STRATIGRAPHY AND SEDIMENTOLOGY OF THE BILLY CREEK FORMATION (CAMBRIAN, FLINDERS RANGES) AND ITS EQUIVALENTS ON THE NORTHEAST COAST OF KANGAROO ISLAND, SOUTH AUSTRALIA

(VOLUME 1)

BY

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THIS THESIS IS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University, nor to the best of my knowledge and belief, does it contain any material previously published or written by any other person except where due reference and acknowledgement is made in the text.

P. S. Moore.

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SUMMARY

Sedimentation in the Adelaide 'Geosyncline' (central and southern South Australia) in the late Early and early Middle Cambrian was largely controlled by the Kangarooian Movements; a complex and persistent tectonism which was most pronounced in the southern portion of the 'geosyncline'.

In the northern part of the 'geosyncline', initial tectonic activity terminated a major phase of Early Cambrian carbonate deposition and promoted the development of a thick sequence of red-beds (the Billy Creek Formation). Five members are defined within the Billy Creek Formation, which outcrops in the Flinders Ranges and occurs in the subsurface to the east. During the early stages of deposition of the Billy Creek Formation, a broad muddy tidal flat developed in the west (the Warragee Member) while to the east, a complex stratigraphy (the Coads Hill Member) was evolving. The great variety of facies in the Coads Hill Member emphasises the instability of this eastern region during the late Early Cambrian, although in general the sequence was deposited in a more open marine environment than the Warragee Member. Minor volcanic activity, probably in the Mt. Wright region of New South Wales, is recorded as thin tuffaceous interbeds in the lower half of the formation. Further uplifts in the source area released silt and fine sand into the basin of deposition, forming the laterally equivalent Nildottie and Erudina Siltstone Members. The red-bed facies of both members were deposited mainly in the intertidal to supratidal zones under the influences of weak wave and current activity, while cyclically interbedded dolomites in the more easterly outcropping Erudina Siltstone Member were probably deposited in sheltered coastal lagoons in the shallow subtidal zone. Final uplifts further increased topographic relief in the source area and a complex of fluvial-dominated deltaic sands (the Eregunda Sandstone Member) prograded across the basin of deposition from the southeast. Palaeocurrent and petrographic data indicate that the main source of the sediment was the Broken Hill-Olary basement high.

In the southern portion of the Adelaide 'Geosyncline' in the late Early and early Middle Cambrian, tectonic movements were pronounced, with the uplift and erosion of the area to the north of Kangaroo Island, and the fault controlled subsidence of the areas to the east and south, forming the Kanmantoo Trough. On the northeast coast of Kangaroo Island, the Cambrian sequence comprises six formations which were deposited in a predominantly shallow marine to intertidal environment, adjacent to the southern shoreline of the uplifted block. The area was subject to strong tidal, minor wave and at times alluvial influence. The palaeoenvironment is thus interpreted as a shoreline along which alluvial deposits, including alluvial fan complexes, interfingered with tidal deposits. Shoreline migration was in response to the interplay of fault uplift of the northern source area and basinal subsidence, which determined the nature and amount of coarse alluvial detritus shed southwards into the basin.

TABLE OF CONTENTS - VOLUME 1

(PARTS 1 and 2)

TABLE OF CONTENTS

Page

PART ONE

PART TWO

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

PART ONE

CHAPTER 1 - GENERAL INTRODUCTION

AIM AND SCOPE OF THE STUDY

This study is aimed at evaluating the palaeogeography of the Adelaide 'Geosyncline' (Figure 1-1) during the late Early Cambrian. In the northern part of the Adelaide 'Geosyncline' (Figure 1-2), up to 1000m of fine-grained red-beds (the Billy Creek Formation) were deposited in a marginal marine to paralic environment (Daily, 1976b). Considerable attention is given to the nature of the red-bed sequence, and its various modes of formation.

The Billy Creek Formation has been correlated by Daily (1976b, Fig. 3) with six formations on Kangaroo Island (Figure 1-3). The Carrickalinga Head Formation, the Stokes Bay Sandstone, the Smith Bay Shale, the White Point Conglomerate, the Emu Bay Shale and the Boxing Bay Formation comprise over 20,000m of sediment which were deposited in the southern portion of the Adelaide 'Geosyncline', some 700km south of the present outcrop of the Billy Creek Formation.

A large area of virtually no outcrop of upper Lower Cambrian strata exists between the Flinders Ranges in the north, and Kangaroo Island in the south (Figure 1-2). Parts of this area (for example, much of Yorke Peninsula) are known to have been subject to subaerial exposure and erosion. However, further north there is no remaining indication of what took place during this period of time. Thus, a particular problem of this study is the wide separation of the relevant outcrops, and the very large area over which palaeogeographic interpretation is attempted.

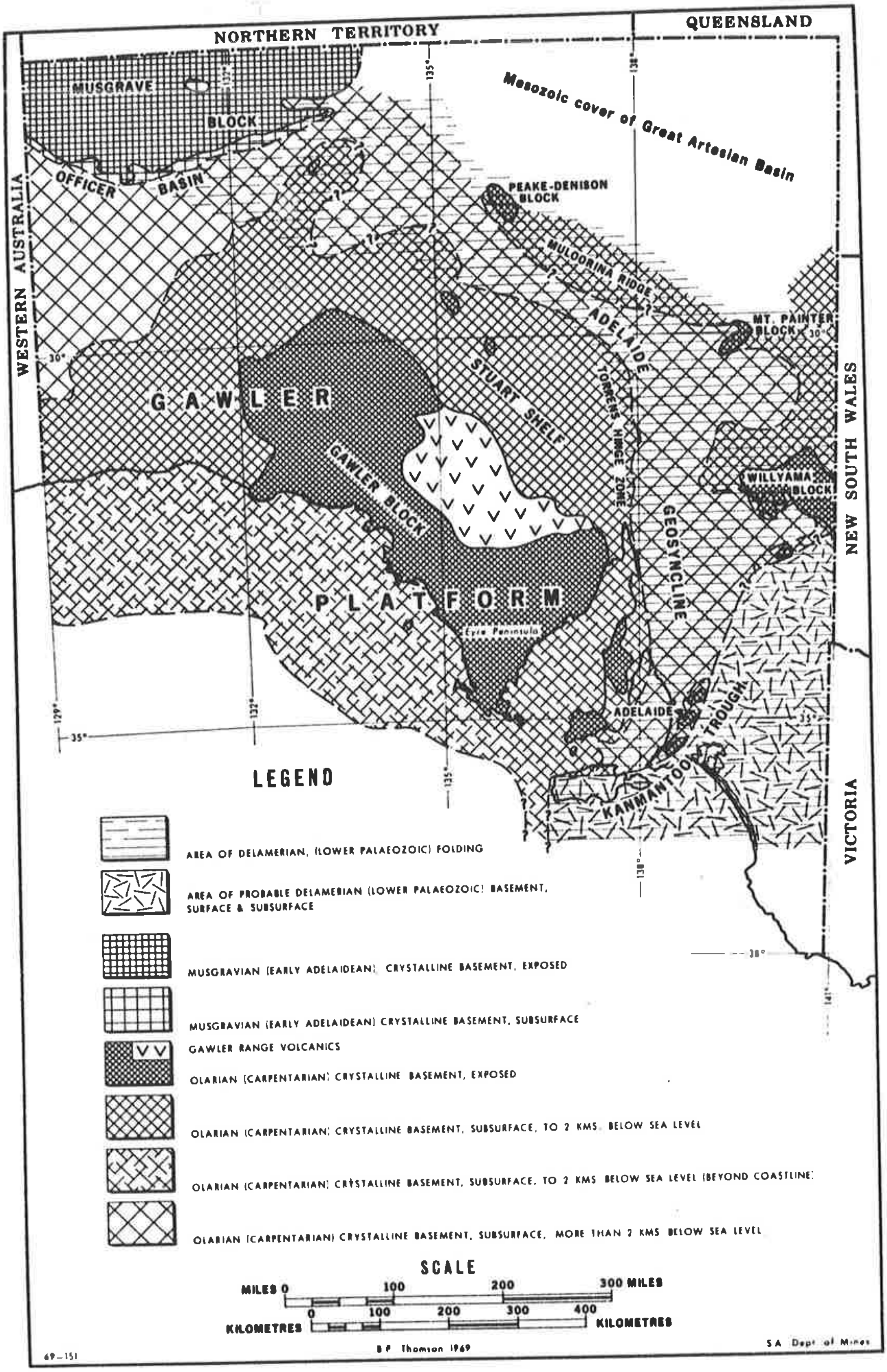
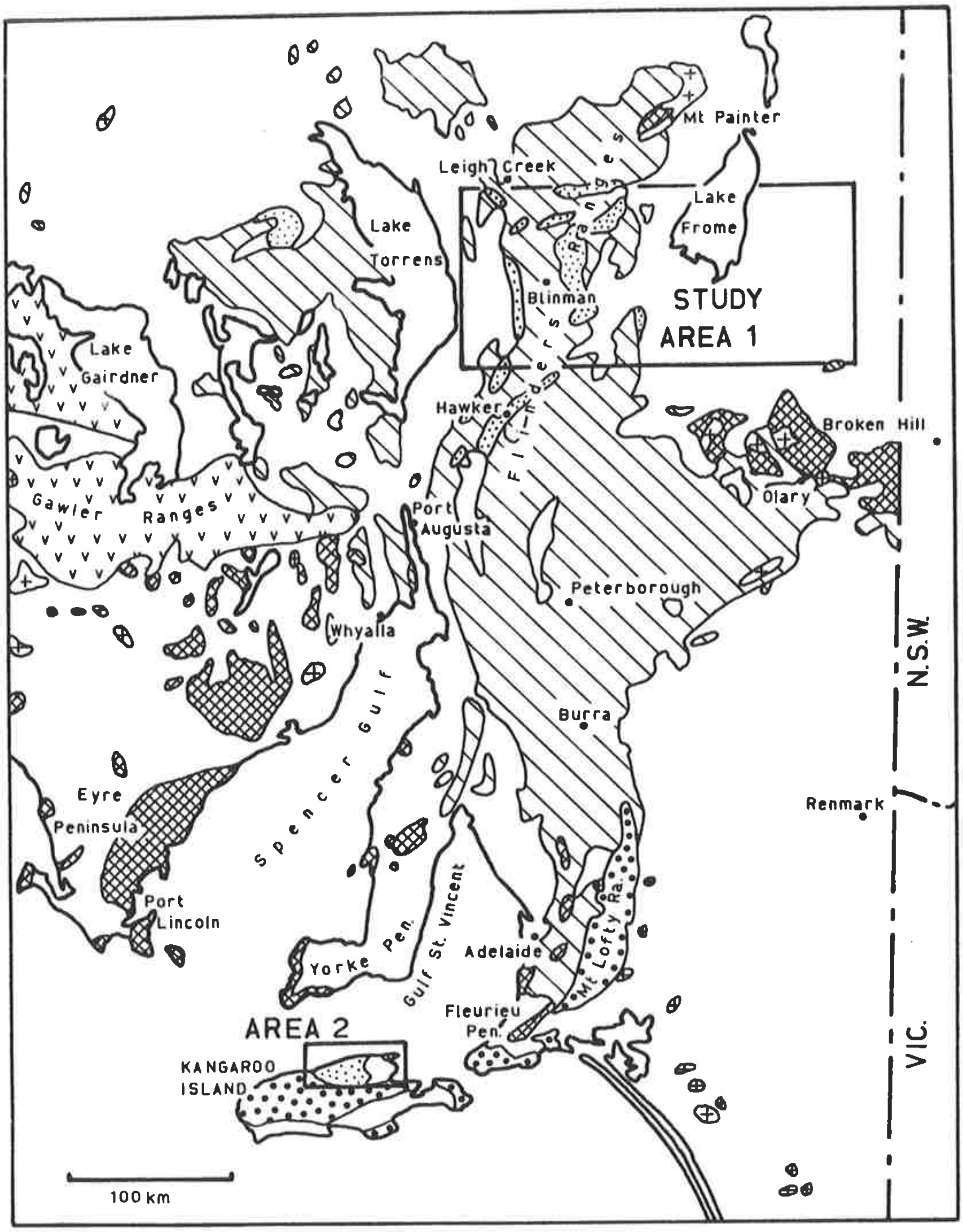


Figure 1-1. Major structural units of South Australia (from Thomson, 1969a).

Figure 1-2. Location map of the two study areas.



Cambrian sediments - Stuart Shelf and Adelaide 'Geosyncline'

Cambrian metasediments - Kanmantoo Trough

Adelaidean

Lower Proterozoic

Acid volcanics

Granites and granitisation complexes

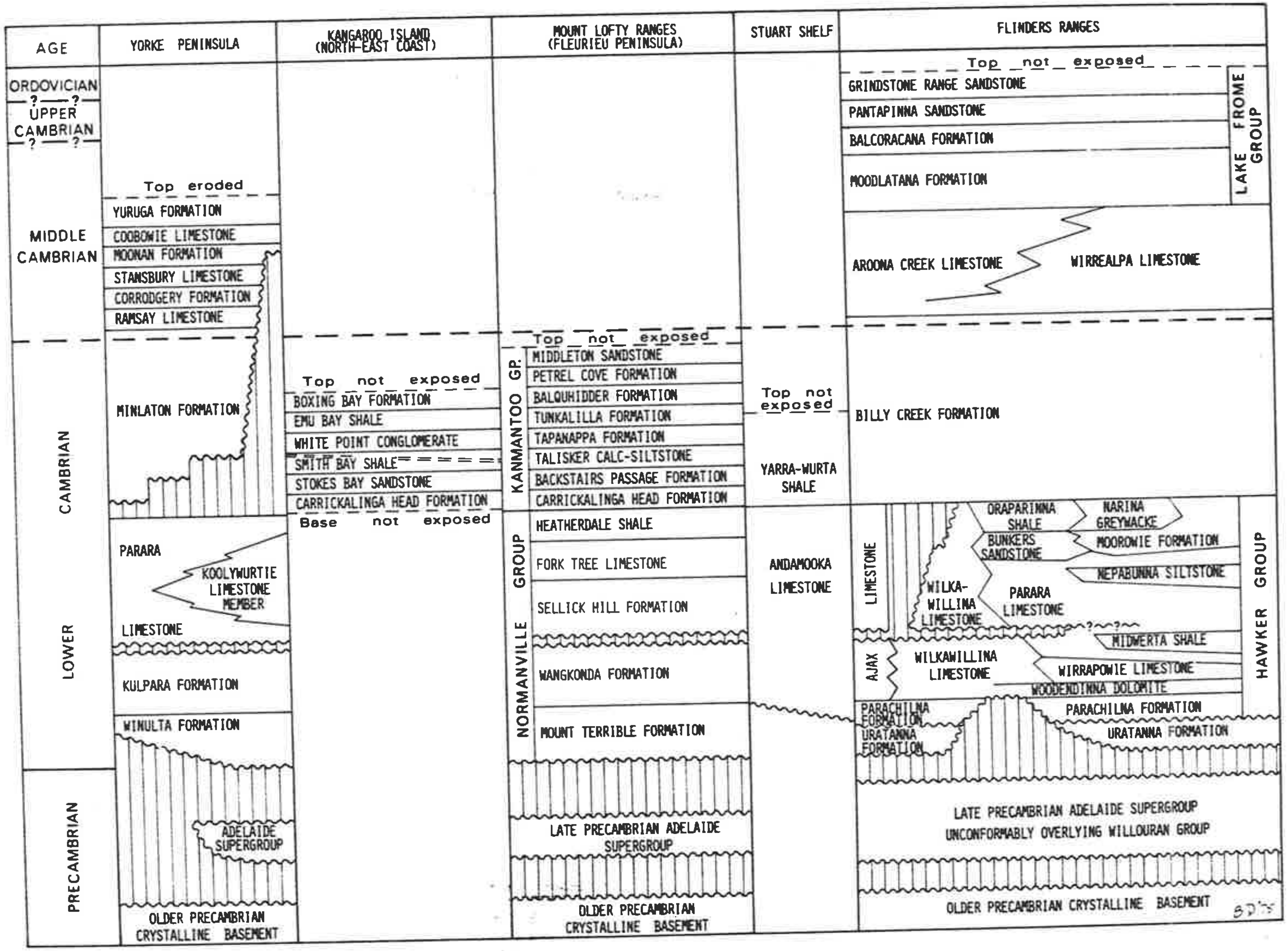


Figure 1-3. Correlation of the Cambrian formations in the Adelaide 'Geosyncline' and adjacent platforms (from Daily, 1969b).

REGIONAL GEOLOGICAL SETTING: THE ADELAIDE GEOSYNCLINE

The Billy Creek Formation and its lateral equivalents on Kangaroo Island were deposited in a large intracratonic basin known as the Adelaide 'Geosyncline' (Figure 1-1). The main features of the Adelaide 'Geosyncline' and the underlying crystalline basement are summarized below and the time, time-rock and rock terms in current use by the South Australian Geological Survey in the Adelaide 'Geosyncline' and adjoining areas are illustrated in Figure 1-4.

Crystalline basement of Precambrian (Carpenterian) age has been recorded from many areas of South Australia. Major surface outcrops include the Gawler, Musgrave, Willyama, Mt. Painter and Peake-Denison Blocks. Smaller basement inliers occur in anticlinal cores in the Mount Lofty Ranges, near Adelaide. The crystalline basement rocks, of diverse composition, are dominated by high grade metamorphics but also include volcanic rocks (the Gawler Range Volcanics) and acid and basic intrusives. Many of the basement highs flank the Adelaide 'Geosyncline' and were major sources of detritus for the basin.

The Adelaide 'Geosyncline' is a complex, intracratonic, basinal feature which accumulated sediment in Proterozoic and Cambrian times. It extends from south of Kangaroo Island, through the Mount Lofty and Flinders Ranges. It has an easterly extension to the Olary Block and a northwesterly extension to at least the Peake-Denison Block (Figure 1-1). Sedimentation commenced in the Willouran, possibly as much as 1400 million years ago, and continued until the Late Cambrian or possibly Early Ordovician. Estimated total stratigraphic thickness of cover rocks varies considerably throughout the basin, with a maximum of over 40,000m on the COPLEY 1:250,000 Geological Sheet (Coats, 1973). There is a marked thinning away from the trough axis, and to the west on the more stable Stuart Shelf the cover is not more than 1,500m thick (Dalgarno and Johnson, 1968). Syndepositional faulting and warping (north to northeasterly trends) had a marked effect on sediment

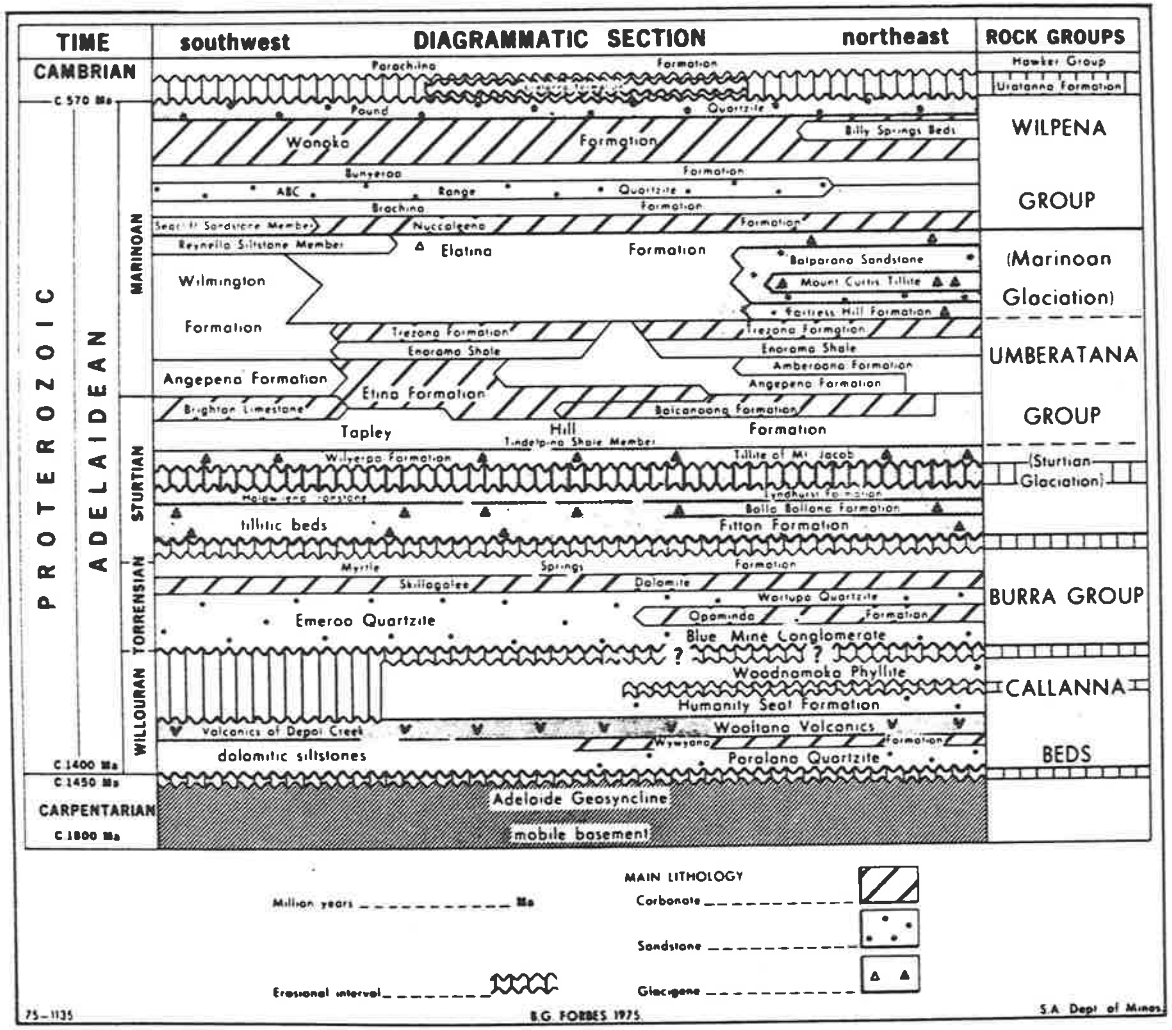


Figure 1-4. Precambrian and basal Cambrian time and rock terms used in the Adelaide 'Geosyncline' and Stuart Shelf.

thickness and facies distribution within the basin.

The basal units (the Lower Callana Beds) lie unconformably on the crystalline basement. They consist of quartzite, siltstone and carbonate, characteristically associated with basic volcanics. The Lower Callana Beds have flowed under the pressure of the overlying sediments, forming discordant diapiric structures. In some cases, the diapirs formed islands and ridges in the shallow seas of the Adelaide 'Geosyncline' during the Adelaidean and Early Cambrian, and thus represented important local sources of detritus.

The remainder of the Precambrian sediments are dominated by clean washed sandstones (subarkoses and quartzarenites), red and green shales and various carbonates, including magnesite and dolomite. The sequence is dominantly shallow water in origin, and no turbidite deposits have been recorded. Two horizons of tillite and associated fluvioglacials are present. The lower, Sturtian glacials are almost ubiquitous, while the upper, Elatina glacials are restricted to the southeast and northwest regions.

A major disconformity separates the Cambrian sequence of the Adelaide 'Geosyncline' and Stuart Shelf from older, Adelaidean sediments. On Yorke Peninsula, Cambrian strata rests nonconformably on Precambrian crystalline rocks. A correlation chart of the Cambrian formations of these regions is shown in Figure 1-3. The basal Cambrian unit in the Adelaide 'Geosyncline' is the dominantly green, silt rich Uratanna Formation, which locally fills deep basins and channels cut in the Pound Quartzite (Daily, 1972a, 1973, 1974, 1976a).

Much of the Lower Cambrian sequence of the Adelaide 'Geosyncline' is characterised by frequent changes both in thickness and facies, leading to intertonguing units in one section and their superposition in another. Collectively, these units from the top of the Uratanna Formation to the base of the Billy Creek Formation are termed the Hawker Group (Dalgarno, 1964). The Hawker Group is dominated by carbonate sedimentation which followed the deposition of the sandy, transgressive Parachilna Formation and its equivalents.

According to Daily (1972b) varying water depths and subsidence rates largely determined the types and thicknesses of the carbonates. The western zone of the basin, including the Stuart Shelf and adjacent areas, was relatively stable and accumulated light coloured carbonates with only minor clastic material. These deposits are represented by the Andamooka, Ajax and Wilkawillina Limestones. Similar carbonates occur on Fleurieu Peninsula (Fork Tree Limestone and Wangkonda Formation) and on Yorke Peninsula (Kulpara Limestone). Maximum sediment accumulation occurred in the central basin area of the Adelaide 'Geosyncline' where darker, impure limestones and shales were laid down. Examples are the Parara Limestone and Oraparinna Shale (Daily, 1976b; Figure 1-3).

According to Daily (1976b, p.18), "the widespread occurrence of 'bird's-eye' limestone, dolomite and stromatolites near the top of the Andamooka Limestone, Ajax Limestone, and in the youngest phases of the Wilkawillina Limestone and the Moorowie Formation point to a general regression of the sea before the influx of redbed clastics which gave rise to the Yarra-wurta Shale and the Billy Creek Formation". Although there is a passage into the Billy Creek Formation in most areas including the type section (Daily, 1956), local disconformities may separate the red-bed sequence from the underlying Hawker Group.

The northern portion of the Adelaide 'Geosyncline' was relatively stable at this period of time, and a slow regression is indicated by much of the Billy Creek Formation stratigraphy. In the southern portion of the geosyncline however, tectonic movements were pronounced. At the close of the period marking Hawker Group sedimentation, the Kanmantoo Trough was formed; the collapse of the seafloor was fault controlled and is termed the Waitpingan Subsidence (Thompson, 1969b, p.99). Approximately 18,000m of flysch-type sediment accumulated in the trough, and these have been directly correlated with the Billy Creek Formation equivalents on Kangaroo Island (Figure 1-3). Compensating uplifts occurred to the north and west of the Kanmantoo Trough, resulting in considerable erosion of the uplifted area and the formation to the south of the White Point Conglomerate and Tapanappa Formation. The earth movements, originally termed the Kangaroo Island Orogeny (Daily, 1956), appear to have affected the whole of the Adelaide 'Geosyncline' and may be responsible for local disconformities at the base of the Billy Creek Formation in the Flinders Ranges, as well as accounting for the regressive nature of the red-bed sequence. The orogeny has more recently been termed the Kangarooian Movements (Daily and Forbes, 1969; Daily, 1969b) and is equivalent to the Cassinian Uplift of Thomson (1969b).

Red-bed sedimentation of the Billy Creek Formation was interrupted early in the Middle Cambrian by a brief marine transgresion, associated with carbonate deposition (the Wirrealpa and Aroona Creek Limestones in the Flinders Ranges, and the Ramsay Limestone on Yorke Peninsula). The overlying Lake Frome Group sediments comprise four formations of dominantly reddish clastics. The basal Moodlatana Formation and the overlying Balcoracana Formation are marginal marine, somewhat akin to the Billy Creek Formation, whereas the Pantapinna Sandstone and the Grindstone Range Sandstone are probably fluvial and deltaic deposits respectively (Stock, 1974; Daily, 1976b). Continuity of sedimentation above the Lake Frome Group is unknown in the Adelaide 'Geosyncline'. However, the whole of the basin was deformed by the Delamerian Orogeny (Thomson, 1969b), which bagan in Upper Cambrian time (Milnes et al., 1977) and reached a climax in the Lower Ordovician with the intrusion of the Palmer and Anabama Granites. Thus, it is the Delamerian Orogeny which gave rise to the complex fold patterns exposed today in the Flinders and Mount Lofty Ranges.

HISTORY OF STUDY: THE ADELAIDE 'GEOSYNCLINE'

It is not feasible to review all previous work on the Adelaide 'Geosyncline' in this article. For a comprehensive review of stratigraphic investigations prior to 1971, with emphasis on the Proterozoic strata, refer to Preiss (1971). For a detailed historical background to studies of the Cambrian strata of South Australia prior to 1956, see Daily (1956). Only a general outline of the course of events is presented below.

Studies of the geology of South Australia began in the mid-nineteenth century, with the first significant contribution by Selwyn (1860, quoted by Howchin, 1904), who made a geological reconnaissance tour of the Mount Lofty-Flinders Ranges Fold Belt from Cape Jervis on the tip of Fleurieu Peninsula, to Mount Serle in the northern Flinders Ranges. Work intensified after the turn of the century with Walter Howchin, lecturer in geology and palaeontology at the University of Adelaide, making many important contributions to the study of the Adelaide 'Geosyncline' and Kanmantoo Trough (eg. Howchin, 1897, 1898, 1903, 1904, 1906, 1907, 1914, 1916, 1918, 1920, 1922, 1924, 1925, 1927, 1928, 1929a, 1930). A summary is given in Howchin's (1929b) "The geology of South Australia".

Meanwhile, Sir Douglas Mawson had become interested in the Adelaide 'Geosyncline' and many publications were forthcoming over the following years (eg. Mawson, 1912, 1925, 1926, 1927, 1934, 1936, 1937, 1938a, 1938b, 1939a, 1939b, 1940, 1941a, 1941b, 1942, 1947, 1948, 1949; Mawson and Segnit, 1949; Mawson and Sprigg, 1950). In particular, Mawson (1936) published the "Progress in knowledge of the geology of South Australia".

Differing from Howchin, who favoured a Cambrian age for the whole sedimentary sequence, Mawson (1938a) believed that the absence of fossils in the lower part of the sequence suggested a Late Precambrian age. He took the Precambrian-Cambrian boundary as the base of the Pound Quartzite.

A major advance was made when Glaessner et al. (1948) published a "Code of Stratigraphic Nomenclature for Australia". Until this time, rock sequences in South Australia had been informally referred to as "series", "groups", or simply "beds". Following this paper, subdivision into Groups, Formations, Members, Systems, Series and so on was possible. Two years later, Mawson and Sprigg (1950) applied the new code in their "Subdivision of the Adelaide System". In this important paper, Mawson and Sprigg replaced the term "Adelaide Series" (David, 1922) with "Adelaide System" and adopted the term "Adelaide Geosyncline" for the regional geological setting. Sedimentation in the Adelaide 'Geosyncline' was discussed by Sprigg (1952) and Voisey (1959), who described the basin as a miogeosyncline, on account of its sedimentary content and paucity of volcanic material.

Daily (1956) published a major compilation of the stratigraphy and palaeontology of the Cambrian of South Australia, defining twelve distinctive faunal assemblages. Many new formations were defined and type sections described, which included the Billy Creek Formation. Two years later, "The geology of South Australia" (Glaessner and Parkin, 1958) appeared as a special issue of the Geological Society of Australia.

Since then, Daily has remained a major contributor to the understanding of the Cambrian of South Australia (Daily, 1957, 1963, 1968, 1969a, 1969b, 1969c, 1972a, 1972b, 1973, 1974, 1976a, 1976b, 1977; Daily, Firman, Forbes and Lindsay, 1976; Daily and Forbes, 1969; Daily and Milnes, 1971, 1972a, 1972b, 1973; Daily, Twidale and Alley, 1969; Glaessner and Daily, 1959), along with other workers from the South Australian Department of Mines, especially Dalgarno (Dalgarno, 1962, 1964; Dalgarno and Johnson; 1962, 1963, 1965, 1966, 1968; Dalgarno, Johnson and Coats, 1964) and Wopfner (1966, 1969a, 1969b, 1970a, 1970b).

The most recent large scale contributions to the regional geology of the Adelaide 'Geosyncline' are "The handbook of South Australian geology" (Parkin, 1969), the "ANZAAS 41st congress geological excursions handbook, section 3" (Daily, 1969a), and the "25th IGC excursion guide No. 33A" (Thomson et al., 1976).

PART TWO

THE STRATIGRAPHY AND SEDIMENTOLOGY

OF THE

BILLY CREEK FORMATION,

FLINDERS RANGES, SOUTH AUSTRALIA.

CHAPTER 2

INTRODUCTION TO THE BILLY CREEK FORMATION

GENERAL

The Billy Creek Formation is a Lower to Middle Cambrian, predominantly red-bed sequence of shale, siltstone and sandstone, with minor limestone, dolomite and tuff. It outcrops sporadically throughout the central and northern Flinders Ranges of South Australia (Fig. 2-1), and has been identified in the subsurface below the Cainozoic and Mesozoic of the Lake Frome region (Fig. 2-2).

This study is essentially a sedimentological one, aimed at evaluating the palaeogeography of the northern portion of the Adelaide 'Geosyncline' during the late Early to early Middle Cambrian. However, detailed examination and redefinition of the stratigraphy of the Billy Creek Formation was a major primary objective. Approximately 13,000m of section were measured and sampled in detail, and these data are summarised briefly in the appendix.

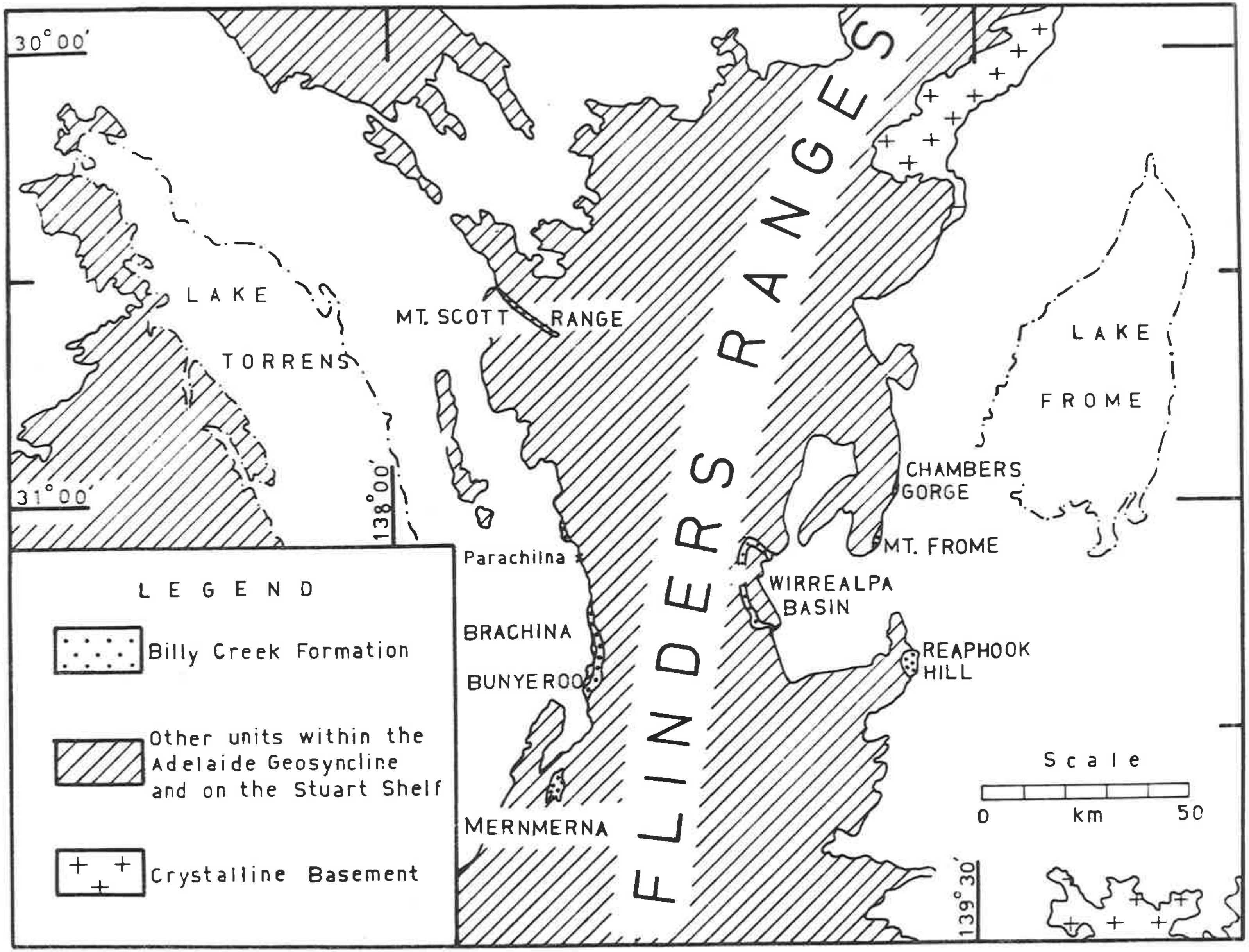


Figure 2-1. Outcrop map, Billy Creek Formation.

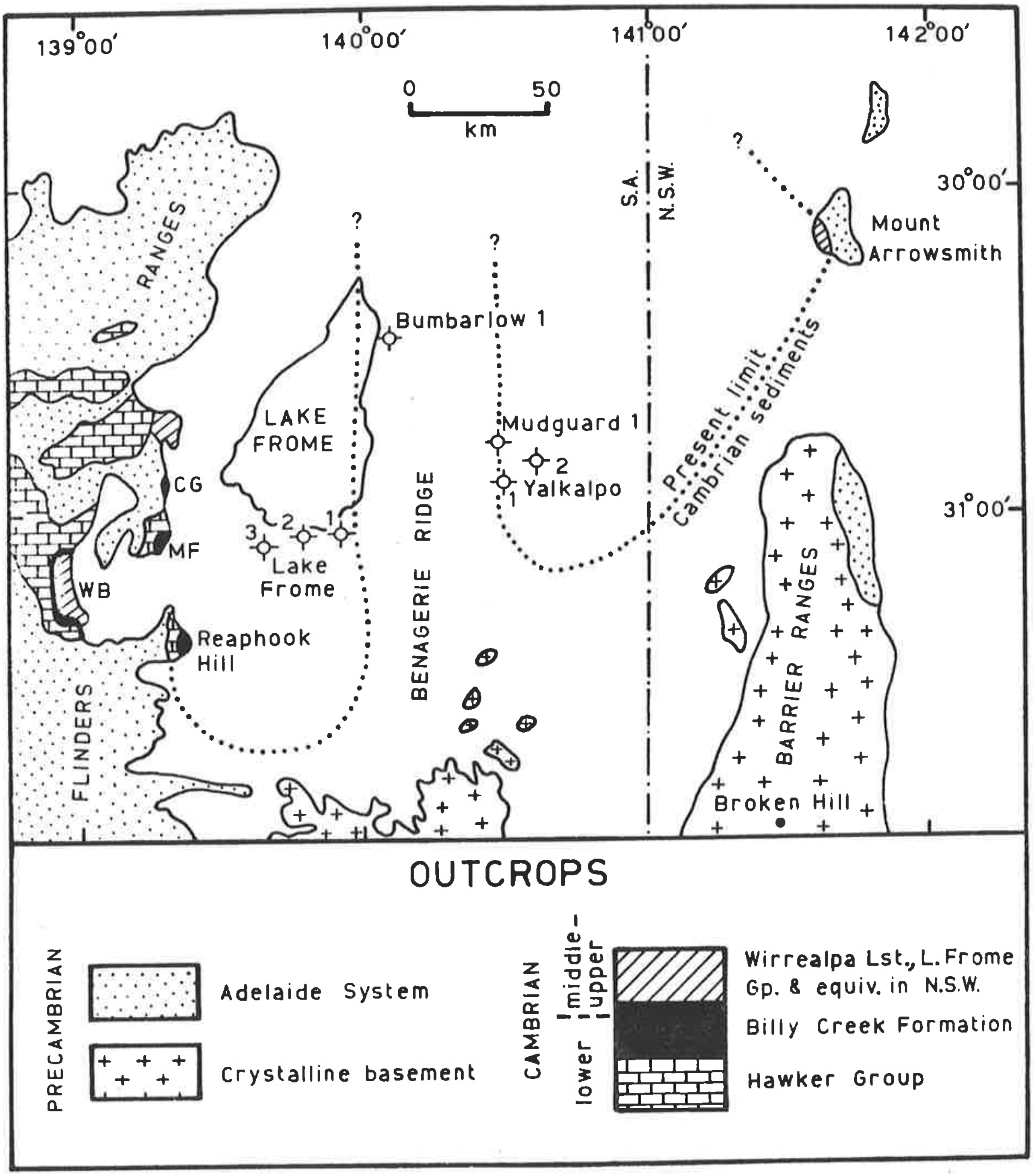


Figure 2-2. Locality map, eastern Flinders Ranges and Lake Frome Embayment (modified from Youngs, 1979). WB: Wirrealpa Basin; MF: Mount Frome; CG: Chambers Gorge. The Billy Creek Formation has also been intersected in Lake Frome Nos. 1 and 2 and Yalkalpo 2.

GEOGRAPHY

Outcrops of the Billy Creek Formation commonly occupy broad, shallow valleys bounded by ridges of limestone. In cases where the underlying Oraparinna Shale is poorly developed or absent, as along the Heysen Range and at Mt. Scott, the Billy Creek Formation lies at the foot of a prominent ridge-system dominated by Pound Quartzite and overlying Cambrian limestones. This chain of ridges and mountains is a characteristic feature of the Flinders Ranges and may rise in excess of 500m above the adjacent countryside. Along the western edge of the Heysen Range, much of the Billy Creek Formation is obscured by alluvial fans which have built out from the main range. Indeed, throughout the study area, alluvial cover is a problem encountered when examining the basal shaly portions of the sequence. An exception occurs at Reaphook Hill, where the basal member is sandy and calcareous.

Vegetation cover is sparse and poses no significant problems to workers examining the Billy Creek Formation. The most common vegetation type is shrub-steppe, which includes porcupine grass (*Triodia*), blue bush (*Eucalyptus macrocarpa*) and saltbush (*Atriplex*). Woodland vegetation is uncommon, and is typically associated with poor outcrop of the formation. Woodland vegetation includes emu bush (*Eremophila longifolia* and *Eremophila freelingi*), mulga (*Acacia aneura*) and she-oaks (*Casuarina*). River red gums (*Eucalyptus camaldulensis*) are useful in delineating major watercourses, both in the field and on aerial photographs.

The climate is semi-arid and most of the region receives less than 200mm of average annual rainfall. However, annual figures may vary considerably from the mean since rainfall is sporadic, coming mainly as thunderstorms between October and May. Copley, adjacent to the most northern outcrop of the Billy Creek Formation, has an average annual rainfall of only 85mm. The entire region experiences hot summers, with maximum diurnal temperatures often well above 40°C and minimum winter temperatures frequently below 0°C. Thus, the best periods for fieldwork are late autumn/early winter (mid April to mid June) and late winter/early spring (August to October). The summer months should be avoided if possible.

PREVIOUS STUDIES RELATING TO THE BILLY CREEK FORMATION

Surface Outcrops

The first direct reference to the sequence now defined as the Billy Creek Formation was by Howchin (1907, p.417), who described the Cambrian rocks overlying the presently recognised Wilkawillina Limestone as "a series of red, softish, sandy flagstones with purple slates, and a few small limestones". Howchin (1907) suggested that the red-beds were dominantly subaerial deposits; an opinion which he reaffirmed on subsequent occasions (Howchin, 1914, 1918).

In a more detailed statement, Howchin (1922) made several references to "purple slates" and "flags" of the Billy Creek Formation. His most detailed description related to a traverse along Balcoracana Creek where he described the now defined Edeowie Limestone Member (p.75) as "a thin bed of laminated limestone that is extremely contorted", and referred to the overlying Billy Creek Formation red-beds as "rotten purple shales". Howchin (1922, p.75) also noted "thick, soft, and red-coloured sandstones, interbedded with purple and other coloured, thin-bedded, argillaceous beds" which preceded the Wirrealpa Limestone. Thus, he was the first person to recognise beds now assigned to the upper sandy member of the Billy Creek Formation.

Mawson (1939a) measured two sections through the Cambrian sequence in the Wirrealpa Basin[1]. The Ten Mile Creek section divided the Billy Creek Formation into eight units (units 39 to 46 of Mawson, 1939a, p.366). He recognised minor thin limestones, a massive dolomite bed, and abundant ripples

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[1]The Wirrealpa Basin constitutes a tectonic basin formed during Delamerian folding, which occurs in the area adjacent to and south of the Wirrealpa homestead (Fig. 2-1). The term was first used by Mawson (1939a) while describing a thick sequence of Cambrian strata which outcrops in the basin.

and halite pseudomorph casts in the formation; total stratigraphic thickness was given as 2395 feet (730m). A second section along Balcoracana Creek correctly identified major strike faulting in the lower portion of the formation.

The first reference to the Billy Creek Formation in the Mount Scott Range was on the COPLEY 1:63,360 Geological Sheet (Parkin and King, 1952), in which all the Cambrian red-beds were grouped together as "red and purple slates and sandstones". The Billy Creek Formation was eventually named and defined by Daily (1956). His type section, adjacent to the Ten Mile Creek in the Wirrealpa Basin, is in a similar position to Mawson's (1939a) section. Daily (1956, p.114) gave the thickness of the Billy Creek Formation in the type section as 3,300 feet (1,006m), and described it as dominantly "chocolate coloured micaceous shales, sandstones and siltstones". He continued: "the shales occupy most of the thickness and are often ripple marked. Pseudomorphs after halite occur in the shales in the upper part of the formation. Thin buff coloured dolomite and calcareous shales are common in the lower 1,200 feet". Daily (1956) noted that the Billy Creek Formation was conformable with the underlying Lower Cambrian Oraparinna Shale which included sixty feet of dark blue-grey, rubbly limestone at its top, and was conformably overlain by Middle Cambrian Wirrealpa Limestone. In the Mount Scott Range, the Billy Creek Formation was defined only as "unnamed clastics", 1,500 to 2,000 feet (457 to 610m) thick, overlying the Lower Cambrian Aroona Creek Limestone. Daily (1956, p.140) suggested that the Billy Creek Formation was deposited during a period of regression when "the sea was partially or even completely excluded from the area". The description of the Billy Creek Formation by Campana (1958b) in "The geology of South Australia" made no addition to Daily's (1956) report.

In 1961, the South Australian Department of Mines published the ARROWIE 1:63,360 Geological Sheet (Horwitz, 1961). Unfortunately the outcrops of Billy Creek Formation in the vicinity of the Chambers Gorge were not recorded. Further mapping by the Department of Mines led to the description of the

Billy Creek Formation along the western flank of the Flinders Ranges. Dalgarno and Johnson (1962) defined the base of the formation in this region as "a two foot thick fossiliferous limestone which carries Hyolithes, unidentified brachipods and occasional trilobite fragments. This bed occurs ten feet or less below a prominent and thin laminated dolomite". Thus Dalgarno and Johnson (1962) described the flaggy, dolomitic Edeowie Limestone Member, and included it as the basal member of the Billy Creek Formation.

The Lower Cambrian in the eastern Flinders Ranges was described by Dalgarno and Johnson (1963). Sections through part or whole of the Billy Creek Formation were given for four localities in the Wirrealpa Basin, at Mount Frome and Reaphook Hill. At Reaphook Hill, Dalgarno and Johnson (1963) described "Bunkers Sandstone equivalent" and "Oraparinna Shale" above the Wilkawillina Limestone. These two units are now considered to be part of the Billy Creek Formation. They also described tuff from the "Oraparinna Shale" at Reaphook Hill.

The Lower Cambrian stratigraphy of the Flinders Ranges was summarized by Dalgarno (1964), who described the Billy Creek Formation in moderate detail, noting its disconformable relationship with the underlying Hawker Group at several localities. Dalgarno (1964) also recorded trilobites in the lower part of the Billy Creek Formation near Balcoracana Creek.

In the following years, a series of Mines Department geological maps were published. The first to appear was the BLINMAN 1:63,360 Geological Sheet (Dalgarno, Johnson and Coats, 1964) which included the geology of the northern portion of the Wirrealpa Basin. The Billy Creek Formation was shown, and the trilobite locality, tuff bands and Edeowie Limestone Member were also marked on the map. This was the first time that the term "Edeowie Limestone Member" had appeared in print.

The ORAPARINNA 1:63,360 Geological Sheet (Dalgarno and Johnson, 1965) mapped the Billy Creek Formation in the southern portion of the Wirrealpa Basin and along the western flank of the Heysen Range. Near the southern end of the Wirrealpa Basin, the Lower Cambrian sequence was mapped in a contemporaneous graben developed above the Oraparinna Diapir. In the centre of the graben, Dalgarno (1964) gave the thickness of the Hawker Group as 4,100 feet (1250m), whereas to the north it is only 1,500 feet (457m) thick. South of the graben, the Hawker Group is represented by only 200 feet (61m) of Wilkawillina Limestone. Walter (1965), in a study of the Hawker Group at this locality suggested that the Ten Mile Creek graben had stabilised prior to the deposition of the Billy Creek Formation. This is now known to be incorrect. In a summary of Palaeozoic tectonism in South Australia, Forbes (1966) suggested that the Ten Mile Creek graben had ceased sinking before Middle Cambrian time. Although somewhat more cautious than Walter (1965), this statement is also probably incorrect.

In 1966, the PARACHILNA 1:250,000 Geological Sheet was published (Dalgarno and Johnson, 1966). It summarised the information on the Blinman and Oraparinna sheets and also mapped outcrops of the Billy Creek Formation at Reaphook Hill, Mount Frome, Parachilna and Mernmerna. Publications relating to the hydrocarbon potential of the Lake Frome Embayment, east of the Flinders Ranges, also appeared in 1966. Much of the work done on the Lake Frome area is by private mining companies and remains in unpublished form (see following section).

Freeman (1966) related the regressive Billy Creek Formation in the Flinders Ranges to a period of non-deposition in the Bancannia Trough, suggesting more extreme uplift in the latter area. Wopfner (1966) described Cambro-Ordovician sediments from the northeastern margin of the Lake Frome Embayment at Mount Arrowsmith in New South Wales (Fig. 2-2). Mount Arrowsmith is important in its intermediate geographical position between the Cambrian outcrops on the Flinders Ranges and the subsurface occurrences in the Cooper's Creek Sub-basin and near Mootwingee-Gnalta, northeast of Broken Hill. On lithological grounds, Wopfner (1966) correlated his members A and B at Mount Arrowsmith with the Billy Creek Formation. However, Wopfner's Member A contains the Middle Cambrian trilobite Xysridura, making this correlation untenable (Daily, pers. comm., 1977).

In 1967, the South Australian Department of Mines published the BALCANOONA 1:63,360 Geological Sheet (Leeson, 1967), showing scattered outcrops of the Billy Creek Formation in the Moro Gorge region. In the same year, Walter (1967) made brief mention of the formation in the western Flinders Ranges, while discussing the role of Archaeocyatha in the biostratigraphy of the Hawker Group. Brown et al. (1968, p.57) in "The geological evolution of Australia and New Zealand" suggested that the Billy Creek Formation was "at least partly terrestrial".

A summary of diapiric activity in the Flinders Ranges, especially with respect to Cambrian occurrences, was presented by Dalgarno and Johnson (1968). In a discussion of the Wirrealpa Diapir, they noted that it intruded the Billy Creek Formation along its eastern margin, thus providing "evidence of the youngest diapirism in the Flinders Ranges" (Dalgarno and Johnson, 1968, p.311). The following year, two students from the University of Adelaide produced Honours theses on the Cambrian stratigraphy adjacent to the Wirrealpa Diapir. In the north, Haslett (1969) suggested that the diapir was a partial source at least for the Narina Greywacke. Haslett mapped the Billy Creek Formation in this region and briefly described the lithologies, but did not measure any sections through the red-bed sequence. In the south, Pierce (1969) mapped the Billy Creek Formation and Edeowie Limestone Member in considerable detail, noting several small basinal structures which underwent rapid subsidence in pre- and early Billy Creek formation time. Pierce (1969, p.21) noted that near Fountain Spring "the lower part of the Billy Creek Formation has been affected both by movements of the diapir and by intrusion of diapiric material into it". Both Haslett (1969) and Pierce (1969) suggested a tidal-flat environment of deposition for the silty portions of the Billy Creek Formation. Pierce (1969) suggested that the upper, sandy member of the Billy Creek Formation was possibly of deltaic origin.

The "Handbook of South Australian geology" edited by Parkin (1969) summarized the stratigraphy and sedimentology of the Billy Creek Formation.

Also excursion notes, relating to the geology section of the 41st ANZAAS Congress (Daily, 1969a), bear reference to the Billy Creek Formation. In this volume, Daily and Forbes (1969) related the regression associated with deposition of the red-bed sequence to widespread uplifts which they termed the Kangarooian Movements.

Wopfner (1969a) suggested that the tuffaceous material of the Billy Creek Formation had a possible source in the Cooper Basin or the Bancannia Trough. He suggested that the rest of the terrigenous material was derived from the Olary Block (Wopfner, 1969b). In a detailed lithofacies evaluation of Lower Cambrian sediments in the Flinders Ranges and Lake Frome area, Wopfner (1970a, 1970b) reported a marked increase in sand content of the Hawker Group towards the southeast, supporting his hypothesis for a source in the Olary-Willyama region. His results are also partially applicable to the Billy Creek Formation and Lake Frome Group, to which he makes brief mention.

Hatcher (1970), Mount (1970) and Wigglesworth (1970) produced detailed maps of the Billy Creek Formation along part of the eastern flank of the Flinders Ranges. In the Chambers Gorge region, Mount (1970) measured four sections through the red-beds. He identified a thin bedded, flaggy limestone with argillaceous partings (his "Book Limestone Member") which he included as the basal unit of the Billy Creek Formation. However, he failed to recognise extensive strike faulting in the basal Billy Creek Formation and the underlying Moorowie Formation in his northern Section J. Thus, his stratigraphy and environmental interpretations for the Billy Creek Formation are, in part, inaccurate and misleading. Hatcher (1970) and Wigglesworth (1970) mapped the Mount Frome outcrops, but did not measure any stratigraphic sections through the Billy Creek Formation.

The trilobites reported by Dalgarno (1964) from the lower portion of the Billy Creek Formation at Balcoracana Creek were described in a Ph.D. dissertation (Pocock, 1967) and the data was subsequently published by the same author (Pocock, 1970). To account for the large number of juvenile forms in his collections of Balcoracania flindersi, Pocock (1967, 1970) presented evidence to show that they represented a living population which underwent mass mortality. However, he failed to recognise extensive mud-crack development on the bedding planes containing the trilobites, and consequently attributed the mass mortality to tuffaceous fallout associated with distant volcanic activity. His description of the stratigraphic position of the trilobites at Balcoracana Creek is also somewhat inaccurate and misleading.

The Billy Creek Formation at Reaphook Hill was mapped in detail by Gaunt (1971) and Gehling (1971), who divided the formation into eight units which varied in thickness and lithology along strike. The lower seven units are dominated by sandstone and dark foetid limestone, the latter being interpreted as lagoonal deposits (Gehling, 1971). The upper unit comprises the more typical red-bed sequence which both workers consider to be dominantly tidal in origin. Emuellid trilobites were reported in the lower portion of the formation and identified as Balcoracania dailyi Pocock (Daily, pers. comm. in Gehling, 1971, p.16). Prior to this discovery, the species was only known from the White Point Conglomerate on Kangaroo Island (Pocock, 1970).

In preparation for the Copley four mile geological sheet, Forbes (1971) published a table of Adelaidean and Cambrian stratigraphic names, which included reference to the Billy Creek Formation. Explanatory notes for the Parachilna four mile sheet were also compiled by Forbes (1972), who suggested a paralic environment for the deposition of the formation. The COPLEY 1:250,000 Geological Sheet (Coats et al., 1973) revised the mapping of the formation in this area which had previously been presented on the COPLEY 1:63,360 Geological Sheet (Leeson, 1967). Explanatory notes accompanying the Copley four mile sheet (Coats, 1973) referred briefly to the Billy Creek Formation.

In a study of the clay mineralogy, petrology and depositional environments of the Lake Frome Group, Stock (1974) made minor reference to the older Billy Creek Formation. Notably, he did a substantial amount of work on heavy mineral suites in the Lake Frome Group and included a few results which he obtained from the upper sandstone units of the Billy Creek Formation in the Delhi-Santos Stratigraphic Wells.

In 1976, excursion No. 33A of the 25th International Geological Congress was conducted. It included examination of the base of the Billy Creek Formation in Brachina Gorge. The excursion guide (Thompson et al., 1976) contained a brief description of the Cambrian sequence in the Flinders Ranges. Daily (1976b, p.18) stated that "a paralic environment is envisaged, mainly regressive to restrictive with evaporitic and emergent conditions favouring red-bed formation under oxidising conditions. A marine influence is shown by rare trilobite occurrences in green shales and shallow-water, foetid dark-coloured limestone and carbonate-rich tuff".

Finally, brief reference to the Billy Creek Formation has been made by Youngs (1978a, 1978b), who studied the environments of deposition of the overlying Wirrealpa and Aroona Creek Limestones.

Subsurface Data from the Lake Frome Region

Most of the data on the Cambrian and Precambrian strata below the Frome Embayment* were obtained in the course of a recent investigation of the petroleum potential of the area. In addition, some old water bores penetrated the basement, and these are described by Ker (1966) and Ludbrook (1962, 1966). The search for uranium in the Lake Frome region has been directed at the Tertiary sequence, and most drilling projects terminated as soon as pre-Tertiary sediments were encountered.

The Zinc Corporation Ltd., Enterprise Exploration Ltd. and Frome Broken Hill Co. Ltd. began drilling for oil in 1945, and a reconnaissance gravity and magnetic survey took place (Kaufman and MacPhail, 1948). Seismic work began with a survey by Geoseismic (Aust.) Ltd. for Santos Ltd. (Dennison, 1960). Further magnetic and gravity surveys were carried out

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*Osborne (1945) was the first person to introduce the term "Frome Embayment" into print, defining it as a synclinal basin bounded by the Flinders and Barrier Ranges. As presently defined (Wopfner, 1969a), the term "Frome Embayment" refers only to the Mesozoic sedimentary basin. The overlying Cainozoic sediments of the Tarkooloo Basin (Callen, 1976) are unconformable on the Cretaceous and relate to a different cycle of events.

by Geophysical Services International for Delhi Australian Petroleum Ltd. and Santos Ltd. (Harding and Geyer, 1963). During 1964-1965, Wongela Geophysical Pty. Ltd. conducted reconnaissance gravity surveys for Delhi-Santos Ltd. Further surveys were made in 1966, and in 1968 Santos Ltd. drilled three stratigraphic wells south of Lake Frome (Delhi-Santos, 1969). Daily (1969c) identified anhydrite in borecore recovered from the Billy Creek Formation in Lake Frome Nos. 1 and 2. In 1969, the area was farmed out to Crusader Oil N.L., who carried out extensive seismic surveys (Crusader Oil N.L., 1971).

Aeromagnetic maps of the area are available, and there is a report on the state magnetic map by Parker (1973). Magnetic interpretation has been done by Tucker and Brown (1973). Other interpretations have been attempted by Westhoff (1968) and Milsom (1965), both of which suffer from incorrect depth estimates (Callen, 1976).

Uranium exploration began in 1969 by E.A. Rudd Ltd. (Rudd, 1970), when 28 holes were drilled in the shallow southern portion of the Tertiary basin. Daily (1970) identified Wirrealpa Limestone in the basal portions of E.A.R. Coondappie Well No. 7, and Cambrian red-beds in several other cores. In the northern portion of the Lake Frome region where the Tertiary is underlain by a thick sequence of Cretaceous sediments, very few holes pentrated into the Cambrian or Precambrian strata. Since most of the exploration licences are still valid, the bulk of the data on the subsurface geology of the Lake Frome region is confidential. However, open file reports on the region include Jarre (1972) for Mines Administration Pty. Ltd., Middleton (1974a, 1974b) for Tricentrol (Aust.) Pty. Ltd., Morgan (1973) for Chevron Exploration Corp., Randell (1973) for Union Corp. (Aust.) Pty. Ltd., Schindlmayr (1970) for Central Pacific Minerals N.L., Flesher (1974) for Southern Ventures Pty. Ltd. and Ryan (1969) for Ker McGee.

In an attempt to both assist uranium exploration in the Tarkooloo Basin and provide general stratigraphic data on the pre-Tertiary rocks of the area, the S.A. Department of Mines recently drilled several deep holes. Yalkalpo I was located approximately midway between Lake Frome and the Barrier Ranges. It intersected only 6m of Cambrian carbonates below the Tertiary and Mesozoic cover before termination (Callen, 1972). Mudguard 1 and Yalkalpo 2 were located 12km northwest and 10km northeast of Yalkalpo 1 respectively (Youngs, 1978c). Mudguard 1 drilled straight from Mesozoic sediments into Precambrian crystalline basement at 194m depth. Yalkalpo 2 intersected approximately 540m of Lower Cambrian sediments before termination. Bumbarlow 1, located on the northeastern margin of Lake Frome, also drilled straight from the Mesozoic cover into Precambrian crystalline basement (Youngs, 1979). All holes were fully cored in the pre-Mesozoic intervals.

CHAPTER 3

STRATIGRAPHY

OF THE

BILLY CREEK FORMATION

GENERAL

The Billy Creek Formation comprises a late Early to early Middle Cambrian, red-bed sequence of shale, siltstone and sandstone with minor limestone, dolomite and tuff. Non-red clastics are uncommon and occur mainly in the lower portions of the sequence.

The formation was defined by Daily (1956). It outcrops sporadically throughout the central and northern Flinders Ranges and at Reaphook Hill, approximately 50km to the east (Fig. 3-1). It has also been identified in the subsurface of the Lake Frome Embayment (Daily, 1969a; Youngs, 1978c). Maximum recorded thickness of the Billy Creek Formation is slightly in excess of 900m.

In this study, the Billy Creek Formation has been divided into five members (Fig. 3-2). The Warragee Member, the Nildottie Siltstone Member and the Eregunda Sandstone Member outcrop in the central and northern Flinders Ranges, and comprise a coarsening-upward red-bed sequence up to 900m in thickness (Plate 1). The Coads Hill Member and the Erudina Siltstone Member outcrop at Reaphook Hill, slightly to the east of the Flinders Ranges. The Coads Hill Member comprises a diverse sequence of sandstones, carbonates and shales, whereas the overlying Erudina Siltstone Member is a red-bed unit, similar in character to the Nildottie Siltstone Member.

The Edeowie Limestone Member, which Dalgarno and Johnson (1962) defined as the basal member of the Billy Creek Formation, has been redefined and grouped as part of the underlying Oraparinna Shale (Moore, 1979; Appendix A).

Subsurface data on the Billy Creek Formation in the Lake Frome region is still very limited. The basal portion of the sequence has been intersected in the S.A.M.D. Yalkalpo 2 drillhole (Fig. 2-2), but is quite different in character from its lateral equivalents at Reaphook Hill and in the central and northern Flinders Ranges. Thus, it is defined only as Billy Creek Formation sensu stricto. The upper portion of the Billy Creek Formation has been intersected in the Delhi-Santos Lake Frome Nos. 1 and 2 wells, but also is markedly different from its lateral equivalent (the Eregunda

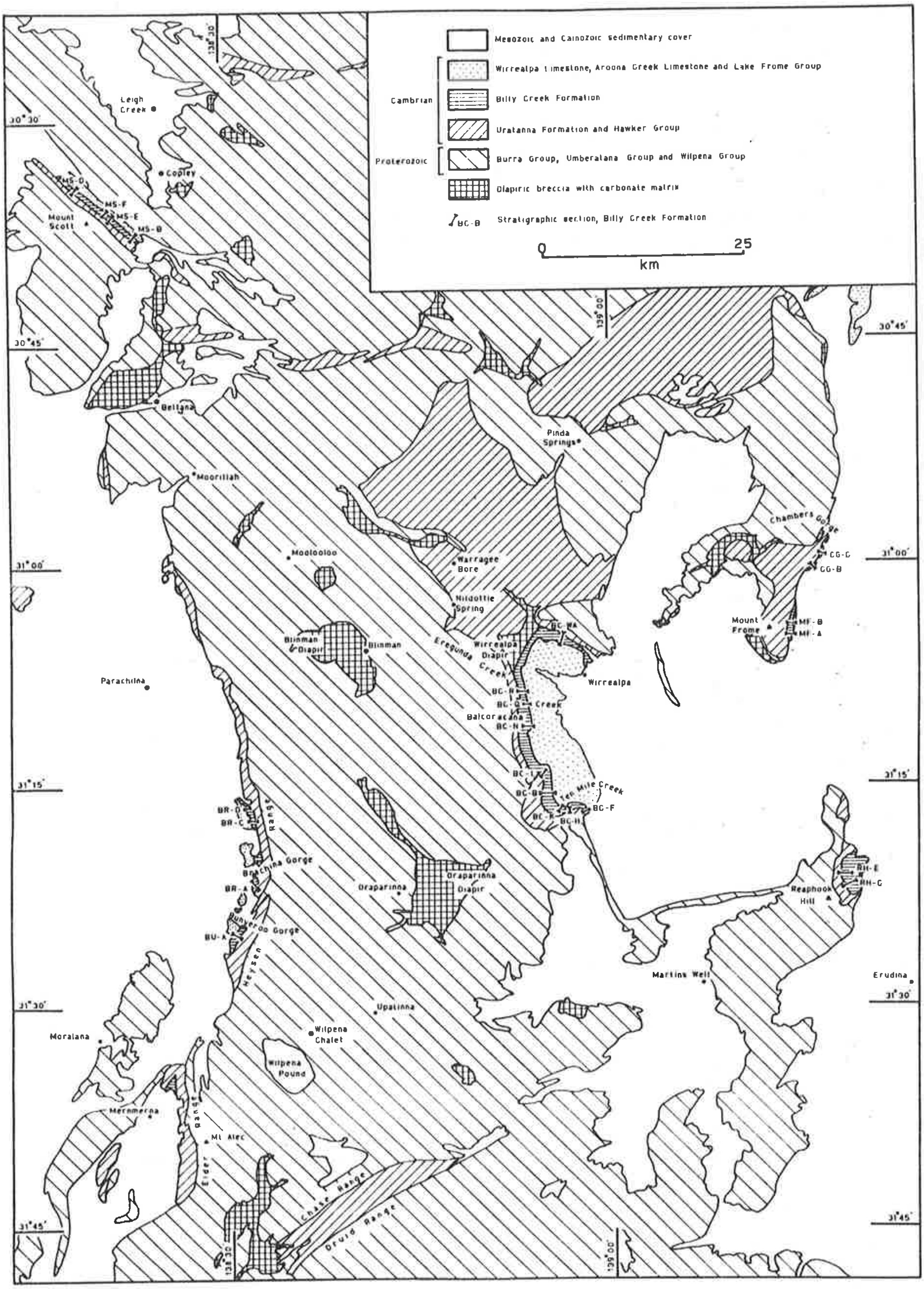


Figure 3-1. Outcrop map and location of measured stratigraphic sections in the Billy Creek Formation (also in rear pocket).

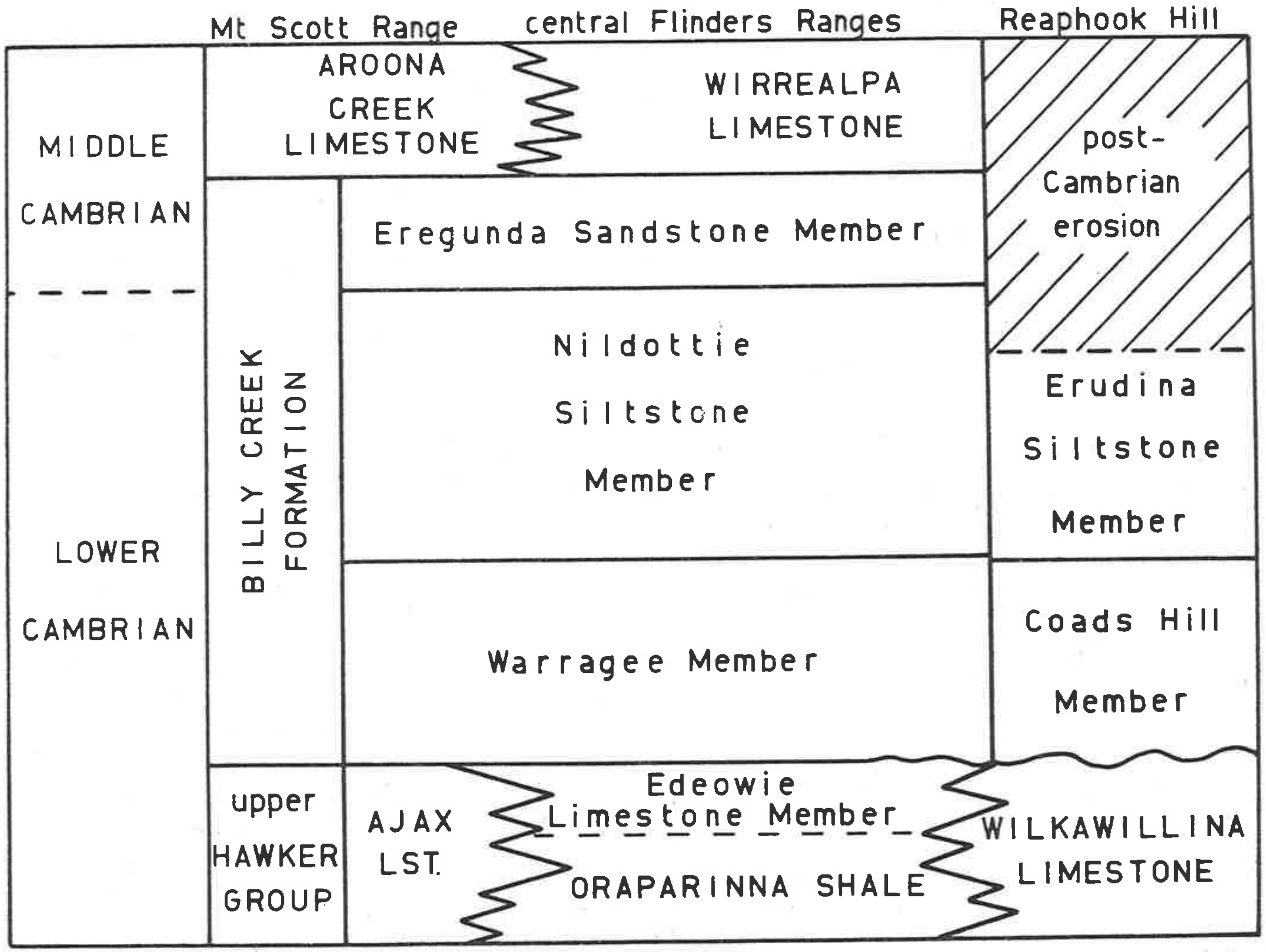


Figure 3-2. Stratigraphy of the Billy Creek Formation.

Sandstone Member) in the Flinders Ranges, and thus has also been termed Billy Creek Formation *sensu stricto*.

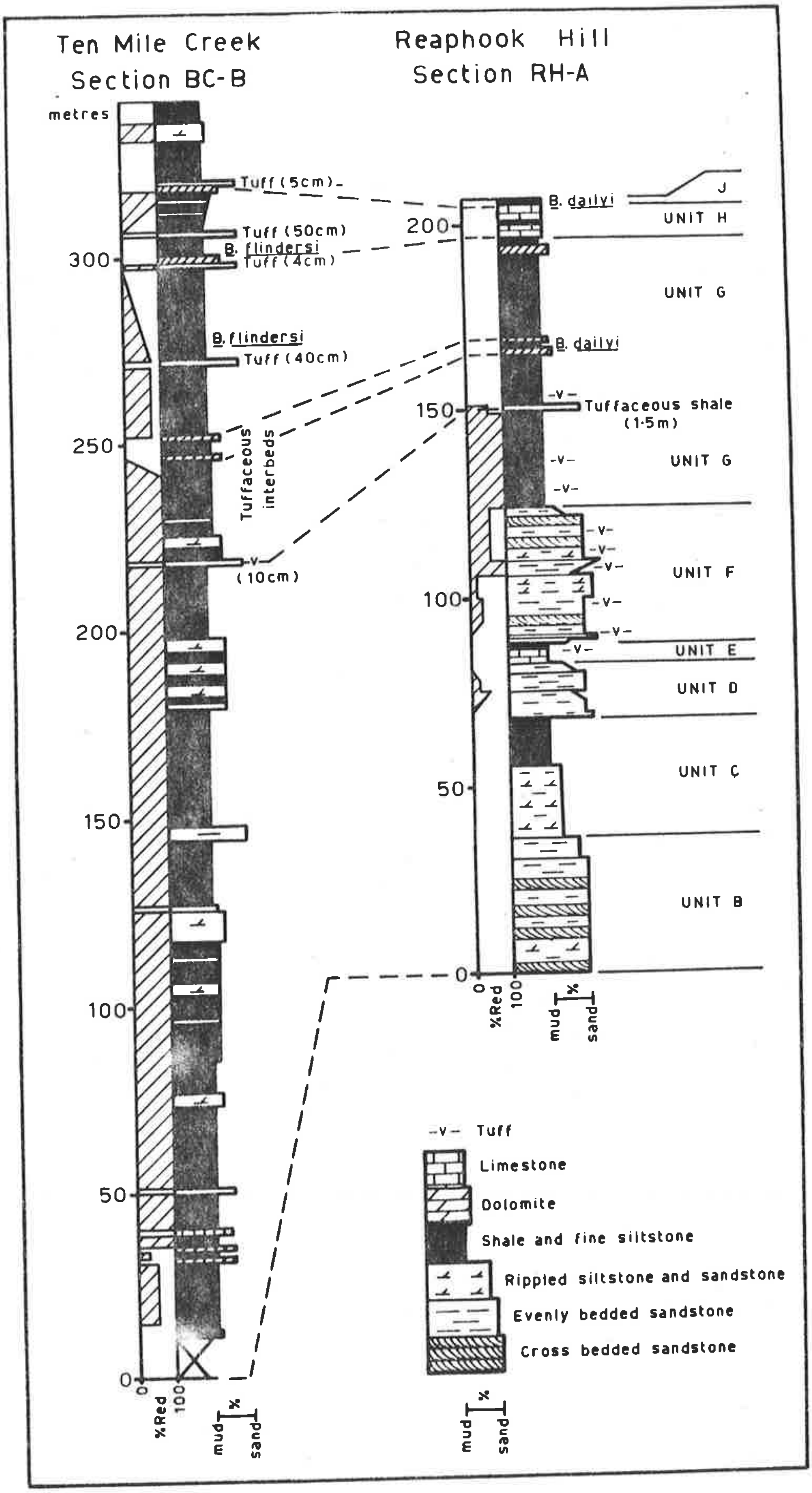
Internal Correlation

The Coads Hill Member at Reaphook Hill is considered to be the approximate lateral equivalent of the Warragee Member in the central and northern Flinders Ranges (Fig. 3-2). Both members contain the Emuellid trilobite genus *Balcoracania*, and a correlation on this basis is possible. *Balcoracania flindersi* occurs in the upper portion of the Warragee Member. (about 25m from the top in the type section), whereas *Balcoracania dailyi* occurs in the upper portion of the Coads Hill Member at Reaphook Hill (in Units G and J, approximately 35m and 3m respectively from the top of the member) (Fig. 3-3). Furthermore, the fossiliferous intervals in both the Coads Hill Member and the Warragee Member occur adjacent to several prominent calcareous and tuffaceous beds.

Assuming that the correlation presented in Figure 3-3 is a valid one, the immediate conclusion is that the occurrences of *B. dailyi* at Reaphook Hill are essentially the same age as the strata containing *B. flindersi* in the Wirrealpa Basin. An important note here however is that the appearance of *B. flindersi* is almost certainly controlled in part by sedimentological factors. The absence of *B. flindersi* at Reaphook Hill however, remains a mystery, and the possibility must be considered that either the identification of *B. dailyi* at Reaphook Hill is wrong, or that *B. dailyi* and *B. flindersi* are indeed the same species. Certainly further study of these most unusual trilobites is deemed necessary.

Correlation of the Billy Creek Formation between Reaphook Hill and the central Flinders Ranges has been made possible only by the fortuitous coexistence of Emuellid trilobites and distinctive tuffaceous and calcareous sequences (Fig. 3-3). Any one of these features on its own would probably have been insufficient for a satisfactory correlation. It was hoped that

Figure 3-3. Correlation of the Billy Creek Formation between Reaphook Hill and the type section in the Wirrealpa Basin.



a similar method could be employed for the correlation of the Billy Creek Formation between the outcrops of the Flinders Ranges and the subsurface occurrences to the east. Unfortunately, neither trilobites, thick tuffaceous beds or carbonate intervals were found in the Yalkalpo 2 borecore, and thus the relationship between this sequence and the rest of the Billy Creek Formation remains uncertain. However, although it is possible that the tuffaceous detritus may have been sufficiently reworked in the Yalkalpo area so as to preclude its recognition as such, it is surprising that no Emuellid trilobites were found in the abundant green shales of the sequence. The most likely possibility therefore is that the youngest sediments of the Billy Creek Formation preserved in Yalkalpo 2 are younger than both the fossiliferous units and the major tuffaceous sequence in the upper portion of the Warragee Member and the Coads Hill Member. Furthermore, if the Billy Creek Formation at Yalkalpo 2 spanned a greater time interval than suggested above, then there would probably be evidence of a regression in the upper portion of the sequence, to correspond with the development of the Nildottie and Erudina Siltstone Members, further west. There is no evidence of such a regression.

The upper portion of the Billy Creek Formation is absent at Reaphook Hill, and the Erudina Siltstone Member is considered to be the approximate lateral equivalent of the Nildottie Siltstone Member in the central and northern Flinders Ranges (Fig. 3-2). This interpretation is based mainly on isopach and palaeocurrent trends, which suggest that the Eregunda Sandstone Member was originally deposited in the vicinity of Reaphook Hill, but has since been removed by erosion. The apparent absence of the Eregunda Sandstone Member in the Delhi - Santos Lake Frome wells is interpreted as an effect of lateral facies change, with deltaic sandstones passing laterally into supratidal evaporitic mudflats. A comparable Recent example of this nature is quoted by Thompson (1968) from the Gulf of California.

Regional Correlations

Correlations between the Billy Creek Formation and other units in the Adelaide 'Geosyncline' and on the Stuart Shelf (Fig. 1-3) are summarized by Daily (1976b). The Yarrawurta Shale, which was deposited on the Stuart Shelf to the west of the Adelaide 'Geosyncline' is similar in character to the Warragee Member of the Billy Creek Formation, comprising approximately 120m of "micaceous, calcareous, red-brown, pink, purple or green-grey shales and siltstones" (Johns, 1968, p.33). According to Daily (1976b, p.18), "the widespread occurrence of 'bird's-eye' limestone, dolomite and stromatolites near the top of the Andamooka Limestone, Ajax Limestone, and in the youngest phases of the Wilkawillina Limestone and the Moorowie Formation point to a general regression of the sea before the influx of red-bed clastics which gave rise to the Yarra-wurta Shale and the Billy Creek Formation". Thus, the northern portion of the Adelaide 'Geosyncline' was relatively stable at this period of time, and a slow regression is indicated by much of the Billy Creek Formation stratigraphy.

In the southern portion of the Adelaide 'Geosyncline' however, tectonic movements were pronounced. At the close of the period marking Hawker Group sedimentation, the Kanmantoo Trough was formed (Daily & Milnes, 1971, 1972b, 1973; Thomson, 1969b). Compensating uplifts occurred to the north and west, resulting in considerable erosion of the uplifted areas and deposition to the south of a thick sequence of shallow-water, shelf sediments which are in part conglomeratic. The earth movements, termed the Kangarooian Movements by Daily (1969b) and Daily & Forbes (1969), appear to have affected the whole of the Adelaide 'Geosyncline' and may be responsible for local disconformities at the base of the Billy Creek Formation in the Flinders Ranges as well as accounting for the regressive nature of the red-bed sequence. Correlation of the Kangaroo Island northeast coast sediments with the Billy Creek Formation (Fig. 1-3) is made on the basis of the trilobite family Emuellidae, and in particular the trilobite genus *Balcoracania* Pocock. In the Flinders Ranges, *Balcoracania flindersi* occurs in the upper portion of the Warragee

Member and Balcoracania dailyi occurs in the upper portion of the Coads Hill Member (Fig. 3-3). On Kangaroo Island Balcoracania dailyi occurs in a thin burrow-mottled limestone and associated shales near the top of the White Point Conglomerate (Pocock, 1967, 1970; Daily, 1977). The Kangaroo Island northeast coast sequence is in turn correlated with the metasediments of the Kanmantoo Group, mainly on the basis of lithological similarities between the two sequences (Daily, 1976b, Fig. 8).

Biostratigraphic correlation is possible between the Billy Creek Formation and the upper portion of the Cymbric Vale Formation in northwestern New South Wales, although the correlation is somewhat indirect. The lower 1500m of the Cymbric Vale Formation are correlated with the Ajax Limestone (Kruse, 1977) however a younger fauna, containing an abundance of Estaingia bilobata has been reported by Warris (1967) and Öpik (1968, 1976) from the uppermost portion of the Cymbric Vale Formation. Estaingia bilobata is a prominent species in the lower portion of the Emu Bay Shale and also occurs in the upper portion of the White Point Conglomerate on Kangaroo Island, and thus occupies a similar stratigraphic position to the trilobite genus Balcoracania Pocock, discussed above. Thus a correlation is suggested between the upper portion of the Cymbric Vale Formation in northwestern New South Wales, the upper portion of the White Point Conglomerate or the lower portion of the Emu Bay Shale on Kangaroo Island, and the upper portion of the Warragee Member in the Flinders Ranges.

More tentative correlations of the Billy Creek Formation have been suggested by Freeman (1966) and Wopfner (1966). Freeman (1966) related the Billy Creek Formation to a period of non-deposition in the Bancannia Trough, suggesting more extreme uplift in the latter area. Wopfner (1966) described Cambro-Ordovician sediments from the northeastern margin of the Lake Frome Embayment at Mount Arrowsmith in New South Wales (Fig. 2-2), and tried to relate the sequence to the outcrops in the Flinders Ranges. On lithological grounds, Wopfner (1966) correlated his members A and B at Mount Arrowsmith with the Billy Creek Formation. However, Wopfner's member A contains the

Middle Cambrian trilobite Xysridura, making this correlation and the correlations suggested by Youngs (1977a, 1977b) between the Wirrealpa Limestone and the Mount Arrowsmith sequence, untenable (Daily pers. comm., 1977).

CHAPTER 4

STRATIGRAPHY AND ENVIRONMENTAL ANALYSIS OF THE WARRAGEE MEMBER

THE STRATIGRAPHY OF THE WARRAGEE MEMBER

Nomenclature

Throughout the central Flinders Ranges and in the Mount Scott Range, the lower portion of the Billy Creek Formation is dominated by red, green and grey shale and fine siltstone (Plates 1 and 2). Minor interbeds of dolomite, dolomitic limestone, tuff and coarse siltstone are also present. The sequence is termed the Warragee Member (Moore, in press). The name is derived from the Warragee Bore, which is located approximately 20km north-west of the Wirrealpa homestead, in the Wirrealpa Basin (Fig. 3-1). The type section (Section BC-B, Figs. 3-1, 4-1, 4-2; Plate 1) is located in an area of undulatory topography 2.5km north of the Ten Mile Creek. The section corresponds with the basal 350m of Daily's (1956) type section of the Billy Creek Formation.

Introduction

The Warragee Member is the basal member of the Billy Creek Formation in the central and northern Flinders Ranges. It is equivalent in part to the Coads Hill Member of the Billy Creek Formation at Reaphook Hill.

Outcrop of the Warragee Member and positions and thicknesses of the major stratigraphic sections are shown in Figure 4-1. The member attains its maximum measured thickness of 371m in Section BU-A, south of the Bunyeroo Gorge, and becomes progressively thinner towards the north and northeast. It is also absent from outcrops immediately south of the Ten Mile Creek Graben (Section BC-F3).

The Warragee Member is not recognised at Reaphook Hill, where the basal portions of the Billy Creek Formation are dominated by medium-grained sand-stones. The best locality to examine the sequence is in the type section (Daily, 1956; Section BC-B, Figs. 4-1, 4-2), 2.5km north of Ten Mile Creek. Fifteen stratigraphic sections have been measured in outcrops throughout the Flinders Ranges, and these are briefly summarized in Figure 4-3 (rear pocket).

Figure 4-1. Thickness variations in the Warragee Member, Nildottie Siltstone Member and Eregunda Sandstone Member of the Billy Creek Formation (from Moore, in press).

