average thickness of 4 to 5 m. This succession contains many of the same facies as succession 2 and displays similar lateral trends. The main difference between succession 5 and succession 2 is the upward change in grain size; succession 5 is fining-upward and succession 2 is coarsening-upward. Most other differences between these two successions can be related to vertical differences in grain size.

Facies succession 5 commonly begins with a thin conglomeratic lag (facies 3), or more rarely a sedimentary breccia. The conglomeratic lag consists of poorly sorted, rounded lithic clasts up to mid-pebble size. Occasionally this lag has a ferruginous and/or manganiferous cement. This facies passes gradationally upward into very coarse-grained sandstone of facies 8. As the grain size decreases upward over several meters, trough cross-stratification gives way to swaley cross-stratification and small scale planar cross-stratification in fine-medium sandstone (facies 12), and hummocky cross-stratification in coarse siltstone and fine sandstone (facies 14).

In finer-grained sections interbedded sandstone and siltstone (facies 15) occur above the coarse sandstone, and facies 12 is thin or missing (*e.g.* sections 148 and 149, **8.3.3**). In sections where the intermediate part of the succession is coarser than fine sandstone, facies 12 predominates over facies 14 and grades upward into silty sandstone (facies 13) (*e.g.* sections 147 and 148, **8.3.3**). Elsewhere, the intermediate part of the succession (facies 15) is thick and passes gradationally upward into hummocky cross-stratified fine sandstone (facies 14). At the top of succession 5, facies 13 or 14 grades upward into a thick siltstone (facies 21) and/or bioturbated claystone (facies 22).

The change in sedimentary structures is the same as in succession 2, but occurs in the reverse order in a vertical sense. The type of sedimentary bedding structure is dependent on grain size and ranges from trough-, swaley-, and planar- cross-stratification in coarser sandstone at the base of the succession, to wave-ripple lamination, planar cross-stratification, graded beds, and rare planar bedding in the intermediate medium to fine sandstone part of the succession. Above hummocky cross-stratified fine sandstone and coarse siltstone and small scale cross-stratified sandstone, the upper part of the succession is intensely bioturbated and preserved sedimentary structures within facies 13, 21 and 22 are rare. Where they have not been completely destroyed by bioturbation these structures change upward from small scale ripple cross-stratification to wave-ripple lamination, to flat lamination.

The degree of bioturbation and fossil content of individual facies of this succession are very similar to succession 2. However, the amount of bioturbation increases upward in this succession whereas bioturbation decreases upward in succession 2. Body fossils are very rare in this succession and are usually limited to poorly preserved molluscan macrofossils. Trace fossils are indistinct and comprise poorly preserved burrows of the *Skolithos* ichnofacies.

Interpretation

Facies succession 5 is interpreted as the deposit of a fining- and deepening-upwards (typically retrograding) storm- (and wave-) dominated shoreface. In proximal localities the basal and intermediate parts of the succession are dominated by coarse to medium sandstone of facies 8 and 12 overlain by finer sandstone and siltstone of facies 13 (*e.g.* sections 7 and 10, **8.2.1**). In places measured sections record two or more stacked examples of succession 5 (*e.g.* sections 4 and 12, **8.2.2**). In more distal localities the basal and intermediate parts of the succession are composed of interbedded sandstone and siltstone of facies 15, and fine sandstone and coarse siltstone of facies 14. In all regions the siltstone and claystone of facies 21 and 22 capping the succession represent the end result of retrogradation (or drowning) of the shoreface, and the transition from a lower shoreface to offshore depositional environment. Here the seafloor was beneath the average storm wave base and would have only been affected by occasional large storms.

Flat lamination in the coarse sandstone interval in proximal localities was probably produced by swash / backswash on the beach. This sandstone passes upward into coarse sandstone (facies 8) of the upper shoreface or beach, which in turn gives way to SCS sandstone of the middle to lower shoreface. In more distal localities crossbedded sandstones of the upper shoreface give way to HCS beds and thinly interbedded facies with wave-ripple lamination, which were deposited as water depth increased. Here storm-generated structures (*e.g.* HCS and sand-filled gutters) are preserved, because the seafloor was beyond the influence of fair-weather processes. With increasing water depth the grain size continued to decrease and laminated to massive silts and clays were deposited under maximum water depth.

The upward change from dominantly vertical burrows (*Skolithos* ichnofacies), to a mixed trace fossil assemblage, to dominantly horizontal burrows (*Cruziana* ichnofacies) records the increase in water depth from the base to the top of the succession. Essentially, the temporal changes in the depositional environment are in the reverse sense to that of succession 2, which was deposited in a similar setting during shoaling events.

7.3.2 Facies Succession 6 - paralic (estuarine and deltaic-marine) systems (Walker River Formation)

This succession is the most variable in the study area and occurs at proximal localities on the shelf. In most places it has a fining-upward character, although some deposits are massive. In the eastern part of the BPRZ facies succession 6 typically occurs as thin sandbodies enclosed within marine sandstones of succession 2. Here the base of succession 6 consists of thickly planar bedded and large-scale planar cross-stratified coarse-medium to medium/fine-grained sandstone. In proximal localities the sandstone (facies 6) is coarse and relatively poorly sorted and fines upward above a basal lag. In more distal localities the basal sandstone (facies 11) is finer-grained, better sorted and contains abundant plant fossils. The plant-bearing sandstone grades into bioturbated, fossiliferous, clayey finer-grained sandstone (facies 12). Commonly, the contact between these two lower facies of the succession is sharp, but is apparently conformable. The grain size may continue to decrease upward until interbedded sandstone and siltstone (facies 15) or silty sandstone (facies 13) is present.

As grain size decreases upward set thickness and foresets of the cross-stratification decrease and the degree of bioturbation increases. Above this zone rare bipolar (herringbone) cross-stratification and current ripples are present. The number and diversity of plant fossils increases from the top of facies 6, through facies 11 and finally decreases near the contact of facies 11 with overlying facies 12. In most parts of the succession the fossil assemblage contains a mix of plant fragments and molluscan shells as well as *Rhizocorallium*, *Skolithos*, and *Arenicolites* trace fossils.

In the western part of the BPRZ there is one similar deposit of facies succession 6 (*e.g.* section 37, **8.3.5**). Here fining-upward cross-stratified and ripple-marked sandstones with rare marine fossils overly thick fluvial channel deposits of facies succession 7.

Interpretation

Facies succession 6 shows considerable variation, but all deposits of this succession represent paralic or marginal marine depositional environments. In most places deposits of facies succession 6 record an upward increase in marine influence; indicated by increasing bioturbation, decreasing grain size, better sorting, and the presence of marine fossils and hardgrounds in the upper part of the succession.

Most deposits of facies succession 6 can be broadly considered as being deltaic of brackish-marine in nature. For example, in the eastern part of the BPRZ a thin 'brackish' sandbody can be seen to wedge out offshore and is enclosed by thick marine sandstones. The 'brackish' sandstones contain a mixed fossil assemblage of plant fossils and marine macrofossils. Most probably these sandstones represent small, thin prograding deltas, but it is difficult to unequivocally assign a deltaic origin to these deposits because a fluvial source and delta morphology are not recognisable.

Evidence of strong wave reworking in succession 6 is preserved in the well-sorted and well-rounded character of facies 8 and 12, which are extensively cross-stratified and contain marine body and trace fossils. This succession has features which are similar to those displayed by prograding wave-influenced deltas (*e.g.* Bhattacharya and Walker, 1991), or possibly related to retrograding estuarine systems (*e.g.* Dalrymple *et al.*, 1992). Support for the interpretation of prograding wave-influenced deltas is given by stratigraphic correlation (**8.3.2**), which shows the lateral facies equivalence of facies succession 6 'deltaic' sandbodies as they prograde and wedge out amongst marine sandstones of facies succession 2.

7.3.3 Facies Succession 7 - fluvial channel fill (Yirrkala Formation)

Facies Succession 7 is common in the central part of northeastern Arnhem Land. Generally it has a fining-upward grain size trend, but in places succession 7 is massive or has an irregular vertical grain size trend. The maximum thickness of stacked channel sandstones of the Yirrkala Formation is 50 m, and the average thickness of channel sandstones is 8 m.

The basal part of succession 7 consists of normally graded chert conglomerate and coarse sandstone (facies 1). This facies is commonly 2 to 5 m thick and grades upward into cross-stratified pebbly sandstone, with or without planar bedding (facies 5). Overlying this facies with a gradational contact is trough cross-stratified, coarse-grained, moderately to poorly sorted sandstone (facies 7). This facies is typically several metres thick and comprises the coarsest sand sized part of the succession, where dispersed clasts are relatively rare. This facies is overlain by finer-grained sandstone (facies 6), still with relatively poor sorting, which contains plant fossils and rare clasts. The contacts between facies are gradational throughout the succession, or at least within each of the fining-upward sub-cycles, which are stacked to make the succession. These small fining-upward sub-cycles typically have erosional-bases produced by local scour, which are defined by erosional truncation of crossbedding and thin conglomeratic lags overlying scours.

Where exposure is good, a distinct upward change in sedimentary structures in succession 7 is distinguishable. The basal conglomeratic facies is normally graded but contains no other structures. The overlying facies (5 and 7) display trough cross-stratification with sets up to 1.2 m thick near the base, high-angle planar cross-stratification (set thicknesses of 40 to 60 cm), and medium to thin planar bedding. The upper facies has planar cross-stratification on a smaller scale, asymmetrical and symmetrical current ripples, and rare trough cross-stratification.

Facies 1, 5, and 7 are not bioturbated and contain no body or trace fossils. Near the top of succession 7 rare *Skolithos* burrows and several other poorly preserved, unidentified trace fossils are present. The top metre or two of the succession contains segmented plant fossils, mostly logs and stems.

Interpretation

I interpret Facies Succession 7 as a channel fill or point bar deposit. This is suggested by the overall fining-upward of the succession, and the fining-upward of individual sub-cycles with erosional bases. The linear or shoestring geometry of the sand bodies in plan view also supports the interpretation of channel deposits. Topographically-high basement ridges, which typically outcrop close to succession 7, are interpreted as the source of most of the pebbles and coarse sand in succession 7. The lack of marine facies indicates that the channels are fluvial-dominated, and the presence of sub-cycles in succession 7 suggests channel filling by a series of waning flows, perhaps associated with flood stages of rivers. The *Skolithos* burrows at the top are possibly related to organisms burrowing down from an overlying marine unit, which has since been eroded.

Succession 7 shows significant variation between areas and does not always exhibit a continuously fining-upward character. For example, in places the bulk of the succession is composed of facies 7 and 11 and the succession is massive or fining-upward (*e.g.* sections 1, 2, 7, and 161, **8.2.1**). Elsewhere, the upper cross-stratified sandstone (facies 11) and basal lag are thicker and the intermediate facies are missing or greatly reduced in thickness. These variations were most likely due to changes in the energy of flow within channels, with thicker and coarser sediments deposited in upstream locations.

7.4 IRREGULAR SUCCESSIONS

7.4.1 Facies Succession 8 - bay / lagoon (sheltered / restricted marine) (Walker River Formation)

This succession has an irregular or fining-upward grain size trend and is well-exposed in the ALZ and the southern part of the BPRZ. The succession has a maximum thickness of 14.5 m, and an average thickness of 7 to 10 m.

The base of the succession sometimes consists of a thin conglomeratic lag. The lag is less than 1m thick, and contains moderately sorted granule to large pebble sized clasts of quartzite, silicified siltstone, and various other fine-grained lithic clasts. This basal lag erosionally overlies facies of succession 2 or 5. Where a lag is missing, the base of the succession is clayey medium- to fine-grained sandstone (facies 10 or 12). Here, the sandstone typically overlies a marine flooding surface (marking the top of succession 5 or 6) with a sharp planar contact.

Grain size trends within succession 8 are somewhat irregular, but fining-upward cycles tend to occur in older or basal parts of the succession whilst coarsening-upward tend to occur in the upper part of succession 8. In any cycle or interval, the dominant rock type is silty fine- to medium-grained sandstone (facies 12 and 13). In places the grain size decreases to fine silt size, but these intervals are thin and poorly defined. The most characteristic feature of the succession is the lack of wave-generated sedimentary structures, even in the coarsest parts of the succession. The dominant bedding style is medium to thick planar bedding, with rarer flat and ripple lamination in the finer-grained parts. Other rare structures include herringbone cross-stratification and stringers of coarse sand and granule sized grains.

Rocks of succession 8 are moderately to intensely bioturbated and the amount of bioturbation increases upward. The succession is highly fossiliferous, and contains a high diversity and abundance of both body and trace fossils. Body fossils include ammonites, bivalves, trigonids, scaphopods, possible belemnites, unidentified bone fragments, and a large range of segmented plant fossils. Plant fossils are restricted to several intervals near the top of the succession. Trace fossils include *Rhizocorallium*, *Planolites*, *Arenicolites*, *Teredolites*, and *Skolithos*.

Interpretation

Facies Succession 8 is interpreted as the deposit of a sheltered and/or restricted marine environment, such as a bay or lagoon. The presence of abundant marine body and trace fossils throughout the succession indicates that the bays or lagoons had full marine connection at most times. Plant fossils suggest a brackish marine influence toward the top of succession 8.

The lack of pervasive wave-generated sedimentary structures suggests that this succession was deposited in a relatively quiet marine environment, where wave energy was significantly reduced compared to high-energy marine environments typical of other facies successions. In several places the upper, finer-grained part of the succession displays delicately-preserved bivalve fossils, which are still articulated; this adds support for an interpretation of a quiet, restricted marine environment.

The trace fossils belong to the *Skolithos* and *Cruziana* ichnofacies. Normally the *Cruziana* ichnofacies is considered to be characteristic of a shallow offshore shelf environment between storm and fair-weather wave base (Pemberton and Frey, 1984; Pemberton *et al.*, 1992). However, it is also widely recognised that the same ichnofacies can occur in shallower, restricted or quieter marine regions. The high degree of bioturbation suggests that the seafloor was well oxygenated and able to sustain abundant and diverse biota.

In several places the abundance of preserved marine macrofossils is enormous, and it appears that the fossils may have been concentrated in banks or shoals. The fact that many of these body fossils are preserved with shells still joined argues against significant transport. The presence of rare bipolar (herringbone) cross-stratification in these areas may indicate bi-directional palaeocurrents, but convincing evidence for tidal processes is lacking. The concentration of plant fossils near the top of the succession is interpreted as an influx of fluvial debris, and a possible change to brackish marine conditions in the upper 1 or 2 metres of the succession.

8. LITHOSTRATIGRAPHIC CORRELATIONS

In the study area Cretaceous rocks occur as isolated "spot" outcrops, which may be weathered or poorly exposed. Consequently, lateral correlation of strata and surfaces on the Carpentaria Basin shelf is not at all obvious. However, local correlation is possible after careful documentation of facies, recognition of facies successions and the bounding surfaces between successions, and detailed comparison of numerous measured sections, well logs and cores. Such local correlation forms the basis for regional correlation, which in turn enables construction of composite sections and a lithostratigraphic framework for the entire shelf.

A regional marker horizon is lacking in many sections, but more subtle marker beds, individual coarsening-upward and fining-upward cycles, and regionally extensive facies successions enabled 'first-pass' correlation over distances of a kilometre to tens of kilometres. Only after this local correlation was tested and refined and the extent of various facies had been distinguished were detailed stratigraphic correlation diagrams constructed.

8.1 DETAILED STRATIGRAPHIC CORRELATION DIAGRAMS

The factual data concerning rocks in the ALZ (the area shown on Fig. 8) are summarised in two local to semi-regional stratigraphic correlation diagrams (Figs. 9 and 10) and a composite lithostratigraphic section (Fig. 11). Data for rocks in the BPRZ (the area shown on Fig. 12) are summarised in five stratigraphic correlation diagrams on four figures (Figs. 13, 14, 15, and 16) and a composite lithostratigraphic section (Fig. 17). The stratigraphic correlation diagrams are not cross sections, and their traces on the ground are less direct than would be expected for true cross sections; this allows inclusion of the most complete and representative measured sections. For economy of space and clarity of correlation, these have been "condensed" from longer correlation diagrams, and only those measured sections that illustrate important elements of the stratigraphy have been included. Numbered field stations are shown on simplified base maps in Appendix 2 and Appendix 3.

All the measured sections are constructed at the same scale, and most are hung on the same datum, a prominent marker labelled C 2 (claystone 2), in the upper part of a transgressive marine cycle in the Walker River Formation. The C 2 marker was chosen as a datum for several reasons:

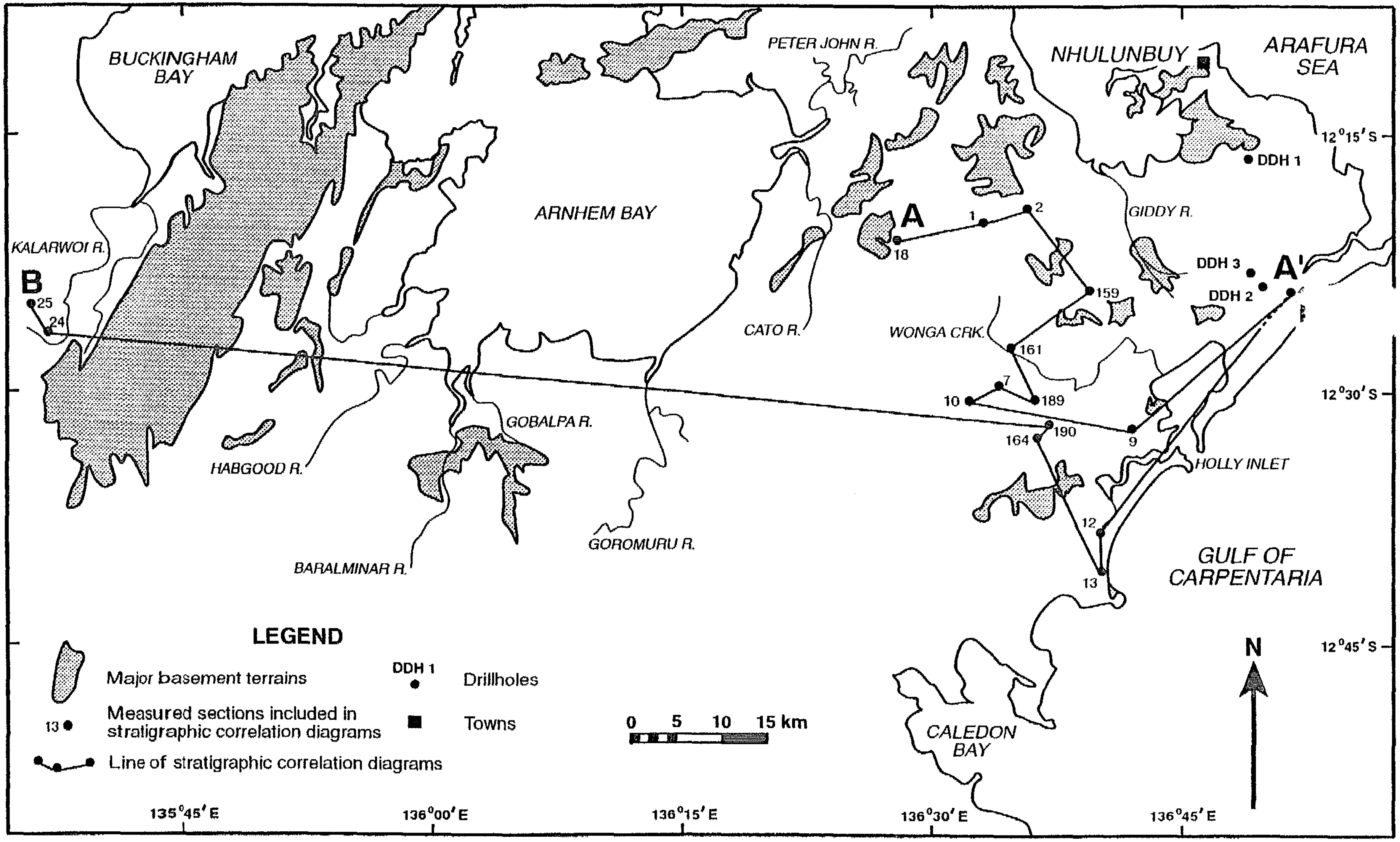


FIG. 8

FIGURE 8. Base map for the Arnhem Land Zone (ALZ). See Fig. 7 for its regional position relative to northeastern Arnhem Land.

