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THE SEDIMENTOLOGY AND STRATIGRAPHY OF THE PERMO-CARBONIFEROUS GRANT GROUP, BARBWIRE TERRACE, CANNING BASIN, WESTERN AUSTRALIA.

Volume 1
Text and Bibliography

JONATHAN REDFERN

A thesis submitted to the University of Bristol
in accordance with the requirements for the degree
of Doctor of Philosophy in the Faculty of Science,
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ABSTRACT

The Canning Basin is a large intra-cratonic basin which underlies an onshore area of 430,000sq. km. The study area, located on the Barbwire Terrace, contains a series of stratigraphic boreholes drilled by Western Mining Corporation Ltd., which provide fully cored sections through the previously poorly exposed Grant Group.

From this core, integrated with seismic data and wireline logs, the Grant Group has been divided into three new formations, each containing a number of distinctive and intimately related facies types.

The basal Hoya Formation comprises a complex suite of interbedded diamictites, sandstones and mudstones. The diamictites are interpreted as lodgement tills, melt-out tills and flow tills, deposited from the retreating ice sheet. Interbedded with the diamictites are massive and laminated mudstones, deposited under fluctuating marine and lacustrine conditions. Stacked cross-bedded sandstone units are restricted to the west of the study area, forming subsurface linear mounded features, clearly displayed on the regional seismic. These sandstones are interpreted to be deposited from braided fluvial outwash systems. However, the majority of sandstones are massive and normally graded, of mass-flow origin, deposited from a series of subaqueous fans fed by meltwater from the ice sheet.

The overlying Calytrix Formation contains a thin basal sandstone unit, rich in marine fauna, but is characterised by a thick sequence of basinal mudstones. It is overlain by the Clianthus Formation, which has a basal fluvial sandstone unit, capped by heterolithic sandstones, siltstones and mudstones, interpreted to be shallow marine shelf deposits.

The Grant Group sediments record the gradual deglaciation of the basin, and indicate that the ice sheet was extensive during the Perm-Carboniferous. The Hoya Formation contains all the glaciogenic sediments, and provides evidence for periodic ice advance and retreat. The mudrock dominated Calytrix Formation is interpreted to reflect the rise in sea level subsequent to the main deglaciation phase, and the regressive package of sediments that form the Clianthus Formation result from isostatic uplift and basin fill under post glacial conditions.

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Within a few weeks of the first field season the opportunity to examine the extensive database held by Western Mining Corporation Ltd resulted in a change of emphasis to concentrate research on the Canning Basin. I am particularly grateful to Western Mining Corporation Ltd. for permission to study their vast amounts of core and the generous logistic and financial assistance during my field seasons in Australia.

Sincere thanks are expressed to Western Mining personnel, especially Rob Weedon, Clinton Foster, Mike Brumby, and also Stewart Jones, Graham Pitt, Tim and Fran, for their continual support both during my field seasons and in answering my begging letters for data left behind. I benefited greatly from their knowledge of the basin, passed on during conversations, generally over a cold beer. They provided a wealth of valuable ideas during discussions and their experience was a invaluable.

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The material presented in this thesis is the result of my own independent research carried out in the Department of Geology, University of Bristol, the Department of Geology, University of Aberdeen and Western Mining Corporation Ltd. Adelaide, under the supervision of Dr. B.P.J. Williams. Any previously published or unpublished work used is given full acknowledgement.

J. Redfern

Jonathan Redfern
August 1990

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CHAPTER 1

INTRODUCTION

1.1 PREFACE

The aim of this thesis is to systematically investigate the sedimentology and stratigraphy of the Permo-Carboniferous Grant Group, deposited on the Barbwire Terrace of the Canning Basin, Western Australia.

The Canning Basin, located in north western Australia, underlies an onshore area of in excess of 430,000 sq.km, an area approximately the same as that of Texas or France. Figure 1 compares the relative size of Western Australia with the United Kingdom. The basin is one of a series that received extensive suites of sediment during the Permo-Carboniferous (Figure 2). For the most part the Canning Basin is covered by the Great Sandy Desert, and as such field exploration is difficult and hazardous (Plate 1A). The thick cover of dune sands also limits outcrops to the marginal shield areas and isolated ranges within the basin proper.