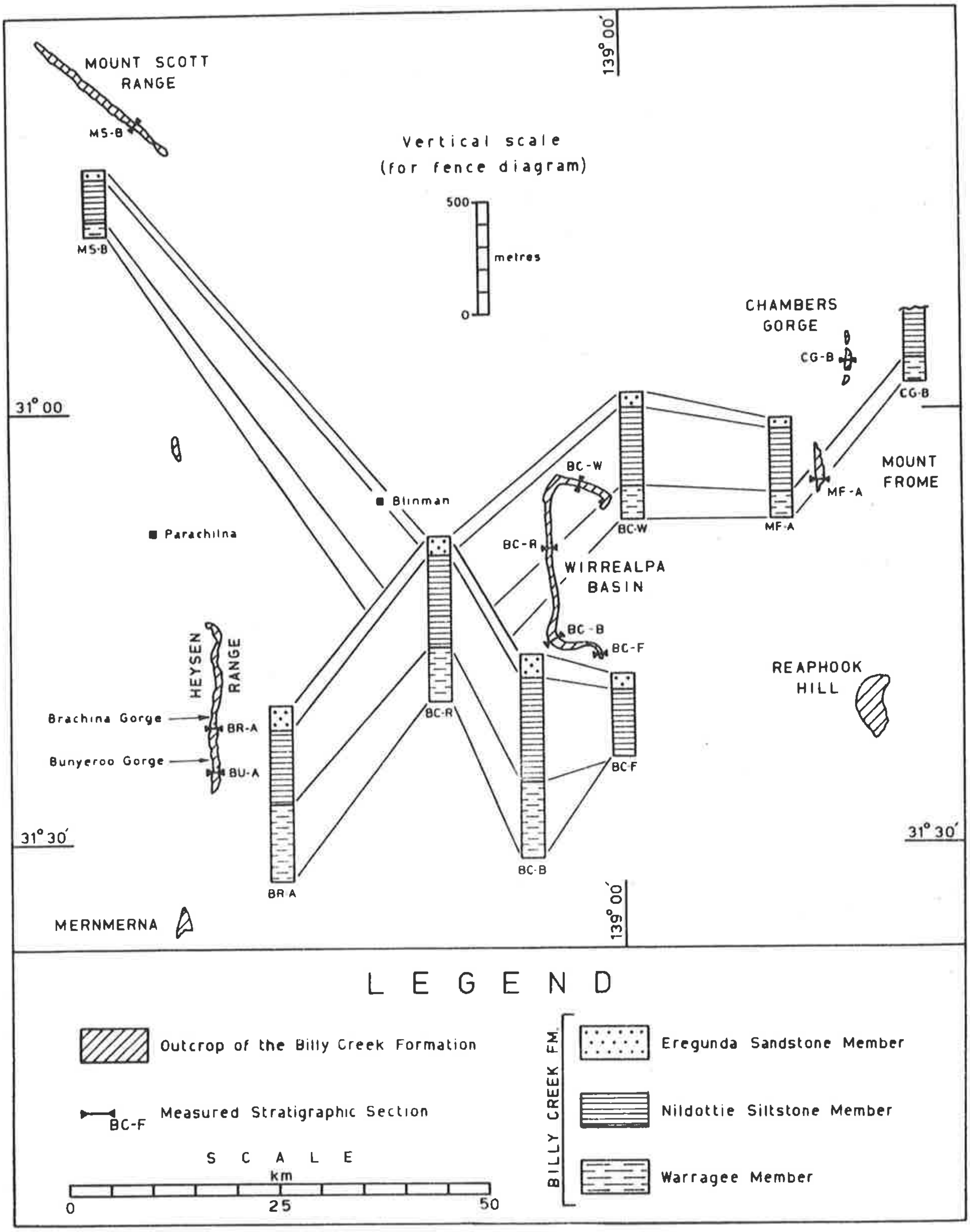
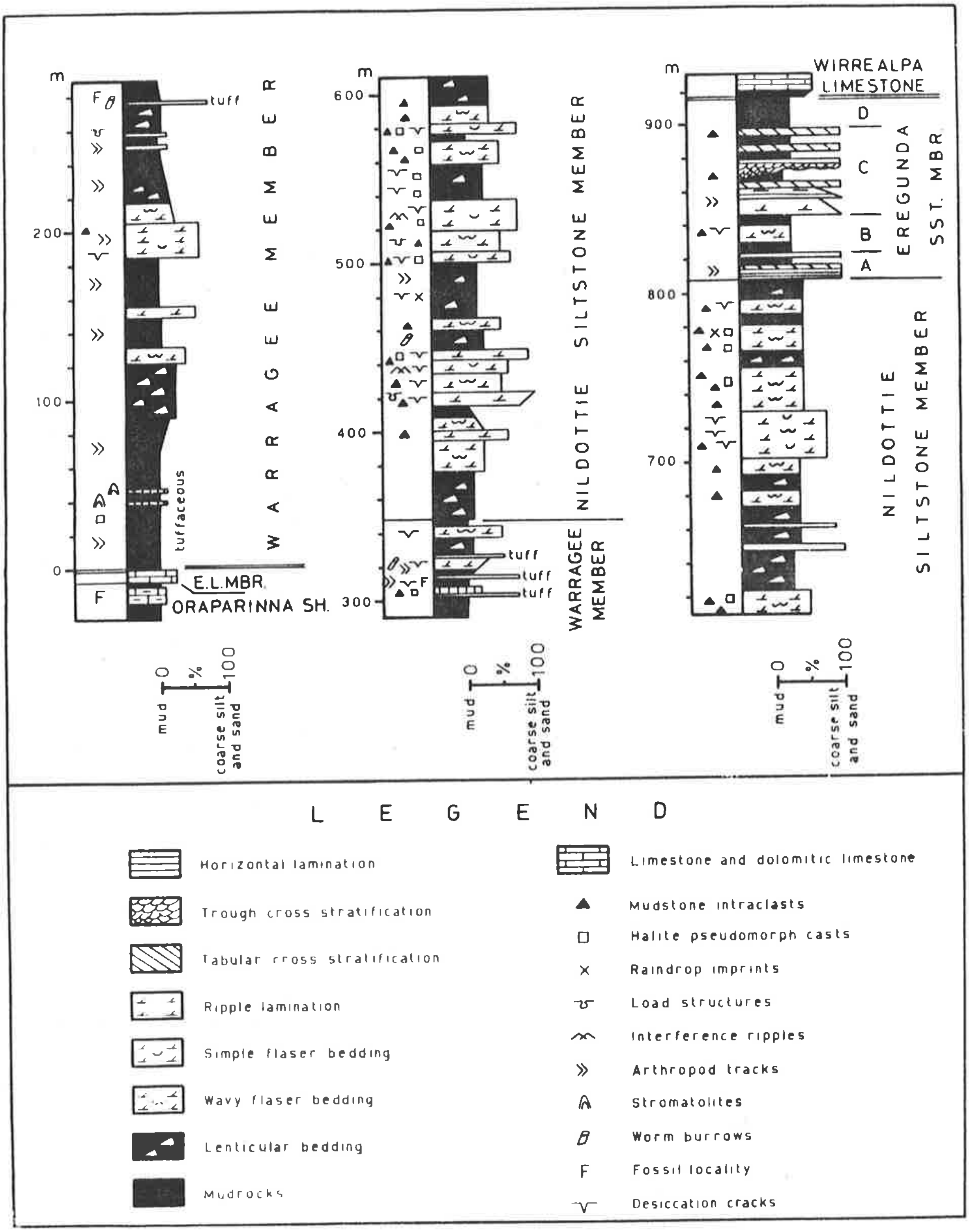


Figure 4-2. Type section of the Warragee Member, Nildottie Siltstone Member and Eregunda Sandstone Member in the Wirrealpa Basin (Section BC-B). This section is located in the same area as Daily's (1956) type section of the Billy Creek Formation.



The Base of the Warragee Member

In most areas, the Warragee Member rests conformably on the Edeowie Limestone Member of the Oraparinna Shale. However, in the Mount Scott Range, red and green interlaminated silty shales of the Warragee Member rest directly and apparently conformably on dolomitized stromatolites of the Ajax Limestone. No erosion of the stromatolitic surface is apparent. A similar situation occurs in the Wirrealpa Basin near the Old Wirrealpa Mine, where green shales of the Warragee Member conformably overlie stromatolitic dolomite of the Wilkawillina Limestone.

In Section MF-C near Mount Frome (Fig. 3-1), the Warragee Member disconformably overlies very sandy Wilkawillina Limestone. The disconformity (or possibly hiatus) is indicated by an erosional ridge, 5cm high, on the upper surface of the Wilkawillina Limestone. The ridge is draped by silty, micaceous shales of the Billy Creek Formation. Further to the north near Chambers Gorge, light olive shales of the Warragee Member rest conformably on flaggy, micritic limestone of the Moorowie Formation (Moore, 1979; Appendix A).

The Top of the Warragee Member

In all sections examined, a transition occurs from the Warragee Member into the overlying Nildottie Siltstone Member. In the type section, the contact is taken at the top of the last major green shale interval, which occurs approximately 32m above the top of a prominent, 2m thick, buff-coloured dolomite (Section BC-B, Fig. 4-4).

In general, the Warragee Member is differentiated from the overlying Nildottie Siltstone Member in the following ways:

(a) The Warragee Member is dominated by shales and fine to medium siltstones, whereas the overlying member is coarser grained.

(b) The Warragee Member contains common green, greyish green and grey interbeds in the dominantly red clastic sequence. Non-red intervals in the Nildottie Siltstone Member are rare, and very thin.

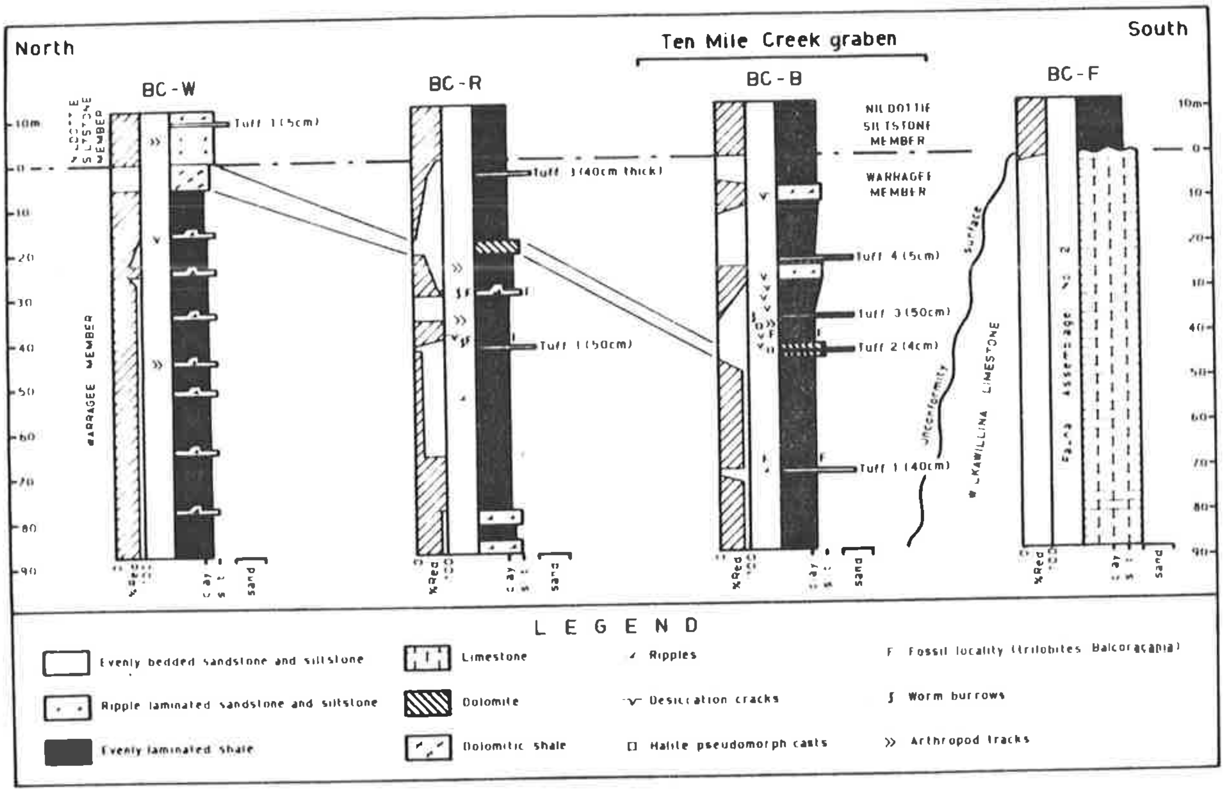


Figure 4-4. Location of major tuff beds, dolomite and fossiliferous intervals in the upper portion of the Warragee Member in the Wirrealpa Basin (see Fig. 3-1 for locations of stratigraphic sections). All of the tuff beds shown in Fig. 4-4 have been mapped continuously throughout the area of outcrop. The thick dolomite marker bed occupies a similar stratigraphic position in relation to the tuffs in all of the outcrops, and thus is considered to be essentially time-synchronous over its area of outcrop. The Warragee Member - Nildottie Siltstone Member boundary however is markedly time transgressive in the Wirrealpa Basin, and is considered to be a very delicate palaeo-environmental indicator. The transition from variegated to all-red sediment (i.e. the member boundary) is interpreted as representing a minor regressive event, and indicates that persistent shallow water, oxidising conditions typical of the Nildottie Siltstone Member developed first in the north and south and then slowly extended into the central, more basinal areas (the Ten Mile Creek graben: Section BC-B) as the regression continued.

(c) The Warragee Member contains minor limestone and dolomitic limestone interbeds, which are absent from the overlying member.

(d) The Warragee Member contains abundant tuffaceous interbeds, whereas tuff beds are rare in the overlying Nildottie Siltstone Member.

Palaeontology

Crawling tracks and "Coffee-bean" scratch marks attributed to trilobites occur sporadically throughout the member and are particularly common in the upper, green unit of the Warragee Member in the Wirrealpa Basin. The tracks are generally very small, with an average width of 5-15mm.

Emuellid trilobite body fossils were first recorded in the Billy Creek Formation by Dalgarno (1964). The fossil locality is a small tributary south of Balcoracana Creek, and is shown of the BLINMAN 1:63,360 Geological Sheet (Dalgarno *et al.*, 1964). The trilobites were subsequently described by Pocock (1967, 1970), who named them *Balcoracania flindersi*. He presented evidence showing that they represent a population which underwent mass mortality, and suggested that the death of the trilobites was due to tuffaceous fallout, associated with distant volcanic activity. However, this particular part of the sequence is not recognisably tuffaceous. Furthermore, the bedding planes which contain the bulk of the fossils are abundantly desiccation cracked, and thus the mass mortality probably resulted from the trilobites being stranded by a receding tide.

During the course of this study, additional collections of *Balcoracania flindersi* Pocock were made from south of Balcoracana Creek. The trilobites were also found at a similar stratigraphic horizon north of Balcoracana Creek (Section BC-R) and in the type section (BC-B) (Fig. 4-4). Mass mortality, associated with desiccation, is also indicated in these sections. Despite an intensive search, trilobites have not been located in any other outcrop of the Warragee Member. As now defined, the trilobites occur in the upper portion of the Warragee Member (Figs. 4-2, 4-4). In many cases, the trilobites are still partly articulated. The host sediments comprise red and green interlaminated shale-siltstone. Desiccation cracks in red shale are infilled with fine to medium, green siltstone, which grades upward into green and red shale. Thicker red units contain rare trilobite fragments, and some horizons contain worm burrows. The burrows are up to 2cm across, and are passively packed.

Regional Variation

Thickness variations in the Warragee Member are shown in Figure 4-1. In general, the sequence thins towards the north and northeast, although a local increase in thickness is associated with the Ten Mile Creek graben (Sections BC-B, BC-L).

The Warragee Member is partly characterised by its fine grain-size and poorly developed grain-size variation. This is true both within and between sections. Coarse siltstones and rare, fine sandstones occur mainly in the middle, red unit of the member, and are most common in the thick Ten Mile Creek graben and Heysen Range sections (BC-B, BU-A, BU-B). These sections also contain the greatest proportion of red coloured clastics. In addition, the Heysen Range sections contain common, small halite imprints.

Carbonate units are particularly common in the Ten Mile Creek graben outcrops, but occur sporadically throughout the Wirrealpa Basin, Mount Frome and Chambers Gorge sections. They are uncommon in the eastern outcrops (Heysen Range and Mount Scott Range sections).

ENVIRONMENTAL ANALYSIS OF THE WARRAGEE MEMBER

Introduction

A marine environment of deposition for the Warragee Member is indicated by the presence of trilobites and marine trace fossils. Thin, dolomite and dolomitic limestone interbeds developed where the supply of detritus was minimal. Shallow, evaporitic conditions are indicated by the presence of stromatolites, halite imprints, desiccation cracks and penecontemporaneous dolomite. The bulk of the sediment is too fine for the development of ripple lamination, but where ripples are present they are dominantly wave-induced, symmetrical or near-symmetrical forms.

Since there is very little grain-size variation in the Warragee Member, distinct facies associations are not recognised. Instead there is a poorly developed facies spectrum from coarse rippled siltstone, through laminated fine siltstone and shale, into calcareous shale and relatively pure carbonate. Volcanic detritus, once in the basin of deposition is subject to reworking like any other clastic material, and thus does not warrant special attention at this stage.

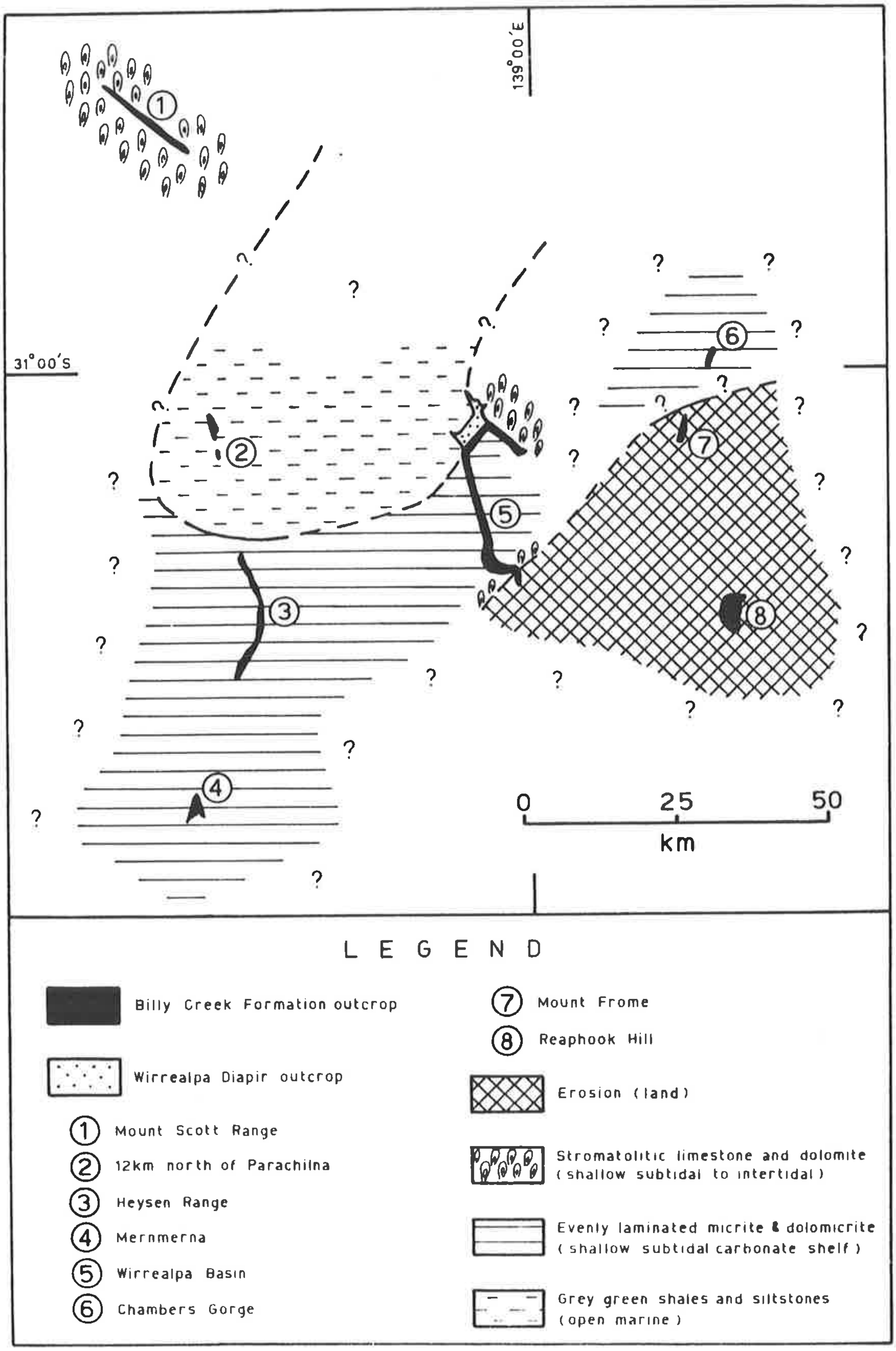
Furthermore, since the facies are poorly defined and gradational into each other, it is difficult to separate them and interpret the respective depositional environments. The task however, is greatly simplified where cycles are preserved, because Walther's Law can then be applied. Walther's Law essentially states that a vertical superposition of facies in the rock record represents deposition in laterally adjacent environments. This is not always the case, especially in tectonically active areas, however it certainly is a useful starting point for the interpretation of the Warragee Member.

Geologic Setting

The interpreted geologic setting immediately preceding the deposition of the Warragee Member is illustrated in Figure 4-5. Despite the obvious restrictions due to the shortage of available outcrops, a moderate degree of regional palaeogeographic interpretation is possible.

Sandy, intraclastic limestones are mainly restricted to the eastern areas. The petrology of the terrigenous fraction in the carbonates indicates derivation from pre-existing sedimentary strata, and thus an easterly or southeasterly land mass was probably exposed and being eroded during parts of the late Early Cambrian. Evidence of minor subaerial exposure is indicated in the southern portions of the Reaphook Hill outcrop, where a pisolitic calcrete horizon is developed at the top of the Wilkawillina Limestone. Evidence also exists for a land mass to the south of the Ten Mile Creek graben, although its extent is not known.

Figure 4-5. Interpreted geologic setting immediately preceding the deposition of the Warragee Member.



Laminated, micritic limestone and dolomitic limestone developed in quiet, shallow shelf environments, well removed from the major sources of terrigenous detritus. Near Parachilna, a greater supply of fine-grained, terrigenous detritus is apparently responsible for the absence of the Edeowie Limestone Member.

The influence of the Wirrealpa Diapir on sedimentation and basin subsidence during this period of time is uncertain. A thick sequence of fine-grained clastics (the Narrina Greywacke) developed to the northwest of the present outcrops of the diapir. However to the east, intertidal to supratidal conditions are indicated by the presence of stromatolitic dolomite. Thus, although there is no evidence of subaerial exposure of the Wirrealpa Diapir immediately prior to the deposition of the Billy Creek Formation, it was probably responsible for minor seafloor elevation in some areas, and considerable subsidence in others.

Stromatolites however, were not restricted to this one area of local seafloor elevation, and the general regression that commenced prior to the deposition of the Billy Creek Formation caused stromatolite growth in the uppermost portions of the Ajax Limestone, as presently exposed along the entire length of the Mount Scott Range.

Approximately 100km to the northwest of the Flinders Ranges, on the northwestern tip of Lake Torrens, a 150m thick sequence of red with minor green and grey shales and siltstones overlies the Early Cambrian Andamooka Limestone. The sequence, termed the Yarrawurta Shale, has been correlated with the Billy Creek Formation (Johns, 1968; Daily, 1976b), and thus it appears that the basin of deposition had a considerable westerly extent during the early stages of deposition of the Billy Creek Formation.

Facies Descriptions

Evenly laminated red shale

This facies is by far the most abundant, and comprises evenly laminated, greyish red shale to fine siltstone (Plate 3). The sediments are commonly weakly calcareous; in a few cases calcite is disseminated throughout the rock, occurring as irregular veins, streaks and patches. Halite casts, small load structures, desiccation cracks (Plate 4) and trilobite tracks are uncommon. Rare, subvertical burrows (Plate 5) and disarticulated trilobite fragments occur in some of the Wirrealpa Basin outcrops.

Evenly laminated green shale

This facies comprises evenly laminated, green and greyish green, calcareous shale to fine siltstone. Green fissile shales which occupy the lower portions of the Warragee Member are only weakly calcareous. However, in the upper portions of the member green shales are commonly very calcareous, and fine green siltstones may contain micritic limestone intraclasts. Arthropod tracks and small halite imprints occur sporadically throughout the sequence. Desiccation cracks are rare. However, some desiccation-cracked horizons in the upper portions of the member contain abundant articulated trilobite remains (Pocock, 1970).

Rippled siltstone

Rippled siltstones occupy only a very minor portion of the Warragee sequence. The facies comprises greyish red and minor greyish green, ripple laminated coarse siltstone to very fine sandstone (Plate 6). Ripple laminated units rarely exceed 30cm in thickness and average 5cm. Rippled cosets typically have undulose to curved basal surfaces and discordant internal laminae typical of wave-generated structures (DeRaaf et al., 1977). Rippled bedding surfaces are rarely preserved, but where they do occur, ripples are typically straight to slightly sinuous, low amplitude (4-10cm), symmetrical and near-symmetrical forms (Plate 7). Catenary and linguoid ripples are rare. Halite casts, desiccation cracks and mudstone intraclasts are commonly associated with the greyish red, silty intervals.

Intraclastic limestone

Intraclastic limestones occupy a very minor portion of the Warragee Member. Typically, they occur as even laminae or thin beds of greenish grey to fawn, argillaceous calcisiltite. Thicker units commonly contain appreciable terrigenous siltstone to very fine sandstone, and may have symmetrical ripples developed on the upper surface. An unusual occurrence of sandy, oolitic limestone occurs near Chambers Gorge, where a lenticular bed up to 1m thick crops out. The unit is herringbone cross-stratified and contains some hydroplastically deformed, micro-crystalline dolomite intraclasts, up to 10cm in length.

Evenly laminated dolomitic limestone and dolomite

Evenly laminated dolomitic limestone and dolomite occur sporadically throughout the upper and lower portions of the Warragee Member, although they are uncommon in the western outcrops (along the Heysen Range, at Mernmerna and in the Mount Scott Range). Most of the units comprise pale yellowish brown micrite to microsparite, which is partly dolomitized (Plate 8). Bedding is defined by thin silt laminae. Polygonal desiccation cracks (Plate 9) and halite imprints up to 2cm across (Plate 10) are common in the silty intervals. In the central portions of the Wirrealpa Basin, a buff-coloured microcrystalline dolomite bed up to 2m thick forms a prominent marker horizon (Fig. 4.4). The unit becomes argillaceous towards the north and passes laterally into green shale.

Stromatolitic carbonate

Low domal stromatolites, up to 15cm across and with 4cm relief on the upper surface, occur in the lower portions of the Warragee Member in the type section (Plate 11). The stromatolites are developed in the upper portions of slightly silty, pale yellowish brown limestone and dolomitic limestone beds, which are up to 15cm in thickness. Elsewhere in the Wirrealpa Basin, wavy laminations are developed in thin carbonate units, and these are also considered to be of algal origin.

Tuff

The majority of the tuffaceous units in the Billy Creek Formation occur in the Warragee Member. Over thirty possible tuffaceous horizons are recognised in the type section, and at Mount Frome volcanic detritus is disseminated throughout the lower portion of the member. Tuffaceous intervals are uncommon in the Heysen Range sections and have not been identified in the Mount Scott Range outcrops.

The tuffaceous units are recognised primarily on the basis of colour. Tuffaceous bands in red shale-siltstone are either salmon pink or bright olive green. The pink bands are generally coarse silt or fine sand size, and contain abundant shards of poorly twinned plagioclase with albitic rims. The green colour in many of the tuffaceous units is due to extensive alteration to chlorite. Rarely, devitrified shards are recognisable. Tuffaceous units associated with carbonate-rich sequences are typically salmon-pink in colour, with common cementation and replacement of detrital grains by calcite.

In the Wirrealpa Basin, two prominent tuffaceous units, 40-50cm thick, occur in the upper portions of the member (Tuffs 1 and 3, Fig. 4-4). Near Balcoracana Creek (Section BC-R), the lower unit forms drapes over pre-existing symmetrical ripples. In the type section (BC-B), the upper unit is horizontally burrowed (Plate 12) and contains "coffee-bean" resting marks, attributed to trilobites. Reworking of some of the tuffaceous detritus has occurred, and several of the thicker tuff bands contain green shale intraclasts and a variety of non-volcanic, sandy detritus. In some cases, tuffaceous sandstones are ripple laminated, with asymmetrical ripples developed on the upper surface. Regional correlation of tuffaceous units in the Billy Creek Formation is considered in a separate section.

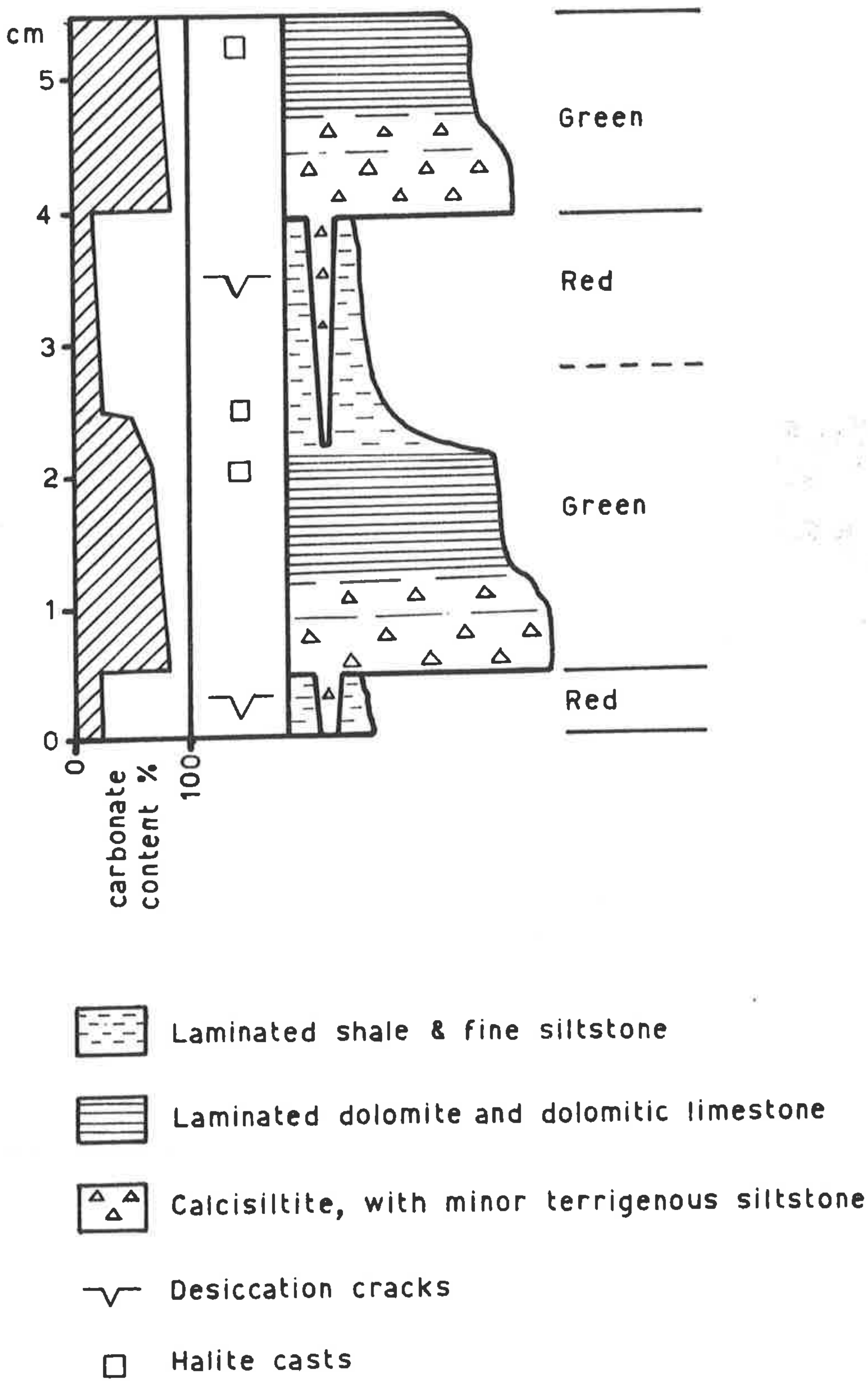
Facies Associations and their Interpretation

Small Scale Cycles

Carbonate - green shale - red shale cycles

Small scale cycles involving laminated carbonate and shale/siltstone are common in the upper portions of the Warragee Member, particularly in the Wirrealpa Basin (Plate 4). The cycles are up to 20cm in thickness, and average 2-5cm. In their most complete development, cycles consist of a characteristic sequence of facies, as shown in Figure 4-6. An initial

Figure 4-6. Ideal small scale shale-carbonate cycles in the Warragee Member.



marine influx of silt-sized clastic carbonate accumulated in pools and shallow sheets on intertidal to supratidal mudflats. Once the initial traction and suspension load was deposited, laminated carbonates accumulated, principally by chemical sedimentation. Progressive evaporation of stranded bodies of salt water led to the precipitation of evaporite minerals and the development of penecontemporaneous dolomite in some cases.

The only clastic sediment to accumulate in the saline pools during this period of time was very fine silt and clay. Initial clay deposits were green, due to a moderate carbonate content. Subsequently, clays were deposited in oxidising conditions on nearly dry supratidal mudflats. Prolonged desiccation led to the development of abundant, polygonal shrinkage cracks, prior to further marine influxes.

Carbonate - green shale couplets

In most cases, the complete cycle shown in Figure 4-6 is not developed. A common alternative however, is the repetition of fining-upward, carbonate/ green shale couplets. Three typical combinations are shown in Figures 4-7a, 4-7b and 4-7c. The couplets represent an initial input of marine clastic detritus (intraclastic silty limestone or terrigenous siltstone), followed by a period of settling of mud from suspension. Frequent inundation maintained a high water table and prevented oxidation of the terrigenous mudstone, although some couplets contain polygonal desiccation cracks, indicating temporary subaerial exposure. Halite casts are often large (up to 2.5cm across) and abundant. The laminated dolomite/shale couplets of Figure 4-7c represent much quieter conditions than the other two examples, although the same process of inundation and evaporation was operative.

Carbonate - red shale couplets

A common type of sedimentary couplet in the Warragee Member is interlaminated red shale and green calcareous siltstone to calcisiltite (Fig. 4-7d). The green sediments represent an initial influx of marine detritus onto intertidal mudflats. However, an overall oxidising environment, with periodic

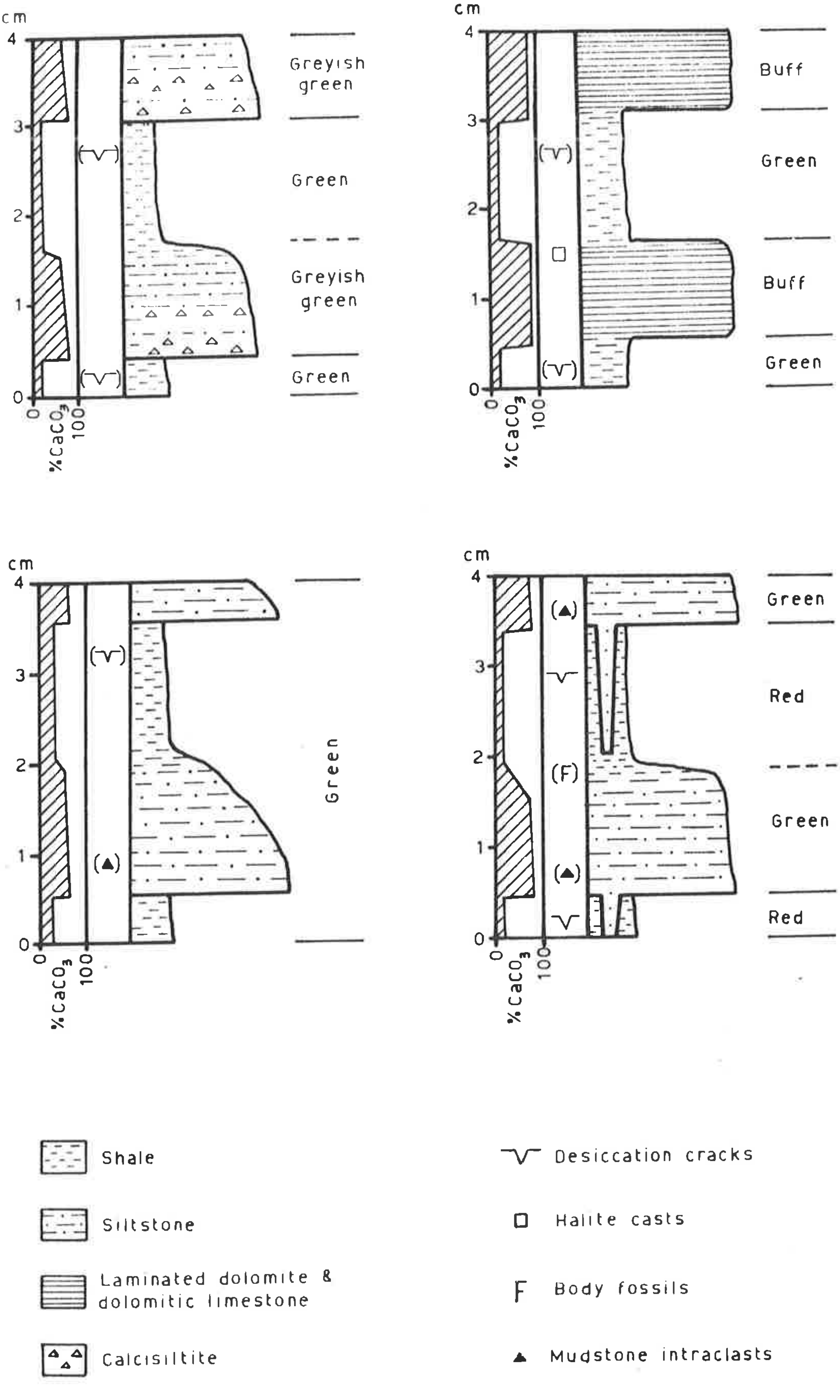


Figure 4-7. Common small scale shale-carbonate cycles (couplets) in the Warragee Member.

desiccation and a very low water table, is indicated by the red mudstone facies. The alternation of red and green laminae mainly reflects differences in grain-size and composition (especially with respect to carbonate content) in the different facies.

Large scale cycles

Laminated carbonate - shale cycles

Large scale cyclic repetition of shale-siltstone and laminated carbonate are common in the upper and lower portions of the Warragee Member, and are particularly well exposed in the Wirrealpa Basin (Plate 8; Section BC-B) and at Mount Frome (Section MF-B). The cycles represent alternations of clastic and chemical sedimentation.

Thick cycles up to 15m are exposed in the Wirrealpa Basin. They contain appreciable red shale intervals, which grade upwards through greyish green shale and calcareous shale into relatively pure dolomitic limestone and dolomite (Fig. 4-8a). A similar, although generally more abrupt gradation back into red shale is common. In the transition zone from red to green shale, small scale cycles, as described above (especially Fig. 4-7d) are common. Desiccation cracks and halite casts are abundant and in rare cases, bedding planes are covered with trilobites. Overlying this transition zone, the sequence is dominated by undulose to evenly bedded dolomite and dolomitic limestone. Bedding plane surfaces rarely contain desiccation cracks and halite casts. Fossils and their traces are apparently absent. Laminae are defined by discontinuous, terrigenous siltstone streaks, which grade upwards into microcrystalline carbonate.

The cycles appear to represent variations in terrigenous sediment input, related to minor transgressions and regressions. Red shale developed in an intertidal to supratidal environment, as indicated by the presence of rare trilobites and trilobite tracks, and common desiccation cracks. In calm conditions, supratidal to upper intertidal mudflats accumulated only the finest-grained clastic detritus. However, during storms and unusual high tides, mudflats adjacent to a more open marine environment were subject

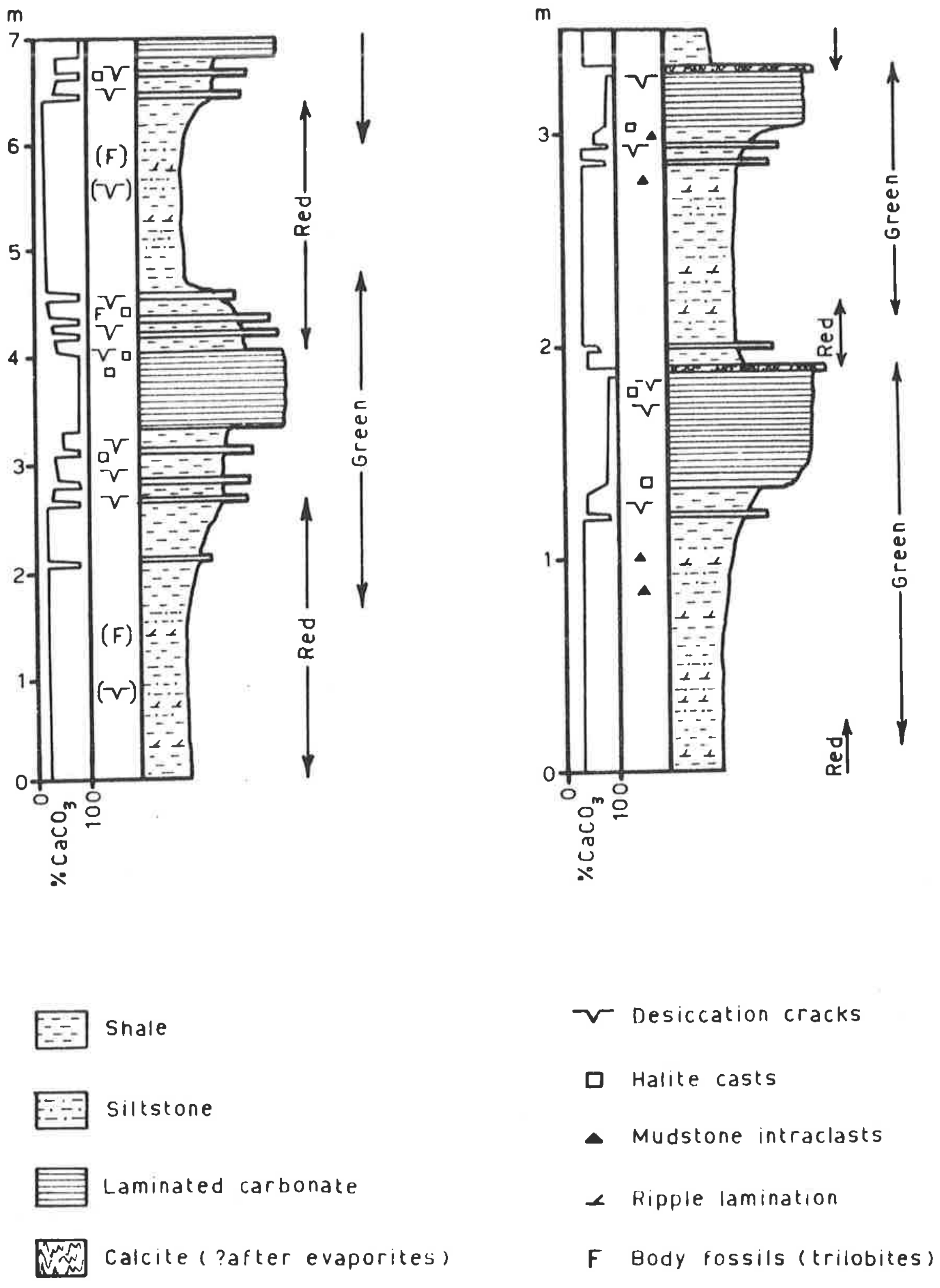


Figure 4-8. Large scale shale-carbonate cycles in the Warragee Member. A: near-symmetrical cycles. B: highly asymmetrical cycles.

to marine influxes. Saline water, once trapped in pools, evaporated to form penecontemporaneous dolomite and dolomitic limestone. Evidence of salt precipitation occurs as large halite casts.

Laminated carbonate-shale cycles in the Mount Frome outcrops are similar, but much more asymmetrical (Fig. 4-8b). Red and green shale and siltstone accumulated in the high intertidal environment subject to minor wave and current activity. In some units, the transgressive, peritidal, laminated carbonate is overlain by a 1-3cm thick unit of chaotic, sparry calcite and mudstone, which may originally have been bedded gypsum or anhydrite. Red or green silty shale of the overlying unit rests abruptly on the carbonate, and indicates further marine regression.

Stromatolitic carbonate - shale cycles

Domal stromatolites are only recorded in the Wirrealpa Basin sections of the Warragee Member (Plate 11). They represent minor transgressions, and occur at the top of dominantly red, shaly sequences which contain subordinate green interbeds with occasional tracks attributed to trilobites. Thin, flat-laminated carbonate horizons are common in the upper portions of the cycles and some show well developed wavy lamination and stromatolitic doming. The stromatolitic units are up to 10cm in thickness, and contain minor terrigenous silt and clay, and rare dolomitic mudflake intraclasts. The stromatolites probably grew in the shallow subtidal or lower intertidal zone, where they were subjected to reducing conditions, and also where they were isolated from the bulk of the clastic deposition.

Random Intercalations

It is important to emphasise that the bulk of the Warragee Member comprises red and green shales and siltstones which appear to lack any sequential order of deposition. However, some general observations can be made:

(a) Ripple laminated siltstones which are red occasionally contain halite imprints and desiccation cracks. Ripples are commonly preserved on bedding plane surfaces as symmetrical or near-symmetrical forms. All of the above features suggest that the units were deposited in a nearshore, commonly intertidal environment.

(b) Both red and green laminated shale and siltstone contain halite imprints. Desiccation cracks are rarely observed, although this is largely a feature of the poor outcrop of these fissile units. Tracks attributed to trilobites occur sporadically throughout the sequence, and are slightly more common in the green shale intervals, which were probably deposited in a marginal marine environment.

The above features suggest that the shaly units of the Warragee Member were deposited in a variety of low energy environments, from shallow subtidal to supratidal.

Conclusions

Cyclic sedimentation in the Warragee Member is recognised, mainly between carbonate-rich and carbonate-poor units. Small scale cycles (a few millimetres to a few centimetres thick) represent single depositional events, as marine water flooded intertidal mudflats. Large scale cycles (up to 15m thick) represent marine transgression and regression with the red-beds developing under restricted, paralic conditions, and the carbonate units forming marginal to a more open marine environment. Since most of the carbonate units occur in the east of the study area, a gentle palaeoslope from west to east is suggested. This is supported by the relative increase in the proportion of red-coloured clastics in the western outcrops (Heysen Range and Mount Scott Range).

Palaeocurrent Analysis

Palaeocurrent data have been collected from the Warragee Member at many localities throughout the Flinders Ranges. However, due to the fine grain-size of the sequence, ripple lamination is uncommon and large scale bedforms are absent. Thus, the interpretations presented below must be considered as extremely tentative. Standard techniques for measurement and correction of data were used, based on Potter and Pettijohn (1978).

Palaeocurrent rose diagrams for the Warragee Member are summarized in Figure 4-9 and presented in more detail in Figure 4-10. Crests of symmetrical and asymmetrical ripples are commonly orientated north - south or northeast - southwest. This orientation is probably an indication of palaeoslope strike, with wave crests aligned subparallel to the coast-line, and weak currents moving up and down the palaeoslope. Thus, the bi-polar orientation of asymmetrical current ripples in the Warragee Member is interpreted as flood and ebb tidal oscillation.

Near-symmetrical ripples possess all the characteristics of asymmetrical wave oscillation structures (Tanner, 1967; Reineck and Singh, 1975; DeRaaf et al., 1977). They have a short wavelength (1.5-3cm), low amplitude (up to 2cm) and very low asymmetry. The bifurcation and sinuosity indices are low, and the ripples are laterally very continuous. Internally, the base of rippled sets are slightly undulose to curved, and foreset laminae are form-discordant. In many cases, persistent orientation of foresets indicates unidirectional sediment movement. The ripples are believed to have originated from wave oscillation, which developed a translational effect of the shallow tidal flats.

Dolomites and dolomitic limestones occur only in the eastern and south-eastern outcrops of the Warragee Member, suggesting that these areas were marginal to more open, marine water. A palaeoslope dip from west to east is consistent with a western source area (the Gawler Block), as interpreted for much of the older clastic sequences in the Adelaide 'Geosyncline'.

Some Basic Considerations

The Significance of Colour in the Sediments of the Warragee Member

The origin and significance of the red colouration in the Billy Creek Formation sediments is considered in detail in Chapter 10. At this stage, it is sufficient to note that red-beds may form in a variety of environments, from continental to marine (Van Houten, 1961, 1973). A marine environment of deposition for some of the Warragee Member is indicated by the

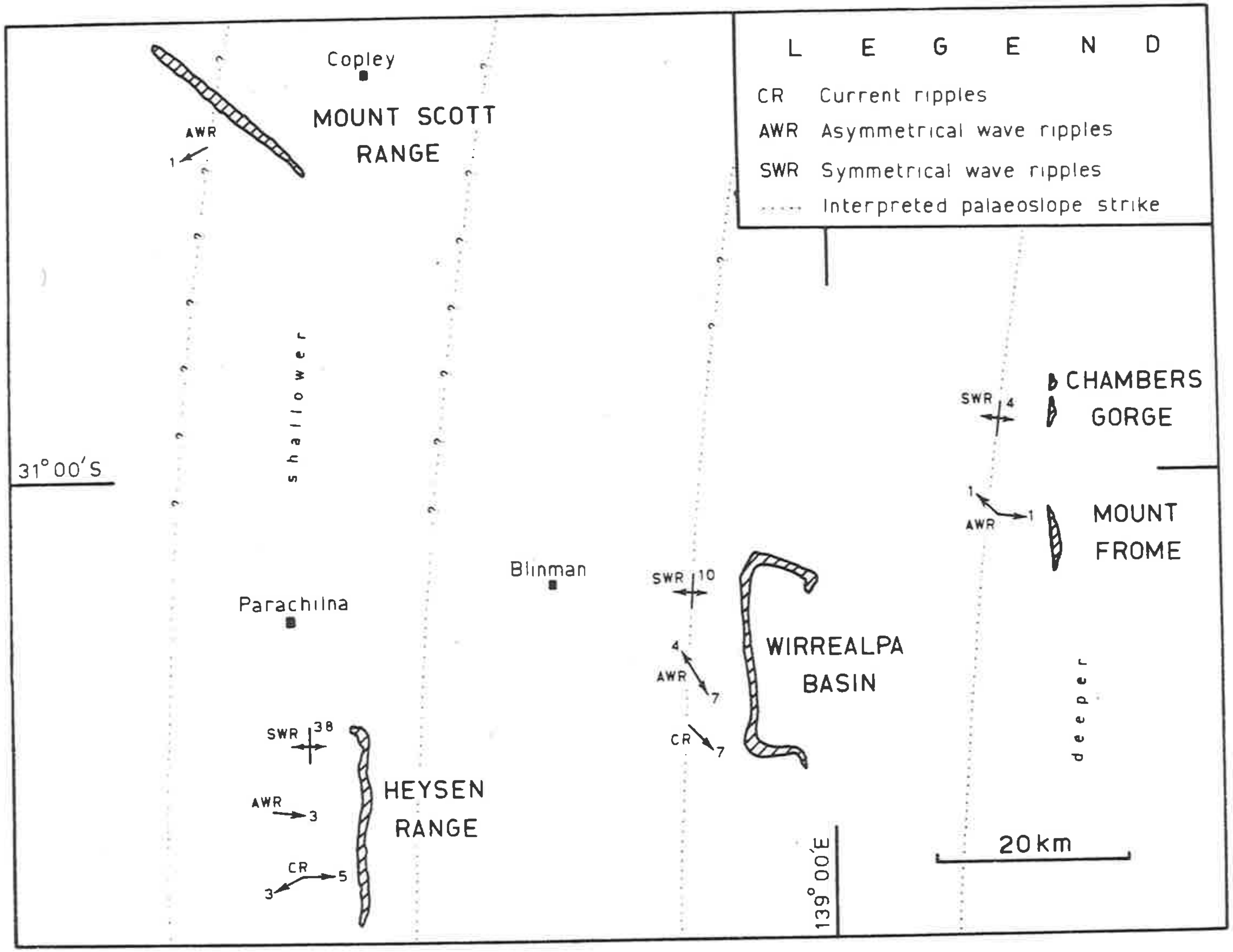


Figure 4-9. Palaeocurrent data, Warragee Member. Arrows represent major palaeocurrent modes. Recognition of the various modes is based on the technique described by Kelling (1969).

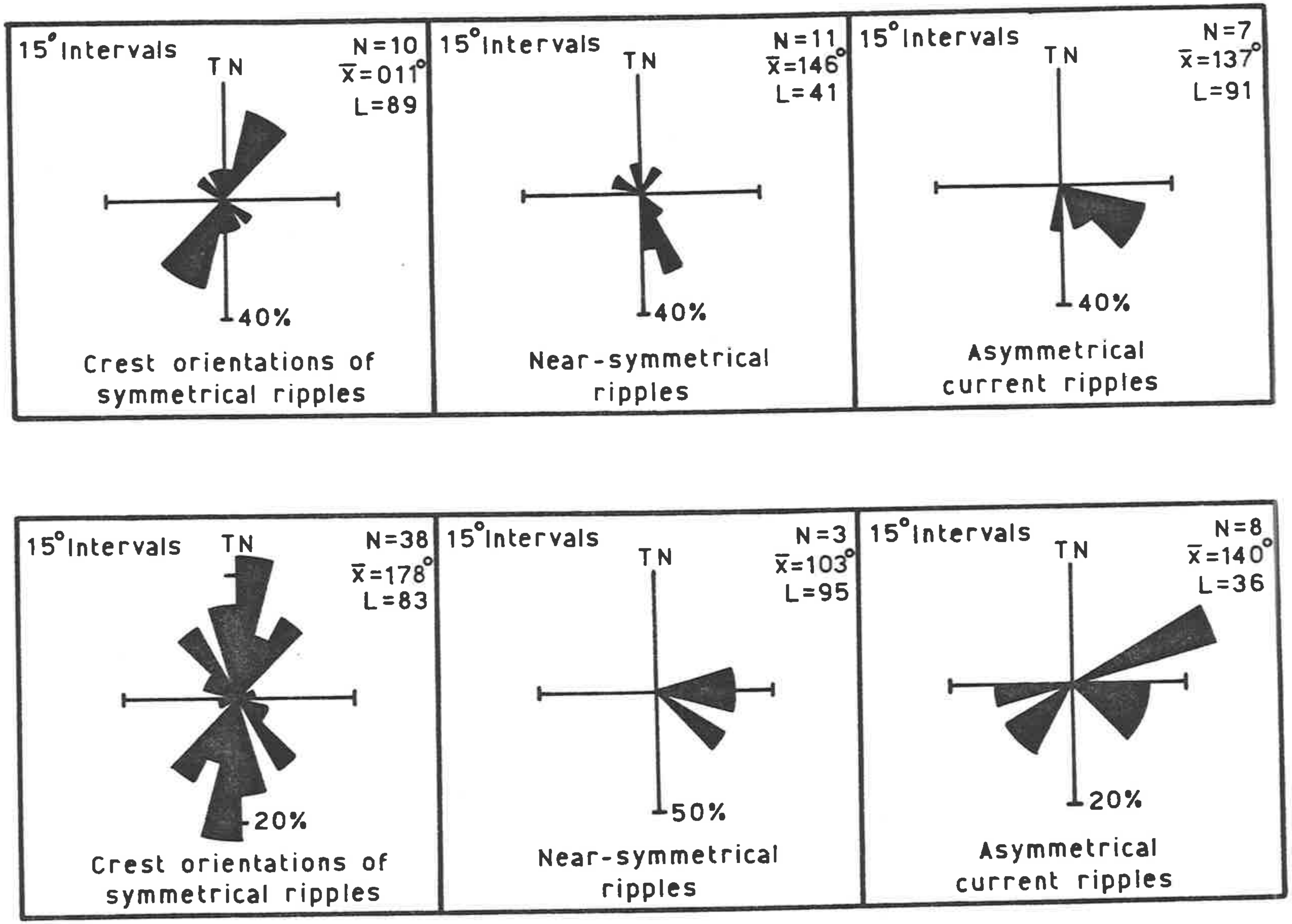


Figure 4-10. Palaeocurrent rose diagrams, Warragee Member. N: number of data. $\bar{x}$: mode. L: vector length (%).

presence of trilobite tracks, scratch marks and rare body fossils. Some of the red-beds are obviously intertidal to supratidal deposits, for they overlie green shales with trilobites, and contain abundant desiccation cracks (Fig. 4-8d above).

Non-red sediments indicate a reducing environment, and originated under a variety of conditions (Chapter 10). The non-red sediments in the lower portion of the Warragee Member are weakly calcareous, and form a transition between the underlying grey marine limestones and the overlying predominantly red sequence. Shallow restricted conditions are indicated by the presence of rare desiccation cracks and small halite casts. Desiccation features are more common in the overlying all-red sequence, which constitutes the middle portion of the Warragee Member. Thus, it appears that the transition from grey marine Edeowie Limestone, through green and greyish green shales and siltstones into red coloured clastics indicates shallowing of the basin of deposition, associated with a progressive increase in the supply of clastic detritus.

The non-red sediments in the upper portion of the Warragee Member are commonly associated with laminated dolomite, dolomitic limestone and rare evaporites. In this case, the colour indicates a 'marine influence' and may imply deeper water. However, it is important to note that the shaly dolomites are commonly desiccation cracked, and thus probably accumulated in the shallow intertidal environment and possibly on sabkhas in some cases. Thus, the development of laminated carbonates in the upper portion of the Warragee Member indicates primarily a reduction in the supply of clastic detritus to the basin of deposition. In conclusion, it appears likely that both regional tectonics and local facies changes are responsible for alternations of red and non-red sediments in the Warragee Member.

The Significance of Evaporite Minerals in the Warragee Member

Halite imprints and crystal casts occur sporadically throughout the Warragee Member, although large casts are confined to the upper, dolomitic portion of the sequence. The relatively high abundance of halite in the evaporite suite is significant, and indicates extreme salinities and high rates of evaporation typical of hot, arid regions. Kinsman (1976) has calculated that halite can only be precipitated in those areas where the mean relative humidity of the atmosphere is less than 76%. Such conditions are uncommon in coastal areas, but do occur where seas are surrounded by large expanses of land, as was the case for the epicontinental Billy Creek Formation.

The precipitation of halite requires the same conditions as those of the calcium sulphate minerals, gypsum and anhydrite. However, the degree of restriction of the basin from the sea must be even greater; halite is known to crystallize from sea water after evaporation has proceeded to 9 to 10 percent of the original water volume (Berner, 1971, p.80). Pyramidal hopper-shaped crystals commonly result from NaCl precipitation adjacent to the air-water interface in a supersaturated brine (Dellwig, 1955). Handford and Moore (1976) have shown that hopper crystals may also form during early diagenesis, and thus care is needed in interpreting their origin. However, in the case of the Billy Creek Formation, halite precipitation was ephemeral, and halite pseudomorph casts are the only remaining evidence that the mineral was ever precipitated. The casts consist of siltstone or very fine sandstone infilling imprints in red shale, or dolomite infilling imprints in greyish green shale. These features are clearly syn-depositional, and not diagenetic in origin.

The association of gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$) with halite should be expected, since they co-precipitate over a wide range of seawater concentrations (Blatt _et al._, 1972). However, although anhydrite and gypsum occur in subsurface occurrences of the Billy Creek Formation, they are rarely preserved in surface outcrops (Chapter 5), and have not been positively identified from the Warragee Member. Lucia (1972) has emphasised that the sulphate salts are typically dissolved from surface outcrops, thus presenting many problems in identification and interpretation of the evaporite mineral suite.

Common replacement products of anhydrite and gypsum are quartz and calcite (Tucker, 1976a, 1976b). Quartz geodes and nodules, up to 1cm across, occur sporadically throughout the Warragee Member, and these may represent diagenetic alteration products of sulphate salts. Veins, irregular disseminations and thin beds of nodular calcite occur in association with laminated dolomite and in red shale, and probably also indicate replacement of anhydrite and gypsum.

Bathurst (1975, p.207) notes that when an isolated body of sea water is evaporated, a mixture of salts results, which is about 78% by volume halite. The actual ratio of halite:gypsum (and their replacement products) in an ancient rock sequence depends largely upon the degree of brine concentration. Very restricted or isolated bodies of salt water will evaporate to form appreciable halite. This appears to be the situation in the case of the Billy Creek Formation.

Evaporite minerals and their replacement products found in association with dolomite may have formed by capillary action as brines were brought to the surface of a sabkha flat by evaporation. The typical evaporite assemblage to originate in this way is gypsum-anhydrite (Curtis et al., 1963; Illing, 1963; Kinsman, 1969), although halite is not unknown (Smith, 1971). In the case of the Warragee Member however, it is much more probable that halite precipitated directly as a result of evaporation of shallow ephemeral pools of sea water, high on the tidal flat and on sabkhas. Bathurst (1975, p.207) has emphasised that halite is promptly dissolved when the surface is flooded or washed with rain. The imprints left by the halite are then infilled with sediment, forming the well known hopper and cube-shaped casts.

The Origins and Significance of Dolomite in the Warragee Member

Microcrystalline dolomite units, up to 2m thick, occur in the upper and lower portions of the Warragee Member. Most beds are slightly argillaceous and uniformly fine-grained, and there are no obvious indications of late-stage, secondary dolomitization. In many cases, they show evidence of an original association with evaporite minerals, especially halite.

The formation of sedimentary dolomite poses many complex problems, some of which are still unsolved. Modern dolomites are forming in association with supersaline brines (von der Borch, 1965; Wells, 1962; Curtis et al., 1963; Shinn et al., 1969), which are commonly precipitating sulphate salts. Deffeyes et al. (1965) suggest that the precipitation of Ca^{++} as gypsum elevates the Mg^{++}/Ca^{++} ratio, and thus promotes dolomite formation. It is important to note however that dolomite formed in this way need not be accompanied by evaporite minerals in the ancient rock sequence, since renewed influxes of water may dissolve any salts before they have a chance to be preserved. It is possible however, that the imprints of halite and gypsum could remain.

An alternative explanation of pene-contemporaneous formation of dolomite has been proposed by Shinn et al. (1965). They have found that on modern supratidal mud flats, dolomite is forming by the interaction of capillary brine with normal marine carbonate sediment. The supersaline brine results from the evaporation of sea water which floods the supratidal flat during storms and unusual high tides. In the thick dolomite units of the Warragee Member, terrigenous and carbonate silt-sized detritus is commonly concentrated at the base of individual laminae, and thus they may well represent tidal flood or storm deposits. Salt minerals are preserved only as casts, probably because subsequent marine flooding caused their dissolution. Thus, the sabkha model for early dolomitization as proposed by Shinn et al. (1965) seems to be applicable to the dolomites of the Warragee Member.

Discussion

Red-beds evaporites and laminated dolomicrites are formed in a variety of environments and considered individually are not diagnostic of any particular sedimentary regime. However their inter-combination, and association with marine fossils and traces indicates deposition on and adjacent to tidal flats.

In general, laminated shales and siltstones accumulated in the subtidal zone of a shallow epicontinental sea and on adjacent intertidal mud flats. Oxidising conditions, possibly related to periodic subaerial exposure, are indicated by the red colour of the sediment. Since there is only minor evidence of former evaporite minerals in the Warragee Member, it appears likely that halite and gypsum were only formed in shallow restricted pools and on supratidal flats. Thus the presence of halite casts may be assumed to represent high intertidal to supratidal conditions in most cases.

Laminated, dolomitic carbonates are commonly found in association with evaporite replacement products, and probably represent carbonate precipitation and subsequent dolomitization by brine solutions in the high intertidal and supratidal zone. The combination of red-beds and evidence of former evaporites suggests that the sequence was deposited in an area with a warm to hot, arid climate. Thus, supratidal carbonate and salt pans may have been rather similar in character to modern sabkhas, as for example, those of the Persian Gulf. Evaporite imprints have not been found in association with stromatolitic carbonate, which probably formed in the subtidal zone or on lower intertidal flats subject to frequent inundation.

A notable property of the Warragee Member is the apparent lack of tidal channels and characteristic tidal bedding. Similar features occur in the fine-grained Irish Valley Member of the Catskill Formation and have been interpreted by Walker and Harms (1971, 1975) as indicative of low palaeotidal range. However, in a detailed study of tidal flat sedimentation in the Gulf of California, Thompson (1968) has shown that the average grain-size of the sediment has a great effect on the nature and development of tidal flat deposits. Despite the presence of a large tidal range (average 4-5m) in the Gulf of California, tidal currents move over the flats as broad, uniform flows, with little tendency to develop channels. Thompson (1968, 1975) attributes this feature to the fine grain-size of the detritus supplied by the Colorado River (mainly fine silt and clay) and notes that many other typical tidal features, such as lenticular bedding, flaser bedding and fining-upward cycles may be absent. Thus the apparent lack of tidal channels and tidal bedding in the Warragee Member does not necessarily imply a low palaeo-tidal range.

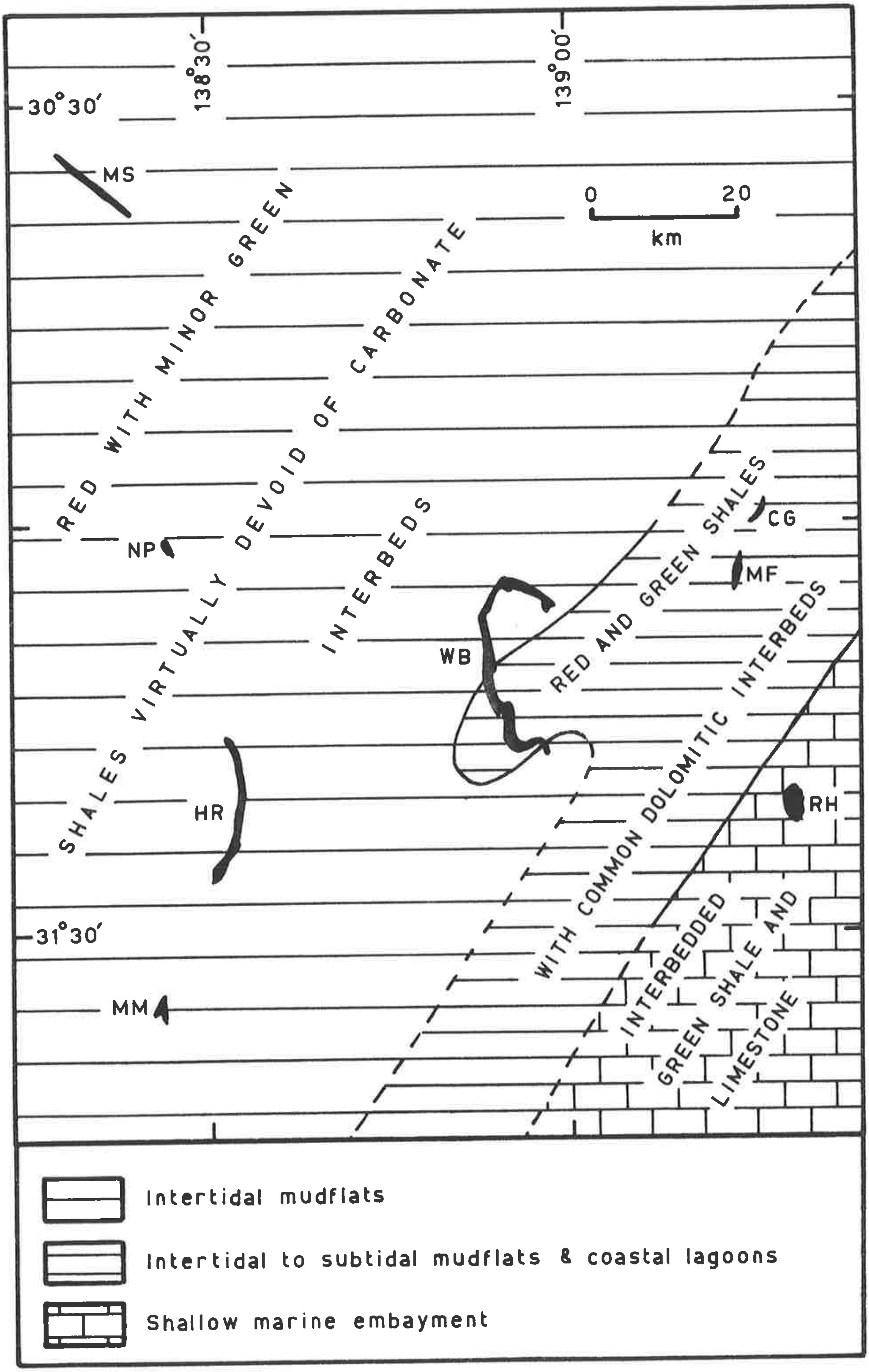
The alternation of shale and dolomitic limestone in the Warragee Member can be attributed to marine transgression and regression, with dolomite signifying the transgressive phase (Ham, 1961; Duff et al., 1967; West et al., 1968; Pearson and Hanley, 1974). In some outcrops, the carbonates are interpreted as entirely shallow subtidal deposits. More commonly however, strata interpreted as intertidal-supratidal are present only at the base and top of individual carbonate units, with subtidal strata either absent or comprising the middle portion of the sequence. This facies spectrum, along with the uniform thickness of the carbonate units, suggest that the carbonates represent transgressive-regressive events, with marine transgressions occurring over an extremely low relief, muddy, high tidal surface.

On the basis of Walther's Law, the peritidal carbonates lay on the seaward (eastern) side of the muddy red-bed sequence, suggesting that the clastic units were deposited either on continental high tidal flats or low relief flood plains. However, it is important to note that the fine grained red-beds formerly extended to the west for at least 100km (the Yarrawurta Shale) with no sign of a transition into coarse-grained, continental deposits. In conclusion therefore, it is suggested that peritidal carbonates developed in areas marginal to more open marine water, where fine-grained clastic detritus was winnowed (Figure 4-11). To the west, red-bed clastic sedimentation prevailed on intertidal mudflats and in a very shallow, restricted, epeiric sea.

SUMMARY AND CONCLUSIONS

The Warragee Member of the Billy Creek Formation was deposited in response to tectonic activity (the Kangarooian Movements of Daily and Forbes, 1969), which carried fine-grained terrigenous detritus into the Adelaide 'Geosyncline'. The source of the detritus is uncertain, although an easterly dipping palaeoslope is inferred from the facies distribution.

Figure 4-11. Simplified depositional environments and their distribution in the Warragee Member and its lateral equivalents at Reaphook Hill.

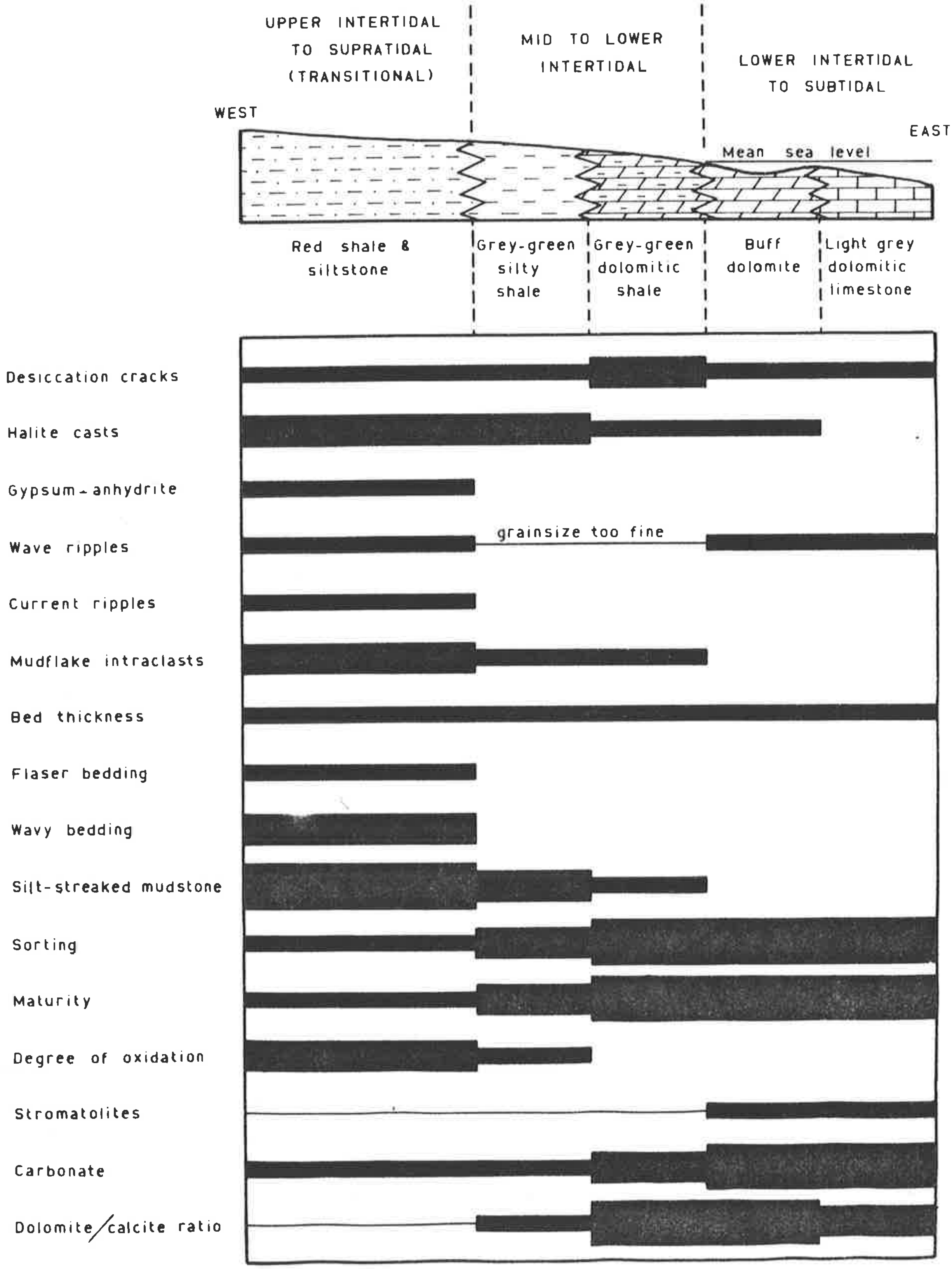


Thus, the probable source was the Gawler Craton.

The fine grain-size of the Warragee Member clastics makes palaeogeographic interpretation difficult. However, there is abundant evidence of marine influence throughout the sequence, and most of the terrigenous muds are believed to have been deposited in a very shallow epicontinental sea and on extensive intertidal flats. Extreme shallow water and infrequent subaerial exposure are indicated by halite casts and desiccation cracks. Carbonate units are equally fine-grained and dolomitic. Their common association with halite casts and desiccation features suggests that they were deposited on intertidal and supratidal flats and in very shallow, restricted lagoons. A generalised palaeogeographic model for the Warragee Member is presented in Figure 4-12.

Soil horizons, massive, blocky mudstones and pisolitic calcrete profiles have not been recognised, and thus it is assumed that no significant amount of the Warragee Member as presently exposed was formed by pedogenesis or alluvial flooding in the continental (meandering fluvial-alluvial plain) environment. The sequence thus accumulated by progradation of broad tidal flats, accompanied by periodic subsidence which initiated new cycles. Outcrops which lack cyclicity may be due to a more balanced equilibrium between the rates of subsidence and sediment accumulation. In most cases however, cycles are absent because carbonates never had a chance to accumulate. In these instances, the absence of carbonates in the red-bed sequence is taken to represent increased sediment input, due either to tectonic uplift or proximity to the source area. Much of the central portion of the Warragee Member shows this characteristic.

Figure 4-12. Depositional model for the Warragee Member.



CHAPTER 5

STRATIGRAPHY AND ENVIRONMENTAL ANALYSIS OF THE NILDOTTIE SILTSTONE MEMBER

THE STRATIGRAPHY OF THE NILDOTTIE SILTSTONE MEMBER

Introduction

Throughout the central Flinders Ranges and in the Mount Scott Range, the middle portion of the Billy Creek Formation is dominated by greyish red siltstone, with minor shale and very fine sandstone (Plate 13). The sequence is herein termed the Nildottie Siltstone Member. The name is derived from Nildottie Spring, which is located approximately 17km northwest of the Wirrealpa homestead, in the Wirrealpa Basin (Fig. 3-1). The type section (Section BC-B, Figs. 3-1, 4-1, 4-2) is located in an area of undulatory topography, 2.5km north of the Ten Mile Creek. The section corresponds with the middle portion of Daily's (1956) type section of the Billy Creek Formation.

Outcrop of the Nildottie Siltstone Member and positions and thicknesses of the major stratigraphic sections are shown in Figure 4-1. The member attains its maximum measured thickness of 460m in the Ten Mile Creek graben (Section BC-B), but generally thins towards the north. The sequence outcrops well in most areas, but is best exposed in Balcoracana Creek, in the Wirrealpa Basin. Sixteen stratigraphic sections have been measured in outcrops throughout the Flinders Ranges, and these are summarized in Figure 5-1 (rear pocket).

The Base of the Nildottie Siltstone Member

In most outcrops, the Nildottie Siltstone Member rests conformably on red and green shale of the Warragee Member, as discussed above. However, in the southern portion of the Wirrealpa Basin south of the Ten Mile Creek graben (Section BC-F), the Warragee Member is absent and the Nildottie Siltstone Member rests directly on Wilkawillina Limestone containing Daily's (1956) Faunal Assemblage No. 2. Although the area is complicated by faulting, it is possible that the Nildottie Siltstone Member originally rested disconformably on Wilkawillina Limestone.

ENVIRONMENTAL ANALYSIS OF THE NILDOTTIE SILTSTONE MEMBER

Introduction

A marine origin for the bulk of the Nildottie Siltstone Member is inferred from the presence of minor arthropod tracks and worm burrows, and from an abundance of symmetrical, oscillation ripples. The palaeocurrent distribution of current ripples is essentially bipolar and indicates a persistent tidal influence. The abundance of desiccation cracks, mudflake breccias and halite casts in the Nildottie Siltstone Member suggests that much of the sequence was deposited in the intertidal zone. Rare, thin, blocky mudstones may have had a continental (alluvial plain) origin.

Since much of the Nildottie Siltstone Member shows evidence of deposition in the intertidal to shallow subtidal environment, it might be expected that a well developed sequence of tidal stratification be present. Unfortunately, this is not the case, due in part to the fine grain-size of the sediment. Instead, there is a poorly defined facies spectrum, which grades from very fine sandstone with primary current lineation, through rippled and flaser bedded siltstone, into poorly defined wavy and lenticular bedding, and finally into shales devoid of coarse silty laminae.

Geologic Setting

The upper portion of the underlying Warragee Member comprises interbedded red and green shale, which is in part calcareous. In the Wirrealpa Basin and at Mount Frome, thin dolomitic limestones occur in this upper interval and are associated with desiccation cracks and halite casts. Thus, the environment immediately preceding the deposition of the Nildottie Siltstone Member is interpreted as a very shallow subtidal to intertidal mudflat (Fig. 4-11). Colour variation in the sequence appears to reflect original oxidation-reduction potential, and the presence of abundant green shale in the upper portion of the Warragee Member is evidence for reducing conditions at the time of deposition.

Facies Descriptions

Planar Laminated Sandstone

This facies comprises greyish red, coarse siltstone to fine sandstone, horizontally laminated in units rarely up to 50cm in thickness (average 10cm) (Plate 14). Primary current lineation is common, and an upward gradation into ripple laminated siltstone is typical. Planar laminated sandstone and coarse siltstone units comprise only a very minor portion of the Nildottie sequence, and occur mainly in the upper part of the member. In rare cases they are associated with large, polygonal desiccation cracks and halite imprints. Some units are weakly calcareous. Thick intervals in the Mount Frome and Chambers Gorge regions are commonly associated with load structures (Plate 15) and dewatering features.

Current Rippled Siltstone

Current ripples in the Nildottie Siltstone Member are typically low amplitude (7-15mm), medium wavelength (4-15cm) forms. Catenary ripples are the more common variety (Plate 16). They are characterised by a marginally coarser grainsize (average very fine sandstone) and are typically underlain by a thin unit of planar laminated sandstone.

Desiccation cracks, halite imprints and mudstone intraclasts are often associated with current-rippled intervals. In a few cases, interference patterns may result from the superposition of smaller, oscillation ripples (Plates 17 and 18). Units may be weakly calcareous and calcite patches and veins are developed in rare cases.

Oscillation-Rippled Siltstone

This facies is very common in the Nildottie Siltstone Member, and comprises greyish red, ripple laminated coarse siltstone. Rippled cosets typically have undulose to highly curved basal surfaces, and discordant internal laminae (Plate 19), typical of wave-generated structures (DeRaaf *et al.*, 1977). Rippled bedding surfaces are abundant.

Ripples are typically straight to slightly undulose, low amplitude (6-12mm), short wavelength (2-4cm), symmetrical and near-symmetrical forms (Plate 20). Desiccation cracks, halite casts and mudstone intraclasts are commonly associated with the rippled intervals. Minor flat-topped and interference ripples (Plate 21) are present. Rarely, worm burrows, trilobite tracks and raindrop imprints have been found on rippled surfaces. The facies may be weakly calcareous, and calcite patches and veins are present in a few cases. Small load structures are occasionally associated with coarse-grained intervals.

Flaser Bedding

Ripple laminated units in the Nildottie Siltstone Member commonly contain thin, discontinuous muddy laminae, and this association is described as flaser bedding (Plate 22; upper portion Plate 23). It is important to note however, that well-developed flaser bedding, as defined by Reineck and Wunderlich (1968, Fig. 2) is rare.

Muddy laminae are found in association with both symmetrical and asymmetrical ripples. Thus, a facies spectrum exists from flaser bedded units, into oscillation and current rippled siltstone devoid of clay laminae. Flaser bedded sequences commonly contain desiccation cracks, mudflake breccias and halite casts. In addition, minor trilobite tracks, load structures, raindrop imprints and interference ripples have also been recorded. The facies is commonly weakly calcareous and calcite patches and veins are present in a few cases.

Wavy Bedding

This facies is common in the Nildottie Siltstone Member, especially in the upper portion. It comprises greyish red, interlaminated to thinly interbedded, coarse rippled siltstone and mudstone (lower part Plate 23; Plate 24). Mudstone layers overlie ripple crests and more or less fill the ripple troughs, so that the surface of the mud layer only slightly follows the curvature of the underlying ripples (Reineck and Wunderlich, 1968, Fig.3).

Both current and oscillation ripples are recorded from this facies, although the latter is more common. Mudflake breccias are abundant (Plates 23, 24) and desiccation cracks (Plate 25) and halite casts (Plate 26) are also very common. Interference ripples, flat-topped ripples, wrinkle marks (Plate 27) and rare raindrop imprints (Plate 28) and trilobite tracks are recorded on bedding surfaces. The facies is commonly weakly calcareous, and calcite patches and veins, showing rare evidence of gypsum replacement, are present in a few cases.

Lenticular Bedding

Lenticular bedding, as defined by Reineck and Wunderlich (1968), is very poorly developed in the Nildottie Siltstone Member, and is represented mainly by isolated, flat lenses of coarse siltstone in fine siltstone or shale. Ripple foresets are rarely observed and an alternate term for this type of intercalation is "silt-streaked shale" (DeRaaf *et al.*, 1977). Sequences of this nature are common in parts of the Nildottie Siltstone Member, and are transitional between wavy bedding and laminated mudstone. Desiccation cracks and halite casts have been found in association with silt-streaked muds, however, they are not very common. Mudstone intraclasts are rare.

Laminated Mudstone

This facies consists of greyish red shale to medium-grained siltstone, evenly laminated in units up to several metres in thickness. Desiccation cracks and halite casts are rare. Subvertical worm burrows and trilobite tracks are uncommon. The facies may be weakly calcareous.

Blocky Mudstone

Blocky, red mudstones are uncommon in the Nildottie Siltstone Member and are restricted mainly to the upper portion of the sequence. Units are rarely in excess of 30cm in thickness. In some cases a gradation into well laminated mudstone (i.e. shale and silty shale) is apparent, although the mudstones are more commonly interbedded with rippled, silty units. The facies is typically calcareous, containing abundant calcite patches, streaks and veins. Halite casts and desiccation cracks are rare.