1) it is the most extensive marker horizon in the entire study area;
2) it is lithologically homogeneous and has a similar thickness across the shelf (documented by regional correlations as part of a larger study);
3) it is one of the rare very fine-grained rocks on the shelf and is easily recognisable amidst enclosing coarser-grained rocks; and
4) it is flat lying and typically conformable on underlying rocks, and the base of the C 2 marker is strongly inferred to represent a time-line across the shelf.

8.2 ARNHEM LAND ZONE (ALZ)

8.2.1 Correlation diagram A - A' (Fig. 9)

This correlation diagram starts with section 18 in the extreme north of the study area at the Cato River and extends 92.3 km (Fig. 8). From the Cato River to section 189 in the southeast, the bulk of the exposed Cretaceous sequence consists of fluvial facies. Fluvial facies of the Yirrkala Formation are composed of coarse-grained, poorly sorted sandstones with large scale trough- and planar cross-stratification. In all sections the fluvial facies are interpreted as channel-fill deposits and have the general morphology of facies succession 7.

The thickness of fluvial facies in the west of A-A' is at least 15 m, and may be significantly greater because most measured sections in this region are incomplete and the contact of fluvial facies with underlying rocks was not observed (except in section 1). There are numerous small, highly weathered outcrops of fluvial sandstone not included in this correlation diagram, and the stratigraphic position of these outcrops and all fluvial facies illustrated in correlation diagram A-A' is inferred to be identical, although their exact age equivalence is problematic due to the lack of fossils and marker beds. This interpretation is supported by good correlation of ferricretes overlying the Yirrkala Formation, and the close similarity in the size and style of sedimentary structures in fluvial sandstones across northeastern Arnhem Land.

In section 1 thick fluvial sandstone disconformably overlies a series of marine sandstones of the Walker River Formation. These marine facies also occur in the southern part of the ALZ, towards the base of sections 4 and 9. There the thickness of preserved marine facies is greater than that of fluvial facies. The basal marine facies consist of massive and coarsening-upward rocks of facies succession 2, and these are the oldest Cretaceous rocks exposed in the ALZ. Further correlation of these basal marine facies with other marine facies is illustrated in Fig. 10. In section 1 fluvial deposits of facies succession 7 have a disconformable contact with underlying marine sandstones of facies succession 2. In the southern and eastern parts of the correlation diagram (sections 4, 7, and 10) transgressive marine rocks of facies succession 5 occur stratigraphically above facies of succession 2, and beneath fluvial deposits of succession 7 which characterise the northern and western parts of the correlation diagram. The transgressive marine deposits are composed of coarse- to fine-grained sandstones which fine upward into siltstone and silty claystone. The upward change in sedimentary structures indicates increasing water depth up section and the transition to a lower-energy, offshore shallow-marine depositional environment.

In general there is an increasing marine influence along the correlation diagram towards the south and east, and a corresponding decrease in the thickness of fluvial facies of the Yirrkala Formation. Fluvial incision and deposition has progressively truncated the Walker River Formation northward in the correlation diagram, and only in the southern part of the correlation diagram is the complete record of marine facies preserved. Evidence for fluvial incision occurs at sections 1, 7, and 10, where an erosional disconformity separates marine

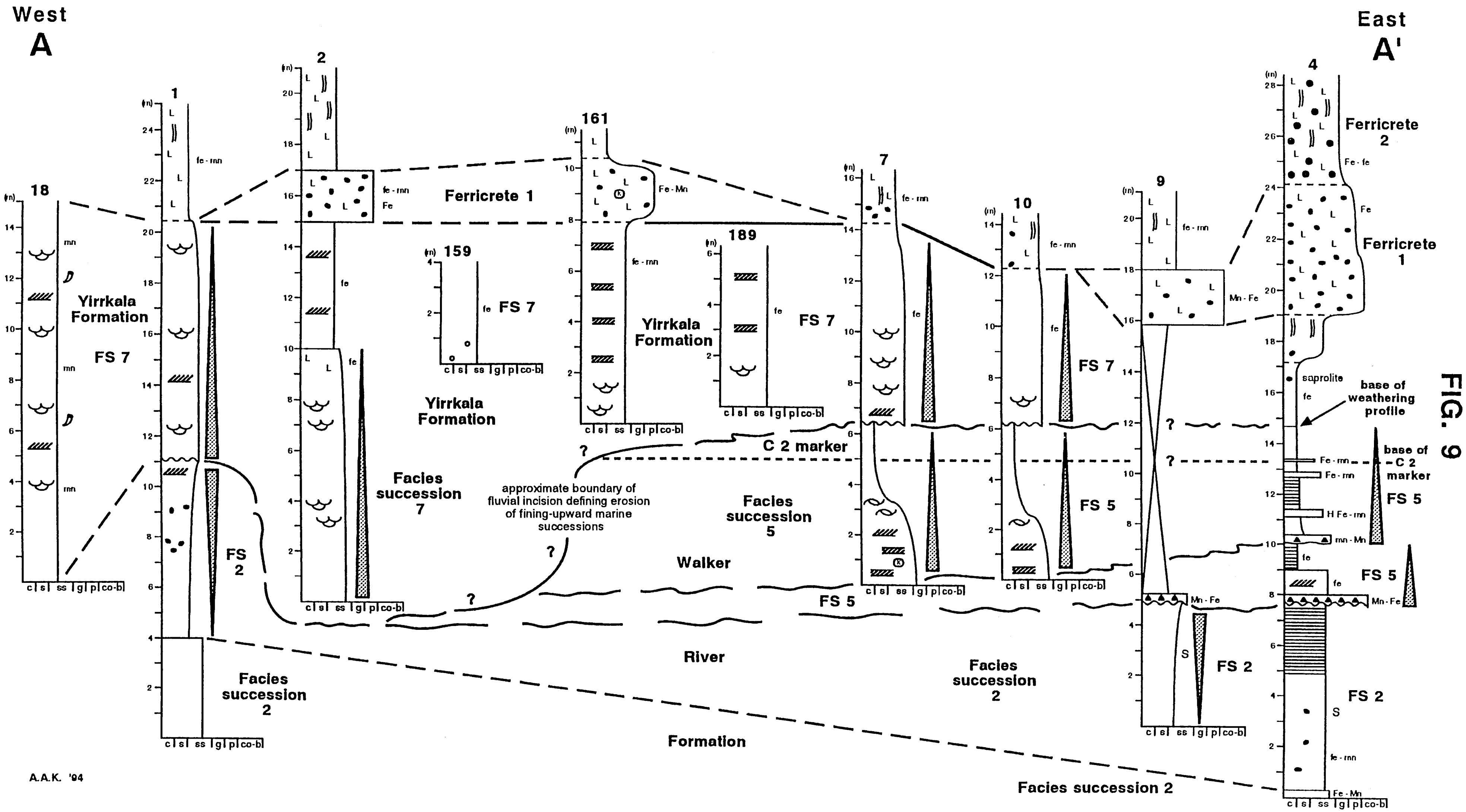


FIG. 9

FIGURE 9. Stratigraphic correlation diagram for part of the ALZ. Refer to Fig. 6 for legend to symbols, and to Fig. 8 for geographical localities. FS= facies succession.

facies (Walker River Formation) and younger fluvial facies (Yirrkala Formation). In the vicinity of sections 7 and 10, fluvial deposits of succession 7 are incised up to 10m into transgressive marine deposits of succession 5. The irregular nature and extent of fluvial incision is probably due to localised channel scouring in a broad regime of lateral accretion. In regions near the present coastline (presumably close to the palaeoshoreline at sea level lowstand), the Yirrkala Formation is thin or missing (*e.g.* section 4). Overall the extent of fluvial incision increases markedly to the north and northwest, inland from the present coastline. The approximate extent of fluvial incision into older transgressive marine successions is illustrated in Fig. 9.

Overlying marine facies succession 2 in section 4 are stacked fining-upward rocks of facies succession 5. On the basis of the C 2 marker, fining-upward marine rocks of facies succession 5 can be confidently correlated between sections 4, 7, and 10. In this correlation diagram these three sections contain the only true marker bed (C 2), and the inferred stratigraphic position of all other sections is relative to this marker bed, which occurs just beneath fluvial deposits in sections 7 and 10. Much of section 9 is covered by alluvium and scree, and the transgressive marine successions expected to occur here are not exposed. However, there is good correlation of coarse-grained marine sandstones between the basal parts of sections 4 and 9.

8.2.2 Correlation diagram B - B' (Fig. 10)

This correlation diagram extends along a 167.9 km line and illustrates dominantly marine deposits from Kalarwoi River in the west to an area 30 km south of Nhulunbuy in the east of the ALZ (Fig. 8). In the western part of Arnhem Land marine and/or restricted marine facies of facies succession 8 of the Walker River Formation occur in numerous measured sections. Here the rocks consist of stacked interbedded sandstone and siltstone displaying marine body and trace fossils. Sedimentary structures, texture, and grain size indicate alternating low-energy (siltstone) and moderate-energy (sandstone) depositional environments, and abundant delicate lamination indicates a sheltered shallow-marine environment. In places this restricted marine sequence is relatively thick (*e.g.* section 24) and is composed of stacked alternating siltstone- and sandstone-dominated intervals.

A similar sequence occurs in section 12 near Holly Inlet (Fig. 8) over 110 km to the east of section 25. Interbedded sandstone and siltstone in both these regions are considered to be correlative and are assigned to facies succession 8. In the area surrounding Holly Inlet and up to 15 km to the northeast (including sections 164 and 190), there are numerous small outcrops of the interbedded sequence, which can be confidently correlated with the more complete sequence at section 12. Such restricted shallow-marine deposits do not occur at section 4 farther to the east, where stacked transgressive rocks are overlain by a younger weathering profile.

In the Kalarwoi River region (*e.g.* section 25) the restricted marine sequence disconformably overlies fine-grained transgressive marine rocks, including the C 2 marker in section 25 and in several other incomplete sections. Sections in the Kalarwoi River area are correlated with those over 110 km to the east at Holly Inlet and Stoney Ridge (sections 12 and 4 respectively), and the thick series of fining-upward transgressive marine deposits of facies succession 5 in both these areas belong to the Walker River Formation.

Correlation of individual fining-upward transgressive marine successions in the eastern part of this correlation diagram is relatively simple, due largely to the presence of several distinctive brecciated and mineralised beds overlying disconformities in the thicker sections

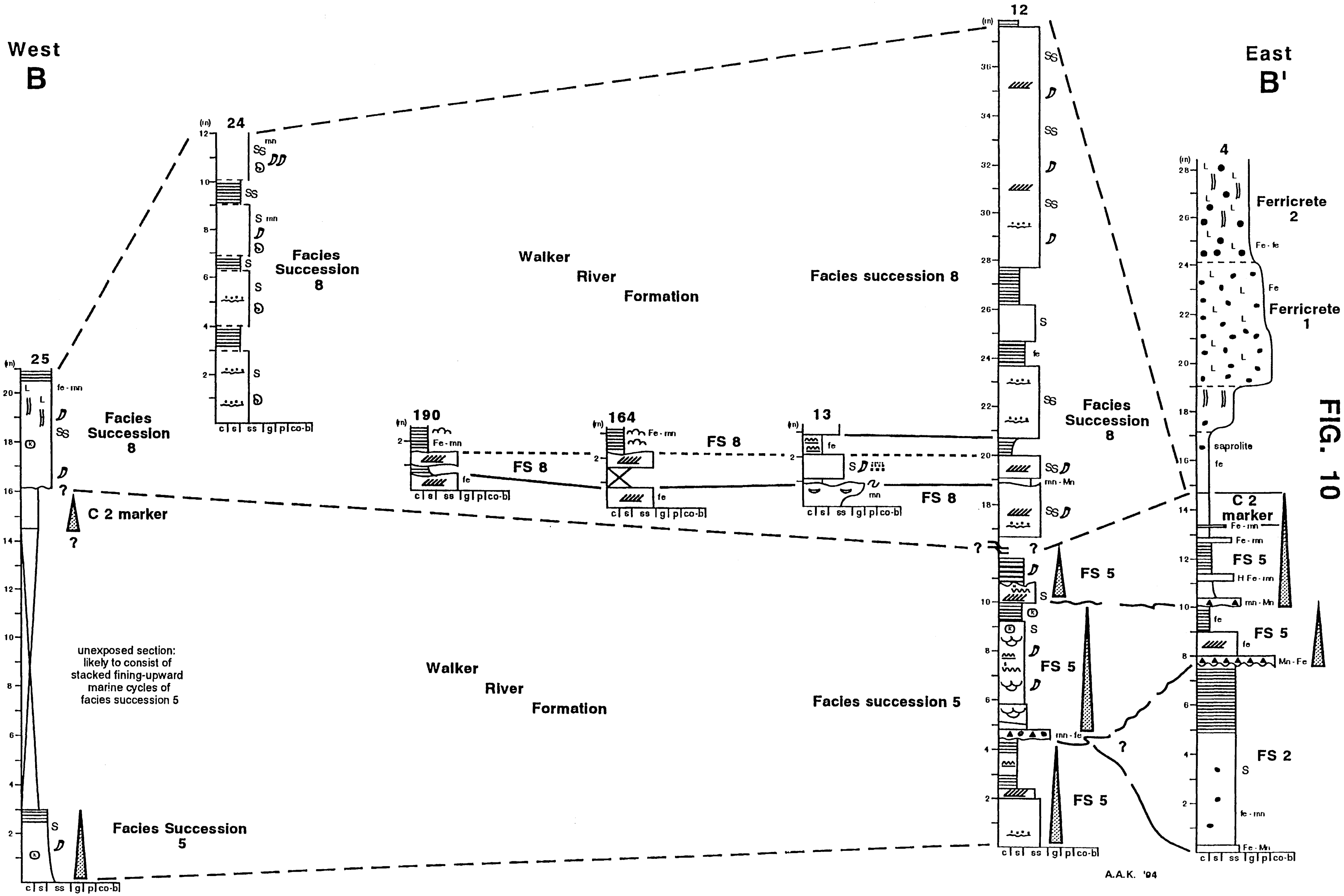


FIG. 10

FIGURE 10. Stratigraphic correlation diagram for part of the ALZ. Refer to Fig. 6 for legend to symbols, and to Fig. 8 for geographical localities. FS= facies succession.

(*e.g.* at 7.5 m and 10 m in section 4; at 4.5 m in section 12). The upper transgressive facies succession in section 4 contains the C 2 marker, which can be correlated with section 25 to the west. However, the C 2 marker is not exposed in section 12, and the stratigraphic level where it should occur is covered. Unequivocal correlation of individual transgressive successions between sections 12 and 25 is difficult due to the incomplete nature of section 25, although they clearly represent closely related depositional environments.

On the eastern edge of the ALZ at section 4, thick transgressive marine deposits of succession 5 disconformably overlie coarse-grained marine facies assigned to facies succession 2. Outcrops of coarse-grained marine rocks of facies succession 2 are restricted to an area close to the present coastline, and were not recorded farther inland. The marine rocks of succession 2 in sections 1 and 4 represent the oldest part of the Walker River Formation in the ALZ.

8.2.3 Summary of facies successions in the ALZ

The oldest Cretaceous rocks observed in *outcrop* in northeastern Arnhem Land are marine sandstones of the Walker River Formation occurring at the base of sections 1 and 4. Their contact with pre-Mesozoic basement was not observed, but the position of Cretaceous rocks near to Proterozoic granite outcrops suggests that basement occurs close to the base of these Cretaceous marine sandstones. The oldest Cretaceous facies have been assigned to facies succession 2, although the succession is thin and the exposures are relatively poor.

A marine depositional environment has been assigned to these rocks (Fig. 11), largely on textural and compositional criteria, since body fossils are lacking and trace fossils are rare. Although the marine nature of these rocks is not unequivocal, their environment likely was offshore marine to marine shoreface marine with progressively shallower water depths up section. This idea is supported by the disconformable contact of this succession with overlying marine facies of facies succession 5, which also belong to the Walker River Formation. The contact is represented in most places by a brecciated, mineralised and/or cemented bed (*e.g.* sections 4, 9, and 12) which represents a major regional surface of submarine erosion, and is the result of shoaling towards the top of facies succession 2.

Stacked fining-upward marine successions occur directly above the basal erosional surface defined by the mineralised breccia, and are also bounded above by an erosional surface in the form of a sharp disconformable contact between the fine-grained top of a fining-upward succession 5, incorporating the C 2 marker, and the overlying coarse-grained fluvial sandstones (Fig. 11). Both of these erosional surfaces have an irregular topography, with the overall thickness of stacked fining-upward cycles of succession 5 controlled by the amount of localised erosion. There are two or three stacked fining-upward cycles of facies succession 5 overlying the basal disconformity (*e.g.* section 12), with the number of cycles exposed in outcrop dependent on the amount of erosion. Each of these fining-upward successions represents a change in relative sea level across the northern region involving transition from shoreface to offshore shallow-marine deposition, followed by a further change in relative sea level which led to accumulation of coarse-grained marine sandstones of the shoreface at the base of the next fining-upward succession.

After deposition of the final fining-upward marine succession of the Walker River Formation, fluvial incision into underlying marine deposits occurred in the central parts of the ALZ. The fluvial facies of the Yirrkala Formation deposited in this region correspond largely to coarse-grained channel-fill facies of succession 7 (see northern half of Fig. 9). Similar facies (Yirrkala Formation) also occur in three stratigraphic drillholes in the same

FIG. 11

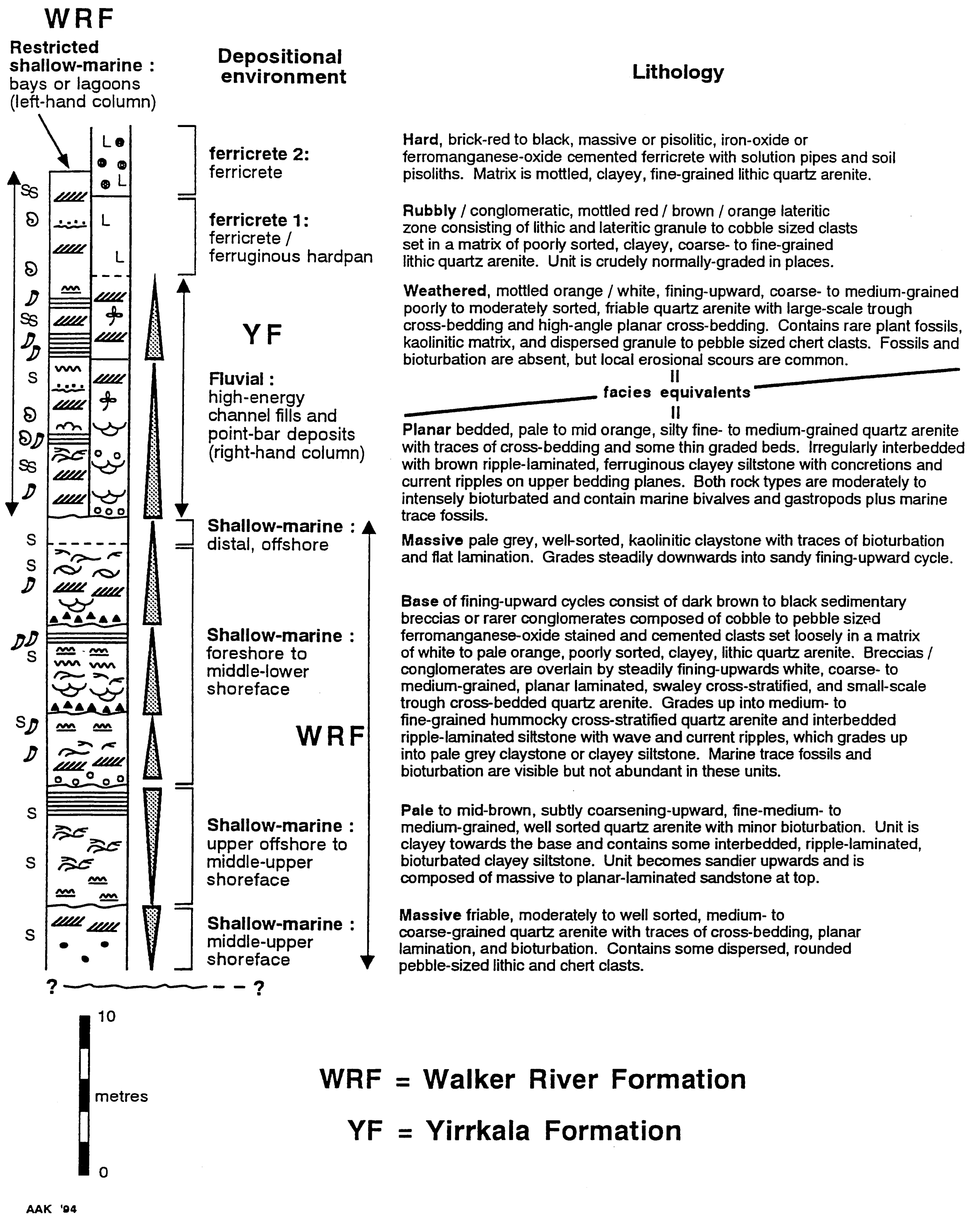


FIGURE 11. Composite Cretaceous section for the Arnhem Land Zone (ALZ). The ALZ is roughly equivalent to the area of the ARNHEM BAY-GOVE 1:250,000 scale map sheet. The age of the rocks (considered as Aptian to Cenomanian) is known here only by correlation with equivalent dated stratigraphic intervals farther to the south. Ferricretes probably formed in Tertiary time, but may represent preserved Late Cretaceous land-surfaces in places. For symbols used in composite section see Fig. 6.

area (Dodson, 1967), and show a large thickness of stacked fluvial channel and interfluvial deposits with the characteristics of facies successions 3 and 7.

The other main Cretaceous deposits in the ALZ are thick restricted-marine to shallow-marine sandstones and siltstones of the upper Walker River Formation which occur close to the present coastline of Arnhem Land (*e.g.* sections 12, 13, 24, 25, 164, and 190). It is likely that these facies accumulated in large bays or along sheltered coastlines to the northwest and southeast of the inland fluvial-dominated area. These restricted marine deposits of facies succession 8 form a thick sequence (*e.g.* upper half of section 12, and section 24), for which there is no direct age control. However, their stratigraphic position overlying stacked transgressive marine facies of succession 5 is identical to fluvial deposits farther inland (*e.g.* sections 7 and 10). This suggests that restricted marine deposition of facies succession 8 occurred in sheltered parts of the palaeoshoreline, with concurrent fluvial incision and deposition of facies succession 7 farther inland. If this is interpretation is correct, both fluvial deposition and restricted marine deposition occurred during the late Albian to early Cenomanian in different parts of the ALZ.

8.3 BATH AND PARSONS RANGES ZONE (BPRZ)

8.3.1 Correlation diagram C - C' (Fig. 13)

This correlation diagram includes measured sections on a line 132.6 km long (Fig. 12) in the area between zones of good outcrop in the ALZ and BPRZ. In this area the Cretaceous successions are thin and poorly exposed, but their documentation is important for regional correlation and for assessment of the extent of marine incursion.

Most Cretaceous successions in correlation diagram C-C' are composed of fining-upward coarse-grained fluvial sandstone with thin conglomeratic pebble lags, and they commonly overlie Proterozoic basement with an angular unconformity. The fluvial deposits have a maximum thickness of 4.5 m, and correspond to channel-fill facies of succession 7. Whilst the stratigraphic equivalence of these numerous small fluvial outcrops cannot be directly proved using biostratigraphic data or marker beds, they occur at a similar topographic height, overlie the same basement unit with an erosional unconformity, and are all very similar in grain size, texture, and composition. Their assignment to the Yirrkala Formation is based on similarity of their morphology and stratigraphic position in comparison with Cretaceous fluvial successions to the north and south. All the fluvial deposits in this correlation diagram occur as thin caps on isolated basement inliers, and are interpreted to have formed a much more extensive and thicker fluvial depositional system before post-Cretaceous erosion dissected the fluvial deposits.

There are also two marine successions or facies within correlation diagram C-C'. The northernmost of these successions consists of coarse- to medium-grained quartz sandstone which fines upward into fine-grained siltstone and silty claystone, and is correlative with fining-upward marine facies of succession 5 to the north and south. The major differences here are that the Walker River Formation is thinner and does not contain obvious marine fossils due to the highly weathered nature of the outcrop.

The other marine succession has not been identified elsewhere on the mainland, and its stratigraphic relationships are obscure. This succession unconformably overlies the same Proterozoic basement unit as Cretaceous fluvial deposits in this area. This unusual marine facies is composed of fine- to medium-grained quartz sandstone with poorly defined hummocky cross-stratification, and is cemented and stained by ferruginous and

FIG. 12

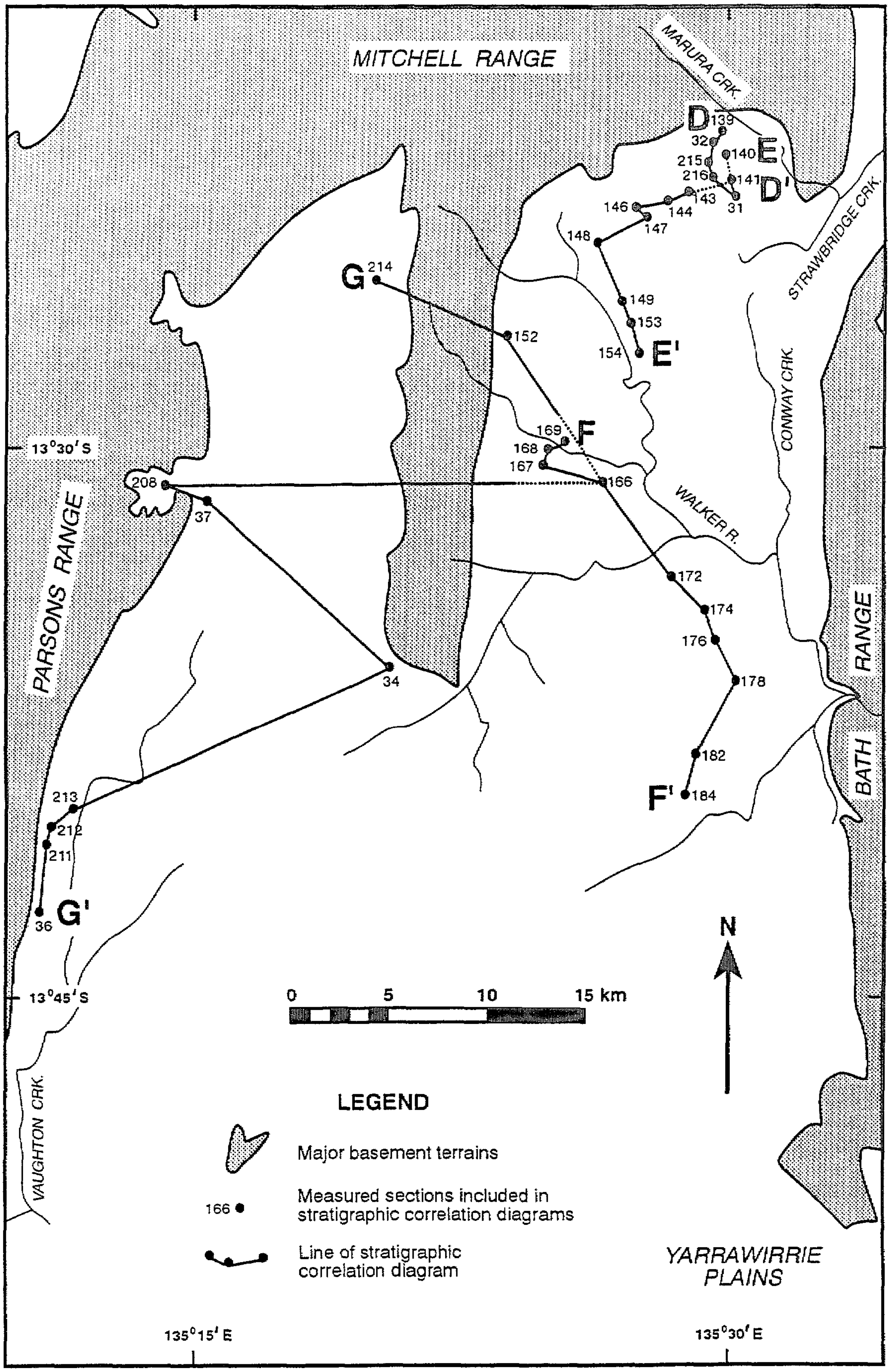


FIGURE 12. Base map for the Bath and Parsons Ranges Zone (BPRZ). See Fig. 7 for its regional position relative to northeastern Arnhem Land. See the inset map on Fig. 7 for sections included in correlation diagram C-C'.

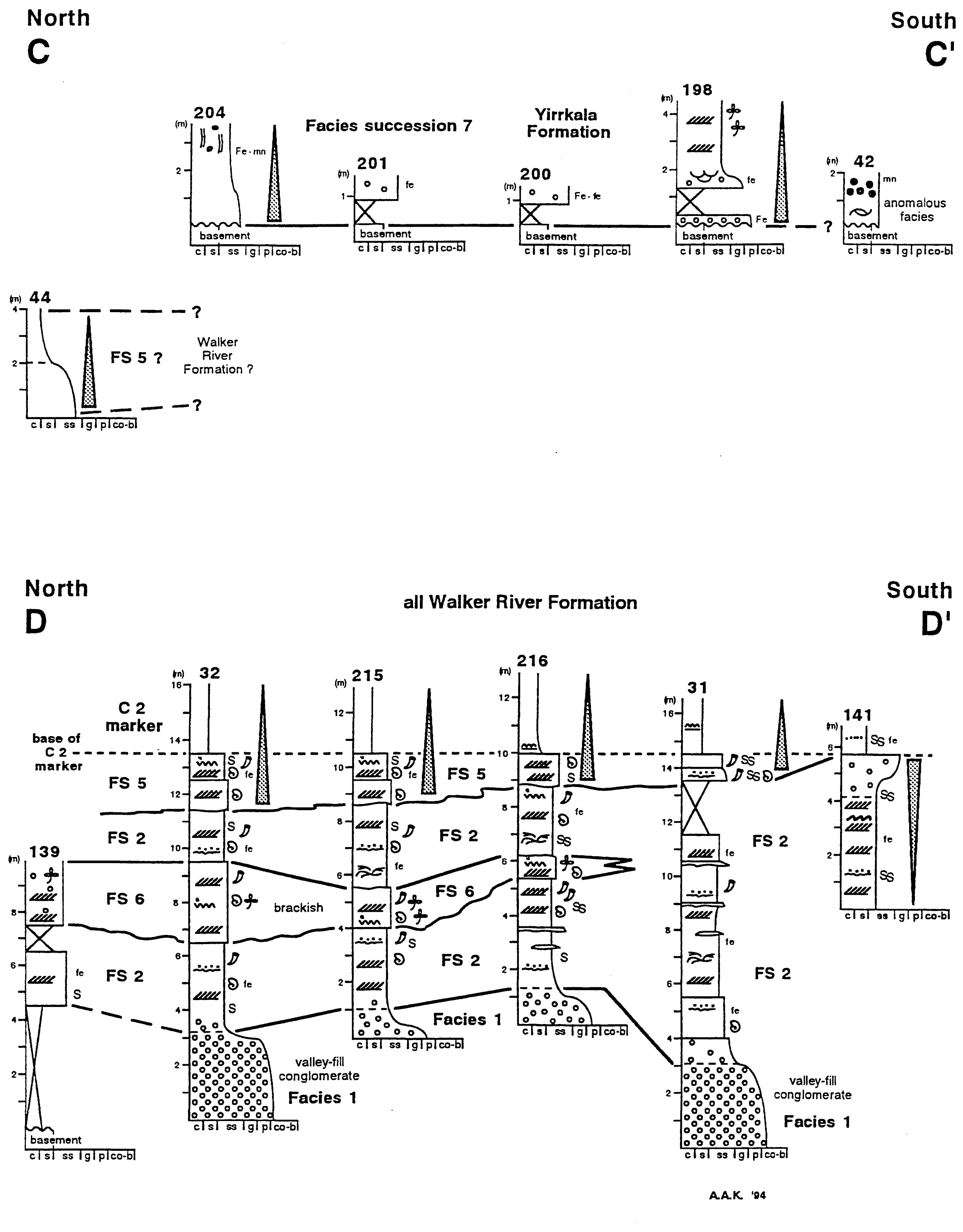


FIGURE 13. Stratigraphic correlation diagram for the central part of the Bath and Parsons Ranges Zone. Refer to Fig. 6 for legend to symbols, and to Fig. 12 for geographical localities. FS= facies succession.

ferromanganese oxides (*e.g.* section 42). The upper part of the deposit contains ferromanganese pisoliths in a sandy matrix. The inferred marine depositional environment for these rocks has not been proven because marine fossils were not observed in outcrop, but the presence of pisoliths and HCS support an interpretation of a high-energy shallow-marine environment. The sandstone is thin, although the scree-covered area around the section indicates a greater true thickness for this anomalous facies. Whether this anomalous pisolitic and mineralised sandstone is contemporaneous with the fluvial deposits farther to the north in this correlation diagram is difficult to assess, but it occurs at a similar stratigraphic level and overlies an identical basement unit. However, this facies may be post-Cretaceous in age.

8.3.2 Correlation diagram D - D' (Fig. 13)

This correlation diagram illustrates the foreshore to shoreface transition in an area where the palaeoshoreline was highly irregular in close proximity to the Bath, Parsons, and Mitchell Ranges (Fig. 12). This correlation diagram highlights the inter-stratified nature of parts of the Walker River Formation deposited in fully marine and paralic environments close to the palaeoshoreline. The correlation diagram covers a distance of 4km near Marura Creek and enables the sensitive changes at the marine/terrestrial interface to be documented.

The oldest part of the Walker River Formation here is a thick, massive to normally graded cobble to pebble chert conglomerate. The contact with basement was not observed in the area of this correlation diagram, but slightly farther to the south this same facies unconformably overlies dipping Proterozoic siltstone. The conglomerate is up to 4 m in thickness in the area covered by Fig. 13, but has a thickness of at least 20 m farther to the south. The presence of conglomerate is interpreted to represent a long period of erosion and accumulation of very coarse-grained clastics during lowstand of sea level when the entire area was subaerially exposed or was sited close to the palaeoshoreline. As such, the normally graded conglomerate represents a fluvial valley-fill. The basal part of the conglomerate grades and fines upward into fossiliferous, conglomeratic Cretaceous marine sandstones, and the upper part of the conglomerate shows evidence of marine reworking. This whole succession represents the initially nonmarine fill of an incised valley, which became progressively more marine as the area was drowned.

The overlying marine sandstones are up to 11 m thick and contain numerous marine body and trace fossils, abundant cross-stratification and ripple marks, and are significantly bioturbated. In places sandstone forms coarsening-upward successions (*e.g.* section 141), but more commonly sandstone intervals are massive at these nearshore localities. Sandstones here are interpreted to have been deposited in the foreshore to upper shoreface, and are examples of facies succession 2. In this area, at or near the palaeoshoreline, marine sandstones of facies succession 2 are thickly interbedded with sandstones containing a mixed marine/nonmarine fossil assemblage. These paralic sandstones of facies succession 6 also belong to the Walker River Formation and are similar to surrounding marine sandstones in most respects, except for a coarser grain size and the presence of plant fossils.

There is one main tongue of brackish sandstone, which can be seen to thin markedly to the south (offshore) until the brackish sandstone interval wedges out (*e.g.* between sections 216 and 31) and is replaced farther offshore by fully marine fossiliferous sandstones of facies succession 2 (*e.g.* section 31). Both the upper and lower contacts of the brackish sandstone are sharp, and in several places the basal contact is defined by erosional incision and a thin lag. Brackish sandstone intervals form massive or fining-upward successions in this region. The interpretation of the depositional environment for sandstones of facies succession 6 is problematic because they are thin, do not occur in many sections, and their three-dimensional geometry is not well defined from the available outcrops. Most probably they represent thin prograding deltaic deposits, but it is difficult to assign a deltaic origin to these deposits with complete confidence because the fluvial source and delta morphology are not recognisable. For these reasons they have been assigned as a more general paralic depositional environment where marine and nonmarine processes were mixed.

The top of the Cretaceous sequence in this area is defined by transgressive fining-upward facies of succession 5, representing deposition in the shoreface to offshore zone. Fining-upward cycles of succession 5 can be confidently correlated between sections in this area, and have a disconformable contact with underlying coarsening-upward and massive sandstones.

The fining-upward succession illustrated in the upper part of correlation diagram D-D' in Fig. 13 is identical to those seen in the ALZ and elsewhere within the BPRZ, and contains the regional C 2 marker. On that basis, this cycle of fining-upward succession 5 is considered correlative throughout the entire northern region. In some places where the marine sediments are very coarse-grained and represent a very high-energy shoreface to foreshore environment, fining-upward succession 5 is not complete (*e.g.* above the shoreface conglomerate in section 141). Here the fining-upward nature of succession 5 is not obvious, and fine-grained facies in the upper part of the succession directly overlie facies of the underlying coarsening-upward or massive shoreface succession. This type of succession occurs in close proximity to the palaeoshoreline, at sites of intense reworking and sediment bypass in the upper shoreface to foreshore zone.