Stromatolitic Carbonate

Only one occurrence of stromatolitic, calcareous siltstone is known from the Nildottie Siltstone Member. It occurs towards the top of a fining-upward, greyish red, shale-siltstone sequence in Section CG-B (Fig. 5-2), and comprises a 10cm thick bed of low domal stromatolites (Plates 29,30). Raindrop impressions, halite imprints, molluscan trails and minute ?shrinkage cracks occur on the upper surface.

Channel Sandstone

Recognisable channels are rare in the Nildottie Siltstone Member, and have only been recognised in the Chambers Gorge, Mount Frome and Mount Scott Range localities. They are characterised by a curved erosional base, and are infilled with sandstone (Plate 31) or shale (Plate 32).

At Chambers Gorge, several channel sequences have been recognised. They average 2-3m in width and 0.4m in depth. In one outcrop near the base of the member, a mudstone lag conglomerate is present at the base of the channel (Plate 33), which has eroded horizontally laminated, greyish red sandstone. The channel is largely infilled with red, fine siltstone, which drapes the margins of the channel, and which contains small, polygonal desiccation cracks.

In the lower portion of the Nildottie Siltstone Member at Mount Frome, a sequence of interbedded sandstone, siltstone and minor shale is also interpreted as a channel deposit (Plate 31). The basal sandstone is greyish green and contains abundant load structures, including large pseudonodules. The overlying sequence comprises units of ripple laminated and low angle tabular cross stratified sandstone with erosional bases. These are interbedded with evenly laminated shaly siltstone containing trilobite tracks, desiccation cracks and mudstone intraclasts.

Facies Associations and their Interpretation

Introduction

A feature of the Nildottie Siltstone Member is its general lack of cyclicity. This is attributed to several factors, the most important of which is the fine grain-size of the sediment. Units coarser than coarse siltstone are very uncommon, and large scale cross-stratified bedforms are rare. Cycles are thus restricted to alternations of shale and siltstone.

Another very important feature of the sequence is the abundance of rippled bedding surfaces. Their preservation is due to the presence of a thin mud veneer. Interlaminated mud is common even in sequences which contain abundant coarse siltstone (eg. the upper portion of Section MS-B). Thus, there was a frequent alternation between slack water conditions and minor sediment reworking and winnowing. The absence of thick, continuously ripple-laminated intervals is indicative of discontinuous and relatively weak wave and current activity.

Tidal cycles, as described by Klein (1971), are notably absent. Their absence is probably due to the combination of fine grainsize and weak current activity, as described above. Flaser, wavy and lenticular-bedded units are often randomly intercalated and are not necessarily diagnostic of a particular sedimentary environment. However, rippled siltstones devoid of clay laminae probably only developed where wave energy was most concentrated, as in the shallow subtidal to lower intertidal zone (Evans, 1965; Reineck, 1967).

Small Scale, Fining-Upward Cycles

An alternation of slack water and current activity is responsible for flaser, wavy and lenticular bedding. The processes involved are explained in detail by Reinneck and Wunderlich (1968), Terwindt and Breuser (1972), and Reineck and Singh (1975) and shall not be repeated here. The alternation of traction-deposited coarse siltstone and suspension-deposited mudstone commonly leads to the formation of fining-upward couplets, 5-20mm in thickness (Plates 23-24). Traction deposited silty units commonly have a sharp, erosional base and may contain abundant mudflake intraclasts. The platy nature of many of the intraclasts suggests that they represent fragments of dried and hardened, desiccation polygons.

Large Scale, Shale-Siltstone Alternations

A common feature of parts of the Nildottie Siltstone Member is the regular alternation of shaly and silty units, repeated on the scale of 0.3-4.0m.

The silty units commonly contain halite imprints, desiccation cracks, mudflake intraclasts and other minor features indicative of extreme shallow water and subaerial exposure. Although desiccation cracks are present in some of the thick shale units, they are rarely abundant. Thus, the cyclic alternation of traction-deposited siltstone and suspension-deposited shale is attributed to changes in water depth. Evenly laminated shales were commonly deposited by suspension settling in quiet water, subtidal conditions. Silty units were deposited in the shallow subtidal to intertidal zone, where minor wave and current activity winnowed any fine detritus.

The small changes in water depth needed to explain the above cycles may have resulted from eustatic sea level change (unlikely), or variation in sediment supply and basin subsidence. Alternatively, large shallow ponds and lagoons may have been present, which accumulated shale laterally adjacent to shallower or more active, silty areas of the tidal flat (cf. Thompson, 1968, 1975). Many alternations are probably related to weather patterns, with intensive winnowing during storms leading to the formation of rippled siltstone. This would account for the lateral persistence (over several kilometres) of many of the very thin, silty units.

Large Scale, Fining-Upward Cycles

Large scale, fining-upward cycles are rare in the Nildottie Siltstone Member, and are restricted to the upper portion of the sequence. They represent major events which are not believed to be typical of Nildottie sedimentation in general.

The best example of a fining-upward cycle known to the author occurs in the lower portion of the member at Chambers Gorge (Section CG-C), and is illustrated in Figure 5-2. The sudden input of current lineated sandstone is attributed to either alluvial flooding or uplift in the source area. As the current waned, a mixture of sand and medium to coarse silt was deposited, which developed load structures due to density variations. A further reduction in sediment supply enabled waves to rework the detritus.

The upper portion of the cycle reflects calm water, shoaling conditions. Shallow subtidal, flaser bedding is overlain by intertidal (desiccation cracked) wavy bedding. Higher in the sequence, low domal stromatolites are associated with molluscan trails, desiccation cracks, halite casts and raindrop imprints, and thus probably grew in the high intertidal zone. They represent the peak of the regression, and the base of the succeeding shale-siltstone sequence marks a fairly gentle transgression. The fining-upward cycle thus represents shoaling conditions, due to progradation of the tidal flat.

Palaeocurrent Analysis

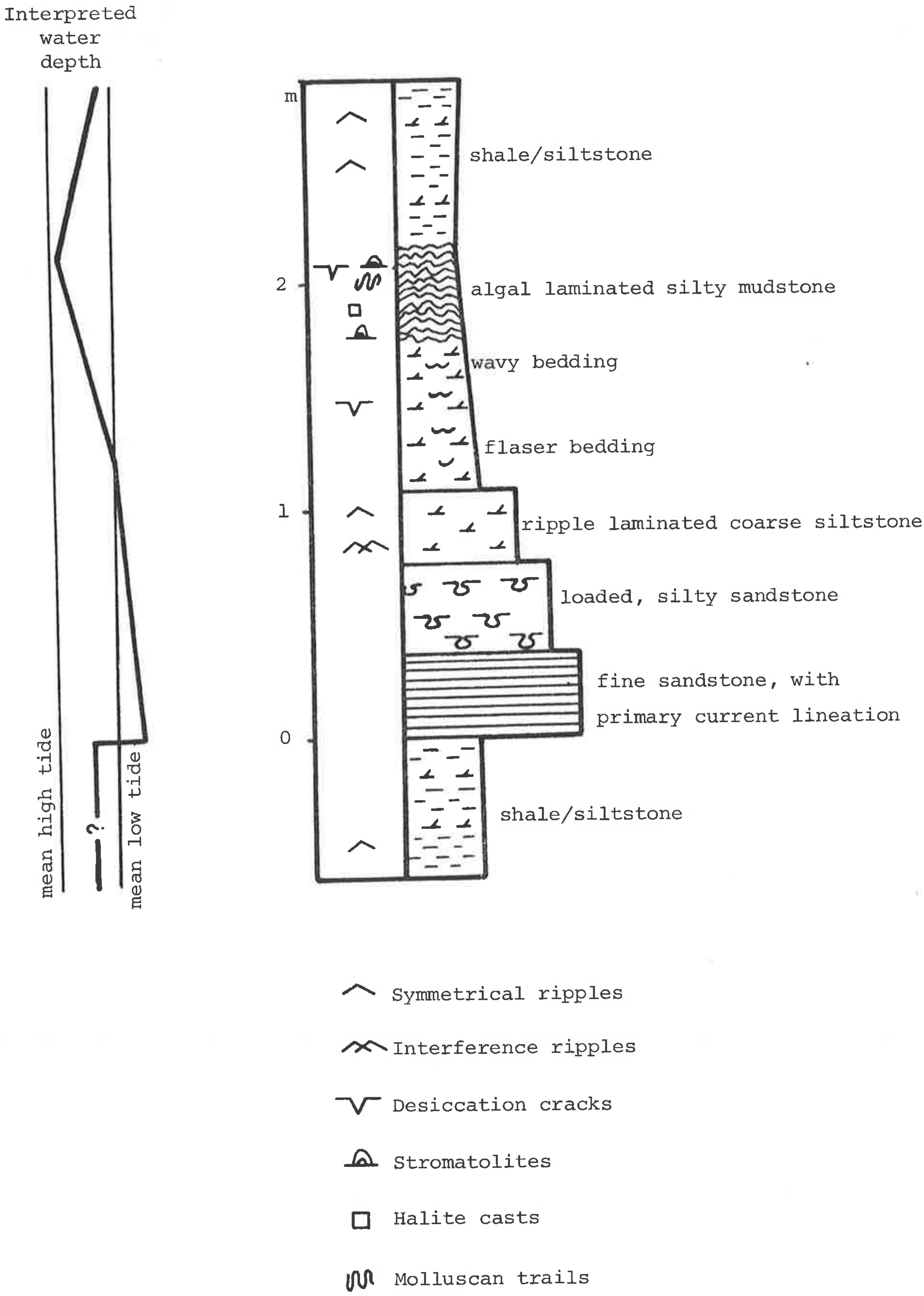
Introduction

Palaeocurrent data have been collected from the Nildottie Siltstone Member at many localities in the Flinders Ranges. Over 750 measurements are summarized in Figure 5-3, and presented in more detail in Figures 5-4 to 5-8. Due to the fine grain-size of the sediment, large scale bedforms are rare. Standard techniques for measurement and correction of data were used, based on Potter and Pettijohn (1978).

Evaluation of data

A detailed study of the hydraulic significance of various ripple types in the Nildottie Siltstone Member is presented in a later section. At this stage it is sufficient to note that there is a remarkable consistency in ripple orientation throughout the sequence.

Figure 5-2. Large scale fining-upward cycle in the Nildottie Siltstone Member near Chambers Gorge.



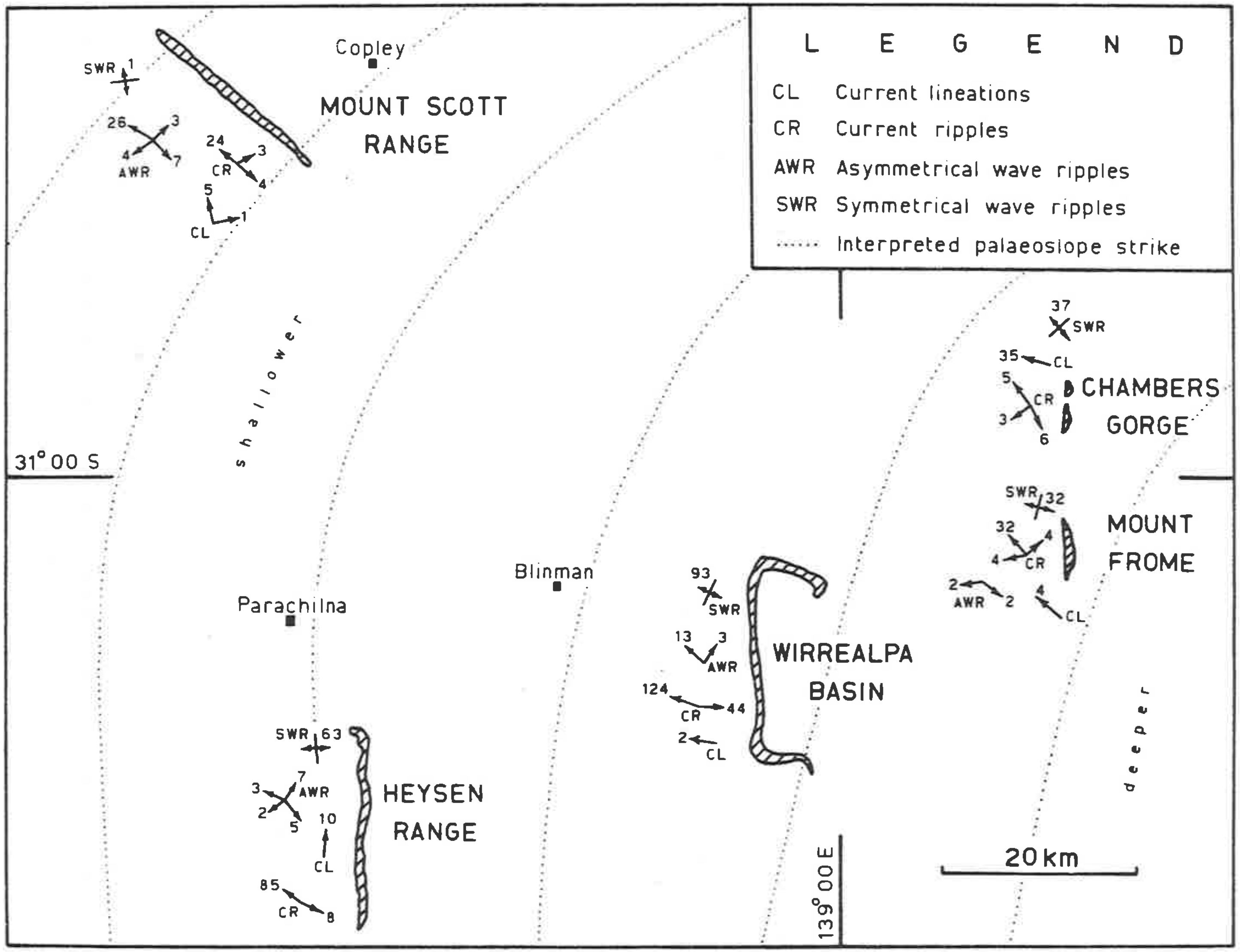


Figure 5-3. Palaeocurrent data, Nildottie Siltstone Member. Arrows represent major palaeocurrent modes. Recognition of the various modes is based on the technique described by Kelling (1969).

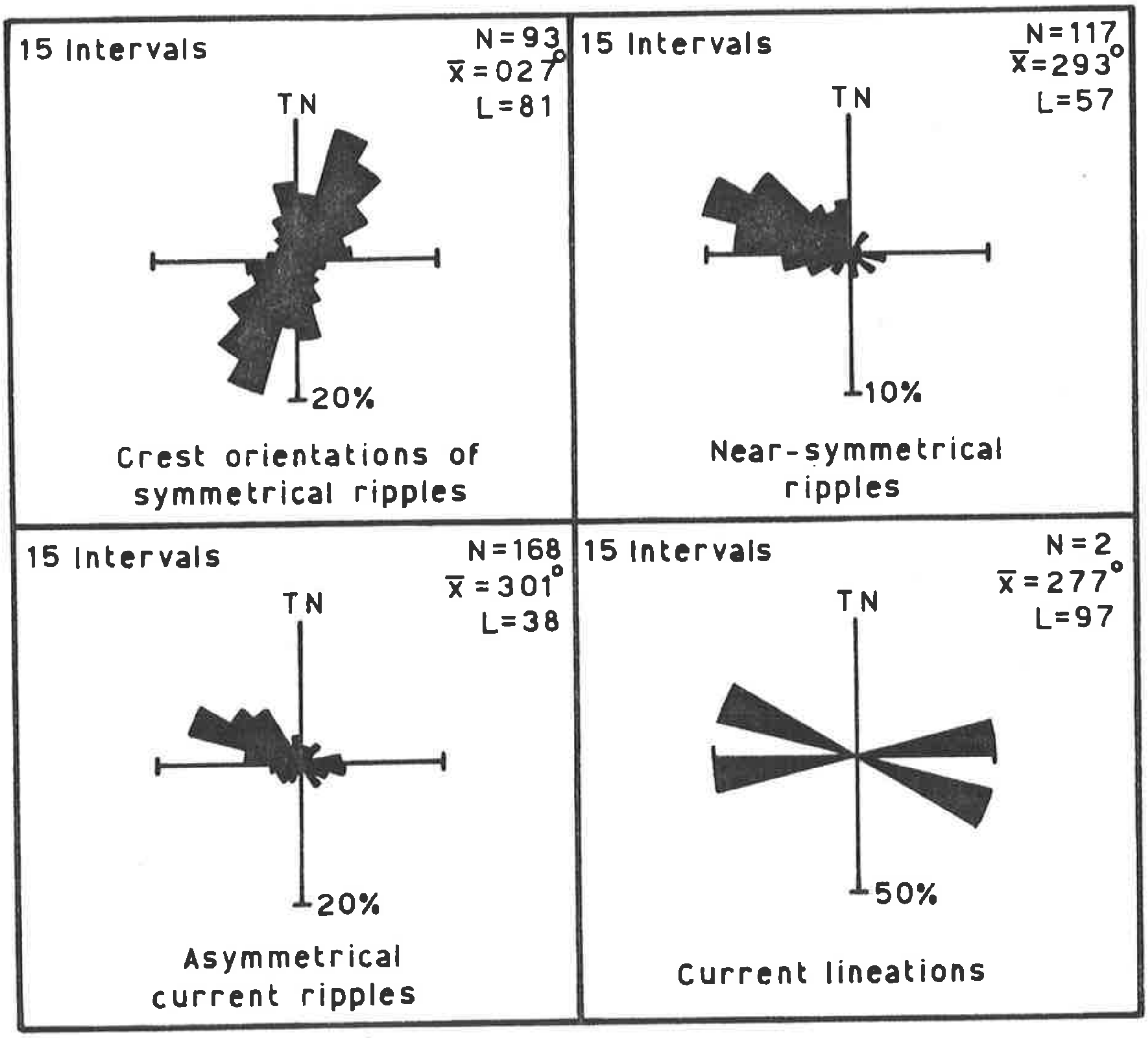


Figure 5-4. Palaeocurrent rose diagrams, Nildottie Siltstone Member, Wirrealpa Basin. N = number of data, $\bar{x}$ = mode, L = vector length (%).

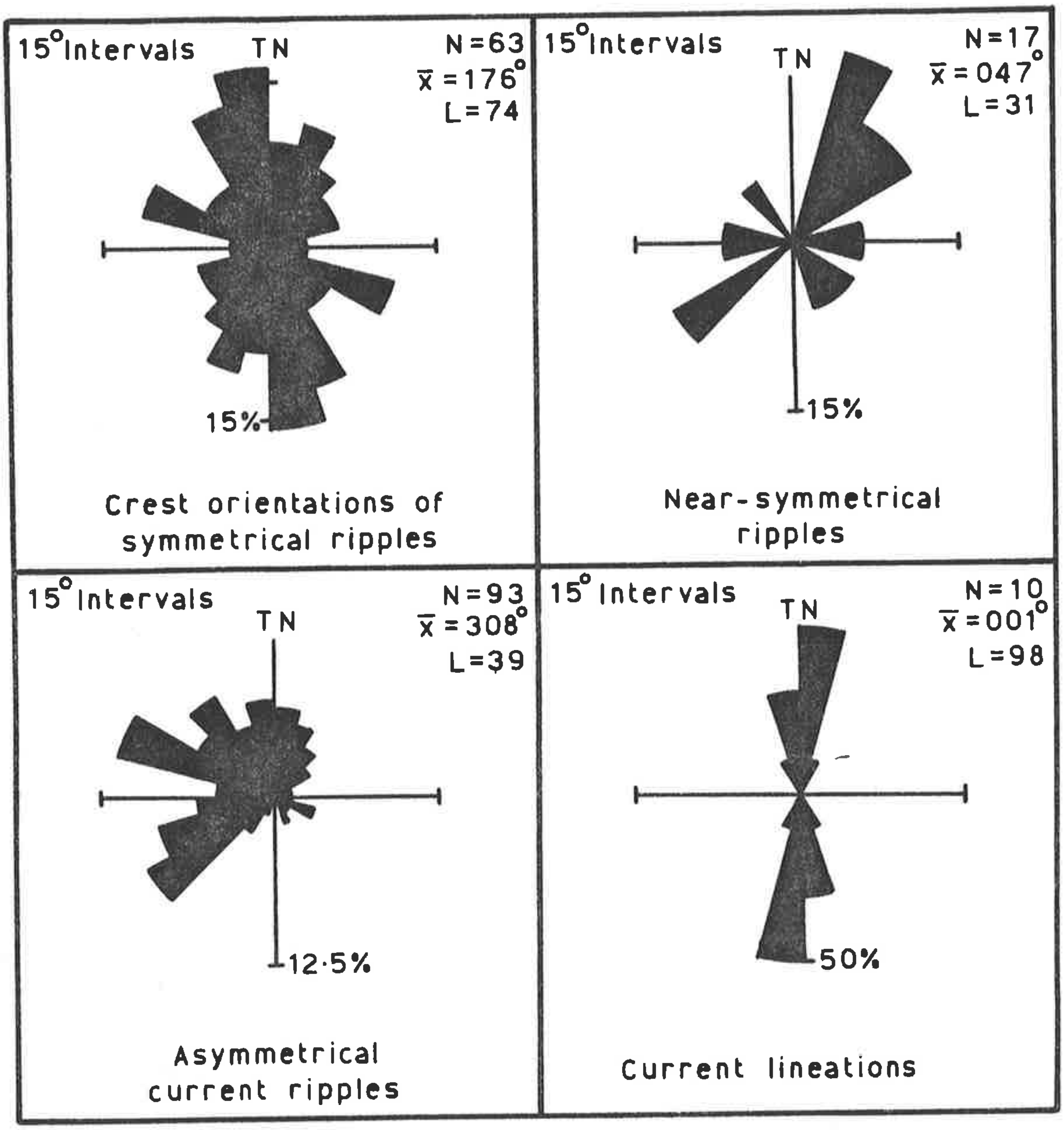


Figure 5-5. Palaeocurrent rose diagrams, Nildottie Siltstone Member, Heysen Range. N = number of data, $\bar{x}$ = mode, L = vector length (%).

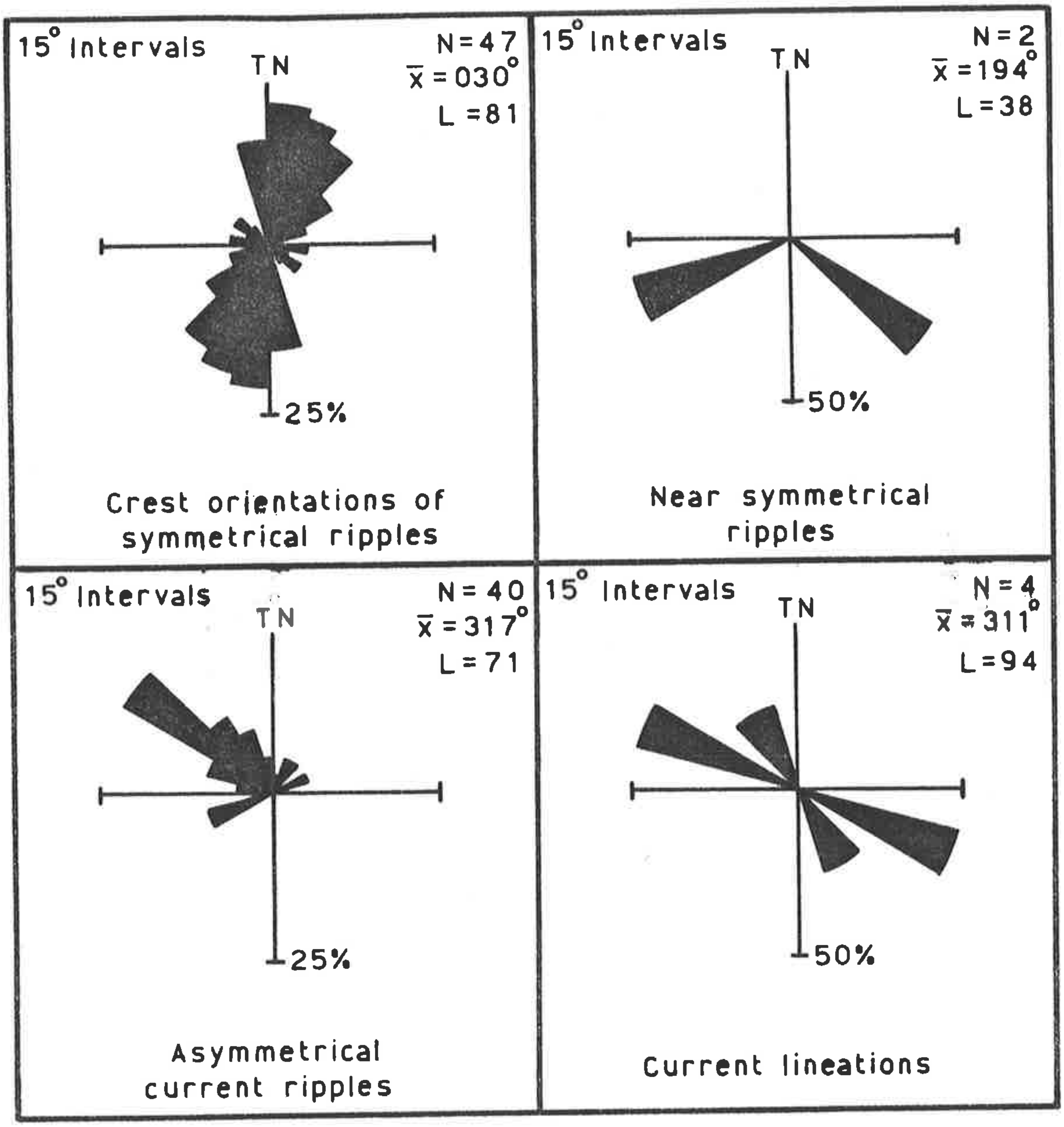


Figure 5-6. Palaeocurrent rose diagrams, Nildottie Siltstone Member, Mount Frome. N = number of data, $\bar{x}$ = mode, L = vector length (%).

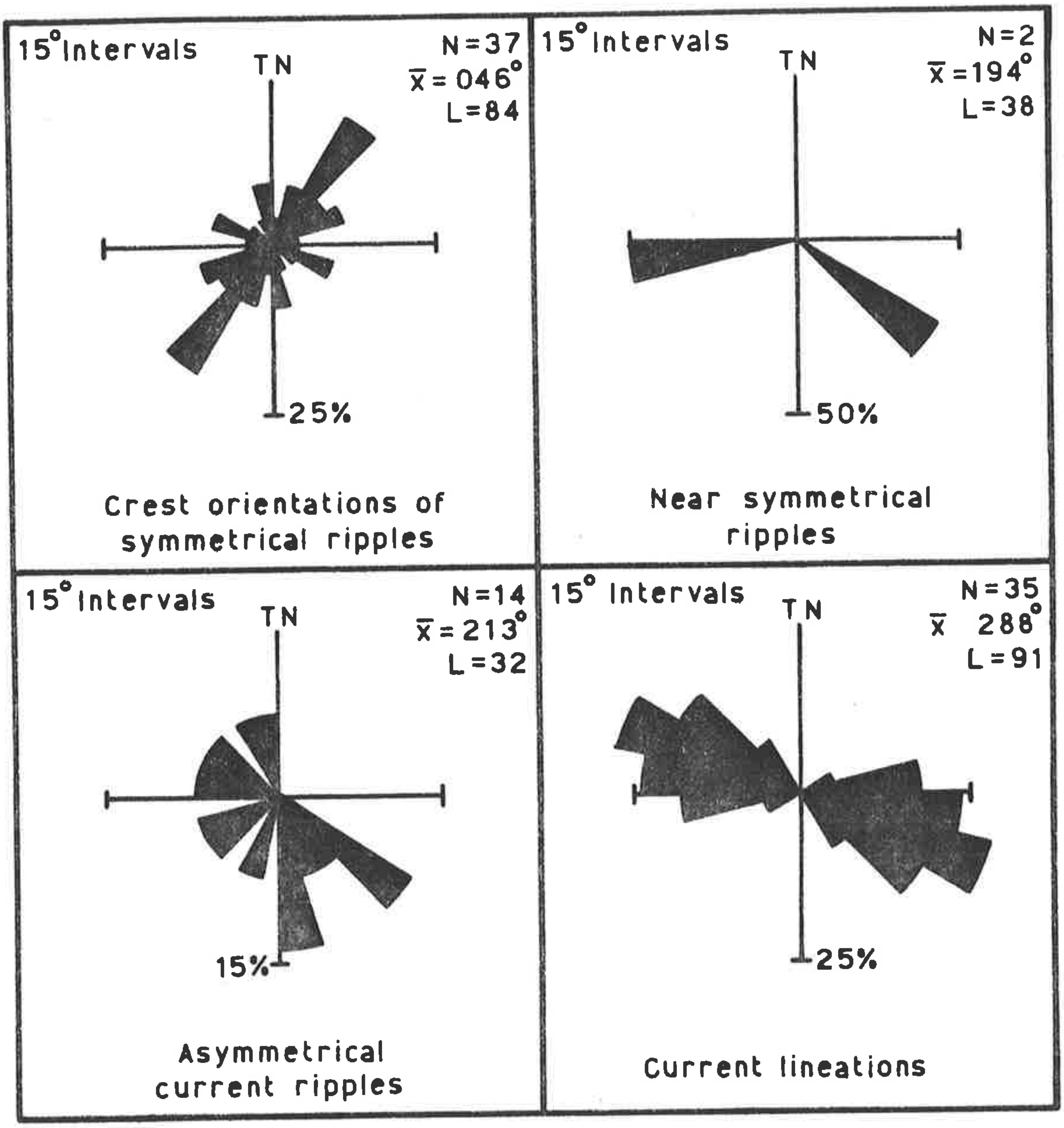


Figure 5-7. Palaeocurrent rose diagrams, Nildottie Siltstone Member, Chambers Gorge. N = number of data, $\bar{x}$ = mode, L = vector length (%).

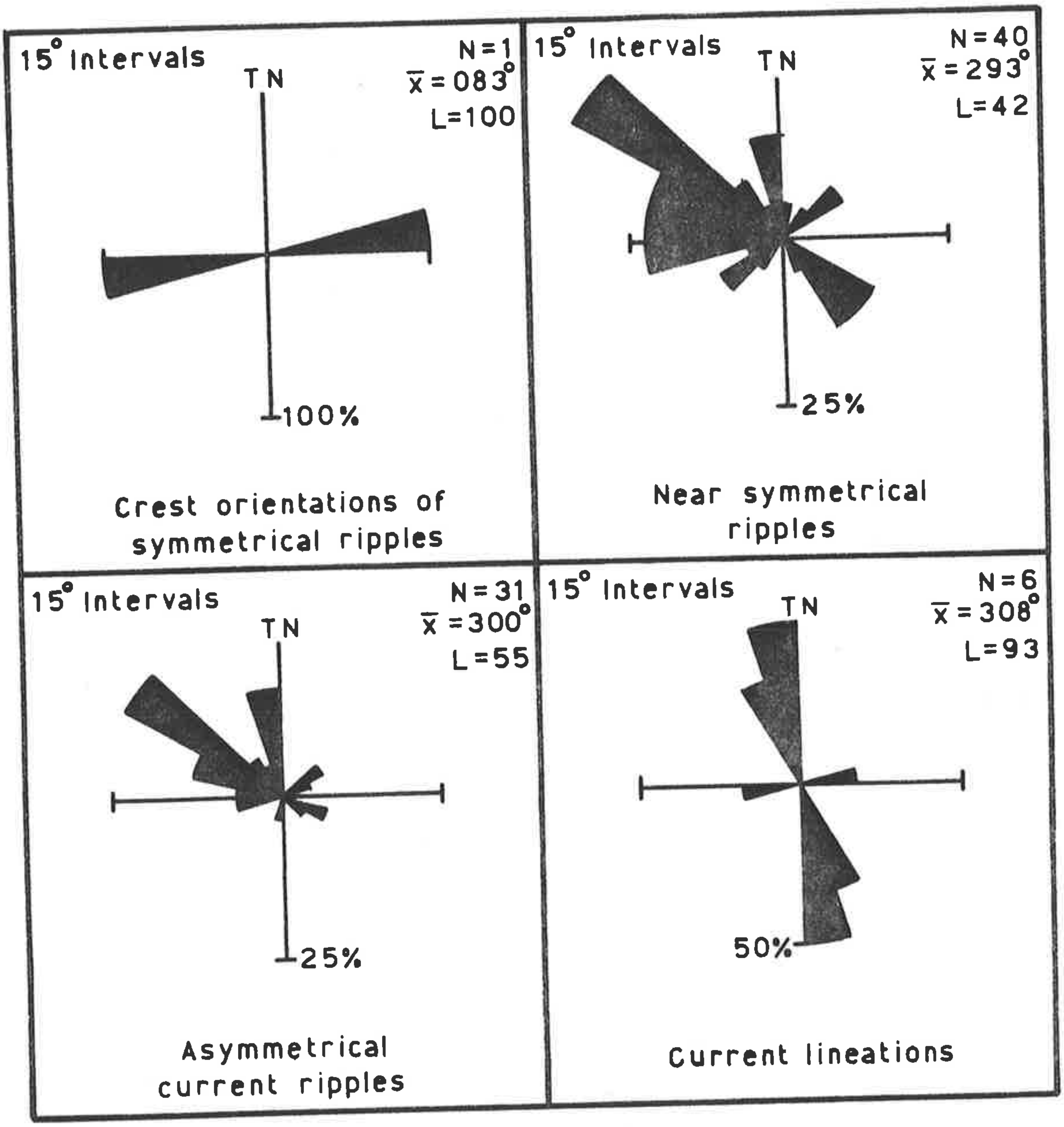


Figure 5-8. Palaeocurrent rose diagrams, Nildottie Siltstone Member, Mount Scott Range.

Crests of symmetrical ripples are commonly orientated north - south or northeast - southwest. These orientations are probably an indication of palaeoslope strike, with crests aligned subparallel to the coastline (Picard, 1967a, 1967b). However, palaeowind patterns may have played an important auxillary role in the orientation of wave-oscillation ripples (Davis, 1967).

An indication of palaeodip is given by the orientation of asymmetrical wave ripples, which typically face shorewards (Reineck and Singh, 1975). In the Nildottie Siltstone Member, asymmetrical wave ripple orientations are bimodal, however there is a considerable dominance of flow (translation) towards the west. Thus, it appears that a north-south striking, easterly dipping palaeoslope was present during deposition of the Nildottie Siltstone Member. This is consistent with evidence from the underlying Warragee Member (Fig. 4-11).

In most areas, current lineations and symmetrical ripple crests are orientated approximately perpendicular to each other. The apparently anomalous situation in the Heysen Range (Figs. 5-3 and 5-5) is probably due to the fact that all ten current lineations were obtained from the uppermost portion of the member. The overlying Eregunda Sandstone Member indicates current flow from the south, and thus uplift and closure of the basin of deposition somewhere to the south of the Heysen Range was probably initiated during the final stages of Nildottie sedimentation.

The palaeocurrent distribution of current ripples is polymodal. The dominant modes are offshore (towards the northwest) and onshore (towards the southeast), although minor longshore modes are present (Fig. 5-3). A bipolar-dominated, quadrimodal sediment distribution pattern is a characteristic feature of tidal deposits. Evans (1965) notes that in the mid to upper intertidal zone of the Wash, currents typically move up and down the shoreface, while in the lower intertidal to subtidal zone, sediment dispersal is by reversing, longshore currents.

Near-symmetrical ripples may also show a quadrimodal sediment dispersal pattern, with a dominance of ebb and flood currents. These ripples possess all the characteristics of asymmetrical, wave-oscillation ripples, as described by Harms (1969), Reineck and Singh (1975) and DeRaaf et al. (1977). Near-symmetrical ripples are particularly common in intertidal and shallow subtidal environments, where they are attributed to the combined effects of waves and currents (Reineck and Singh, 1975). In the Nildottie Siltstone Member low asymmetries, very continuous crestlines and low bifurcation indicies indicate that the bulk of the ripples were wave-dominated, with only minor current influence.

Thus, the palaeocurrent distribution for the Nildottie Siltstone Member is polymodal. The dominance of a bipolar, ebb and flood distribution for asymmetrical ripples is typical of tidal environments. The presence of thin, current lineated, fine sandstones derived from the south and south-east indicates a minor alluvial influence during the closing stages of Nildottie sedimentation. The dominance of flood-orientated asymmetrical ripples is consistent with observations on modern tidal flats (Reineck, 1967; Reineck and Singh, 1975).

DEPOSITIONAL MODEL

Introduction

Although it is apparent that the Nildottie Siltstone Member was largely deposited in a paralic environment, there are several depositional models which need to be considered. The following study concentrates on the relative roles of shallow marine and tidal deposition, and alluvial plain progradation. Some initial comments on theoretical epeiric sea sedimentation are also presented.

A General Theory of Epeiric Sea Sedimentation, and its Relationship to the Nildottie Siltstone Member

It is apparent from the above discussion that the bulk of the Nildottie Siltstone Member must have been deposited in an extremely shallow epicontinental (epeiric) sea. A generalised model for epeiric sea sedimentation is presented by Shaw (1964). Irwin (1965) has described clear-water (carbonate-evaporite) deposition in epeiric seas, and an example of epeiric sea deltaic deposition is presented by Visher et al. (1975).

The deposits of epeiric seas are commonly quite different from those which accumulated in the shallow marine environment, along coastlines exposed to the open ocean. In epeiric seas the great width of shelves, their low order of slope and extreme shallowness of water are often sufficient to restrict or eliminate circulation. As both Irwin (1965) and Shaw (1964) have pointed out, the bottom slope of many ancient epeiric seas must have been in the order of 1m per 5km, or even less. Based on this assumption, Irwin (1965) predicted the existence of three energy belts, each of which helps to control the type of sediment forming on the sea floor. These three energy zones are shown in Figure 5-9.

Irwin's model has been successfully applied by many geologists over the years, and recently formed the bases for Youngs' (1978a, 1978b) palaeogeographic interpretation of the Wirrealpa and Aroona Creek Limestones, which overlie the Billy Creek Formation. Youngs (1978a,b) identified two megafacies which she related directly to the "Y" and "Z" zones proposed by Irwin (1965), and concluded that quiet water (Z zone) conditions prevailed over much of the study area. Daily (1976b, p.18) related this phase of carbonate formation to "a widespread transgression of the sea", and thus it can be assumed that the basin was even further dominated by epeiric conditions during the deposition of the regressive Billy Creek Formation. Thus if Youngs' (1978a,b) analysis of the Middle Cambrian carbonates is correct, the bulk of the Nildottie sequence was deposited in an extremely shallow, low energy zone of an epeiric sea, in which water circulation was very restricted (zone "Z" of Fig. 5-9). This conclusion is supported by an abundance of desiccation features and evidence of former evaporites throughout the present stratigraphic and geographic extent of the Nildottie Siltstone Member

The "Z" energy zone of Irwin (1965) is probably the most poorly under-

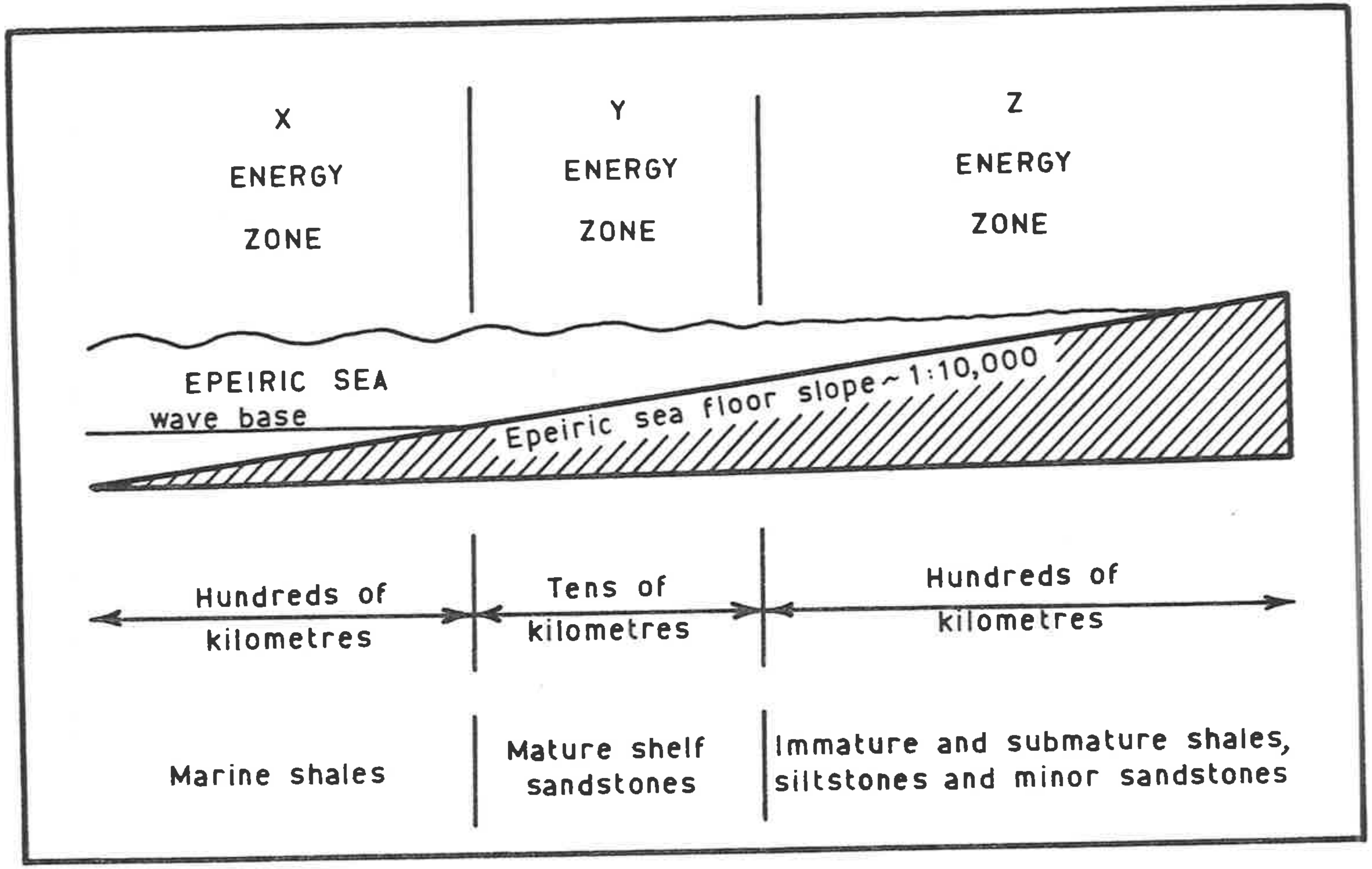


Figure 5-9. Theoretical model for epeiric sea clastic sedimentation.

stood of the three regimes, and certainly is the most difficult to interpret. In the absence of appreciable terrigenous influx, salinities increase shoreward so that "a regular pattern of facies from dolomite, through anhydrite or gypsum, to salt and other evaporites is established" (Irwin, 1965, p.450). However, in an epeiric sea dominated by terrigenous influx, sedimentation is considerably more complex. In the "Z" energy zone, circulation and sediment redistribution is principally by epeiric waves and currents. According to Shaw (1964, p.36), "the most effective agent of distant transport of allochthonous debris within an epeiric sea would have been those epeiric currents that were persistent in direction and regularly in contact with the sea bottom. Their lack of power could partly be made up if they were persistent". Thus, provided the rate of sedimentation was small, the same basic pattern with respect to grain-size and related hydraulic parameters would be established for detrital terrigenous sediments as for autochthonous carbonates. If terrigenous detritus was being supplied at a much faster rate than could be redistributed, then the epeiric sea deltaic model proposed by Visher et al. (1975) would apply.

In the Nildottie Siltstone Member, the abundance of flaser, wavy and lenticular bedded siltstone indicates that there was considerable reworking of the incoming sediment, with hydraulic separation of fine and coarse grains. The polymodal distribution of palaeocurrents is further evidence for reworking of fine-grained detritus, and the abundance of symmetrical and near-symmetrical oscillation ripples is strong evidence that wave action played an important role in sediment dispersal.

Currents may be generated in epeiric seas in a variety of ways. Downslope density currents, resulting from a salinity gradient (Shaw, 1964, p.36), were probably weak and relatively unimportant. However, wind and wave induced currents may have been substantial, and were probably much more effective than Shaw (1964) envisaged. For example, during normal conditions in the Laguna Madre of southern Texas, wind tides have an amplitude of 30 to 50 cm, despite the fact that the maximum possible wave fetch is only 20km

(Miller, 1975). The wind-generated tides are sufficiently strong and persistent to produce characteristic facies and tidal lamination. A similar situation occurs in the shallow, protected bays along the Texas Gulf Coast (Shepard and Moore, 1955; Moore and Scruton, 1957).

The possibility of celestial tides in a shallow epeiric sea cannot be ignored. Shaw (1964) pointed out that parts of Florida Bay are tideless (see Ginsburg, 1956), however, this is an unfair comparison since major subaerial barriers oppose the flow of water into the bay, and in any case, open ocean tides in this area average only 0.7m. By way of contrast, Klein (1975c, p.408) states that "it is conceivable that most epeiric sea sediments were dominated by tidal processes both in the intertidal and the shallow, subtidal ... domain".

The solution to this controversy appears to lie in a study of modern environments. Tidal range is generally large on coastlines which are exposed to the open ocean, and flanked by broad, shallow shelves (Redfield, 1958; Off, 1963). In restricted bays however, such as on the Texas Gulf Coast and in Florida Bay, the tidal range is extremely low. This is due to the fact that ocean tides have only a few narrow channels along which they can gain entry. Thus, the influence of celestial tides in an epeiric sea would largely depend upon its degree of isolation from the open ocean. If there is only a narrow restricted passage between open ocean and epicontinental sea, then celestial tides will be minimal. However in the case of a relatively broad-mouthed epeiric sea, celestial tides may have been important. For example, tides of up to 10m occur at the top of the Gulf of California, which is over 1000km long (Thompson, 1968), and tides in excess of 3m occur in Hudson Bay, the Persian Gulf, and the Yellow Sea.

In extremely shallow water situations, tides may be considerably reduced due to bottom friction (Mazzullo & Friedman, 1975; Mazzullo, 1978). This is probably the case for the Nildottie Siltstone Member, however it is emphasised that their is no reason to assume that diurnal, celestial tides were totally absent (Klein, 1977a, 1977b).

A form of sediment transport not discussed so far is the direct influence of rivers carrying sediment into the sea. Once rivers enter the basin of deposition, they rapidly lose their competence, and are generally incapable of appreciable sediment reworking. However, rivers do influence the pattern of sediment dispersal in an indirect way, as Shepard and Moore (1955) have shown. Shallow restricted embayments along the central Texas coast are supplied with sediment from southerly flowing rivers. Most currents are wind generated, however measurements in Aransas Pass have shown that a dominance of southerly (ebb) flow is due to fluvial discharge (Shepard and Moore, 1955). Regular lamination in the sediment of the embayment is largely attributed to fluctuation in river competence (Moore and Scruton, 1957, Table I).

On the basis of the above discussion, it is possible to draw some generalised conclusions with respect to Nildottie sedimentation:

(a) Deposition occurred in an extremely shallow epeiric sea, subject to frequent emergence, desiccation and evaporite formation.

(b) Deposition occurred within the lowest energy zone of the epeiric sea (zone "Z" of Irwin, 1965).

(c) Some lamination may be due to primary deposition, associated with fluvial discharge. Most however is due to sediment reworking and redistribution, with winnowing of fines.

(d) Wave activity was a major process involved in sediment redistribution. In normal conditions, waves were generated entirely within the basin of deposition.

(e) Considering the extreme shallow conditions during Nildottie sedimentation, it is possible that the effects of celestial tides were small. However, epeiric, wind-generated tides may have been important.

Hydraulic Analysis of Nildottie Sedimentation

Introduction

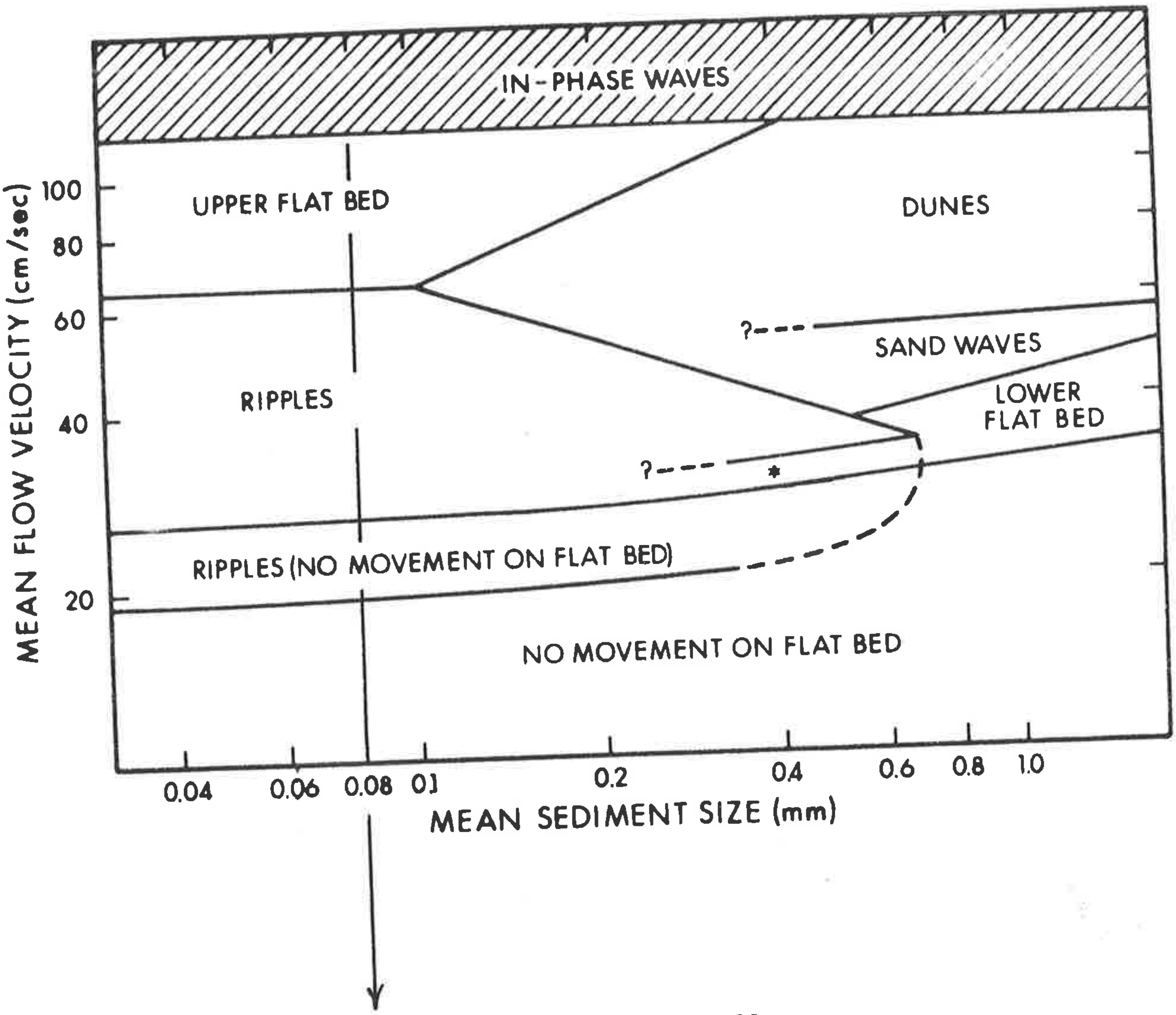
The coarser grained units in the Nildottie Siltstone Member typically comprise grains of coarse silt to very fine sand (average 0.05mm). At this grain-size, ripple lamination is the stable bedform for current velocities in the range 20-65 cm/sec (Fig. 5-10). With increased velocity, ripples pass into upper flow regime horizontal lamination, commonly with current lineation. Large scale cross stratified bedforms, such as dunes and sand waves, are absent. The presence of only minor upper flow regime horizontal lamination in the Nildottie Siltstone Member indicates that currents rarely exceeded about 65cm/sec.

Symmetrical Ripples

Symmetrical ripples are common throughout the Nildottie Siltstone Member, and are defined by a symmetrical external form (ie. ripple symmetry index RSI = 1.0). In addition, symmetrical ripples are characterised by fairly straight, continuous crests, with only occasional bifurcations (Plate 20). Ripple parameters were measured for 14 samples where the ripples were exposed over an area of at least $0.5m^2$ (Table 5-1). In all cases, there is a 98% probability that the ripples were wave formed (Tanner, 1967).

Internally, the ripples comprise intersecting sets of laminae with curved, erosional bases. In some cross sections, they may be confused with current-generated nu cross-stratification of Allen (1963). Laminae are typically form-discordant, and in many cases the chevron pattern so commonly described in the literature (eg. Reineck and Singh, 1975, Fig.20) is poorly developed or absent. This is not an unusual feature however, for as Picard (1967b, p.2474) has pointed out, "ripple marks formed by stationary oscillation waves are apparently rare in the geologic record". Furthermore, in a review of lacustrine sedimentation, Picard and High (1972, p.126) note that "all the ripple marks, even those with perfect symmetries (RSI = 1.0), display foreset laminae ... we have not seen any symmetric ripples that have a

Figure 5-10. Highly Schematic Size - Velocity Diagram for a Flow Depth of about 20cm.*



mean grain-size of rippled and horizontally laminated units in the Nildottie Siltstone Member.

*After Harms et al. (1975, Fig. 2-5). Based on data from Barton and Lin (1955), Costello (1974), Guy et al. (1966), Hill et al. (1969), Pratt and Smith (1972), Pratt (1973), Southard and Harms (1972), Stein (1965), Williams (1967, 1970) and Willis et al. (1972).

Table 5-1 Symmetrical Ripple Indicies, Nildottie Siltstone Member

s	h	RI	RSI	CI	SI	BI	PL_1	PL_2
1. Wirrealpa Basin								
45	4.0	11.3	1.0	20^+	8.3	22.2	17.8	0.22
30	3.0	10.0	1.0	10^+	30	10^+	14.3	0.23
28	2.5	11.2	1.0	14.3^+	16.0	17.9	19.0	0.18
9	1.0	9.0	1.0	16.6^+	66.7	44.4^+	8.5	0.90
15	3.5	4.3	1.0	30^+	10	20	4.7	0.30
30	3.3	9.1	1.0	22^+	26.1	28.3	12.9	0.37
30	4.5	6.7	1.0	18.4^+	80.9	32^+	10.0	0.17
20	8	2.5	1.0	20^+	19.5	18.4	5.47	0.27
13	1.0	13.0	1.0	30.8^+	24.0	15.4	7.4	0.23
15	3.5	4.3	1.0	30.0^+	10.0	20.0	4.7	0.33
2. Heysen Range								
25	2.3	10.9	1.0	14.0^+	15.0	15.2	4.2	0.48
3. Chambers Gorge/Mount Frome								
30	3.5	8.6	1.0	100^+	8.0	20.0	4.3	0.40
37	3.2	11.6	1.0	54.1^+	33.3	27.0	18.6	0.35
27	4.5	6.0	1.0	37.0^+	60.0	18.5	8.6	0.26

$^+$outcrop too small to determine accurately. Minimum probable value.

where: s = ripple spacing in mm
h = ripple height in mm
RI = ripple index
RSI = ripple symmetry index
CI = continuity index
SI = straightness index
BI = bifurcation index
PL_1, PL_2 are parallelism indices, based on Tanner (1967).

chevron-like internal structure".

The abundance of foreset laminae in the symmetrical ripples of the Nildottie Siltstone Member is attributed to generation in shallow water. Under these conditions, wave motion is distorted and a net forward motion results. If the degree of translation is large enough, combined-flow (current and wave oscillation) ripples result.

The hydraulic effects of oscillatory water motion are complex, and vary considerably with respect to water depth. Komar (1974) has developed two semi-empirical theories; one for shallow water wave propogation, and the other for deep water conditions. Failure to recognise these environmental regimes can lead to mistaken interpretations. In shallow water, the ripple length λ is approximately equal to the bottom orbital diameter d_o. This is an important simplification which allows calculation of a variety of ancient wave conditions. However, it can only be made where there is adequate evidence of shallow water deposition. In the Nildottie Siltstone Member, symmetrical ripples are commonly associated with desiccation cracks, and on this basis, we can safely assume that $\lambda \simeq d_o$.

Unfortunately, Komar's study is based on observations of fine to coarse sand, and cannot confidently be applied to the rippled coarse siltstones of the Nildottie sequence. His study however, confirms the validity of Tanner's (1971) work for shallow water conditions. Tanner's study is considered to be particularly useful, because it involves a consideration of grain-size, which most other studies lack.

Table 5-2 contains a summary of the hydraulic parameters which were derived from Table 5-1 data. The methods used are summarized in Appendix B. The actual numbers presented in Table 5-2 are probably not correct, however they are not intended to be results, but rather approximations and limitations. They clearly indicate that the waves had a short period, low height, and relatively short wavelength. Generation in shallow water (generally in the range 15-100cm) is also indicated. The fetch of 19km obtained from Tanner's (1971) method is compatable with empirical results (Bretschneider,

Table 5-2 Estimation of the Hydraulic Environment during the formation of Symmetrical Ripples in the Nildottie Siltstone Member

A. HYDRAULIC LIMITATIONS:

water wave height H = 7-17cm

water depth h = at least 15cm

fetch f = 3-500km

B. CALCULATIONS BASED ON RIPPLE SPACING AND GRAIN-SIZE

av. ripple spacing s = 2.53cm

av. grain-size g = 60um

water wave height H = 14cm

water depth h = 62cm

fetch f = 19km

water wave length L = 4.0m

wave period T = 1.7sec

C. COMPARISON WITH EMPIRICAL TABLES (Bretschneider, 1966)

water wave height H = less than 30cm

water depth h = less than 1m

fetch f = less than 10km

1966, Fig. IV-B) at moderately low wind speeds (<20km/hr).

Near-Symmetrical Ripples

Near-symmetrical ripples are abundant throughout the Nildottie Siltstone Member, and are defined by a slightly asymmetrical external form (RSI generally less than 1.5). They are similar in appearance to the symmetrical ripples described above, with a wavelength of just under 3cm and a ripple height of about 3mm. They are typically slightly sinuous, with minor bifurcations and occasional current break-throughs. Ripple parameters were measured for 11 examples where the ripples were exposed over an area of at least $0.5m^2$ (Table 5-3). In all cases, there is a 98% probability that the ripples were wave or swash generated (Tanner, 1967).

Internally, the ripples comprise intersecting sets of laminae, with gently curved, erosional bases (Plate 19). Laminae are generally form-concordant, although form-discordant foresets are common. Thus, they are distinguished from symmetrical ripples mainly on the basis of their external form.

Traditionally, asymmetrical ripples have been attributed to current activity; Evans (1941) was the first worker to clearly demonstrate a wave origin for some varieties of asymmetrical ripples. Evans observed ripples migrating in response to wave oscillation, despite the fact that there was negligible net translation of the water in any one direction. In all cases, the steeper lee slope faced in the direction of wave propogation. The ripple asymmetry was attributed by Evans (1941, p.40) to "a relatively strong surge" followed by "a reversal of the direction of bottom movement which is weaker but longer continued".

Some recent workers (Harms, 1969; Harms _et al._, 1975; Picard and High, 1968, 1972) have suggested a 'combined-flow' origin, with both weak current activity and wave oscillation. However, the presence of unidirectional currents is unnecessary, as shown by Reineck and Singh (1975, p.25-28) and DeRaaf _et al._ (1977). On this basis, the same statistical analysis was applied to the asymmetrical wave ripples as was used earlier for the symme-

Table 5-3. Near-Symmetrical Ripple Indicies, Nildottie Siltstone Member

s	h	RI	RSI	CI	SI	BI	PL_1	PL_2
1. Wirrealpa Basin								
40	3.0	13.3	1.2	-	30.0	-	6.6	0.13
30	4.9	6.1	1.7	-	10.0	10	2.8	0.20
15	3.0	5.0	1.1	-	40.0	20	15	0.27
13	2.0	6.5	1.6	31^+	24.0	16^+	7.4	0.23
25	3.0	8.3	1.2	12.0	8.3	16^+	10.7	0.25
25	3.0	8.3	1.3	20.0	25.0	10	6.5	0.44
22	2.5	8.8	1.4	14^+	15.0	18.2	4.5	0.36
16	3.0	5.3	1.7	21.9	15.0	5.0	6.1	0.37
2. Heysen Range								
25	3.2	7.3	1.5	-	19.7	-	7.2	0.29
3. Mount Scott Range								
16	3.0	5.3	1.7	16^+	12.5	7.5	4.4	0.38
21	3.5	6.0	2.2	19^+	16.7	14.3^+	7.7	0.26

where: s = ripple spacing in mm

h = ripple height in mm

RI = ripple index

RSI = ripple symmetry index

CI = continuity index

SI = straightness index

BI = bifurcation index

PL_1, PL_2 are parallelism indices, based on Tanner (1967).

trical variety. Since both types are wave-generated, similar results were expected. Table 5-4 contains a summary of the hydraulic parameters which were derived from Table 5-3 data. The methods used are summarized in Appendix B. Once again, it is emphasised that the actual numbers presented in Table 5-4 are probably not correct, but merely represent rough approximations. They clearly indicate that the waves had a short period, low height, and relatively short wavelength. In fact the results emphasise that the near-symmetrical wave generated ripples originated under essentially the same conditions as the symmetrical wave ripples.

Asymmetrical Current Ripples

Asymmetrical, current-formed ripples occur sporadically throughout the Nildottie Siltstone Member, and are defined by a marked asymmetry (RSI $\geqslant$3.0). They are generally much larger than wave ripples, with a steep lee slope and highly sinuous form (Plates 16-18). All gradations occur between sinuous types with occasional current spurs, to out-of-phase lunate (catenary) ripples with abundant current spurs. Linguoid ripples are rare. Ripple parameters were measured for 5 examples where the ripples were exposed over an area of at least 0.5m^2 (Table 5-5). In all cases, there is a 98% probability that the ripples were current formed, and are not of the 'dry creek' type (Tanner, 1967).

Internally, the ripples consist of low angle foresets, all inclined in the same direction. For moderately sinuous forms, laminae are typically form-concordant. Internal lamination in catenary ripples may also be form-concordant, but more commonly the catenary form is developed on a thin bed of horizontally laminated very fine sandstone. Thus, a discordancy exists between the internal disposition of laminae and the external ripple morphology.

Despite many intensive and detailed studies of current ripples (eg. Allen, 1963, 1968), very little can be stated about the hydraulic conditions responsible for their formation. As Harms et al. (1975, p.21) point out, "it is a standing fact ... that systematic changes in average height and spacing of fully developed ripples with either grain size or flow velocity

Table 5-4 Estimation of the Hydraulic Environment during the formation of Near-symmetrical Ripples in the Nildottie Siltstone Member

A. HYDRAULIC LIMITATIONS:

water wave height H = 7-17cm

water depth h = at least 15cm

fetch f = 2-500km

B. CALCULATIONS BASED ON RIPPLE SPACING AND GRAIN-SIZE:

av. ripple spacing s = 2.25cm

av. grain-size g = 60um

water wave height H = 14cm

water depth h = 60cm

fetch f = 18km

water wave length L = 3.8m

wave period T = 1.7sec

C. COMPARISON WITH EMPIRICAL TABLES (Bretschneider, 1966)

water wave height H = less than 30cm

water depth h = less than 1m

fetch f = less than 10km

Table 5-5. Asymmetrical Current Ripple Indices, Nildottie Siltstone Member

s	h	RI	RSI	CI	SI	BI	PL_1	PL_2	type
1. Wirrealpa Basin									
40	7	5.7	4.0	7.5	5.0	5.0	1.9	0.98	S
60	6	10.0	3.0	6.7^+	4.0	-	0.9	0.53	C
2. Heysen Range									
118	12	9.8	3.4	3.0^+	15.0	3.2	0.9	0.53	C
3. Chambers Gorge/Mount Frome									
130	25	5.2	7.7	3.8^+	2.0	-	0.3	0.54	L
80	15	5.3	4.7	2.5	4.0	-	0.7	0.72	S

where s = ripple spacing in mm
h = ripple height in mm
RI = ripple index
RSI = ripple symmetry index
CI = continuity index
SI = symmetry index
BI = bifurcation index
PL_1, PL_2 = parallelism indices, based on Tanner (1967)
S = straight crested to sinuous
C = catenary
L = linguoid

are so small that they are overshadowed by the inevitable substantial variations in size within a single ripple train". Since current ripples are not dependant upon the oscillatory motion set up by passing waves, there is no way of estimating the depth of water in which they were formed. However, from Figure 5-10 it is apparent that for coarse silt to very fine sand, current ripples are only stable for velocities in the range 25-65 cm/sec.

A relatively diagnostic feature of current ripples is their shape in plan view. With increasing flow velocity and turbulence, relatively straight crested ripples pass into sinuous, then linguoid forms (Allen, 1965b; Middleton, 1965; Harms, 1969; Harms et al., 1975). Catenary ripples are apparently rare in the geological record and Allen (1968, p.77) has noted that "although smallscale ripples very infrequently assume the catenary form, it is only the largescale structures that give rise to whole trains of this type". Thus, the relative abundance of catenary ripples and the paucity of linguoid ripples in the Nildottie Siltstone Member is a most unusual feature.

Transverse catenary ripples develop by "a further increase of the three-dimensionality on the flow patterns developed by sinuous ripple trains" (Allen, 1968, p.283). Thus, they probably represent relatively high flow velocity and turbulence, as indicated by their large scale (lunate/mega-ripple) counterparts. Well developed examples are known to occur in ephemeral streams (Williams, 1971), thus supporting an high-velocity, high-turbulence origin. Isolated and connected sets of catenary ripples have been produced in flume experiments by Mantz (1978). Their origin and stability is partly attributed to the fine grain-size of the sediment (av. medium to coarse silt), but is principally due to a limited sediment supply (cf. Rees, 1966). Thus, a variety of possible mechanisms is available for the production of these catenary ripples. However, one of the most important features not discussed in any detail in the literature is the importance of intergranular cohesion. Flume studies are typically conducted using well washed, moderately sorted, quartz sand which is essentially cohesionless. In the Nildottie Siltstone Member, minor clay and very fine silt was probably responsible for a degree of cohesion between grains during deposition, and may have further assisted the development of the catenary ripple form.

Recent Analogues

Marginal Marine and Paralic Environments and their Relationship to Nildottie Sedimentation

High energy shorelines: beach deposits

Beaches can be defined as "the comparatively narrow zones which lie above the low water mark and which are mainly shaped or at least strongly influenced by wave action" (Van Straaten, 1954, p.203). There is no evidence of beach deposits in the Nildottie Siltstone Member, and thus it is assumed that wave action at the shoreline was slight. Keulegan and Krumbein (1949) have shown that on very gentle sloping shelves (slopes in the order of 1:10,000), oceanic waves may be entirely dissipated, so that they neve reach the shoreline. This is probably the reason for the lack of distinctive shoreline deposits (especially beach deposits) in the Nildottie Siltstone Member. A similar modern example is reported by Niino and Emery (1961) in the Yellow Sea.

Very low energy shorelines

Mudflats may accumulate along unprotected coastlines in regions of very low wave activity and low tidal range. In the case of the western Louisiana coast (Beall, 1968), the sediments are characteristically fine-grained, and there is an absence of well-defined, meandering drainage channels. The preserved, regressive sequence from the base upwards comprises inner shelf mud, grading upwards into breaker bar sand, and then into mid and upper tidal flat sand and mud, and finally into muddy, organic rich, marsh facies. The Nildottie Siltstone Member also combines fine grain-size with a general lack of well-developed tidal channels, and in this respect, is very similar to the western Louisiana shoreline. However it lacks a distinctive marsh facies and instead, contains a wide variety of facies in which periodic exposure and desiccation is indicated. These features, combined with an abundance of lenticular, wavy and flaser bedding, are characteristic of moderate energy, wave and tide-affected environments.

Moderate energy shorelines: tidal flats

"Tidal flats develop along the gently dipping sea coasts with marked tidal rhythms, where enough sediment is available and strong wave action is not present" (Reineck and Singh, 1975, p.355). They are found in protected zones landward of coastal barriers, in estuaries and, exceptionally, facing the open sea. Particularly well documented examples occur along the coasts of the Neatherlands, Germany, Denmark and Holland (eg. Van Straaten, 1954, 1959; Reineck, 1967; Reineck and Singh, 1975; De Jong, 1977), and in the United Kingdom (the Wash; Evans, 1965).

Sediments are distributed according to their grain-size. Below effective wave base, mudstones predominate. Sandy sediments are concentrated in the zone of coastal wave attack, where finer-grained detritus is winnowed. Wave and tidal current activity decreases towards the high tide zone, and due to the settling-lag theory (Van Straaten and Kuenen, 1957, 1958), muds reappear in increasing abundance in this direction.

According to Klein (1977a, p.10), "a tidal circulation model tends to favour the continued abrasion, sorting and rounding of sand. This high rate of abrasion between sand particles in tidal areas tends to remove unstable rock and mineral fragments, leaving a quartzose residue". For example, excellent sorting has been reported from tidal sand bodies by Klein (1970a) and Houbolt (1968), while supermature rounding has been documented to be consistent with a tidal circulation system (Balazs and Klein, 1972). This is obviously not the case for the Nildottie Siltstone Member, where fine sandstones commonly contain mica (including biotite), feldspar (including plagioclase) and strained quartz. In addition, the Nildottie sandstones and coarse siltstones are only moderately sorted, and subangular. There is, of course, evidence of minor reworking of Nildottie sediments, however there is no reason to believe that they have undergone abrasion and winnowing over a prolonged period of time. Thus, the sediments of the Nildottie Siltstone Member reflect minor reworking, due to either rapid deposition or weak tidal flux. Their fine grain-size supports the view that the sequence was deposited in a low energy environment, probably intermediate in character between the low energy, muddy Louisiana coast (Beall, 1968) and the moderate energy North Sea tidal flats.

Klein (1970b, 1971, 1975a, 1975b, 1977a) has described many features and processes which he considers indicative of tidal deposition. A composite list is presented in Table 5-6, and a comparison with sedimentary structures in the Nildottie Siltstone Member is included. Due to the fine grain-size of the Nildottie sequence, many of the large scale structures referred to by Klein are absent; however the general similarity should be obvious.

Probably the closest modern equivalent to the Nildottie Siltstone Member is the tidal flat sequence of the Gulf of California (Thompson, 1968, 1975). These tidal flats are dominated by silt and clay, which are supplied in abundance by the Colorado River. Despite an extreme tidal range (average 4-5m), distinctive tidal channels are absent, and tidal currents move over the flats as broad uniform flows. The main difference between the Gulf of California tidal flats and those of the North Sea are:

(a) suspension-deposited silty clays in the subtidal and lower intertidal zone rather than cross bedded sands. (Cross bedded sandstones are generally absent from the Nildottie Siltstone Member too);

(b) typically uniform horizontal lamination and bedding on the intertidal flats rather than lenticular, wavy and flaser bedding. (Lenticular, wavy and flaser bedding are poorly developed in the Nildottie Siltstone Member, as discussed previously);

(c) predominance of silt and clay and lack of a significant upward-fining of texture. (It is also difficult to assign any particular facies in the Nildottie Siltstone Member to the subtidal, intertidal or supratidal zone);

(d) an abundance of evaporites in the upper intertidal and supratidal

Table 5-6. A Tidal Process - Response Model and its Relationship to the Nildottie Siltstone Member

Transport Process	Criterion	Occurrence in the Nildottie Siltstone Mbr.
A. Tidal current bedload transport with bipolar reversals of flow direction.	1. Cross-stratification with sharp set boundaries	n.a.
	2. Herringbone cross-stratification	c*
	3. Bimodal-bipolar distribution of orientation of maximum dip direction of cross-stratification.	c*
	4. Parallel laminae	r
	5. Complex internal organization of dunes and sand waves.	n.a.
B. Time-velocity asymmetry of tidal current bedload transport.	6. Reactivation surfaces	n.a.
	7. Bimodal or multimodal frequency distribution of dip-angle of cross-strata.	n.a.
	8. Bimodal frequency distribution of dip angle of cross-strata.	n.a.
	9. Unimodal distribution of orientation of maximum dip direction of cross-strata.	n.a.
	10. Orientation of cross-strata parallels sand body trend and basinal topographic strike.	n.a.
	11. 5 (from above)	n.a.
C. Late-stage ebb flow and emergence with sudden change in flow directions at extremely shallow water depths.	12. Trimodal distribution of orientation of maximum dip direction of cross-strata.	a
	13. Quadrimodal distribution of orientation of maximum dip direction of cross-strata.	a

Table 5-6 (cont'd) A Tidal Process - Response Model and its Relationship to the Nildottie Siltstone Member

Transport Process	Criterion	Occurrence in the Nildottie Siltstone Mbr.
C. (cont'd) Late-stage ebb flow and emergence with sudden change in flow directions at extremely shallow water depths	14. Small current ripples superimposed at 90° or obliquely on larger current ripples.	c
	15. Interference ripples	c
	16. Double crested ripples	r
	17. Current ripples superimposed at 90° and 180° of crest and slip faces of dunes and sand waves, and cross-stratification.	n.a.
	18. Flat-topped current ripples	c
	19. "B-C" sequences of cross-stratification overlain by micro-cross laminae.	n.a.
	20. Symmetrical ripples	a
	21. Etch marks on slip faces of cross-strata	r
D. Alternation of tidal current bedload transport with suspension settlement during slack water periods	22. Cross-stratification with flasers	r(p)
	23. Simple flaser bedding	c(p)
	24. Bifurcated flaser bedding	c(p)
	25. Wavy flaser bedding	c(p)
	26. Bifurcated-wavy flaser bedding	c(p)
	27. Wavy bedding	a
	28. Lenticular bedding, connected thick lenses	c(p)
	29. Lenticular bedding, connected flat lenses	a
	30. Lenticular bedding, isolated thick lenses	r(p)

Table 5-6 (cont'd)   A Tidal Process - Response Model and its Relationship to the Nildottie Siltstone Member

Transport Process	Criterion	Occurrence in the Nildottie Siltstone Mbr.
D. (cont'd) Alternation of tidal current bedload transport with suspension settlement during slack water periods	31. Tidal bedding	c(p)
	32. Convolute bedding	r
	33. Current ripples with muddy troughs	c
	34. Laminated calcilutite and dololutite	r
E. Tidal slack water mud suspension deposition	35. 22-26, 32 (from above)	c
F. Tidal scour	36. Mud-chip conglomerates at base of washouts and channels.	a
	37. Shell-lag conglomerates at base of washouts and channels.	-
	38. Intraformational conglomerates	a
	39. Flutes	r
	40. Rills	c
G. Exposure and evaporation	41. Mudcracks	a
	42. Birdseye structure	n.a.
	43. Diagenetic dolomite	n.a.
	44. Nodular anhydrite	r-c
	45. Intraformational conglomerates and rip-up clasts.	a

Table 5-6 (cont'd) A Tidal Process - Response Model and its Relationship to the Nildottie Siltstone Member

Transport Process	Criterion	Occurrence in the Nildottie Siltstone Mbr.
G. (cont'd) Exposure and evaporation	46. Runzelmarken	r-c
	47. Raindrop imprints	r
	48. Evaporite casts and imprints	a
H. Burrowing and organic diagenesis	49. Burrowing	r
	50. Tracks and trails	r
	51. Drifted plant remains	n.a.
	52. Impoverished fauna	a
	53. Laterally linked stromatolites	r
I. Differential compaction, loading and hydroplastic readjustment	54. Convolute bedding	r
	55. Load casts	c
	56. Pseudonodules	r

Table 5-6 (cont'd) A Tidal Process - Response Model and its Relationship to the Nildottie Siltstone Member

Transport Process		Criterion	Occurrence in the Nildottie Siltstone Mbr.
J. High rates of sedimentation combined with regressive sedimentation	57.	Graded, fining-upward sequence	r
	58.	Cyclic alternation of coarse limestone, laminated calcilutite, algal dolomite, and dololutite.	n.a.

*small scale (ripple cross-stratification) only.

where: "a" is abundant

"c" is common

"r" is rare

\- is absent

"p" means poorly developed

"n.a." means not applicable

zones and absence of marshes. (This is due to the arid climate in the Gulf of California: the presence of evaporites in the Nildottie Siltstone Member is also attributed to an arid climate);

(e) the absence of barrier sands and channels. (This is due to the lack of strong wave activity and the fine grain-size of the detritus in the Gulf of California: the absence of barrier sands and channels in the Nildottie Siltstone Member is also attributed to these factors);

(f) the virtual lack of biogenic traces and predominance of red-brown, oxidised sediments in the upper intertidal zone. (This is also attributed to the extreme aridity of the Gulf region: similar conditions probably existed during deposition of the Nildottie Siltstone Member. In addition, the elevated salinity of the epeiric sea during Nildottie sedimentation may have been sufficient to restrict biogenic activity in the intertidal zone (Van Straaten, 1959, p.203)).

Ancient Analogues

Introduction

Very few deposits which are similar to the Nildottie Siltstone Member have been described in the literature to date. This is mainly due to the difficulty of interpretation associated with a fine-grained, monotonously repetitious sequence which lacks large scale bedforms. Van Houten (1961, p.96) grouped sediments of this type as "coastal plain - tidal flat red beds on cratons". His interpretation of their origin is as follows (Van Houten, 1961, p.96):

"Red detritus ... accumulated in a warm to hot, semi-arid to arid climate with a long dry period, on broad featureless flood plains and coastal plains with local dunes and lakes, on wide tidal flats and in shallow restricted seas. Because of the very low gradient, minor changes in topography affected extensive advances and retreats of the sea".

Three ancient deposits have been selected for discussion, in an attempt to highlight the sedimentological characteristics of the Nildottie Siltstone Member. They are:

(a) the Irish Valley Member of the Catskill Formation (a muddy shoreline deposit);

(b) the Psammites du Condroz (a tidal lagoon deposit);

(c) the Peak Red Formation (a paralic and tidal flat deposit).

Irish Valley Member, Catskill Formation

The Upper Devonian Irish Valley Member of the Catskill Formation is about 600m thick, and consists of alternating marine and nonmarine strata (Walker, 1971; Walker and Harms, 1971, 1975). Poorly defined cycles are dominated by a transition from drab shale and siltstone with marine fossils, into blocky red mudstone with desiccation cracks and rootlet horizons. Conspicuously absent are flaser and lenticular bedding, as well as evidence of scouring. Like the Nildottie Siltstone Member, the Irish Valley sequence is fine-grained and lacks distinctive channels. However, the two sequences are dissimilar in most other respects. The lack of cyclicity in the Nildottie Siltstone Member indicates that subsidence and sedimentation were delicately balanced. Furthermore, the lack of drab sediments probably indicates persistent, shallow water oxidising conditions, and a much higher rate of sedimentation than for the Irish Valley Member. This marked contrast between the Nildottie sequence and the Irish Valley Member is important, since the latter is interpreted as having been deposited in a large epicontinental sea virtually devoid of tides.

Psammites du Condroz

The Devonian Psammites du Condroz comprises a 600m thick sequence dominated by sandstone, siltstone and shale. It is particularly rich in ripple marks of various kinds, including interference ripples, rib and furrows and double-crested forms. However, wave ripples predominate (Van Straaten, 1954). Mudstone intraclasts are abundant, and much of the sequence displays poorly developed tidal lamination. After a detailed study of the Recent Wadden Sea tidal flats, Van Straaten (1954) concluded that the Psammites du Condroz is a tidal lagoon deposit. His main reasons for the choice is that the sequence contains relatively few desiccation cracks or current ripples, especially when compared with Recent intertidal environments.

Although it is not suggested that any great proportion of the Nildottie Siltstone Member is of a tidal lagoon origin, there are many similarities between the sequence and the Psammites du Condroz. For example both sequences, by comparison with the Recent North Sea tidal flats, contain:

(a) relatively small wash-outs and scours;

(b) relatively even, continuous, sublenticular lamination;

(c) absence of marsh lamination;

(d) relative abundance of wave ripples;

(e) relative paucity of current ripples;

(f) relative abundance of small load casts.

As Van Straaten (1954) concluded, the above features suggest relatively quiet water deposition, with only weak tidal current activity. In the absence of desiccation features, a subtidal, tide-dominated lagoonal origin is likely. However, since most of the Nildottie Siltstone Member contains an abundance of desiccation cracks, an alternative mode of formation must be considered. Van Straaten (1954, p.43) was aware that "so long as the water can flow unhindered over the whole breadth of the (tidal) zone ... the currents may remain comparitively weak". Although he concluded that such situations are not very likely, they may have occurred in ancient epeiric seas, especially those dominated by fine-grained detritus. Thus, it would have been possible to have many of the features characteristic of shallow tidal lagoons actually preserved in the intertidal zone. In this later case, they would commonly be found in association with desiccation cracks. This is the situation which is believed to have existed in much of the Nildottie Siltstone Member.

<u>Red Peak Formation, Chugwater Group</u>

The Red Peak Formation occurs in the lower portion of the Chugwater

Group and comprises a 300-600m thick sequence of red shale, siltstone and minor sandstone (Picard, 1966). A marginal marine to paralic origin for the red beds has been suggested by several workers, including Branson (1915, 1927), Reeside (1929) and Burk (1953). The formation is informally divided, from oldest to youngest, into five facies: silty claystone, lower platy (siltstone), alternating, upper platy, and sandy (Picard, 1964, 1967c; Picard and Wellman, 1965).

The platy facies of the Red Peak Formation are lithologically very similar to the upper, silty portions of the Nildottie Siltstone Member. An abundance of mudstone intraclasts, ripples of various types, and the presence of desiccation cracks, and minor evaporites and very small channels led Picard (1967c) to suggest a mainly intertidal origin for the sequence. The multi-modal palaeocurrent distribution (Picard and High, 1968) is also consistent with a tidal origin (Table 5-6).

Interpretation of the fine-grained silty claystone facies of the Red Peak Formation is much more difficult. This facies is lithologically very similar to much of the lower portion of the Nildottie Siltstone Member, and also to most of the red units in the underlying Warragee Member. Typically the outcrop is covered by a veneer of shaly material, through which ledges of sandstone, siltstone and silty shale are exposed. Ripple stratification is abundant. Picard (1967c) assigned the silty claystone facies to a "transitional" environment, comprising upper tidal and muddy alluvial plain sediments. However, his evidence in support of such a conclusion is very scant and, by comparison with Recent environments (eg. Beall, 1968; Thompson, 1968, 1975), at least part of the facies may have been deposited on muddy intertidal flats and in tidal lagoons.

SUMMARY AND CONCLUSIONS

The bulk of the Nildottie Siltstone Member comprises red shale and shaly siltstone which were deposited on a paralic environment. A general lack of cyclicity in the sequence suggests that there was a delicate balance between subsidence and sedimentation. The considerable lateral extent and thickness of the paralic facies suggests that the palaeoslope was very low, and epeiric conditions pertained. A lack of coarse detritus in the sequence is further evidence for an extremely low amplitude, senile topography, with sediment supply by sluggish, low competence streams. Thus, an extensive, muddy alluvial flood plain probably flanked a broad zone of intertidal sediments.

The tidal range during deposition of the Nildottie Siltstone Member is unknown, since there are no palaeotidal range sequences (cf. Klein, 1971). However, the relative abundance of wave-formed ripples (commonly associated with desiccation cracks), suggests that tidal currents were relatively weak. The poor sorting of the sediment and a general lack of tidal channels are further evidence of weak tidal flux.

Modern studies of muddy intertidal environments (eg. Thompson, 1968, 1975) suggest that channel development is inhibited by a lack of coarse-grained detritus. Thus, in the absence of barrier sands, tidal waters move over the flats as broad, uniform flows. Ebb currents also flow across the tidal flats, instead of draining into tidal gullies, thus promoting the development of mudflake intraclasts and ebb-flow ripple orientation.