In a previous study, Skwarko (1966, fig. 4) divided the Cretaceous rocks in the area of site TT 65 (between sections 31 and 141) into 3 simplified, conformable units. The basal "unit 1" was interpreted as a lacustrine sandstone, the intermediate "unit 2" as a marine sandstone, and the upper "unit 3" as marine siltstone and claystone. In this study "unit 3" corresponds to marine facies succession 5, including the C 2 marker bed; "unit 2" corresponds to coarsening-upward rocks of facies succession 2; and "unit 1" corresponds to fining-upward transitional marine conglomerate and sandstone at the base of facies succession 2. All of these facies belong to the Walker River Formation. Detailed correlation during this study shows that the contact between the "units" are typically disconformable, and does not support a lacustrine origin for the basal rocks. Despite these differences, Skwarko's (1966) detailed palaeontological analysis is useful for comparison of fossil assemblages between measured sections in the BPRZ, and provides palaeontological detail which is otherwise beyond the scope of this study.

At site TT 65 Skwarko (1966) recorded 7 species of bivalves in sandstones of facies succession 2 (his "unit 2"), but did not record any fossils in the overlying rocks of facies succession 5 (his "unit 3") which includes the C 2 marker bed. The marine origin, sparsely fossiliferous nature, and wide distribution of facies succession 5 as illustrated in the detailed correlation diagram is confirmed by Skwarko (1966, p. 26).

8.3.3 Correlation diagram E - E' (Fig. 14)

This correlation diagram is a continuation of Fig. 13 from Marura Creek to the northern arm of the Walker River (Fig. 12), and illustrates facies variations along a 15.6 km line across the shoreface to offshore transition zone on the inner shelf. As in Fig. 13 most sections are hung on the base of the C 2 marker, which marks the upper part of the

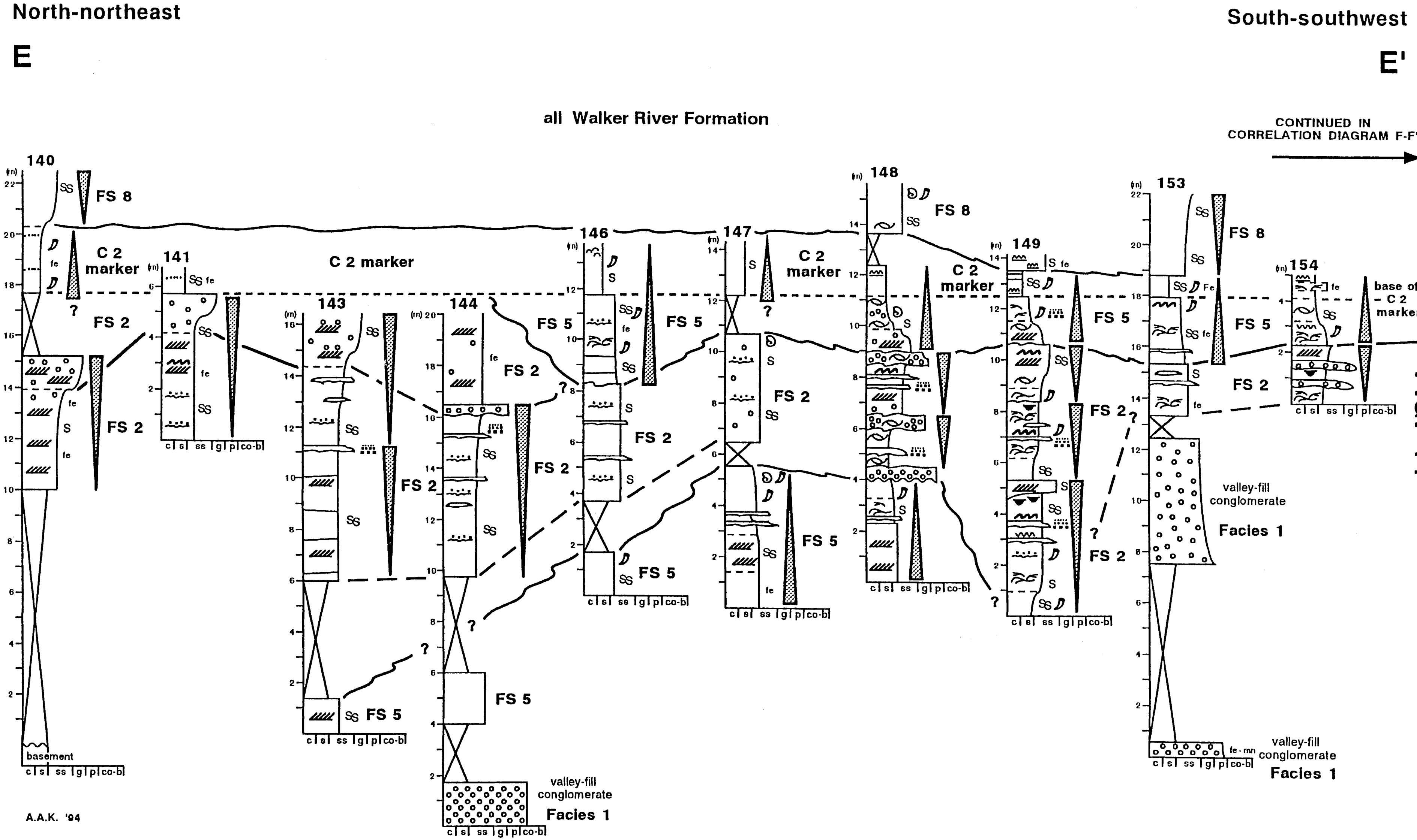


FIG. 14

FIGURE 14. Stratigraphic correlation diagram for the central part of the Bath and Parsons Ranges Zone. Refer to Fig. 6 for legend to symbols, and to Fig. 12 for geographical localities. FS= facies succession.

regionally extensive transgressive marine facies succession in the middle of the Walker River Formation.

In the northern part of the correlation diagram rocks are relatively coarse-grained and were deposited largely above fair-weather wave base, where constant reworking obliterated much of the detail of individual beds. In these areas coarse-grained marine sandstones and shoreface conglomerate dominate the stratigraphy (*e.g.* sections 140, 141, 143, and 144), and finer-grained rocks are poorly preserved. Farther offshore towards the south there is a general trend towards finer-grained rocks, and sedimentary structures and successions are better preserved. Here the stacking patterns of marine cycles are easily recognisable, and detailed correlation between individual coarsening- and fining-upward facies successions is possible.

The base of the sequence in this inner shelf setting is a normally graded chert cobble to pebble conglomerate as described in **8.3.2**. In the area of this correlation diagram this facies is up to 12.5 m thick and overlies Proterozoic basement with an angular unconformity. The conglomerate fines upward into Cretaceous fossiliferous marine sandstone and siltstone of facies succession 5, which occurs at the base of sections 143, 144, 146, 147, and 148 and represents the initial marine incursion in the region. This fining-upward transgressive succession is not preserved to the north (Fig. 13), presumably due to reworking and erosion during subsequent relative sea level fall. The transgressive marine succession is disconformably overlain by a series of stacked coarsening-upward cycles of facies succession 2. The disconformable contact is marked by a pebble conglomerate or shelly lag up to 2m thick (typically 0.5 to 0.75 m thick), which contains clasts or fossil fragments up to cobble size (*e.g.* section 148 at 4 to 4.5 m level). There are at least 3 stacked cycles of succession 2, although the exact number and thickness of all cycles is not always clear due to erosion between cycles. The contacts between coarsening-upward successions are also erosional and are commonly mantled by thinner conglomeratic and shelly lags, or very coarse-grained sandy beds. In the foreshore to upper shoreface zone at the same stratigraphic level in sections 140 through 144, the boundaries of individual coarsening-upward successions are not readily apparent due to the coarse grain size and lack of preserved sedimentary structures relative to areas farther offshore.

A regionally extensive transgressive fining-upward marine cycle disconformably overlies the stacked coarsening-upward successions in the area covered by Fig. 14. The same fining-upward cycle of facies succession 5 is also illustrated in Figs. 9, 10, and 13 and represents a major marine flooding event across the shelf. The contact of this succession with underlying successions is sharp and involves minor transgressive erosion in places, but not to the same degree as erosion which occurred between accumulation of each of the underlying coarsening-upward successions. This sharp contact is occasionally defined by a thin conglomeratic or rip-up lag, but the erosional nature of the contact becomes less obvious farther offshore (see Fig. 15). The preserved thickness of the transgressive facies succession ranges from 2.5 to 5 m, with the upper part composed of fine-grained pelagic facies including the C 2 marker. The thickness of this transgressive succession decreases slightly in an offshore direction along with a general decrease in grain size reflecting retrogradational deposition in a quieter, more distal setting.

The rocks at the top of the Cretaceous shelf succession in this region are composed of clayey fine-grained sandstone and siltstone, and have been grouped as succession 8, which is significantly different from marine facies of successions 2 and 5. Facies of succession 8 represent the upper part of the Walker River Formation and reflect deposition in marine to restricted marine settings, and changes in the energy of the depositional environment are apparent from one outcrop to another. The generally fine grain size, high clay content, fine lamination, and delicate preservation of articulated fossils implies that much of this succession was deposited in low to moderate energy marine settings, such as large bays. However, the presence of HCS and conglomeratic facies in this succession (particularly farther to the south) indicates that quieter sedimentation was episodically overprinted by high-energy storm reworking and rapid deposition.

The contact of succession 8 with underlying transgressive marine facies of succession 5 is sharp and typically disconformable, and the C 2 marker was eroded in places prior to deposition of the overlying rocks of facies succession 8.

8.3.4 Correlation diagram F - F' (Fig. 15)

This correlation diagram is a continuation of correlation diagram E-E' and illustrates the same Cretaceous successions as in Figs. 13 and 14. This correlation diagram forms a 23.5 km line close to the Walker River (Fig. 12). The main differences between the Cretaceous sequence present in Fig. 15 *vs.* Fig. 14 are:

1) the stacked coarsening-upward cycles of facies succession 2 are thicker and better preserved;
2) the basal fining-upward rocks (facies succession 5) overlying the valley-fill conglomerate in Fig. 14 are missing here;
3) the transgressive fining-upward succession disconformably overlying the stacked coarsening-upward successions is missing or greatly reduced in thickness in most places;
4) the preserved thickness of restricted marine deposits of succession 8 at the top of the sequence is much greater;
5) fluvial incision and subsequent deposition of the Yirrkala Formation occurred in this area in close proximity to topographically high-standing basement ridges (*e.g.* section 166), and;
6) in general the evidence for erosion at the contacts between successions is less obvious, although many of these contacts are still disconformable on this part of the inner shelf.

Marine body and trace fossils, and rare plant fossils occur in rocks of facies succession 2, particularly in the south (Fig. 15). At sites TT 66 and TT 67 (close to sections 174 and 184 respectively), Skwarko (1963; 1966) described 9 species of bivalves and indeterminate plant fossils within rocks of facies succession 2. This fossil assemblage is common for the succession, and can be used to aid local correlation. Unfortunately, the age of the fossil assemblage is problematic, and the fossils have poor biostratigraphic resolution (**8.4**).

Good exposure of individual coarsening-upward marine cycles of facies succession 2 in this area allows accurate correlation between successions within the Walker River Formation, and highlights subtle lateral changes in grain size and sedimentary structures within particular coarsening-upward cycles. The contacts between these successions are obviously erosional and feature discrete conglomeratic lags in places, but at the identical stratigraphic level in other outcrops the same erosion surface may be defined by a shelly lag, or just a sharp contact with overlying fine-grained siltstone of the overlying succession. This correlation indicates that individual coarsening-upward successions have a similar thickness in different outcrops, but that grain size (and hence many sedimentary structures) vary laterally within these cycles, particularly in the upper coarse-grained parts of the cycles.

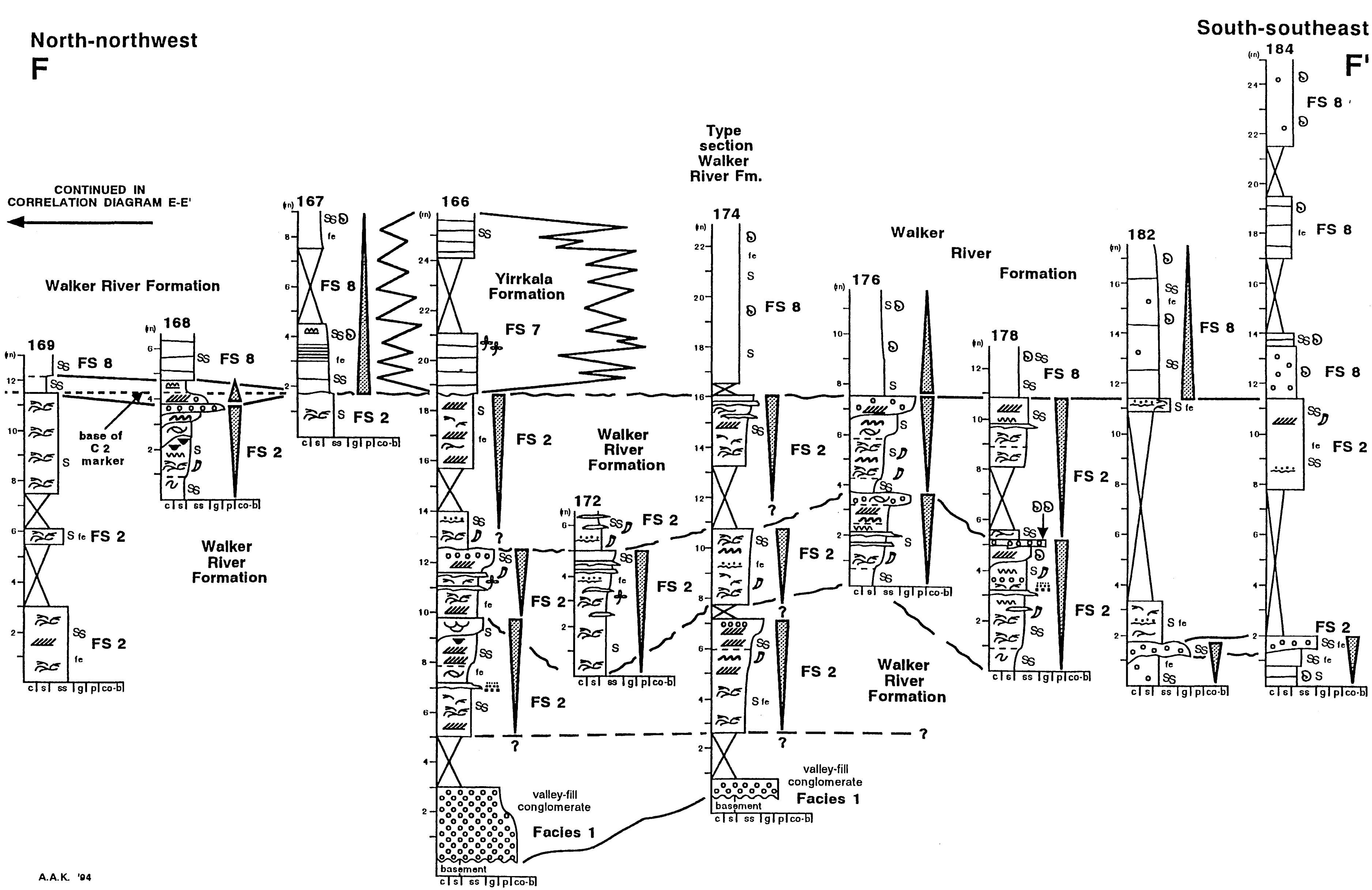


FIG. 15

FIGURE 15. Stratigraphic correlation diagram for the southern part of the Bath and Parsons Ranges Zone. Refer to Fig. 6 for legend to symbols, and to Fig. 12 for geographical localities. FS= facies succession.

Another lateral trend involves the decrease in thickness, and eventual disappearance, of the upper transgressive fining-upward facies succession 5 towards the south. This succession contains the C 2 marker bed and can be traced southwards to the vicinity of section 168 (Fig. 15). South of section 168 the transgressive succession has been eroded by overlying restricted marine to marine facies of succession 8. However, there is a noticeable thinning of the fining-upward succession 5 north of section 168, probably due to condensed sedimentation in more distal regions to the south.

On the inner part of the shelf in the BPRZ there are several areas where Cretaceous facies have an onlapping stratal relationship with high-standing basement terrain. These topographically-high basement regions are not capped by Cretaceous marine facies, and formed islands or barriers on the Cretaceous shelf. However, these basement highs are commonly partly covered by fluvial units (*e.g.* section 166). Fluvial facies here contain unidentified plant fossils of uncertain age, but regional correlation and similarity in lithology and stratigraphic position suggest that these rocks belong to the Yirrkala Formation. Marine deposition on the inner shelf was seemingly concurrent with Cretaceous fluvial deposition on basement highs.

In the south (Fig. 15), coarsening-upward marine cycles of facies succession 2 are immediately overlain by restricted marine to marine facies of succession 8. The contact of succession 8 with underlying coarsening-upward marine succession 2 is sharp and disconformable in most places, but involved only minor erosion farther offshore to the south. In correlation diagram F-F' and areas to the south, the thickness of succession 8 is relatively great, and a gradual increase in thickness of this succession is apparent from Fig. 14 to Fig. 15. Succession 8 becomes thicker and more conglomeratic towards the south, where sedimentary structures indicate an increasing storm influence. This trend is more apparent in Fig. 16.

8.3.5 Correlation diagram G - G' (Fig. 16)

Measured sections in this correlation diagram occur along a 75.4 km line stretching from west of the Walker River to Vaughton Creek (Fig. 12), and illustrate Cretaceous nonmarine, paralic, and shallow-marine depositional environments. In the northern part of correlation diagram G-G' a relatively thin interval of fluvial rocks of the Yirrkala Formation are incised into thick stacked coarsening-upward marine sandstones of the Walker River Formation. Farther to the west and south, near the flanks of topographically-high basement ridges Cretaceous fluvial deposits are much thicker and marine facies were not deposited (*e.g.* sections 37 and 208-210).

Section 208-210 is nominated as the type section of the Yirrkala Formation, and fluvial rocks here overlie Proterozoic basement with an angular unconformity along parts of the eastern edge of the Parsons Range in the southwest of the BPRZ. The upper part of this thick fluvial succession contains rare plant fossils, and is considered correlative with fluvial successions to the north and east, including those at sections 166 and 214. Part of the thick fluvial succession at section 208-210 appears to be equivalent in age to coarsening-upward marine facies of successions 2 and 8 offshore to the east and south. Slightly to the east of section 208-210 and close to the palaeoshoreline, there is a transition from the Cretaceous fluvial succession into a paralic (deltaic or estuarine) succession (*e.g.* upper 3 m of section 37). The paralic rocks of facies succession 6 fine upward and contain rare marine molluscan fossils, shallow-water ripple marks and cross-stratification, indicating an increasing marine influence. The paralic succession is not overlain by marine successions and there is no obvious correlation with marine successions just to the east and south.