Intertidal and shallow subtidal, tide-influenced deposits constitute the bulk of the sequence. Evidence for tidal activity occurs in the intimate association of wave, current, flat-topped and interference ripples, desiccation cracks, mudflake breccias, halite casts, rare marine trace fossils and raindrop imprints. In addition, poorly defined wavy and lenticular bedding occur in the Nildottie Siltstone Member which is identical in character to bedding structures in Recent, fine-grained tidal deposits (Thompson, 1968, 1975). The consistent bipolar orientation of ripple marks favours a low energy tidal origin for these sediments, with crests aligned subparallel to the coastline and currents directed on and off shore (Picard, 1967b; Picard and High, 1968).

The sequence thus comprises a series of poorly differentiated, evenly laminated to ripple laminated red-beds. The major characteristics of each facies are summarised in Table 5-7, and shown diagramatically in Figure 5-11. River flood plain deposits have not been positively identified, although it is acknowledged that the "transitional environment" is, in part, continental in origin. It is important to emphasise that the red colour of the sediment does not necessarily imply continental deposition, since it may have been preserved in a marginal marine environment, where salinity was sufficiently high to prevent the activity of sulphate-reducing bacteria (McKee, 1954).

A similar Recent deposit is the Gulf of California tidal flat, described by Thompson (1968, 1975). Ancient analogues are recorded from the Palaeozoic and Mesozoic interior epeiric basins of the United States. They include the Red Peak Formation (Picard, 1965, 1966, 1967c; Picard and High, 1968), and probably also the middle, red member of the Moenkopi Formation (McKee, 1954).

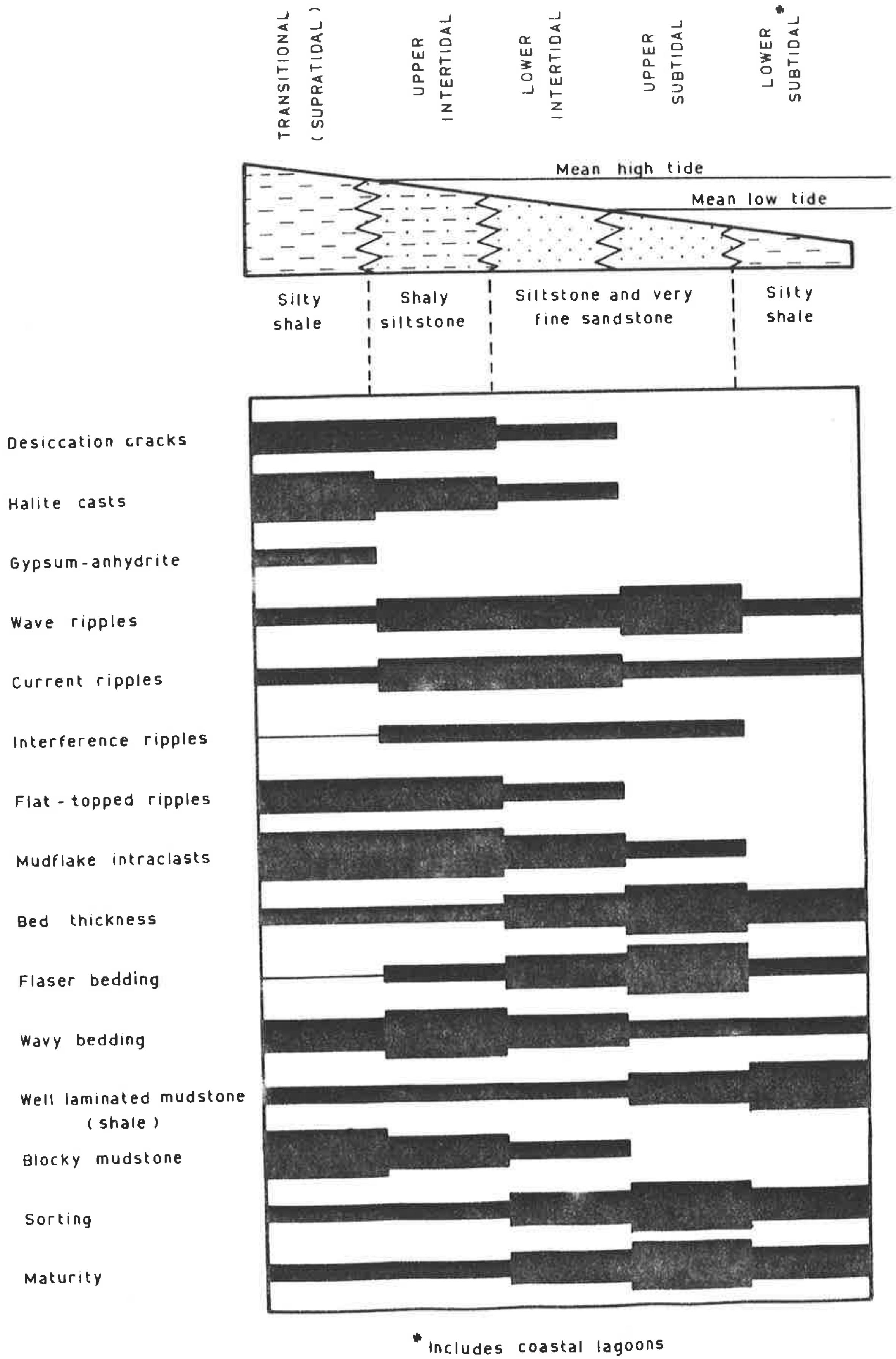
Table 5-7. Depositional Environments in the Nildottie Siltstone Member

Environment of Deposition	Grain-size and Sorting	Internal Structures and Bedding Plane Features	Abundance
Lower Subtidal	Shale and fine to medium siltstone. Minor coarser interbeds. Sorting is moderate.	Fine-grained sediments are horizontally laminated, with minor lenticular bedding. Coarse interbeds are ripple laminated. Minor symmetrical wave ripples. Occasional small load structures. Uncommon marine tracks and trails.	Common, especially in the lower part of the sequence.
Shallow (upper) Subtidal	Coarse siltstone. Sorting is moderate to good.	Ripple laminated. Poorly developed flaser and wavy bedding. Abundant wave ripples. Minor current ripples, interference ripples and load structures. Uncommon marine tracks and trails.	Common, especially in the lower part of the sequence.
Lower Intertidal	Coarse siltstone. Sorting moderate to good.	Ripple laminated, with minor horizontal lamination. Poorly developed flaser bedding. Abundant wave and current ripples. Minor current lineation, flat-topped ripples, interference ripples, desiccation cracks and mudflake intraclasts. Uncommon marine tracks and trails.	Common throughout

Table 5-7 (cont'd) Depositional Environments in the Nildottie Siltstone Member

Environments of Deposition	Grain-size and Sorting	Internal Structures and Bedding Plane Features	Abundance
Upper Intertidal	Medium to coarse siltstone, with minor shale. Sorting moderate to poor.	Ripple laminated, wavy and lenticular bedded. Abundant current ripples. Common asymmetrical wave ripples, and flat-topped and interference ripples. Abundant desiccation cracks and mudflake intraclasts. Common halite casts. Rain-drop imprints and small load structures. Rare marine tracks and trails.	Very common throughout, especially in the upper part of the sequence.
Transitional Environment	Shaly siltstone and silty shale. Sorting is poor.	Poorly bedded to blocky. Some poorly defined wavy bedding. Minor asymmetrical wave and current ripples. Occasional flat-topped and interference ripples. Common small load structures. Abundant desiccation cracks, halite casts, and calcite and quartz replacement after evaporites. Anhydrite preserved in borecore. Minor rain-drop imprints. Rare stromatolitic laminae. Rare marine tracks and trails.	Common throughout. Dominant facies in parts of the Lake Frome borecore.
Alluvial Plain	Shaly siltstone and silty shale. Sorting poor.	Poorly bedded. Blocky. Minor desiccation cracks and evaporites. Absence of trace fossils.	Not positively identified. Presumably rare.

Figure 5-11. Depositional model, Nildottie Siltstone Member.



CHAPTER 6

STRATIGRAPHY AND ENVIRONMENTAL ANALYSIS
OF THE EREGUNDA SANDSTONE MEMBER

Modified from the paper titled

"Deltaic sedimentation - Cambrian of South Australia"

and submitted to *Journal of Sedimentary Petrology*

by the author.

THE STRATIGRAPHY OF THE EREGUNDA SANDSTONE MEMBER

Introduction

Throughout the central Flinders Ranges and in the Mount Scott Range, the upper portion of the Billy Creek Formation is dominated by sandstone (Plate 34). This sandy sequence is herein termed the Eregunda Sandstone Member after Eregunda Creek, which disects the sequence 7km west-nor-west of the Wirrealpa Homestead (Fig. 3-1). The type section (Section BC-B, Figs. 3-1, 4-1 and 4-2) is located in an area of undulatory topography 2.5km north of the Ten Mile Creek. The section corresponds with the upper 107m of Daily's (1956) type section of the Billy Creek Formation.

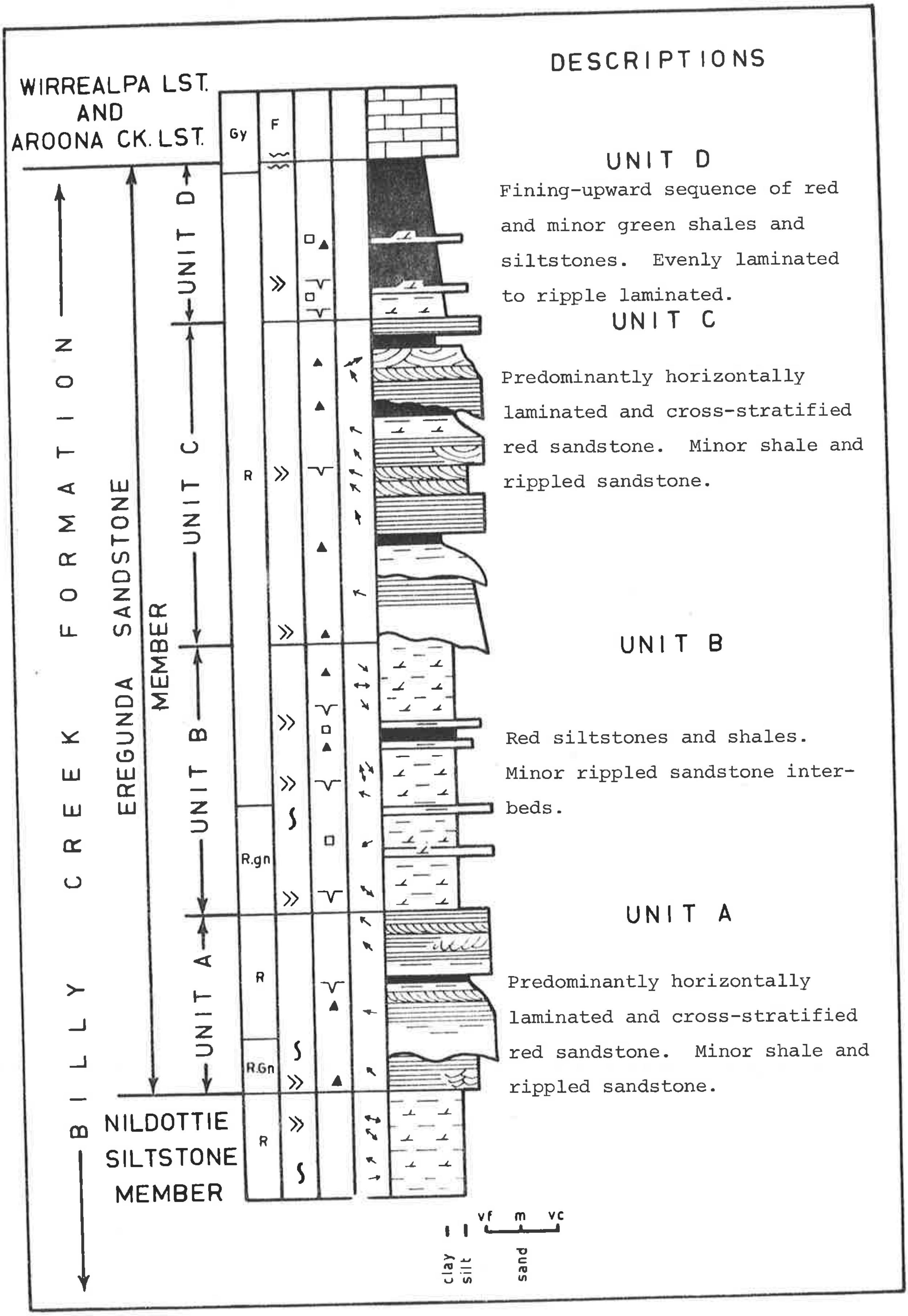
Outcrops of the Eregunda Sandstone Member and positions and thicknesses of principal stratigraphic sections are shown in Figure 4-1. It attains its maximum measured thickness of 166m in section BU-B south of the Bunyeroo Gorge, and becomes progressively thinner towards the north and north-east. It has not been identified in the Delhi-Santos Lake Frome Stratigraphic Wells. It is also absent from Reaphook Hill and Mernmerna, where the upper portions of the Billy Creek Formation are missing, due to post-Cambrian erosion.

The member is divisible into four regionally mappable units (Plate 35; Figure 6-1). Units A and C are dominated by sandstone, whereas Units B and D comprise shale and siltstone, with minor rippled sandstone interbeds. Eighteen stratigraphic sections have been measured in outcrops throughout the Flinders Ranges, and these are briefly summarized in Figure 6-2, and presented in detail in Figure 6-3 (rear pocket).

The Base of the Eregunda Sandstone Member

The Eregunda Sandstone Member rests sharply but conformably on red shales and siltstones of the Nildottie Siltstone Member. In most outcrops, the basal unit of the Eregunda Sandstone Member comprises plane laminated or ripple laminated, red micaceous arkose.

Figure 6-1. Generalised stratigraphy of the Eregunda Sandstone Member Legend as for Figs. 4-2 (p.42) and 6-4 (p.131).



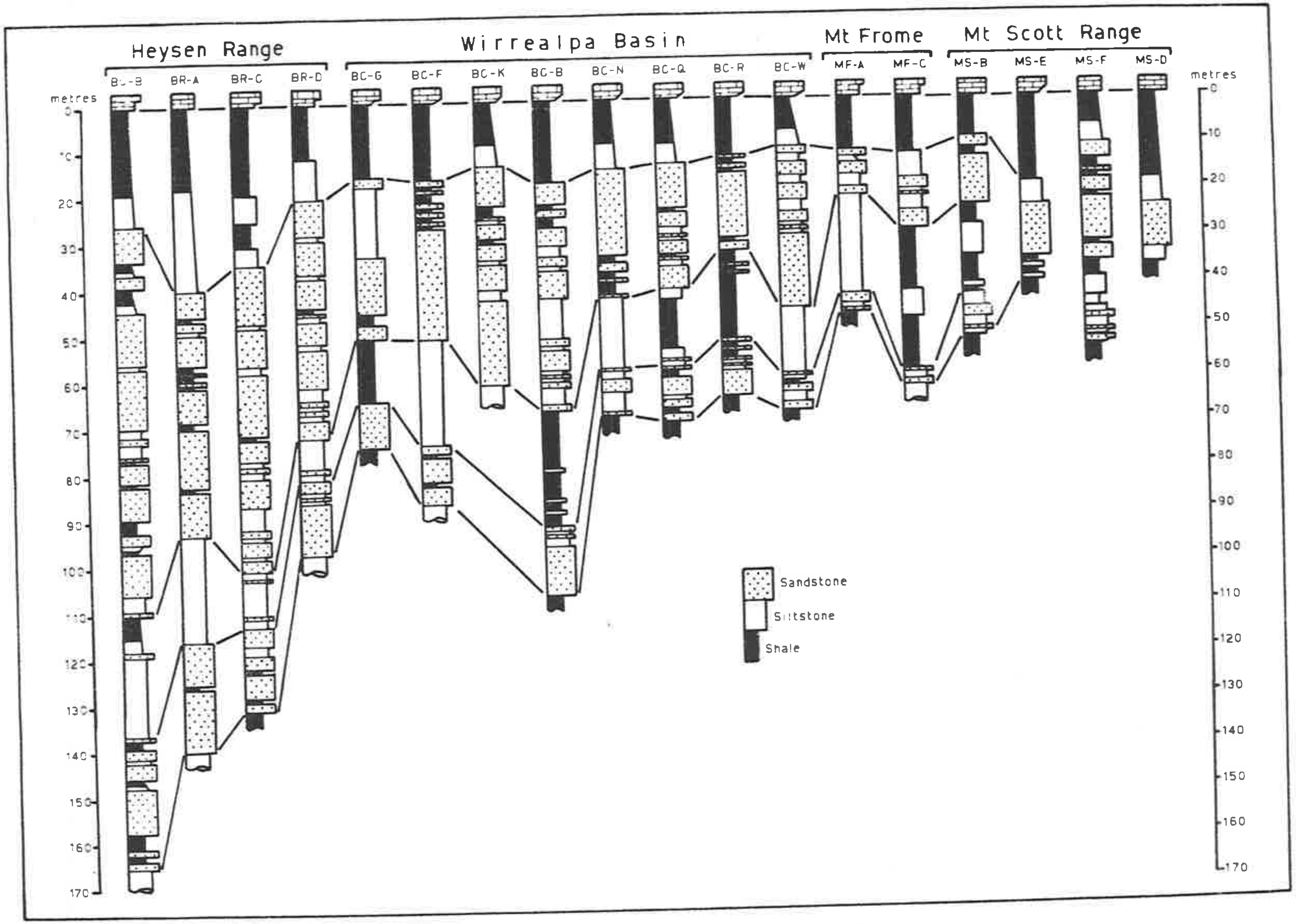


Figure 6-2. Lithology and thickness variation in the Eregunda Sandstone Member.

The Top of the Eregunda Sandstone Member

The Eregunda Sandstone Member is overlain comformably by the Aroona Creek Limestone in the Mount Scott Range, and by the Wirrealpa Limestone in all other outcrops (Plate 36).

The upper portion of the Eregunda Sandstone Member comprises a fining upward sequence from red, ripple laminated coarse siltstone to evenly laminated, fine siltstone and shale. The upper few metres of shale are greyish green, and contain rare carbonate patches and lenses. A transition zone, between 0.2m and 3m in thickness, separates the fine silts and shales of the Eregunda Sandstone Member from the prominently outcropping, well bedded limestones of the overlying formations. The transition zone is characterised by thinly interbedded greyish siltstone and microsparite, which may be dolomitic or develop wavy, algal laminations. This has been chosen by Youngs (1978a) as the basal unit of the Middle Cambrian limestones.

Palaeontology

Tracks attributed to trilobites are common in the Eregunda Sandstone Member, and occur mainly in the fine-grained lithologies. Worm burrows and molluscan trails are common in the Mount Scott Range outcrops, however no body fossils have been found in the member to date.

Regional Variation

The sedimentological characteristics of the sandstone lithologies vary considerably across the region, whereas the finer grained sediments are relatively uniform in character. A feature of the sandy sequences is their lateral variability, and siltstone and shale interbeds cannot be used to correlate stratigraphic sections.

In the Wirrealpa Basin, current lineated sandstones are prominent, and are commonly associated with massive to poorly bedded sandstones and erosional surfaces. In the thicker sections along the Heysen Range, current lineated sandstones are less abundant, and large scale cross-stratified and ripple-laminated sandstones occupy an increased proportion of the sequence. Near Mount Frome and along the Mount Scott Range, ripple laminations are common in the sandstone units, which also contain trilobite tracks and several prominent bioturbated intervals. A general conclusion is that the thicker sequences of the Eregunda Sandstone Member contain a greater proportion of high energy, current laid deposits.

ENVIRONMENTAL ANALYSIS OF THE EREGUNDA SANDSTONE MEMBER

Introduction

Little attempt has been made to interpret the environment of deposition of the Eregunda Sandstone Member, although Pierce (1969) suggested that the sequence in the Wirrealpa Basin possessed deltaic characteristics. In the course of this study it became apparent that two, clearly distinguishable lithological associations are present in the member. The fine-grained deposits contain evidence of marine influence, and were deposited in a low energy, paralic environment. In contrast, the sandstones contain erosional surfaces and abundant, horizontally laminated, current lineated units, indicative of unidirectional, high energy currents.

Sequences showing an intimate association of high and low energy, fluvial and marine-dominated deposition have received little attention in the literature to date, in part because of the scarcity of modern analogues. This study is aimed at evaluating the environment of deposition of the Eregunda Sandstone Member, with emphasis of the roles of water depth and overall basin morphology in the evolution of vertical facies profiles.

Geologic Setting

In all outcrops, the Eregunda Sandstone Member is underlain by red shales and siltstones of the Nildottie Siltstone Member (Fig. 4-1), which were deposited in a paralic environment (Daily, 1976b). The siltstones contain distinctive, very low energy wave and tidal features, and were probably deposited on a very gentle palaeoslope. Red-bed sedimentation of the Eregunda Sandstone Member was terminated in the Middle Cambrian by a brief marine transgression associated with carbonate deposition in a shallow intracratonic basin (the Wirrealpa and Aroona Creek Limestones; Youngs, 1978a, 1978b).

Facies Analysis

Introduction

The Eregunda Sandstone Member can be divided into seven facies, which represent unique combinations of lithology, sedimentary structures and organic features (Fig. 6-4). The approach used in this study is similar to that adopted by Cant and Walker (1976) in the development of the Battery Point Sandstone braided-fluvial model. Twenty one stratigraphic sections from the Eregunda Sandstone Member were divided into facies and subjected to Markov chain analysis. Four of the sections which summarize the facies variations throughout the region are examined in detail. Facies codes are based on a scheme designed by Miall (1977) and modified by Rust (1978) and Miall (1978).

Sandstone Facies

Sandstones are dominantly fine- to very fine-grained, red micaceous arkoses and minor subarkoses.

Sandstone facies (with intraclasts) with basal scour surface - Facies Se

Identical to facies SS of Cant and Walker (1976, p.104), the sandstone facies with a basal scour surface (Se) comprises an erosional surface overlain by massive to poorly bedded sandstone up to 4m in thickness and averaging 0.8m (Plate 37). Maximum depth of erosion on scour surfaces in the Eregunda Sandstone Member is about 2.5m at Balcoracana Creek in the Wirrealpa Basin (Plate 38). Red shale or siltstone intraclasts, up to 15cm across, are commonly present on the scoured surface. The scour surface has load casts, with sandstone pseudonodules developed in rare cases. Flute casts may also be present.

The scours represent prominent distributary channels, formed by

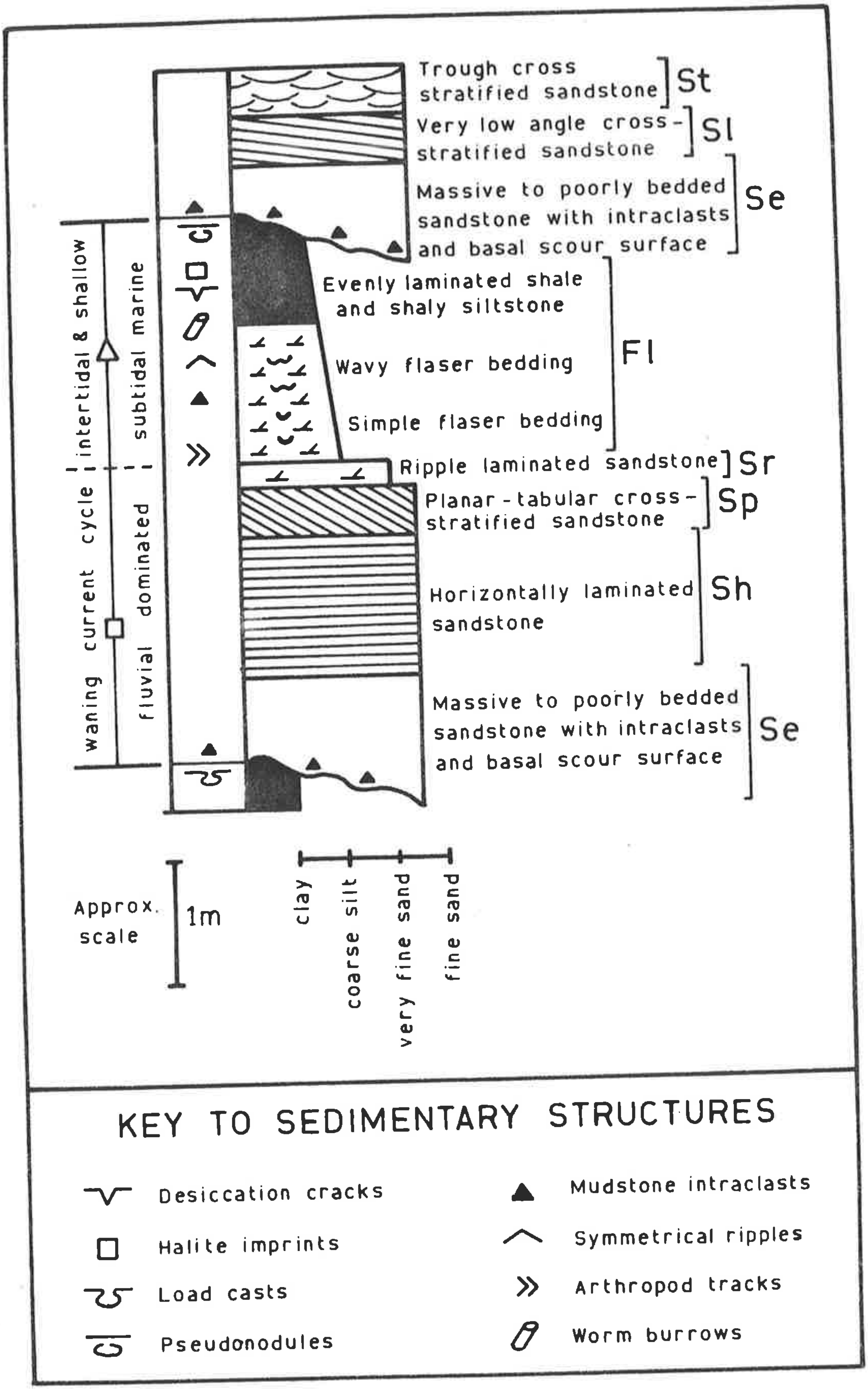


Figure 6-4. Key to sedimentary structures, lithologies and facies symbols for the Eregunda Sandstone Member. An ideal fining-upward cycle is also shown.

avulsion or bar dissection, as described by Collinson (1970), Williams and Rust (1969) and Miall (1977). The channels are infilled with a variety of sandy facies or rarely shale, and thus were not simultaneously cut and infilled. Mudstone intraclasts at the base of channels represent lag conglomerates. The associated poorly bedded to massive sandstone was probably deposited rapidly under high current velocities (Reineck and Singh, 1975, p.113; Middleton, 1977, p.4). A high sediment concentration in the initial flow is inferred.

Horizontally laminated sandstones - Facies Sh

Facies Sh comprises horizontally laminated and current lineated, greyish red fine- to very fine-grained sandstone, in units up to 2m in thickness (Plates 38 and 39). Laminae are typically defined by concentrations of mica, although heavy mineral bands are also present.

The abundance of current lineation in facies Sh (Plate 40), and the common upward transition into large scale tabular cross-stratification suggest that much of the planar laminated sandstone was deposited during upper regime flow.

Harms *et al.* (1975, p.50) note that "parting lineation is known to be associated with upper flat-bed lamination; it has not been demonstrated within lower flat bed deposits". The formation of horizontal lamination in the Eregunda Sandstone Member was primarily favoured by the fine grain-size of the sediment (Harms *et al.*, 1975, Fig. 2-5) and possibly assisted by deposition in very shallow water (Willis *et al.*, 1972; Smith, 1971b). McGowen (1971) has attributed an abundance of horizontal lamination in the Gum Hollow fan delta to extensive longitudinal bar formation during ephemeral flooding.

Planar - tabular cross - stratified sandstones - Facies Sp

Facies Sp comprises medium to high angle sets of tabular cross-stratification, which range in set thickness from 0.2-1.0m and average 0.6m (Plate 41). The most common type of tabular unit is alpha cross-stratification (Plate 42) (terminology of Allen, 1963), with foreset laminae defined by minor grain-size variations from fine- to very fine-grained sandstone, or by concentrations of mica. The contact between foreset and bottomset laminae is typically tangential. Beta cross-stratification, with planar erosional bases, and gamma cross-stratification, with irregular scoured bases are uncommon. Multiple sets of tabular cross-stratification (omikron cross-stratification) with asymptotic foreset laminae are rare.

The planar-tabular cross-stratification is attributed to migration of sand waves (Harms and Fahnestock, 1965; Harms et al., 1975) or transverse bars (Smith, 1972). Graded foreset laminations are produced by continuous avalanching at bar margins of sediment previously sorted by small scale bedforms on the bar surface. Strongly asymptotic foresets are common and are due to the development of a strong separation eddy during flood stage (Collinson, 1970).

Trough cross-stratified sandstones - Facies St

Facies St is composed of poorly defined sets of trough cross-bedding (pi cross-stratification of Allen, 1963) and larger, solitary troughs (theta cross-stratification; Plate 43). Generally, trough cross-stratification comprises multiple, intersecting troughs, averaging 20cm in depth and 1.2-2.0m in width. Sets are composed of fine to very fine sandstone, which may show slumping down the cross strata. Both the single and multiple intersecting sets of trough cross-stratification are attributed to the migration of dunes (Collinson, 1970; Harms et al., 1975), synonymously, mega-ripples (Williams, 1971; Singh and Kumar, 1974).

Ripple laminated sandstones - Facies Sr

Facies Sr comprises various types of ripple laminated, greyish red, fine-grained micaceous sandstones. Rippled sandstones occupy a minor portion of the Wirrealpa Basin and Heysen Range sequences, but are more common in the Mount Scott Range and at Mount Frome.

Three basic types of ripple laminated sandstone (Facies Sr) are present in the Eregunda Sandstone Member. The first type overlies tabular cross-stratification (Facies Sp) and occurs as an 8-15cm thick unit of ripple-laminated sandstone, with linguoid ripples preserved on the upper surface (Plate 44). The ripples are very irregular in form, with an average wavelength of 15cm and amplitude of 6cm. They are interpreted as bar- and dune-top, waning current bedforms.

The second type of Facies Sr occurs as 10-25cm thick units of evenly bedded to ripple laminated sandstone, interbedded in silty or shaly sequences (Plate 45). The sandstones are commonly lenticular over five or more metres, and may have abundant load structures at the base. Climbing ripple laminations (Plate 46) are rare. The sandstones are commonly burrowed (Plate 47) with minor arthropod tracks and molluscan trails. They are interpreted as crevasse splay deposits.

The third type of Facies Sr is particularly common in the Mount Scott Range and at Mount Frome. It comprises continuously rippled (nu cross-stratified), greyish red, micaceous sandstone, laminated in units up to several metres in thickness (Plate 48). Bedding surfaces are characterised by well developed rib and furrow structures (Stokes, 1953; Pettijohn, 1975, p.109). Tracks attributed to trilobites are common. The rib and furrowed sandstones commonly overlie current lineated units (Facies Sh), and grade upwards into ripple laminated siltstones and shales of Facies Fl. The rib and furrowed sandstones represent constant reworking of sand in the marine environment.

Very low angle cross-stratified sandstones - Facies Sl

Facies Sl is difficult to distinguish from horizontally laminated sandstones of Facies Sh, and has been recorded from only a few areas with excellent outcrop. It comprises very low angle cross-stratified sandstone, with abundant parting lineation and rare current crescents. Original dips are less than 10 degrees. The sandstones are greyish red, fine to very fine-grained, and abundantly micaceous. The wedge-shaped sets of Facies Sl generally occur in sequence with other high energy sandstone deposits

(Facies Se, Sh and Sp) and are laterally continuous (up to 10m) over the width of the outcrop. By analogy with similar deposits described by Cant and Walker (1976) and Rust (1978), Facies Sl is interpreted as representing deposition of planar laminated sand in shallow scours.

Fine-Grained Facies

Siltstones are also arkosic, however they contain a greater percentage of mica and clay minerals than their coarser-grained equivalents.

Rippled and evenly laminated mudrocks - Facies Fl

Facies Fl is dominated by rippled and evenly laminated, micaceous, coarse siltstone with minor mudstone drapes and interbeds (Plate 49). The sediments are mostly dark greyish red in colour although some secondary reduction to greyish green and pale olive has occurred. Stratification is on the scale of a few centimetres to a few millimetres. Coarse-grained units are generally evenly laminated, with laminae defined by abundant mica. However, much of the sequence is ripple laminated, either as multiple intersecting small troughs (nu cross-stratification of Allen, 1963), or as very poorly developed flaser bedding. Both simple and wavy flaser bedding (Reineck and Wunderlich, 1968) are represented. With increasing clay content, rippled siltstones are transitional into evenly laminated shales and mudstones (Plate 50).

Ripples are commonly preserved on bedding plane surfaces, typically as very continuous, symmetrical to slightly asymmetrical, low sinuosity forms with a wavelength of 1-3cm and a wave height of 4-12mm. The facies is also characterised by abundant tracks and scratch marks attributed to trilobites (Plate 51). Polygonal desiccation cracks up to 0.2m across, halite casts up to 8mm across, mudstone intraclast horizons and soft sediment deformation structures are common in some outcrops. Irregular, elongate patches of sparry calcite and quartz-lined geodes are uncommon.

The intimate association of marine trace fossils and desiccation features indicates that facies Fl was deposited in a shallow marine, commonly intertidal, environment. Evidence for tidal activity is the bipolar palaeocurrent distribution pattern (described below) and the close association of wave and current ripples, desiccation cracks, mudflake intraclasts, halite pseudomorph casts and marine trace fossils. In addition, very poorly defined simple and wavy flaser bedding are similar in character to structures in Recent, fine-grained tidal deposits from the Gulf of California (Thompson, 1968, 1975). Silt-streaked, evenly laminated shales comparable with the fine-grained portions of Facies F1 are described by Shepard and Moore (1955) and Moore and Scruton (1957) from shallow bay environments near river mouths in the central Texas gulf coast.

Markov Chain Analysis

With twenty one stratigraphic sections, and up to seven facies represented in each section, a large amount of data is available for analysis. In addition, four sections were analysed separately, and these illustrate regional variations in the data. The four representative sections were chosen because of their widely spaced geographic localities and good, continuous outcrop. They are presented in Figures 6-5 and 6-6 and their locations are shown in Figure 6-8.

Fining-upward sequences are abundant in the Wirrealpa Basin outcrops, and can be recognised elsewhere. Thus, a cyclicity in the vertical facies distribution is suggested, and the sequence lends itself to Markov chain analysis. A markov process is one "in which the probability of the process being in a given state at a particular time may be deduced from knowledge of the immediately preceding state" (Harbaugh and Bonham-Carter, 1970, p.98). The application of Markov chain analysis to geological successions is discussed by Miall (1973).

Using Markov chain analysis, diagrams may be constructed showing all the facies changes that occur much more frequently than random. These 'facies flow charts' are shown in Figure 6-7. The charts represent only a summary of the available data, and omit those transitions which occur on a statistically random basis or less commonly.

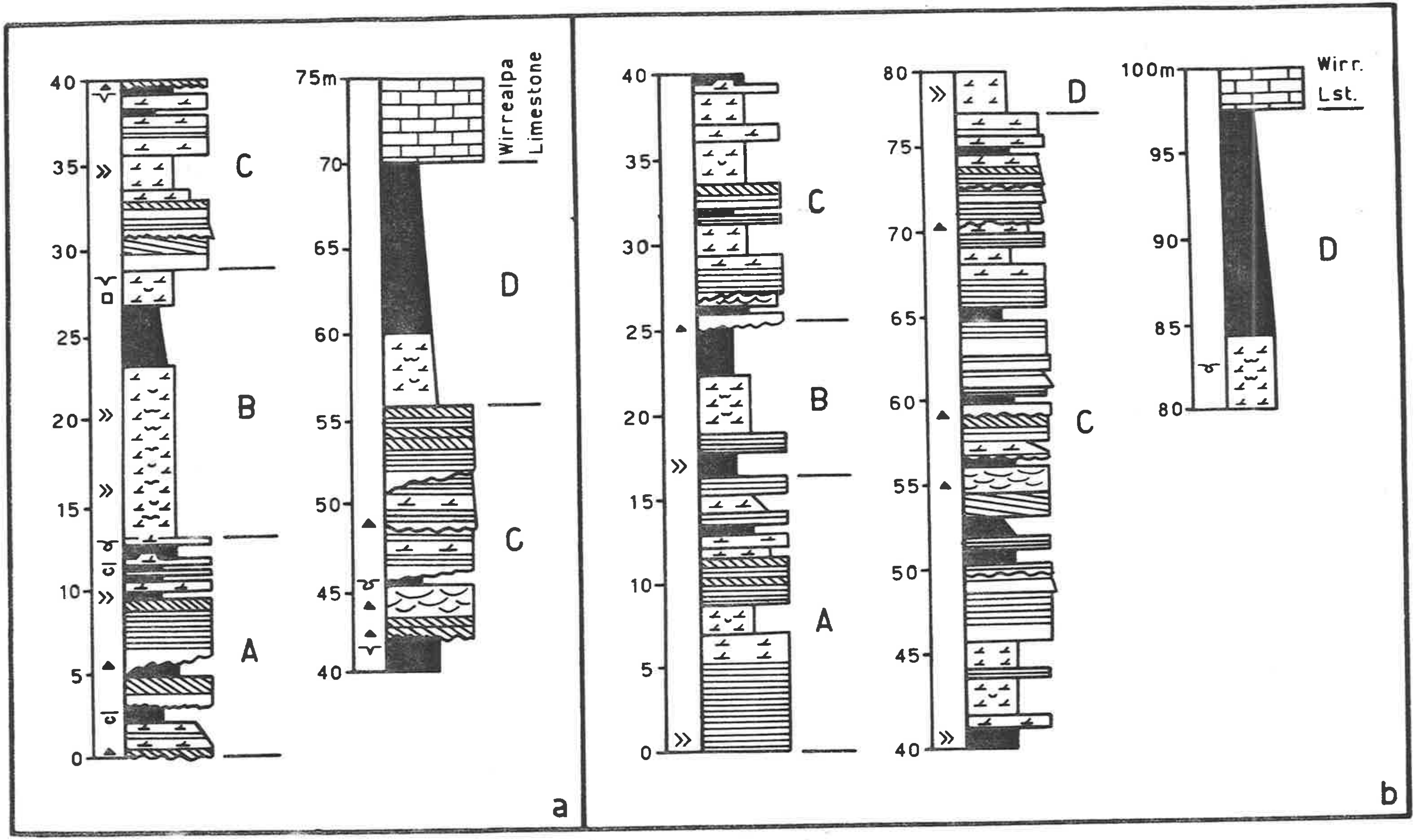


Figure 6-5. Stratigraphic sections, Eregunda Sandstone Member. A: Section BC-Q, in Balcoracana Creek (Wirrealpa Basin). B: Section BR-D, 14km north of Brachina Gorge (Heysen Range). Location of sections is shown in Fig. 6-8(p.144).

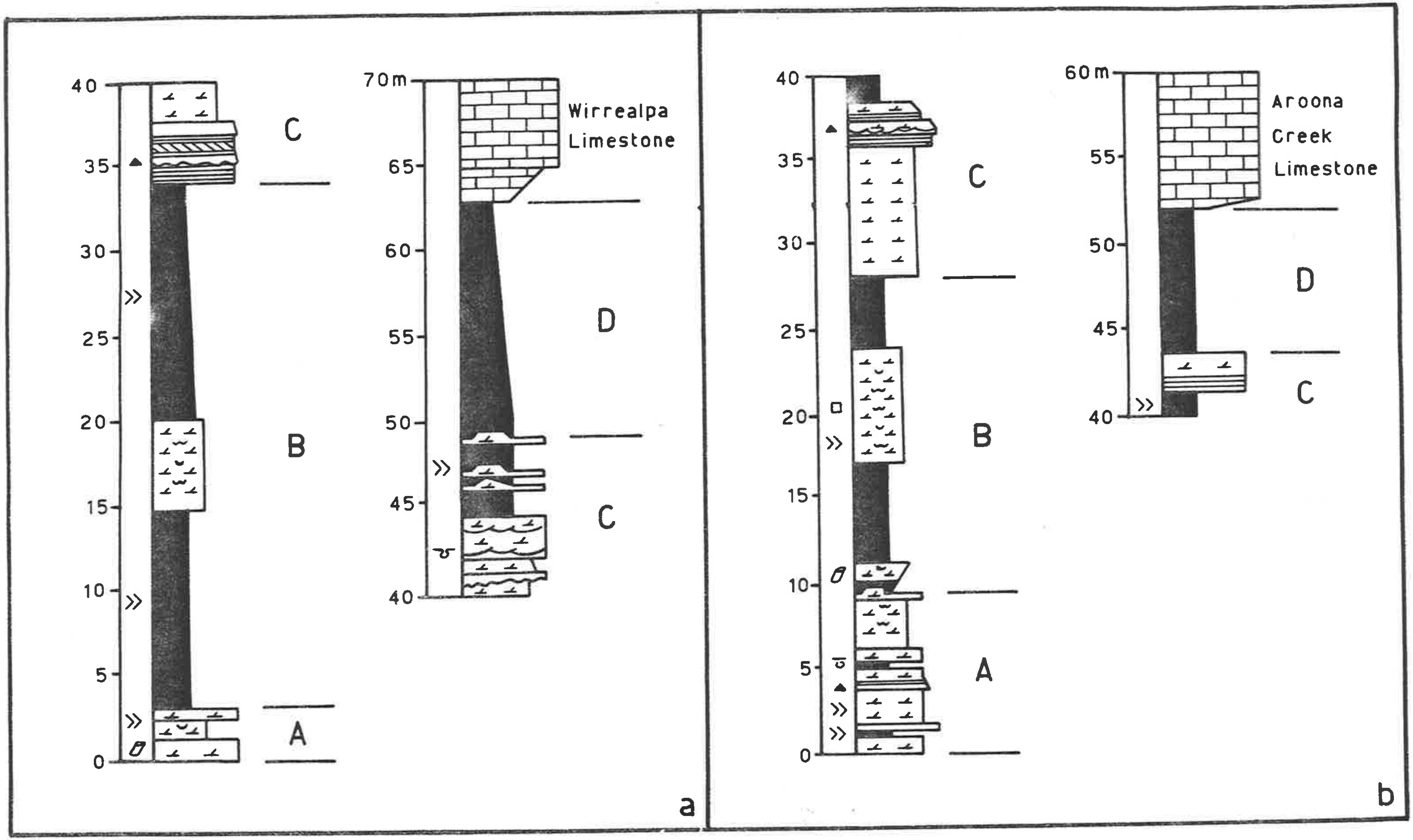


Figure 6-6. Stratigraphic sections, Eregunda Sandstone Member. A: Section MF-C, near Mount Frome. B: Section MS-B, Mount Scott Range. Location of sections is shown in Fig. 6-8 (p.144).

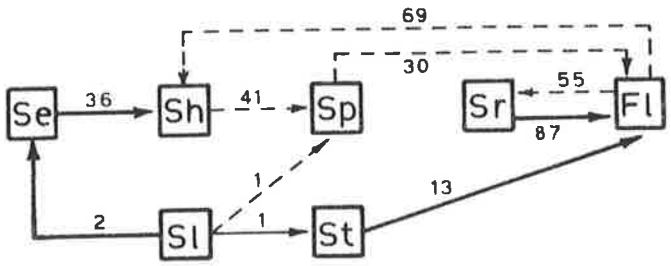
Grouped data (all 21 sections)

Two distinctive overall facies associations are present in the Eregunda Sandstone Member (Fig. 6-7a). The first association comprises massive, plane laminated and cross-stratified sandstones, which have scoured into the underlying sediment in some cases. The major feature of this association is the vertical superposition of Facies Se, Sh and Sp, indicating an initial phase of channeling (Se) followed by a transition from upper to lower flow regime (Simons et al., 1965). For some cycles, this transition may reflect waning flow associated with a single flood (McKee et al., 1967). More commonly however, the cycles represent lateral migration of bedforms in braided, sandy channels, causing the progradation of lower flow regime transverse bars (facies Sp) over horizontally laminated, current lineated sandstone (facies Sh), deposited by upper regime flow in the more active parts of the channel. The absence of very large scale bedforms is attributed to the fine grain-size of the available sediment.

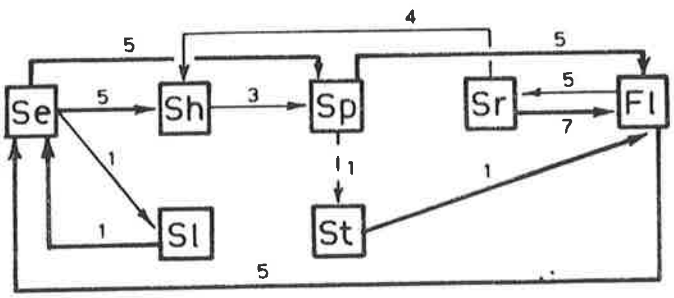
The second association is the fine-grained facies association (Fl), which is characteristically shallow marine to intertidal in origin. The rippled sandstone interbeds (facies Sr) probably represent minor inputs of terrestrially-derived sand, deposited in shallow channels (crevasse splay deposits) or as vertical accretion (levee) deposits.

In order to evaluate the sediment transport mechanisms involved in the evolution of the sequence, several fining-upward cycles were examined from the Ten Mile Creek section in the southern portion of the Wirrealpa Basin. Grain-size analyses, based on the techniques described by Freidman (1958, 1962), indicate that facies Se, Sh and Sp have similar textural characteristics: average very fine-grained sand, moderately well sorted, fine skewed. Thus, the fining-upward portions of the cycles are restricted to facies Sr and Fl. However, the stratification types and thicknesses of the sandstones and the presence of intraclasts suggest that the currents were capable of transporting quite coarse detritus. Consequently, the grain-size limit of fine-grained sand in the Eregunda Sandstone Member probably repre-

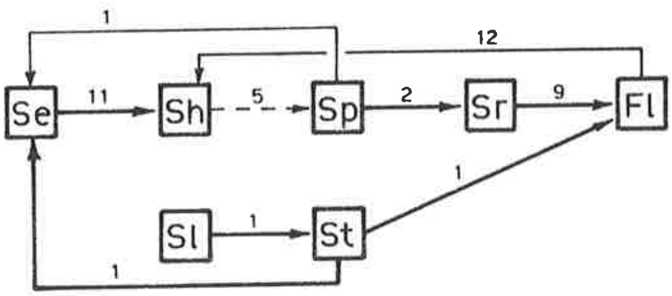
Figure 6-7. Facies sequence diagrams, Eregunda Sandstone Member. Only statistically significant transitions are shown. Thick arrows indicate observed minus random transition probability greater than 0.2. Thin unbroken arrows indicate a probability between 0.1 and 0.2 Thin, dashed arrows indicate a probability between 0.05 and 0.1. Numbers above the arrows indicate the number of transitions observed.



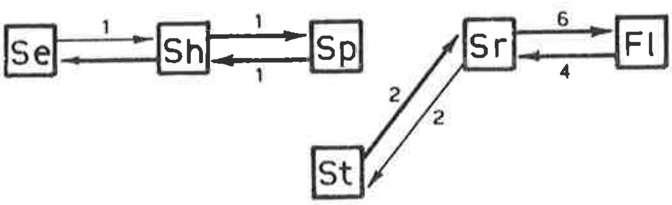
(a) All areas (21 sections, 655 transitions)



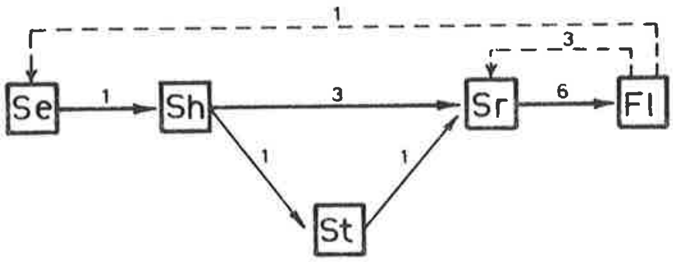
(b) Wirrealpa Basin (Section BC-Q, 58 transitions)



(c) Heysen Range (Section BR-D, 83 transitions)



(d) Mount Frome (Section MF-C, 26 transitions)



(e) Mount Scott Range (Section MS-B, 21 transitions) sents the maximum size of detritus available in the source area. A similar example of this type of grain-size limitation occurred in the Bijou Creek floods of 1965 (McKee et al., 1967).

Wirrealpa Basin sections

Outcrops in the Wirrealpa Basin contain well developed fining-upward cycles which are commonly associated with prominent channels. Section BC-Q is a typical example and a facies sequence diagram for this section is presented in Figure 6-7b. The facies sequence Se → Sh → Sp is very well defined and represents a period of initial channeling, followed by strong but constantly decreasing currents typical of flood deposits (Miall, 1977, p.38). The interbedded fine-grained facies (Sr and Fl) are interpreted as intertidal mudflat deposits.

Heysen Range sections

A facies sequence diagram for Section BR-D, north of Brachina Creek in the Heysen Range, is presented in Figure 6-7c. The section typifies the Eregunda Sandstone Member lithofacies in the Heysen Range outcrops. The transition Se → Sh → Sp is still apparent, but not as well developed as for the Wirrealpa Basin outcrops. Not all cycles have a scoured base, and sequences commonly start with non-erosional, horizontally laminated, current lineated sandstone of facies Sh. This lack of well developed channels suggests that the currents which deposited the sequence did not have the erosive capacity of those responsible for the Wirrealpa Basin sequences. Furthermore, tabular and trough cross-stratification are much more common in the Heysen Range sections and this factor is attributed to the greater abundance of current activity in the lower flow regime. Thus, the Heysen Range outcrops appear to represent deposition in a lower energy environment and a relatively more distal environment with respect to the terrigenous sources area than the Wirrealpa Basin outcrops.

Mount Frome sections

A facies sequence diagram for Section MF-C is presented in Figure 6-7d. Cycles may start with either shallow, scoured surfaces or horizontally laminated sandstones. Facies Se, Sh and Sp are closely associated, but cycles are poorly defined. Instead, the sequence appears to represent the migration of various bedforms in poorly defined, shallow channels under the influence of weak currents. Burrows and trilobite tracks associated with some of the rippled sandstones indicate that the sand was deposited in a marine environment.

Mount Scott Range sections

A facies sequence diagram for Section MS-B is presented in Figure 6-7e. Rib and furrowed sandstones (Facies Sr) are prominent in the Mount Scott Range outcrops and these, combined with an abundance of organic markings, suggest that the environment of deposition was dominantly low energy, shallow marine to intertidal. This helps to explain the poorly developed cyclicity in the sequence, as typified by Section MS-B.

Conclusions

The markovian characteristics of the member are largely a result of fining-upward, waning-current cycles, 1-5m in thickness (typically 1.5-2.0m). Such cycles are best developed in the Wirrealpa Basin, where they reflect a strong fluvial influence. In outcrops to the north (Mount Scott Range) and northeast (Mount Frome) where flood deposits are less apparent, cyclic sedimentation is either poorly expressed or absent.

Palaeocurrent Analysis

Introduction

Palaeocurrent data have been collected from the Eregunda Sandstone Member at many localities throughout the Flinders Ranges, and nearly 800 measurements of wave- and current-formed structures were made. Standard techniques for measurement and correction of data were used, based on Potter and Pettijohn (1978). Palaeocurrent directions in the underlying Nildottie

Siltstone Member are strongly bipolar, with ripple crests orientated approximately north-northeast to south-southwest, parallel to the strike of the inferred regional palaeoslope (Chapter 5). No palaeocurrent data are available from the overlying Aroona Creek and Wirrealpa Limestones, and Youngs (1978a, 1978b) based her palaeogeographic reconstructions for these formations mainly on petrological evidence.

Palaeocurrent data for the Eregunda Sandstone Member are summarized in Figure 6-8 and presented in detail in Figures 6-9 to 6-12. Only the mean orientation of data sets (15 degree sectors) are presented, but where the data sets are polymodal an attempt has been made to recognize individual modes and present them separately. This method of palaeocurrent analysis is described by Kelling (1969) and Akhtar and Srivastava (1976). Palaeocurrent directions obtained from major bedforms in the Eregunda Sandstone Member indicate predominantly unimodal transportation, with currents flowing from the southeast or south-southeast, presumably down the regional palaeoslope.

Wirrealpa Basin, Heysen Range and Mount Frome localities

Flute casts and current crescents associated with the fining-upward, sandy sequences indicate flow to the northwest and north-northwest, with a moderate spread about this mean. A northwesterly transport direction is supported by the orientation of tabular cross beds and current ripples. Trough cross-stratification indicates sediment movement commonly at high angles to the mean transportation direction. The palaeocurrent distribution however, cannot be explained entirely in terms of transportation during alluvial flooding. In the north of the Wirrealpa Basin and along the Heysen Range, a few tabular cross bed orientations indicate transportation to the east and south. These are interpreted as representing shoreward and longshore reworking of sand by marine processes.

In the finer-grained sediments interpreted as dominantly intertidal deposits (Facies F1), ripple orientations indicate transportation predominantly to the west and northwest, with minor longshore- and shoreward

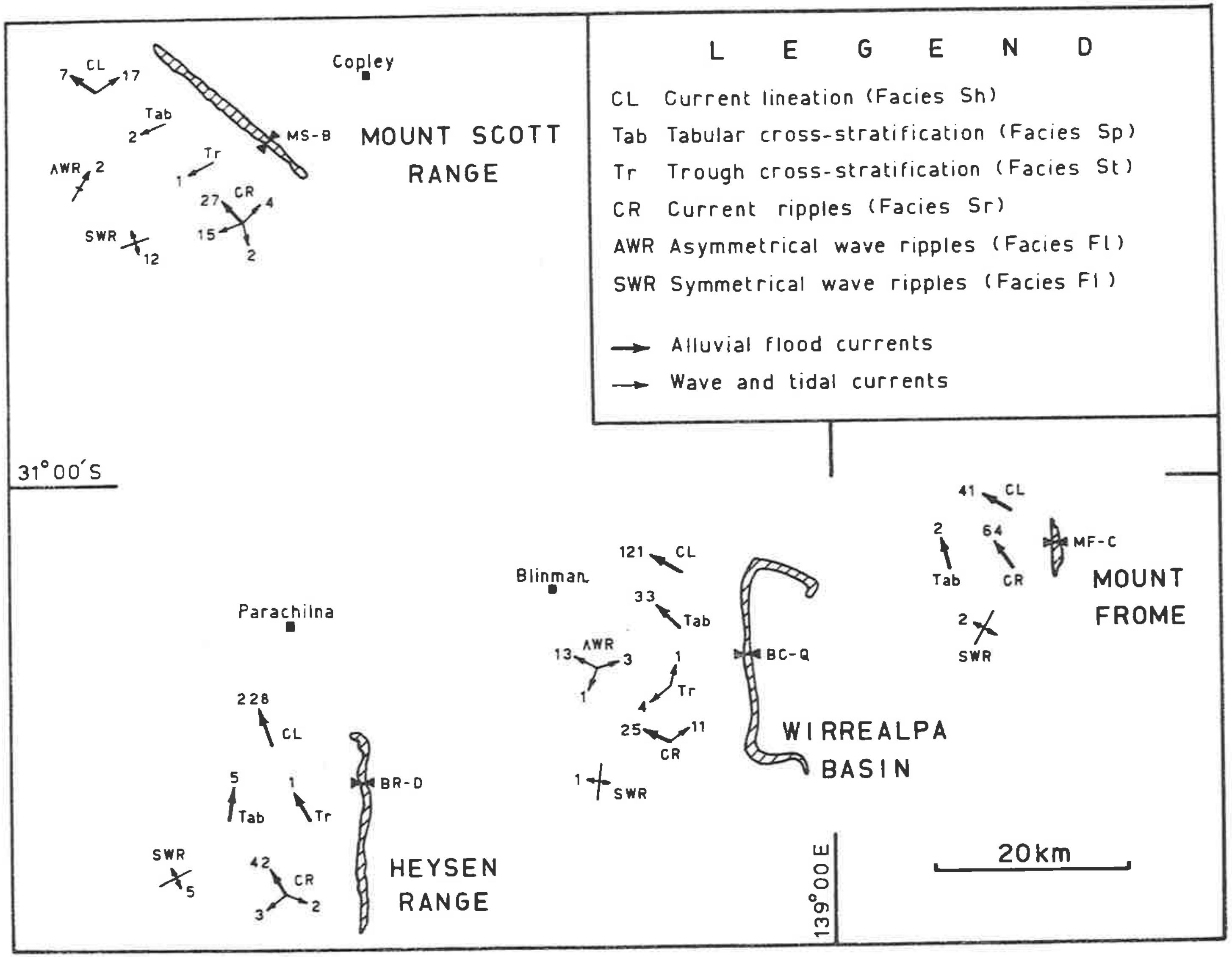


Figure 6-8. Palaeocurrent data, Eregunda Sandstone Member. Arrows represent major palaeocurrent modes. Recognition of the various modes is based on the technique described by Kelling (1969).

Figure 6-9. Palaeocurrent rose diagrams, Eregunda Sandstone Member, Wirrealpa Basin. N = number of data. $\bar{x}$ = mode. L = vector length.

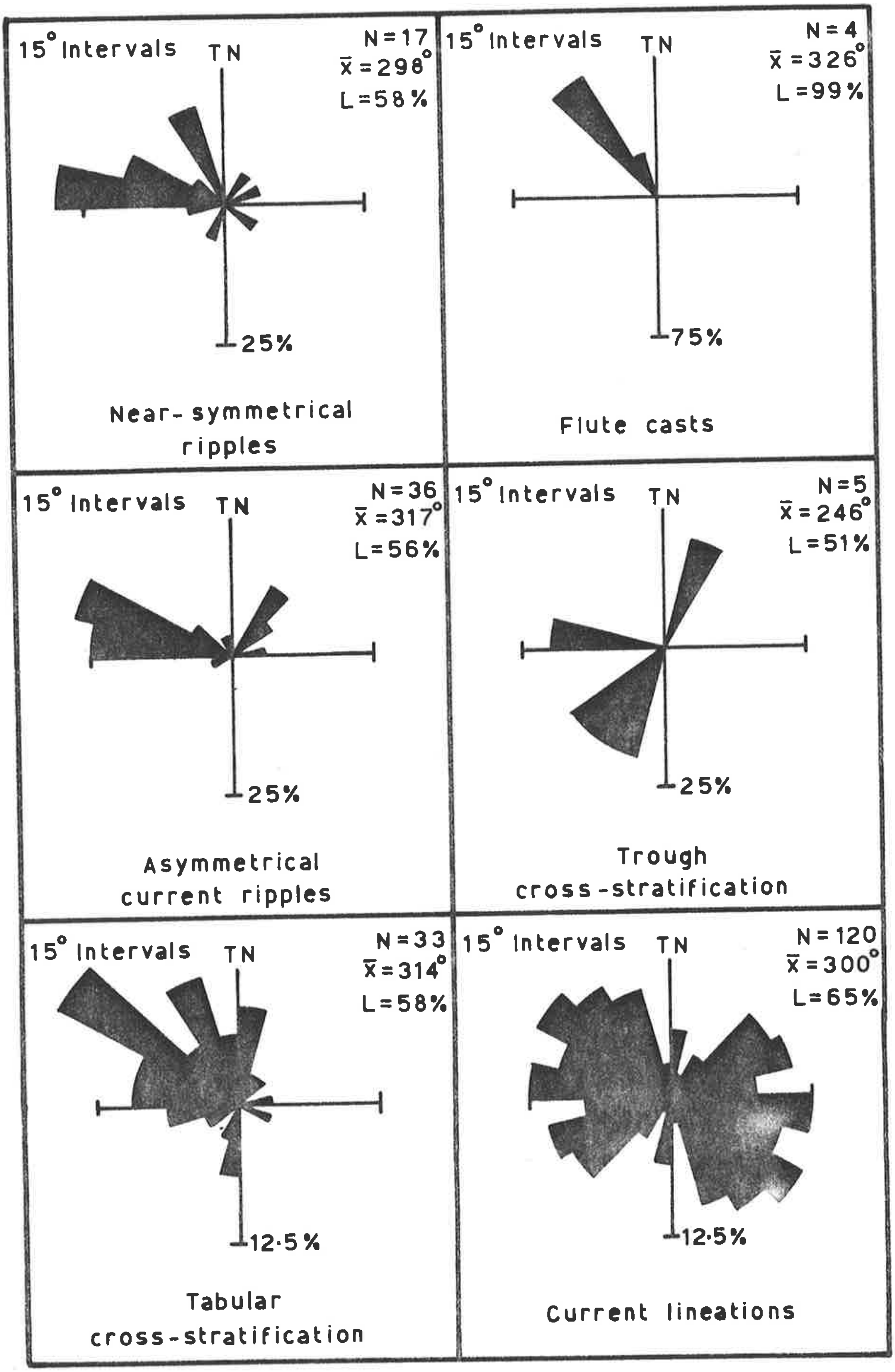
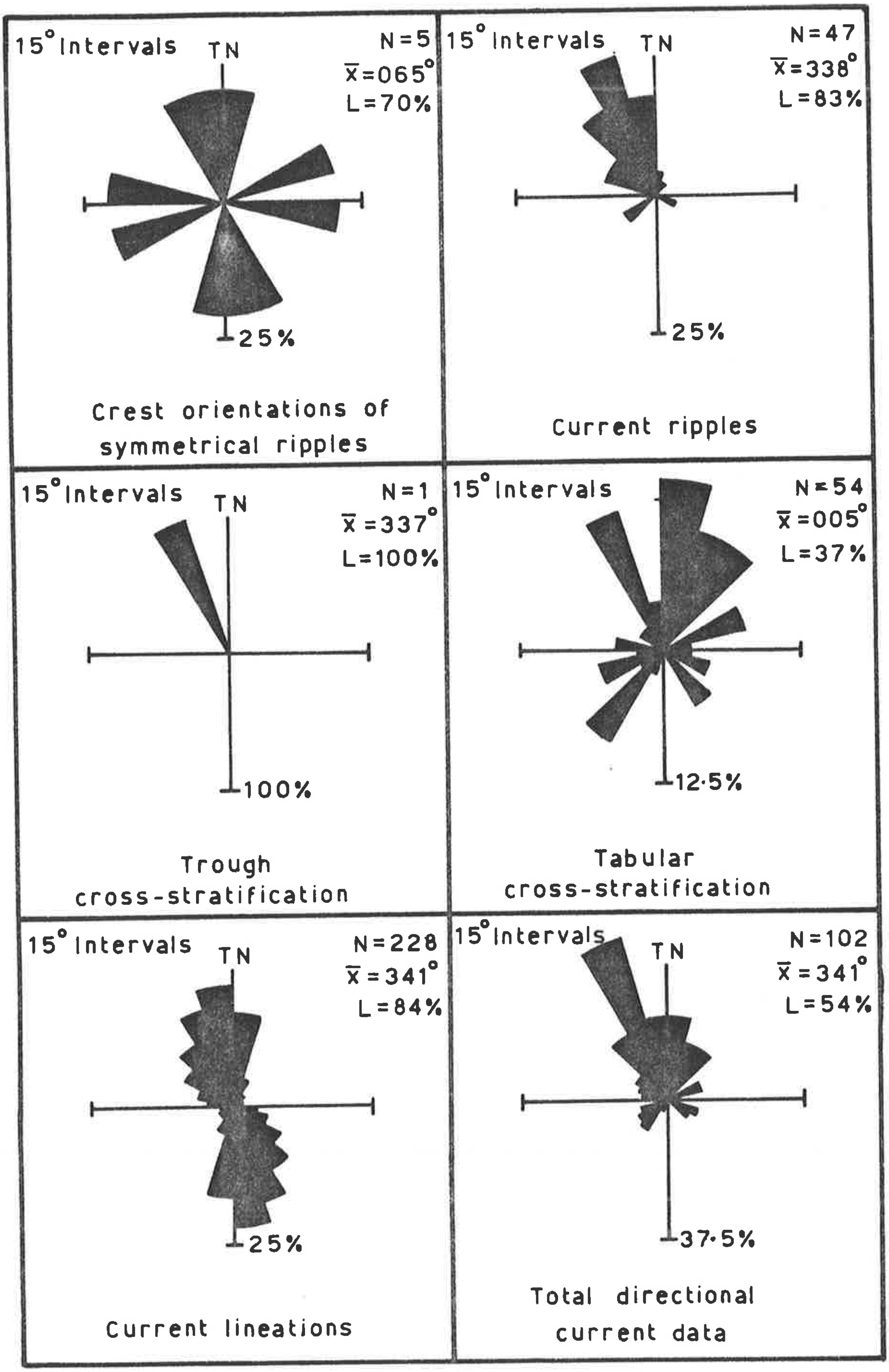


Figure 6-10. Palaeocurrent rose diagrams, Eregunda Sandstone Member, Heysen Range. N = number of data, $\bar{x}$ = mode, L = vector length.



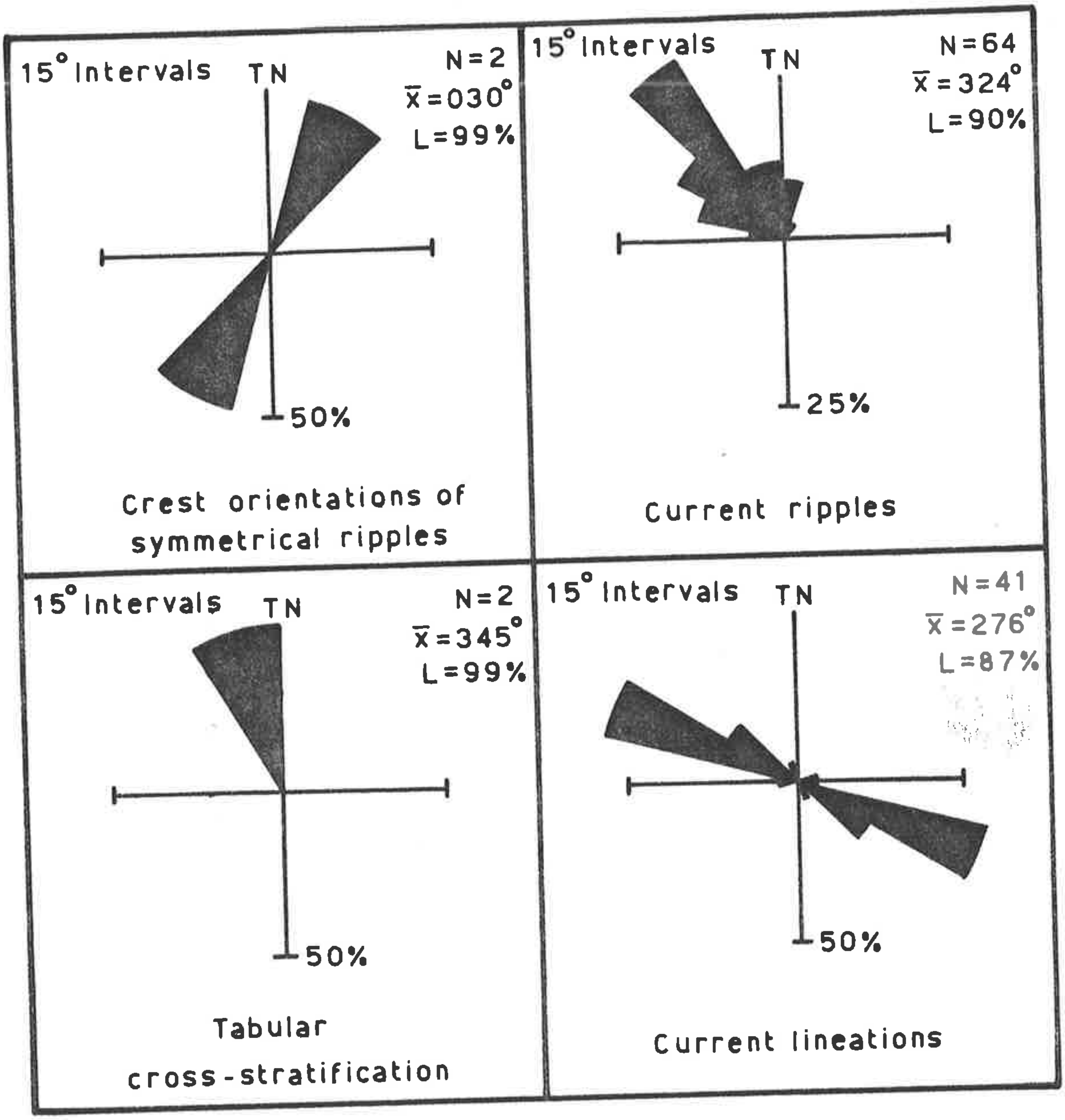


Figure 6-11. Palaeocurrent rose diagrams, Eregunda Sandstone Member, Mount Frome. N = number of data, $\bar{x}$ = mode, L = vector length.

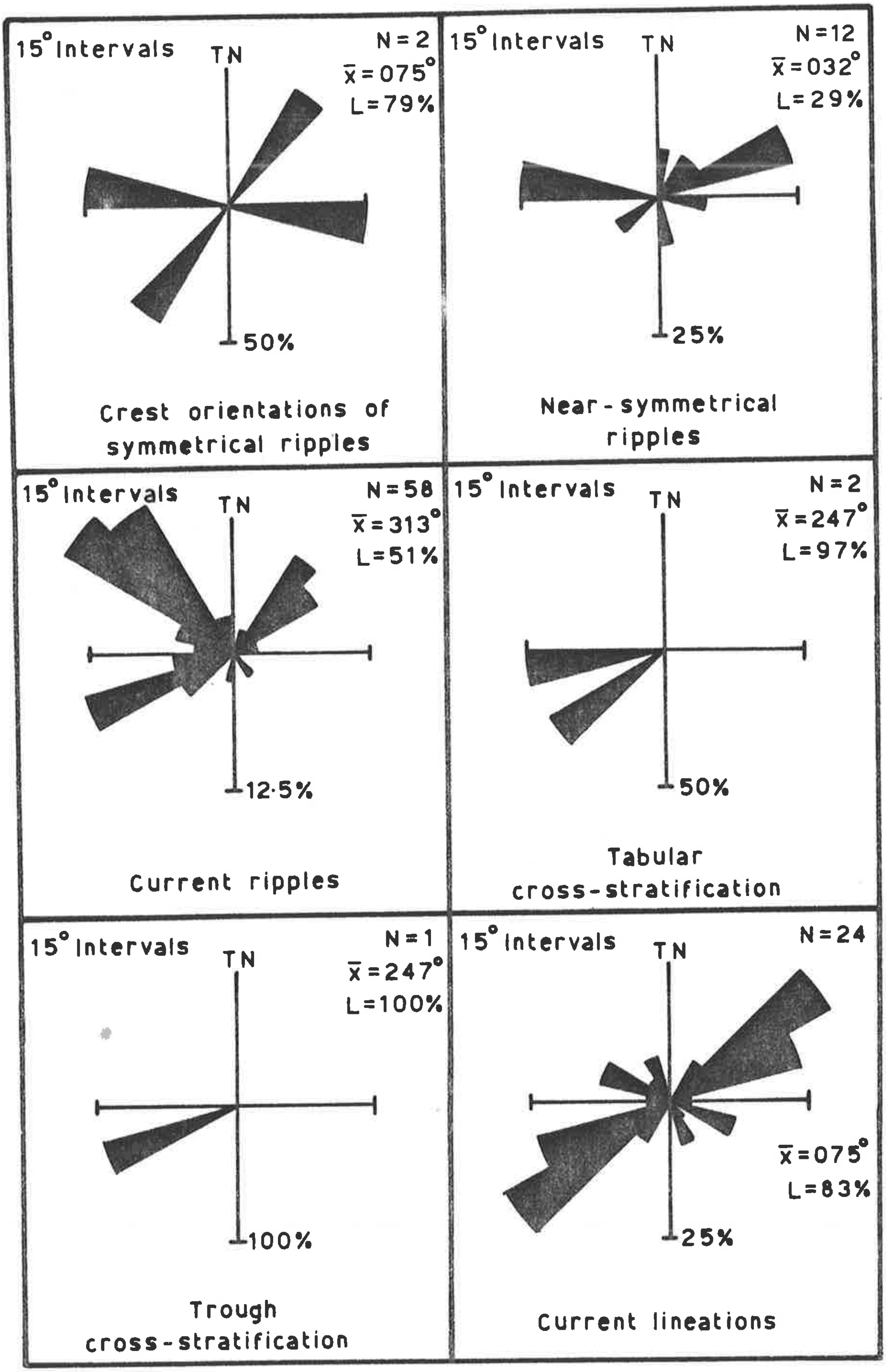


Figure 6-12. Palaeocurrent rose diagrams, Eregunda Sandstone Member, Mount Scott Range. N = number of data, $\bar{x}$ = mode, L = vector length.

orientated directions. The near-symmetrical ripples possess all the characteristics of asymmetrical, wave-generated structures (Tanner, 1967; DeRaaf et al., 1977), and probably result from the interaction of currents (either tidal or fluvial) and waves (Reineck and Singh, 1975). Their predominantly offshore orientation indicates the prevalence of ebb tidal or (less likely) rip currents, possibly assisted by fluvial discharge.

Mount Scott Range

A rather unusual palaeocurrent distribution is present in the Mount Scott Range outcrops of the Eregunda Sandstone Member. On the basis of near-symmetrical ripple crest orientations in the Billy Creek Formation at this locality, a palaeoslope strike of northeast-southwest is inferred. Thus, from Figure 6-8 it is apparent that a strong tendency is for current-orientated structures to be aligned subparallel to the ancient shoreline.

Current lineated, horizontally laminated sandstones (Facies Sh) occur as thin units, typically overlain by ripple laminated (rib and furrowed) sandstone (Facies Sr). The orientation of current lineations and their associated crescents indicates derivation of sand predominantly by longshore migration from southwest to northeast, with a minor fluvio-deltaic influence from the southeast. The overlying rib and furrowed sandstone also indicates a prominent, northeasterly directed, longshore transport component.

DEPOSITIONAL MODEL

The finer-grained sediments of the Eregunda Sandstone Member contains both marine trace fossils and desiccation cracks, and thus are shallow marine to intertidal. Although some of the sandstone units contain trace fossils and shoreward-orientated cross-stratification indicative of deposition in a marine environment, in general they are characterised by a predominantly unimodal transportation system, with abundant current lineated, horizontally laminated units. Thus, they possess many fluvial characteristics. A consideration of all these features leads to the conclusion that the Eregunda Sandstone Member represents a shoreline to marginal marine deposit.

Although the intimate interbedding of channeled, current-laid sandstones and marginal marine siltstones and shales is indicative of a fluvial-dominated, deltaic environment, the classical subdivision of deltas into topset, foreset and bottomset (eg. Reineck and Singh, 1975; Selley, 1970) cannot be reconciled with facies associations in any of the available outcrops of the Eregunda Sandstone Member. Furthermore, the typical coarsening-upward cycles of delta progradation are absent, and a radiating distribution pattern around a single fluvial input is not supported by palaeocurrent analyses. Thus, if the Eregunda Sandstone Member is largely deltaic in origin, it displays some peculiar characteristics which require closer scrutiny.

A more basic objection to a deltaic connstation is that it implies deposition related to the base level of the sea, with markedly different subaerial and submarine parts: a situation which is not observed in the Eregunda Sandstone Member. Environments in which high energy alluvial deposits have prograded into the sea are termed fan deltas (McGowen and Scott, 1974) and a recent example from Nueces Bay, Texas, is described by McGowen (1971). The bulk of the sediments in the Gum Hollow fan delta at Nueces Bay comprise fine-grained sandstones which are horizontally laminated, with minor trough and tabular cross-stratification and ripple lamination. The subaerial portions of the delta (the fan plain) are dissected by shallow, braided channels which extend to the submerged, distal portions of the fan complex. Although sediment dispersal is typically by means of the braided channels, high rainfall causes sheetfloods, with subsequent fan aggradation.

An important conclusion to be drawn from McGowen's (1971) study is that horizontal lamination may develop in the shallow water, marginal marine (distal fan) environment due to alluvial flooding. Sudden increases in stream capacity and competence in response to ephemeral flooding result in the formation of characteristic flood deposits, which are vertical aggradations of sand with abundant, upper flow regime horizontal lamination. Miall (1977) notes that such systems are uncommon in the modern environment;

but Schumm (1968) emphasises that deltas consisting of braided channels would probably have been abundant prior to the appearance of land vegetation.

The process of ephemeral stream flooding has been described in more detail by McKee et al. (1967), Williams (1971) and Miall (1977, 1978). The Bijou Creek model (McKee et al., 1967) characterises the deposits of braided ephemeral streams which are subject to major floods, and also relates very well to the sequence of sandy facies preserved in the Eregunda Sandstone Member. Sand is transported under upper flow regime conditions, and horizontal lamination with current lineation is the major stratification type. In the Bijou Creek floods of 1965, horizontally laminated sands infilled the river channel and extended beyond the banks for distances of up to 1km (McKee et al., 1967). The resulting horizontally laminated units were up to 4m in thickness. McKee et al. (1967) estimated that horizontal strata constituted 90 to 95 percent of all deposits, the rest being made up principally by tabular cross-stratified or ripple laminated units. Small scale cycles (0.25-1.4m) were recognised, with horizontally laminated sandstones passing upwards into tabular cross-stratified or ripple laminated units. The cycles were interpreted as representing waning flow deposits, and were accompanied by only minor fining-upwards (from fine to very fine sand). Similar cycles are recognized in the Eregunda Sandstone Member, however the sequences Se → Sh → Sp are interpreted as predominantly within-channel alluvial flow, and probably represents much greater discharge and sediment concentration than anything described by McKee et al. (1967). The thickest waning-current cycles in the Eregunda Sandstone Member are associated with the greatest relief scour surfaces, and occur in the Wirrealpa Basin outcrops. On the basis of palaeocurrent analyses, these outcrops are relatively proximal to the interpreted source area (Broken Hill - Olary; see Wopfner, 1970) and, thus, represent an area subjected to intense alluvial flooding. Similarly, McGowen (1971) reports an increase in the depth of channeling towards the proximal end of the Gum Hollow fan delta. Outcrops along the Heysen Range contain thick sequences of horizontally laminated sandstone, but lack well developed scour surfaces. According to the Bijou Creek braided alluvial model, these deposits represent poorly channelized sheet flooding. Similar deposits are particularly common in the distal fan environment of the Gum Hollow fan delta, which lies between normal sea level and the area represented by the most seaward development of the horizontally laminated, longitudinal bars (McGowen, 1971).

An example of an ancient sequence which shows an alternation between high energy, current-laid sandstones and low energy, tidal deposits is the upper unit of the Glenelg Formation (Miall, 1976; Young, 1974; Young and Jefferson, 1975). The sequence is very similar to parts of the Eregunda Sandstone Member as preserved in the Wirrealpa Basin and especially along the Heysen Range. It comprises horizontally laminated and tabular (alpha) cross-stratified sandstones, with thin silt and mud interbeds. Scour surfaces and trough cross-stratification are rare. The fine-grained interbeds are ripple laminated and desiccation cracked, and are interpreted by Miall (1976) as intertidal deposits. Miall (1976) interprets the sandstone/siltstone alternations as probably resulting from lateral migration of braided, fluvial-dominated, deltaic distributaries, and notes that these types of environments have been described by McGowen and Scott (1974) as fan deltas. However, it would appear from accumulated evidence that the Eregunda Sandstone Member represents not one, but a series of adjacent, possibly overlapping, fan deltas.

GEOLOGIC EVOLUTION

The pattern of sedimentation in the Eregunda Sandstone Member is one of filling a very shallow, continually subsiding, epicontinental basin. Fine to very fine sand was transported to the basin of deposition from the south and southeast by braided streams (Fig. 6-13). Flow was probably ephemeral, with abundant upper flow regime plane lamination developing in response to major floods.

The basal sandstones of the Eregunda Sandstone Member (Unit A, Figs. 6-5 and 6-6) spread over intertidal to very shallow subtidal mudflats,

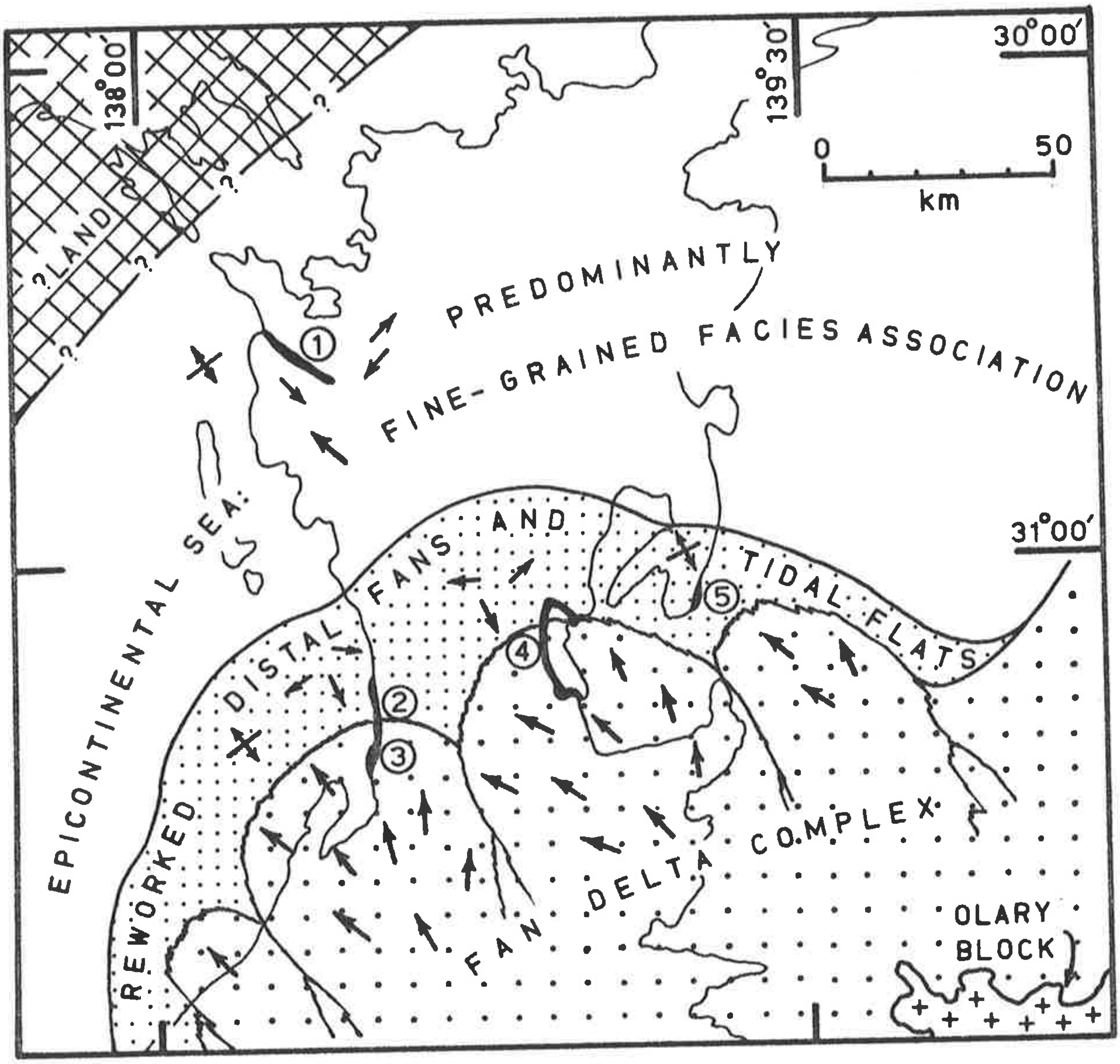


Figure 6-13. Depositional model, Eregunda Sandstone Member.
Outcrops are shown in black.
1: Mount Scott Range. 2: Brachina Gorge
3: Bunyeroo Gorge. 4: Wirrealpa Basin
5: Mount Frome.

probably in response to uplifts in the source area (the Kangarooian movements of Daily and Forbes, 1969). The bulk of the sandstones were deposited as parallel laminae adjacent to the margins of the basin. However, Unit A is also represented in the distal, northern and southwestern areas (Mount Frome and the Mount Scott Range), where the fine-grained sandstones and siltstones accumulated in a shallow marine environment subject to minor alluvial inputs. The shoreline at this period of time probably lay at least tens of kilometres to the southeast of the Wirrealpa Basin, since major distributary channels are rare.

A marine transgression virtually terminated sand deposition in the areas of present outcrop when Unit B was deposited. This unit comprises a sequence of very shallow marine to intertidal mudflat deposits. Abundant, near-symmetrical ripples, a lack of tidal channels and an abundance of desiccation cracks all point towards a very quiet environment of deposition, with only minor wave and tidal current activity.

Maximum regression occurred during the deposition of the Unit C sands. Major delta distributary channel sequences developed in the areas proximal to the source, and are preserved in the Wirrealpa Basin outcrops. Subsidence during Unit C deposition was at a low rate, and much of the area was at or near sea level during the growth of the deltas. Interdistributary areas consisted of intertidal to very shallow subtidal mudflats. Occasional crevassing from major distributaries gave rise to thin, lenticular, crevasse splay channel sands and rare, overbank and levee, climbing ripple deposits. However, most sand deposition occurred as a result of lateral migration of poorly defined, braided channels which were probably incapable of confining the flow during peak flood. Major bedforms probably were longitudinal bars (mainly planar laminated-facies Sh) and transverse bars (predominantly planar-tabular cross-stratified-facies Sp). Transverse bars and dunes were commonly covered by linguoid ripples at low water stage. Fining-upward cycles resulted principally by the lateral migration of distributary systems. However, some fining-upward cycles may be the product of single depositional events associated with ephemeral flooding. The abundance of upper flow regime horizontal lamination is attributed to high velocity, shallow water alluvial flow, and probably was restricted mainly to the subaerial portions of the delta except during times of maximum alluvial flooding. In the more distal outcrops of Unit C (Mount Frome and the Mount Scott Range), the sands are thinner and show signs of considerable marine reworking, especially by long-shore currents.

A relatively rapid, basin-wide marine transgression terminated Unit C sand deposition. Unit D comprises a fining-upward cycle representing a gradual deepening of the basin of deposition. Clastic sedimentation finally became subordinate to carbonate deposition, and the marine Wirrealpa Lime-stone was formed. In the northwest, where subsidence had been least, conditions remained relatively shallow and the Aroona Creek Limestone was deposited on and adjacent to sabkhas (Youngs, 1978a, 1978b).

CONCLUSIONS

Although the Eregunda Sandstone Member accumulated in an epicontinental sea at or near sea level, it contains some high energy, current deposited sandstones. These high energy bedforms are interpreted as resulting from alluvial flooding, the effects of which extended into the marine basin of deposition.

No single environmental model, as presently developed, adequately explains the facies transitions displayed by the Eregunda Sandstone Member. However, the sequence appears to display many characteristics of the Gum Hollow fan delta. In terms of depositional mechanisms, the fine-grained facies association is typical of epeiric sea clastic sedimentation (Shaw, 1964), whereas the sandstone facies association is similar to deposits resulting from ephemeral flooding (McKee *et al.*, 1967).

CHAPTER 7

STRATIGRAPHY AND ENVIRONMENTAL ANALYSIS

OF THE

COADS HILL MEMBER

THE STRATIGRAPHY OF THE COADS HILL MEMBER

Introduction

The lower part of the Billy Creek Formation at Reaphook Hill comprises a sequence of interbedded, fine to medium-grained, pale brown sandstone, dark foetid limestone, and minor red and green shale and shaly siltstone. Interbeds of calcareous shale, shaly limestone, dolomite and tuff occur in some units. The sequence is herein termed the Coads Hill Member. The name is derived from 'Coads Hill' which is located approximately 7km west of Reaphook Hill. Outcrop of the Coads Hill Member and positions and thicknesses of measured sections are shown in Figure 7-1. Section RH-C has been chosen as the type section (Figs. 7-1, 7-2, 7-3). The member attains its maximum measured thickness of 200m in Sections RH-A, and becomes slightly thinner towards the north (Figure 7-2). Detailed stratigraphic columns for the Coads Hill Member are presented in Figure 7-4 (rear pocket).

The Base of the Coads Hill Member

In the north of the Reaphook Hill region, the basal 8m of the Coads Hill Member comprise limestone conglomerate (Plate 52), with boulders of Wilkawillina Limestone up to 30cm across. The conglomerate rests sharply and unconformably on pale grey, fenestral and oolitic Wilkawillina Limestone. Further south (south of Section RH-F), calcareous sandstones of the Coads Hill Member rest disconformably on Wilkawillina Limestone (Plate 53). A pisolitic calcrete horizon, 5-20cm in thickness, caps the disconformity surface (Plate 54).

The Top of the Coads Hill Member

The uppermost portion of the Coads Hill Member (Unit J) comprises greyish green shale and calcareous shale with minor, thin, mottled limestone interbeds. The uppermost mottled limestone is overlain sharply but conformably by a thick sequence of fine-grained redbeds, attributed to the Erudina Siltstone Member.

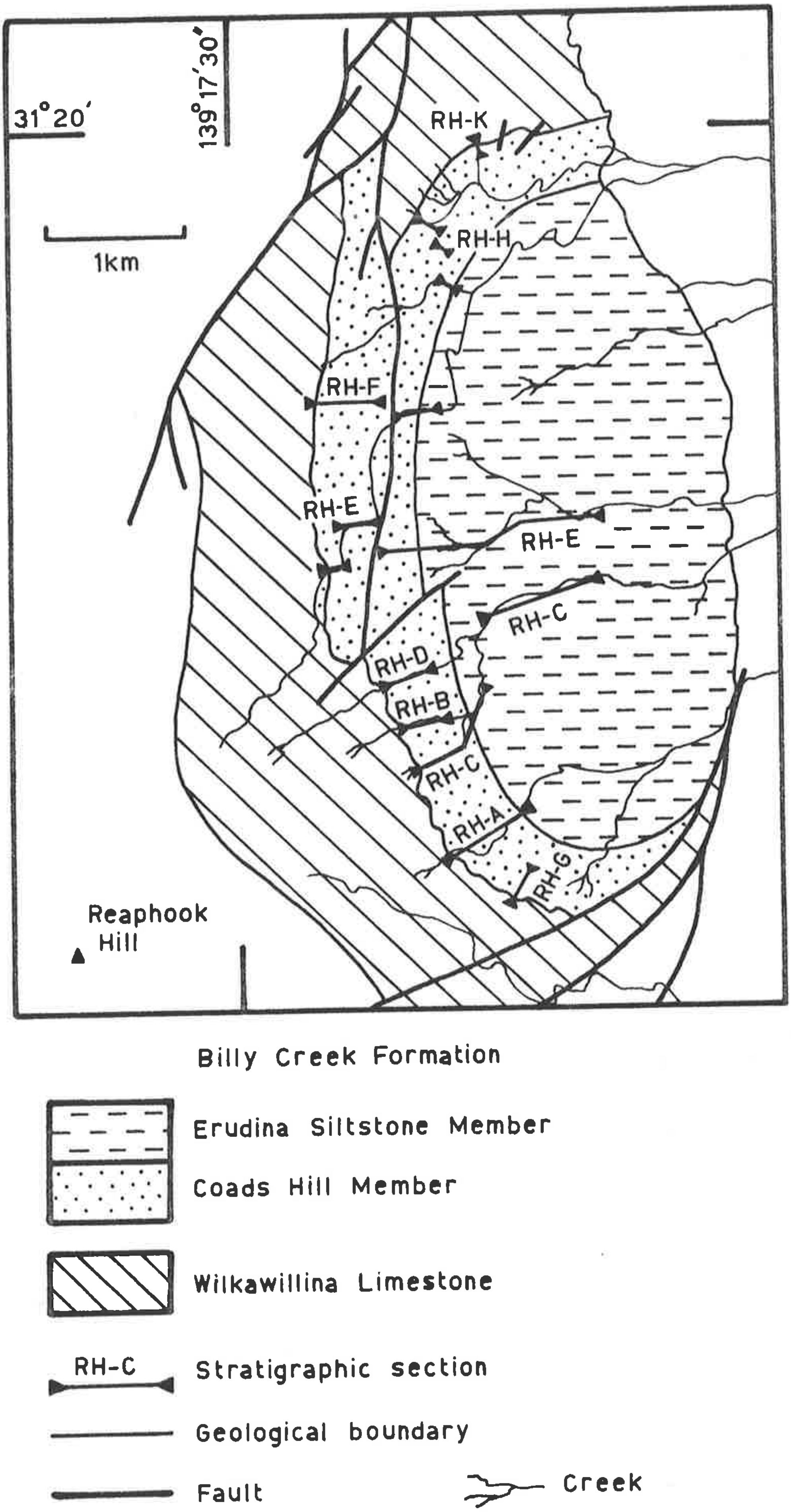


Figure 7-1. Location of measured stratigraphic sections in the Billy Creek Formation, Reaphook Hill.

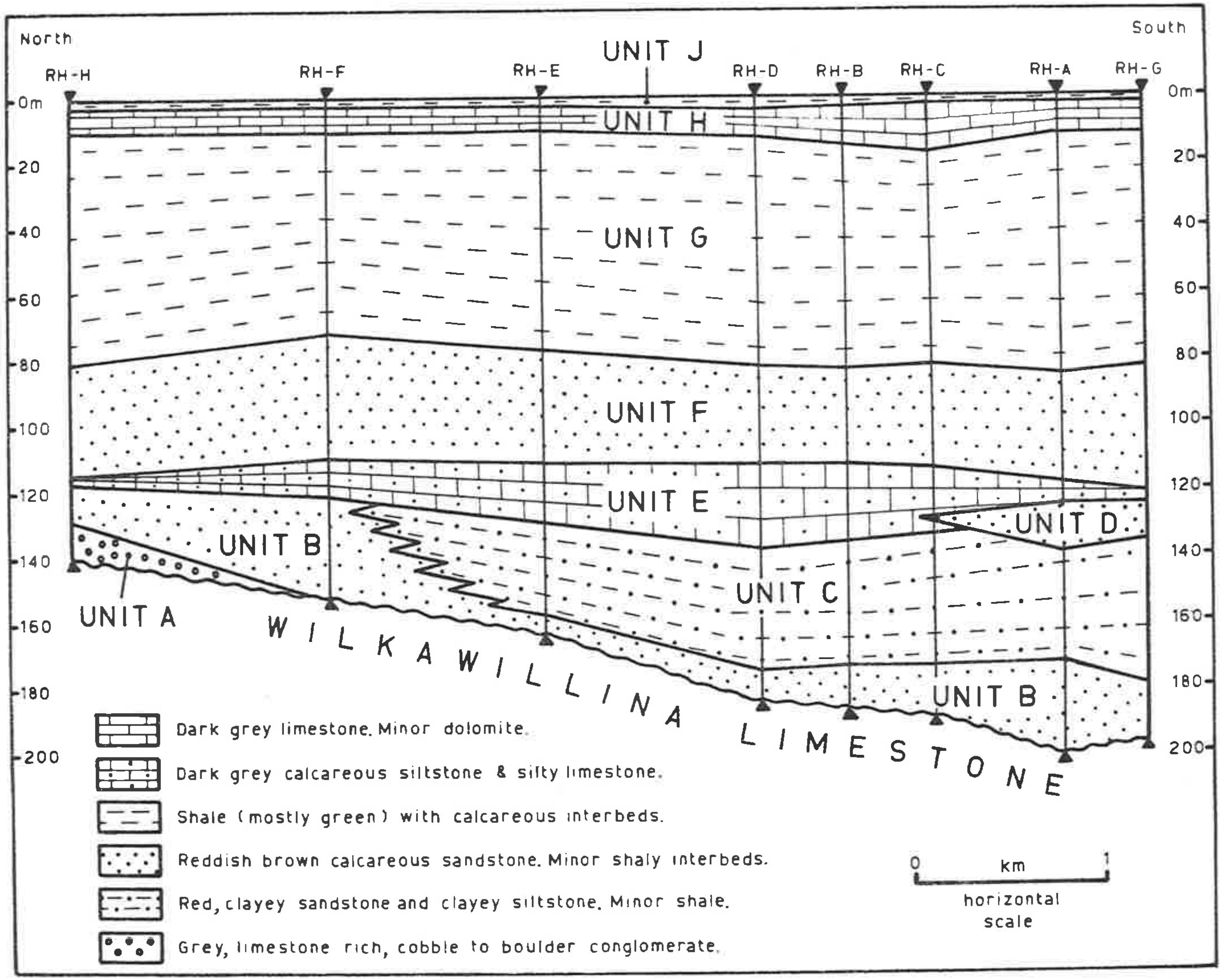


Figure 7-2. Stratigraphy of the Coads Hill Member of the Billy Creek Formation, Reaphook Hill.

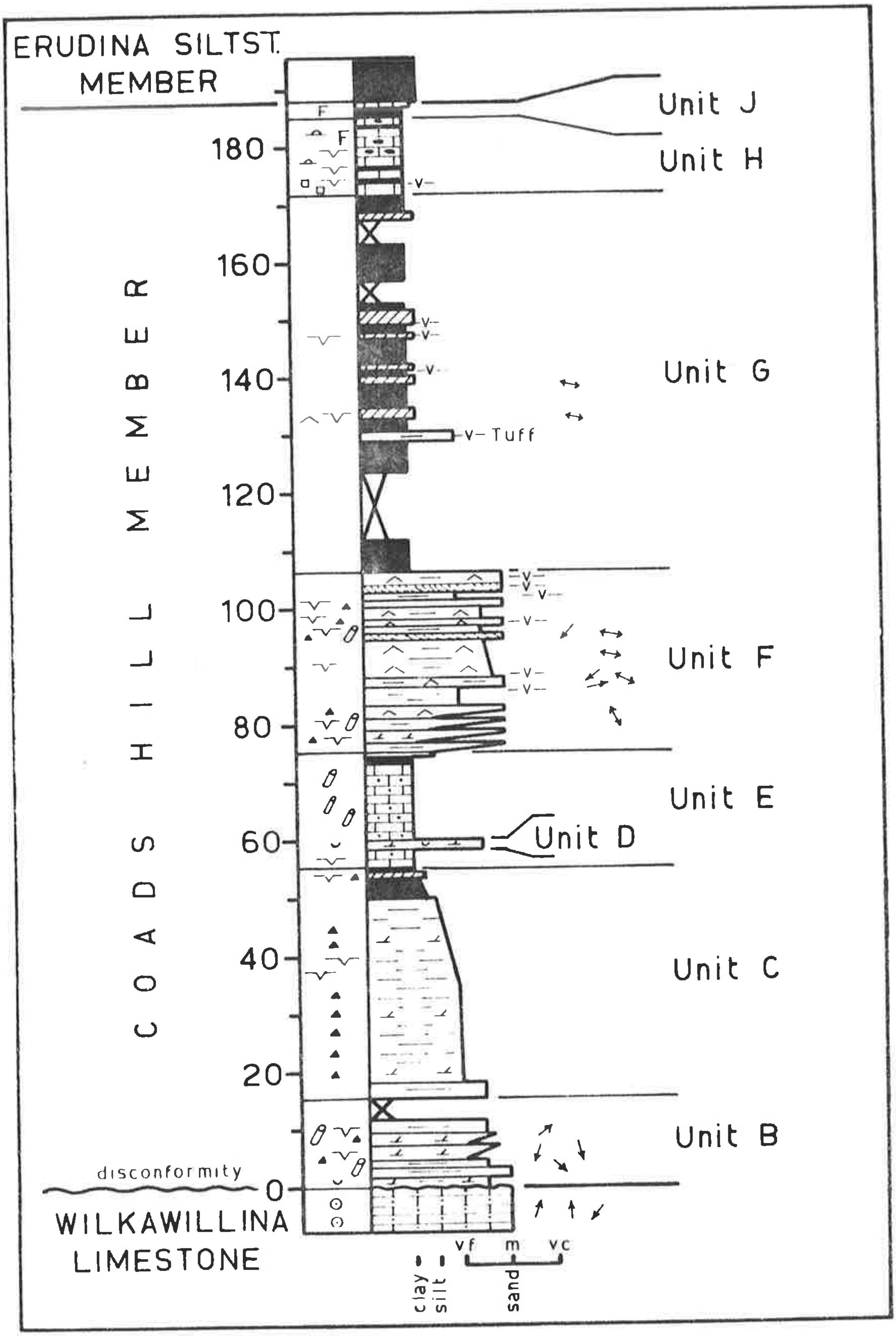


Figure 7-3. Type section (RH-C) of the Coads Hill Member of the Billy Creek Formation, Reaphook Hill. Legend as for Figs. 4-2 (p.42) and 7-4 (rear pocket). Scale in metres.

Age and Palaeontology

Trilobite tracks, worm burrows and molluscan trails occur sporadically throughout the Coads Hill Member. At least one type of trace fossil is present in every unit, with the exception of Unit C. Emuellid trilobites were first discovered by Gaunt (1971) and Gehling (1971), in what is now defined as the basal portion of Unit J of the Coads Hill Member. B. Daily (pers. comm. in Gehling, 1971) identified the trilobites as Balcoracania dailyi Pocock. The species also occurs in the upper portion of the White Point Conglomerate on Kangaroo Island, where it has been assigned a late Early Cambrian age (Pocock, 1970).

Additional collections of Balcoracania dailyi were made from Unit J throughout the Reaphook Hill region. In Section RH-F, they were found in association with rare, unidentified brachiopod fragments. A new locality was discovered in the middle portion of Unit F, approximately 40m stratigraphically below the main fossiliferous horizon, described above.

ENVIRONMENTAL ANALYSIS OF THE COADS HILL MEMBER

Introduction

The Coads Hill Member is known from only the Reaphook Hill area. However, even in this small region, it comprises a complex sequence of interbedded shale, sandstone, dark foetid limestone, dolomite and tuff. Trace fossils, indicating marine deposition, occur sporadically throughout the sequence with the exception of Unit C. Persistent shallow water deposition is indicated by an abundance of desiccation cracks and mudflake intraclasts.

Geologic Setting

The Coads Hill Member rests unconformably on oolitic and fenestral Wilkawillina Limestone. Thus, immediately prior to the deposition of the Billy Creek Formation in this region, land was exposed and the Lower Cambrian Hawker Group carbonates were being eroded (Figure 4-5).

Facies Analysis

Unit A

Description

Unit A is the basal unit of the Coads Hill Member in the north of the Reaphook Hill region (north of Section RH-F). It comprises cobble to boulder conglomerate, with clasts of pale grey Wilkawillina Limestone up to 30cm across (Plate 52). The conglomerate has a closed fabric, with the matrix comprising medium to very coarse sand-sized quartz and minor carbonate. Clasts are generally subangular to subrounded. Some are fossiliferous, containing fragments of trilobites and other shelly debris.

Unit A rests sharply and unconformably on fenestral and oolitic Wilkawillina Limestone. The unit thickens towards the north, and is approximately 6m thick at locality RH-K (Fig. 7-2). The northern outcrops generally contain the larger clasts. A transition into the overlying pale brown, calcareous sandstone of Unit B is indicated as the conglomerate fines upwards into pebbly sandstone and finally into calcareous sandstone devoid of coarser detritus.

Interpretation

There are no palaeocurrent data for Unit A, since the conglomerate is not imbricate. However, since the unit is absent from the south and instead, a pisolitic calcrete caps the disconformity surface, it is considered possible that land persisted in the south while the conglomerate was deposited in a shallow nearshore or shoreline environment further north (Figure 7-7a).

Unit B

Description

Unit B is the basal unit of the Coads Hill Member in the south of the Reaphook Hill region, and overlies Unit A in the north (Fig. 7-2). It comprises pale red to reddish brown, fine to medium-grained, feldspathic sandstone (Plate 55). Interbeds of greyish red shale and shaly siltstone are common in the upper portions of the sequence, especially where it is overlain by Unit C. Unit B is poorly represented in the central region (Section RH-E) where it is only about 4m thick. It thickens towards the north and south, where it is considerably more mature. Maximum measured thickness is 31m in Section RH-F.

The sequence is evenly bedded to ripple laminated on the scale of 3-15cm (Plate 55). Small to medium scale tabular cross-stratification (10-15cm in height) is common in the thicker sections. Desiccation cracks (Plate 56), symmetrical ripples, mudstone intraclasts (Plate 57) and small scour and fill structures are common throughout the unit and worm burrows, interference ripples and pebble horizons occur in some outcrops. A 5cm thick, bright green tuffaceous interval with devitrified glass shards occurs in the middle portion of Section RH-J, in the north of the area (Fig. 7-4, rear pocket).

In the south of the region, Unit B rests sharply and disconformably on Wilkawillina Limestone (Fig. 7-2). The disconformity surface is slightly undulose and is capped by a thin pisolitic calcrete, 5-30cm in thickness. In the north, Unit B rests conformably on Unit A. Throughout most of the region, Unit B is overlain by greyish red, very poorly sorted, shaly silt-stone and silty sandstone of Unit C. The two units are interbedded over a moderate stratigraphic thickness (up to 10m), and thus a well-defined passage exists. In the north, Units C and D are absent, and a gradation occurs from pale brown, fine sandstone of Unit B into greyish green, cal-careous shale of Unit E.

Palaeocurrent data

Palaeocurrent data for Unit B are presented in Figures 7-5a and 7-5b. Symmetrical ripple crests are aligned northeast-southwest, and probably reflect the orientation of the ancient shoreline, with land possibly to the south and southeast, as suggested above. The orientation of large scale cross-stratification is polymodal, with the major mode facing towards the

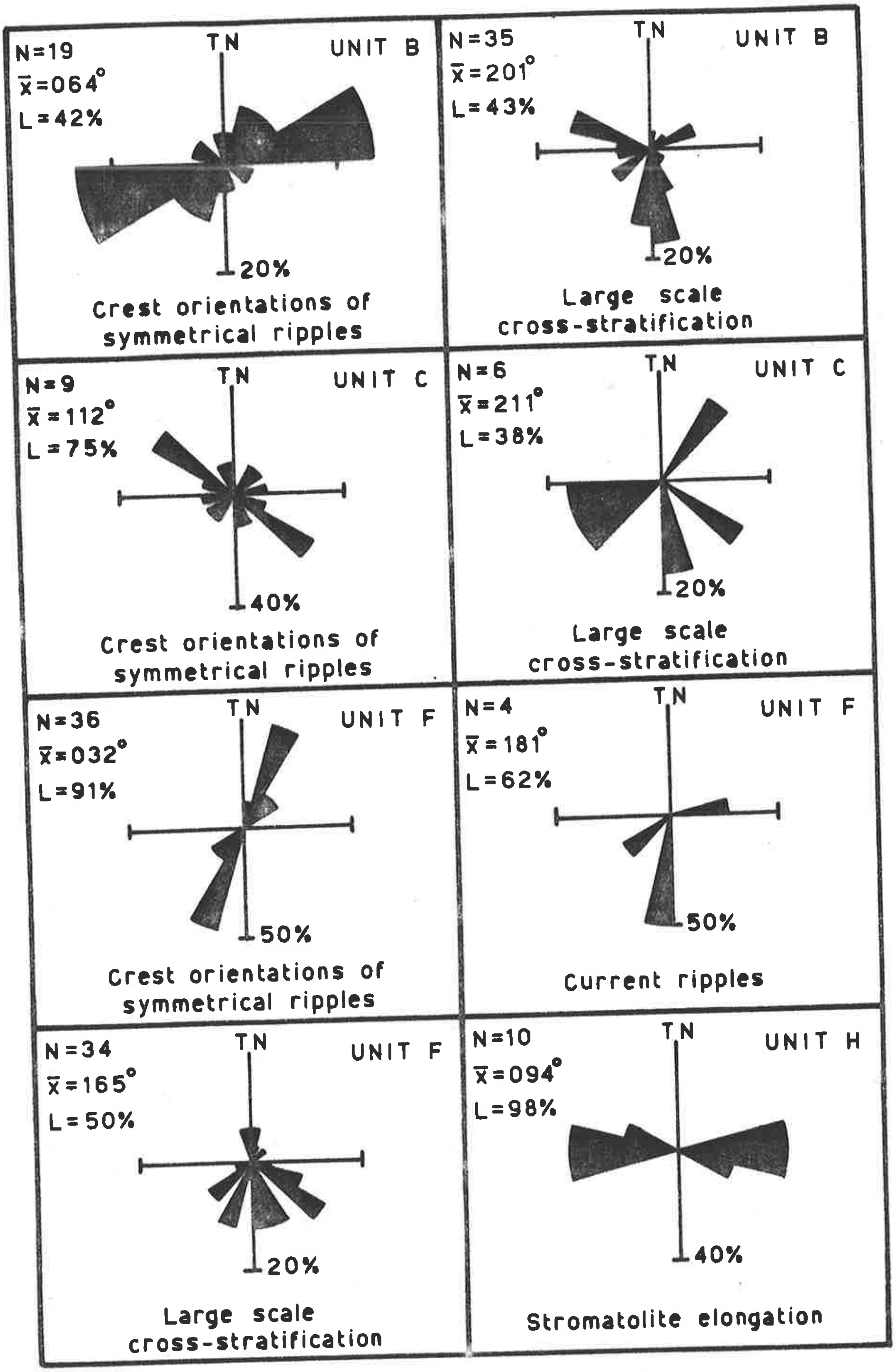


Figure 7-5. Palaeocurrent rose diagrams, Coads Hill Member, Reaphook Hill. N = number of data, $\bar{x}$ = mode, L = vector length.

southeast (?onshore). Accessory modes are orientated subparallel to the shoreline.

Interpretation

A shallow marine origin for Unit B is indicated by the combination of worm burrows, desiccation cracks and red mudstone intraclasts. In some cases however, shrinkage cracks are sinuous in form and discontinuous, and may be attributed to sinaeresis. The cross-bedded sandstones of the northern outcrops probably originated in a shallow nearshore environment subject to minor wave activity. Small tabular and trough cross-stratification most likely represent shoreward facing megaripples with minor longshore migration. The presence of carbonate intraclasts and peloids in these units emphasises their marine origin.

The cross-bedded marine sandstones pass laterally into evenly-bedded to symmetrically-rippled sandstones, which probably represent shallow subtidal to lower intertidal sand flats. The minor red shales and siltstones which occur in Unit B are desiccation cracked and represent intertidal to supratidal mudflat deposits (Fig. 7-6a).

It is important to emphasise that the sediments of Unit B are petrologically quite distinct from the micaceous, arkosic red-beds which occur in outcrops of the Billy Creek Formation in the main Flinders Ranges. They are much coarser-grained, better sorted and rounded, and mineralogically much more mature than the red-beds. The extreme maturity of the heavy mineral suite (dominantly rounded tourmaline and zircon) suggests derivation from pre-existing sedimentary strata (eg. Bunkers Sandstone or possibly Adelaidean sandstones). Since the Coads Hill Member is laterally equivalent to the arkosic red-beds which outcrop to the west and northwest of Reaphook Hill, it would appear that the Unit B-type sandstones were derived from the east or southeast.

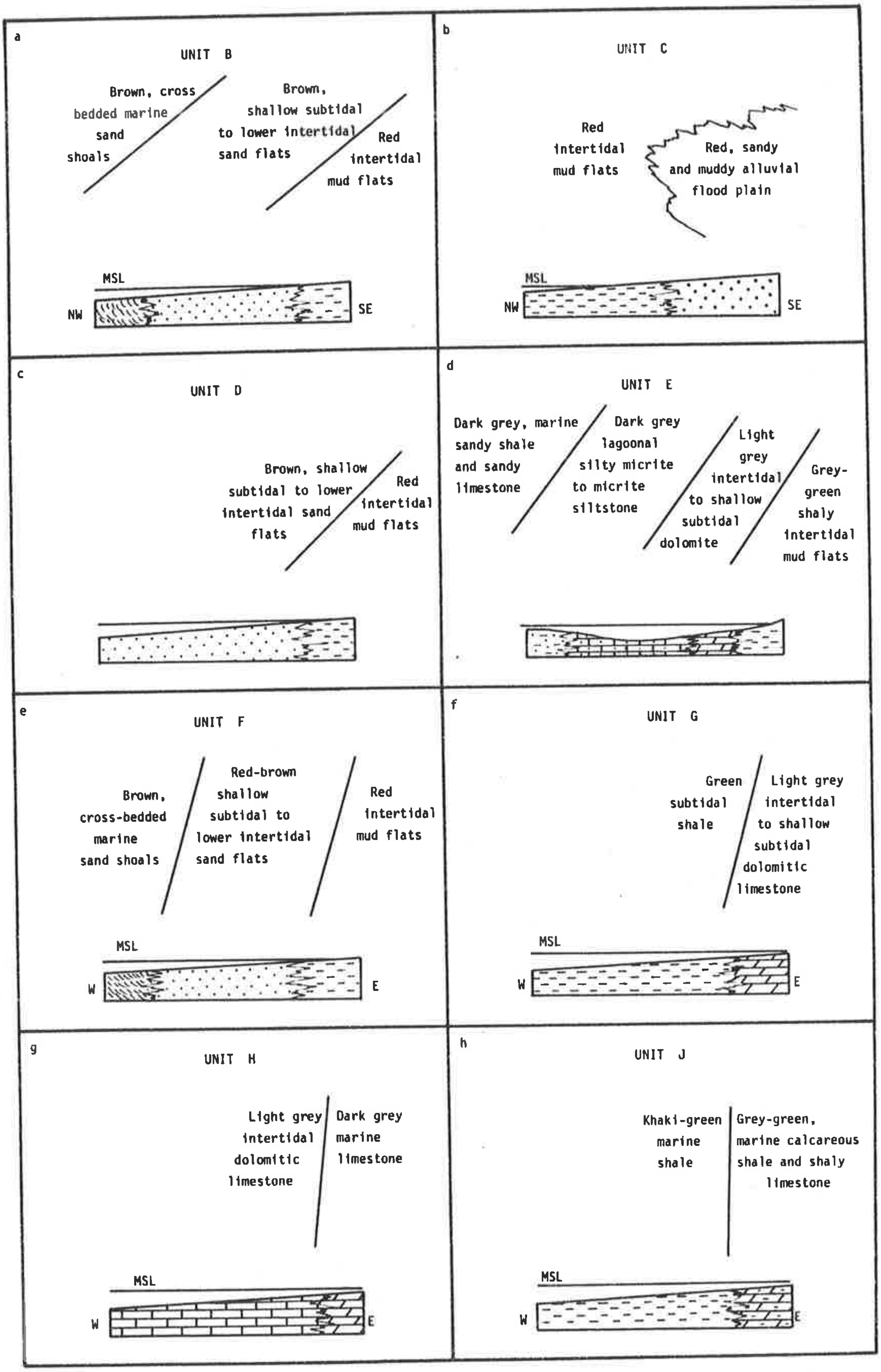


Figure 7-6. Depositional models for various units within the Coads Hill Member, Reaphook Hill.

Unit C

Description

Unit C comprises greyish red, very poorly sorted, shaly siltstone (Plate 58) to silty sandstone (Plate 59), with minor granule and pebble-rich bands (Plate 60). Ripple laminated interbeds of moderately sorted, reddish brown sandstone, 5-20cm in thickness, are common in the lower portion of the member, and define a passage from the underlying unit. A few of the interbeds contain deformed intraclasts of buff-coloured dolomite, up to 4cm across. Mudstone intraclasts and desiccation cracks are abundant. Bedding is poorly defined in the lower, sandy portion of the unit, however the upper few metres are dominated by red silty shale, with well developed, even lamination.

Unit C is thickest in the southern portion of the area (44m in Section RH-G), but thins rapidly towards the north and is absent from Section RH-E (Fig. 7-2). Towards the north, Unit C is conformably overlain by dark foetid silty limestone of Unit E. The transitional interval comprises buff-coloured dolomite and shaly dolomite, with well-developed wavy algal lamination and small, low domal stromatolites. In the southern outcrops, Unit C is overlain by relatively mature, medium-grained sandstone of Unit D. The contact is sharp but conformable.

Palaeocurrent Data

Palaeocurrent data for Unit C are presented in Figures 7-5c and 7-5d. Most of these data are derived from thin interbeds of Unit B sandstone which outcrop in the lower portion of the sequence. Symmetrical ripple crests have a variety of orientations, probably indicative of very shallow water deposition. The few small tabular cross strata which were present show a similar palaeocurrent distribution to the Unit B cross-sets, with possible shoreward and longshore orientations.

Interpretation

The lack of sorting of the red-beds, combined with the absence of marine fossils and traces, suggests that the bulk of the sequence is non-marine. However thin, symmetrically-rippled and cross-bedded, Unit B-type sandstones outcrop in the lower portion of the sequence, and indicate sporadic marine transgression. Hydroplastically deformed dolomite intraclasts in these units were probably derived from high intertidal to supratidal mudflats.

The bulk of Unit C is thinly bedded to weakly ripple laminated, with individual beds being very discontinuous (Plates 58 and 59). A lack of well-defined channels and fining-upward cycles suggest that the sequence is not a typical meandering-fluvial one. The fine grain-size and extreme poor sorting suggest that the sequence is not braided-fluvial in origin either. Rather, it represents dumping of unsorted, fine-grained detritus, with minimal winnowing of mud, and negligible reworking after deposition. Possible environments are distal alluvial fan and river flood plain. The latter is favoured, since it is improbable that even a distal, muddy alluvial fan sequence could develop without the inclusion of the occasional cobble or small boulder. According to Reineck and Singh (1975, p.252), river flood plain deposits not only comprise muddy sediment, but also an abundant amount of sand. Units are generally evenly bedded to ripple laminated, from a few centimetres to a few decimetres in thickness. Desiccation cracks are abundant in the muddy layers.

The upper portion of Unit C is finer-grained and much more evenly laminated. The red shales and shaly siltstones were probably deposited in a transitional environment, comprising high intertidal mudflats and muddy alluvial flood plains (Fig. 7-6b). The overlying greenish grey shales developed in an intertidal, slightly reducing environment. Dolomitic interbeds are commonly desiccation cracked, and in some cases contain wavy algal laminae and small stromatolites, indicating deposition in the lower intertidal zone.

Unit D

Description

Unit D comprises a thin tongue of pale yellowish brown, moderately sorted, feldspathic sandstone which outcrops in the southern portion of the area (Plate 61), where it rests conformably on Unit C. Maximum measured thickness is 14m in Section RH-A (Fig. 7-2). The sandstones are evenly bedded on a scale of 3-12cm, with some poorly defined ripple lamination and rare symmetrical ripple marks. Large scale cross-stratification is absent. A thin, bright olive green, tuffaceous interval outcrops in the upper portion of the unit in Section RH-G. Green shale intraclasts and incipient shrinkage cracks (Plate 62) are abundant throughout the sequence.

In all outcrops, Unit D is overlain conformably by dark, foetid silty limestone and calcareous siltstone of Unit E. A transition zone about 2m in thickness overlies the medium-grained sandstones of Unit D and comprises a fining-upward sequence from evenly laminated, greyish green siltstone to silty, calcareous shale.

Palaeocurrent Data

The lack of palaeocurrent data in this unit is significant, for it emphasises the evenly bedded nature of the sequence. The absence of large scale cross-stratification and current lineation in particular indicate that the sandstones were deposited by relatively weak currents, possibly in very shallow water.

Interpretation

Rare worm burrows in the upper portion of Unit D indicate that the sequence was deposited in a marine environment. Polygonal desiccation cracks occur in a few of the shaly intervals, and are evidence for shallow water deposition, with intermittent subaerial exposure. Shrinkage cracks are also abundant in many of the sandstones, however their sinuous, discontinuous nature suggests that they may have resulted from sinaeresis.

Since the sandstones of Unit D are underlain by muddy intertidal sediments and overlain by shallow marine limestone, it would appear that they represent a marginal marine deposit. The lack of large scale cross-stratification and current lineation indicate deposition in a relatively low energy environment. Thus, Unit C probably represents sandflat deposition in the shallow subtidal to lower intertidal zones (Fig. 7-6c). Constant, gentle reworking of the sand accounts for its relatively well-washed nature, and moderate sorting and rounding.

Unit E

Description

Unit E comprises a sequence of dark foetid limestone, shaly limestone and calcareous shale (Plate 63). Maximum measured thickness is 32m in the central portion of the area (Section RH-D), where it overlies red shale of Unit C (Fig. 7-2). In the northern and southern area where Unit E overlies sandstone, it is poorly represented and comprises only a thin unit of greyish green calcareous shale.

In the thicker sections, a well-developed sequence exists from buff-coloured shaly dolomite at the base, through burrow-mottled shaly grey limestone in the lower portion, into dark grey foetid limestone in the middle and upper portion (Fig. 7-4, rear pocket). Much of Unit E is bioturbated, and desiccation cracks occur sporadically throughout the sequence. Large quartz-lined geodes, up to 12cm across, are present in some outcrops. Thin green tuffaceous interbeds may occur in the upper portions of the sequence. In all outcrops, Unit E passes gradationally into the overlying medium-grained sandstones of Unit F.

Interpretation

The lamination and fine grain-size of this facies indicates deposition out of suspension, in a low energy environment. The absence of body fossils suggests restricted marine conditions. The environment of deposition was either relatively deep water below effective wave base, or shallow water sheltered from the open sea. The presence of desiccation cracks and stromatolites in the sequence and its close lateral and vertical proximity to dolomites and red-beds suggests that the latter alternative is the correct one. Thus the dark, shaly and silty, foetid limestone facies is attributed to a lagoonal or semi-enclosed tidal flat environment (Fig. 7-6d).

The nodular texture of the limestone is due to early diagenetic separation of shale and carbonate, and reflects the very shaly nature of the sediment. The actual mechanisms involved in the formation of nodular texture are poorly understood, and various hypotheses are discussed by Pettijohn (1975, p.378). The dark colour and foetid odour of the limestone are due to a combination of features, including poor oxygenation and water circulation, and an abundance of preserved organic matter. As pointed out by Byers (1977), oxygen is mixed in from the atmosphere at the surface of the sea. Poor oxygenation and partial stagnation can thus develop in shallow, enclosed basins due to isolation from normal oceanic circulation (both waves and currents). Stagnation is further assisted by a salinity gradient, which is most easily produced where there is a large freshwater influx. All of these features may have been in operation during the deposition of Unit E. However, the presence of a few stromatolitic intervals suggests that stagnation was incomplete, or at least periodically interrupted.

Dickinson et al. (1972) and Reineck and Singh (1975, p.353) note that lagoonal facies are generally dominated by dark shale and calcareous shale, with minor associated tidal flat sediments. Certainly the limestones of Unit E are very shaly and silty, and fit quite well into this category. Furthermore, the transition from the underlying units (especially Unit C) into the dark, foetid sediments is characterised by light grey, stromatolitic dolomite and dolomitic limestone, containing abundant desiccation cracks and halite casts. The dolomites thus represent intertidal, evaporitic deposits, accumulating on the margins of the lagoon (Fig. 7-6d). Large, quartz-lined geodes may have originated by diagenetic replacement of gypsum or anhydrite, in the upper intertidal to supratidal environment.

Unit F

Description

This unit comprises pale reddish brown to brown, fine to medium-grained, feldspathic sandstone. Interbeds of shale and siltstone are common in some outcrops. Several bright olive green tuffaceous intervals of up to 30cm are present, and are particularly prominent in the upper, shaly portion of the sequence. Unit F has a relatively consistent thickness throughout the area, with a maximum measured thickness of 41m in Section RH-F (Fig. 7-2).

The sequence is generally evenly bedded to ripple laminated on a scale of 5-15cm (Plate 64). However, medium scale tabular cross-stratification (Plate 65) is common in the northern outcrops (Sections RH-F, RH-H). Mudcracks, quartz-lined geodes, oscillation ripples, current ripples, mudstone intraclasts, small scour and fill structures and worm burrows (Plate 66) are common throughout the sequence. Interference ripples occur in some outcrops. In the north, the sandstones are relatively mature, and are partly cemented by calcite. Further south, the sandstones are interbedded with red shale and siltstone, and contain rare pebble beds (Fig. 7-4, rear pocket). In all outcrops, a well-defined passage exists into the overlying shales of Unit G.

Palaeocurrent Data

Palaeocurrent data for Unit F is presented in Figures 7-5e, 7-5f and 7-5g. Symmetrical ripple crests are aligned north-northeast to south-southwest, and probably reflect the orientation of the ancient shoreline. Note that there has been a slight change in the palaeoslope strike, as determined from Unit B. The orientations of current ripples and large scale cross-stratification are polymodal, with the major mode facing towards the southeast (most probably shorewards). Minor longshore and ?offshore orientations are also present.

Interpretation

A shallow marine origin for Unit F is indicated by the combination of worm burrows, desiccation cracks and red mudstone intraclasts. Relatively clean, cross-bedded sandstones originated in a shallow marine, nearshore environment, subject to minor wave activity. Small tabular and trough cross-stratification probably represent shoreward facing megaripples, with minor longshore migration.

Evenly, thinly bedded sandstones are commonly associated with red, shaly intervals, and the entire sequence typically contains desiccation cracks and mudstone intraclasts. A relatively low energy, tidal flat environment is envisaged for these facies. The sequence appears to represent a continuum from muddy, upper intertidal sediments to sandy, lower intertidal to subtidal sediments (Fig. 7-6e). Coarsening-upward and fining-upward cycles, 0.5-3.0m in thickness, are common. The fining-upward sequences are probably autocyclic, and originated by progradation of tidal flat sediments. Coarsening-upward cycles are more common, and were produced either by lateral migration of facies, or relatively gentle marine transgressions.

Unit G

Description

Unit G comprises green shale and calcareous shale, with common thin interbeds of shaly, dolomitic limestone and dolomite (Plate 67). Minor red shale intervals occur in the lower portion of the unit, especially in the south. Bright olive green tuffaceous interbeds, rarely up to 1.4m in thickness, are common throughout the sequence. Units are generally evenly laminated although rare, asymmetrical ripple marks are present in silty intervals in the south. Desiccation cracks (Plate 68) and small halite casts are common in some sections and in particular, large polygonal desiccation cracks up to 50cm across may occur in shales interlaminated with dolomite. Abundant small trilobites (*Balcoracania dailyi* Pocock) and rare, unidentified brachiopod fragments are present in green shale overlying dolomite, approximately 43m above the base of Unit G in Section RH-A (Fig. 7-4, rear pocket).

Dolomitic intervals increase towards the top of Unit G, where a fairly short transition into dark grey, foetid limestone of Unit H occurs.

Interpretation

A marine origin for at least part of the sequence is inferred from the presence of rare trilobite fragments. A low-energy environment is interpreted from the fine grain-size of the sediment, with deposition primarily out of suspension. Desiccation cracks and halite casts are common in parts of the sequence, and are evidence of intermittent subaerial exposure. Thus, the most likely environment of deposition is the tidal flat, with evenly laminated to wavy laminated dolomite and dolomitic limestone developing in the intertidal to shallow subtidal zone, and passing seawards into green shale (Fig. 7-6f). The alternation of green shale and shaly, dolomitic limestone can be attributed to either fluctuation in the rate of supply of clastic detritus, or marine transgression and regression.

The position of the basin margin at this period of time is unknown. However, it is important to emphasise that the green shales of Unit G represent the first major influx of fine-grained, micaceous clastics into the Reaphook Hill region. Furthermore, the lack of medium-grained sandstones from this point onwards in the stratigraphy suggests a cessation of second cycle sand supply from the east. The site of deposition is thus interpreted to be a very shallow, epeiric basin from this period of time onwards.

Unit H

Description

Unit H comprises a sequence dominated by dark grey, foetid limestone (Fig. 7-2). Interbeds of shaly limestone are common, and much of the sequence has a well-developed nodular texture (Plate 69). Small domal stromatolities and desiccation cracks occur sporadically throughout the sequence, although they are generally restricted to fairly light coloured, non-foetid limestone.

The upper and lower portions of Unit H are shaly and dolomitic. Stromatolites are common (Plate 70), especially in the basal dolomitic interval, and may be up to 25cm in height. This basal unit also contains polygonal desiccation cracks up to 40cm across, and halite casts up to 1.5cm across (Plate 71). Unidentified trilobite fragments are uncommon and occur mainly in the middle to upper portion of the sequence. Unit H is overlain fairly sharply by fossiliferous green shale of Unit J.

Palaeocurrent Data

Domal stromatolites in the basal portion of Unit H (Plate 70) are markedly elongate in an east-west direction (Fig. 7-5h). By analogy with Recent stromatolites in Shark Bay, the direction of elongation is inferred to be perpendicular to the ancient shoreline (Logan *et al.*, 1970). Thus, the trend of the shoreline during deposition of Unit H was probably north-south.

Interpretation

The basal dolomitic interval is interpreted as an intertidal to shallow subtidal deposit, with elongate stromatolites growing perpendicular to the shoreline in the lower intertidal zone. Large, polygonal desiccation cracks and halite casts are evidence of subaerial exposure and evaporite formation.

The overlying sequence of dark, foetid limestones is very similar in character to parts of Unit E, although the presence of trilobites suggests that the environment of deposition was somewhat less restricted. The sequence also contains much less terrigenous detritus, despite the persistence of a nodular texture in some units. Thus, the dark foetid limestones of Unit H probably accumulated in a semi-restricted, very shallow marine environment, subject to minor fine-grained terrigenous influx. Deposition was principally by settling out of suspension. A connection with the open sea is indicated by the presence of trilobites, however the water was generally quite shallow, as indicated by sporadic desiccation cracks and stromatolitic intervals, and was also poorly oxygenated, as indicated by the high organic content of the limestone, its dark colour and foetid odour (Fig. 7-6g).

Unit J

Description

Unit J comprises evenly laminated, khaki shale and fine siltstone, with minor carbonate bands and nodules (Plate 72). It outcrops throughout the area, with a maximum measured thickness of 3m in Section RH-F (Fig. 7-6h). The trilobite *Balcoracania dailyi* Pocock is abundant in the basal portion, and is associated with rare, unidentified brachiopod fragments. A 0.5m thick peloidal and algal, mottled limestone forms a prominent marker bed at the top of Unit J, and is overlain fairly abruptly by red and red-green interlaminated shale and fine siltstone of the Erudina Siltstone Member.

Interpretation

The abundantly fossiliferous nature of the lower, shaly portion of the unit indicates that it was deposited in a relatively unrestricted, shallow marine environment (Fig. 7-6h). A rapid decrease in fossil fragments towards the top of the unit indicates progressive restriction, and shallowing of the basin. The uppermost, mottled limestone bed contains abundant algal structures, and minor peloids which may be oncolitic in origin. Deposition of the limestone probably occurred in a very low energy environment, on intertidal to very shallow subtidal carbonate flats.

Discussion

The environment of deposition of each unit in the Coads Hill Member is shown diagramatically in Figure 7-6. Cross-bedded, medium-grained sandstones most probably represent shoreward facing dunes and megaripples, and indicate deposition in a shallow marine, nearshore environment under moderately energetic conditions. Thinly, evenly bedded sandstones represent subtidal to lower intertidal sand flats, which pass shorewards into upper intertidal, argillaceous sediments. Dark grey calcareous shales and shaly foetid limestones of Unit E are interpreted as lagoonal or ponded tidal flat deposits. Note however that cross-bedded barrier sands (eg. Carter, 1978) have not been identified from the Coads Hill Member, and thus Unit E (Fig. 7-6d) is probably not a lagoonal deposit of the Laguna Madre style (Dickinson et al., 1972). Rather, it appears to have been bordered on the shoreward side by continental and intertidal red-beds (Unit C), and enclosed on the seaward side by evenly bedded to ripple laminated, intertidal to subtidal sand flats (Units B and F). Thus, Unit E appears to represent a very shallow water, near stagnant, ponded environment amidst an array of tidal flat facies.

It is important to realise that no single sedimentary model can be presented which would adequately explain all the facies transitions in the Coads Hill Member. In general however, the member represents a fining-upward sequence, even allowing for the fact that at any one period of time the grain-size of the sediment being deposited varied considerably between adjacent sedimentary regimes. Thus, it appears that the coastline profile evolved from a high energy (moderate palaeoslope) regime, into a low energy (epeiric basin) regime dominated by shaly and calcareous sediments.

Tuffaceous fallout contributed a minor amount of detritus during the deposition of the Coads Hill Member. Most tuffaceous units are bright olive green, due to extensive alteration to chlorite. A few contain abundant devitrified shards. Correlation of tuffaceous intervals between sections is possible where outcrop is continuous and the sequence is fine-grained. Tuffaceous intervals do occur in the sandy units (eg. Unit F), however they are often laterally discontinuous (Fig. 7-4, rear pocket).

The actual proportion of tuffaceous detritus in the Coads Hill Member is unknown, although the presence of tuffaceous units up to 1.5m in thickness and the general abundance of tuff bands by comparison with other outcrops of the Billy Creek Formation suggests that the Reaphook Hill outcrop was relatively proximal to the volcanic source.

CONCLUSIONS

On the basis of several marker horizons in the Coads Hill Member, it is possible to construct palinspastic maps which represent various points in time during the deposition of the sequence. The basal disconformity and the thin marine shale of Unit J are taken to be essentially chronostratigraphic. In addition, a very distinctive, 1.5m thick, tuffaceous interval in the middle of Unit G can be traced throughout the region, and serves as an excellent time line (Fig. 7-4, rear pocket).

The evolution of the Coads Hill Member in the Reaphook Hill region is summarized in eight sketch maps, shown in Figure 7-7. Following deposition of shallow marine and supratidal carbonates of the uppermost Hawker Group, the Adelaide 'Geosyncline' in the vicinity of Reaphook Hill was uplifted and the Hawker Group eroded (Fig. 7-7a). Deposition of the Billy Creek Formation commenced when the area once again became submerged. Limestone-boulder conglomerate eroded from nearby areas was deposited in a nearshore marine environment in the north (Unit A) while a thin calcrete profile developed on the land surface to the south (Fig. 7-7b). Subsequently a sequence of shallow marine to intertidal, calcareous sandstones (Unit B) spread over the area.

Following the initial transgression, land reappeared in the southeast, and a 30m thick sequence of very poorly sorted, alluvial plain sediments accumulated (Unit C) laterally adjacent to the intertidal and shallow marine deposits of Unit B (Fig. 7-7c). Minor transgression and subsequent stabilization of the environment led to the development of a dark-grey, fine-grained, carbonate-rich lagoonal sequence (Unit E), probably in a protected zone adjacent to a muddy tidal flat (Fig. 7-7d). The lagoon or tidal marsh was flanked on its shoreward margin by a broad sequence of intertidal sediments

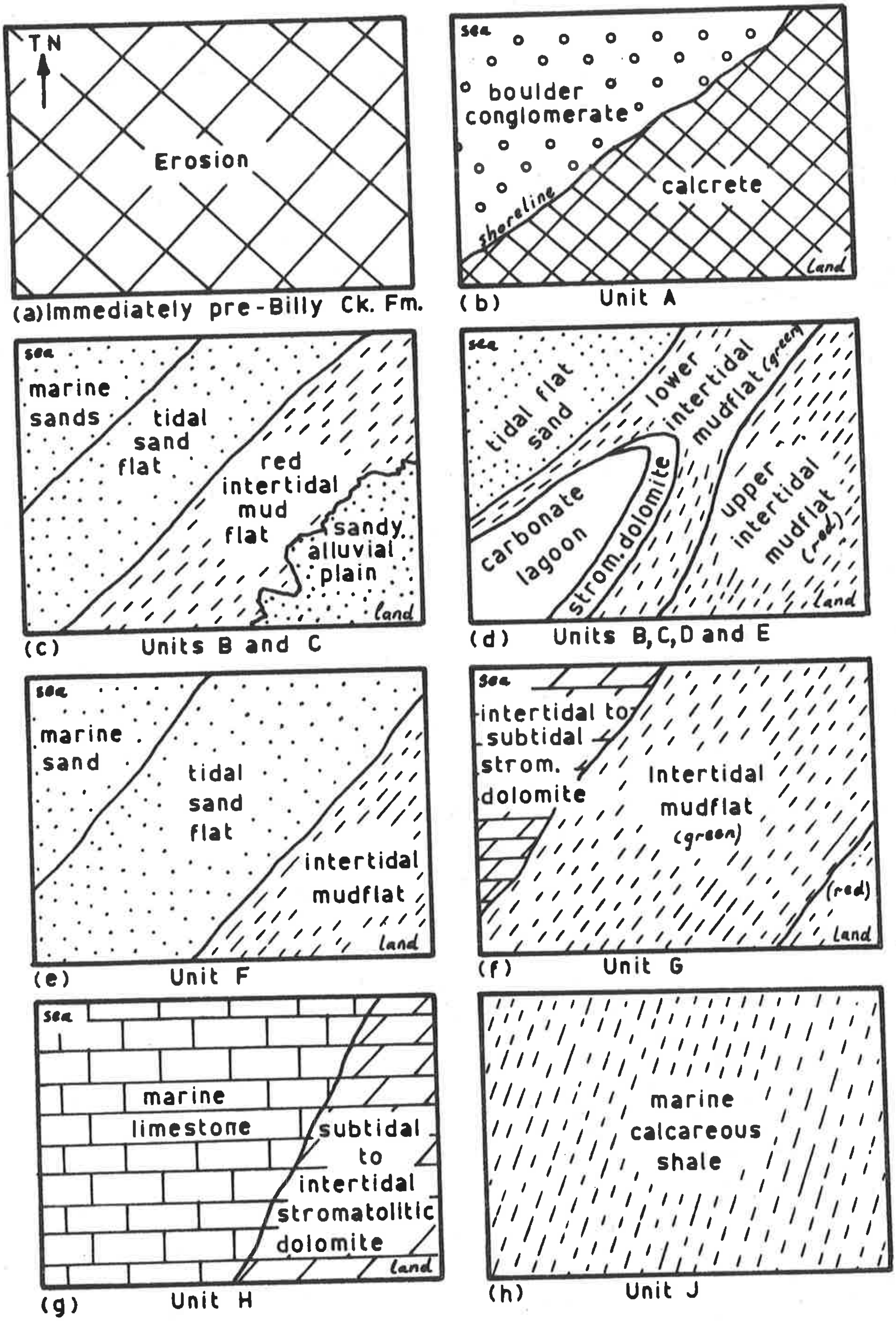


Figure 7-7. Palinspastic maps for eight time intervals during the deposition of the Coads Hill Member.

(upper portion of Unit C). The nature of the protective barrier is unknown, although it may have comprised in part a broad zone of sandy intertidal sediments (Units B and D). Certainly there is no evidence of a barrier-island complex of the seaward side of the dark foetid shaly carbonate.

Shallow marine calcareous sandstones of Unit F pass gradationally into micaceous shales of Unit G (Figs. 7-7e and 7-7f). The absence of coarse-grained clastics in the sequence from Unit F onwards is evident in Figures 7-7g and 7-7h. Facies are much more widespread and much more nearly time synchronous, indicating the development of near-stable conditions in a very shallow, epeiric basin. Deposition of the Coads Hill Member was terminated by the sudden influx of fine-grained red-beds of the Erudina Siltstone Member.

CHAPTER 8

STRATIGRAPHY AND ENVIRONMENTAL ANALYSIS

OF THE

ERUDINA SILTSTONE MEMBER

THE STRATIGRAPHY OF THE ERUDINA SILTSTONE MEMBER

Introduction

The upper portion of the Billy Creek Formation at Reaphook Hill comprises a sequence of greyish red siltstone and silty shale, with minor dolomitic, tuffaceous and sandy interbeds. The sequence is herein termed the Erudina Siltstone Member. The name is derived from the Erudina homestead, which is located approximately 15km south-east of Reaphook Hill. The Erudina Siltstone Member conformably overlies the Coads Hill Member, and is considered to be the approximate lateral equivalent of the Nildottie Siltstone Member. Section RH-C has been chosen as the type section (Fig. 8-1). The upper portion of the member has been removed by erosion, and thus the original thickness is unknown. The maximum measured thickness is 270m in Section RH-C (Fig. 7-1). The sequence appears to thin slightly towards the north. Detailed stratigraphic columns for the Erudina Siltstone Member are presented in Fig. 8-2 (rear pocket).

The Base of the Erudina Siltstone Member

The Erudina Siltstone Member rests sharply but conformably on a thin (0.3m-0.5m), grey, mottled limestone, which marks the top of the Coads Hill Member (Fig. 8-2, rear pocket). The basal sediments of the Erudina Siltstone Member comprise interbedded greyish green and red, micaceous shales. Minor buff-coloured dolomites occur in the basal 35m.

Palaeontology

Worm burrows, molluscan trails and tracks attributed to trilobites occur sporadically throughout the Erudina Siltstone Member. The only body fossils found to date are tiny carbonaceous imprints in green shale in the lower portion of the member. These are tentatively interpreted as fossil annelids.

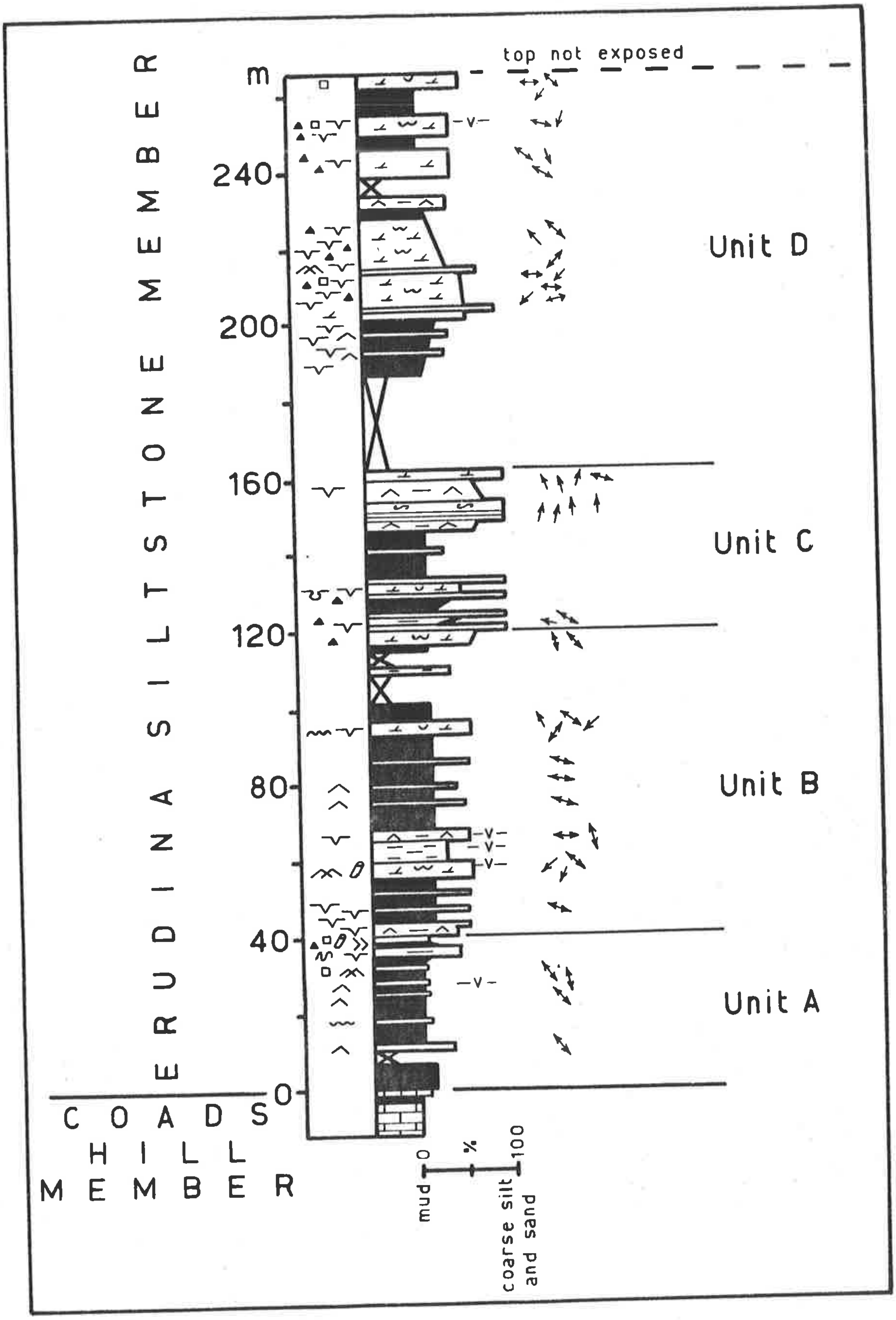


Figure 8-1. Type section (RH-C) of the Erudina Siltstone Member of the Billy Creek Formation at Reaphook Hill. Legend as for Figs. 4-2 (p.42) and 8-2 (rear pocket). Scale in metres.

ENVIRONMENTAL ANALYSIS OF THE ERUDINA SILTSTONE MEMBER

Introduction

A marine origin for the bulk of the Erudina Siltstone Member is inferred from the presence of arthropod tracks and worm burrows, and from an abundance of oscillation ripples. The palaeocurrent distribution of asymmetrical ripples is essentially bipolar, and indicates a persistent tidal influence. The abundance of desiccation cracks, mudflake breccias and halite cast in the Erudina Siltstone Member suggest that much of the sequence was deposited in the intertidal zone.

The member comprises four units, designated Units A, B, C and D (Fig. 8-1). Units B and D show marked similarities in their facies associations and thus have been grouped together. The other units are discussed separately, since each requires the development of a unique environmental model.

Geologic Setting

The uppermost unit of the underlying Coads Hill Member (Unit H) comprises fossiliferous khaki shale with minor, thin, calcareous interbeds. Thus, in the Reaphook Hill area, the environment immediately preceding the deposition of the Erudina Siltstone Member was that of a relatively open, although very shallow, marine shelf (Fig. 7-7h). The rapid transition into red-beds of the Erudina Siltstone Member at Reaphook Hill is related to a widespread regression which occurred at that period of time. The regression was probably accompanied by a marked increase in the supply of clastic detritus to the basin of deposition.

Facies Analysis - Unit A

Introduction

Unit A of the Erudina Siltstone Member is characterised by cyclic sedimentation, with half cycles grading from red shale through greyish green shale, into buff-coloured dolomite or dolomitic limestone (Plate 73). In this respect, the facies are similar to those described for the Warragee Member (Chapter 4), although the cycles are much better developed. Thus, only a summary of the various facies is presented below.

Facies Descriptions

Rippled siltstone facies

This facies occupies only a very minor portion of the Unit A stratigraphy, and comprises greyish red to greyish green, ripple laminated coarse siltstone. Ripple laminated units rarely exceed 8cm in thickness, and average 3cm. The ripples are typically straight to slightly sinuous, low amplitude (4-10mm), symmetrical and near-symmetrical forms. Halite casts, desiccation cracks and mudflake intraclasts are commonly associated with the facies.

Evenly laminated red shale facies

This facies is by far the most extensive in Unit A, and comprises evenly laminated greyish red shale and silty shale. The sediment is weakly calcareous and in rare cases, calcareous algal mats are developed. Halite casts and desiccation cracks (Plate 75) are common, whereas small load structures, arthropod tracks and worm burrows are rare.

Evenly laminated green shale facies

This facies comprises evenly laminated, green and greyish green calcareous shale to medium siltstone. Desiccation cracks, small halite casts, arthropod tracks and worm burrows all occur in the facies, although none is abundant. Small (1-2mm long) carbonaceous imprints in green shale are interpreted as fossil annelids.

Dolomitic limestone facies

This facies comprises buff-coloured, shaly, dolomitic limestone and dolomite, laminated in units up to 2m in thickness. Shaly partings in the basal and upper portions of dolomitic units are commonly desiccation cracked, and may display large halite imprints. In most cases, the carbonate units are evenly laminated, however there are several intervals which contain low domal stromatolites (Plate 74).

Facies Associations and their Interpretation

Large scale cyclic repetition of shale and carbonate is a feature of Unit A of the Erudina Siltstone Member. Cycles, up to 20m thick, contain appreciable red shale, which grades upward through greyish green shale and calcareous shale into relatively pure dolomitic limestone and dolomite. A similar, although more abrupt gradation back into red shale is common (Plate 73).

The cycles appear to represent variations in terrigenous sediment input, possibly related to widespread transgressions and regressions. Red shales developed in the high intertidal zone, as indicated by the association of rare arthropod tracks and common desiccation cracks. Dolomites and dolomitic limestones were generally deposited in the lower intertidal to shallow subtidal zone, and passed landwards into fine-grained red-beds through a zone of reduced clastic muds (now preserved as green shale).

Palaeocurrent Analysis - Unit A

Due to the fine grain-size of the sequence, ripple lamination is uncommon and large scale bedforms are absent from Unit A. Ripples are characteristically symmetrical in form, with straight to slightly sinuous crestlines. The orientation of symmetrical ripples in Unit A is shown in Figure 8-3. Crests are generally aligned northeast-southwest, and this direction is inferred to approximate to the orientation of the palaeocoastline (Picard, 1967a, 1967b).

Depositional Model - Unit A

It is apparent that Unit A of the Erudina Siltstone Member is similar in character to much of the Warragee Member (Chapter 4), despite the fact that the shale-carbonate cyclicity is much better developed in the example to hand. Consequently, the discussion on "Depositional Model" for the

Warragee Member applies equally well to this sequence, and shall not be repeated here.

However one point which bears further discussion is the asymmetry of the shale-carbonate cycles. Typical cycles pass gradationally from red shale through green shale into carbonate over a stratigraphic thickness of several metres, and then pass fairly rapidly from carbonate back into red shale. This asymmetry was noted for shale-carbonate cycles in the Warragee Member, especially at Mount Frome, and is characteristic of Unit A of the Erudina Siltstone Member. Furthermore, the same asymmetry has been noted consistently in cyclic sequences in the Balcoracana Formation of the Lake Frome Group.

If the cycles merely record marine transgressions and regressions related to eustatic changes in sea level, there would be no reason for a consistent asymmetry in the cycles, as preserved in the rock record. It is likely therefore that the cycles are associated with local events, at least in part.

Many asymmetrical cyclic sequences in the stratigraphic record are autocyclic in character. That is, the cyclicity results principally from the natural growth and development of a prograding sequence. Thus, for example, in a tidal environment subtidal sediments tend to be overlain by intertidal and supratidal sediments respectively, and the thickness of the intertidal succession is vaguely related to the palaeo-tidal range (Klein, 1971). New cycles are initiated by relatively rapid marine transgression. The cycles are thus asymmetrical, and record a slow regression (associated with progradation of the sequence) followed by a rapid transgression which initiates a new cycle.

It should be noted that the asymmetry produced in autocyclic sequences is generally the opposite of that observed in the shale-carbonate cycles of the Billy Creek Formation. It is unlikely therefore that they are autocyclic in origin, and another mode of formation must be considered. Since the cycles must be largely related to local events, a likely alternative is that they reflect local tectonic instability. Thus, carbonates accumulated in the shallow subtidal to lower intertidal zone during periods of relative tectonic quiescence. Carbonate sedimentation was periodically interrupted by tectonic activity, which caused uplift of the source area and adjacent basin margins. Such events are recorded in the stratigraphy by a series of rapid regressions, associated with a sudden influx of red-bed clastics. In each case, the return to stability caused cessation of clastic supply and winnowing of the red-beds with the production of a fining-upward, transgressive sequence in which carbonates eventually predominated.

This explanation of the asymmetry of the shale-carbonate cycles in the Billy Creek Formation does not deny that for certain intervals of time, red-beds were accumulating in the upper intertidal and supratidal zones, landward of shallow marine carbonates. However, it does imply that the carbonates could only accumulate during periods of relative tectonic quiescence, when the supply of clastic detritus was minimal. At other times, the carbonates would be absent from the margins of the basin, or at least restricted to protected embayments along the coastline.

Facies Analysis - Units B and D

Introduction

Units B and D of the Erudina Siltstone Member comprise approximately 80m and 100m respectively of red shale, shaly siltstone and minor sandstone, very similar in character to the Nildottie Siltstone Member. Indeed, the similarity is so great that a repetition of the facies analysis for this type of sequence (Chapter 5) would be pointless.

Both units are evenly laminated (Plate 76) with flaser bedding, wavy bedding (Plate 77) and ripple lamination in the coarser units. Symmetrical ripples predominate (Plate 78), although asymmetrical, interference (Plate 79), and flat-topped ripples also occur. Desiccation cracks (Plate 80) and mudstone intraclasts (Plate 81) are abundant, whereas halite casts and small load structures are relatively uncommon. The red-beds are weakly calcareous, and crenulated, carbonate-rich algal mats occur at a few localities in Unit B. Trilobite tracks (Plate 83) and bioturbated intervals (Plate 82) are rare. Pink, silty, tuffaceous units are also rare.

Facies Descriptions

The facies present in Units B and D of the Erudina Siltstone Member are listed below in their order of relative abundance. For a detailed description of each facies, refer to Chapter 5.

(a) Wavy bedded, red siltstone facies.

(b) Laminated red mudstone facies.

(c) Flaser bedded red siltstone facies.

(d) Silt-streaked and lenticular bedded red shaly facies.

(e) Oscillation rippled, red siltstone facies (includes minor sandstone).

(f) Current rippled, red siltstone facies.

(g) Blocky, calcitic, red mudstone facies.

(h) Stromatolitic carbonate facies.

Facies (a) and (b) generally dominate the sequence, whereas facies (g) and (h) are rare.

Facies Associations and their Interpretation

Units B and D of the Erudina Siltstone Member are dominated by fine-grained, evenly bedded to ripple laminated red shales and siltstones, which generally lack evidence of cyclicity. In this respect, the units are very similar in character to the red-beds of the Nildottie Siltstone Member (Chapter 5).

Tidal cycles, as described by Klein (1971), are typically absent, due to the fine grain-size of the sediment and the lack of large scale cross-stratification. However, fining-upward cycles do occur at rare intervals in the sequence and probably formed in a similar manner to Klein's tidalites. The cycles generally have a sharp, erosional base on red mudstone, and in the lower portion comprise rippled coarse siltstone to fine sandstone, with common mudstone intraclasts. The overlying sequence fines upwards through flaser and wavy bedded shale/siltstone into evenly laminated to blocky red mudstone. Fining upward cycles are generally 0.5-1.5m in thickness and represent a gradual reduction in energy of the depositional environment. Such cycles are typical of prograding muddy tidal flats (Thompson, 1968) where subtidal sandstones and coarse siltstones pass landwards into rhythmites with an increasing proportion of mud. Blocky, red mudstones probably accumulated in the upper intertidal to supratidal zone, as indicated by the presence of minor patches and veins of calcite, interpreted as alteration products of gypsum and anhydrite.

Palaeocurrent Analysis - Units B and D

An abundance of ripples were available for analysis from Units B and D of the Erudina Siltstone Member and over 200 measurements are summarized in Figures 8-3 and 8-4. Standard techniques for measurement and correction of data were used, based on Potter and Pettijohn (1978).

Crests of symmetrical ripples in both units are typically orientated northeast-southwest. This orientation is considered to be a good indication of the mean palaeoslope strike, with ripple crests aligned subparallel to the coastline (Picard, 1967a, 1967b). The palaeodip direction is calculated from the orientation of asymmetrical wave ripples, which typically face shorewards (Reineck and Singh, 1975). Unfortunately, there is a paucity of data on the orientation of asymmetrical wave ripples in the Erudina Siltstone Member (Fig. 8-4) and conclusions drawn of the basis of these data are only tentative. However, since most of the observed asymmetrical wave ripples in Units B and D indicate flow (translation) from southeast to northwest, it is assumed that land existed towards the northwest. Furthermore, the concept of a northeast-southwest striking palaeoslope with land on the westerly side is consistent with data gathered from the Nildottie Siltstone Member (Chapter 5), which is the approximate lateral equivalent of the Erudina

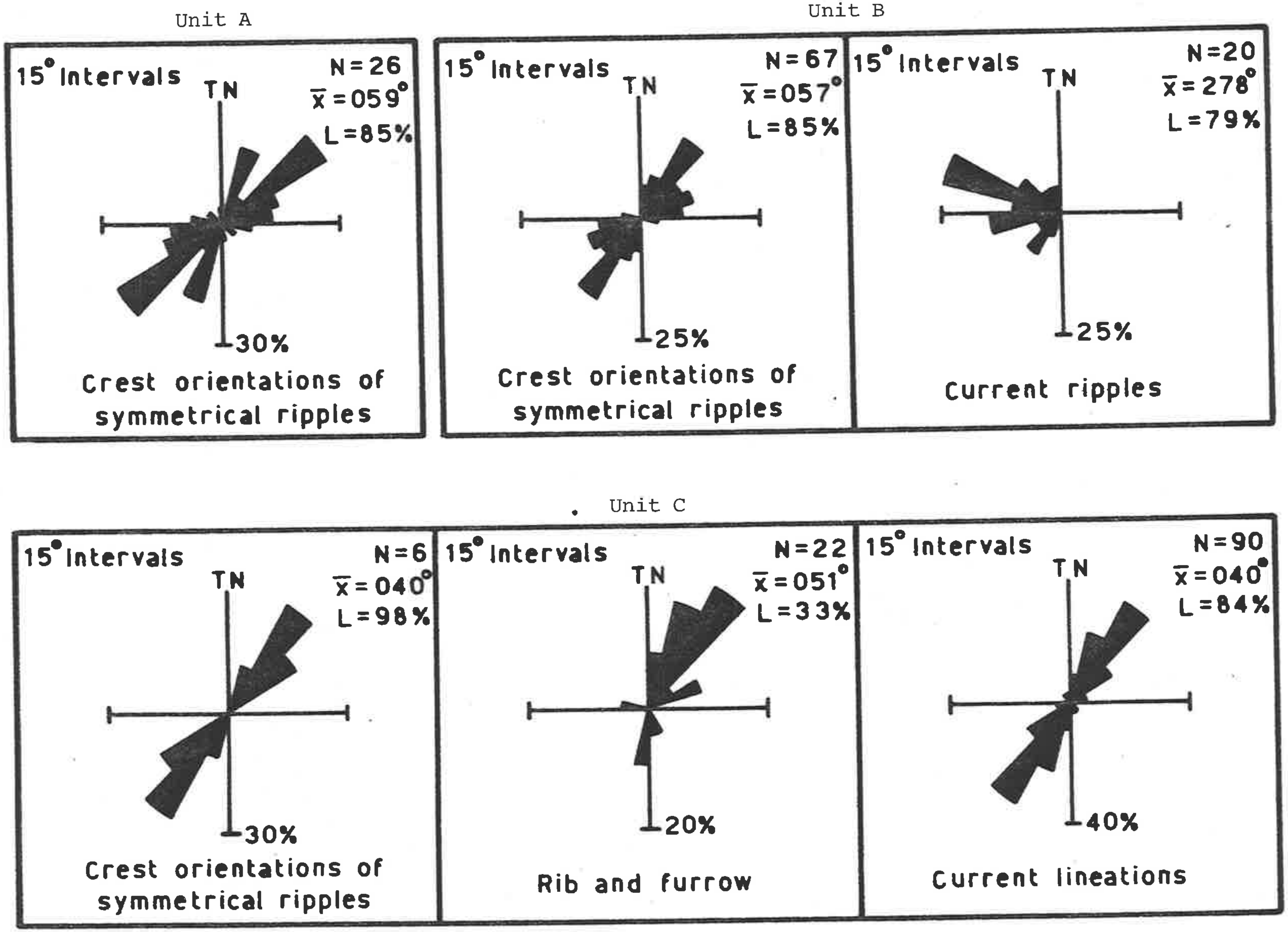


Figure 8-3. Palaeocurrent rose diagrams, Units A, B and C of the Erudina Siltstone Member, Reaphook Hill. N = number of data, $\bar{x}$ = mode, L = vector length.

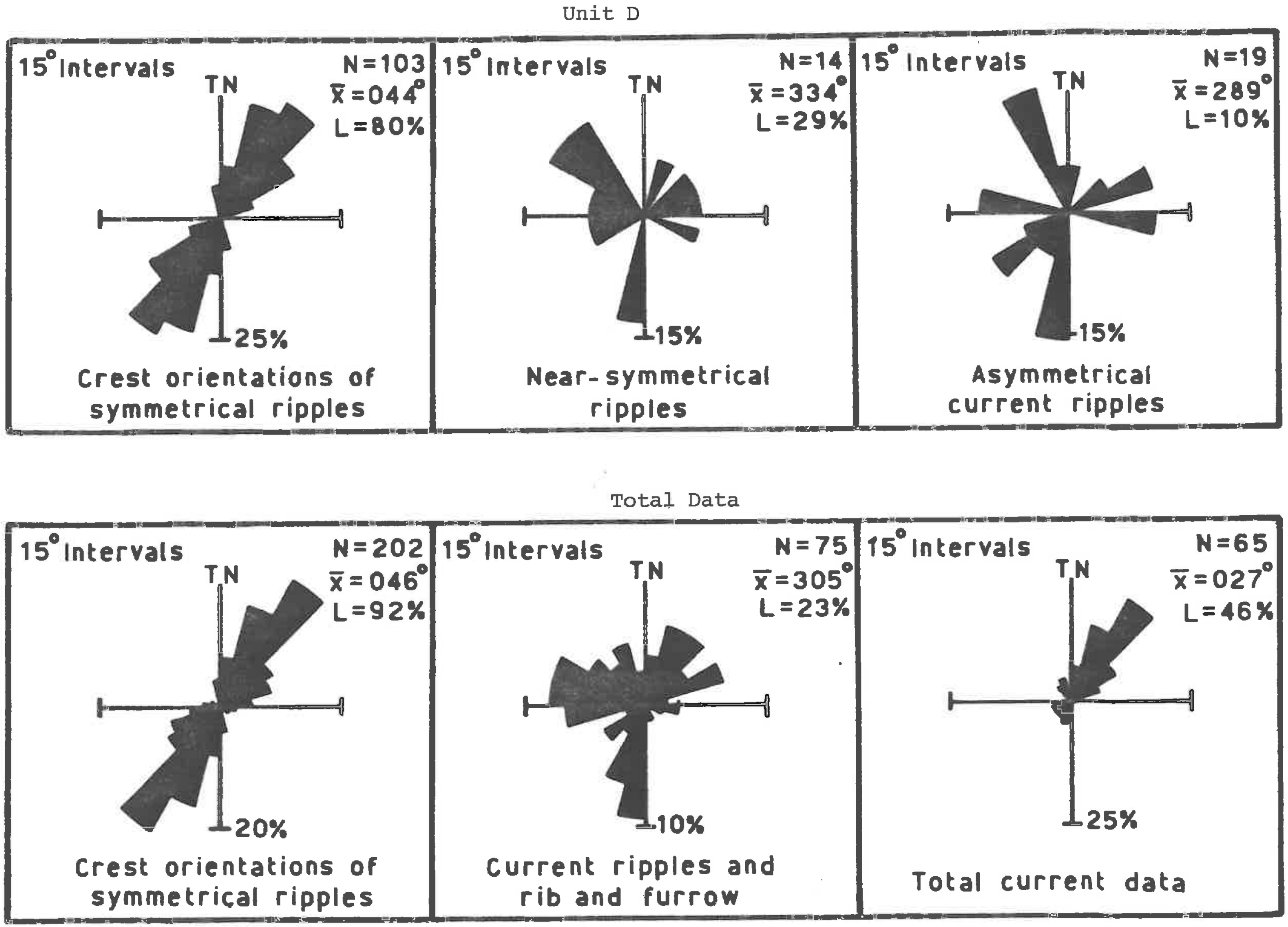


Figure 8-4. Palaeocurrent rose diagrams, Unit D, and total data, for the Erudina Siltstone Member at Reaphook Hill, N = number of data, $\bar{x}$ = mode, L = vector length.

Siltstone Member in the central and northern Flinders Ranges.

Current ripples in Units B and D of the Erudina Siltstone Member (Figs. 8-3 and 8-4) show a variety of orientations, with onshore, offshore and longshore flow, based on the above palaeoslope interpretation. The large variation in orientations of the current ripples is consistent with formation in a low energy tidal environment. As shown in Figure 8-4 (bottom) onshore (flood) currents predominate. This fact is also consistent with data from modern tidal environments, where flood currents are commonly stronger than their ebb counterparts (Reineck, 1967, 1975).

Depositional Model - Units B and D

Since Units B and D of the Erudina Siltstone Member are extremely similar in character to outcrops of the Nildottie Siltstone Member, it is assumed that the environment of deposition was very similar for both. Depositional models for this type of sequence have already been discussed in detail in Chapter 5, and the discussion will not be repeated here. The only difference noted between the sequence at Reaphook Hill and that in the central Flinders Ranges is that halite casts tend to be less common and smaller in the Reaphook sequence. This could be explained by assuming that the Erudina Siltstone Member was slightly more marine in character than its counterpart in the central and northern Flinders Ranges. Otherwise, the depositional model proposed in Chapter 5 (Fig. 5-11) applies equally well to both sequences.

In summary however, the bulk of Units B and D of the Erudina Siltstone Member comprise red shale and shaly siltstone which were deposited in a paralic environment. A lack of coarse detritus in the sequence is evidence for an extremely low relief, senile topography, with sediment supply by sluggish, low competence streams. Thus, an extensive muddy alluvial plain probably flanked a broad zone of intertidal sediments.

It is the intertidal and shallow subtidal, tide-influenced deposits which constitute the bulk of the sequence. Evidence for tidal activity occurs in the intimate association of wave, current, flat-topped and interference ripples, along with desiccation cracks, mudflake intraclasts, halite casts and minor marine trace fossils. In addition, wavy, lenticular and poorly defined flaser bedding occur in the sequence, which are identical in character to bedding structures in Recent, fine-grained tidal deposits from the Gulf of California (Thompson, 1968).

The tidal range during deposition of Units B and D of the Erudina Siltstone Member is unknown, since there are no definite palaeotidal range sequences (cf. Klein, 1971). However, the relative abundance of wave-formed ripples (commonly associated with desiccation cracks), suggests that tidal currents were relatively weak. The consistent bipolar orientation of the ripple marks also favours a low energy tidal origin for these sediments, with crests aligned subparallel to the coastline and currents directed on- and off-shore. The poor sorting of the sediment and an absence of tidal channels are further evidence of weak tidal flux.

Facies Analysis - Unit C

Introduction

Unit C comprises a 40m thick sequence of interbedded shaly, silty and sandy red-beds. Coarsening-upward cycles are present, and vary in thickness from a few metres (Plate 84) to twenty metres. Shaly units are evenly laminated whereas coarser grained, silty units are wavy laminated to ripple laminated, and are commonly associated with desiccation cracks, mudstone intraclasts, trilobite tracks, worm burrows and symmetrical, interference and current ripples.

Sandy intervals are commonly ripple laminated, with rib and furrow structure on the upper surface (Plate 85). Thicker intervals in the upper portion of Unit C are plane laminated, with well-developed current lineation (Plate 86), current crescents and rare bounce marks. Several horizons of convolute bedding are also present (Plate 87). Trilobite tracks and scratch marks are common in the sandy units, which also contain dessication cracks, mudstone intraclasts, load structures, rare worm burrows and molluscan trails.

Facies Associations and their Interpretation

Coarsening-upward cycles from red shale to sandstone are a feature of Unit C of the Erudina Siltstone Member. The transition from sandstone back into mudstone is generally quite sharp, extending over a stratigraphic thickness of only 5-20cm (top of Plate 84). The cycles reflect progressive increase in current activity, with upper flow regime plane lamination developing in the sandy portions of some cycles. Intervals of convolute bedding indicate rapid sedimentation, with an abundance of sediment supply.

The cycles cannot clearly be related to marine transgression of regression, since desiccation cracks occur sporadically in both the fine-grained and coarse-grained facies. It is likely however, that the metre-thick beds of convolute lamination were deposited in a depth of water several times greater than the thickness of the convolute interval.

Palaeocurrent Analysis - Unit C

Palaeocurrent data for Unit C of the Erudina Siltstone Member are shown in Figure 8-3. Symmetrical wave ripple orientations were obtained from siltstones in the fine-grained facies, in the lower portion of the coarsening-upward cycles. Ripple crests are aligned northeast-southwest, and despite the paucity of data, are remarkably consistent with symmetrical wave ripple orientations in the rest of the member. Thus, it is assumed that the ripple crests were aligned subparallel to a northeast-southwest striking palaeoslope. Rib and furrow orientations were obtained from rippled sandstones in the upper portion of coarsening-upward cycles. They indicate current flow parallel to the coastline, as determined from the orientation of symmetrical wave ripples throughout the member. The bipolar distribution of rib and furrow orientations indicates periodic reversal of flow direction, as could be expected for tidal currents flowing parallel to the coastline in a shallow offshore zone.

Current lineations in Unit C of the Erudina Siltstone Member (Fig. 8-3) also indicate flow parallel to the coastline, as determined from above. Eight current crescents in the sequence all indicate flow from southwest to northeast.