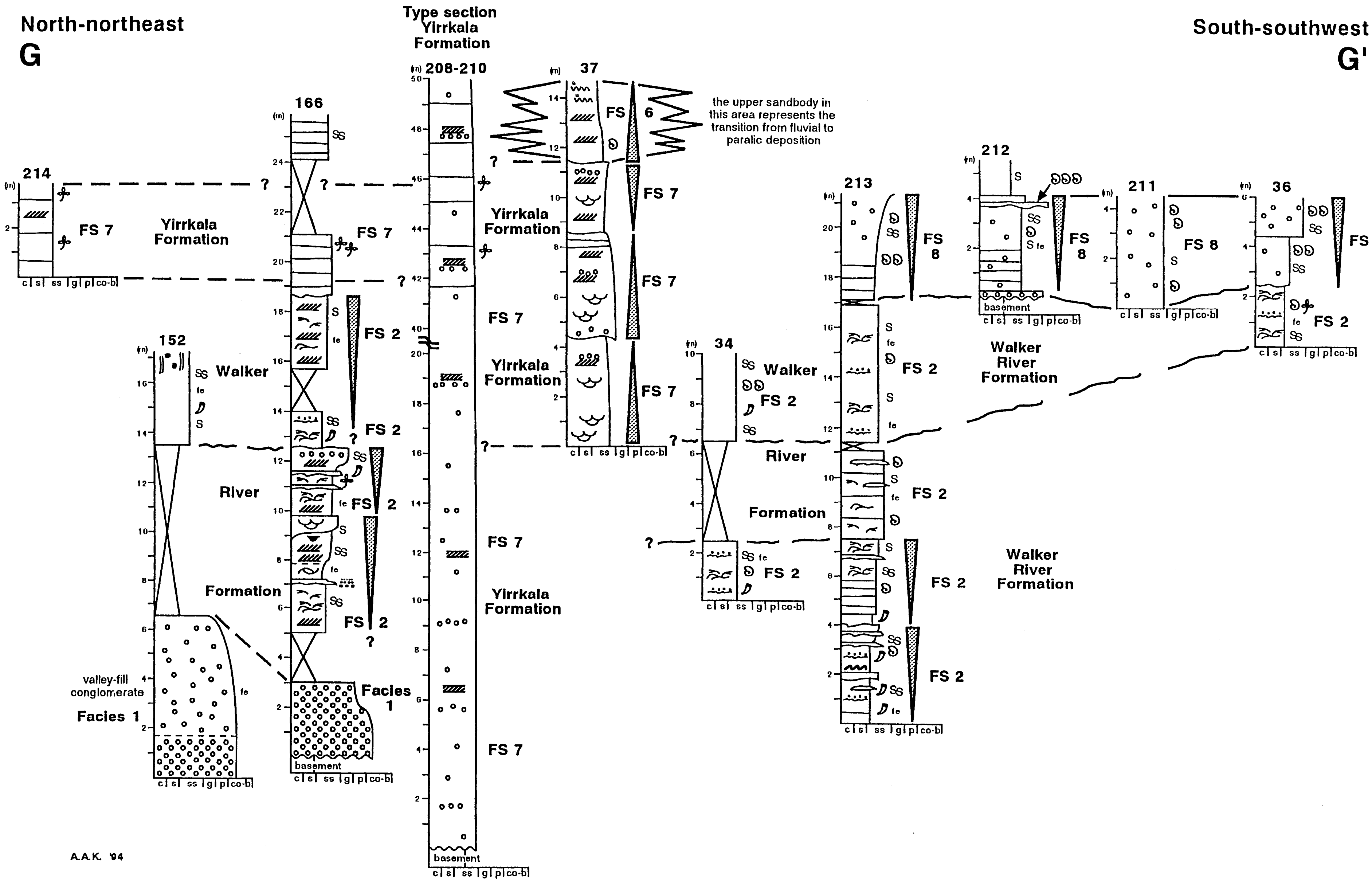


FIG. 16

FIGURE 16. Stratigraphic correlation diagram for the southern part of the Bath and Parsons Ranges Zone. Refer to Fig. 6 for legend to symbols, and to Fig. 12 for geographical localities. FS= facies succession.

However, the paralic succession reflects partial drowning of the alluvial zone which existed along the eastern edge of the north-south striking Parsons Range, and is possibly a facies equivalent of fining-upward facies succession 5 marking maximum transgression on the inner shelf.

Offshore to the south and east of section 37, the Cretaceous sequence is composed entirely of marine facies (successions 2 and 8) of the Walker River Formation. The lower part of the sequence is composed of stacked coarsening-upward and massive cycles of succession 2, similar to those documented to the northeast (*e.g.* Figs. 13, 14, and 15, sections 34, 36, and 213). Similar to the southern half of Fig. 15, the upper transgressive fining-upward succession 5 is missing and storm-influenced restricted marine deposits of succession 8 directly overlie coarsening-upward marine deposits of succession 2 (*e.g.* sections 36 and 213). Facies of succession 8 in Fig. 16 are coarser-grained than similar deposits to the north and show abundant indicators of storms including coquinas, event beds, and dispersed granule to pebble-sized clasts. Comparison of Figs. 15 and 16 highlights the increasing storm-influence and general coarsening of succession 8 to the south. This trend probably indicates a less sheltered depositional environment to the south, and a sheltered restricted-marine environment to the north, sheltered by the topographically-high Bath Range to the east which acted as a barrier for most depositional episodes. In the less-sheltered region to the south, succession 8 has a number of similarities with underlying deposits of succession 2; farther to the northeast differences between the two successions are more readily apparent and they are often separated by transgressive fining-upward deposits of succession 5.

8.3.6 Summary of facies successions in the BPRZ

The oldest Cretaceous rocks observed in *outcrop* in the BPRZ are cobble to pebble chert conglomerate and coarse-grained sandstone at the base of the Walker River Formation which have an angular unconformity with underlying Proterozoic units (Fig. 17). The base of the conglomerate probably represents a fluvial valley-fill conglomerate which becomes reworked upwards and grades into a shoreface marine conglomeratic sandstone. The upper conglomeratic sandstone contains molluscan macrofossils which are inferred to be middle to late Albian in age by regional correlation (Krassay, unpubl. data). The age of the basal cobble conglomerate is problematic because it contains no fossils and directly overlies Proterozoic basement; most likely it is early Aptian in age.

In Fig. 14 the conglomerate and conglomeratic sandstone are apparently overlain by fining-upward marine shoreface rocks (facies succession 5), although the contact between these units was not directly observed. This fining-upward succession represents the first major transgression of the Cretaceous sea in the BPRZ, and drowning of older fluvial and fluvio-deltaic deposits. The fining-upward transgressive succession (or the conglomeratic sandstone where the transgressive succession is missing) is disconformably overlain by stacked coarsening-upward and massive cycles representing shallowing-upward marine shoreface successions (Fig. 17). These cycles are well exposed throughout the region, and compose the entire Cretaceous sequence in places. In nearshore zones (*e.g.* Fig. 13, D-D'), the shallowing-upward shoreface successions are massive, coarser-grained, and are interbedded with sandstone containing mixed nonmarine/marine fossils. These sandbodies only occur close to the palaeoshoreline, thin rapidly in an offshore direction, and represent localised paralic or deltaic depositional environments.

In most parts of the BPRZ stacked coarsening- and shallowing-upward shoreface successions are disconformably overlain by an upper fining-upward transgressive shoreface succession, which marks the middle of the Walker River Formation. This succession marks

FIG. 17

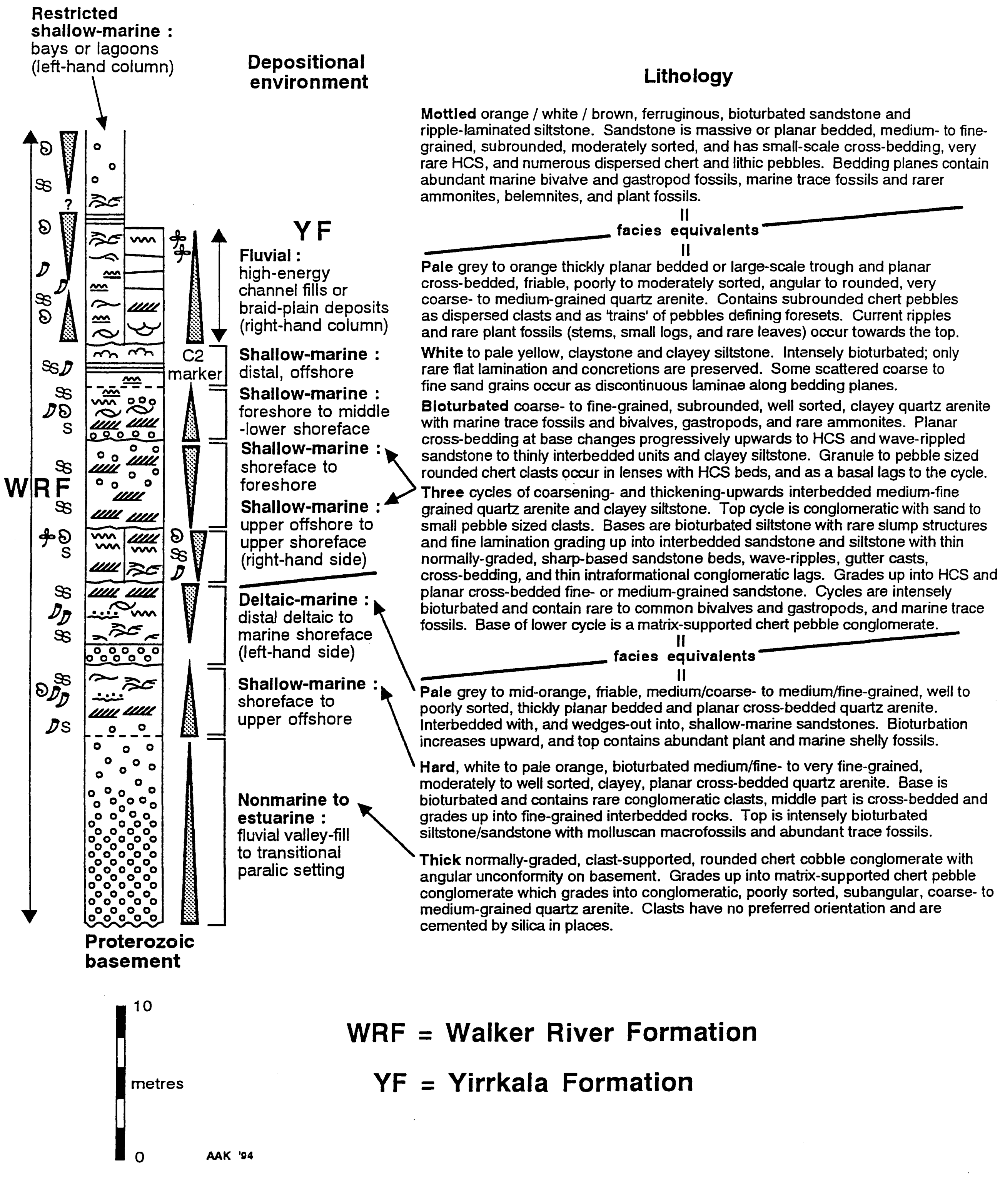


FIGURE 17. Composite Cretaceous section for the Bath and Parsons Ranges Zone (BPRZ). The BPRZ occupies part of the BLUE MUD BAY 1:250,000 map sheet area. The age of the rocks (considered as Aptian to Cenomanian) is known here only by correlation with equivalent dated stratigraphic intervals farther to the south. See Fig. 6 for explanations of symbols used in the section.

the time of maximum transgression on the shelf and can be correlated over the entire study area using the C 2 marker, which occurs toward the top of the fining-upward succession. Where the Cretaceous sequence is complete, restricted marine facies of succession 8 in the upper Walker River Formation overlie the fining-upward transgressive succession with a disconformable contact (Fig. 17). Where the transgressive succession is missing, restricted marine facies directly overlie stacked coarsening- and shallowing-upward shoreface cycles of facies succession 2.

In many areas the restricted marine sandstones and siltstones of facies succession 8 represent the top of the preserved Cretaceous sequence. However, Cretaceous fluvial facies of the Yirrkala Formation are present in close proximity to high-standing basement ridges, and have incised into underlying marine successions. These fluvial successions are facies equivalents of marine successions in other parts of the BPRZ (Fig. 17). Their greatest thickness occurs on the edges of large basement ridges. Rare paralic sandbodies in the upper part of the fluvial succession (*e.g.* top of section 37) represent the transition from a fluvial to a marine depositional environment at the palaeoshoreline. These fluvial and paralic facies successions represent the youngest preserved Cretaceous deposits in the BPRZ.

8.4 BIOSTRATIGRAPHIC CONTROL

Many facies successions in the ALZ are unfossiliferous and biostratigraphic data are highly limited. Body fossils, if present, occur as poorly preserved, low diversity molluscan macrofaunas of indeterminate age. In a previous regional palaeontological study of these rocks (formerly known as the Mullaman Beds), Skwarko (1966) did not record any fossil occurrences in northeastern Arnhem Land. However, during this study a few fossil localities were recorded; for example, at section 25 several ammonites were observed, but their poor preservation precluded positive taxonomic identification and biostratigraphic zoning. Faunas appear to be similar to molluscan macrofossils which occur in Cretaceous facies farther to the south in the BPRZ.

Microfossils were not recovered from any outcrops in the ALZ, and this thus limits biostratigraphic control. However, microfossils from fluvial successions in stratigraphic drillholes in northeastern Arnhem Land yielded a late Albian age (Evans, in Dodson, 1967). The fluvial successions occurring in the stratigraphic drillholes are considered to be correlative with outcrops of fluvial rocks of facies succession 7 in the ALZ, and all are assigned to the Yirrkala Formation.

Biostratigraphic control for Cretaceous outcrops in the BPRZ is similar to the ALZ. That is, there is no accurate biostratigraphic zonation directly available because the only fossils recovered from outcrops are poorly preserved, low diversity molluscan macrofaunas of indeterminate age or trace fossils of no use for biostratigraphic zonation. Ammonites were recorded at several field stations, but their poor preservation precluded positive taxonomic identification and age dating. Laboratory analysis of samples from the BPRZ for microfossils proved fruitless, probably due to the high degree of chemical alteration in most outcrops.

The molluscan faunas of the Walker River Formation in the BPRZ appear similar in all respects to molluscan macrofossils which occur in Cretaceous marine facies farther to the north in the ALZ, and to the south of Arnhem Land. Plant fossils observed in the Yirrkala Formation in the BPRZ appear to have similar sizes, affinities, and styles of preservation in all outcrops. However, the plant fossils are not diagnostic of any particular age, and may only be regarded as being Upper Mesozoic in age (Skwarko, 1966, p. 32).

The details of marine macrofossil assemblages in these rocks (equivalent to part of the "Coastal Belt") were presented in a previous palaeontologically-based study (Skwarko, 1966). Skwarko regarded these rocks as being generally Neocomian and Aptian in age, with rarer Albian-aged rocks. However, microfossil age determinations and regional correlations as part of a larger study (see also biostratigraphic zonation in **5.1** and **5.2**) indicate that all Cretaceous facies successions illustrated in Figs. 13, 14, 15, and 16 are younger than middle Albian.

Skwarko's stratigraphic interpretations are based on recognition and correlation of fossil assemblages from widely spaced outcrops of unknown age. Although Skwarko's (1966) palaeontological age determinations appear to be superseded, his study documents fossil systematics and the fine details of fossil assemblages which are beyond the scope of the present study. Using these data, fossil assemblages can be compared between widely spaced outcrops in the onshore western Carpentaria Basin, and can be used to test or refine lithostratigraphic correlations made during the present study.

Trace fossils are often well preserved in the Walker River Formation in northeastern Arnhem Land, and also assist in initial correlation of successions in many areas where other fossils are absent and the environments of deposition are not readily apparent from sedimentological criteria alone. There is no apparent biostratigraphic zonation based on trace fossils, and similar trace fossils occur within particular facies independent of age, at least for mid-Cretaceous times.

9. REGIONAL CORRELATION OF COMPOSITE OUTCROP SECTIONS

The following section documents regional lithostratigraphic correlations in northeastern Arnhem Land, encompassing the Arnhem Land Zone (ALZ) and the Bath and Parsons Ranges Zone (BPRZ).

Construction of the composite sections was based on measured sections from isolated "spot" outcrops and their local correlation as illustrated in Figs. 9 and 10 and Figs. 13 through 16. Individual components of the composite sections in Fig. 18 represent the maximum thickness of a given succession on a particular region of the shelf, and were compiled to yield the stratigraphic section with the least interference by erosion. Even so, the amount of erosion on proximal parts of the shelf was high and many of the thicknesses shown in the composite sections are likely to be minimum values.

The shelf sequence can also be broadly subdivided into 3 parts on the basis of age; the basal part (exposed in the BPRZ) is composed of relatively coarse-grained Early Cretaceous nonmarine and Aptian marine rocks (Walker River Formation); the intermediate part is composed of finer-grained marine and paralic rocks of Albian age (Walker River Formation); and the upper part is composed of fine-grained marine and restricted marine rocks (Walker River Formation), and nonmarine rocks (Yirrkala Formation), mostly of Cenomanian age. Clearly, the Cretaceous sequence could be divided into a greater number of units, but these would be difficult to map, and therefore impractical to define as formations. The new nomenclature is the simplest practical scheme.

The only prominent marker bed, the C 2 marker whose top marks the base of the upper (post-Albian) part of the shelf succession, is common in more complete outcrops of the Walker River Formation in northeastern Arnhem Land. The C2 marker bed is composed of silty claystone and very fine-grained siltstone and has a maximum thickness of 3 m in the

FIG. 18

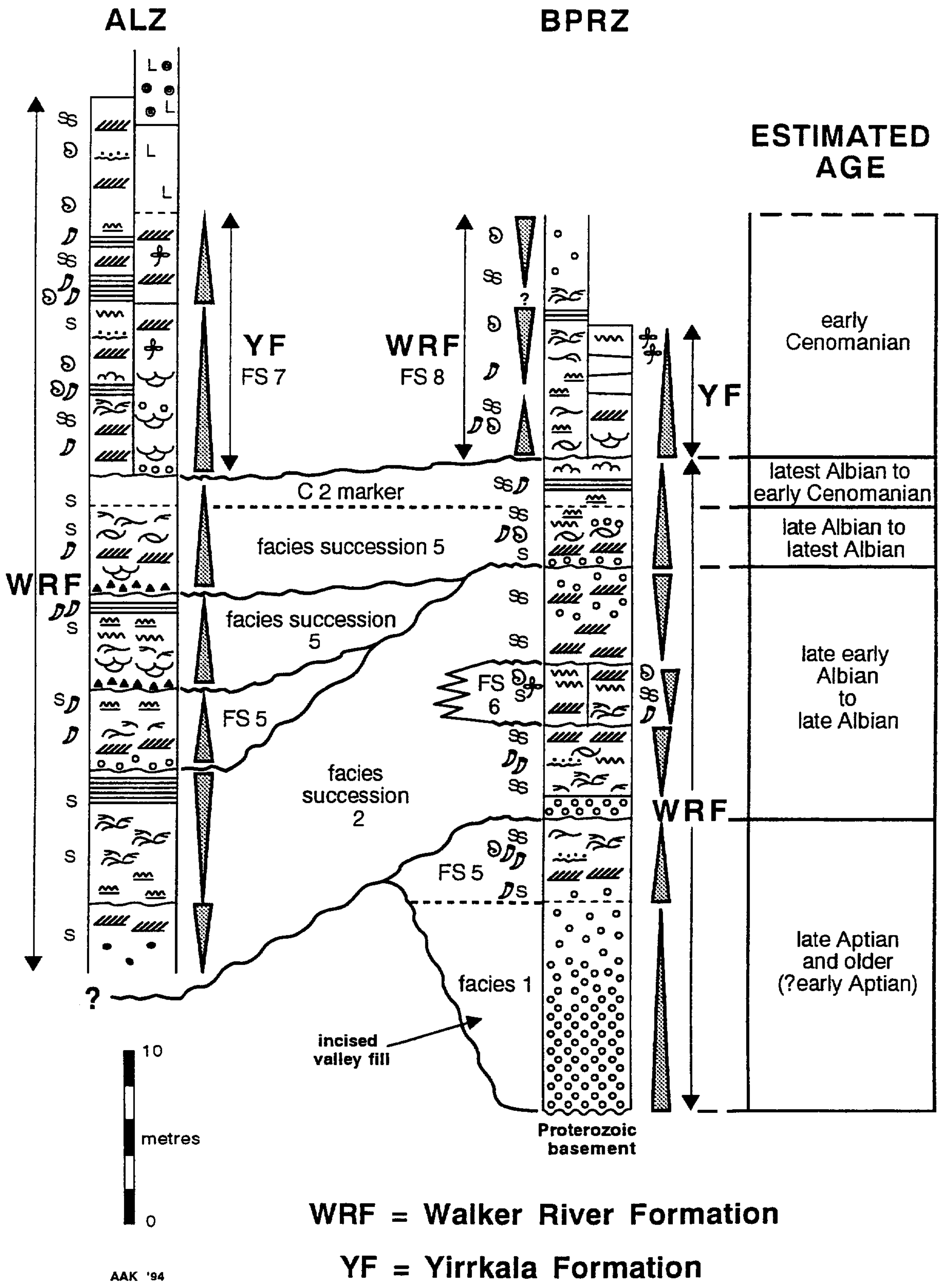


FIGURE 18. Regional facies successions, lithostratigraphic correlations, and estimated ages of Cretaceous rocks in northeastern Arnhem Land. Age estimates are based on regional correlations and biostratigraphic analyses as part of a larger study. FS = facies succession.

BPRZ. The preserved thickness of the C2 marker varies across the shelf in response to the amount of erosion prior to deposition of overlying successions. Evidence for erosional thinning and truncation of the C2 marker bed is evident in numerous localities in the northern and central regions.

In northeastern Arnhem Land the C2 marker is incised by fluvial rocks of facies succession 7 (Yirrkala Formation). The amount of fluvial incision varies laterally, and the C2 marker bed and upper part of facies succession 5 have been completely eroded in places. At the same stratigraphic level in low-lying areas closer to the coast, such as in the BPRZ and the northwestern edge of the ALZ, the C2 marker is incised by thick restricted marine deposits of facies succession 8.

In all areas the broad age equivalence of rocks of succession 7 (Yirrkala Formation) and succession 8 (upper Walker River Formation) overlying the C2 marker can be clearly seen; lateral facies changes between the two successions are visible over distances of a few kilometres, and they both exhibit the same stratigraphic relationship with underlying marine successions (Figs. 11 and 17). In Fig. 18 the composite sections are hung relative to the C2 marker interval. The depth to basement varies greatly across the shelf, and the basement topography becomes more obvious to the northwest where basement units are exposed and progressively younger marine rocks of the Walker River Formation onlap basement terrain.

Further evidence for an irregular basement topography is given by the irregular exposure of basement highs across the region, and by the varying thickness of the Cretaceous sequence and depth to basement measurements in drillholes across the shelf. In the northern region, the Nhulunbuy drillhole logs indicate that the basement topography varies by as much as 123 m over a lateral distance of less than 5 km (Dodson, 1967). Seismic lines offshore from the northern and central regions also show irregular basement topography on the western shelf of the Carpentaria Basin (Burgess, 1984; Thomas *et al.*, 1992).

9.1 SHELF-TO-BASIN REGIONAL CORRELATION: STRATIGRAPHIC TIES TO THE GREAT ARTESIAN BASIN

The age-range of the Walker River and Yirrkala Formations has been documented as Aptian to early Cenomanian (5). Comparison with the ages of various formations of the central Carpentaria Basin (documented from onshore drillholes, Meyers, 1969; Passmore, 1979; Smart, 1976; Smart *et al.*, 1980), suggests that the Walker River and Yirrkala Formations are equivalent to the stratigraphic interval represented by the upper Gilbert River Formation and the Rolling Downs Group.

The oldest exposed rocks of the shelf succession are thick conglomerates at the base of the Walker River Formation which grade up into paralic and marine facies. The exact age of these rocks is unknown, but they are older than late Aptian. These rocks may be equivalent in part to the Gilbert River Formation, and may be Early Cretaceous in age. Although previous correlations (*e.g.* Meyers, 1969) suggest that the Gilbert River Formation does not extend west onto the shelf, it is likely that isolated remnants of the formation occur near the base of the Cretaceous shelf sequence in topographic lows. The base of the sequence in the BPRZ has many similarities with the Gilbert River Formation in terms of lithology and depositional environments.

Fining-upward sandstone and siltstone (*e.g.* FS 5 in the BPRZ) have been correlated with late Aptian-aged rocks, and thus correspond to the lower Wallumbilla Formation, which is quite sandy in places. Overlying stacked coarsening- (and sandier-) upward cycles in the ALZ and BPRZ are middle Albian to late Albian in age (by correlation); the same age as the upper Wallumbilla Formation, Toolebuc Formation, and the Allaru Mudstone in the central Carpentaria Basin.

Significantly, the Toolebuc Formation was not recognised anywhere on the shelf, and there are no bituminous and calcareous units within the Walker River Formation that are obvious candidates as shelfal equivalents of this formation. According to correlation in the present study, the Toolebuc Formation does not extend onto the western shelf of the Carpentaria Basin. Other workers have also noted the absence of the Toolebuc Formation at the margins of the Carpentaria Basin, and Haig and Lynch (1993) state that at latitudes north of 16^0 S the Wilgunya Subgroup cannot be subdivided into formations (Wallumbilla vs. Allaru) due to the absence of the lithologically distinctive Toolebuc Formation.

In the absence of the Toolebuc Formation on the shelf, the stratigraphic level of the contact between the Wallumbilla Formation and Allaru Mudstone is thought to occur somewhere within the stacked coarsening- (and sandier-) upward cycles of facies succession 2 in the Walker River Formation in the BPRZ. The overlying stacked fining-upward sandstones of facies succession 5 (including the C 2 marker) in northeastern Arnhem Land, are considered through regional correlation to be late Albian to latest Albian in age, and thus are probably coarse-grained equivalents of the Allaru Mudstone.

The age-range of late Albian to early Cenomanian reported for the Normanton Formation is similar to the age of the C2 marker and underlying shoreface sandstones in the northern and central regions of the shelf (Fig. 18). However, I propose that the C2 marker bed and underlying fining-upward sandstones of the Walker River Formation correspond to the transgressive Allaru Mudstone, whilst overlying early Cenomanian fluvial rocks (Yirrkala Formation) and restricted marine rocks (Walker River Formation) correspond to the regressive Normanton Formation. Thus, in northeastern Arnhem Land the C2 marker probably corresponds to the top of the Allaru Mudstone, and is incised by fluvial and nonmarine rocks equivalent to the Normanton Formation.

10. REGIONAL PALAEOGEOGRAPHY AND PALAEOCLIMATE

Reconstructions for the mid-Cretaceous indicate that the western shelf of the Carpentaria Basin lay at latitudes between 55^0 and 65^0 S (Embleton, 1984). The main marine connection of the Carpentaria Basin occurred to the north, over the Bramwell Arch into the Papuan Basin, and ultimately with the Cretaceous Pacific Ocean (Riccardi, 1991). Throughout most of the Aptian and Albian the narrowest part of the Great Artesian Basin epeiric seaway, at about the latitude of Weipa (Fig. 2), had an east-west dimension of over 500 km (Frakes *et al.*, 1987). Farther to the south along most of the shelf, the east-west dimension of the seaway exceeded 750 km.

The nature of the palaeoclimate of the Great Artesian Basin and surrounding regions during the Cretaceous is controversial because, despite the general acceptance of a warm Cretaceous Period, there is evidence which suggests that surface waters of the Great Artesian Basin were cool to cold (Dettmann and Playford, 1969; Dettmann *et al.*, 1992; Frakes and Francis, 1988; Gregory *et al.*, 1989; Haig, 1979; Haig and Barnbaum, 1978; Rich *et al.*, 1988). Winter temperatures were likely cold enough to produce seasonal freezing along shorelines in the mid-Cretaceous, probably at least during the late Aptian (Frakes and Krassay, 1992). Surface temperatures appear to have increased through the Albian and into the Cenomanian

(Dettmann, 1981), and may have been conducive to hurricane generation in the mid-Cretaceous Pacific Ocean.

Palaeoclimate modelling shows a Pacific Ocean high pressure zone at latitude 30^0 S during the peak hurricane generation period for the mid-Cretaceous (Barron, 1989, fig. 9). This high pressure zone would have been relatively close to the northern marine connection with the Great Artesian Basin, and may have been responsible for large storms that affected the western epeiric shelf of the Carpentaria Basin. Model predictions for winter storms in the southern hemisphere (Barron, 1989, fig. 10) show a winter storm belt at latitudes between 40^0 and 70^0 S, but it is poorly developed and highly zonal. However, there would have been potential for winter storm generation just to the northeast of the northern oceanic connection of the Carpentaria Basin.

It has been documented that fluctuations in relative sea level and climatic conditions caused key oceanographic parameters, such as palaeogeography, palaeobathymetry, stratification, wind stresses, and boundary tides, to vary throughout the history of the Cretaceous Interior Seaway of North America (Ericksen and Slingerland, 1990). There are many similarities between the Great Artesian Basin seaway and the Cretaceous Interior Seaway of North America including their long north-south axes, the 5 or 6 major transgressive-regressive cycles which characterised the seaways, and their general intracratonic setting and Cretaceous palaeogeography (despite the lack of topographically-significant mountain belts on the margins of the Great Artesian Basin seaway).

Considering the broad palaeogeographical similarities of the two seaways, it is probable that fluctuations in relative sea level and climate also controlled oceanographic parameters in the Great Artesian Basin seaway of Australia. Such fluctuations, in turn, would have caused variations in circulation and sediment-transport regimes, but these are not yet documented. What is known is that the Great Artesian Basin involved a large, uninterrupted marine connection to the northwest and northeast with storm centres in the mid-Cretaceous Pacific Ocean, and storm-influenced deposits occur in great abundance and regional extent within the Walker River Formation, including the northeastern Arnhem Land region (Krassay, 1994).

10.1 SHELF DYNAMICS

Wave-generated structures are common in Cretaceous sediments of northeastern Arnhem Land. This indicates that water depth was less than about 100 m, and probably less than 50 m during most depositional episodes. Limited lithological data (grainsize, sorting, sedimentary structures *etc.*) from stratigraphic boreholes in the onshore part of the central Carpentaria Basin (Smart *et al.*, 1980) suggest that the water depth in the depocentre was considerably greater, and probably more than 150 m.

On the basis of foraminiferal evidence Haig and Lynch (1993) have suggested water depths of 150 m for the northern Carpentaria Basin, and 50-100 m for the southeastern Carpentaria Basin during maximum flooding in the late early Albian to late Albian (the time of accumulation of stacked shoreface deposits of the Walker River Formation in the BPRZ). Somewhat lesser water depths are envisaged for the shelf along the western and southwestern margin of the Carpentaria Basin, probably less than 50 m in most places. The change in bathymetry during the transgressive pulse was greatest in the northern marginal basins (possibly a deepening of 100 m or more), and decreased to the southeast (about 10-20 m) where sand deposition occurred (Haig and Lynch, 1993).

Trace fossils of the Walker River Formation belong a· ·t exclusively to the *Skolithos* and *Cruziana* ichnofacies (5 and 6), and give clues to th ·laeobathymetry of the shelf. The *Skolithos* ichnofacies typifies rather high-energy hydrodynamic conditions in clean winnowed sediments that are subject to abrupt erosion or deposition (Ekdale, 1988). This is highlighted in the Walker River Formation where trace fossils of the *Skolithos* ichnofacies are abundant within high-energy shallow marine deposits of facies successions 2 and 5 in northeastern Arnhem Land. The *Cruziana* ichnofacies typically occurs below normal wave base (but not necessarily below storm wave base) in environments of somewhat lower-energy hydrodynamic conditions in muddy and clean sands and silts (Ekdale, 1988). Such trace fossils and substrates exist in fine-grained rocks of facies successions 2 and 5 in the Walker River Formation. The trace fossils documented on the Carpentaria Basin shelf provide additional evidence that the water depth was consistent with an intertidal to inner neritic setting.

10.2 SEDIMENT SUPPLY, SHELF PROFILE, AND SHELF CIRCULATION

During the mid-Cretaceous the depositional setting of the western Carpentaria Basin was a broad shelf with a width of more than 200 km in places, and an estimated gradient of less than one degree. The low gradient of the shelf is extrapolated from the depositional gradient and bedding attitude of Cretaceous strata from offshore shallow seismic lines (*e.g.* Passmore *et al.*, 1992; Thomas *et al.*, 1992), and from variations in the stratigraphic height of the C2 marker bed in northeastern Arnhem Land.

A very shallow, broad, gently-sloping shelf such as the western margin of the Carpentaria Basin produces a conceptual problem in terms of the rate of sediment supply across the shelf. Given a high sediment supply in such a setting, the shoreface would rapidly prograde, fill in the accommodation space available on the shelf, and potentially narrow the seaway (*cf.* Cotter, 1990). This would occur even with most rates of relative sea level rise. However, the shelf appears to have maintained a low gradient throughout the mid-Cretaceous without the formation of many thick, regionally extensive, prograding sandbodies; *i.e.* at most times accommodation space was not filled.

There are three important reasons for this: Firstly, the low sediment supply and reworking of older sedimentary rocks is documented by the local provenance of much of the Walker River Formation, where clear trends in the lateral extent and thickness of coarse-grained sediment wedges shed off Proterozoic and Cambrian landmasses are apparent along the western margin of the shelf. The intense degree of bioturbation of most marine sediments also provides evidence for low sedimentation rates (except for episodic storm sedimentation) on the shelf. The low-diversity trace fossil assemblages of the Walker River Formation, combined with the high degree of bioturbation, lead to the inference that sedimentation was slow and there was little physical reworking (*cf.* Maples and Suttner, 1990), except during storms when there was intense physical reworking and rapid deposition.

Secondly, nearly all of the sandstones (and most finer-grained rocks) on the shelf have supermature to mature compositions and mature to supermature textures. The maturity of the rocks is indicated by their high ratio of quartz + chert grains compared to feldspar + rock fragments, their negligible matrix content, their moderate to good sorting, and the subrounded to rounded nature of the grains (see detailed rock descriptions in the OZROX database). This suggests that sediment delivered to the shelf was reworked extensively by shallow-marine processes, including during storms, and that rapid burial and removal (isolation) of sediment from the erosional/depositional 'cycle' on the shelf was uncommon.

Thirdly, subsidence appears to have been steady and slow (with little structural displacement), and was limited to gentle sagging away from basement highs (Passmore, 1979; Passmore *et al.*, 1993; Smart *et al.*, 1980). The low rate of sediment supply, the intense storm reworking of accumulated sediment, and the postulated dominance of sea level fluctuation over and above subsidence, appear to have combined to maintain the shelf as a stable feature and to keep the seaway open. Judging by the preserved sedimentary structures, the depositional surface of the shelf was maintained approximately between average storm wave base and sea level. This combination of parameters has been reported in other shallow marine shelves and ramps where the depositional gradient is very gentle (*e.g.* Cotter, 1990), and has resulted in the formation of thin, small-scale coarsening- and shallowing-upwards sequences similar to those of the Walker River Formation.

Due to the regional scope of the study and the large distances between outcrops there is a general lack of closely-spaced palaeocurrent data, although regional trends are apparent. Tool markings in HCS beds and associated gutters in the Walker River Formation in the BPRZ show offshore palaeocurrent directions, normally to the east and southeast, but to the west in palaeoembayments with an eastern barrier. The situation is more complex for coarser-grained intervals with planar- and trough-cross stratification in the Walker River Formation, and interbedded intervals with current-ripples and ripple cross-stratification. Here palaeocurrent directions indicate a major along-shore or slightly oblique-to-shore palaeoflow to the south and southwest, with a minor opposing palaeoflow to the northeast. These structures were probably formed by longer term, time-averaged flow reflecting the net along-shore transport direction, whereas tool markings and gutter casts were likely to have been formed by instantaneous bed shear stresses during peak storm conditions (*e.g.* Duke *et al.*, 1991).

Cross-bedding in fluvial rocks at the base of the Walker River Formation, and throughout the Yirrkala Formation indicate fluvial transport (and the palaeoslope) broadly to the east-southeast and southeast. Deltaic progradation (interbedded facies succession 6 sandbodies in the Walker River Formation) in the BPRZ occurred to the south, in the direction of the marine connection of the large palaeoembayment.

The regional trends suggest a complex combined flow regime on the shelf during accumulation of the Walker River and Yirrkala Formations in the mid-Cretaceous. This is supported by regional analysis of sedimentary facies of the Carpentaria and Eromanga Basins for the middle to late Albian (Ozimic, 1986), which shows a regional north to south bottom flow along the western shelf of the Carpentaria Basin. Further, computer modelling predicts counter-clockwise circulation in the Cretaceous Pacific Ocean to the north of the Carpentaria Basin (Barron and Peterson, 1990).

11. PALAEOGEOGRAPHY OF NORTHEASTERN ARNHEM LAND

11.1 INTRODUCTION

The western shoreline of the shelf had a regional north-northeast orientation in the mid-Cretaceous, changing to a north-northwest palaeoshoreline trend along the southern half of the shelf. However, at times of significant transgression the shoreline had a ragged irregular profile with arms of the seaway extending much farther to the west in some places than in others.

The size and shape of the sea during various times in the mid-Cretaceous was greatly affected by the pre-existing topography of the landsurface across which it flooded. Many large high-standing basement terrains existed as islands and peninsulas along the western margin of the shelf, and formed barriers to westward transgression during times of Cretaceous inundation. The position, size, and type of these basement blocks is summarised in Table 3, and illustrated in Fig. 19. The local effects of these basement blocks upon the paths of transgression, positions of the palaeoshoreline, and the accumulation of Cretaceous sediments, are discussed in the following sections.

TABLE 3. Major mainland basement blocks which affected Cretaceous palaeogeography.