Depositional Model - Unit C

The unique features of Unit C are the coarsening-upward cycles, and the relatively sandy nature of the red-bed sequence overall. Both features could be explained by lateral facies migration, or by tectonic activity, or by some combination of both. Gehling (1971) considered the cycles to be tectonic in origin, with the current lineations and convolute bedding indicating flow down a relatively steep palaeoslope, from southwest to northeast. However, he did not measure any ripple orientations, and thus could not appreciate the regional palaeogeography of the area. Furthermore, the present study has failed to recognise any preferred orientation to the load structures which Gehling (1971) termed slump rolls, and thus his evidence for a north-northwest dippling palaeoslope is considered to be invalid. In most cases, the structures have originated by differential loading on finer-grained sediment.

Coarsening-upward cycles could also be the result of marine transgressions, where muddy intertidal to supratidal red-beds are overlain by lower intertidal to subtidal sandstones. The concept of a subtidal sandflat (with currents directed parallel to the coastline) lying on the seaward side of an intertidal mudflat (with weaker currents directed onshore and offshore) is consistent with modern tidal flat sedimentation as observed in the Wash (Evans, 1965). However, under normal conditions of sedimentation, such sequences commonly prograde seawards, resulting in regressive, fining-upward cycles. The coarsening-upward nature of cycles in Unit C of the Erudina Siltstone Member is thus inconsistent with tidal flat sedimentation in a stable environment, and it would appear that there must have been some form of tectonic control over the sequence.

In conclusion, it is suggested that muddy red-beds accumulated in the shallow subtidal, intertidal and supratidal environments during periods of relative tectonic quiescence, as discussed in Chapter 5. However, local periodic tectonism during deposition of Unit C released fine sand into the basin of deposition, producing a sequence dominated by coarsening-upward cycles. The coarser units are interpreted as corresponding with periods of maximum tectonism, and may reflect tempory increase in the palaeoslope. Since equivalent sandy intervals are not found in the Nildottie Siltstone Member, which is the lateral equivalent of the Erudina Siltstone Member to the north and west of Reaphook Hill, it is assumed that the sand came from the eastern side of the basin; for example, from the Broken Hill-Olary basement high. Palaeocurrent data gathered from the sandy units indicate that the sand has been transported along a line striking northeast-southwest. However, this direction is inferred to be parallel to the ancient coastline, and thus these data indicate the directions of reworking of the sediment, and not the direction of initial transport of the sand as it was carried into the Adelaide 'Geosyncline'.

CONCLUSIONS

The Erudina Siltstone Member consists of four units which are distinguished primarily on the basis of grain-size. Unit A is fine-grained, comprising red shale with dolomitic interbeds. The shales were deposited in an oxidising environment on muddy tidal flats probably as a response to mild tectonism (the Kangarooian Movements; Daily and Forbes, 1969). Carbonate mudstones accumulated in the lower intertidal to subtidal environment during periods of relative tectonic quiescence. Cycles in the shale-carbonate sequence of Unit A are attributed to local transgressions and regressions, and reflect the unstable nature of the basin of deposition and adjacent source areas during this period of time.

Unit B was deposited in response to increased tectonic activity, whereby red shales and siltstones were deposited on muddy intertidal flats and in the shallow subtidal environment. The rate of sedimentation was sufficient to obscure carbonate accumulation and instead, a sequence of fine-grained red-beds with distinctive tidal stratification (cf. Reineck and Wunderlich, 1968) was developed.

During the deposition of Unit C, sand was carried into the basin of deposition, forming coarsening-upward cycles of red-bed clastics. The cycles are attributed to pulses of tectonism which reached a peak late in the history of deposition of Unit C. Unit D represents a return to more stable conditions, as experienced earlier during the evolution of Unit B. Fine-grained, shaly and silty red-beds dominate the sequence, which contains an abundance of simple and wavy flaser bedding.

There is evidence for weak tidal activity throughout most of the Erudina Siltstone Member, and it appears that intertidal and shallow subtidal deposits constitute the bulk of the sequence. Evidence for tidal activity occurs in the intimate association of tidal rhythmites with desiccation cracks, halite casts, marine trace fossils and a wide variety of ripple types, including interference and flat-topped ripples. Unfortunately, the tidal range during deposition of the Erudina Siltstone Member is unknown since there are no large scale bedforms, and thus no distinctive palaeotidal range sequences (cf. Klein, 1971). However, the poor sorting of the sediment, the absence of tidal channels and the general abundance of wave-formed ripples suggests that tidal currents were relatively weak.

CHAPTER 9

STRATIGRAPHY AND ENVIRONMENTAL ANALYSIS

OF THE

BILLY CREEK FORMATION

EAST OF THE FLINDERS RANGES

THE STRATIGRAPHY OF THE BILLY CREEK FORMATION EAST OF THE FLINDERS RANGES

Introduction

The Billy Creek Formation occurs in the subsurface, generally below the Mesozoic of the Lake Frome Embayment and in some places below the Cainozoic of the Tarkooloo Basin (Callen, 1976)*. The present limits of the Cambrian Basin in this region, as suggested by Youngs (1979), are shown in Figure 2-2.

The Billy Creek Formation (sensu stricto) has been identified by Daily (1969c) from the Lake Frome Stratigraphic Wells Nos. 1 and 2, and has also been identified by Youngs (1978c) from S.A.M.D. Yalkalpo 2 (Fig. 2-2). No other positive identification of the Billy Creek Formation is recorded. This study is thus an attempt to summarize the relevant drillhole data presently available in open file at the South Australian Department of Mines, and to draw attention to the nature and location of probable occurrences of the Billy Creek Formation in the subsurface to the east of the Flinders Ranges.

Geologic Setting

Early work by Wopfner (1966) at Mount Arrowsmith in northwestern New South Wales (Fig. 2-2) showed the existence of Middle-Late Cambrian and Early Ordovician sediments in the area. Since then, it has been assumed (Wopfner, 1969a, 1969b, 1970a, 1970b, 1972; Youngs, 1978a, 1978b, 1978c, 1979) that deposition was continuous across the basin (between Mt. Arrowsmith and the Flinders Ranges), at least for part of the Cambrian. This belief was supported by the results of drilling for artesian water in the Frome Embayment and Tarkooloo Basin. In a summary of this work, Ker (1966) reported the occurrence of "basement" rocks in the subsurface of the Lake Frome Region, similar in character to outcropping Cambrian strata of the Flinders Ranges.

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*As presently defined (Wopfner, 1969a), the term "Frome Embayment" refers to the Mesozoic sedimentary basin bounded by the Flinders and Barrier Ranges. The unconformably overlying Cainozoic sediments were deposited in the "Tarkooloo Basin" (Callen, 1976).

Later drilling by E.A. Rudd Ltd. (Rudd, 1970) and Santos Ltd. (Delhi-Santos, 1969) firmly established the existence of Cambrian red-beds to the south of Lake Frome. Following this work, Crusader Oil N.L. (1971) carried out a seismic survey from the eastern margin of the Flinders Ranges eastwards to within approximately 40km of the New South Wales border. Strong reflections were obtained from the Wirrealpa Limestone in the region between Lake Frome and the Flinders Ranges, however the reflections became progressively weaker towards the east. On this basis, Crusader Oil N.L. (1971) suggested that the Wirrealpa Limestone had been removed by erosion in this area prior to deposition of the Mesozoic cover.

Partly to test this hypothesis, S.A.M.D. Mudguard 1 was drilled, approximately 40km east of Lake Frome, in what was considered to be the shallow southern portion of the Cambrian basin (Fig. 2-2). No Cambrian or Adelaidean sediments were encountered. The well drilled through 194m of Tertiary and Mesozoic sediments before intersecting crystalline basement (massive rhyolite, dated by Rb-Sr geochronology at between 1,160 and 1,350 million years). At that stage, it was realised that the scattered outcrops of crystalline basement which extended northwards from the Olary Block comprised a major structural ridge (the Benagerie Ridge) which was buried beneath the Mesozoic of the Lake Frome Embayment. Since a few metres of Cambrian limestones had been recorded from the base of Yalkalpo 1 (Callen, 1972), which lay only about 4km to the east of Mudguard 1, it was suggested that the Benagerie Ridge was fault bounded, at least on the eastern side (Youngs, 1978c, 1979). Thus, S.A.M.D. Yalkalpo 2 was drilled further towards the east (Fig. 2-2), and intersected Tertiary and Mesozoic sediments lying unconformably on the Lower Cambrian. The Cambrian basement comprised 265m of Billy Creek Formation and more than 276m of Lower Cambrian Hawker Group carbonates (Youngs, 1978c). The upper portion of the Billy Creek Formation, and the overlying Wirrealpa Limestone and Lake Frome Group were missing, due to post-Cambrian - pre-Cretaceous erosion.

In yet another attempt to drill a full Cambrian sequence, S.A.M.D.

Bumbarlow 1 was drilled (Fig. 2-2) on the northeastern margin of Lake Frome (Youngs, 1979). However, once again the Mesozoic was found to rest directly on the Precambrian basement. In this case, the Precambrian comprised basalts and dacites, interbedded with minor maroon to cream mudstones, siltstones and sandstones.

Thus, on the basis of present knowledge, it would appear that the Benambrie Ridge is a major Precambrian crystalline basement high which extends northwards from the Olary Block to well beyond Bumbarlow 1. It is probably bounded on both sides by major north-south trending faults (Fig. 2-2).

Since the Billy Creek Formation is present and somewhat similar in character on both sides of the Banambrie Ridge, it would appear that the basement high was not in existence during the Early Cambrian, but probably developed as a horst during the later Palaeozoic.

The present distribution of the Cambrian and Precambrian strata below the Mesozoic and Tertiary cover of the Lake Frome region is shown in Figure 9-1. The diagram is interpretive, and certainly will be refined as more drilling is carried out in the basin.

Delhi-Santos Lake Frome Wells

Introduction

The Billy Creek Formation (*sensu stricto*) has been identified from the Lake Frome Wells Nos. 1 and 2 by Daily (1969c), and this identification is confirmed here. Only the upper part of the Billy Creek Formation was penetrated, and this interval is considered to be the approximate lateral equivalent of the Eregunda Sandstone Member in the central and northern Flinders Ranges. However, the interval penetrated by the Lake Frome stratigraphic wells is not appreciably sandy and thus cannot be equated with the Eregunda Sandstone Member. Rather, it is considered only as Billy Creek Formation (*sensu stricto*).

With increased silt content, evenly laminated shales grade into wavy bedded and poorly defined flaser bedded siltstones (Plate 88). Ripple

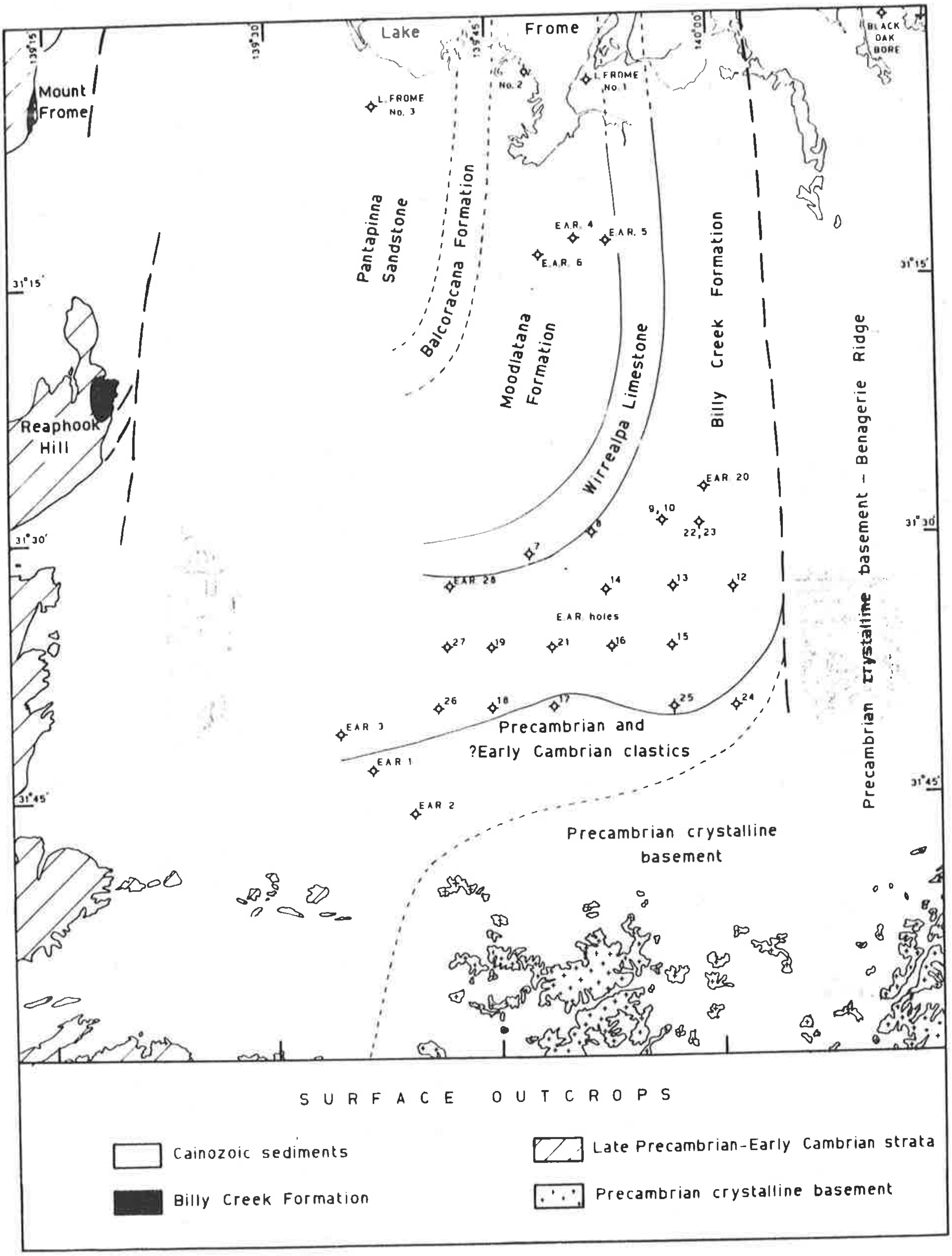


Figure 9-1. Interpreted distribution of Cambrian and Precambrian strata below the Mesozoic and Cainozoic cover rocks of the Lake Frome region.

laminated siltstones devoid of clay laminae are uncommon, although in one interval, climbing ripples were noted (Plate 89). Anhydrite and calcite patches (Plate 90), veins (Plate 91), and lenses are common throughout the sequence although they are more abundant in the finer-grained intervals. Secondary reduction, associated with a change from red to green, commonly surrounds the anhydrite. Halite pseudomorph casts occur sporadically throughout the sequence, and typically occur on rippled bedding plane surfaces. Desiccation cracks, which are V-shaped downwards and up to 1.2cm in width at the top, are common. Mudstone intraclasts and rill marks are also common in parts of the sequence, particularly in the coarser-grained intervals. Thin, pinkish intervals at 2560.0 feet (780.3m) and 2561.5 feet (780.7m) in Lake Frome 1 contain abundant altered, subangular feldspar, and by analogy with outcrops in the Flinders Ranges, are considered to be tuffaceous in origin.

The Top of the Billy Creek Formation

The Billy Creek Formation is overlain by Wirrealpa Limestone (Delhi-Santos, 1969). Borecore from the uppermost portion of the Billy Creek Formation in Lake Frome 1 comprises greenish grey with minor red calcareous siltstone. Irregular lamination between 1672 feet (509.6m) and 1674 feet (510.2m) are interpreted as wavy algal laminae (Plate 92), and thus it is likely that a transition occurs between the Billy Creek Formation and the overlying Wirrealpa Limestone.

Palaeontology

Tracks attributed to trilobites occur in several of the cored intervals, however no body fossils have been found to date.

S.A.M.D. Yalkalpo 2

Introduction

The Billy Creek Formation was identified from Yalkalpo 2 by Youngs (1978c), and this identification is confirmed here. A summary log of the sequence is presented in Fig. 9-2 and the detailed section is shown in

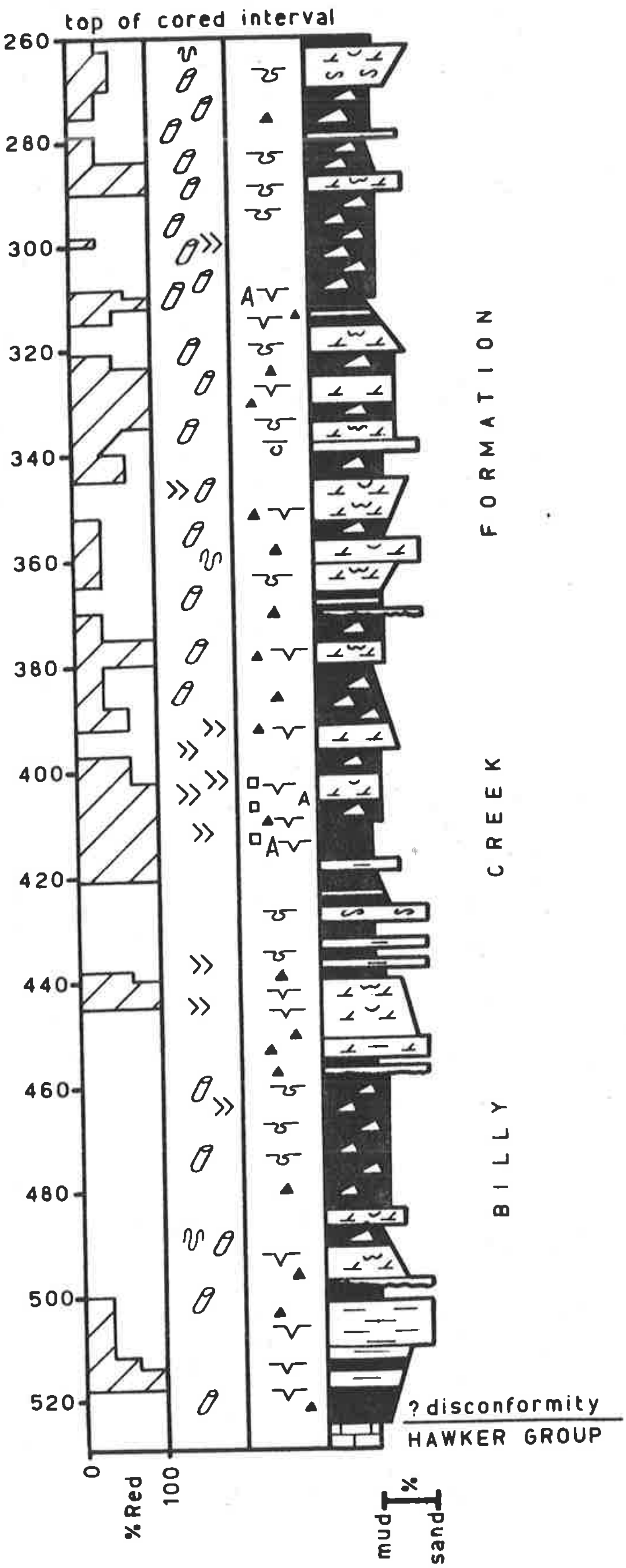


Figure 9-2. Summary log, Billy Creek Formation in Yalkalpo 2, east of Lake Frome. Legend as for Fig. 4-2 (p.42) and 9-3 (rear pocket).

Figure 9-3 (rear pocket). The entire interval was cored by the South Australian Department of Mines, with core recovery essentially 100%.

The Billy Creek Formation in Yalkalpo 2 comprises red and green shales and siltstones, with common reddish brown sandy intervals. Approximately 265m of strata attributed to the lower portion of the Billy Creek Formation were intersected. The original total thickness of the formation at this locality is unknown, since the upper portion of the sequence has been removed by post-Cambrian, pre-Cretaceous erosion. A moderate to high sand content, and a dominance of non-red sediment differentiates the Yalkalpo 2 sequence from most other known occurrences of the Billy Creek Formation. Certainly these features differentiate it from the Warragee Member, which is defined as the basal member of the Billy Creek Formation in the central and northern Flinders Ranges. At Reaphook Hill, slightly to the east of the main ranges, the basal member (the Coads Hill Member) is considerably sandy and contains appreciable non-red intervals (Chapter 7). However, it also contains a significant number of carbonate units and in particular, two prominent, dark grey, foetid limestone intervals. Thus, the Yalkalpo 2 sequence between 258m and 523m depth is defined as Billy Creek Formation sensu stricto.

The Base of the Billy Creek Formation

Bright olive green, ?tuffaceous shales and fine siltstones of the Billy Creek Formation rest sharply on medium grey, micritic limestones attributed to the Hawker Group. Youngs (1978c) has suggested that the contact is a disconformity.

Palaeontology

Worm burrows are common, and occur mainly in the sandstones, and green shaly intervals. Molluscan trails, and tracks attributed to trilobites occur in both red and green shale although they are slightly more common in the latter.

A.E. Rudd & Co. Stratigraphic Wells

Prior to 1970, twenty eight holes were drilled by A.E. Rudd and Co. south of Lake Frome (Fig. 9-1). Many of the holes terminated in weathered

red-beds, attributed by Daily (1970) to either the Lake Frome Group or the Billy Creek Formation.

Assuming that the tectonic structure of the basin in this region is relatively simple (as suggested by Crusader Oil N.L., 1971), the holes E.A.R. 3, 8, 9, 10, 12, 13, 14, 15, 16, 18, 19, 20, 21, 22, 23, 25, 26, 27 and 28 are all tentatively interpreted as terminating in Billy Creek Formation *sensu stricto*. In most cases, the uppermost 10-20m of the Cambrian sequence are extremely weathered and leached, obscuring most of the original sedimentary features, including the original oxidation state (i.e. whether red or drab in colour). The ?Cambrian strata comprise shale and fine to medium siltstone, which are evenly laminated and commonly micaceous. Desiccation cracks were observed in variegated siltstones of E.A.R. 23.

ENVIRONMENTAL ANALYSIS OF THE BILLY CREEK FORMATION EAST OF THE FLINDERS RANGES

Introduction

Very little data is available on the sedimentology of the Billy Creek Formation to the east of the Flinders Ranges, since most drilling projects terminated as soon as they intersected pre-Tertiary strata (Chapter 2). The E.A.R. holes south of Lake Frome mostly ended in weathered and leached, shaly red-beds, which are too grossly altered to be of much sedimentological use. A few cored intervals in the Delhi-Santos Lake Frome stratigraphic wells revealed the presence of anhydrite in the upper portion of the sequence (Plates 90, 91), however, none of the three holes intersect very much of the Billy Creek Formation.

The bulk of the interpretations in this chapter are thus based on S.A.M.D. Yalkalpo 2, drilled approximately 50km to the east of Lake Frome: and even in this hole, the sequence is incomplete, with the upper portion of the Billy Creek Formation missing due to post-Cambrian erosion. Yalkalpo 2 however, offers a unique opportunity to study a wide range of facies, many features of which are preserved in perfect detail in the borecore.

Facies Analysis

Introduction

The facies described below, unless otherwise stated, are based on examination of the Yalkalpo 2 borecore. Note in particular the relatively coarse grain-size of many of the facies, the absence of carbonates, and the dominance of non-red sediments, which comprise about 65% of the Yalkalpo 2 sequence.

Sandy Facies

There are two sandy facies, although at times they are difficult to distinguish from each other in the borecore. The sandstones comprise very fine to medium-grained arkose and subarkose, with occasional coarser grains and pebble-sized mudstone intraclasts.

Channel sandstone facies

This facies is difficult to recognise in borecore, however some of the sequences in Yalkalpo 2 are quite distinctive. In these examples, green shale is overlain sharply and erosionally by a medium to coarse sandstone unit, 20-35cm in thickness, which contains mudstone intraclasts in the basal portion (Plate 93). The sandstone is poorly bedded and typically fines upwards into evenly bedded to ripple laminated, very fine sandstone or siltstone.

Erosional surfaces are occasionally present between successive sandstone units, and these may also represent channel migration. None of the examples appear to indicate very large or very deep channel development.

Evenly bedded and convolute bedded sandstone facies

Most of the major sandy intervals in the Billy Creek Formation of Yalkalpo 2 are evenly bedded (Plate 94), to ripple laminated (Plate 95), frequently showing signs of loading and convolute lamination (Plates 96 and 97). Units average 2-5m in thickness, and pass gradationally into shales and siltstones of the surrounding sequence. The sandstones are generally pale brown in colour and finer-grained than those of the channel sandstone facies, averaging fine sand-size. Mudstone intraclasts are uncommon and worm burrows rare. Large scale cross-stratification is absent.

Mixed Facies (Sandstone - Green Shale)

Simple flaser and wavy bedded facies

In many cases, the evenly bedded sandstone facies passes vertically into sandstone with green shale or fine siltstone flasers. Simple flaser bedding, with isolated lenses of green shale, is poorly developed and in rare cases the shaly intervals have been reworked to form green mudflake intraclasts. Wavy flaser bedding, with connected lenses of green shale (Plate 98), is more common and compares very well with examples illustrated by Reineck and Wunderlich (1968). Worm burrows and small load structures are common in these facies, particularly in the wavy bedded intervals (Plate 99). Trilobite tracks and molluscan trails occur sporadically on rippled, bedding plane surfaces. Desiccation cracks are rare (Plate 100).

Lenticular bedded facies

This facies is the most common, and probably the most distinctive facies of the Yalkalpo 2 borecore. It comprises isolated ripples and single trains of ripple laminae, separated by intervals of green shale (Plate 101). The ripples are slightly asymmetrical in form, and comprise pale brown to pink, fine to medium sandstone. Load structures are common at the base of ripple trains (Plate 101). The facies is commonly bioturbated, and tracks attributed to trilobites have been found in a few intervals. Desiccation cracks are absent.

Lenticular bedding, as preserved in Yalkalpo 2, has been described in detail by Reineck and Wunderlich (1968) and Reineck and Singh (1975). It is important to note that this lithology, which is so common and well developed in the Yalkalpo borecore, is virtually absent from outcrops of the Billy Creek Formation to the west, in the central and northern Flinders Ranges.

Mixed Facies (Sandstone - Red Shale)

A well developed facies spectrum, from simple flaser bedding, through wavy bedding into lenticular bedding is present in units comprising sandstone and green shale/siltstone. In contrast however, the facies spectrum in the sandstone red shale units is very poorly developed. Simple flaser bedding, comprising red shale flasers in fine to medium-grained, reddish brown sandstone (Plate 102), occurs sporadically throughout the Yalkalpo 2 borecore, but is generally uncommon. Wavy bedding (Plate 103) is also uncommon, although the examples that are present are generally well formed. Desiccation cracks (Plate 104) and arthropod tracks are common in the red shale intervals of the wavy bedded facies. Anhydrite is rare, occurring mainly as secondary patches (Plate 105), although it may also occur as reworked intraclasts (Plate 106). In marked contrast to the facies spectrum in the green intervals however, there is no clearly distinguishable lenticular bedded facies in the red-bed sequence. Instead, wavy bedded units pass gradationally into poorly sorted, silty red-beds devoid of ripple lamination (Plates 107, 108). These fine-grained units are commonly disrupted by desiccation cracks and anhydrite (Plates 109,110).

Shaly Facies

Green shaly facies

Evenly laminated green shales and fine siltstones are uncommon in the Yalkalpo 2 borecore. Green shaly intervals devoid of sandstone lenses rarely exceed 1m in thickness, and are generally associated with the green lenticular bedded facies. In some cases, the facies comprises graded beds, from 0.5-2.5cm in thickness, with medium-grained siltstone at the base, fining upwards into green shale at the top. Arthropod tracks are rare.

Variegated shaly facies

A small proportion of the Billy Creek Formation in Yalkalpo 2 comprises evenly laminated to evenly bedded, variegated shale and fine to medium siltstone. This facies however, appears to be much more common in the E.A.R. and Delhi-Santos Lake Frome borecore. The alternations of red and green sediment, from a few millimetres to a few centimetres in thickness, are conformable with bedding. In some cases, laminae are graded, from green siltstone at the base to red shale in the upper portion. Desiccation cracks are common, and halite casts, arthropod tracks, worm burrows and rarely anhydrite patches and veins have been found in association with the facies.

Red shaly facies

Red shales and fine to medium siltstones dominate the Billy Creek Formation in the Delhi-Santos Lake Frome borecore, and are also very common in the E.A.R. holes. However, only a minor proportion of the sequence in Yalkalpo 2 comprises shaly red-beds. The facies is generally poorly bedded and poorly sorted, although some very well laminated shales are recorded from Yalkalpo 2 (Plate 111). Desiccation cracks are abundant, and halite imprints are common in some units. In much of the Delhi-Santos borecore, and in a few intervals in the Yalkalpo 2 core, bedding is further disrupted by patches and secondary veins of anhydrite. Arthropod tracks have been recorded at only rare intervals in the sequence.

Facies Associations and their Interpretation

Although cyclic sedimentation occurs in part of the Yalkalpo 2 borecore, it is not a prominent feature of the sequence. The cyclicity occurs mainly between shaly red-beds, with abundant desiccation cracks and evaporites, and slightly coarser-grained, green or greyish green sediments, devoid of desiccation features and showing evidence of abundant organic activity. Cycles vary in thickness from 1-10m, and average about 2.5m. The green sediments are interpreted as having been deposited in a low to moderate energy, shallow subtidal environment, whereas the red-beds accumulated in a very low energy intertidal or supratidal environment.

The sequence is complicated however by the presence of sandy intervals, which generally are associated with green shales and siltstones. Coarsening-upward cycles occur in some of the units, while many others appear to first coarsen upwards, and then fine upwards. In most cases, the sandstones appear to be subtidal in origin, and accumulated in environments where wave and tidal energy was most strongly concentrated. The transition zone between shale and sandstone is characterised by simple and wavy flaser bedding.

DEPOSITIONAL MODEL

A depositional model for sediments in the Billy Creek Formation to the east of the Flinders Ranges is presented in Figure 9-4. Poorly sorted, shaly red-beds accumulated on high intertidal to supratidal mud flats, and in some cases were associated with evaporite formation. This facies is particularly well represented in the Delhi-Santos Lake Frome borecore, but is less common in the Billy Creek Formation at Yalkalpo 2.

In the lower intertidal zone, shaly and fine silty sediments are commonly variegated. Crawling tracks indicate that the environment was capable of supporting arthropods and rare molluscs, although common desiccation cracks emphasise the intertidal origin of these sediments.

In many cases, the variegated sediments pass gradationally into subtidal, green, evenly laminated shales or lenticular bedded shales with minor fine sandstone. Graded bedding in some of the units emphasises the low energy of the environment, with deposition primarily by suspension settling. Worm burrows and arthropod tracks, although present in the green shales, are not very common, presumably because the sediment was too muddy to preserve the arthropod tracks, and too fine-grained for most organisms to construct stable burrows.

Sandy intervals in the Yalkalpo 2 borecore are interpreted as moderate energy, lower intertidal to shallow subtidal sand flats. The paucity of large scale cross-stratification is considered to be unusual, although Reineck (1967) has noted that dunes and meggaripples are commonly absent in the very shallow zones of broad tidal sandflats. The absence of meggaripples is probably also due to the fine grain-size of the sand (average very fine to fine),

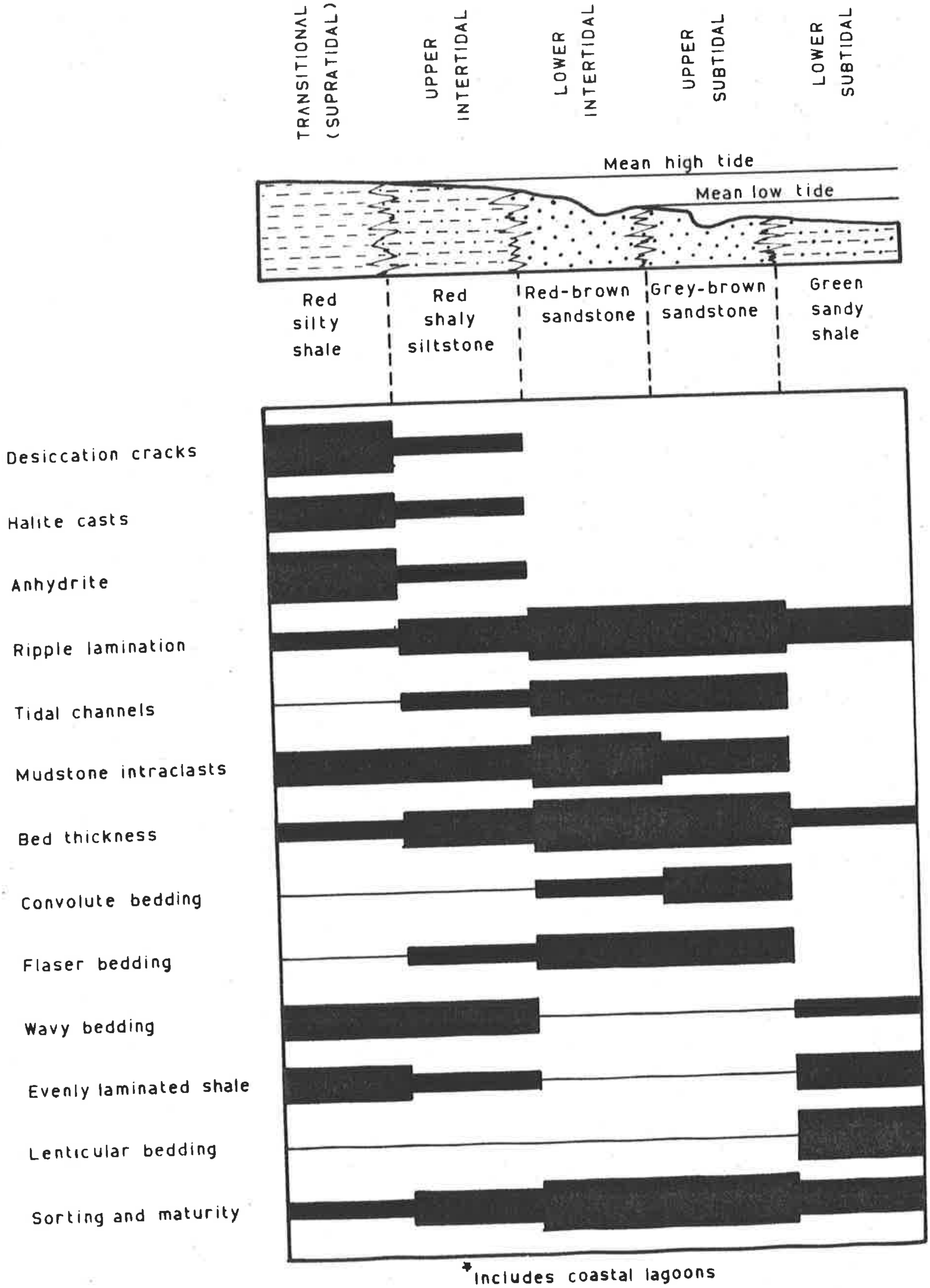


Figure 9-4. Depositional model for the Billy Creek Formation as intersected in Yalkalpo 2, east of Lake Frome.

which is considered to be responsible for the abundance of convolute lamination. Reineck and Singh (1975) have reported similar examples of convolute lamination from fine-grained sandy tidal flats along the North Sea coastline.

Further evidence for the tidal origin of the evenly bedded and convolute sandstones is the presence of small sandy channels in the sequence, the bases of which are occasionally lined with mudstone intraclasts. Gradations from sandstone to red shale are present, but are generally not very well defined. The sandflats appear to pass landwards into mixed flats with poorly defined simple flaser bedding, and then into wavy bedded intervals, where sandstone and red mudstone occur in approximately equal proportions. Still further landwards, the sand becomes subordinate, and evenly laminated shales and poorly sorted siltstones dominate the sequence. Note particularly the absence of a lenticular bedded red shaly facies in this transition.

The sandflats also appear to be transitional into green shales and siltstones, however it is not known whether this transition represents a change into deeper water or simply a change into more protected conditions of deposition. The transition from the sandflat facies into the green shale facies is well developed, as the energy of the environment of deposition is gradually decreased. Evenly bedded sandstones thus give way to simple and wavy flaser bedding, which in turn passes gradationally into well developed lenticular bedding and finally into green shales devoid of sandy laminae. The development of lenticular bedding appears to be related to a constant, although relatively small input of energy (possibly from wave action) which enables the sediment to become sorted into its two constituent grain-sizes (fine sand and mud). Since this process of constant reworking is restricted mainly to the subtidal and lower intertidal zones, it is not surprising that well developed lenticular bedding is absent from the red-bed facies.

CONCLUSIONS

Conclusions regarding the depositional history of the Billy Creek Formation in the Lake Frome region are limited by the paucity of drillhole data. Most significantly, the total thickness of the formation in this region remains unknown.

The upper portion of the Billy Creek Formation, as intersected in the Delhi-Santos Lake Frome wells, comprises shaly red-beds rich in anhydrite. Deposition was most probably on muddy supratidal flats similar to those reported by Thompson (1968, 1975) from the Gulf of California. The absence of the Eregunda Sandstone Member in this locality suggests that the main deltaic sand body lay to the south and southwest of the Lake Frome wells. Once again, a comparison can be made with modern sediments in the Gulf of California, where shaly red-beds are accumulating on tidal flats adjacent to the Colorado River Delta (Thompson, 1968).

The Billy Creek Formation in Yalkalpo 2 is at least partly equivalent to the Warragee Member in the central and northern Flinders Ranges. A more precise correlation is not possible, since no trilobites have been found to date and there are no major tuff bands in the Yalkalpo 2 core. The absence of major tuffaceous intervals is attributed to reworking and redistribution of the volcanic fallout. The inability to find trilobites is unfortunate, considering the abundance of green shale in the Yalkalpo core. One possibility is that the small Emuellid trilobites, which have been found in the upper portions of the Warragee and Coads Hill Members, represent a younger time interval than anything preserved in the Yalkalpo 2 borecore. This would infer that the Billy Creek Formation in Yalkalpo 2 is entirely equivalent to the lower and possibly middle portions of the Warragee and Coads Hill Members. However, it appears that only further drilling will adequately resolve this problem.

The most important aspect of the Billy Creek Formation in the Yalkalpo 2 core is its predominantly green and greyish green colour, indicating deposition under reducing conditions. The bedding structures and facies associations suggest that deposition was mainly in a low to moderate energy, shallow marine environment. This is in contrast to sediments of the Warragee Member, which were deposited on muddy tidal flats, commonly in the intertidal zone. Thus, it would appear that during the early stages of deposition of the Billy Creek Formation, shallow marine conditions existed in the Lake Frome region, while the basin was flanked on the western margin by a broad zone of muddy tidal flats. The presence of sandstones, and the absence of carbonate units in the Billy Creek Formation in Yalkalpo 2 is further evidence of the relatively energetic, open water conditions of deposition in this region.

CHAPTER 10

PETROLOGY OF THE BILLY CREEK FORMATION

INTRODUCTION

In the course of this study, nearly 1000 thin sections were prepared. Major rock-types were identified and these were grouped into the four lithological associations discussed below. Thin-section identification numbers are included for reference purposes in Appendix C.

LITHOLOGICAL ASSOCIATION 1 - THE MICACEOUS, ARKOSIC, CLASTIC ASSOCIATION

This association comprises red and minor green sandstones, siltstones and shales. Sediments are characterised by a high feldspar content (generally more than 25%), abundant mica (including biotite) and an immature heavy mineral suite. Indications are that the sediments were derived from Precambrian basement rocks cropping out in the Broken Hill-Olary region.

Red Arkosic Sandstones

Red sandstones, rich in feldspar and mica, characterise outcrops of the Eregunda Sandstone Member,but also occur sporadically in the underlying Nildottie Siltstone Member and its lateral equivalent, the Erudina Siltstone Member. Red sandstones occur rarely in the Yalkalpo 2 borecore. Point count analyses of 20 thin sections from this lithology are summarized in Table 10-1 and Figure 10-1a. The details of the individual modal analyses are presented in Appendix C. Using the classification of Folk (1974), the sandstones lie clearly within the arkose field. In general, the lithology comprises moderately well sorted, fine to very fine, micaceous arkose (Plate 112). Rock colour (as defined by the U.S. Geological Survey rock colour chart; Goddard, 1951) is typically greyish red. The colour is due to an haematite cement, which coats the grains and fills small interstitial spaces (Plate 113). A notable feature is the relative abundance of biotite, which comprises up to 3% of the rock and generally is as abundant as muscovite. Another important feature is the fairly low proportion of heavy minerals in this lithology, and their considerable mineralogical diversity.

Table 10-1. Modal Analyses, Lithological Association 1 Rocks.*

Modal component		Red sandstones (20 analyses)	Red siltstones (visual estimate)	Green sandstones (5 analyses)
Quartz		42.4	40.0	46.0
Orthoclase		20.0	15.0	16.0
Microcline		0.2	0.2	-
Perthite		0.4	0.2	0.2
Plagioclase		3.0	3.0	2.6
Muscovite		1.9	5.0	3.5
Biotite		1.3	5.0	3.0
Heavy minerals		1.1	2.0	1.0
	sedimentary	0.8	-	3.1
Rock	igneous	-	-	-
fragments	metamorphic	0.5	-	-
	indeterminate	0.5	-	0.8
Overgrowths		11.0	4.5	13.8
Iron cement		11.6	15.0	1.4
Carbonate cement/matrix		0.7	-	2.6
Indeterminate matrix		4.7	10.1	5.8
Total		100.1	100.0	99.8
Q : F : R		63 : 35 : 3	68 : 32 : 0	67 : 27 : 6
Clan name		feldsarenite	feldsarenite	feldsarenite

*For details of individual analyses, refer to Appendix C and Figure 10-1.

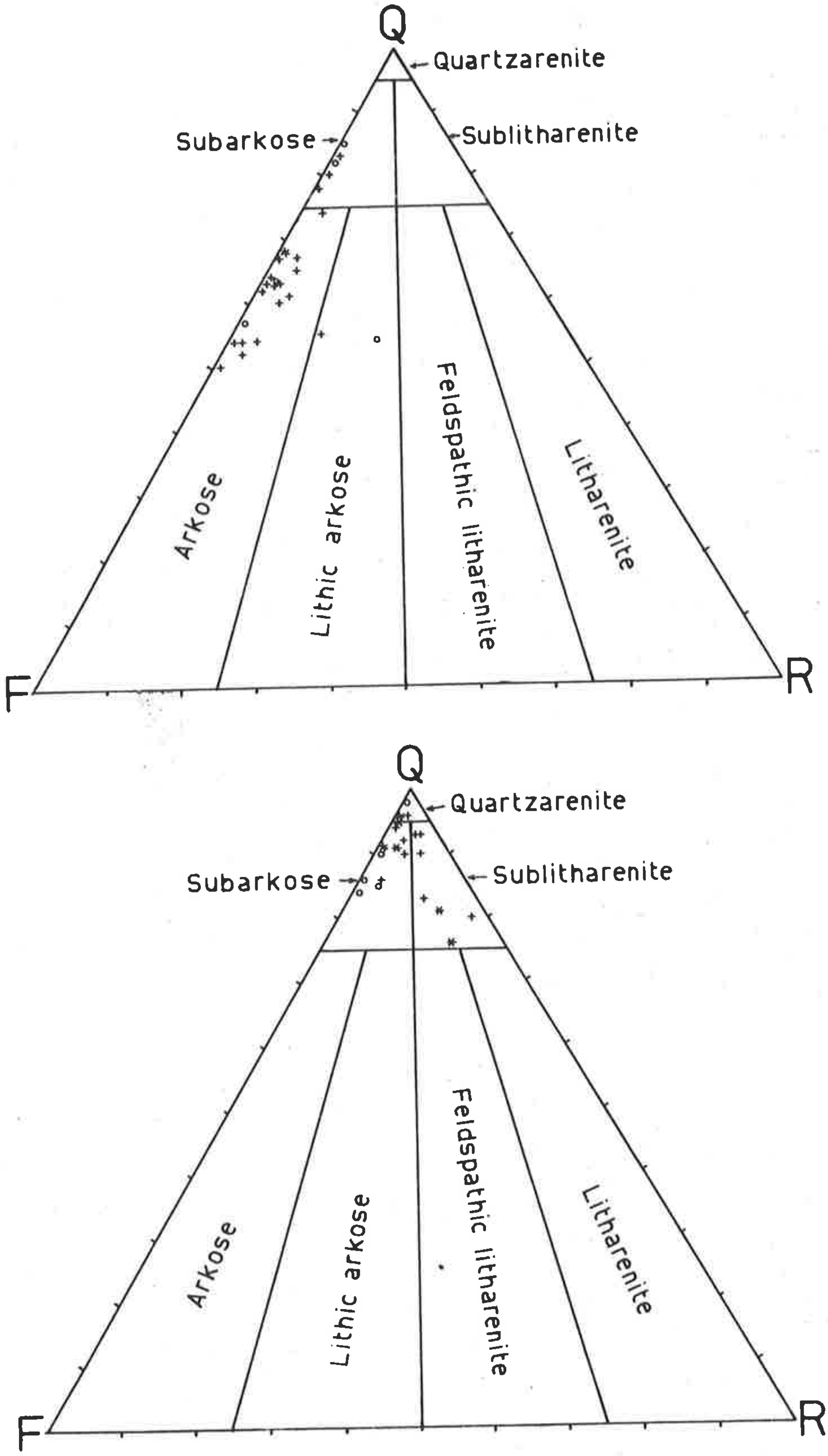


Figure 10-1. Composition of sandstones in the Billy Creek Formation.
A: Lithological association 1 arkosic sandstones. Crosses are red sandstone, circles are green sandstone.
B: Lithological association 2 sandstones. Crosses are relatively massive calcarenite sandstone. Stars are immature sandstones. Circles are mature sandstone devoid of appreciable carbonate grains and cement.

Red Arkosic Siltstones

Red siltstones, rich in feldspar and particularly mica, characterize outcrops of the Nildottie and Erudina Siltstone Members, and occur sporadically throughout most other occurrences of the Billy Creek Formation, with the exception of the Coads Hill Member at Reaphook Hill. Most are non-calcareous to very weakly calcareous, however samples from the eastern areas (Reaphook Hill and in the subsurface below the Lake Frome Embayment) commonly contain appreciable interstitial calcite cement. Rarely, the arkosic red siltstones contain anhydrite. Visual estimates of average modal composition of thin sections from this lithology are summarized in Table 10-1. The red arkosic siltstones are very similar in composition to their coarser-grained, sandy counterparts, however important differences are the greater percentage of haematite cement and clay matrix, and in the greater proportion of micas in the siltstones. Also, they tend to have a slightly higher feldspar to quartz ratio, and the grains are subangular to subrounded, whereas the red sandstones comprise predominantly subrounded grains.

Red Shales

Red shales, containing appreciable feldspar and abundant mica, characterize outcrops of the Warragee Member, and Unit A of the Erudina Siltstone Member. Red arkosic shales are interbedded with coarser-grained clastics in the rest of the Billy Creek Formation, with the exception of the bulk of the Coads Hill Member at Reaphook Hill. Most are weakly calcareous, however a few samples from the eastern areas contain appreciable carbonate, both as a matrix and cement. One sample from the Warragee Member near Balcoracana Creek (BC-R4) contains abundant fine veins of calcite replacing anhydrite. The shales and fine red siltstones contain abundant mica, which, by way of contrast with the arkosic sandstones, is predominantly muscovite. Although the micas are commonly aligned in the plane of the bedding many are not, and a feature of the coarser grained, silty shales is the poor sorting of these sediments.

Green Arkosic Sandstones

Green sandstones, rich in feldspar and mica, are a minor lithology in the Billy Creek Formation. They occur sporadically in the Eregunda Sandstone Member, and also in the Yalkalpo 2 borecore east of Lake Frome. Point count analyses of 5 thin sections from the lithology are summarized in Table 10-1 and Figure 10-1a. The details of the individual modal analyses are presented in Appendix C. Mineralogically, the green sandstones of the arkosic association vary little from their red counterparts. Both are rich in feldspar and mica, and in both cases the biotite tends to be grossly oxidised (Plate 114). The most significant difference however is in the virtual absence of haematite cement, which makes the green sediment appear more mature. In place of the haematite cement there are quartz overgrowths, carbonate and presumably a small amount of ferrous oxide cement. Thus, there are two factors which probably have contributed to the green colour of the sediment. Deposition in channels, particularly where the channels are cut into shaly sequences, suggests that a constantly high water table was available to restrict the oxidation of the sediment. Also, the abundance of organic markings in these sediments, and the fact that they are channel deposits suggests that reduction may have been promoted by a high organic content.

Green Arkosic Siltstones

The green arkosic siltstones are similar to their coarser-grained equivalents, discussed above, apart from their finer grain-size and greater proportion of muscovite and biotite. The lithology is generally associated with the green sandstones in the Eregunda Sandstone Member, but also occurs rarely in the Nildottie Siltstone Member. Green siltstones also occur in the Warragee Member and especially in the Yalkalpo 2 borecore. Reduction of the sediment occurred as a result of quiet water deposition well below the mean water table, and was promoted by the presence of organic material.

Green Shales

Green, micro-micaceous shales are common in the Warragee Member and in parts of the Yalkalpo 2 borecore. Green shales also occur sporadically throughout other units within the Billy Creek Formation. The shales are evenly laminated, and in the Warragee Member are commonly found in association with dolomitic limestone. The shales comprise very fine, angular to subangular quartz and feldspar grains, with accessory opaque oxides and common flakes of mica. Most of the mica is muscovite, although some oxidised biotite is present. Diagenetic and low grade metamorphic chlorite is a minor constituent of most samples.

LITHOLOGICAL ASSOCIATION 2 - CALCAREOUS SANDSTONE ASSOCIATION

This association comprises sandstone, with minor siltstone and shale. It is differentiated from the arkosic association by its low content of feldspar and mica, and by a relatively high proportion of heavy minerals. Grains are typically subrounded, and a very high ZTR index (average 95%) indicates that the rocks are mineralogically mature. Thus, the calcareous sandstone association comprises multi-cycle clastic detritus, presumably reworked from older, relatively unmetamorphosed sediments (Bunkers Sandstone or possibly Adelaidean strata) adjacent to the basin margin. Since the sediments occur mainly in the Coads Hill Member at Reaphook Hill, a local source to the south-east of Reaphook Hill is inferred. The absence of Association 2 sediments in the upper part of the Billy Creek Formation suggests that only Precambrian crystalline basement rocks were exposed and being eroded from the various source areas at this period of time.

Sandstones without Carbonate Grains or appreciable Carbonate Cement

Pale brown quartzarenites and subarkoses characterize outcrops of Units B and D of the Coads Hill Member at Reaphook Hill, and also outcrop sporadically throughout the rest of the member. Point count analyses of 5 thin sections are summarized in Table 10-2 and Figure 10-1b. The details of the individual modal analyses are presented in Appendix C. The rocks generally comprise subrounded to rounded, medium-grained sandstone (Plate 115). The major mineral is quartz, however feldspars constitute up to about 11% of the cross-sectional area of many samples. The dominant feldspar is orthoclase,

Table 10-2. Modal Analyses, Lithological Association 2 Rocks.*

Modal component	Submature sandstones (5 pt. counts)	Calcarenitic sandstones (10 pt. counts)	Immature sandstones (3 pt. counts)	Very immature sandstones (3 pt. counts)
Quartz	69.8	63.2	60.9	44.7
Orthoclase	3.7	1.4	1.3	1.1
Microcline	1.7	1.0	1.3	1.1
Perthite	1.0	0.1	0.4	0.5
Plagioclase	1.9	0.6	1.1	0.4
Muscovite	-	-	-	0.1
Biotite	-	-	-	-
Heavy minerals	0.5	0.4	0.8	0.1
Rock fragments sedimentary	0.6	3.8	0.5	4.7
Rock fragments igneous	-	-	-	-
Rock fragments metamorphic	-	-	-	-
Rock fragments indeterminate	-	-	-	-
Overgrowths	14.8	9.0	6.0	3.1
Iron cement	-	-	2.7	-
Carbonate cement/matrix	2.6	18.4	-	3.9
Indeterminate matrix	3.4	1.9	24.9	40.4
Total	100.0	99.8	99.9	100.1
Q : F : R	89 : 11 : 1	90 : 4 : 5	93 : 6 : 1	85 : 6 : 9
Clan name	subfelsarenite	sublitharenite	subfelsarenite	sublitharenite

*For details of individual analyses, refer to Appendix C.

however microcline is also common. In contrast with Association 1 arkoses, plagioclase is only a minor constituent. Heavy minerals are common by comparison with their Association 1 counterparts, and comprise mainly rounded grains of tourmaline and zircon. Grains are cemented mainly by quartz, although an haematite cement is developed in some samples. In most cases, the sandstones are well sorted and well washed, and thus only a minimal amount of clay and fine silt matrix is present.

Calcarenitic Sandstones

Pale brown to cream calcarenitic sandstones are common in outcrops of Units B and F of the Coads Hill Member at Reaphook Hill, and also outcrop in several other units within the member. In addition, there is a thin unit of calcarenitic sandstone at the base of the Warragee Member in three small basinal structures near Balcoracana Creek. The sandstones are evenly bedded, with minor cross-stratification and ripple lamination. Point count analyses of 10 thin sections from this lithology are summarized in Table 10-2, Figure 10-1b. The details of the individual modal analyses are presented in Appendix C. Using the classification of Folk (1974), the calcarenitic sandstones lie mostly within the sublitharenite field. In general, the lithology comprises subrounded, medium-grained quartz and minor feldspar with accessory heavy minerals, set in a carbonate cement. Many samples contain abundant sand-sized carbonate grains (Plate 116), although some are virtually devoid of them. The carbonate grains are mainly recrystallised micrite (microsparite), although coarse sparite aggregates are common. Intergranular spaces are typically filled with medium-crystalline calcite, which in some cases has been converted to dolomite. Quartz overgrowths are minor. The original texture was probably that of a grainstone, with only minor carbonate mud matrix.

Immature (slightly clayey) Sandstones

Reddish brown, immature quartzarenites, with only about 5-10% clay matrix, outcrop sporadically throughout the sandy units of the Coads Hill Member at Reaphook Hill. The rocks are extremely similar to the quartzarenites and subarkoses discussed above, except for the clay cement (Plates 117 and 118). Point count analyses of thin sections from this lithology are summarized in Table 10-2, Figure 10-1b. Based on the classification of Folk (1974), the sandstones are quartzarenites and subarkoses. Carbonate fragments are rare. The matrix is dark greenish grey in colour, and comprises clays, sericite and minor chlorite and iron oxide. Grains are closely packed, and are cemented by opaque iron oxide.

Very Immature (clayey) Sandstone

Greyish red, very immature sublitharenites, with 20-40% clay matrix, outcrop in Unit C of the Coads Hill Member at Reaphook Hill. The sequence has been interpreted as a continental (alluvial plain) deposit (Chapter 7), largely due to the extreme poor sorting of the sediment and the lack of fossils and their traces. Point count analyses of thin sections from this lithology are summarized in Table 10-2 and Figure 10-2b. The rocks comprise very poorly sorted, medium-grained sandstone. Grains are typically subrounded to rounded, and their high roundness index contrasts strongly with the poor sorting of the sediment and the abundance of fine-grained matrix (Plates 119 and 120). The sand grains have thus passed through a moderate to high energy (probably fluvial) environment and then been dumped, with minimal sorting, in a low energy (alluvial plain) environment.

The presence of up to 10% coarse sand and granule-sized carbonate grains indicates that part of the source area comprised limestone. Furthermore, the relatively coarse grain-size and the subrounded to subangular shape of the carbonate grains indicates that the source of this detritus was relatively close. Carbonate clasts comprise mainly medium crystalline sparite, with minor micrite and microsparite. Carbonate is also present as synsedimentary veins parallel to bedding (eg. RH-C8), which may indicate minor calcrete development during periods of non-deposition. A fine-grained interval, 2cm thick in sample RH-G12 shows a distinctive muddy profile, with a superimposed subvertical microstructure typical of palaeosols

(Retallack, 1976, 1977).

LITHOLOGICAL ASSOCIATION 3 - CARBONATES

This association comprises a variety of limestones, dolomitic limestones and dolomites, many of which contain minor clastic impurities. Subdivision into lithotypes is based primarily on the textural classification of Dunham (1962). In addition, the group 'calcisiltites' is added to describe those carbonate sediments which comprise silt-size grains.

Carbonate Mudstones

Micrites and dolomicrites occur sporadically in the Warragee Member, particularly in the Wirrealpa Basin, and also in Unit H of the Coads Hill Member at Reaphook Hill. Minor silty laminae, with both carbonate and terrigenous clastic detritus, occur in some samples. The silty beds are attributed to weak wave and current activity in a very low energy environment. They generally rest sharply and in some cases are loaded onto the underlying carbonate mudstone, and grade upwards into micrite. In Unit H of the Coads Hill Member at Reaphook Hill, the carbonate mudstones are shaly and nodular, with relatively pure carbonate nodules surrounded by shaly micrite.

Calcisiltites

Calcisiltites comprise predominantly silt-sized carbonate detritus, although many examples from the Billy Creek Formation contain up to 20% terrigenous silt and fine sand. Calcisiltites are not characteristic of any one member of the Billy Creek Formation, but rather occur sparadically throughout the sequence, representing deposits of moderate energy, generally interbedded in a low energy, muddy sequence. Silt sized carbonate grains are typically angular to subangular, and indicate minimal transport of microcrystalline detritus. They are cemented by finely crystalline sparite, and are difficult to distinguish even in thin section from slightly recrystallised micrites (microsparites). Generally however, the abundance and dispersed nature of the terrigenous silt grains in the rock is a diagnostic feature of these sediments.

Wackestones

Carbonate wackestones occur sporadically throughout the Warragee Member, in limestones of the Coads Hill Member, and in Unit A dolomites of the Erudina Siltstone Member. They vary from slightly sandy micrites to extremely sandy sediments. Terrigenous grains dominate the sandy fractions of some samples, particularly those in which sand-sized grains are uncommon. The terrigenous sandy fraction comprises dominantly subangular quartz, with minor feldspar and muscovite. Carbonate intraclasts are subrounded and micritic. The sandy micrites were thus deposited in a low energy carbonate environment subject to occasional terrigenous input.

Wackestones which are rich in sand-sized detritus are common at Reaphook Hill, particularly in the carbonates of Unit E and Unit G. The sandy grains comprise mainly subrounded to subangular carbonate intraclasts, although carbonate peloids are abundant in some samples, and quartz and feldspar are generally uncommon. These sediments were deposited in a low to moderate energy environment, adjacent to a much more energetic region of carbonate deposition. Wackestones in Unit A of the Erudina Siltstone Member contain appreciable oxidised mica, indicating minor but persistent terrigenous input.

Packestones and Grainstones

Packestones (with a carbonate mud matrix) and grainstones (well washed and cemented by sparite) are rare in the Billy Creek Formation, being restricted to a few thin beds in the uppermost portion of the Coads Hill Member. The carbonates comprise mainly fine to very fine sand-sized peloids with minor fossil fragments. Terrigenous detritus is rare. The sediments presumably accumulated in moderate to high energy carbonate-rich environments and were carried into the Reaphook Hill area by storms or unusual high tides.

Boundstones

Flat algal laminates and domal stromatolites are present in several carbonate interbeds in the Warragee Member, and also occur in Unit H of the Coads Hill Member at Reaphook Hill. In addition, a silty stromatolitic interval in the Lake Frome borecore (sample LFI-1672) is associated with anhydrite. The boundstones comprise dark grey to buff micrite, with common silt and fine sand laminae. The dark colour of the micrite is attributed to an high organic content. Domal stromatolites commonly contain angular micrite intraclasts up to 2mm in length, re-bound into the stromatolitic structure. Carbonate peloids may also be associated with the stromatolitic intervals, however ooliths have not been identified from any of the sections.

LITHOLOGICAL ASSOCIATION 4 - TUFFS AND TUFFACEOUS SEDIMENTS

Tuffs and tuffaceous shales and siltstones occur sporadically throughout the lower half of the Billy Creek Formation, and are known at rare intervals higher in the sequence. The abundance and thickness of tuff beds increases from northwest (in the Mount Scott Range) to southeast (near Wirrealpa) in the Flinders Ranges, with tuff beds particularly prominent at Reaphook Hill, approximately 50km east of Wirrealpa. Tuffs also occur in the Billy Creek Formation in the Yalkalpo 2 borecore, 50km east of Lake Frome. In the Yalkalpo 2 core, volcanic fragments up to 2.5mm across are set in a fine-grained, chloritic matrix. These are the largest volcanic fragments found in the Billy Creek Formation to date, and together with the overall distribution and thickness patterns of the tuff beds, indicate that the source of the volcanic detritus lay to the east or southeast of the present outcrops of the Billy Creek Formation.

Since the Billy Creek Formation is late Early Cambrian to early Middle Cambrian in age (Daily, 1956, 1976b), the likely source of the tuff is the Mt. Wright region, about 120km northeast of Broken Hill in New South Wales. In this region, a thick sequence of intermediate and basic volcanics and tuffs, with chert interbeds and uncommon archaeocyathid-bearing limestone lenses (the Mt. Wright Volcanics) is overlain by the late Early Cambrian Cymbric Vale Formation (Öpik, 1968, 1976). The Cymbric Vale Formation comprises a thick sequence of fine-grained clastics and chert, with minor interbeds of tuff, andesite, acid volcanics and limestone (Neef and Tuckwell, 1978). The formation is broadly correlated with the Ajax Limestone (Kruse, 1977), however Warris (1967) and Öpik (1968, 1976) recorded Estaingia bilobata Pocock from the upper part of the sequence, and thus correlate the uppermost Cymbric Vale Formation with the Billy Creek Formation. Tuffs in the Cymbric Vale Formation are grossly altered, but were considered by Warris (1967) as being derived from intermediate igneous rocks similar in composition to parts of the underlying Mt. Wright Volcanics. Scheibner (1972) considered the Mt. Wright Volcanics to have been produced by island arc volcanism along the 'Mt. Wright Volcanic Arc', which supposedly extended from Mt. Wright north to Mt. Arrowsmith. Thus, volcanic material in the Cymbric Vale Formation and in the Billy Creek Formation indicates waning volcanism along the island arc, possibly as the Gnalta Shelf stabilized.

Most distinguishable tuffaceous rocks in the Billy Creek Formation comprise crystal tuffs, with shards of quartz, feldspar and altered mafic minerals set in a fine-grained matrix (Plate 121). Feldspars are common, comprising up to 60% of the shard assemblage of many tuffs (Plate 122). K feldspar and plagioclase occur in subequal proportions, with the majority of the K feldspar present as perthite and the rest as orthoclase. Plagioclase composition, based on extinction angles of crystals with albite or combined albite-carlsbad twins, is typically sodic andesine. Weak compositional zoning is common. Several thick carbonate-rich tuff beds south of Wirrealpa contain plagioclase shards with albitic rims.

Quartz comprises up to 40% of the shard assemblage in many tuffs, with crystals generally displaying the high temperature beta form and resorption patches infilled with fine-grained tuffaceous detritus (Plate 123). Minor mafic minerals are present, however they are all grossly altered to chlorite, sericite and brown ?'iddingsite-bowlingite', and thus the original composition is unknown. In addition, up to 5% of the clast assemblage comprises fragments of fine-grained volcanic material, largely sericitized, but similar in appearance to the fine-grained matrix which surrounds the crystal shards.

The tuffs of the Billy Creek Formation are distinguished in the field primarily by their colour, which is typically either salmon pink or light olive green. The pink coloured tuffs are carbonate rich, and alteration of feldspars to sericite and clay, and replacement by calcite is the major form of alteration. The high carbonate content of the tuffs is attributed to their deposition in a carbonate-rich environment, and is not considered to be related to the original composition of the tuffaceous detritus. The olive green colour of many of the tuffs is due to extensive chloritization of the matrix (Plate 121);a feature typical of many pyroclastic rocks. These rocks are typically devoid of carbonate. In general, outcropping tuffs in the Billy Creek Formation contain crystal shards which are much more altered than their counterparts in the subsurface to the east, suggesting that much of this alteration is due to surface weathering. In a few examples, very dark brown to black patches may represent oxidised chlorophaeite, due to alteration of vitric shards. A thin crystal tuff in the Delhi-Santos Lake Frome No. 1 borecore is associated with anhydrite.

Assuming that the sixteen tuffaceous intervals examined by the author are representative of the composition of the tuffaceous detritus in the Billy Creek Formation, a rhyodacitic, and in a few cases, a dacitic origin for the tuff is inferred. These compositions support the view that the tuffs of the Billy Creek Formation were derived from the Mt. Wright Volcanic Arc during the later stages of its existence, when intermediate and acid volcanism predominated.

ORIGIN OF RED AND VARIEGATED SEDIMENTS OF THE BILLY CREEK FORMATION

Introduction

Red coloured sediments comprise approximately 85% of the Billy Creek Formation in the type section near Wirrealpa (Daily, 1956; Moore, in press), and are even more predominant in outcrops to the west (Heysen Range) and northwest (Mt. Scott Range). In all of these areas, non-red sediments are restricted to minor, thin, green shale intervals in the Warragee Member, and rare green sandstones, siltstones and shales in the Eregunda Sandstone Member. Further east, at Reaphook Hill and in the Yalkalpo 2 borecore, appreciable non-red intervals are present in the lower part of the Billy Creek Formation.

This study examines the nature and distribution of the red cement in the Billy Creek Formation, in order to evaluate the processes responsible for its formation. A similar study by Stock (1974) on the red-beds of the Middle to ?Late Cambrian Lake Frome Group concluded (p.91) that "ferric pigment is probably inhereted directly from red soil and derived from limonite in the source area or in transit by post-depositional conversion from brown to red minerals". Stock (1974) considered that intrastratal alteration of iron minerals constituted a negligible source of red pigment. Although the present study shows that the conversion of limonite to haematite was an important process in the formation of the red-beds of the Billy Creek Formation, the factors controlling the development of the red pigment were considerably more complicated than Stock (1974) envisaged.

The Red Bed Problem

The origin of the haematite pigment in ancient red-beds has long been a focus of interest for geologists, and a centre of controversy. For a review and summary of research carried out prior to 1962, see Van Houten (1961). Up until about 1966, the view was held that red-beds were valuable palaeo-climatic indicators, and that most red-beds were formed in tropical-humid and warm savannah climates. Proponents of this hypothesis argue that the haematite cement forms in lateritic soils in the source area and is subsequently transported to desert basins where it is preserved. However, the whole red-bed problem was re-opened by Walker (1963, 1967a, 1967b) when he showed that red-beds could develop diagenetically in hot desert climates, mainly by *in situ*, intrastratal weathering of heavy minerals during deep burial, aided by aging. A third alternative for red-bed formation which has since received considerable attention (see Van Houten, 1973) was suggested by Friend (1966). Friend related red-bed cyclicity in the Catskill Mountains to variations in the oxidation-reduction potential due to watertable fluctuations. Walker (1974) expanded this idea, and suggested that it may be possible to form red-beds in moist climates by processes of intrastratal alteration. In summary, research over the last decade has repeatedly emphasised the danger in assigning haematite-pigmented sediments to a particular climatic regime. Rather, red-beds form where the physical and chemical conditions are suitable, regardless of climate.

Folk (1976, p.605) considers that there are three basic prerequisites which are necessary for red-bed formation:

(a) some source of abundant iron - either heavy minerals or ferruginous clays;

(b) deposition above or not very far below the water table, for readier access of oxygen;

(c) rate of organic accumulation must be exceeded by the rate of oxidation or destruction of organic matter.

In the red intervals of the Billy Creek Formation, all of these three prerequisites are met. The sediments are micaceous and arkosic, containing up to 10% biotite (av. 2-3%) which is a very unstable, iron-rich mineral. The red-beds are typically associated with halite pseudomorph casts and desiccation cracks, indicating frequent subaerial exposure. Since the Billy Creek Formation (Cambrian) was deposited prior to the evolution of land plants, the rate of organic accumulation may have been low, considering the restricted, tidal flat environment of deposition of the sequence.

Furthermore, the abundant evidence of evaporite precipitation in the Billy Creek Formation red-beds suggests that the climate was warm and dry, and, as pointed out by Folk (1976, p.605) "the lack of vegetation and low water table in deserts provides ideal circumstances for oxidation".

Source of the Red Pigment in the Billy Creek Formation

Numerous studies on ancient red-beds have shown that the source of the red pigment is amorphous and microcrystalline haematite. Possible sources of the haematite are:

(a) detrital;

(b) *in situ* dehydration of limonite;

(c) *in situ*, intrastratal weathering of iron-rich minerals.

There is no evidence in the Billy Creek Formation that any of the pigment was detrital in origin. Although detrital haematite is a source of pigment for some red-beds (eg. Schulger, 1976), Van Houten (1973, p.50) notes that "actively eroded uplands in almost any climate, and regardless of the colour of their soils, generally deliver brown to greyish-brown sediment". This observation alone implies that the red colour of most red beds developed after deposition. In poorly sorted sandstones and mudstones of the Billy Creek Formation, pigment is commonly present between grains (Plate 124), suggesting introduction of free ferric oxide during sedimentation. Furthermore, ferric oxide cements are also common surrounding quartz overgrowths, indicating that formation of pigmenting oxide continued even after very early diagenetic silica cementation. Thus, there is abundant evidence of *in situ* formation of ferric oxide cement in the Billy Creek Formation red-beds.

Silt and clay fractions in the Billy Creek Formation red-beds generally are more strongly stained by haematite than associated coarser sediments (Plates 125 and 126). This is a general characteristic of many red-beds, and in the past led some authors (eg. Krynine, 1949; Stock, 1974; Van Houten, 1964, 1968) to conclude that the clay fraction was derived from iron-oxide rich soils, formed in moist regions characterized by intense weathering.

However, Walker et al. (1967) showed that much of the clay in Pliocene red-beds in Baja, California, comprised iron-rich montmorillonite formed by in situ intrastratal solution of hornblende. Walker and Honea (1969, p.535) later extended their results to suggest that "other iron-bearing silicates such as other amphiboles, pyroxenes and biotite will similarly produce iron-bearing clay". In a study of Recent alluvium eroded from upland areas in the Sonoran Desert, Walker and Honea (1969) showed that the clay fraction was rich in iron, due to initial concentration of iron-bearing clay minerals and biotite in fine-grained sediment. The concentration of haematite pigment in the fine-grained fractions of the Billy Creek Formation indicates that a significant amount of weathering or intrastratal solution of iron-bearing minerals took place in the source area, in order to form the iron-rich clays. Berner (1969) has shown that fine-grained goethite is stable relative to haematite plus water below about 40^{o}C. Thus, the initial product of surface weathering of iron-bearing minerals was probably yellow-brown limonite (which comprises mainly goethite, $HFeO_2$), which altered to haematite once in the basin of deposition. In situ, dehydration of limonite is a well documented method for forming red haematite pigment in ancient sequences (eg. Berner, 1969, 1971; Walker, 1967b, Hubert and Reed, 1978).

There is also abundant evidence of in situ intrastratal weathering of iron-bearing minerals in the red-beds of the Billy Creek Formation. Several lines of evidence suggest that intrastratal weathering was an important source of free iron, especially in the coarser-grained sediments:

(a) Grains of biotite are opacitized (Plate 127), and have poorly defined, fuzzy, or very ragged margins. The alteration must be post-depositional, since the grains could not have withstood transportation in this form.

(b) Opaque oxides commonly have poorly defined margins (Plate 128), with weak haematite rims developed in rare cases (cf. Walker, 1967a).

(c) Haematite coatings are rarely present at grain-to-grain contacts, indicating that the development of the pigment was post-depositional.

(d) Ferric pigments may be developed both beneath, and as coatings on silica overgrowths (Plate 129), indicating that formation and migration of iron-rich pigment occurred over a prolonged period of time, and at least into the early stages of diagenesis of the sequence.

(e) The ZTR (heavy mineral) index for arkosic red-beds in the Billy Creek Formation is anomalously high (average 95%) considering that these sediments were derived from Precambrian crystalline basement rich in amphibole, pyroxene and biotite. Thus, the high ZTR index probably indicates removal of unstable iron silicates (eg. pyroxene, amphibole) by post-depositional weathering and intrastratal solution. A similar example of heavy mineral (ZTR) enrichment is reported by Schluger (1976).

In conclusion, it appears that two processes are responsible for the haematite pigment in the Billy Creek Formation red-beds. Source area weathering and subsequent oxidation of iron-rich clays is considered to be the origin of most of the red pigment in the red shales and fine-grained siltstones of the Billy Creek Formation. Moderately sorted, coarse red siltstones and sandstones however, were largely stained red by intrastratal solution of iron-bearing grains. There is no evidence supporting a detrital origin for any of the red pigment.

Origin of variegated sequences

According to Walker and Honea (1969, p.542), "the vital factor for the formation of red beds is the occurrence within the depositional basin of special interstitial chemical conditions (for example, favourable Eh and pH) that favour the formation and preservation of haematite". Valuable clues as to the nature of these special conditions are obtained from variegated sequences, where red and non-red intervals are closely associated. Variegated units are common in the basal member of the Billy Creek Formation in the Flinders Ranges, and also occur in the Yalkalpo 2 and Delhi-Santos Lake Frome borecores. Examination of these sequences has revealed several origins for the variegation, which can be grouped into two major classes: those essentially syndepositional, and those cleary postdepositional.

Syndepositional formation of variegated sequences

Fining-upward cycles, from greyish green sandstones to red mudstones, are common and well developed in the Billy Creek Formation in the Yalkalpo 2 borecore. Cycles are typically 2-5m in thickness, and represent regressive events associated with tidal flat progradation. Medium-grained, calcareous, green sandstones rest sharply on finer-grained sediment. The contact is commonly erosional, and the calcareous sandstone may contain red or green mudstone intraclasts in the basal portion, which are interpreted as channel lag deposits. The overlying drab sandy sequence is evenly laminated or rippled, and is typically bioturbated. Grey-green siltstones grade upwards into evenly laminated shaly red-beds, containing halite imprints, desiccation cracks, minor arthropod tracks and rare anhydrite. The fining-upward sequences are thus divisible into a coarse, drab unit and a fine, red unit and in this respect are similar to variegated fluvial cycles described by Allen (1965a, 1970), Friend (1966), Van Houten (1973) and Braunagel and Stanley (1977), despite the fact that they were formed in a different sedimentary environment. Red intraclasts in the green sandstones indicate that the red pigment developed and stabilized as haematite prior to erosion of the mudstone. Thus, the haematite formation is essentially syndepositional. Since the process of intrastratal solution of iron-rich grains to form haematite cement (discussed above) requires thousands and possibly millions of years (Walker, 1967a, 1974), it is extremely unlikely that in situ intrastratal solution was important in the formation of these shaly red-beds. Rather, the process of oxidation of iron-rich clay minerals and limonite in an intertidal mudflat environment was responsible for the red pigmentation. This observation is consistent with, and lends support to the thesis presented earlier, that intrastratal solution is only a significant process in coarse silty and sandy units.

Other types of variegated sequences occur in the Billy Creek Formation. Parts of the Yalkalpo 2 borecore are characterized by cyclic repetition of red and green shale. Similar, although rather poorly developed cycles occur in the Warragee Member in the Flinders Ranges. Cycles vary from 0.5m to 15m in thickness, and average 1-2m. Basal scour surfaces are absent, and red and green intervals pass gradationally into each other. In the Yalkalpo 2 borecore, green mudstones are evenly laminated, with laminae 1-5mm in thickness, commonly graded, from medium or fine siltstone to shale. Arthropod tracks are present and indicate a marine influence. Coarser-grained intervals contain starved ripples or lenticular bedding, with common bioturbation. Red mudstones are only slightly finer grained, and comprise evenly laminated shale with common halite imprints, desiccation cracks and minor anhydrite. The cycles are interpreted as resulting from minor transgressions and regressions along a very low energy, muddy shoreline. It is obvious that in this type of fine-grained sequence sufficient clay minerals were present to stain the entire cycle red, given the right chemical conditions. Thus, the green colour of the low energy subtidal deposits is related entirely to the Eh-pH environment at the site of deposition. The arguments that the green intervals contain insufficient clay minerals to supply the necessary iron for pigmentation, or that the coarse grain-size of the green intervals allowed migration of groundwater and subsequent reduction, have no relevance to these uniformly fine-grained variegated sequences. However, what is relevant is that reduction of limonite to ferrous oxide and stabilization of iron-bearing clay minerals as illite-montmorillonite and chlorite is favoured particularly by low Eh (Berner, 1971). Such conditions commonly pertain below the water-table, particularly in organic rich sediment. Finally, the oxidation of the red-beds and the reduction of the green intervals must have occurred essentially syn-depositionally, otherwise the variegation would have been masked by the changing physicochemical conditions during early burial, and also by subsequent fluctuations in the water table.

The essentially syndepositional stabilization of iron (either as haematite of ferrous oxide) is a feature of the fine-grained sediments of the Billy Creek Formation. In outcrops in the Flinders Ranges, cycles which grade from red intertidal shale through green shale into buff-coloured subtidal carbonate contain additional evidence of syndepositional pigmentation. In parts of these cycles, fining-upward couplets of green shaly siltstone and red, desiccation cracked shale are present, repeated on the scale of 1-5cm. The desiccation cracks in the red shale are infilled with green shaly siltstone, with essentially no transfer of pigment from one unit to the next. The couplets are interpreted as single depositional events, associated with flooding of upper intertidal mudflats and subsequent desiccation. The fact that the green shaly siltstones remain green indicates that ferrous oxide had formed and stabilized prior to the desiccation of the tidal flat. The fact that the red desiccation cracked shales remained red during the next marine incursion indicates that the conversion to haematite had also occurred essentially syndepositionally.

It is concluded that the large majority of variegated sequences in the Billy Creek Formation reflect differences in the original depositional environment of the red and non-red intervals. Preservation of sequences containing primary depositional colour alternations on the scale of only a few centimetres in thickness requires that the iron stabilized as ferric or ferrous oxide before the deposition of the succeeding cycles. Thus the development of the variegation was essentially syndepositional.

Post-depositional formation of variegated sequences

Post-depositional bleaching of red sediment is responsible for the production of some variegated sequences. Generally however, post-depositional bleaching is easy to recognise, since it transgresses primary depositional structures. Bleaching of red-beds below drab channel deposits, as described by Allen (1965a, 1970) and Van Houten (1973) is uncommon, although examples do occur in the Eregunda Sandstone Member. In an outcrop in Ten Mile Creek, a 20-30cm thick, green, crevasse-splay sandstone is associated with bleaching of the enclosing shales above, below and laterally adjacent to the sandstone. This indicates that the bleaching is not entirely related to reducing conditions in the channel sand during its deposition, but rather, reflects reduction of the sequence subsequent to the deposition and oxidation of the overlying red shale. The reduction is thus related to post-depositional fluid migration in the permeable sandstone, and may have occurred thousands or millions of years after the deposition of the sequence.

Most other post-depositionally bleached intervals are related to Recent weathering. Green aureoles around fractured blocks of red sandstone or siltstone are common in surface outcrops. Rare examples of red, desiccation-crack infillings in green siltstone are also related to Recent weathering. Invariably, the sediment infilling these mudcracks is finer than the mudcracked material. The entire sequence is interpreted as being formerly red, however Recent weathering has preferentially bleached the oarser, silty sediment, leaving the appearance of red desiccation crack infillings in green siltstone.

The Billy Creek Formation is characterised in part by the presence of tuffaceous interbeds, which are either salmon pink or bright olive green in colour. Bright green tuffs are comprised of fine ash, with only minor crystal shards. The green colour is due to diagenetic alteration of the volcanic ash to chlorite and clay minerals (Williams _et al._, 1954). In the Nildottie Siltstone Member, rare green tuffs are the only intervals which are not stained red, and thus it is apparent that the tuffaceous detritus was deposited in an oxidising environment. Thus, it is concluded that the green colour of the tuffs developed post-depositionally, by diagenetic alteration of the chemically unstable, fine-grained ash.

Green haloes around anhydrite in the Delhi-Santos Lake Frome borecores are also interpreted as post-depositional reduction of red sediment.

Some of the anhydrite has undergone post-depositional migration, because it occurs as irregular veins and patches, commonly disrupting bedding. Reduction haloes around these veins are therefore also post-depositional in origin. Berner (1971) has shown that reduction of haematite can occur by lowering either the Eh or the $pS^{=}$ of the sediment. Release of $SO_4^{=}$ ions from anhydrite ($CaSO_4$) during diagenesis could thus be responsible for creation of local reducing conditions surrounding anhydrite patches and veins.

CHAPTER 11

CONCLUSIONS - DEPOSITIONAL HISTORY OF THE BILLY CREEK FORMATION

NATURE OF THE BASIN OF DEPOSITION

The Billy Creek Formation comprises up to 1000m of sediment which is predominantly red in colour. Although the thickness of the formation is partly controlled by local structure (eg. the Ten Mile Creek graben), in general the sequence thickens towards the south (Fig. 11-1B). This trend is consistent with isopach data compiled by Stock (1974) for formations in the Lake Frome Group, which also comprises predominantly red-coloured sediments. The isopach trends however, contrast strongly with thickness variation in the underlying Early Cambrian Hawker Group which tends to thicken towards the northeast (Fig. 11-1A). Since the Hawker Group comprises predominantly carbonate and green shale, it is apparent that major changes in the type of sedimentation and the nature of the basin of deposition were associated with the evolution of the red-bed sequences.

Wopfner (1966) and Freeman (1966) recognised that the thickest sequences within the Hawker Group lay in the Arrowie region, in the north-eastern portion of the Flinders Ranges. Thus, they named the Early Cambrian basin of deposition the Arrowie Basin, and distinguished it from the much larger, Precambrian entity; the Adelaide 'Geosyncline'. Outcrop and sub-surface occurrences of Early Cambrian strata in <u>southern</u> South Australia were considered by Wopfner (1970b, 1972) as having been deposited within a separate basin, which he termed the Stansbury Basin. The inference in this nomenclature is that the Arrowie and Stansbury Basins were distinct, and at times isolated, Cambrian basins of deposition. Since there are no out-crops of Early Cambrian strata between the two areas (Fig. 1-2), this concept is difficult to prove, especially since Daily (1969a, 1976b) has shown that the sequences in the two basins are remarkably similar in character. Thus, the term Adelaide 'Geosyncline' is still commonly used in describing the site of deposition of these Cambrian strata, although it is recognised that several areas of maximum accumulation were probably present.

The term Arrowie Basin however, has been used in association with

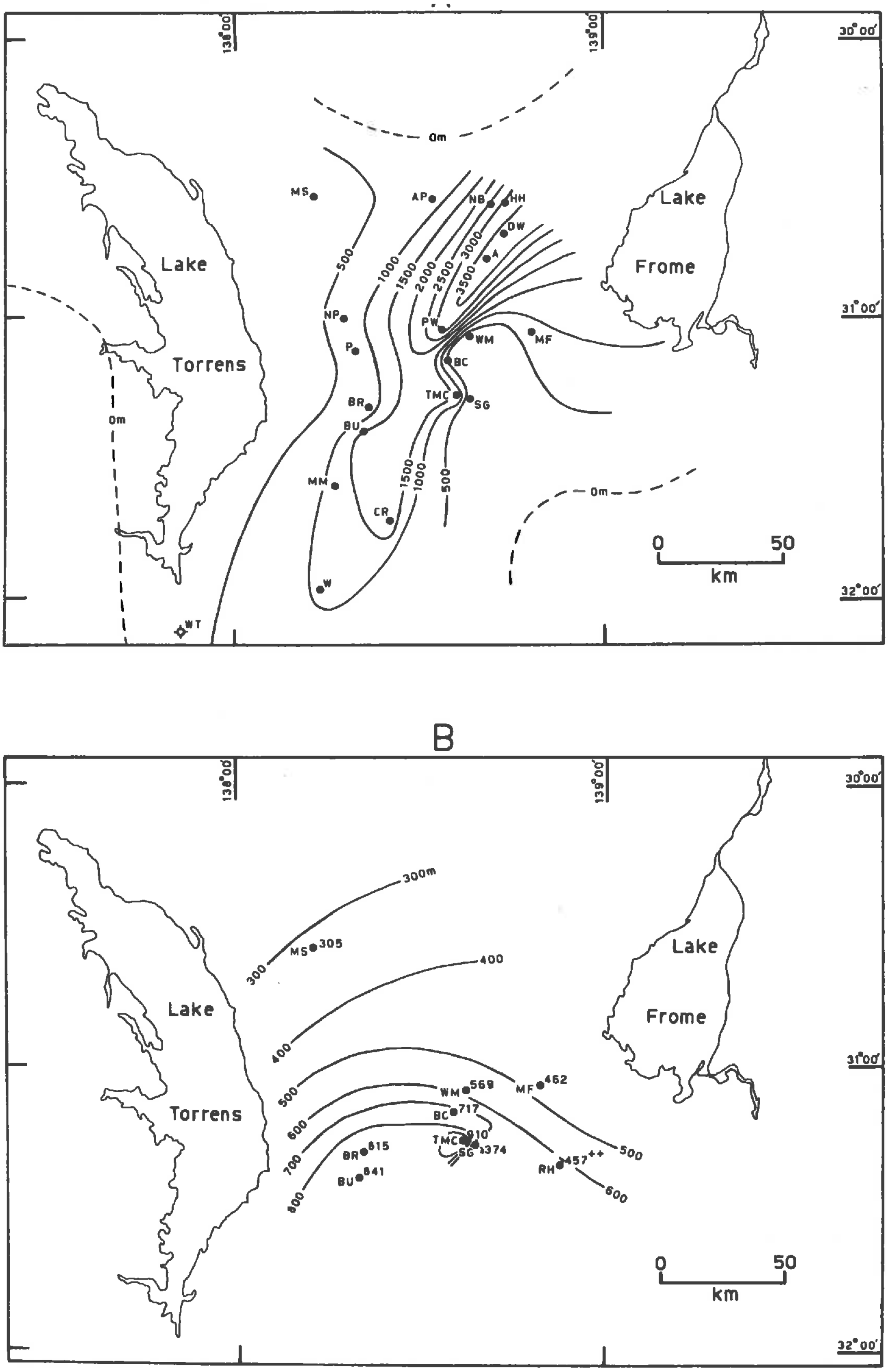


Figure 11-1. Generalized isopach maps of original depositional thicknesses. A: Hawker Group (after Wopfner, 1970a) and B: Billy Creek Formation. Localities are A: Arrowie, AP: Angepena, BC: Balcoracana Creek, BR: Brachina Gorge, BU: Bunyeroo Gorge, CR: Chase Range, DW: Donkey Well, HH: Hawker Hill, MF: Mount Frome, MM: Mernmera, MS: Mount Scott Range, NB: Nepabunna, NP: 12km north of Parachilna P: Parachilna, PW: Point Well, RH: Reaphook Hill, SG: South of the Ten Mile Creek Graben, TMC: Ten Mile Creek Graben, W: Wilson WM: Wirrealpa Mine, WT: Wooltana No. 1.

more than just the Early Cambrian Hawker Group. Wopfner (1970a, 1970b) and Devine (1975) have inferred that the entire Cambrian sequence of the Flinders Ranges was deposited in the Arrowie Basin, while Youngs (1978a, 1978b) has confirmed that the Middle Cambrian Wirrealpa Limestone had its depocentre in the Arrowie region. Isopach maps for the Billy Creek Formation (Fig. 11-1B) and the Lake Frome Group (Stock, 1974, Fig. 2.3) do not show a thickening of the red-bed sequences towards the Arrowie region however, and special care is needed in interpreting their significance. In both cases, there is evidence that they thicken towards the terrigenous source area, in the south or southeast. Although sequences which thicken towards the source area are common in the geological record, they are generally non-marine in origin (Visher et al., 1975). Since the Billy Creek Formation comprises marginal marine and deltaic red-beds, it is inferred that these pass laterally into a thick wedge of continental sediment towards the southeast. Thus, it was this sudden, large supply of clastic detritus associated with the deposition of the Billy Creek Formation which affected subsidence in the region, and shifted the centre of deposition away from the Arrowie region onto the margins of the marine basin.

Recent drilling to the east of the Flinders Ranges (Youngs, 1979) suggests that this area was subject to comparatively open marine conditions during at least the early stages of deposition of the Billy Creek Formation (Chapter 9). Thus, despite the fact that the site of maximum sediment accumulation was probably to the southeast marginal to the marine basin, the area of deepest water within the basin still lay generally in the Arrowie region (Figs. 11-2 and 11-3). In conclusion therefore, Wofner's (1966) concept of the Arrowie Basin appears to have some significance in relation to the sequence of facies present in the Billy Creek Formation. Conversely, if the thickest sequences in the Billy Creek Formation and Lake Frome Group do pass laterally into continental sediments (as inferred here and by Stock, 1974), then closure of the marine Arrowie Basin to the south of the present outcrops during at least part of the late Early and late Middle Cambrian was most probable.

RESUME - DEPOSITIONAL HISTORY OF THE BILLY CREEK FORMATION

Prior to the deposition of the Billy Creek Formation, the northern portion of the Adelaide 'Geosyncline' comprised a shallow basin (the Arrowie Basin), dominated by carbonate sediments of the Hawker Group. The widespread regression which finally initiated red-bed sedimentation commenced prior to the deposition of the Billy Creek Formation, and produced shallowing-upward sequences throughout the area of deposition (Fig. 11-2A). In the central, deeper portions of the basin, the subtidal to ?intertidal Edeowie Limestone Member was deposited, while on the basin margins stromatolitic dolomite (the Ajax Limestone and parts of the Wilkawillina Limestone) and fenestral limestone (the Wilkawillina Limestone) accumulated, mainly in the intertidal to supratidal environment. At Reaphook Hill in the southeast, land was exposed, and the uppermost portion of the Wilkawillina Limestone was eroded and redeposited as a limestone-boulder conglomerate at the base of the overlying Billy Creek Formation.

During the early stages of deposition of the Billy Creek Formation, a broad muddy tidal flat developed in the west (the Warragee Member) while shallow marine calcareous sandstone and minor green shale were deposited further east at Reaphook Hill (Unit B of the Coads Hill Member), and in the Lake Frome region (Fig. 11-2B). Minor calcareous sandstones at the base of the Warragee Member in the vicinity of Balcoracana Creek probably were derived from the east, and may correlate with Unit B of the Coads Hill Member. The sandstones indicate slightly deeper, more open water conditions, with winnowing of mud and the development of subtidal and rarely intertidal sandflats and megaripples. The presence of moderately sorted, medium grained sandstone in the sequence at this period of time emphasizes the fact that sandy detritus was available, but was being concentrated in the more energetic, deeper water environments to the east. The marked increase

Figure 11-2. Interpreted environments of deposition for the lower part of the Billy Creek Formation.

A: Regression, immediately preceding the deposition of the red-beds.

B: Lower Warragee Member, Unit B of the Coads Hill Member, and lower Yalkalpo 2.

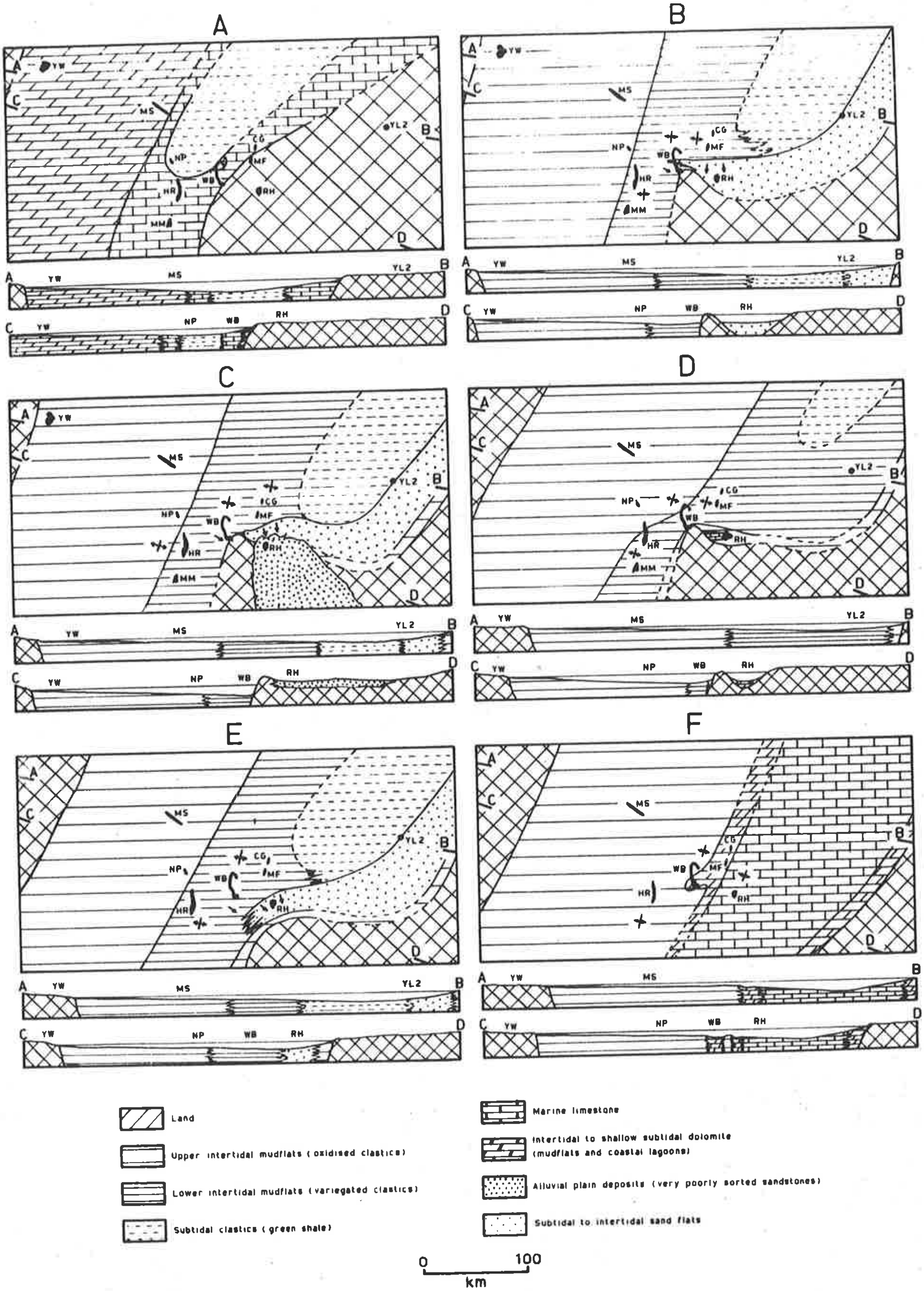
C: Lower Warragee Member, Unit C of the Coads Hill Member and lower Yalkalpo 2.

D: Middle Warragee Member, Unit E of the Coads Hill Member and middle Yalkalpo 2.

E: Upper middle Warragee Member, Unit G of the Coads Hill Member and upper Yalkalpo 2.

F: Upper Warragee Member, and Unit H of the Coads Hill Member.

Localities are Yarrawunta (YW), Mount Scott Range (MS), 12 km north of Parachilna (NP), Heysen Range (HR), Mernmerna (MM), Wirrealpa Basin (WB), Mount Frome (MF), Chambers Gorge (CG), Reaphook Hill (RH) and Yalkalpo 2 borecore (YL2).


A
B
C
D
E
F
YW
MS
NP
WB
HR
MM
CG
MF
RH
YL2
Land
Upper intertidal mudflats (oxidised clastics)
Lower intertidal mudflats (variegated clastics)
Subtidal clastics (green shale)
Marine limestone
Intertidal to shallow subtidal dolomite (mudflats and coastal lagoons)
Alluvial plain deposits (very poorly sorted sandstones)
Subtidal to intertidal sand flats
0 100
km

in sand content towards the east also suggests that the source area lay in this direction. The moderate sorting and rounding of the sandstones and the very mature ZTR index suggests that the source rocks comprised predominantly unmetamorphosed or weakly metamorphosed sedimentary strata.

Palaeocurrent data suggest that the basin was elongate in a north-northeast-south-southwest direction, with symmetrical and near-symmetrical wave ripples aligned subparallel to the shoreline (Fig. 11-2, B-F). A gentle slope on the western margin of the basin is inferred from the abundance of muddy red-beds in the area, while the presence of coarser-grained sediments, and the rapid lateral and vertical facies changes in the sequence towards the east (particularly at Reaphook Hill) suggest that the slope on the eastern margin was greater, and possibly associated with faulting. Palaeocurrent data derived from the sandstones of the Coads Hill Member at Reaphook Hill indicate migration of dunes and megaripples in a variety of directions, but predominantly towards the southeast (Fig. 11-2, B, C & E). These are most likely shoreward-facing structures, and thus the proximity of the eastern margin of the basin to Reaphook Hill at this period of time is indicated.

During the early period in the depositional history of the Billy Creek Formation, the tectonic graben in the vicinity of Ten Mile Creek continued to subside, but not as rapidly as during the deposition of the underlying Hawker Group. Evidence that the graben was marginally deeper than the surrounding areas is sparse, however the slightly increased thickness of the sequence and the greater abundance of carbonate units (eg. Fig. 11-2F) suggests that marine incursions in this region were somewhat more common and more persistent than elsewhere. The Warragee Member is absent south of the graben, and although the sequence in this small area is possibly complicated by faulting, it is considered likely that the area existed as a landmass during much of the period of deposition of the Warragee Member (Fig. 11-2, A-D inc.).

The carbonates of the Warragee Member, which generally increase in abundance from west to east across the Flinders Ranges, confirm the gentle easterly dip of the palaeoslope in this region. They are dolomitic, and in some cases stromatolitic, and are interpreted as having been deposited generally in shallow subtidal to lower intertidal environments, marginal to the more continental, muddy red-bed facies.

Although the western portion of the basin was relatively stable during the deposition of the Warragee Member, with only minor lateral and vertical variation in the sequence, to the east a complex stratigraphy was evolving. The Coads Hill Member at Reaphook Hill comprises mine distinct units, some of which are laterally discontinuous over the area of outcrop (Chapter 7). The fact that the Coads Hill sequence is absent from all other known occurrences of the Billy Creek Formation indicates that the environment of deposition in the vicinity of Reaphook Hill was in some ways unusual. The great variety in the Coads Hill Member emphasises the instability of the region during the late Early Cambrian, with first the development of continental, alluvial-plain red-beds (Unit C of the Coads Hill Member; Fig. 11-2C) and later the development of a dark, foetid limestone (Unit D) in a semi-restricted, marine embayment, isolated from the adjacent areas of clastic sedimentation (Fig. 11-2D). The extent and significance of these facies variations is uncertain, since the only data on the basal portion of the Billy Creek Formation east of Reaphook Hill comes from the Yalkalpo 2 drillhole, which lies over 100km to the northeast. The presence of continental deposits in the Coads Hill Member indicates that the sediments at Reaphook Hill were deposited marginal to a landmass, which may have been the southeastern margin of the Arrowie Basin. However, only further drilling to the east of Reaphook Hill will adequately establish the true nature of the basin of deposition and the sequence of lateral facies changes in this region.

On the basis of the correlations discussed in Chapter 3 (particularly Fig. 3-3), it appears that the dark foetid limestone (Unit H) of the Coads

Hill Member at Reaphook Hill is laterally equivalent to green calcareous shales and thin dolomites of the uppermost Warragee Member near Wirrealpa, and red shales further west (Fig. 11-2F). Thus, oxidising conditions persisted on a muddy tidal flat in the west while to the east at Reaphook Hill, a shallow, restricted marine sequence of carbonate and green shale was accumulating. A similar situation existed during the deposition of the green marine shales of Unit J of the Coads Hill Member (Fig. 11-3A), although clastic sediments are predominant.

The development of the Erudina Siltstone Member at Reaphook Hill signified a major change in the style of sedimentation in the eastern portion of the basin, as muddy red-beds spread from west to east across the region. The red-bed facies of the Erudina Siltstone Member were probably deposited on a very gentle palaeoslope, much different in character from the more steeply dipping palaeoslope for the underlying Coads Hill Member. Unit A of the Erudina Siltstone Member comprises red shale with minor dolomite interbeds and correlates with the lower shale portion of the Nildottie Siltstone Member. Thus, shaly red-beds extended from at least Mt. Scott and the Heysen Range in the west, to Reaphook Hill in the east. The regional palaeoslope was from west to east, with the marine influence at Reaphook Hill indicated by the presence of cyclically interbedded dolomites in the sequence (Fig. 11-3B). The dolomites were probably deposited in sheltered, coastal lagoons and on adjacent intertidal flats. The nature of the basin of deposition to the east of Reaphook Hill at this period of time is unknown.

As time progressed, the red-bed facies spread even further east (Fig. 11-3C), and red siltstones devoid of carbonate interbeds were eventually deposited at Reaphook Hill (Unit B of the Erudina Siltstone Member). The increase in average grain-size of the sediment is considered to be a response to increased tectonic activity in the source areas, and emphasises the temporal persistence of the Kangarooian Movements. The abundance of wave ripples, and the type of bedding structures present in Unit B of the

Figure 11-3. Interpreted environments of deposition for the middle and upper parts of the Billy Creek Formation.

A: Uppermost Warragee Member and Unit J of the Coads Hill Member.

B: Lower Nildottie Siltstone Member, and Unit A of the Erudina Siltstone Member.

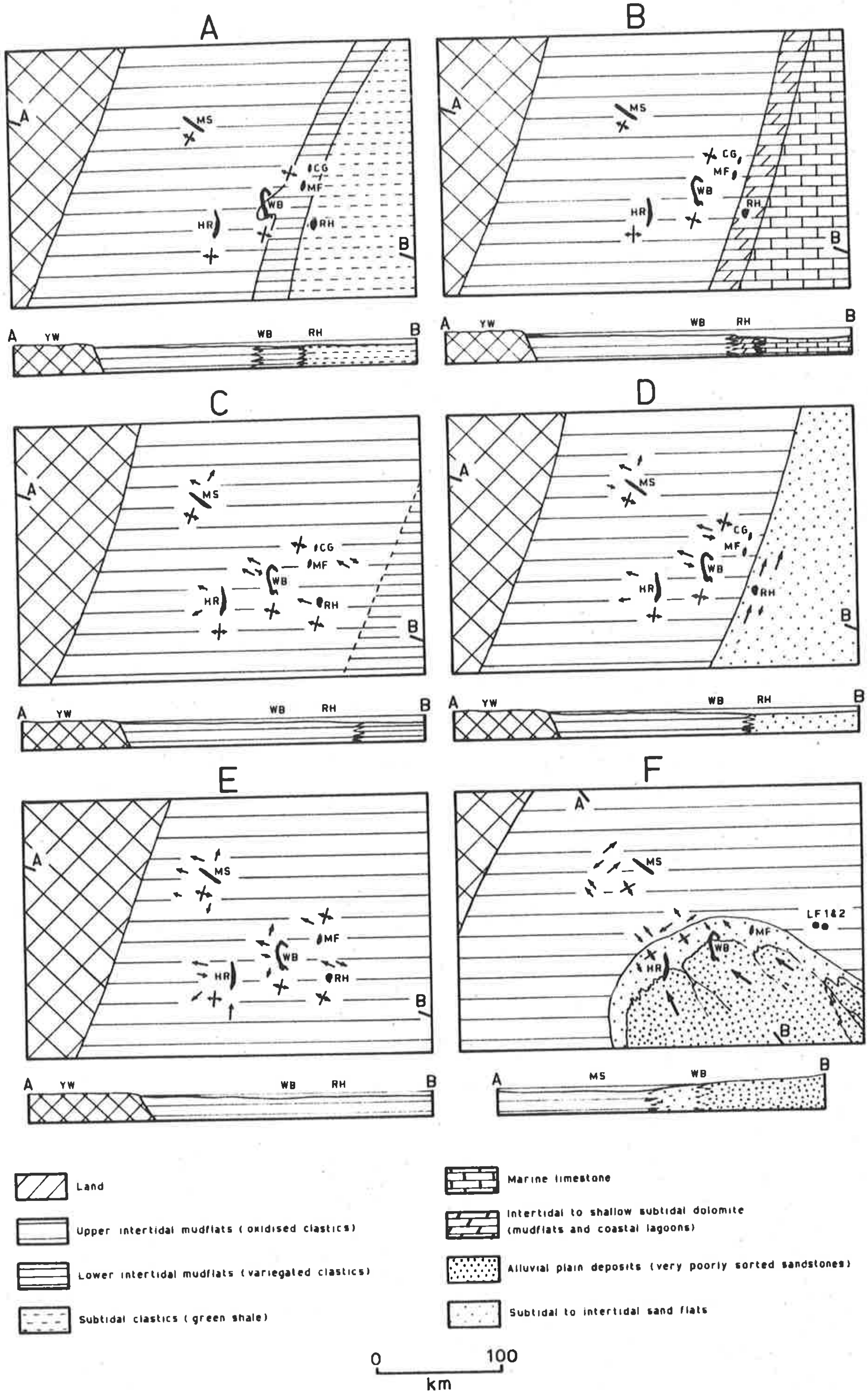
C: Middle Nildottie Siltstone Member, and Unit B of the Erudina Siltstone Member.

D: Middle Nildottie Siltstone Member, and Unit C of the Erudina Siltstone Member.

E: Upper Nildottie Siltstone Member, and Unit D of the Erudina Siltstone Member.

F: Eregunda Sandstone Member, and red anhydritic shales and siltstones of the Lake Frome wells.

Localities are Mount Scott Range (MS), Heysen Range (HR), Wirrealpa Basin (WB), Mount Frome (MF), Chambers Gorge (CG), Reaphook Hill (RH) and Lake Frome Nos. 1 and 2 wells (LF1 & 2).



A
B
C
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E
F
MS
CG
MF
WB
HR
RH
YW
LF 1&2
Land
Upper intertidal mudflats (oxidised clastics)
Lower intertidal mudflats (variegated clastics)
Subtidal clastics (green shale)
Marine limestone
Intertidal to shallow subtidal dolomite (mudflats and coastal lagoons)
Alluvial plain deposits (very poorly sorted sandstones)
Subtidal to intertidal sand flats
0
100
km

Erudina Siltstone Member and its lateral equivalent to the west (the lower and middle portion of the Nildottie Siltstone Member) indicate that the area of present outcrop was frequently subject to marine inundation, despite the oxidising nature of the sediment. Ripple crests are aligned north-south, or northeast-southwest; a direction that is inferred to approximate to the strike of the palaeoslope. The wave ripples are commonly asymmetrical, with a large majority indicating translation from east to west (ie. shorewards). Desiccation cracks and anhydrite also increase in abundance from east to west, and are further indications that the palaeoslope in the region of study had a gentle easterly dip.

Unit C of the Erudina Siltstone Member was deposited in slightly deeper water than the underlying red-beds, although rare desiccation cracks indicate periodic subaerial exposure. The coarsening-upward cycles from shale to sandstone appear to be related primarily to tectonic activity in the source area, since the cycles vary considerably in thickness, and bedding characteristics. Sand was carried to the site of deposition from the south and southwest, and since this direction is subparallel to the strike of the palaeoslope as indicated by wave ripple orientations in adjacent units, the mode of transportation is inferred to be longshore tidal drift (Fig. 11-3D). An alternative suggestion is that the area to the south of Reaphook Hill was temporarily uplifted, with a resultant change in palaeoslope. However, in the absence of supporting evidence, this suggestion is considered to be most unlikely.

The change in the style of sedimentation which produced Unit C of the Erudina Siltstone Member at Reaphook Hill had little effect on the silty red-bed deposits to the west. The event cannot be recognised in outcrops of the Nildottie Siltstone Member in the Wirrealpa Basin, nor in the Heysen and Mount Scott Range outcrops (Fig. 11-3D). A sandy interval, with tidal channels, load structures, worm burrows and abundant arthropod tracks in the middle portion of the Nildottie Siltstone Member at Mt. Frome may correlate with Unit C of the Erudina Siltstone Member. However, in the absence of tuffaceous marker beds and palaeontological evidence, this correlation is only very tentative.

Unit D of the Erudina Siltstone Member at Reaphook Hill was deposited in slightly shallower water, and under relatively more stable conditions than Unit C, and indicates a return to silty red-bed sedimentation similar in character to that of the Nildottie Siltstone Member (Fig. 11-3E). Thus, a broad, muddy oxidising tidal flat spread from the Mt. Scott and Heysen Ranges in the north and west, to beyond Reaphook Hill in the southeast. Little change in the style of sedimentation existed over this large area, although the outcrops in the west show a marginally greater proportion of the supratidal and transitional facies. Wave and current ripples are abundant throughout the sequence, and indicate persistent, gentle reworking of the sediment by waves and tides. Ripple crests are generally aligned north-south or northeast-southwest, with currents directed both on- and off-shore. Asymmetrical wave ripples typically indicate translation towards the west (onshore).

The upper portion of the Billy Creek Formation is missing at Reaphook Hill, however it is difficult to assess just how much of the sequence has been removed by erosion. There is no evidence of the Eregunda Sandstone Member or a lateral equivalent at Reaphook Hill, however since the palaeocurrent trends in the member indicate derivation from the southeast, it is probable that the sandstone was originally deposited in this region (Fig. 11-3F). Furthermore, the coarsening-upward silty sequence which characterizes the uppermost portion of the Nildittie Siltstone Member is not recognised in the Erudina Siltstone Member outcrops, despite the fact that a feature as prominent as this should be easily recognisable. Thus, it is suggested that the eroded top of the Erudina Siltstone Member at Reaphook Hill correlates approximately with the middle portion of the Nildottie Siltstone Member.

The increased silt content in the upper portion of the Nildottie Siltstone Member is probably a result of tectonic activity in the source area. The abundance of desiccation cracks and mudstone intraclasts emphasises the shallow water nature of the sequence, while the lateral extent of the facies emphasises the extremely low slope on this eastern margin of the depositional basin.

The Eregunda Sandstone Member spread from the southern and south-eastern margins of the basin, presumably in response to marked tectonic activity in the source areas (Fig. 11-3F). The abundance of current lineated units in the member indicates high current velocities, attributed to increased topographic relief between the source area and the basin of deposition. The sands migrated as a complex series of shallow-water deltas, fed by braided streams carrying arkosic sediments from the exposed basement highs in the Broken Hill-Olary region. As the sands spread across the basin, there was recorded a reversal in palaeodip, from gently eastwards, to markedly northwestwards. This change in the palaeoslope orientation is related to changing patterns of sedimentation in a fairly large although very shallow epicontinental sea and, although related to tectonism, should not be interpreted as indicating major tectonic modification of the actual site of deposition.

Two major phases of delta growth are recorded in the Eregunda Sandstone Member (Units A and C) and these probably represent transgressive periods related to widespread tectonic activity. The two sandstone units are separated by intertidal to subtidal shales and siltstones, and Unit C is overlain by a similar fine-grained, mostly subtidal sequence, which passes gradationally into the Wirrealpa and Aroona Creek Limestones. The Middle Cambrian limestones were deposited in response to a major transgression which affected much, if not all of the Adelaide 'Geosyncline' (Youngs, 1978a, 1978b).

Plate 1: Outcrop of the Billy Creek Formation in Daily's (1956) type section, 2.5km north of Ten Mile Creek (Section BC-B). A: Oraparinna Shale. B,C,D: Billy Creek Formation. E: Wirrealpa Limestone and Lake Frome Group. This area is also the type locality for the Warragee Member (B), the Nildottie Siltstone Member (C) and the Eregunda Sandstone Member (D) of the Billy Creek Formation.

Plate 2: Typical shaly outcrop of the Warragee Member, Billy Creek Formation. Location: Ilka Creek, Mernmerna.

Plate 3: Red and green interlaminated shales of the Warragee Member. Thin siltstone interbeds are evenly laminated to ripple laminated. Hammer 31cm long. Location: 3km north of Brachina Gorge.


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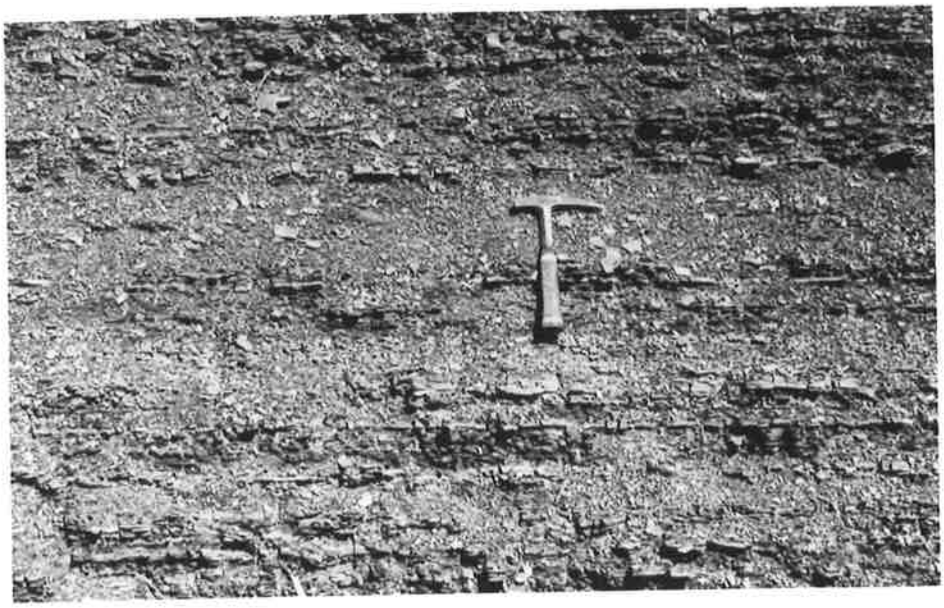

Plate 4: Desiccation cracks in red shale of the Warragee Member, infilled with green calcareous siltstone. Scale 54mm diameter. Location: upper portion of Section BC-R, 3km north of Balcaracana Creek in the Wirrealpa Basin.

Plate 5: Subvertical worm burrows in red shaly siltstone of the Warragee Member. Location: upper portion of Section BC-R, 3km north of Balcaracana Creek in the Wirrealpa Basin.

Plate 6: Rippled, coarse red siltstone interbeds in the Warragee Member. Scale 54mm diameter. Location: 2km south of Brackina Gorge in the Heysen Range.

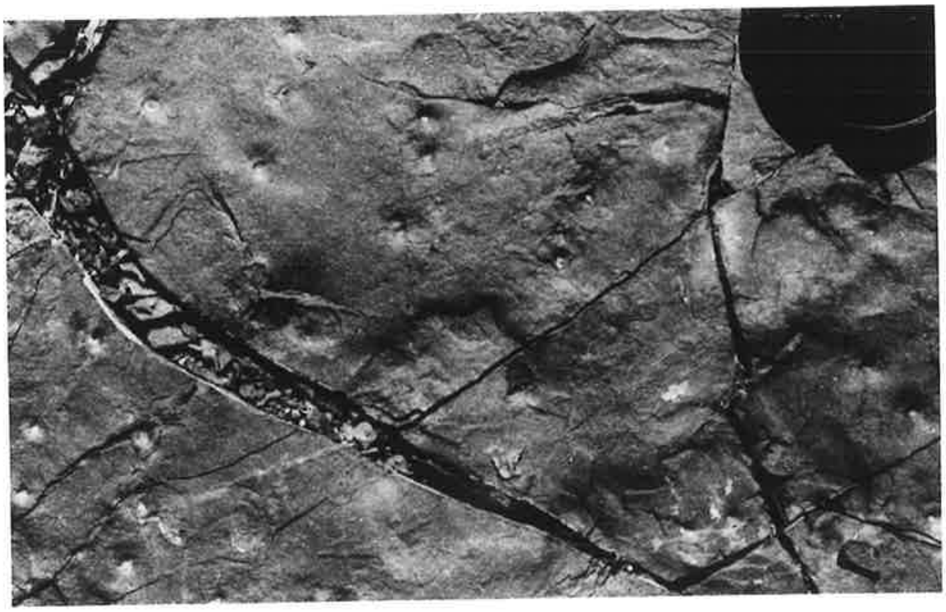

Plate 7: Symmetrical wave ripples in very fine ?tuffaceous sandstone. Location: lower portion of the Warragee Member in the Type Section (BC-B), 2.5km north of Ten Mile Creek.

Plate 8: Large scale shale-dolomite cycle in the Warragee Member. Red silty shales (bottom left) are overlain by green shales (adjacent to hammer) and then yellowish brown dolomite. A rapid transition back into red shaly siltstone (top right) is typical of these cycles. Hammer: 31cm long. Location: lower portion of the Warragee Member in the Type Section (BC-B), 2.5km north of Ten Mile Creek.

Plate 9: Polygonal desiccation crack infillings at base of yellowish brown dolomite. Lenscap scale 54mm. Location: upper portion of the Warragee Member, 2km north of Ten Mile Creek in the Wirrealpa Basin.

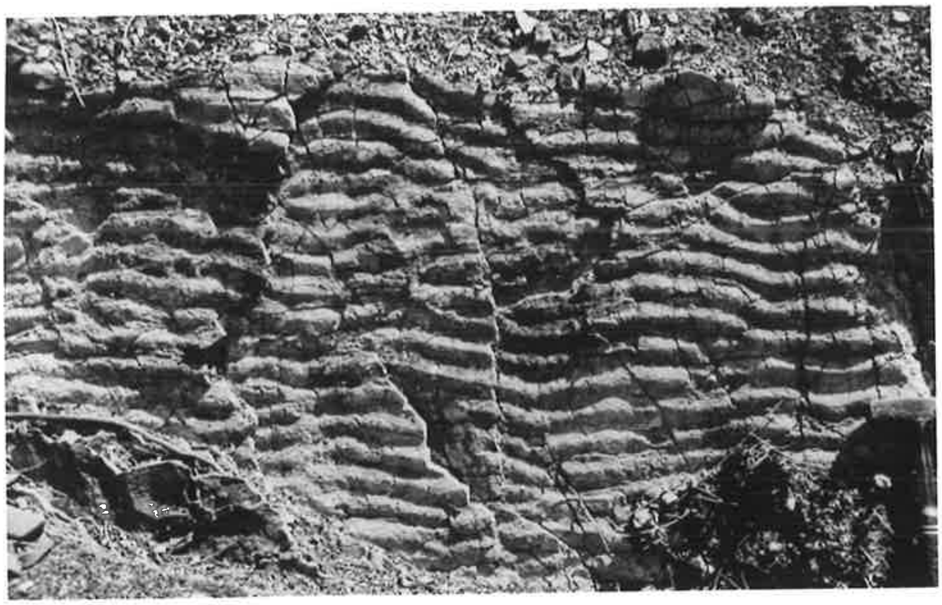

Plate 10: Hopper shaped halite pseudomorph casts at the base of a thin yellowish brown dolomite interval. Location: upper portion of the Warragee Member, just north of Section BC-R, near Balcaracana Creek in the Wirrealpa Basin.

Plate 11: Domal stromatolites in yellowish brown silty, dolomitic limestone. Location: lower portion of the Warragee Member in the Type Section (BC-B), 2.5km north of Ten Mile Creek in the Wirrealpa Basin.

Plate 12: Subhorizontal burrows in pink, tuffaceous and calcareous sandstone. Scale: 54cm diameter. Location: upper portion of the Warragee Member in the Type Section (BC-B), 2.5km north of Ten Mile Creek.


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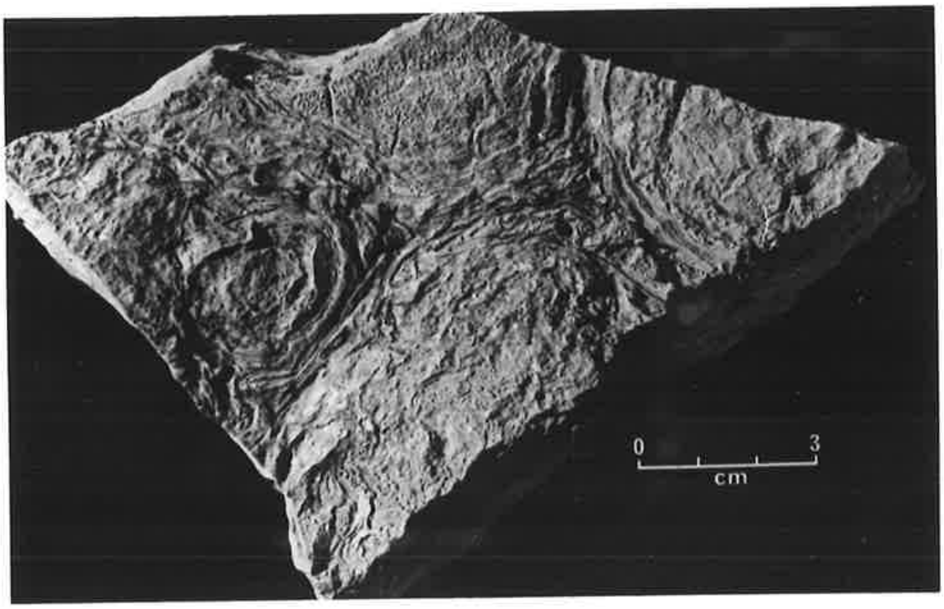
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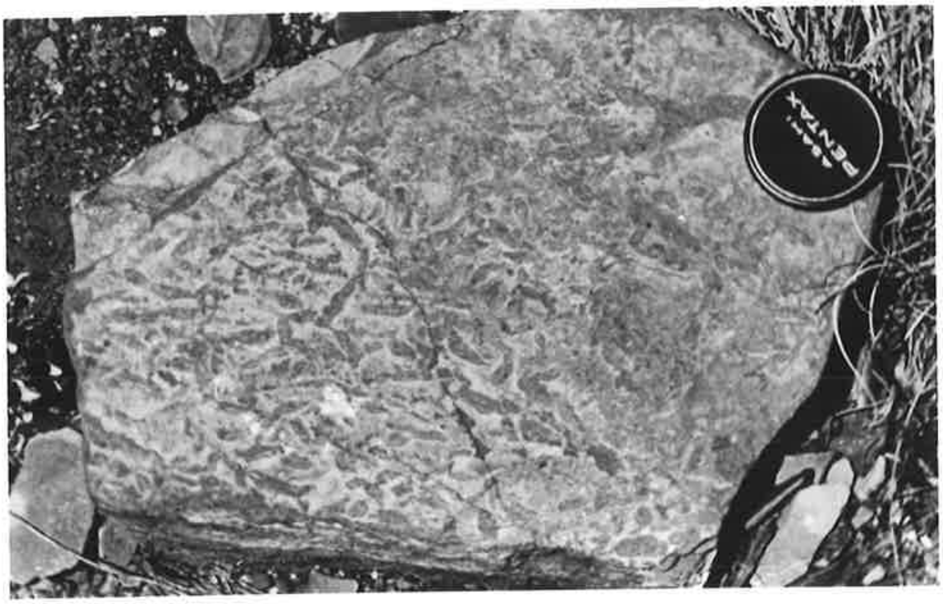
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Plate 13: Coarse red rippled siltstone interval in the upper portion of the Nildottie Siltstone Member of the Billy Creek Formation. Hammer 31cm long. Location: Section MS-B, Mount Scott Range.

Plate 14: Horizontally laminated, current lineated very fine red sandstone overlain by red silty sandstone with well-developed dewatering structures. Pen scale: 14cm long. Location: lower portion of the Nildottie Siltstone Member in Section CG-C, south of the Chambers Gorge.

Plate 15: Load structures and pseudonodules in sandy siltstone interbed. Scale: 54mm diameter. Location: lower portion of the Nildottie Siltstone Member, Section BR-C, 8km north of Brachina Gorge in the Heysen Range.

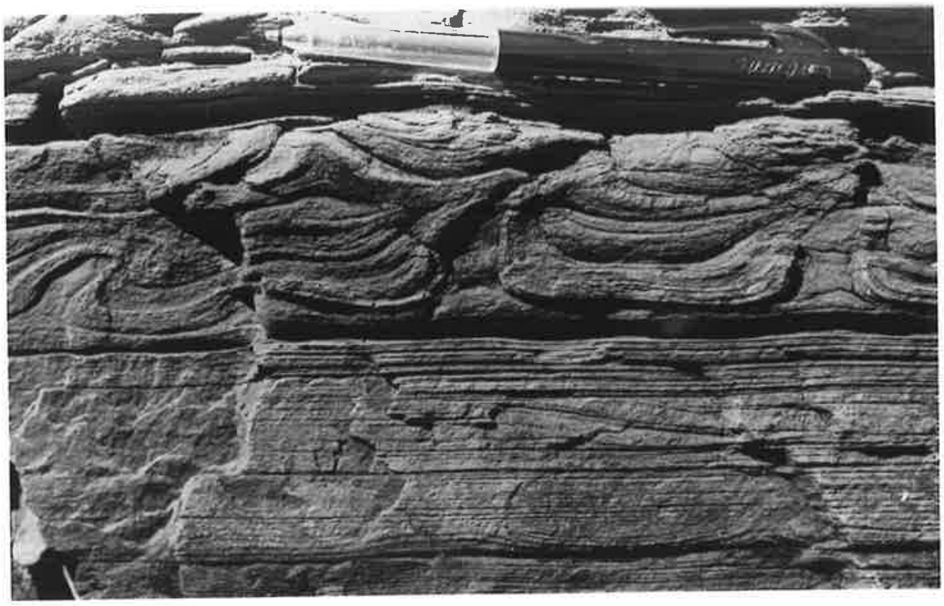


Plate 16: Catenary-rippled coarse red siltstone unit overlying symmetrically-rippled siltstone. Current from bottom right to top left. Lenscap scale: 54mm diameter. Location: middle portion of the Nildottie Siltstone Member in Balcaracana Creek (Section BC-N) in the Wirrealpa Basin.

Plate 17: Interference ripples in coarse red siltstone, formed by the interaction of waves and currents. Asymmetrical current ripples indicate flow from right to left. Wave oscillation was then superimposed at almost right angles. Location: middle portion of the Nildottie Siltstone Member in the Type Section (BC-B), 2.5km north of Ten Mile Creek.

Plate 18: Ladder ripples in coarse red siltstone, formed by the combined effects of currents (from right to left) and waves (at right angles to the currents). Location: upper portion of the Nildottie Siltstone Member in the Type Section (BC-B), 2.5km north of Ten Mile Creek.

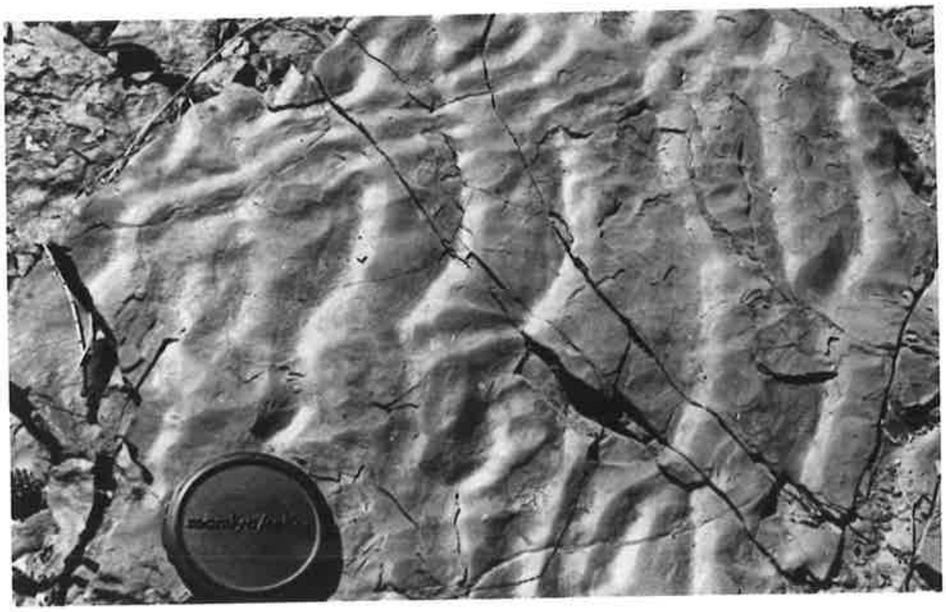
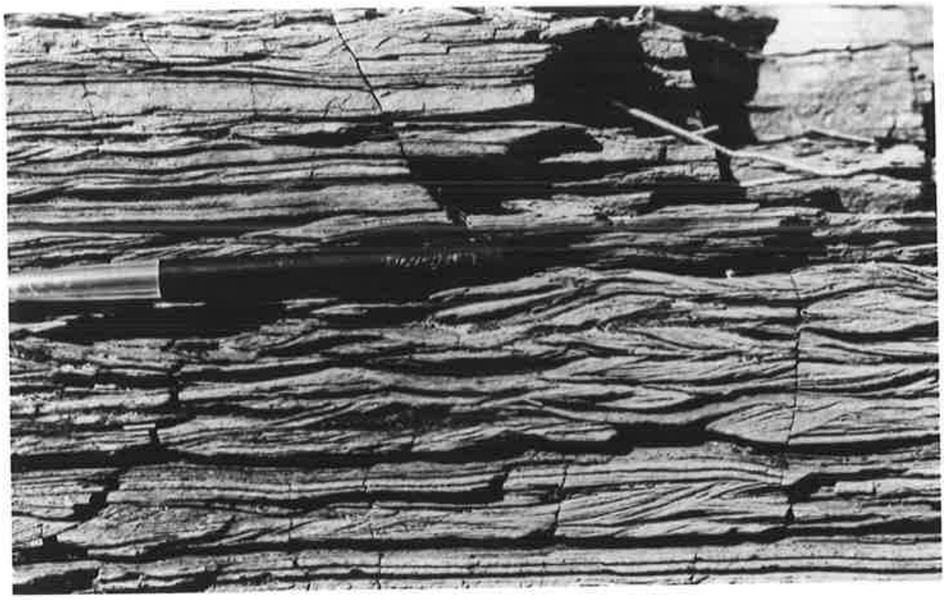


Plate 19: Cross-section of oscillation-rippled, very fine red sandstone. Note the presence of curved basal surfaces, bundled foresets and bidirectional orientations of foreset laminae. Pen scale: 14cm long. Location: lower portion of the Nildottie Siltstone Member in Section CG-C, south of Chambers Gorge.

Plate 20: Symmetrical and near-symmetrical wave ripples in very fine red sandstone. Lenscap scale: 54mm diameter. Location: middle portion of the Nildottie Siltstone Member in Section CG-C, south of Chambers Gorge.

Plate 21: Interference ripples in coarse red siltstone, formed by the simultaneous influence of two sets of wave oscillations approximately at right angles. Scale: 54mm diameter. Location: middle portion of the Nildottie Siltstone Member in Section MF-A, near Mount Frome.



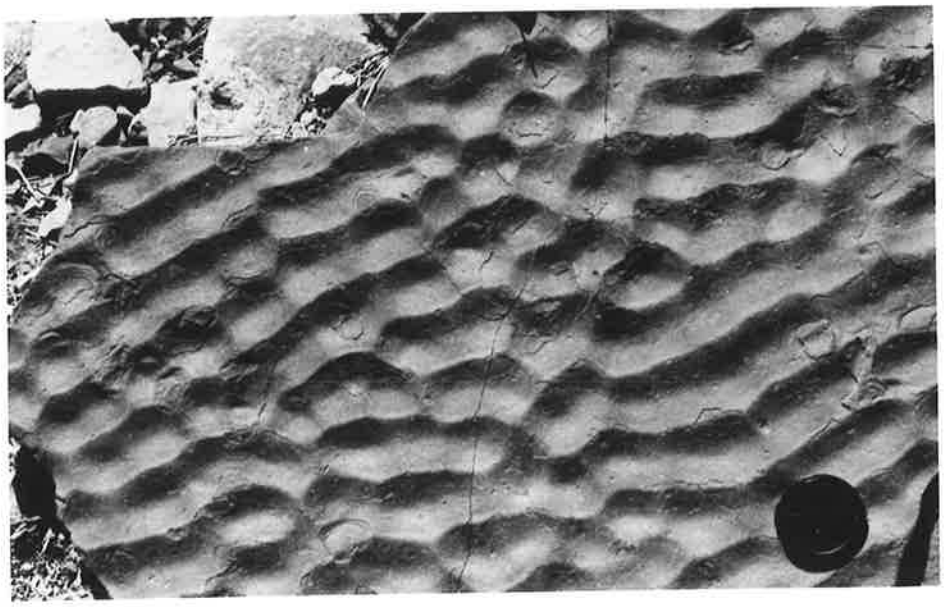
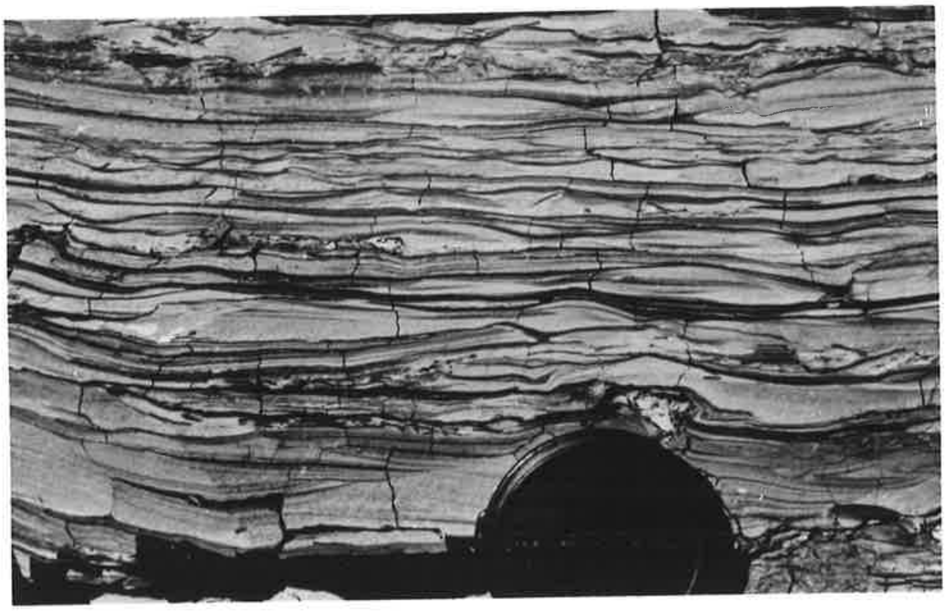


Plate 22: Shale flasers and thin interbeds in rippled siltstone. Mudstone intraclasts occur in the lower portion of the outcrop. Scale: 54mm diameter. Location: middle portion of the Nildottie Siltstone Member in Balcoracana Creek (Section BC-N) in the Wirrealpa Basin.

Plate 23: Poorly developed wavy and flaser bedding in red shaly siltstone. Wavy bedding is differentiated from simple flaser bedding on the basis of the continuity of the clay drapes: in simple flaser bedding, the clay drapes are confined to the ripple troughs, whereas in wavy bedding the clay laminae is laterally continuous. Location: middle portion of the Nildottie Siltstone Member in Balcaracana Creek (Section BC-N) in the Wirrealpa Basin.

Plate 24: Wavy bedded red clayey siltstone, with abundant mudflake intraclasts. Location: middle portion of the Nildottie Siltstone Member in Balcaracana Creek (Section BC-N), in the Wirrealpa Basin.



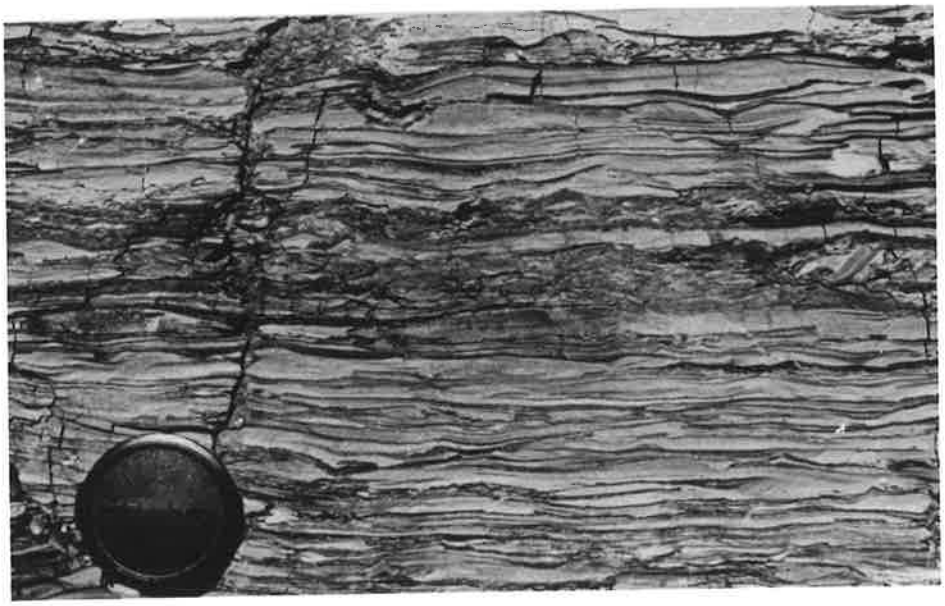


Plate 25: Large polygonal desiccation cracks in coarse red siltstone of the wavy bedded facies. Hammer length: 31cm. Location: middle portion of the Nildottie Siltstone Member in Section MF-A, near Mt. Frome.

Plate 26: Imprints of hopper-shaped halite crystals preserved in red siltstone of the wavy bedded facies. Scale 54mm diameter. Location: upper portion of the Nildottie Siltstone Member 1km north of Balcaracana Creek, in the Wirrealpa Basin.

Plate 27: Wrinkles in red muddy siltstone, probably associated with late-stage run-off in an intertidal environment. Location: middle portion of the Nildottie Siltstone Member in Section MS-B, in the Mount Scott Range.

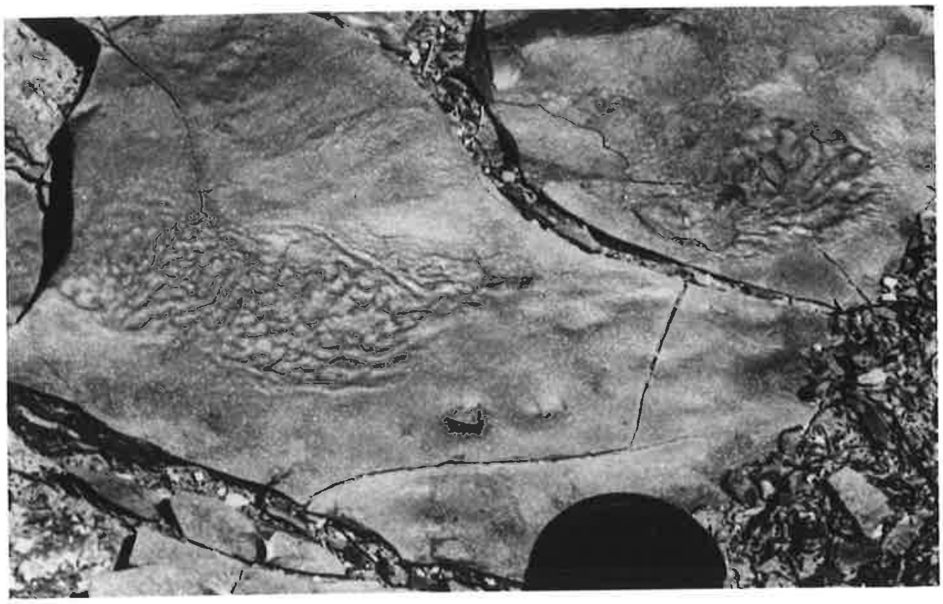
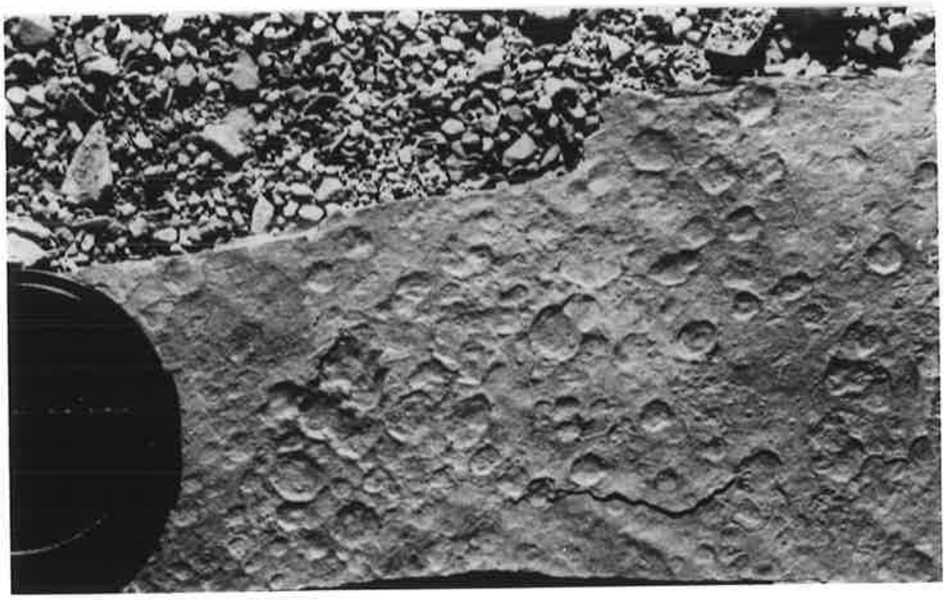


Plate 28: Raindrop imprints on bedding plane of red siltstone in wavy bedded facies. Location: middle portion of the Nildottie Siltstone Member in Section MF-A, near Mt. Frome.

Plate 29: Cross section of red, wavy laminated fine to medium calcareous siltstone. The wavy laminations are interpreted as being of algal origin. Scale: 54mm diameter. Location: lower portion of the Nildottie Siltstone Member in Section CG-C, south of the Chambers Gorge.

Plate 30: Small domal stromatolites in fine, red, very calcareous siltstone. The bedding surface is intersected by desiccation cracks, and a faint molluscan trail is present on the extreme right of the photo. Location: same outcrop as Plate 29, south of Chambers Gorge.



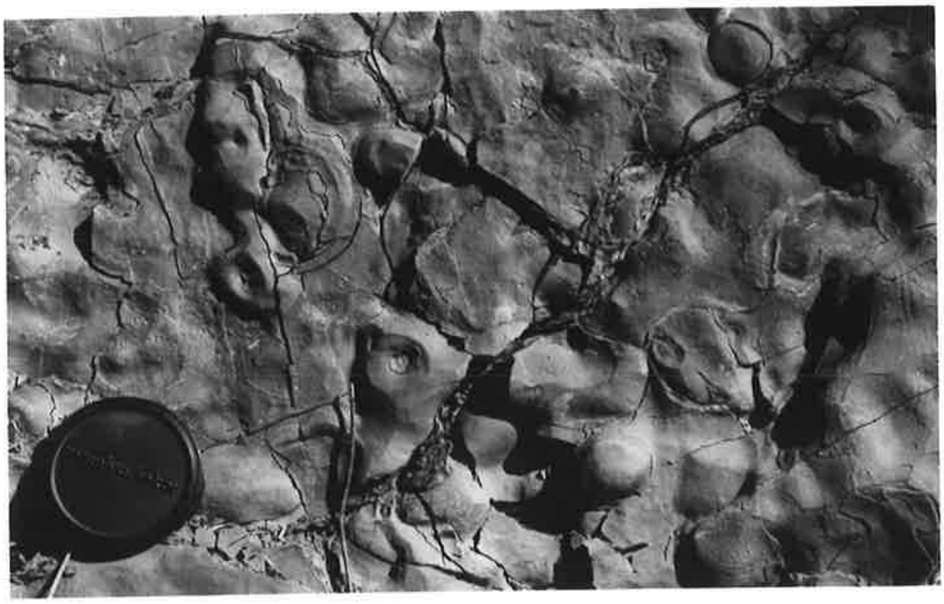


Plate 31: Channel, infilled with reddish brown to green sandstone. Trilobite tracks and desiccation cracks are present in the shaly portions of this sequence. The sandstones occur both as tidal channel infillings (curved, erosional basal surfaces) and as sandy shoals (flat bases, with curved upper surfaces). These deposits are restricted to the Mt. Frome outcrops of the member. Hammer: 31cm long. Location: middle portion of the Nildottie Siltstone Member in Section MF-B, near Mt. Frome.

Plate 32: Tidal channel, cut into horizontally laminated very fine red sandstone, and infilled with red shale and siltstone. Location: lower portion of the Nildottie Siltstone Member in Section CG-B, south of the Chambers Gorge.

Plate 33: Red mudstone intraclast lag conglomerate at the base of a shallow tidal channel. Scale: 54mm diameter. Location: lower portion of the Nildottie Siltstone Member in Section MS-B, in the Mount Scott Range.

Plate 34: Prominent outcrop of the Eregunda Sandstone Member of the Billy Creek Formation in Ten Mile Creek (Section BC-K) in the Wirrealpa Basin.

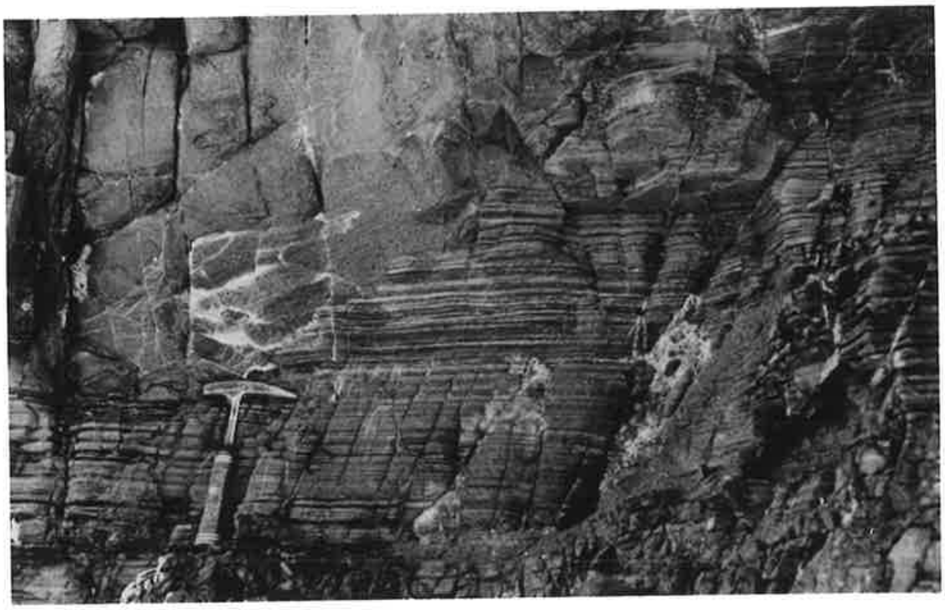
Plate 35: Outcrop of the Eregunda Sandstone Member in the Wirrealpa Basin. The member is divisible into four units. The basal unit (A) is mainly sandstone, and forms the prominent outcrop half way down the ridge. Unit B is shaly and silty and outcrops poorly. The ridge photographed is capped by sandstones of Unit C, which form the bulk of the Eregunda Sandstone Member.

Plate 36: Conformable contact between red silty shales of Unit D of the Eregunda Sandstone Member and grey Wirrealpa Limestone. A transition through green shale and wavy algal limestone is present. Hammer length (far right) 31cm. Location: Section BC-K, Ten Mile Creek in the Wirrealpa Basin.

Plate 37: Poorly bedded to massive sandstone with a basal scour surface (Se) overlain by horizontally laminated (Sh) red sandstone. Mudstone intraclasts occur above the scour surface, which has eroded into evenly laminated to wavy bedded red shales and siltstones (Fl). Arthropod tracks are common in the shaly intervals. Hammer: 31 cm long. Location: Unit C of the Eregunda Sandstone Member in Section BC-K, at Ten Mile Creek (Wirrealpa Basin).

Plate 38: Massive to poorly bedded sandstone (Se) infilling a 2m deep channel cut into horizontally laminated, current lineated sandstone (Sh). Hammer: 31 cm long. Location: Unit C of the Eregunda Sandstone Member in Section BC-Q, at Balcoracana Creek (Wirrealpa Basin).

Plate 39: Thick sequence of horizontally laminated, current lineated sandstone (Sh). Dark coloured partings are mica-rich laminae deposited during temporary reductions in current velocity. Hammer: 31 cm long. Location: Unit C of the Eregunda Sandstone Member in Section BC-Q, at Balcoracana Creek (Wirrealpa Basin).



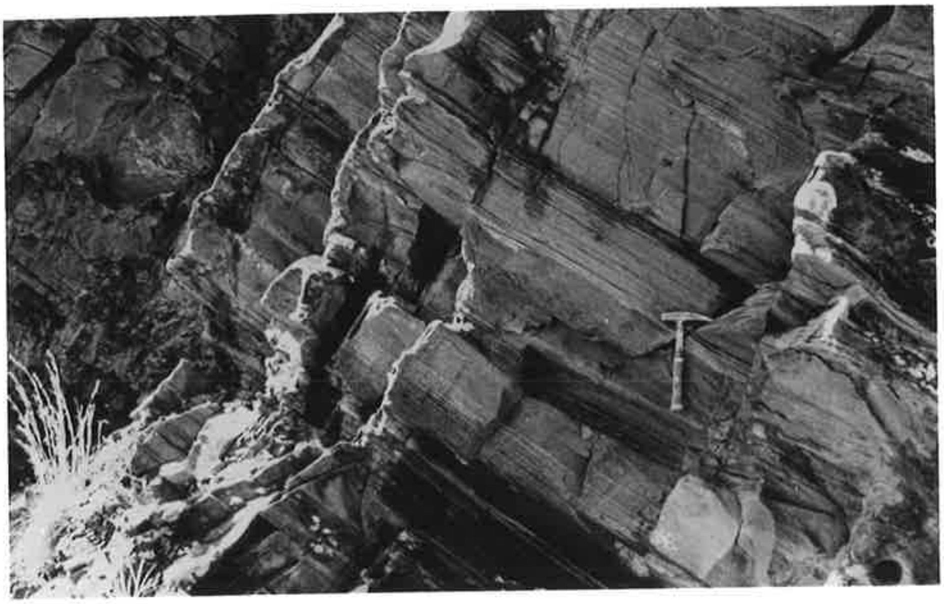


Plate 40: Basal view of bedding plane, containing current lineations and current crescents, (facies Sh). Currents flowed from top right to bottom left. Scale: 54mm diameter. Location: Unit A of the Eregunda Sandstone Member in Section BC-Q at Balcoracana Creek (Wirrealpa Basin).

Plate 41: Multiple sets of planar-tabular cross-stratification (facies Sp) (Omikron cross-stratification of Allen, 1963) overlying horizontally laminated, current lineated sandstone (Sh). Hammer: 31 cm long. Location: Unit C of the Eregunda Sandstone Member in Section BC-Q at Balcoracana Creek (Wirrealpa Basin).

Plate 42: Planar-tabular cross-stratification, with asymptotic foresets (facies Sp). Hammer: 31cm long. Location: Unit C of the Eregunda Sandstone Member in Section BC-K at Ten Mile Creek (Wirrealpa Basin).

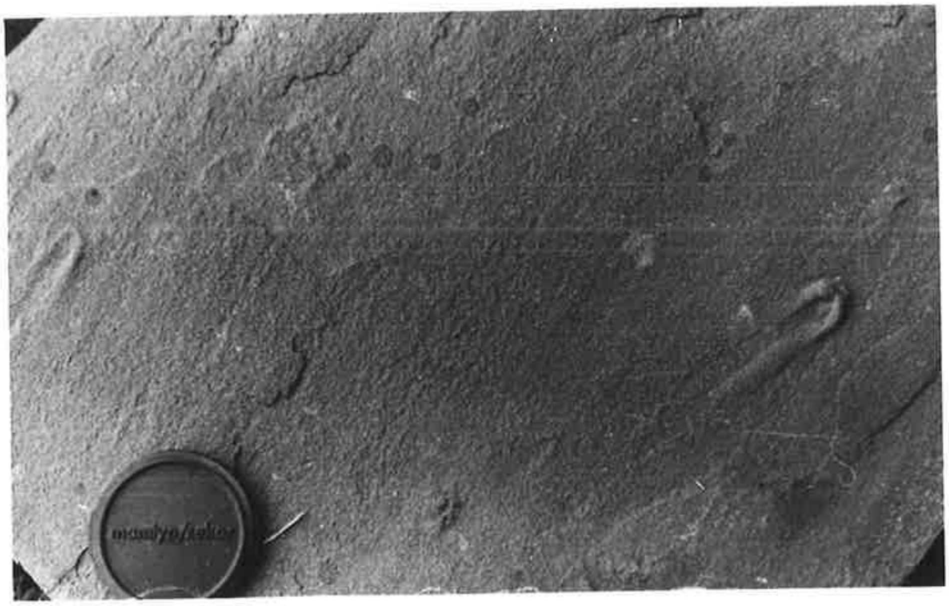


Plate 43: Edge of a large unit of trough cross-stratified fine red sandstone (facies St). The trough is a solitary one, defined as theta cross-stratification (Allen, 1963). Hammer: 31 cm long. Location: Unit C of the Eregunda Sandstone Member in Section BC-K at Ten Mile Creek (Wirrealpa Basin).

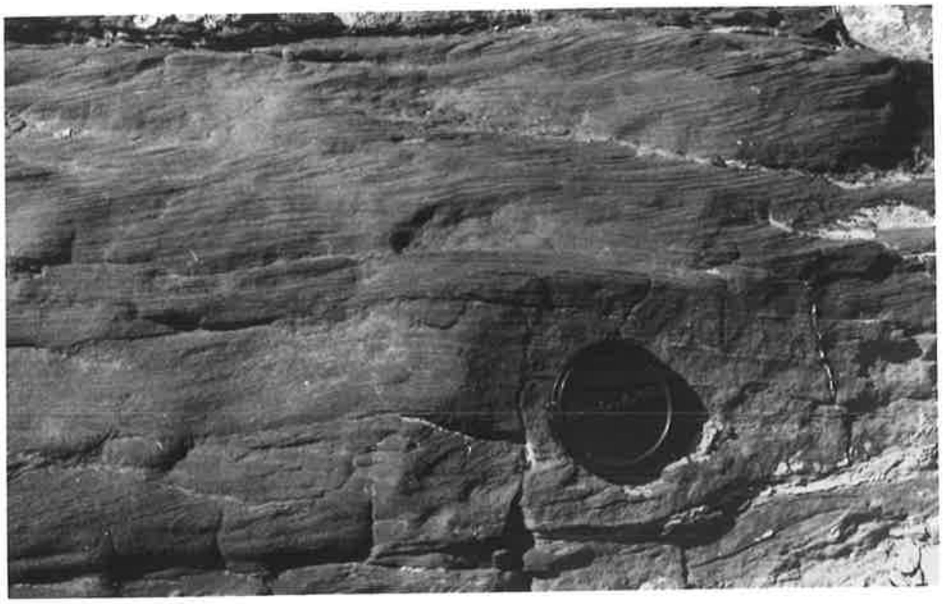
Plate 44: Linguoid ripples in fine red sandstone (facies Sr), directly overlying planar-tabular cross-stratification (Sp). Scale 54mm diameter. Location: Unit C of the Eregunda Sandstone Member in Section BC-Q at Balcoracana Creek (Wirrealpa Basin).

Plate 45: Evenly bedded to rippled sandstone, with loaded and in some cases scoured bases (facies Sr). These sandstone units are interbedded with shales of facies Fl, and are interpreted as crevasse-splay deposits. Hammer: 31cm long. Location: Unit C of the Eregunda Sandstone Member in Section BC-K at Ten Mile Creek (Wirrealpa Basin).

Plate 46: Horizontally laminated sandstone (facies Sl) passing upwards into climbing ripple lamination of facies Sr. Scale: 54mm diameter. Location: Unit A of the Eregunda Sandstone Member in Section BC-Q at Balcoracana Creek (Wirrealpa Basin).

Plate 47: Subvertical worm burrows and incipient shrinkage cracks in thinly bedded to ripple laminated sandstone (facies Sr). Scale: 54mm diameter. Location: Unit C of the Eregunda Sandstone Member in Aroona Creek, Mt. Scott Range.

Plate 48: Plan view of rib and furrows in fine red sandstone (facies Sr), current from bottom to top. Hammer length 31cm. Location: Unit C of the Eregunda Sandstone Member in Section MS-B, Mt. Scott Range.



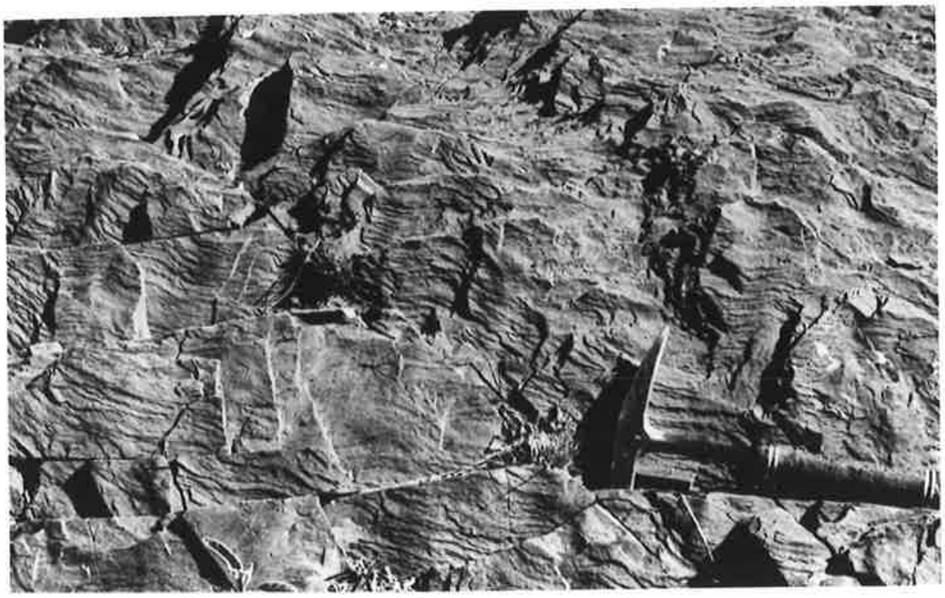


Plate 49: Abundant mudflake intraclasts, and bioturbation (far left) in facies Fl. Scale: 54mm diameter. Location: Unit D of the Eregunda Sandstone Member in Section BC-K at Ten Mile Creek (Wirrealpa Basin).

Plate 50: Evenly laminated shales and siltstones with minor wavy and lenticular bedding (facies Fl). Scale: 54mm diameter. Location: Unit D of the Eregunda Sandstone Member in Section BC-K at Ten Mile Creek (Wirrealpa Basin).

Plate 51: Crawling tracks attributed to trilobites in fine red siltstones of facies Fl. Scale: 54mm diameter. Location: Unit D of the Eregunda Sandstone Member in Section BC-K at Ten Mile Creek (Wirrealpa Basin).

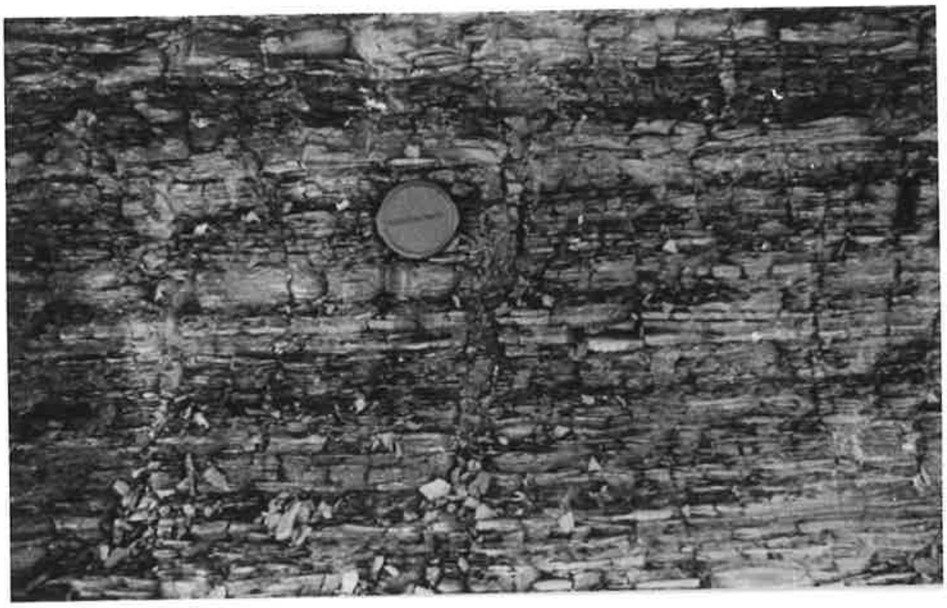


Plate 52: Pebbles and cobbles of Wilkawillina Limestone set in a calcareous sandstone matrix. Upper portion of Unit A of the Coads Hill Member. Scale: 54mm diameter. Location: Section RH-H, Reaphook Hill.

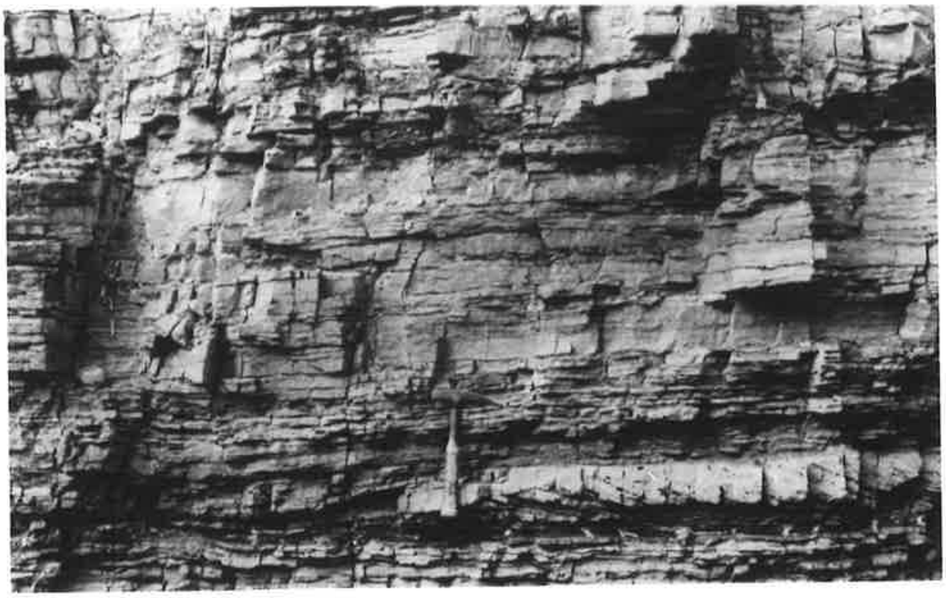
Plate 53: Red shaly siltstones and sandstones of Unit B of the Coads Hill Member draping an irregular disconformity surface at the top of the Wilkawillina Limestone. Hammer 31cm long. Location: Section RH-C, Reaphook Hill.

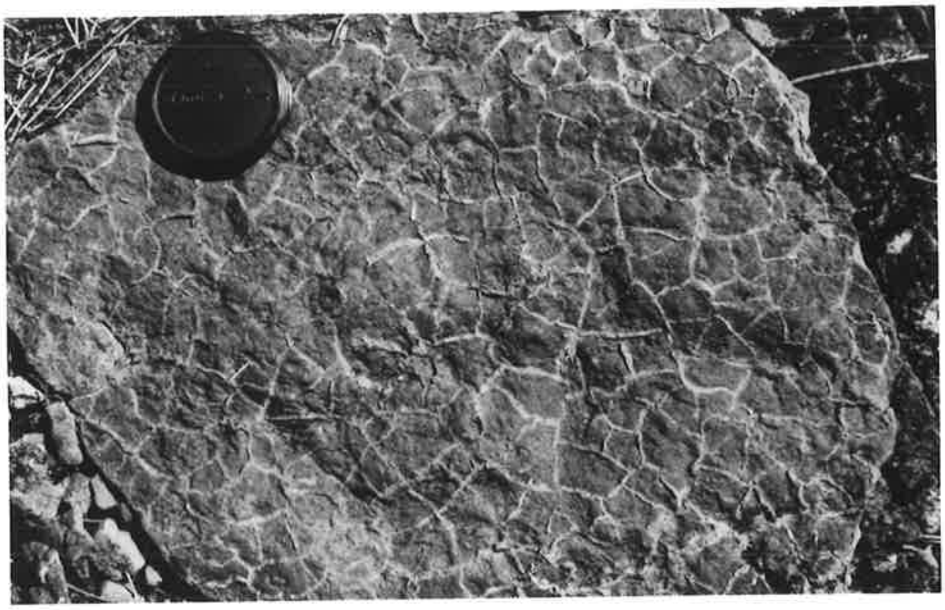
Plate 54: Pissolites in a 20cm thick calcrete unit which caps an irregular disconformity surface at the top of the Wilkawillina Limestone. Pencap scale: 5cm long. Location: 100m north of Section RH-C, Reaphook Hill.

Plate 55: Evenly bedded to cross-stratified reddish brown siltstones and sandstones of Unit B of the Coads Hill Member. Hammer: 31cm long. Location: Section RH-D, Reaphook Hill.

Plate 56: Basal view of casts of small polygonal desiccation cracks. Unit B of the Coads Hill Member. Scale: 54mm diameter. Location: Section RH-G, Reaphook Hill.

Plate 57: Red mudstone intraclasts in evenly bedded sandstone. Unit B of the Coads Hill Member. Scale: 54mm diameter. Location: Section RH-D, Reaphook Hill.





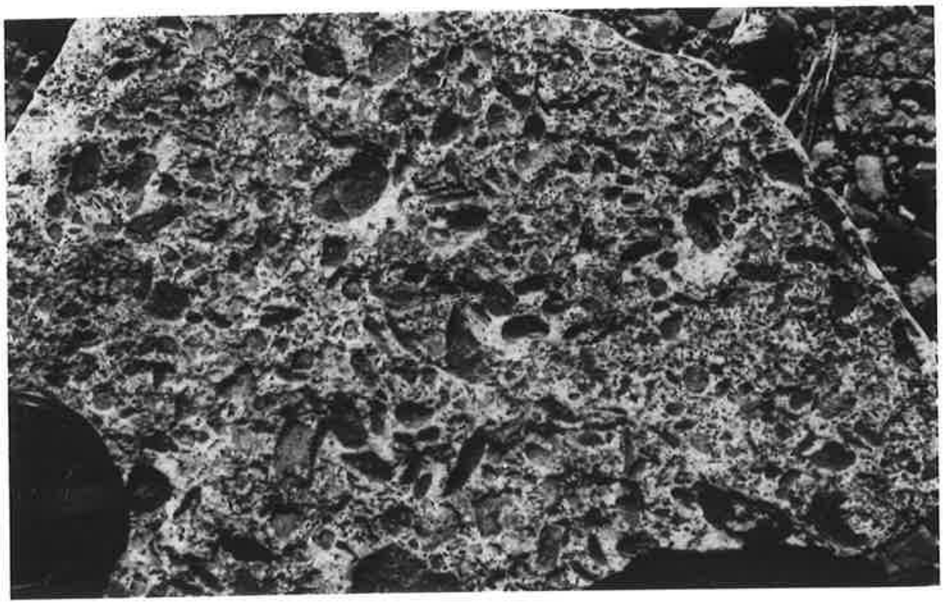
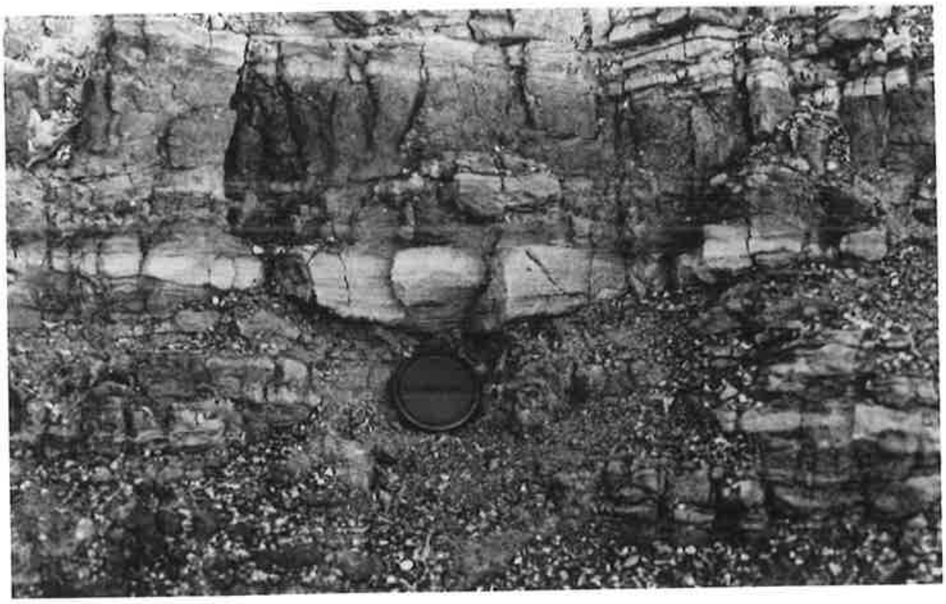


Plate 58: Small sandy channel in very poorly sorted red shaly siltstone of Unit C of the Coads Hill Member. Scale: 54mm diameter. Location: Section RH-A, Reaphook Hill.