Basement terrain #	Region	Local name (informal)	Shape/type of basement block	exposed Length x width (km)*	Composition and age
1	ALZ	Mitchell Range	elongate strike range	115 x 15	Proterozoic sedimentary rocks
2	ALZ	Dhalingbuy area blocks	elongate ridges	various < 30 x 8	Proterozoic sedimentary rocks
3	ALZ	granite island chain	linear NE-trending chain of small blocks	various < 15 x 12	Archean and Proterozoic granites
4	BPRZ	Bath Range block	NNE-trending strike range	40 x 15	Proterozoic McArthur Group
5	BPRZ	Parsons Range block	NNE-trending strike range	75 x 15	Proterozoic Parsons Range Group sedimentary rocks
6	BPRZ	central spur	NNE-trending ridge	25 x 15	Proterozoic Parsons Range Group sedimentary rocks
7	Arnhem Land	Jalboi block	irregular crescent-shaped block	90 x 55	Proterozoic Roper Group sedimentary rocks

* The length and width are estimates of maximum values; the exact area of basement terrains cannot be calculated from these figures because most basement blocks had irregular widths along their length.

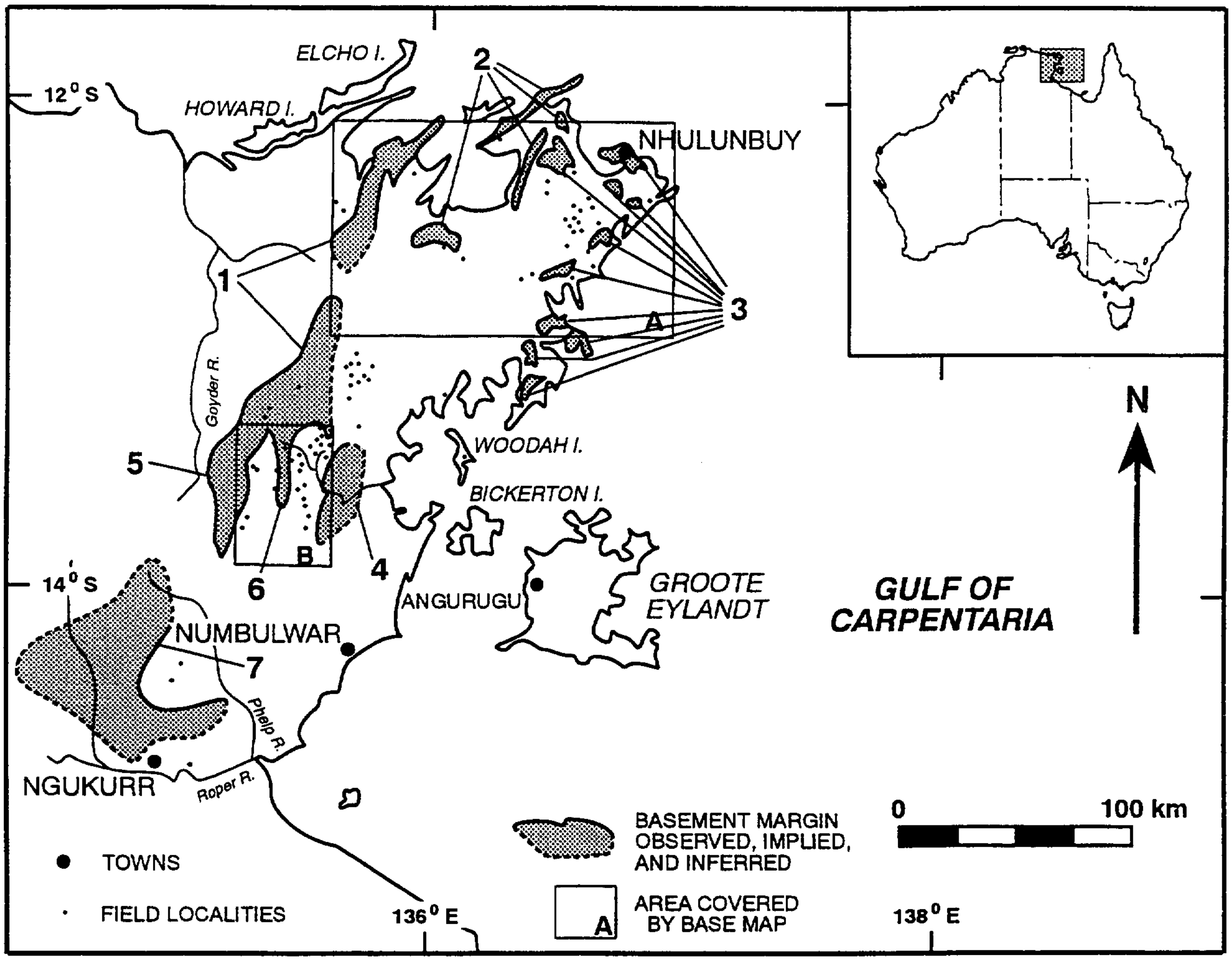


FIGURE 19. Location of major basement terrains within northeastern Arnhem Land which affected Cretaceous palaeogeography. For more details on the nature of the numbered basement terrains refer to Table 3 in main text.

11.2 PALAEOGEOGRAPHY OF THE ARNHEM LAND ZONE

The three prominent palaeogeographic elements of the ALZ which influenced Cretaceous sedimentation are as follows (see Table 3 and Fig. 19):

1) the northeast-trending Mitchell Range (terrain #1) in the west;
2) a zone of northeast-trending Proterozoic sedimentary rocks (terrain #2) lying south and east of Arnhem Bay; and
3) a belt of largely crystalline rocks (terrain #3) trending north-northeast along the present Gulf of Carpentaria coastline.

Ridges of Proterozoic rocks and a belt of granitic inliers with a north-northeast structural trend were exposed in the ALZ and served as barriers to transgressions of the sea at various times during the mid-Cretaceous. Notable among these was the Mitchell Range, which restricted the sea on the west. The stratigraphic position of Mesozoic onlap, the regional lateral continuity of marginal shelf facies, and the localised nature of coarse-grained sediment wedges shed off the Proterozoic ridges, indicate that these ridges and granitic terrains had relatively low topographic elevations during the Cretaceous. These ridges and terrains probably would not have interrupted the flow of prevailing winds, although they were islands, and provided partial barriers to marine circulation and resulted in the formation of several large palaeoembayments.

It is likely that the main Cretaceous inner shallow-marine basin in the ALZ lay between the Mitchell Range (terrain #1) and the granite island chain (terrain #3), with extensions to the open sea being mainly to the east through breaks in the granite chain in the Dalywoi Bay and Caledon Bay areas (at about latitudes 12^0 20' S and 12^0 50' S respectively). Maximum flooding of the northern shelf came from the open sea located to the east and southeast, as indicated by lateral facies changes to more distal (finer-grained) sedimentation in these directions. Arms of this sea are also interpreted to have extended to the Groote Eylandt area.

Landward of the intermittent belt of granitic islands, deposition of the Walker River Formation on the mainland was restricted by basement ridges in the Dhalingbuy (terrain #2) and Mitchell Range areas, and there was thus limited deposition in areas in the north of the Arnhem peninsula and in western Arnhem Land. Cretaceous sediments in these more distant areas (Arnhem peninsula) are thin and patchy in their distribution and probably relate to transgressions of unknown ages from the Arafura Sea to the north (west of the Mitchell Range).

Sediments derived from the bounding ridges in the Dhalingbuy and Mitchell Range areas were deposited relatively rapidly, and thin sheets of marine sandstone were spread over most northern parts of the shelf; these were later eroded and reworked by fluvial systems, primarily in the late Albian. Ferruginous and/or manganiferous sandstone of facies successions 2 lies adjacent to and southeast of the basement ridge near Arnhem Bay in the Dhalingbuy area, and the basement ridge apparently served to provide the sand so thickly developed and to block marine transgression any farther to the southwest.

The dominant marine rock type in the ALZ is sandstone, except for interbedded siltstones in facies succession 8 and siltstone-claystone developed at the top of facies succession 5. This relatively coarse-grained material was apparently derived from the basement terrains surrounding marine Cretaceous deposits. Energy conditions were high during accumulation of the Walker River Formation, and judging from occurrences of HCS and gutters, storm waves were generated at times. The sediment supply rate was not high however, because the sediment cover on this broad shelfal platform is thin and discontinuous. Disconformities throughout the sequence indicate that this was a "cannibalising" shelf, with just-deposited sediments being reworked through subaerial erosion during regressions and submarine erosion during transgressions (Krassay, 1992). Nonmarine and restricted marine deposits of facies successions 7 and 8 respectively occur only in proximal areas that were close to the palaeoshoreline.

The directions of sediment transport during transgression and regression can be generalised as nonmarine and marine progradation towards the east and southeast during times of regression, and coastal onlap towards the north and northwest during transgression. Sedimentary facies suggest only a slight decrease in grain size from west to east in the ALZ, but this trend becomes more pronounced farther south along the shelf. The ALZ has abundant palaeogeographical parallels with the Groote Eylandt area during the Early Cretaceous in that it was characterised by shallow-marine embayments with low sedimentation rates.

11.3 PALAEOGEOGRAPHY OF THE BATH AND PARSONS RANGE ZONE

Significant areas of exposed Cretaceous rocks occur in a sizeable embayment (approximate area of 2400 km^2) between the Bath and Parsons Ranges, which was flooded at various times. Here, the Walker River Formation onlaps the flanks of both ranges and the area where the ranges converge in the vicinity of section 33. Sections examined along these ancient shorelines consist of conglomerates and sandstones of the Walker River Formation, with only minor siltstone and claystone. The sandstones, of facies successions 2 and 5, contain coarse and angular grains directly derived from the adjacent source rocks, and clasts in the conglomerates show a local provenance (especially chert).

Near the central spur (terrain #6), the sandstones are very coarse-grained (*e.g.* section 152). On the western side of the palaeoembayment small sandstone 'deltas' composed of facies succession 6 are preserved in smaller embayments in the Parsons Range (*e.g.* sections 37, 208-210). This all constitutes strong evidence that conditions here were quite different from the ALZ; erosion was active and sedimentation was comparatively rapid. Even near the centre of the embayment accumulation of sand dominated, and finer-grained material is present only in minor amounts. The stratigraphic repetition of fossiliferous sandstones of facies succession 2 reflects the unusual palaeogeography in the northern end of the Bath and Parsons Range embayment, which resulted in rapid facies changes and large-scale interbedding of marine and paralic units in the proximal part of the embayment.

This large palaeoembayment was connected to the open sea in the south, in the area north of Numbulwar. No other link to the sea is possible owing to the elevated terrain (up to 300 m above sea level (a.s.l.)) surrounding the Bath-Parsons Ranges Cretaceous outcrops, which lie at elevations of less than 130 m a.s.l.. Over time this seaway deepened, as indicated by upward fining of the sequence and the presence of thick highstand and transgressive deposits.

Accepting an age of early Albian to early Cenomanian for rocks in northeastern Arnhem Land leads to a reasonable reinterpretation of the palaeogeography of northeastern Arnhem Land, including the Groote Eylandt region. There is no longer a need, for example, for a "barrier" between the so-called coastal and inland belts of Skwarko (1966), sedimentary evidence for which is lacking in northeastern Arnhem Land in any case. Instead, each facies succession is seen to have been deposited within the confines of an embayment or sub-basin. Several of these large embayments existed at various times on the broad shallow shelf which deepened eastward into the Carpentaria Basin.

12. ECONOMIC GEOLOGY

Accumulations of bauxite, iron, manganese, and clay within Cretaceous and Tertiary rocks of northeastern Arnhem Land documented herein all have some potential economic importance. Known economic resources are, firstly, large bauxite reserves of the Gove Peninsula in the far northeastern part of northeastern Arnhem Land about 10 km south of Nhulunbuy. Secondly, the Cretaceous shelf sequence is host to a large sedimentary manganese deposit (oxides and carbonates) on Groote Eylandt, about 45 km offshore to the southeast of Arnhem Land. Both of these resources are currently being exploited.

There is little, if any, obvious relationship between either of the ferricretes described in this study and the bauxites of the Gove Peninsula near Nhulunbuy. In general, the ferricretes associated with the Walker River and Yirrkala Formations are less commonly pisolitic, have much poorer sorting, contain higher percentages of contaminants (weathered lithic clasts), and have higher proportions of silty kaolinitic clay and quartz sand, compared to the bauxites near Nhulunbuy. Whether these textural and compositional differences are due to a different degree of weathering, unusual fluid migration or remobilisation of iron species, or different parent material is unclear. In any case, no true bauxites (besides the known bauxite deposits of the Gove Peninsula) were recognised within northeastern Arnhem Land during the present study. For a full discussion of the bauxites at Nhulunbuy and insights into their possible origins the reader is referred to the text by Bardossy and Aleva (1990, p. 438-445).

The clay content of the Cretaceous sedimentary facies varies greatly, but generally facies of the Walker River Formation have larger clay contents than those of the Yirrkala Formation. However, in outcrop these formations do not contain pure uncontaminated clay in any significant quantity. The main occurrences of thick clayey intervals occur where the Cretaceous facies have been extensively weathered, and where a vertically-zoned lateritic weathering profile has been developed along the southern edge of the Cainozoic plateau on the Gove Peninsula, and more rarely within smaller dissected plateaus to the south. The basal leached and mottled parts of these profiles contain kaolinitic intervals up to about 10 m-thick.

Staining by iron-oxides is ubiquitous within Cretaceous sedimentary facies of northeastern Arnhem Land, but rarely are any of the facies cemented extensively by iron-oxides. However, ferricretes 1 and 2, of probable Tertiary age at most sites in northeastern Arnhem Land, contain high but variable amounts of iron-oxides; typically the iron occurs as hematite, but goethite and limonite are also present. Whilst the iron-oxide content of these rocks is typically high (>50% in places), they commonly contain significant proportions of clay, sand, and lithic clasts, and this probably limits their potential as an economic resource. Further, the thickness of these ferruginous layers in commonly only 1 or 2 metres, and the amount of iron-oxide decreases markedly down section from these weathering horizons into less weathered rocks.

Manganese-oxides occur in many sedimentary facies in northeastern Arnhem Land, mainly as staining on weathered surfaces but also as grain coatings and cement between framework grains in places. Within Cretaceous facies the richest manganese-oxides are found within well-sorted quartz sandstones at the contacts between fining-upward cycles of facies succession 5, although the cement is not solely manganese-oxide and is commonly intimately mixed with iron-oxides in the same rocks. The enrichment of manganese at these stratigraphic levels is related to major disconformities in the sequence, and may be due to changes in the redox state of the Cretaceous sea at times of major changes in relative sea level (*i.e.*, at times of regression following long periods of transgression and stillstand when dissolved manganese species where concentrated in the water column). This potential scenario is based on the model proposed by Frakes and Bolton (1984) for the formation of the Groote Eylandt manganese ore deposits.

Elsewhere within rocks of northeastern Arnhem Land, particularly ferricrete 2, manganese-oxide is present in the form of pisoliths. These pisoliths are rarely composed purely of manganese-oxide, but tend to be concentrically zoned with the various 'skins' of the pisoliths being either iron-oxide rich, manganese-oxide rich, or composed of ferromanganese-oxides. In general, the shape of these pisoliths is more irregular, and they are not as well sorted or tightly packed as the pisolithic manganese-oxide ore horizons on Groote Eylandt.

At a few localities, unrelated to measured sections described herein, poorly-exposed rubbly ferruginous and manganiferous hardpans occur at the surface of the coastal plain near the present coastline. Some granule to cobble sized clasts within these hardpans are hard, grey, have a metallic lustre, and appear to be enriched in manganese-oxide, whereas the surrounding matrix (if any) is ferruginous. This suggests a partitioning of iron vs. manganese-oxides, but it is not clear whether this is due to weathering, or to mechanical break-up of a primary manganifeous unit followed by recementation (mainly by iron-oxide). These poorly-exposed and commonly semi-lithified units also contain soil pisoliths, which are locally enriched in manganese-oxide. The soil pisoliths do not have well-developed concentric layers, but are zoned and sometimes form irregular shapes or larger amorphous blocks. In most places the outer zone of these pisoliths are rich in manganese-oxide, whereas the middle zone and core are ferruginous.

The best potential for economic bauxite, iron-oxide, and clay accumulations exists in the northern part of northeastern Arnhem Land, related to deep weathering and its products at or near the edges of the major weathered plateaus. Preliminary observations relating to mineralisation during this study indicate anomalous enrichment of manganese-oxide, iron-oxide, and ferromanganese-oxides within the Cretaceous sequence. A large part of northeastern Arnhem Land, especially near the coast, is prospective for as yet undiscovered manganese concentrations and ores (oxides and/or carbonates) at shallow depth beneath Cainozoic cover near the base of the Cretaceous shelf succession.

CONCLUSIONS

The mid-Cretaceous Walker River and Yirrkala Formations were deposited on a gently-sloping shelf, which formed the western margin of the Carpentaria Basin within a large epeiric seaway. The configuration of this seaway, and the depositional processes that operated within it closely resemble storm- and wave-dominated parts of the Cretaceous Interior Seaway of North America.

Siliciclastic marine sedimentation of the Walker River Formation from the late Aptian to the early Cenomanian in the Carpentaria Basin was dominated by storm-related processes, which produced numerous prominent sedimentary structures and repeated vertical grain-size and facies stacking patterns. Deposition in the intervals between episodic storms was wave-dominated. Coarsening-upward facies successions are the norm, and stacked coarsening-upward successions are sometimes capped by fining-upward facies successions. Changes in the style, abundance, and scale of storm features and facies successions are discernible from proximal to distal within the Walker River Formation.

The degree of bioturbation of the sediments is generally high, and conditions on the sea floor are interpreted to have been generally aerobic to slightly dysaerobic, with high to moderate energy environments being the norm. Invertebrate faunas are poorly preserved due to chemical diagenesis and fragmentation, and the general endemic nature and low-diversity of most faunas presents problems for accurate biostratigraphic dating. Trace fossils are of the *Skolithos* and *Cruziana* ichnofacies, and are characteristic of high-energy environments where opportunistic colonisation occurred after episodic storms.

The fifteen lithofacies and the five corresponding facies successions of the Walker River and Yirrkala Formations in northeastern Arnhem Land are also recognisable over the entire length and width of the shelf and are repeated at different stratigraphic levels. The widespread distribution and gross vertical accretion of the facies and facies successions indicates that shelf dynamics remained relatively stable over the 12-14 million year period of accumulation. Fluctuations of relative sea level, together with these storm processes, are interpreted to have controlled the depositional architecture and maintained the low gradient of the shelf.

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APPENDIX 1 - SITES TABLE. ** denotes site numbers used throughout this record; they correspond to site numbers in Krassay (unpubl. thesis).