Plate 59: Evenly bedded to cross-stratified, very poorly sorted red silty sandstone of Unit C of the Coads Hill Member. Scale: 54mm diameter. Location: Section RH-A, Reaphook Hill.

Plate 60: Carbonate pebbles in very poorly sorted red shaly sandstone of Unit C of the Coads Hill Member. Scale: 54mm diameter. Location: Section RH-E, Reaphook Hill.



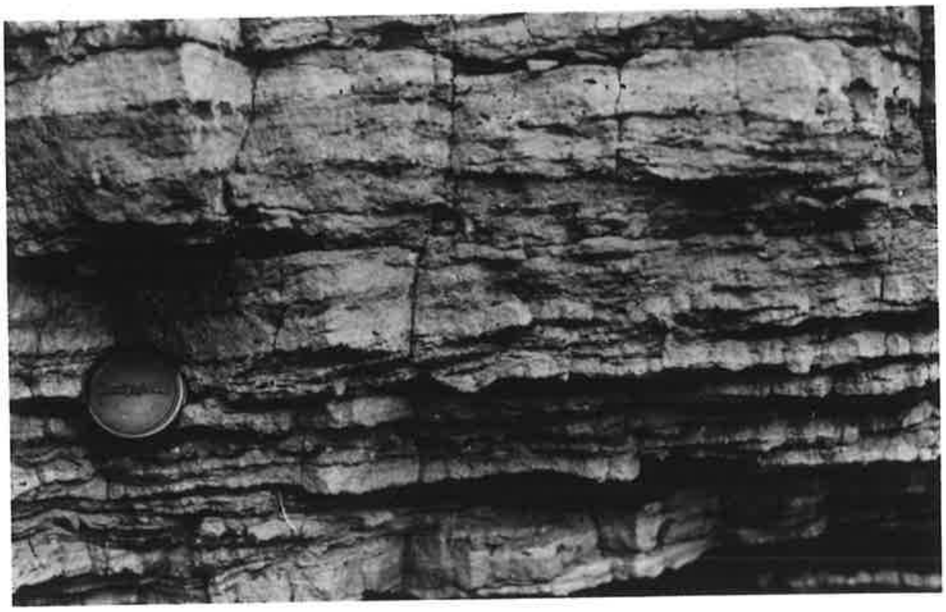
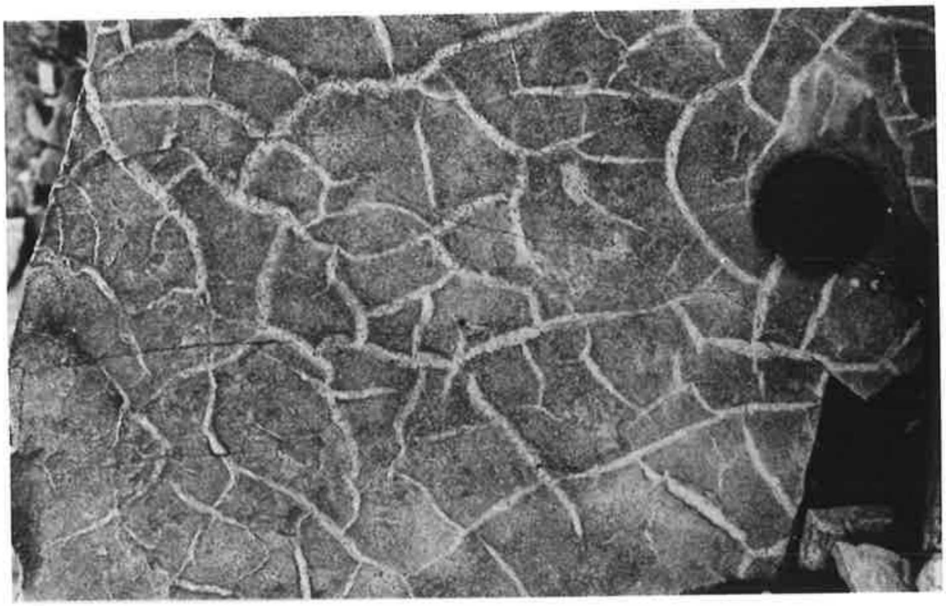


Plate 61: Typical outcrop of Unit D of the Coads Hill Member, showing prominent ridge of evenly bedded and rarely, ripple laminated, medium-grained sandstone.
Location: Section RH-A, Reaphook Hill.

Plate 62: Incipient shrinkage cracks in fine red sandstone of Unit D of the Coads Hill Member. Scale: 54mm diameter.
Location: Section RH-A, Reaphook Hill.

Plate 63: Prominent ridge of grey, foetid, silty limestone and calcareous siltstone. The basal unit is lighter coloured and dolomitic. Location: Unit E of the Coads Hill Member in Section RH-E at Reaphook Hill.



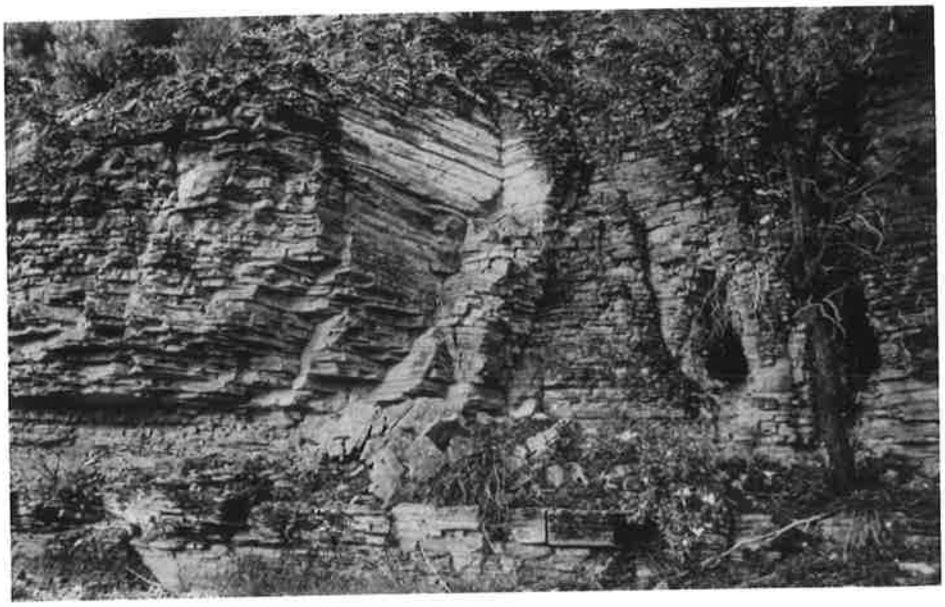
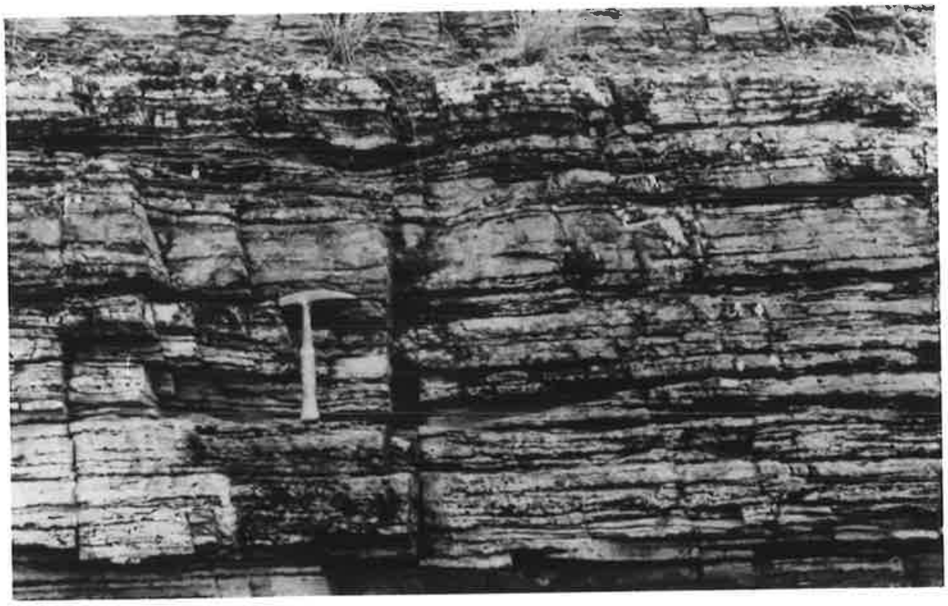
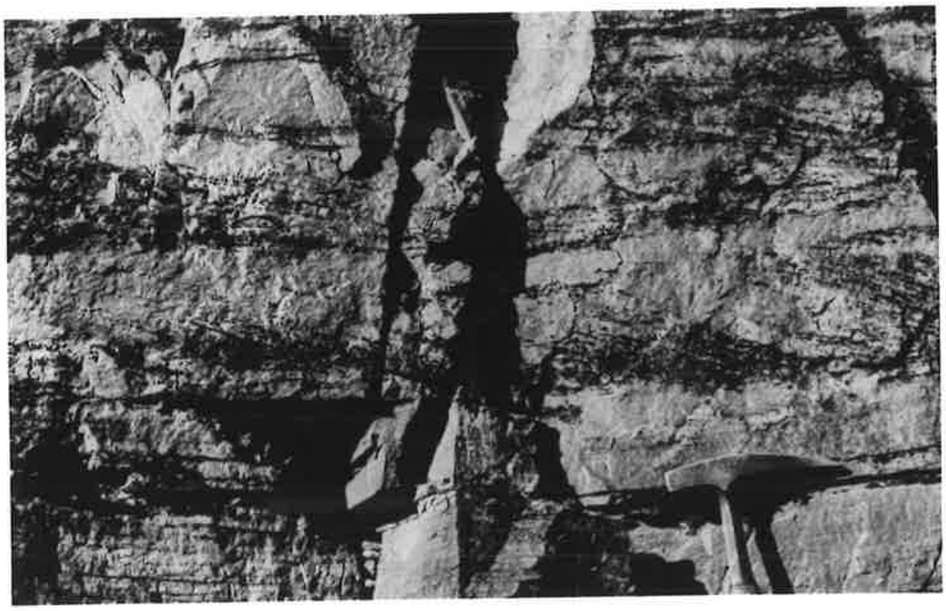


Plate 64: Evenly bedded to ripple laminated reddish brown calcareous sandstone, containing abundant red mudstone intraclasts. Hammer: 31cm long. Location: Unit F of the Coads Hill Member in Section RH-A at Reaphook Hill.

Plate 65: Cross-stratification in reddish brown calcareous sandstones of Unit F of the Coads Hill Member. Note the abundance of mudstone intraclasts concentrated on the foresets of the cross-strata. Location: Section RH-F, Reaphook Hill.

Plate 66: Subhorizontal worm burrows in reddish brown fine sandstone of Unit F of the Coads Hill Member. Scale: 54mm diameter. Location: Section RH-D, Reaphook Hill.





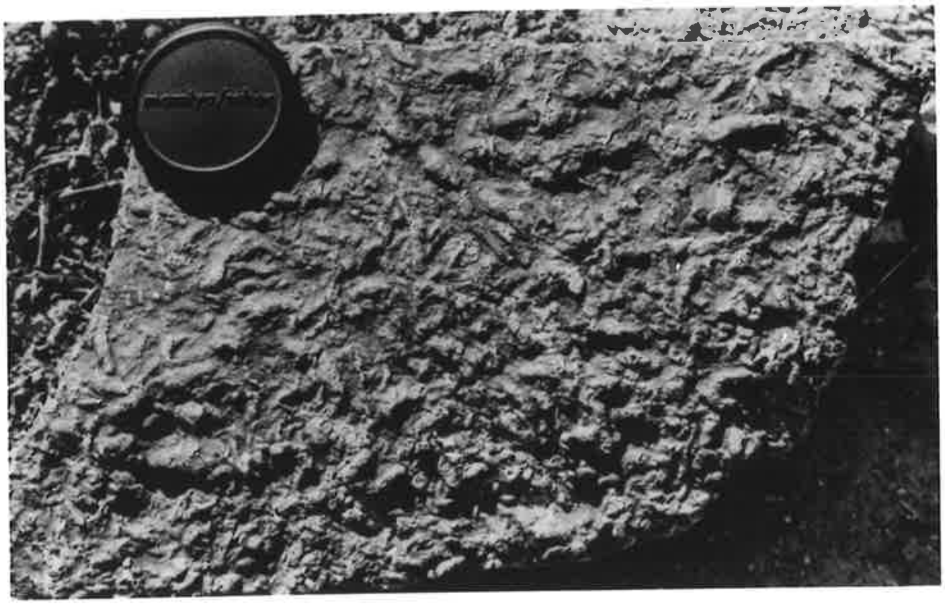
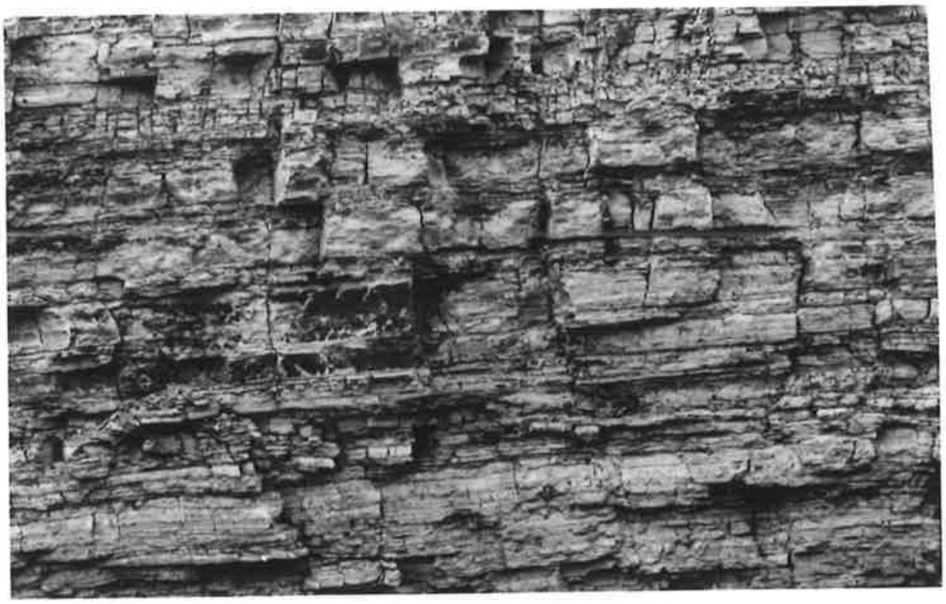
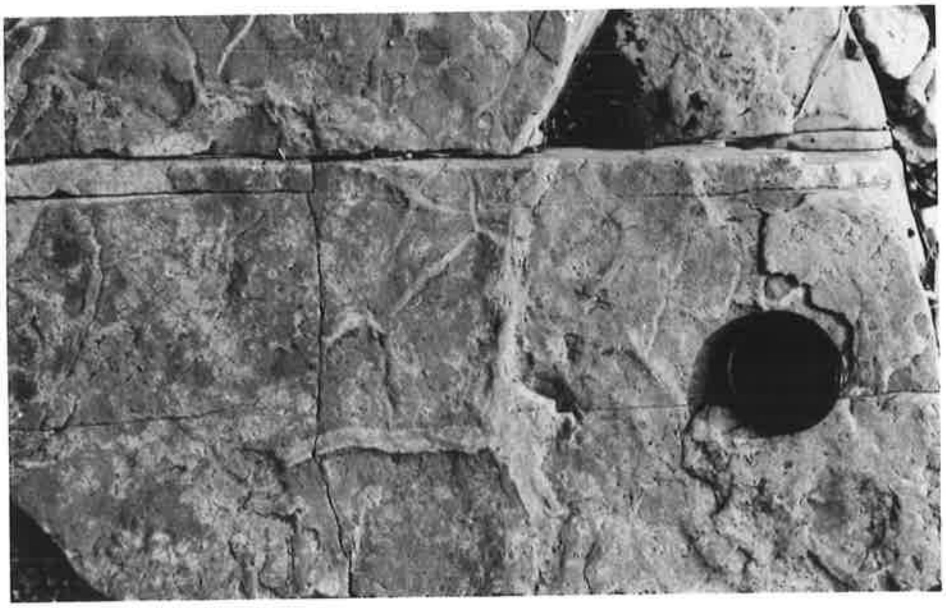


Plate 67: Interbedded green shale (fissile units) and yellowish brown shaly dolomite of Unit G of the Coads Hill Member. Hammer: 31cm long. Location: Section RH-A, Reaphook Hill.

Plate 68: Desiccation cracks in green shale infilled with shaly dolomite (basal view). Scale: 54mm diameter. Location: Unit G of the Coads Hill Member in Section RH-C at Reaphook Hill.

Plate 69: Grey, foetid, nodular limestone of Unit H of the Coads Hill Member. Cliff is approximately 5m high. Location: Section RH-F, Reaphook Hill.





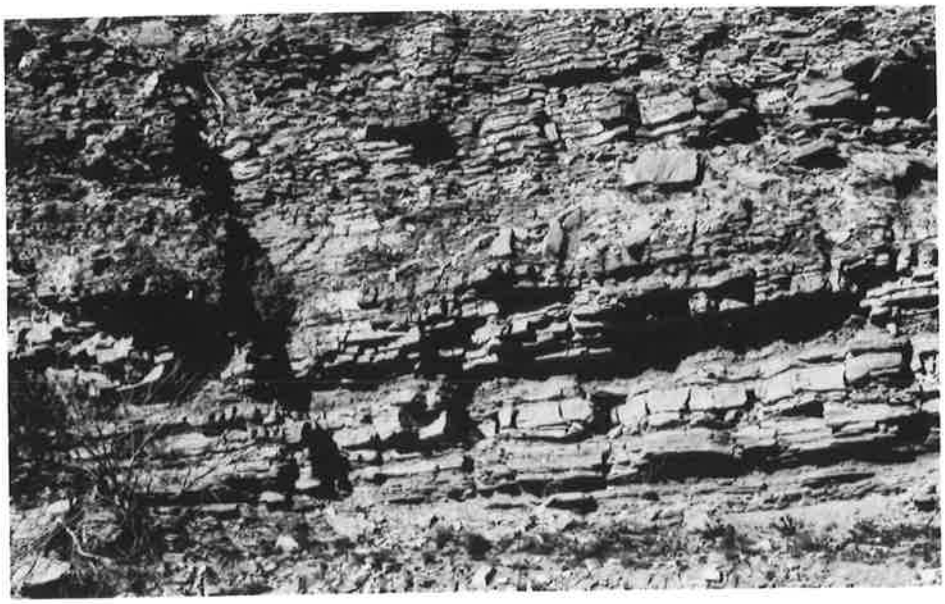
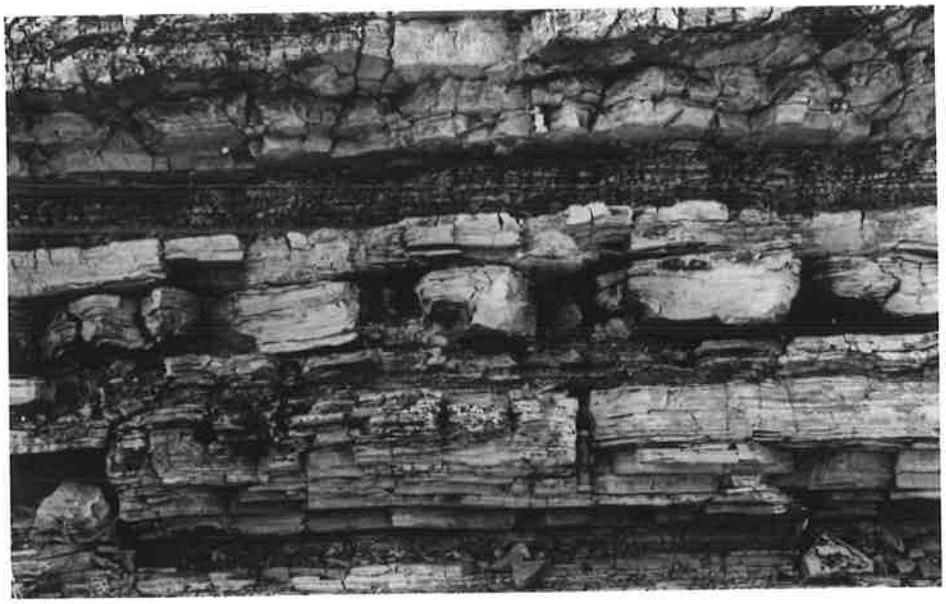


Plate 70: Interbedded grey calcareous shale and shaly limestone of Unit H of the Coads Hill Member. Note the presence of weathered-out stromatolites in the centre of the photo. Stromatolite elongation is perpendicular to the outcrop. Hammer: 31cm long. Location: Section RH-F, Reaphook Hill.

Plate 71: Basal view of yellowish brown shaly dolomite containing abundant halite pseudomorph casts. Scale: 54mm diameter. Location: Unit H of the Coads Hill Member, in Section RH-C at Reaphook Hill.

Plate 72: Yellowish brown dolomitic limestone interbed in khaki green shale of Unit G of the Coads Hill Member. The shales contain abundant fragments of the trilobite *Balcoracania dailyi* Pocock. Hammer: 31cm long. Location: Section RH-A, Reaphook Hill.



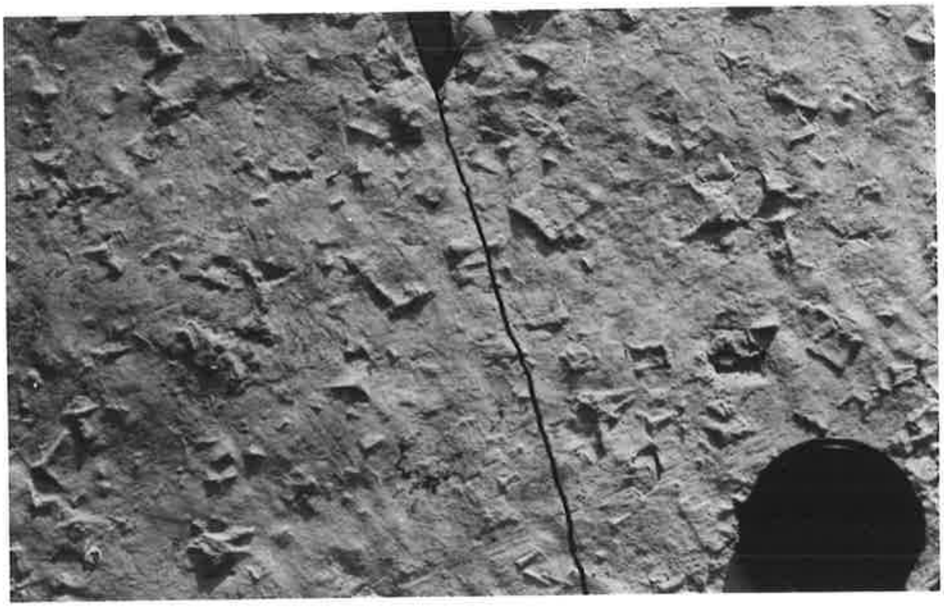


Plate 73: Large scale shale-carbonate cycle in Unit A of the Erudina Siltstone Member. Red shales pass gradationally through green shales and greyish green calcareous shales into pale grey to buff-coloured dolomitic limestone. A rapid transection back into red shale as shown here is typical of the cycles. Hammer: 31cm long. Location: Section RH-C, Reaphook Hill.

Plate 74: Thin unit of yellowish brown shaly dolomite with wavy, stromatolitic laminations in the middle of an asymmetrical shale-dolomite-shale cycle. Scale: 54mm diameter. Location: Unit A of the Coads Hill Member in Section RH-A at Reaphook Hill.

Plate 75: Curled polygonal desiccation cracks in red silty shale of Unit A of the Coads Hill Member. Lenscap scale: 54mm. Location: Section RH-A, Reaphook Hill.

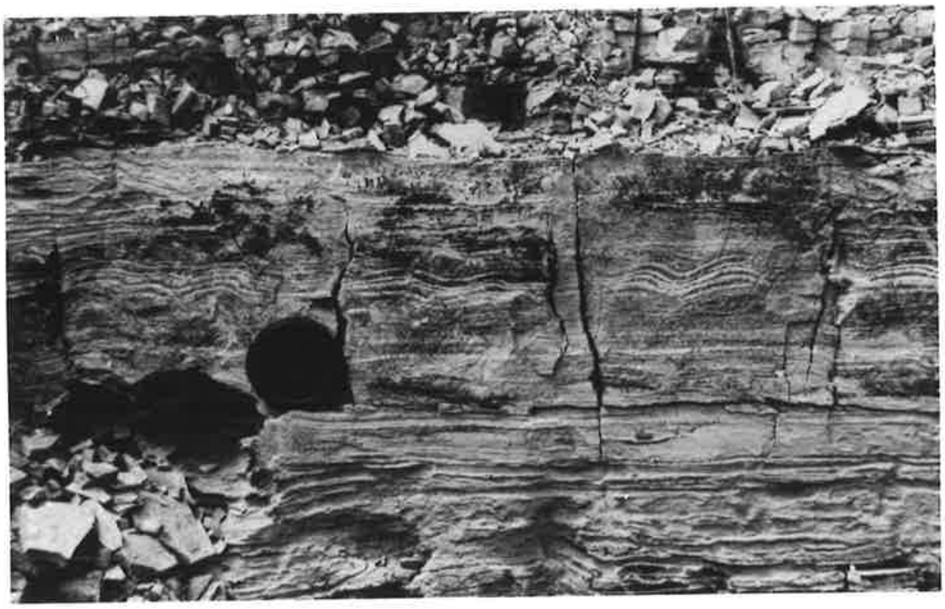
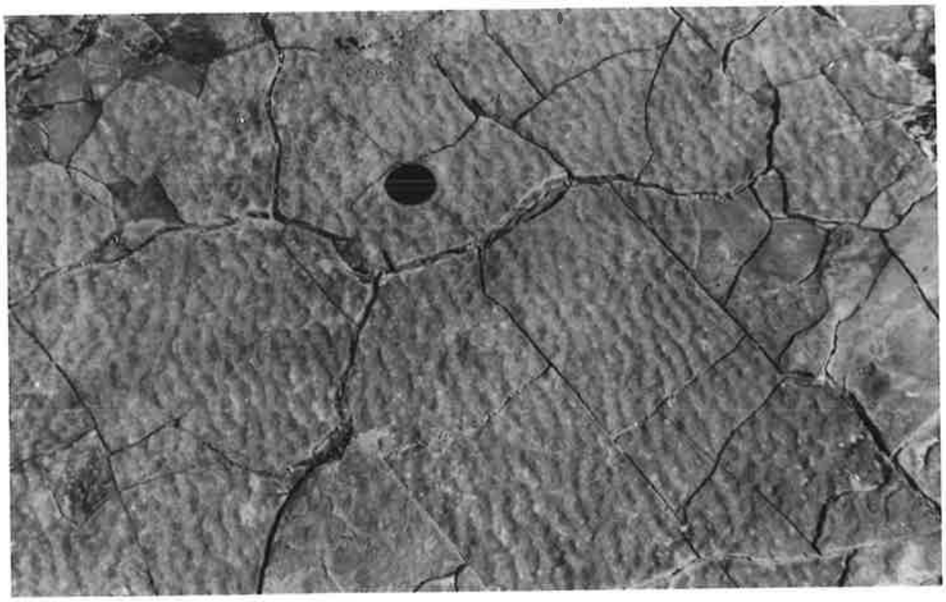


Plate 76: General view of Unit D of the Erudina Siltstone Member. Note the even continuous nature of the laminae. Hammer: 31cm long. Location: Section RH-C, Reaphook Hill.

Plate 77: Wavy and lenticular bedding in shaly siltstones of Unit D of the Erudina Siltstone Member. Mudflake intraclasts are common in these units. Location: Section RH-C, Reaphook Hill.

Plate 78: Symmetrical wave ripples in coarse red siltstone. The bedding surface is dissected by large, polygonal desiccation cracks infilled with red mudstone. Lenscap scale: 54mm diameter. Location: Section RH-C, Reaphook Hill.



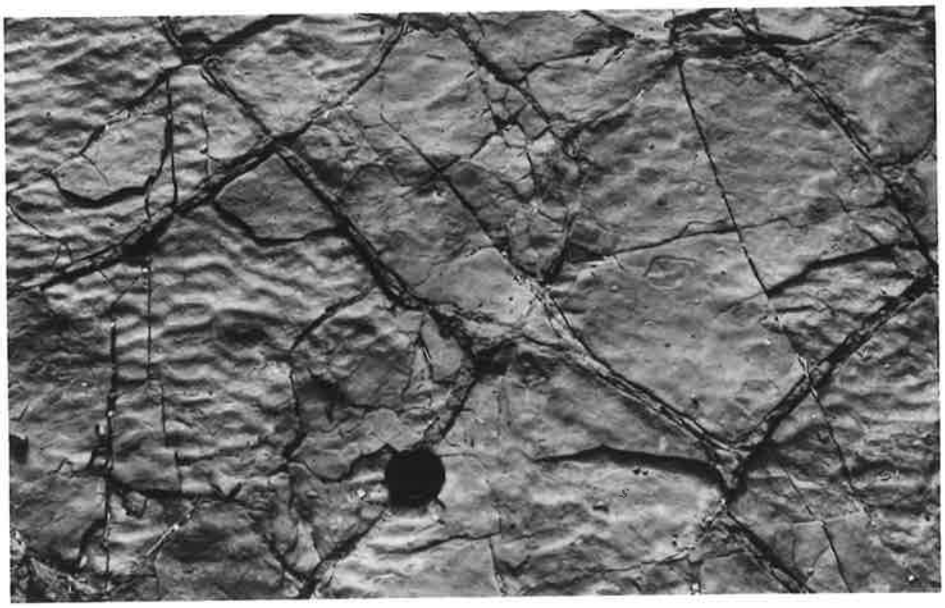
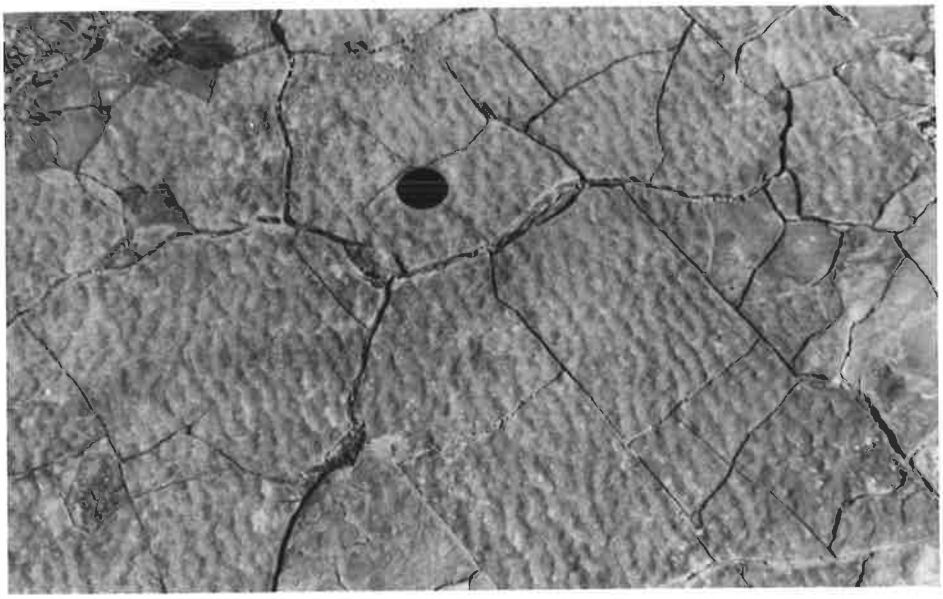


Plate 79: Interference wave ripples on bedding plane surface of coarse red siltstone, dissected by polygonal desiccation cracks. Scale: 54mm diameter. Location: Unit B of the Erudina Siltstone Member in Section RH-A at Reaphook Hill.

Plate 80: Large polygonal desiccation cracks in coarse red siltstone. Symmetrical ripples on the bedding plane surface appear to have been planed off in some areas. Scale: 54mm diameter. Location: Unit D of the Erudina Siltstone Member in Section RH-C, at Reaphook Hill.

Plate 81: Mudstone intraclasts in red siltstone of Unit B of the Erudina Siltstone Member. Scale: 54mm diameter. Location: Section RH-A, Reaphook Hill.



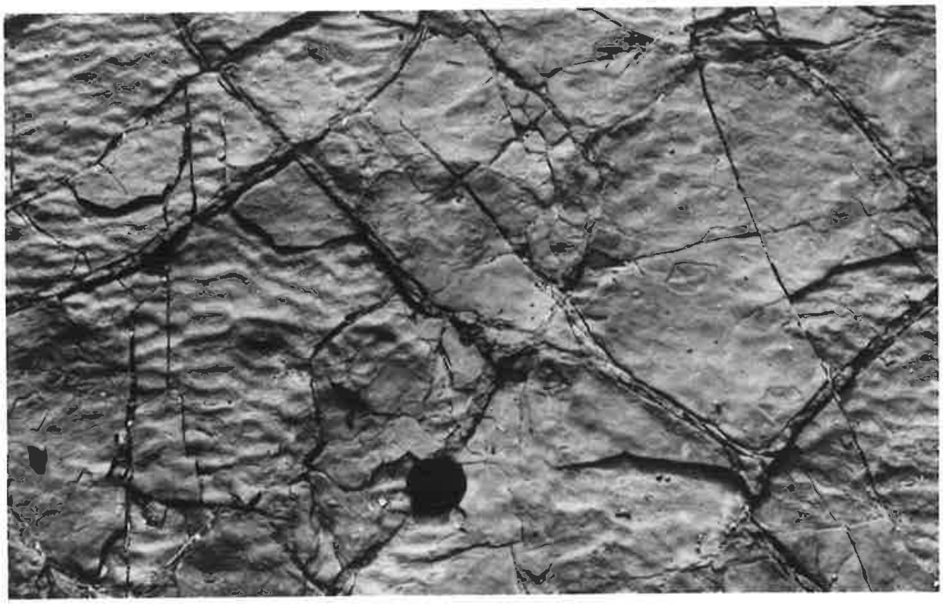


Plate 82: *Planolites* burrows at the base of a red siltstone interval in Unit B of the Erudina Siltstone Member. Scale: 54mm diameter. Location: Section RH-A, Reaphook Hill.

Plate 83: Arthropod tracks (?trilobites) on bedding plane of fine-grained, red micaceous siltstone (plan view). Scale: 54mm diameter. Location: Unit B of the Erudina Siltstone Member in Section RH-A at Reaphook Hill.

Plate 84: Small, coarsening-upward cycle in evenly bedded to rippled red siltstone and sandstone of Unit C of the Erudina Siltstone Member. Desiccation cracks are present in the upper, sandy part of the cycle. Hammer: 31cm long. Location: Section RH-C, Reaphook Hill.

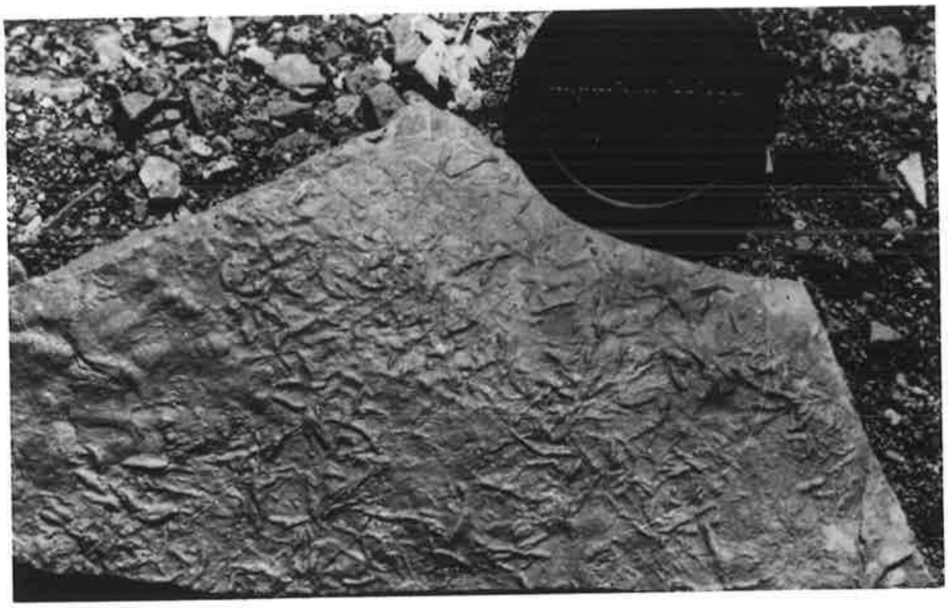


Plate 85: Rib and furrow structure in red micaceous sandstone of Unit C of the Erudina Siltstone Member. Current from left to right. Scale: 54mm diameter. Location: Section RH-C, Reaphook Hill.

Plate 86: Current lineated red micaceous sandstones of Unit C of the Erudina Siltstone Member. Scale: 54mm diameter. Location: Section RH-C, Reaphook Hill.

Plate 87: Large load structures with subvertical symmetry, probably associated with dewatering. Hammer: 31cm long. Location: Unit C of the Erudina Siltstone Member in Section RH-C at Reaphook Hill.

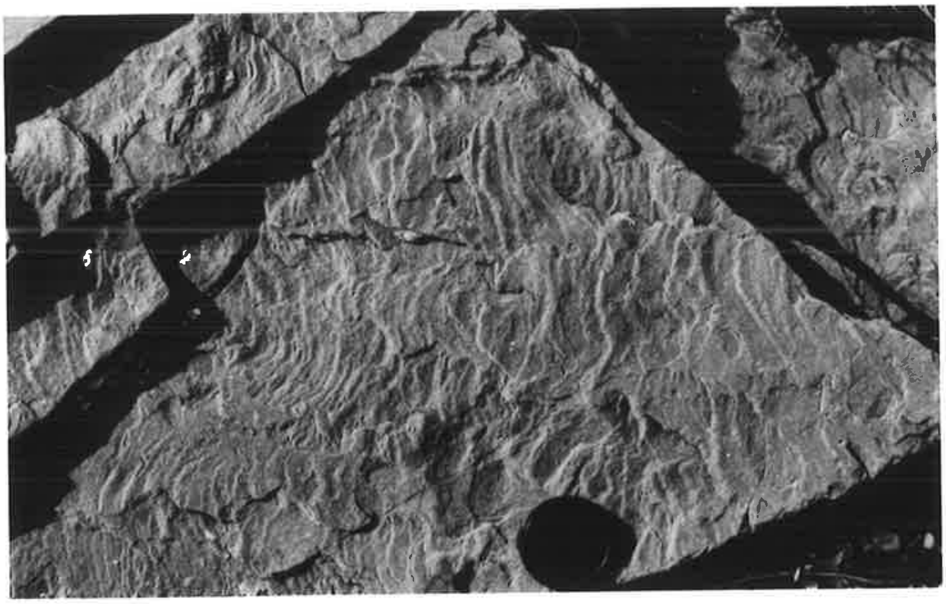


Plate 88: Poorly defined simple and wavy flaser bedding in red shaly siltstones of the Billy Creek Formation sensu stricto. White patches are anhydrite. Bar scale in 1cm intervals. Depth: 2517'6" (Core 8) of Lake Frome No. 1 well.

Plate 89: Climbing ripples in red siltstone of the Billy Creek Formation sensu stricto. Bar scale in 1cm intervals. Depth: 1670' (core 5) of Lake Frome No. 1 well.

Plate 90: Patchy anhydritic (white) in variegated fine siltstones of the Billy Creek Formation sensu stricto. Bar scale in 1cm intervals. Depth: 1663' (Core 5) of Lake Frome No. 1 well.

Plate 91: Secondary vein of anhydrite in variegated shaly siltstones of the Billy Creek Formation sensu stricto. Bar scale in 1cm intervals. Depth: 1665' (Core 5) of Lake Frome No. 1 well.

Plate 92: Wavy algal laminae in greyish green calcareous siltstones of the Billy Creek Formation sensu stricto. Bar scale in 1cm intervals. Depth: 1674' (Core 5) of Lake Frome No. 1 well.

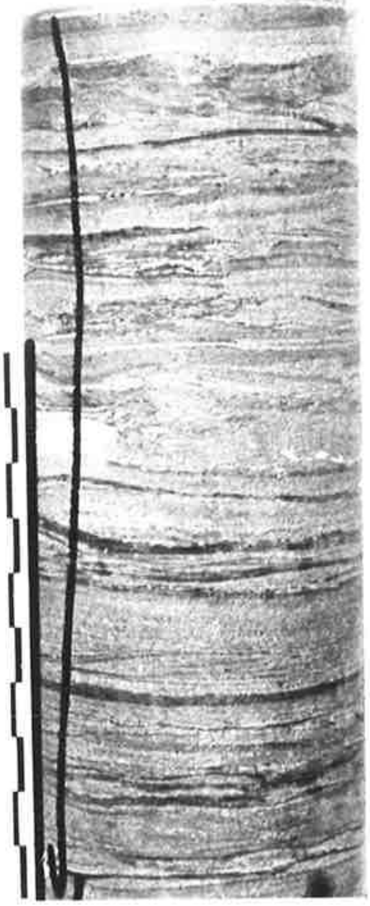


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Plate 93: Channel sandstone facies, comprising medium-grained brown calcareous sandstone with abundant green mudstone intraclasts, which has eroded into the underlying green shaly sequence. Billy Creek Formation sensu stricto in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 454.5m.

Plate 94: Evenly bedded, reddish brown medium-grained sandstone with common red mudstone intraclasts. Billy Creek Formation sensu stricto in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 503.5m.

Plate 95: Ripple laminated, pale brown fine-grained sandstone with green shaly flasers. Billy Creek Formation sensu stricto in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 491.5m.

Plate 96: Convolute bedded, reddish brown fine- to medium-grained sandstone. Billy Creek Formation sensu stricto in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 427.4m.

Plate 97: Loads and pseudonodules in reddish brown fine-grained sandstone. Billy Creek Formation sensu stricto in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 334.0m.

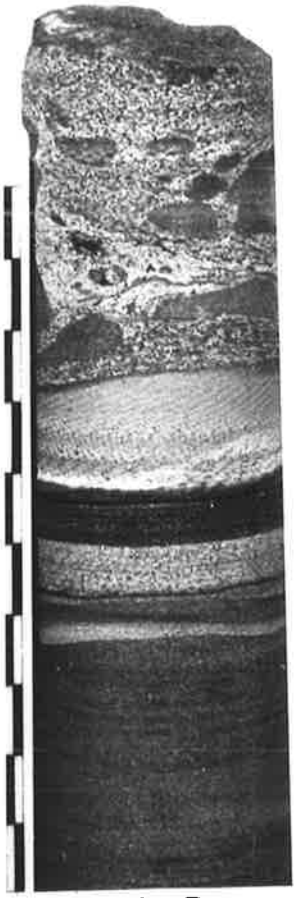
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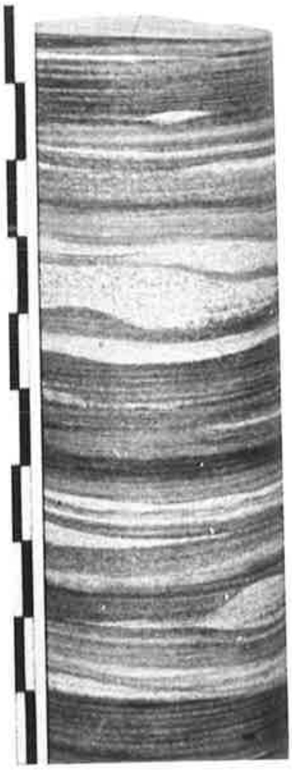
Plate 98: Wavy bedded green silty shale and pale brown sandstone. Billy Creek Formation _sensu stricto_ in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 482.6m.

Plate 99: Sand-infilled worm burrows in green wavy bedded facies. Billy Creek Formation _sensu stricto_ in Yalkalpo 2. Bar Scale in 1cm intervals. Depth: 318.5m.

Plate 100: Desiccation crack in green wavy bedded facies. The desiccation crack extends down from overlying shaly red-beds. Billy Creek Formation _sensu stricto_ in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 445.7m.

Plate 101: Lenticular bedded green shale and pale brown sandstone. The sand lenticles represent poorly connected or isolated ripples, which migrated on the muddy substratum. Note the abundance of small load structures at the base of the sandstone lenses. Billy Creek Formation _sensu stricto_ in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 477.6m.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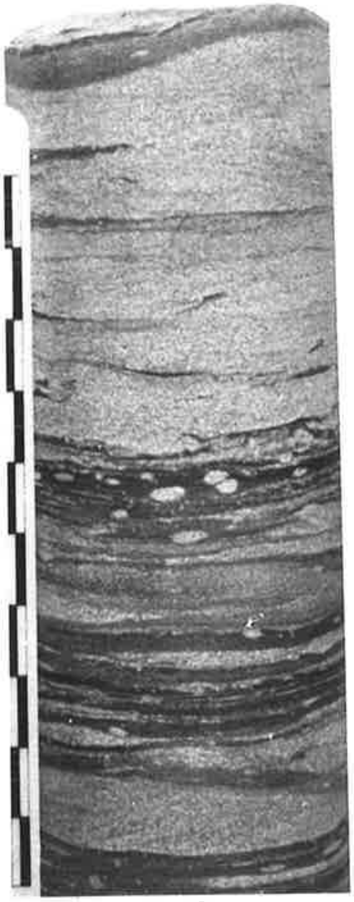
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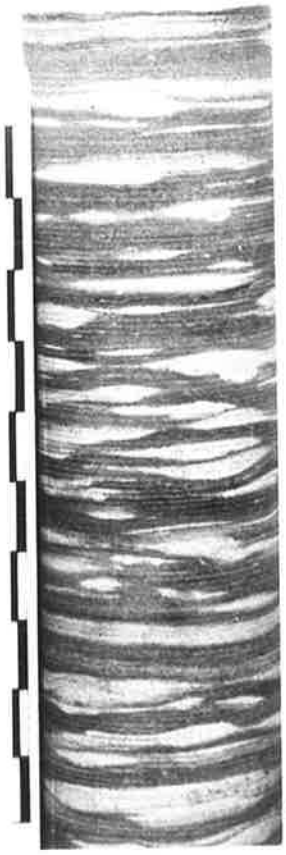
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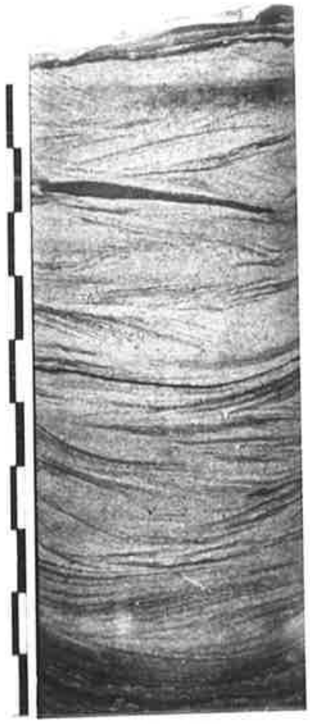
Plate 102: Simple flaser bedding in red shaly sandstone. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 263.8m.

Plate 103: Wavy bedding in red shale and sandstone. Note the presence of very small, sand-infilled worm burrows, and load structures. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Depth: 289.4m.

Plate 104: Desiccation crack (lower portion of core) and ?dewatering structure or possibly bioturbated desiccation crack (upper portion of core) in the red wavy bedded facies. Both features are planar, not cyclindrical structures. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Depth: 327.6m.

Plate 105: Patchy anhydrite (white) in very shaly portions of the red, wavy bedded facies. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Depth: 415.7m.

Plate 106: Reworked intraclasts of anhydrite (white) in red wavy bedded facies. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Depth: 344.6m.



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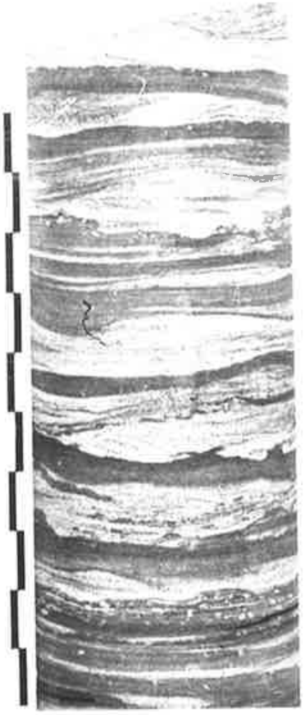

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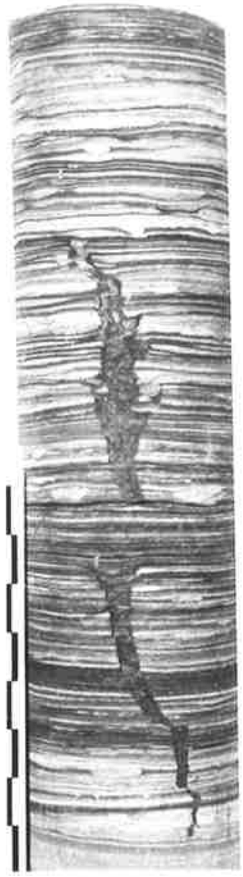

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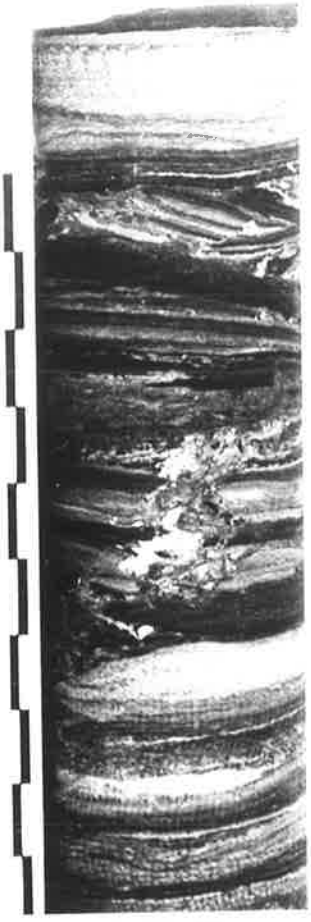

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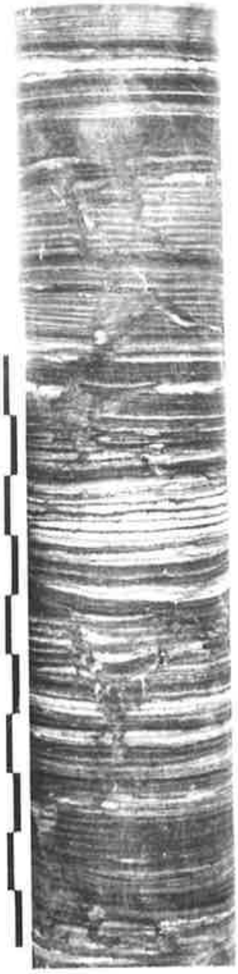
Plate 107: Very shaly, red, wavy bedded facies. Poorly defined sub-vertical structures are either desiccation crack infillings, or are related to fluid migration in the sediment shortly after deposition. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 380.4m.

Plate 108: Silt-streaked red shale facies. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 275.5m.

Plate 109: Disturbed bedding in red, silt-streaked shale facies. White patches are anhydrite. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 411.5m.

Plate 110: Desiccation-cracked red silty shale facies. White patches are anhydrite. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 406.5m.

Plate 111: Evenly laminated red silty shale facies. Billy Creek Formation *sensu stricto* in Yalkalpo 2. Bar scale in 1cm intervals. Depth: 391.3m.



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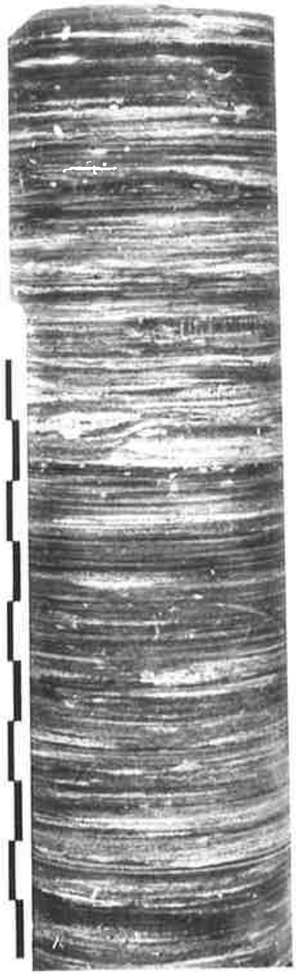

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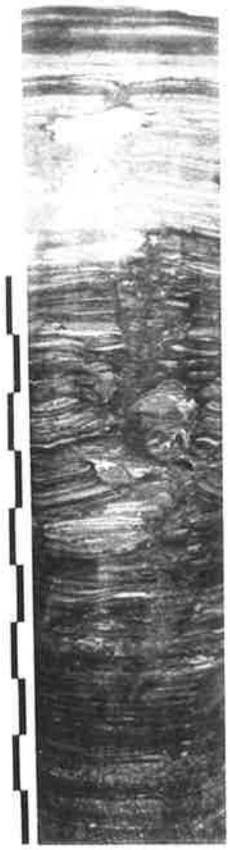

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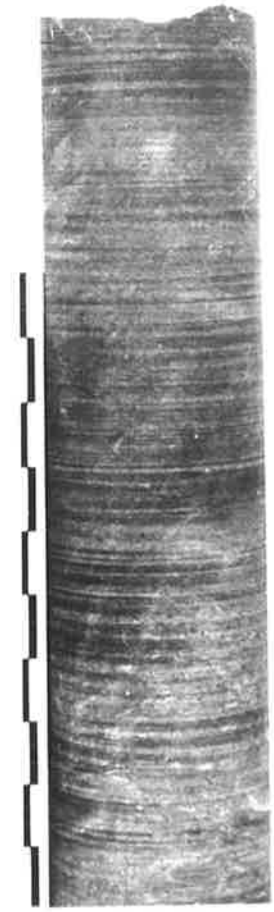

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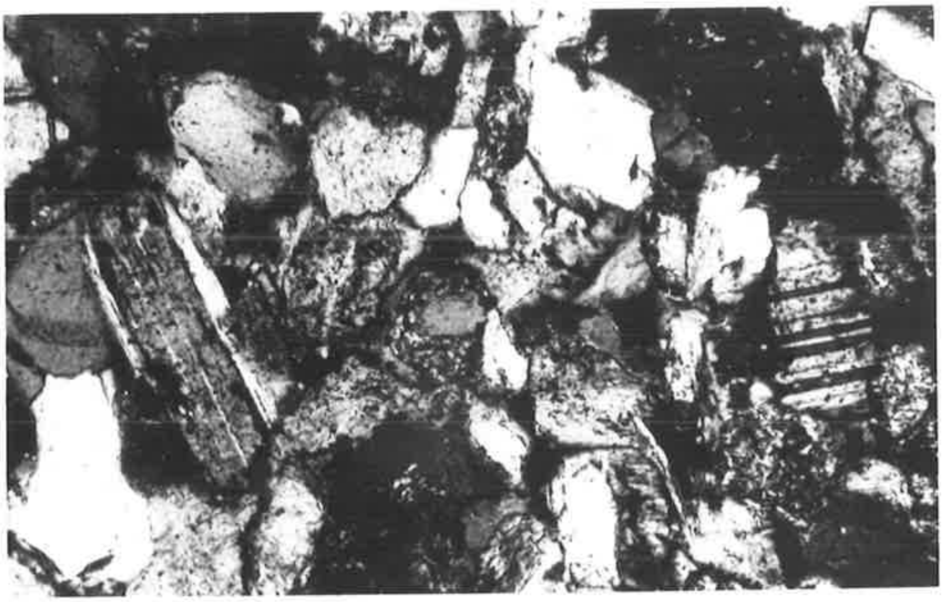
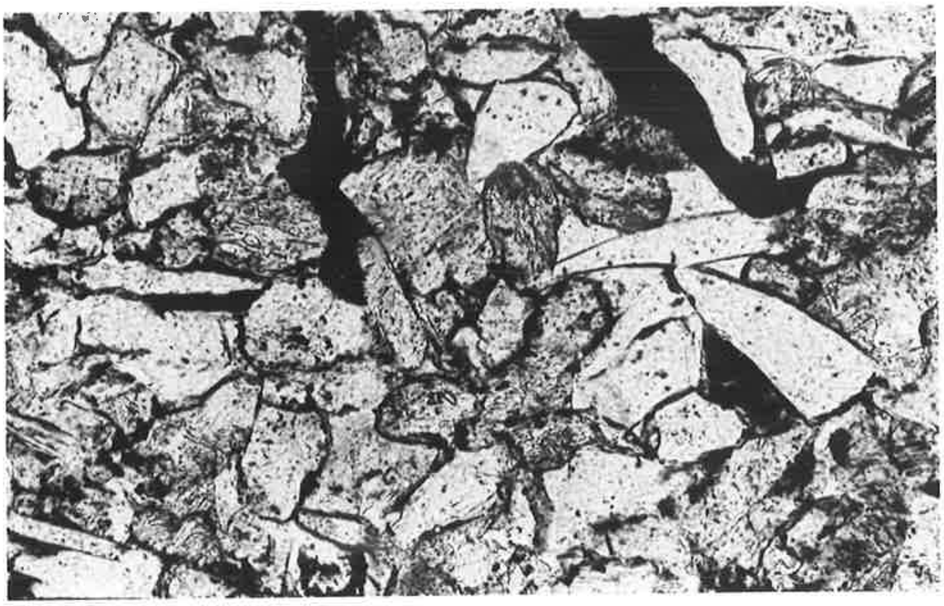
Plate 112: Fine-grained, red micaceous arkose, containing abundant altered orthoclase grains and common laths of twinned plagioclase. Sample BC-K15 with crossed polars. Location: Unit C of the Eregunda Sandstone Member in Ten Mile Creek in the Wirrealpa Basin. Field of view is 0.8mm wide.

Plate 113: Very fine-grained, red micaceous arkose, comprising massivly subangular grains of quartz (clear), feldspar (greyish) and opacitized biotite. Grains are coated with a thin haematite cement (black). Silica overgrowths are also common. Sample BR-A27 in plane polarized light. Location: Unit C of the Eregunda Sandstone Member in Section BR-A, 3km south of Brachina Gorge in the Heysen Range. Field of view is 0.8mm wide.

Plate 114: Very fine-grained, green micaceous arkose, very similar in composition to Plate 113, but without the prominent haematite cement to reveal the original grain shapes. Sample BC-K13 in plane polarized light. Location: Unit C of the Eregunda Sandstone Member in Section BC-K in Ten Mile Creek (Wirrealpa Basin). Field of view is 0.8mm wide.





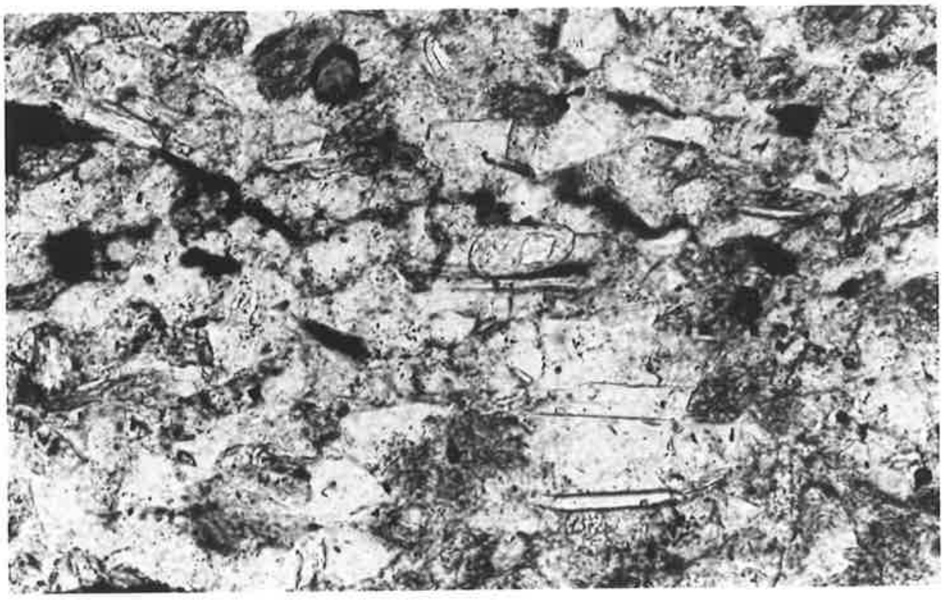
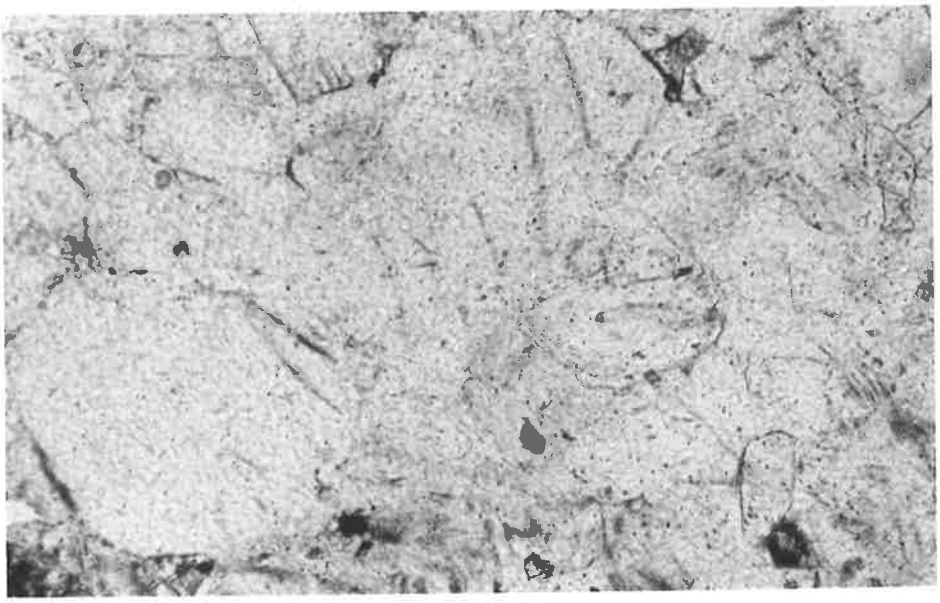
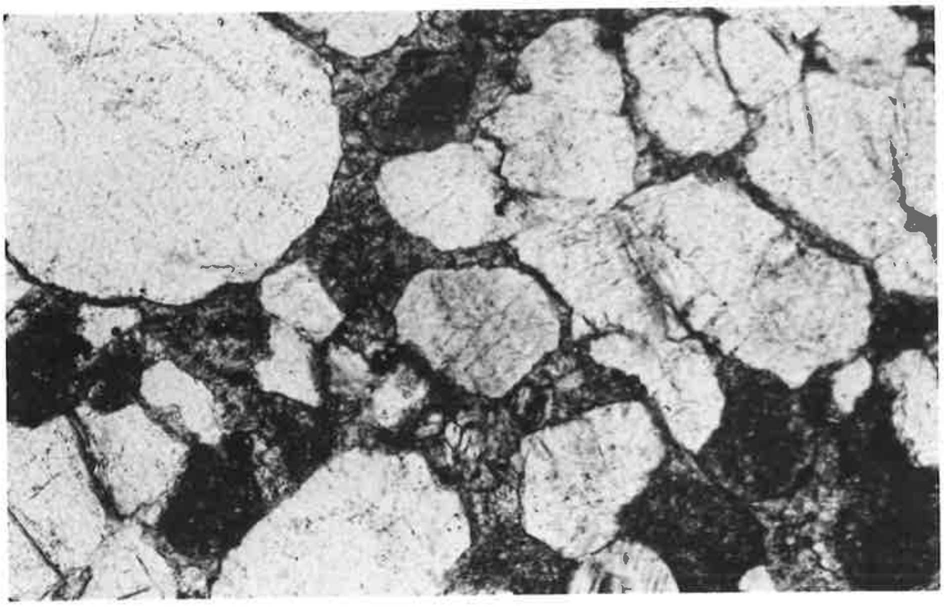


Plate 115: Medium-grained, pale brown subarkose. Grains are predominantly subrounded quartz, and the major cement is silica. Sample RH-C3 in plane polarized light. Location: Unit B of the Coads Hill Member in Section RH-C at Reaphook Hill. Field of view is 2.0mm.

Plate 116: Medium-grained, pale brown sublitharenite, comprising predominantly quartz (clear) and carbonate ooliths (very dark grains), cemented in a silt-sized carbonate-rich matrix. Sample RH-F1 in plane polarized light. Location: Unit B of the Coads Hill Member in Section RH-F at Reaphook Hill. Field of view is 2.0mm.

Plate 117: Reddish brown, immature quartz arenite, comprising fine-grained quartz set in a silty matrix. Sample RH-G14 in plane polarized light. Location: Unit F of the Coads Hill Member in Section RH-G at Reaphook Hill. Field of view is 2.0mm.





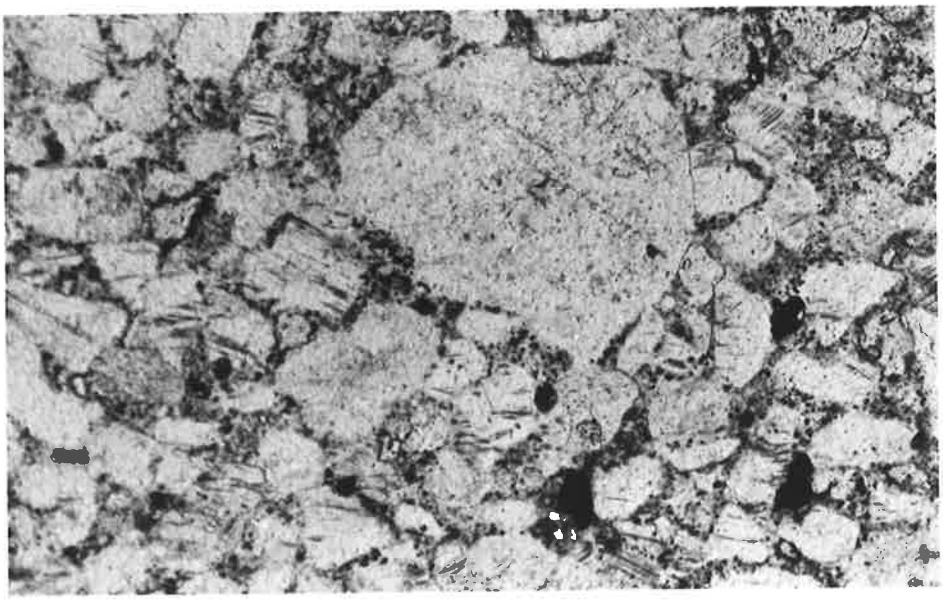
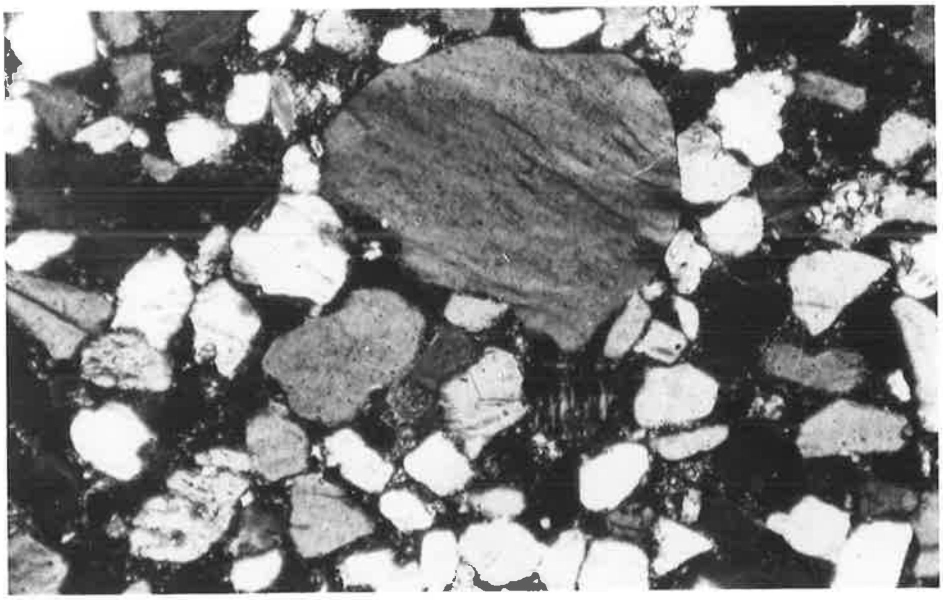
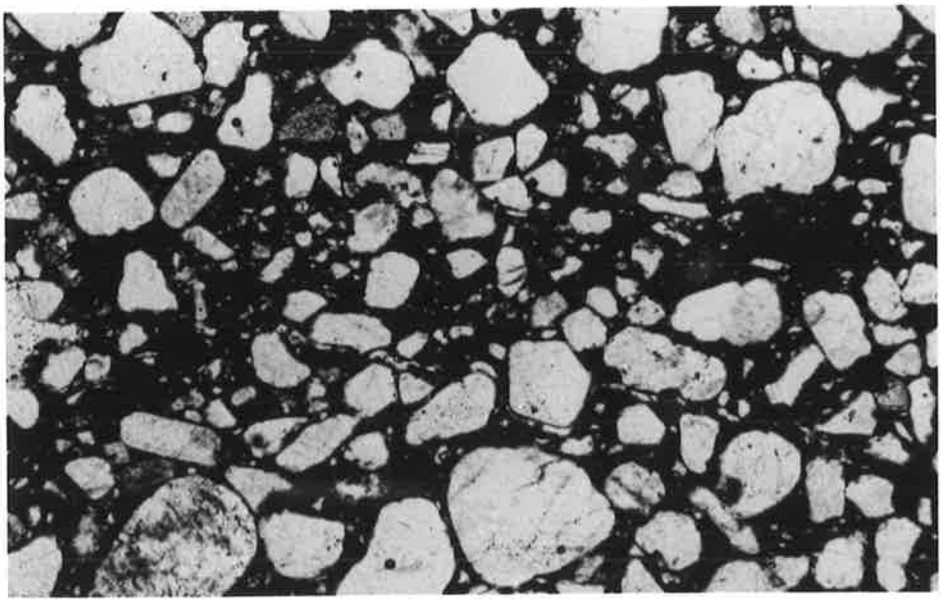


Plate 118: As for Plate 117, except viewed under crossed polars. Note the presence of rare feldspars and polycrystalline quartz grains, and the dark appearance of the clay-rich matrix. Field of view is 2.0mm.

Plate 119: Very immature, clayey sandstone, comprising subrounded, poorly sorted quartz and minor feldspar grains set in a red clayey matrix. Sample RH-C4 in plane polarized light. Location: Unit O of the Coads Hill Member in Section RH-C at Reaphook Hill. Field of view is 3.3mm.

Plate 120: Very immature, clayey sandstone, comprising predominantly subrounded, monocrystalline quartz and microcline set in a red clay-rich matrix. Sample RH-C4 in plane polarized light. Location: Unit D of the Coads Hill Member in Section RH-C at Reaphook Hill. Field of view is 3.3mm.





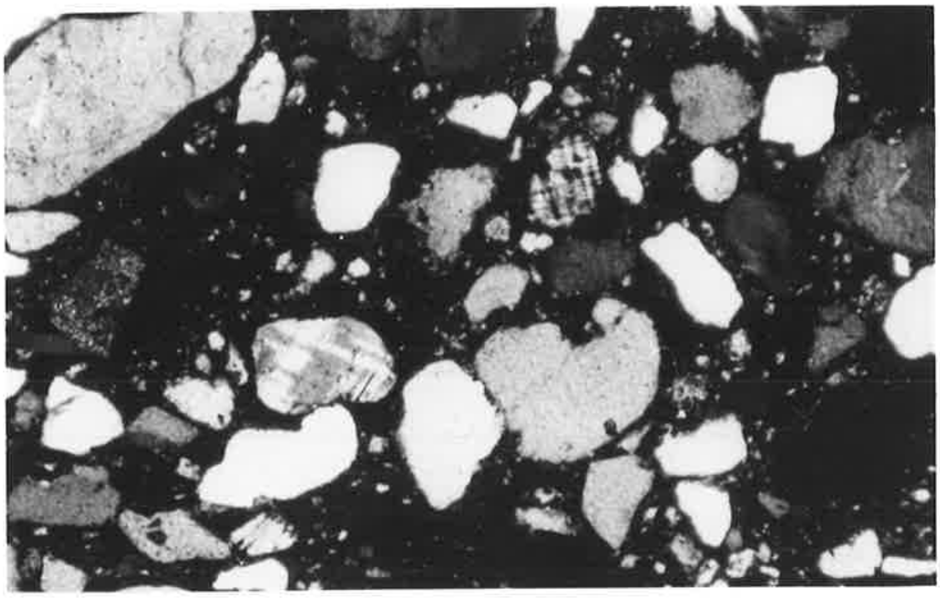
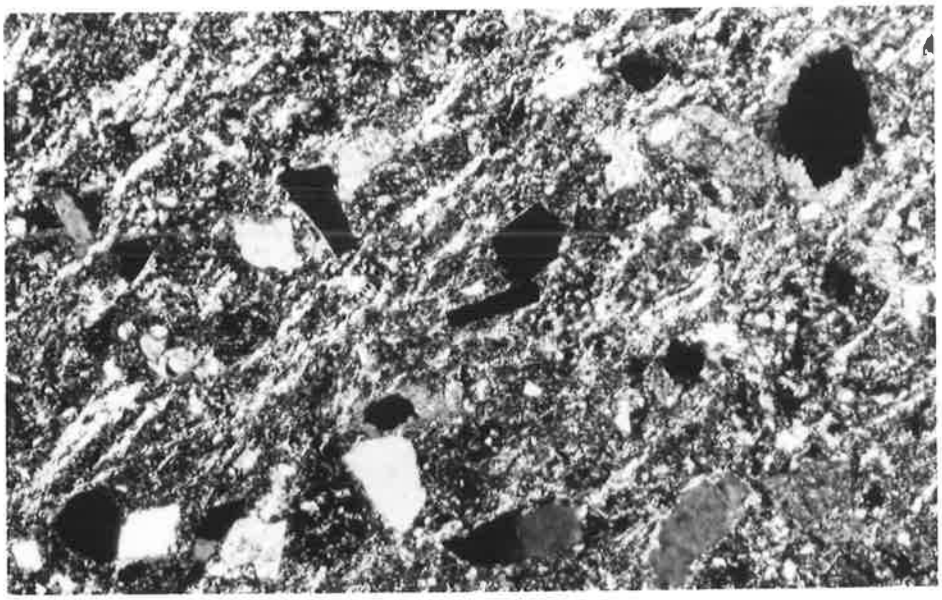
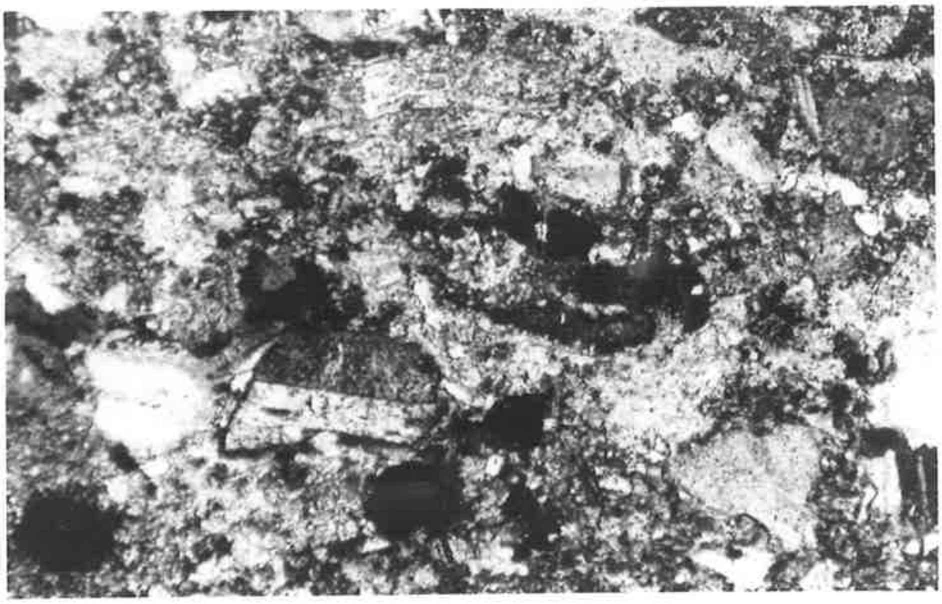


Plate 121: Bright olive green crystal tuff, comprising mainly strands of quartz set in a chloritized microcrystalline matrix. Bedding from bottom left to top right. Sample YLZ-524 with crossed polars. Location: Billy Creek Formation *sensu stricto* at 524m in Yalkalpo 2. Field of view is 2.0mm.

Plate 122: Plagioclase-rich, pink calcareous tuff, comprising mainly very altered shards of plagioclase, K-feldspar, perthite and quartz. Sample BC-T3 with crossed polars. Location: Upper portion of the Warragee Member in Section BC-R, 3km north of Balcoracana Creek in the Wirrealpa Basin. Field of view is 2.0mm.

Plate 123: Quartz grain in tuff, showing prominent resorption patches due to interaction with the fine-grained chloritic matrix. Sample MF-All, with crossed polars. Location: lower portion of the Nildottie Siltstone Member at Section MF-A near Mt. Frome. Field of view is 2.0mm.





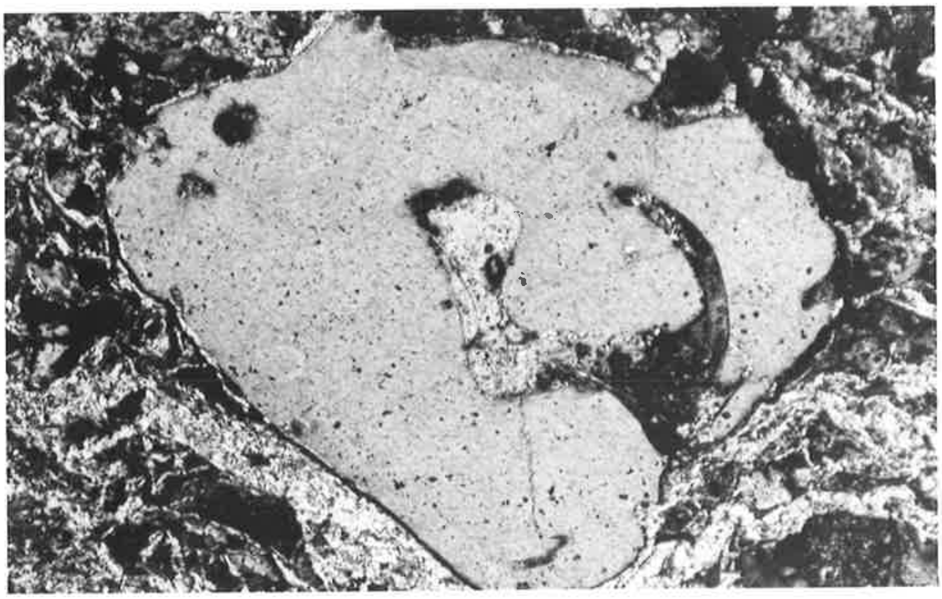
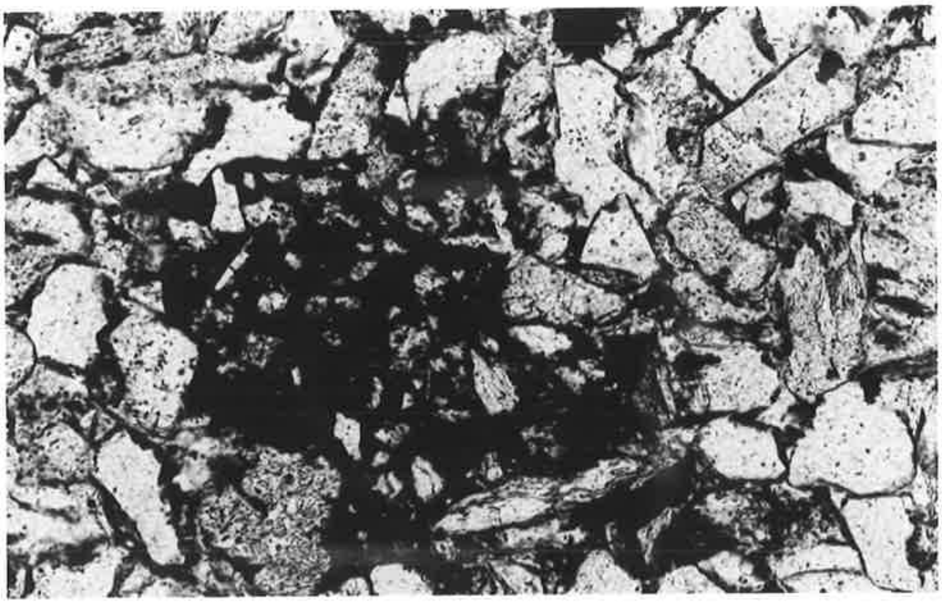


Plate 124: Red, very fine-grained micaceous arkose, with well-developed haematite rims around detrital grains. The haematite rims could not have been preserved during transportation of the grains to their final site of deposition, and thus must be syn- or post-depositional in origin. Sample BR-A26 in plane polarized light. Location: Unit C of the Eregunda Sandstone Member in Section BR-A, 3km south of Brachina Gorge in the Heysen Range. Field of view is 0.8mm.

Plate 125: Silty interval in very fine-grained red micaceous arkose, showing the prominent development of haematite cement (opaque) in this area. Sample BR-A27 in plane polarized light. Location: Unit C of the Eregunda Sandstone Member in Section BR-A, 3km south of Brachina Gorge in the Heysen Range. Field of view is 0.8mm.

Plate 126: Silty clay-ball in fine-grained, reddish brown subarkose. Note that the clay-rich area is heavily pigmented with haematite, but that there is minimal pigment on the surrounding sand-sized grains, nor evidence of a haematitic halo around the mud-ball. Sample RH-G1 in plane polarized light. Location: Unit B of the Coads Hill Member in Section RH-G at Reaphook Hill. Field of view is 2.0mm.



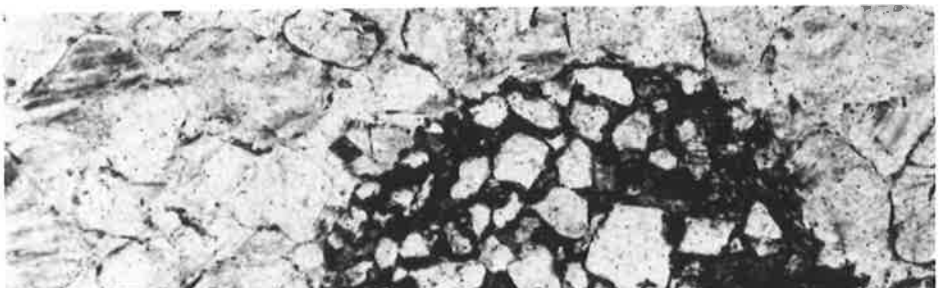


Plate 127: Opacitized flakes of biotite, commonly with poorly defined grain boundaries, in red, very fine-grained micaceous arkose. Sample BR-A27 in plane polarized light. Location: Unit C of the Eregunda Sandstone Member in Section BR-A, 3km south of Brachina Gorge in the Heysen Range. Field of view is 0.8mm.

Plate 128: Detrital grain of opaque oxide, showing secondary growth of haematite around the grain margins. Sample BR-A21 in plane polarized light. Location: Unit C of the Eregunda Sandstone Member in Section BR-A, 3km south of Brachina Gorge in the Heysen Range. Field of view is 0.8mm.

Plate 129: Very fine-grained, red micaceous arkose, showing haematite cement surrounding clear quartz and greyish feldspar grains, occurring in fractures and along cleavage planes and weakly outlining several growth phases in the formation of the silica cement. Sample MS-B11 in plane polarized light. Location: upper portion of the Nildottie Siltstone Member in Section MS-B in the Mount Scott Range. Field of view is 0.33mm.