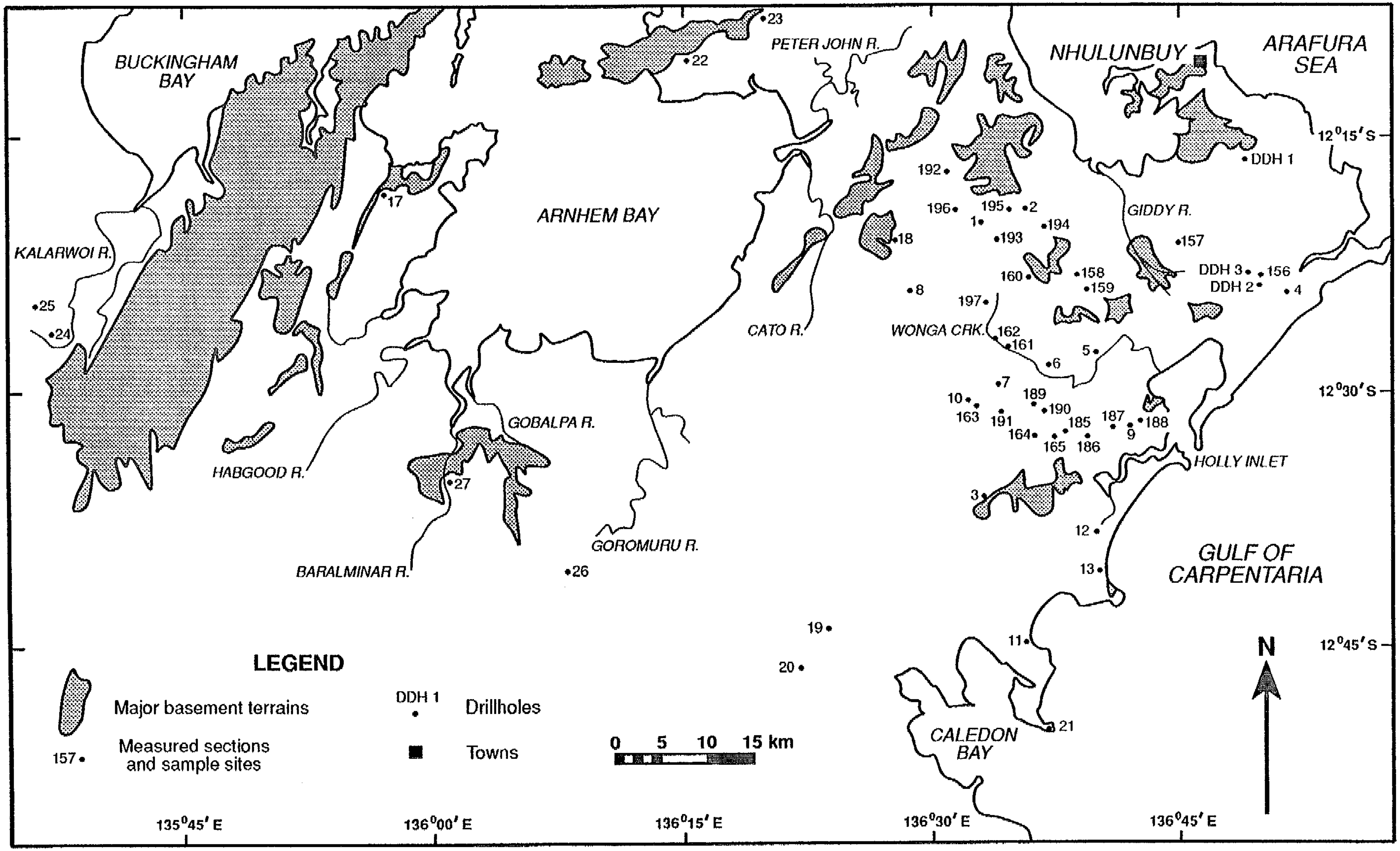
AGSO SITE #	SITE No **	LATITUDE degrees minutes	LONGITUDE degrees minutes	LOCAL SITE NAME	1:250,000 MAP SHEET	SAMPLE #	ROCK TYPE	SECTION THICKNESS	# OF UNITS
akal 0001	33	13 22.95	135 31	Marura Ck	Blue Mud Bay...	B-1	SILTSTONE	18	2
akal 0002	135	13 23	135 30.3	"	"	~~~~~~~	~~~~~~~	~~~~~~~	~~~~~~~
akal 0003	136	13 22.6	135 30.25	"	"	~~~~~~~	~~~~~~~	~~~~~~~	2
akal 0004	137	13 20.79	135 30.22	Marura Ck NE	"	~~~~~~~	~~~~~~~	~~~~~~~	2
akal 0005	138	13 21.27	135 30.1	"	"	B-2	SILTSTONE	14	3
"	"	"	"	"	"	B-3	QTZ ARENITE	"	"
"	"	"	"	"	"	B-4	QTZ ARENITE	"	"
akal 0006	139	13 21.25	135 29.88	Marura Ck N	"	B-5	QTZ ARENITE	14.5	3
akal 0007	140	13 21.73	135 29.88	"	"	B-6	SANDSTONE	22.5	4
"	"	"	"	"	"	B-7	SILTSTONE	"	"
akal 0008	141	13 22.33	135 30.17	Marura Ck	"	B-8	SILTSTONE	6.8	2
akal 0009	142	13 21.79	135 29.56	Walker R	"	~~~~~~~	~~~~~~~	11.8	2
akal 0010	143	13 23	135 28.42	"	"	B-9	QTZ ARENITE	16.5	1
akal 0010A	144	13 23.1	135 27.42	"	"	B-10	SANDSTONE	20	5
"	"	"	"	"	"	B-11	SANDSTONE	"	"
akal 0011	145	13 23.04	135 27.29	"	"	~~~~~~~	~~~~~~~	11.75	2
akal 0012	146	13 23.34	135 26.95	"	"	B-12	SILTSTONE	13.75	4
"	"	"	"	"	"	B-13	CLAYEY SANDSTONE	"	"
"	"	"	"	"	"	B-14	SANDSTONE	"	"
"	"	"	"	"	"	B-15	QTZ ARENITE	"	"
"	"	"	"	"	"	B-16	CLAYEY SANDSTONE	"	"
akal 0013	147	13 23.68	135 27.02	"	"	B-17	QTZ ARENITE	14.25	3
"	"	"	"	"	"	B-18	QTZ ARENITE	"	"
"	"	"	"	"	"	B-19	QTZ ARENITE	"	"
"	"	"	"	"	"	B-20	SANDSTONE	"	"
"	"	"	"	"	"	B-21	SILTSTONE	"	"
akal 0014	148	13 24.23	135 26.12	"	"	B-22	CONGLOMERATE	15.5	13
"	"	"	"	"	"	B-23	SILTSTONE	"	"
"	"	"	"	"	"	B-24	SANDSTONE	"	"
"	"	"	"	"	"	B-25	SANDSTONE	"	"
"	"	"	"	"	"	B-26	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-27	CLAYEY SANDSTONE	"	"
"	"	"	"	"	"	B-28	QTZ ARENITE	"	"

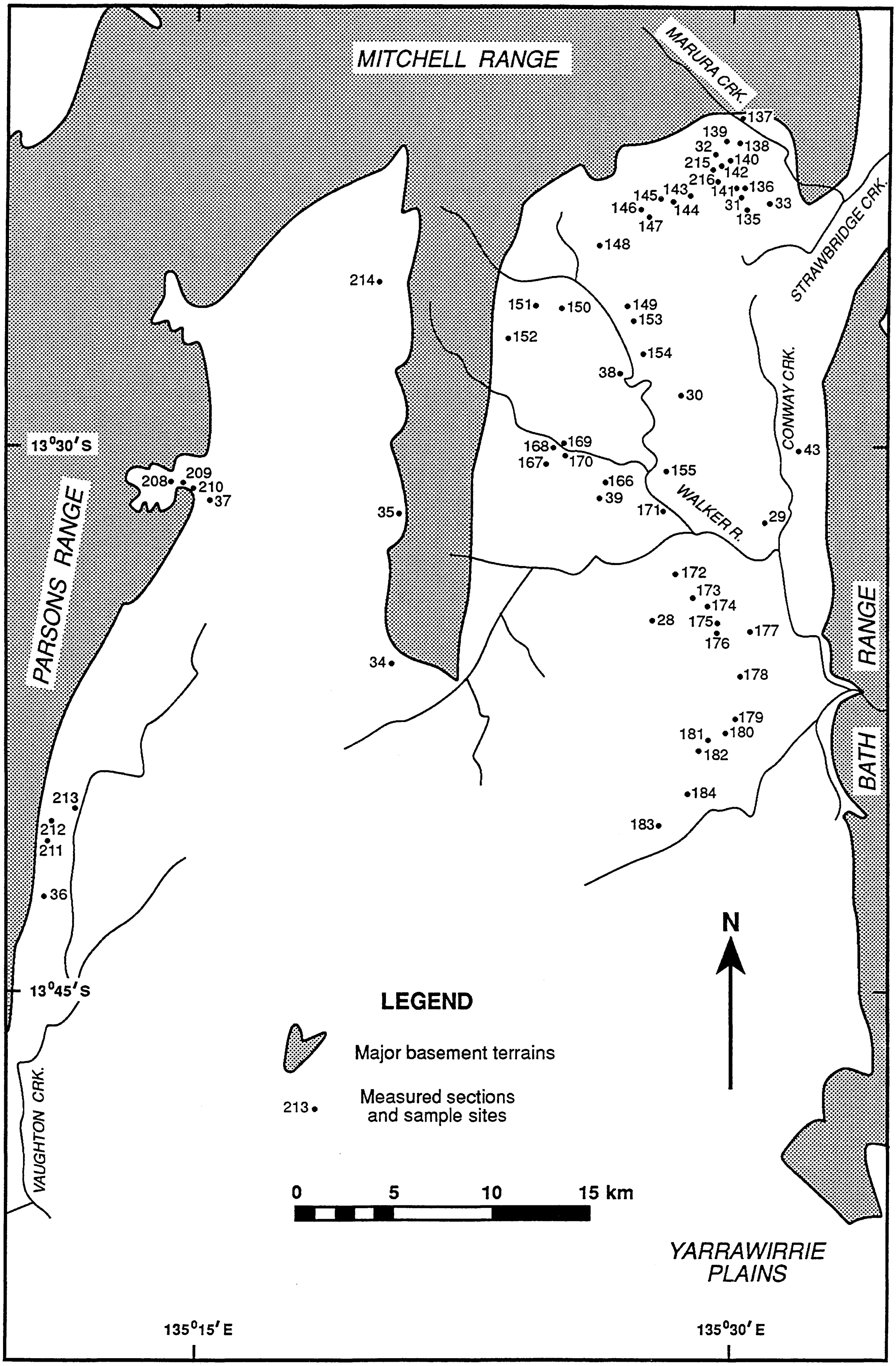
akal 0015	149	13 25.86	135 26.9	"	"	B-29	SILTSTONE	14	6
"	"	"	"	"	"	B-30	CLAYSTONE	"	"
"	"	"	"	"	"	B-31	SILTY SANDSTONE	"	"
akal 0016	150	13 26.04	135 25.38	Walker R W	"	B-32	QTZ ARENITE	4.75	5
akal 0017	151	13 26	135 24.31	"	"	~~~~~~~~	~~~~~~~~	6.3	3
akal 0018	152	13 26.84	135 23.50	Walker R	Blue Mud Bay...	~~~~~~~~	~~~~~~~~	17.25	2
akal 0019	153	13 26.41	135 26.9	"	"	~~~~~~~~	~~~~~~~~	22	4
akal 0020	154	13 27.25	135 27.32	"	"	B-33	SILTSTONE	5	8
akal 0021	155	13 30.53	135 28.05	"	"	~~~~~~~~	~~~~~~~~	19.5	3
akal 0022	4	12 24.49	136 51.50	Stoney Ridge	Arnhem Bay-Gove	B-34	MN SANDSTONE	28.5	16
akal 0023	156	12 23.05	136 50	Durabudboi	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0024	157	12 21.15	136 44.95	8km Bulman Rd	"	B-35	RUBBLY LATERITE	~~~~~~~~	1
akal 0025	158	12 23	136 39	15.5km Bul. Rd	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0026	159	12 24	136 39.72	Giddy R Fishole	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0027	160	12 23.2	136 36.1	Jump-up	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0028	161	12 27.15	136 34.75	Wonga Ck	"	B-36	QTZ ARENITE	~~~~~~~~	3
akal 0029	162	12 26.9	136 33.9	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0030	163	12 30.63	136 32.9	Pt Bradshaw Rd	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0031	164	12 32.60	136 36.30	"	"	B-37	QTZ ARENITE	3.25	2
"	"	"	"	"	"	B-38	SILTSTONE	"	"
akal 0032	165	12 32.5	136 37.6	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0033	166	13 30.75	135 26	Conway Ck	Blue Mud Bay...	B-39	SILICIFIED WOOD	27.5	8
akal 0034	167	13 30.25	135 24	? ? ?	"	~~~~~~~~	~~~~~~~~	9	2
akal 0035	168	13 29.75	135 25	Conway Ck S	"	~~~~~~~~	~~~~~~~~	6.75	2
akal 0036	169	13 29.5	135 25.5	Conway Ck NE	"	~~~~~~~~	~~~~~~~~	12.5	2
akal 0037	170	13 30.25	135 25.75	Conway Ck	"	B-40	QTZ ARENITE	~~~~~~~~	1
akal 0038	171	13 31.5	135 28	Walker R	"	B-41	QUARTZITE	8	4
"	"	"	"	"	"	B-42	CLAYSTONE	"	"
akal 0039	172	13 33	135 28.5	Walker R	"	B-43	CLAYEY SANDSTONE	6.75	2
akal 0040	173	13 33.75	135 29	SSW Nulapitji	"	B-44	SILTY SANDSTONE	28.75	4
"	"	"	"	"	"	B-45	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-46	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-47	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-48	CONGLOMERATE	"	"
akal 0041	174	13 34	135 29.5	"	"	B-49	SILTSTONE	23.35	7

"	"	"	"	"	"	B-50	SANDSTONE	"	"
"	"	"	"	"	"	B-51	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-52	QTZ ARENITE	"	"
akal 0042	175	13 34.5	135 29.5	"	"	~~~~~~~	~~~~~~~	~~~~~~~	1
akal 0043	176	13 34.5	135 29.5	"	"	~~~~~~~	~~~~~~~	11.75	2
akal 0044	177	13 34.5	135 30.75	S Nulapitji	"	B-53	SILTY SANDSTONE	~~~~~~~	1
akal 0045	178	13 36	135 30.25	"	"	B-54	SILTY SANDSTONE	13	4
"	"	"	"	"	"	B-55	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-56	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-57	SILTY SANDSTONE	"	"
akal 0046	179	13 37	135 30.25	S Nulapitji	Blue Mud Bay...	B-58	CONGLOMERATE	2.5	7
"	"	"	"	"	"	B-59	SANDSTONE	"	"
"	"	"	"	"	"	B-60	SANDSTONE	"	"
"	"	"	"	"	"	B-61	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-62	SANDSTONE	"	"
"	"	"	"	"	"	B-63	CONGLOMERATE	"	"
akal 0047	180	13 37.5	135 30	"	"	B-64	CONG SANDSTONE	~~~~~~~	1
akal 0048	181	13 37.75	135 29.25	"	"	B-65	CLAYEY SANDSTONE	14	2
"	"	"	"	"	"	B-66	CLAYEY SANDSTONE	"	"
akal 0049	182	13 38	135 29	"	"	B-67	CLAYEY SANDSTONE	17.5	5
"	"	"	"	"	"	B-68	CLAYEY SANDSTONE	"	"
"	"	"	"	"	"	B-69	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-70	CONG SANDSTONE	"	"
"	"	"	"	"	"	B-71	CONGLOMERATE	"	"
"	"	"	"	"	"	B-72	CONGLOMERATE	"	"
akal 0050	183	13 40.25	135 27.5	"	"	~~~~~~~	~~~~~~~	~~~~~~~	2
akal 0051	184	13 39.25	135 28.75	S Nulapitji	"	B-73	SILTY SANDSTONE	25	8
"	"	"	"	"	"	B-74	SANDSTONE	"	"
"	"	"	"	"	"	B-75	SANDSTONE	"	"
akal 0052	185	12 32.25	136 38.25	Pt Bradshaw Rd	Arnhem Bay-Gove	~~~~~~~	~~~~~~~	~~~~~~~	2
akal 0053	186	12 32.5	136 39.5	"	"	~~~~~~~	~~~~~~~	~~~~~~~	1
akal 0054	187	12 32	136 41	"	"	B-76	QTZ ARENITE	~~~~~~~	1
akal 0055	188	12 31.75	136 42.5	"	"	~~~~~~~	~~~~~~~	~~~~~~~	1
akal 0056	189	12 30.75	136 36.25	"	"	B-77	QTZ ARENITE	~~~~~~~	1
akal 0057	190	12 31	136 37	"	"	~~~~~~~	~~~~~~~	~~~~~~~	1

akal 0058	191	12 31	136 34.25	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	2
akal 0059	192	12 17	136 31	Dhalingbuy airpt.	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0060	193	12 21.25	136 34	Mata Murta Rd	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0061	194	12 20.25	136 37	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0062	195	12 19.25	136 34.75	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0063	196	12 19.25	136 31.5	NNE Dhalingbuy	"	B-78	LATERITE	~~~~~~~~	1
akal 0064	161	12 27.15	136 34.75	Wonga Ck	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0065	197	12 24.7	136 33.4	Wonga Ck NW	"	B-79	CLAYSTONE	~~~~~~~~	2
akal 0066	198	13 11.89	135 35.12	S Koolatong R	Blue Mud Bay...	B-80	QTZ ARENITE	~~~~~~~~	3
"	"	"	"	"	"	B-81	SILTSTONE	"	"
akal 0067	199	13 07.4	135 36.25	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0068	200	13 07.25	135 37.1	"	"	B-82	CONG SANDSTONE	~~~~~~~~	2
akal 0069	201	13 05.6	135 36.5	"	"	B-83	SANDSTONE	~~~~~~~~	2
akal 0070	202	13 03	135 36.7	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	2
akal 0071	203	13 02.7	135 37	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	2
akal 0072	204	13 02.75	135 37.7	S Koolatong R	Blue Mud Bay...	~~~~~~~~	~~~~~~~~	~~~~~~~~	2
akal 0073	205	13 03.75	135 39.85	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	2
akal 0074	206	13 05.9	135 38.25	"	"	B-84	SANDSTONE	~~~~~~~~	1
akal 0075	207	13 06	135 38.6	"	"	B-85	CONGLOMERATE	~~~~~~~~	1
akal 0076	208	13 30.7	135 14.25	Tiger Ck	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	2
akal 0077	209	13 30.75	135 14.5	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0078	210	13 30.7	135 14.6	"	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0079	211	13 40.6	135 11.1	Vaughton Ck	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1
akal 0080	212	13 40	135 11	"	"	B-86	CONG SANDSTONE	~~~~~~~~	4
akal 0081	213	13 39.7	135 11.5	"	"	B-87	CLAYEY SANDSTONE	~~~~~~~~	6
"	"	"	"	"	"	B-88	QTZ ARENITE	"	"
"	"	"	"	"	"	B-89	QTZ ARENITE	"	"
"	"	"	"	"	"	B-90	SILTY SANDSTONE	"	"
"	"	"	"	"	"	B-91	SANDSTONE	"	"
akal 0082	214	13 25.25	135 19.9	Mt Ramsay SW	"	~~~~~~~~	~~~~~~~~	~~~~~~~~	1

APPENDIX 2. ALZ base map with site numbers and geographical features.





APPENDIX 3. BPRZ base map with site numbers and geographical features.