The Permo-Carboniferous Grant Group has been recorded from scattered outcrops throughout the basin, but the bulk of the sequence is restricted to the subsurface, encountered only by a number of deep boreholes of varying vintages. The basin has potential for hydrocarbon accumulations and over the last 40 years exploration by a number of oil companies has been undertaken, adding scattered well control to the available geological database. In particular, the glacial sediments of the Grant Group have significant economic importance as potential hydrocarbon reservoirs within the Canning Basin. Similar deposits in the Cooper Basin of South Australia /Queensland, described by Williams and Wild (1984), contain major gas reserves. It is also worthy of note that a sequence analogous to the Grant Group, the Al Khlata Formation of Oman contains over 3.5 billion barrels of oil in place, reservoired in glaciogenic sediments (Levell et al. 1988).

Since the early pioneering work of Talbot (1920) and Guppy et al. (1952) established the glaciogenic nature of the Grant Group little progress has been made in detailing the sedimentology of the sequence.

This has primarily been due to the lack of outcrop and previously unavailable extensive subsurface core data, which together prevented a detailed analysis of the complete section.

This research project takes advantage of the recent acquisition of extensive core by Western Mining Corporation Limited (WMC) as part of their hydrocarbon exploration programme. The study area, located on the Barbwire Terrace, is remote and was virtually unexplored prior to WMC's acquisition of exploration rights. Only four deep wells were available in an area of over 32,000 sq.km. where no Grant Group outcrop occurs (Figures 3 & 4). WMC have drilled a total of 32 wells in the study area, most of which contain core from the Grant Group section. These wells, when integrated with geophysical wireline logs and seismic lines provide an excellent data set in an area previously poorly documented. In addition, correlation has been attempted to selected deep boreholes from within the main Fitzroy Graben.

1.2 AIMS OF THE STUDY

In recent years the study of ancient glacial sediments has undergone a renaissance, largely due to the application of integrated sedimentological facies analysis. This study applies this technique to evaluate the sedimentology of the Grant Group. In addition seismic data has been integrated into the study to aid the regional stratigraphic interpretation, and contemporary concepts of seismic stratigraphy have been utilised to re-evaluate the stratigraphic framework of the Grant Group. The main aims of the research project can be summarised as follows:

1. To provide a detailed description of Permo-Carboniferous Grant Group sediments deposited in the study area.

2. To investigate the lateral variability of the section and attempt to produce a regional correlation integrating core, geophysical log and seismic data.

3. To produce a stratigraphic framework for the Grant Group in the study area, and relate this to the generalised stratigraphy for the basin.

4. To interpret the depositional processes and the environment of deposition of the sediments.

5. To establish the controls on evolution in style of deposition during this major glacial period.

6. To provide a predictive model for use in hydrocarbon exploration within the basin, leading to a fuller understanding of the controls on sedimentation and distribution both spatially and temporally of the Grant Group sedimentary facies, with a view to aid the recognition and delineation of potential hydrocarbon reservoirs.

1.3 LOCATION AND DELINEATION OF STUDY AREA

The study area is located in the Canning Basin, Western Australia (Figure 3) and lies within Western Mining Corporation Limited's (WMC) exploration permits. The WMC permits EP 143 and EP 225 are restricted to the Barbwire Terrace, a marginal fault bounded feature trending northwest-southeast; adjacent to the main Fitzroy Graben to the northeast and the Crossland Platform to the southwest (Figures 3, 4 & 5). The permits were initially granted to WMC in 1979 (EP 143) and 1981 (EP 225) and later subdivided in 1983 into the northern Acacia Block and southern Percival Block, following a farm in agreement with Posiedon Oil and Australian Hydrocarbons NL. WMC remain the sole operator.

1.4 DATA BASE AND METHODOLOGY

1.4.1 General

The Grant Group does not form outcrops within the study area, and information is restricted to exploration boreholes. To date some 39 wells have been drilled on the Barbwire Terrace and the immediate vicinity (Figure 5). As part of this study a total of 15 fully cored wells have been logged in detail (Figure 6, Appendix 1), all located on the Barbwire Terrace within the WMC licence areas (Figure 7). The research involves analysis of 3255 metres (10,680 feet) of core, integrated with geophysical wireline logs and seismic data. Analysis of the fully cored sections and wireline logs, associated with interpretation of selected seismic lines have enabled a series of regional correlations and interpretive maps to be produced. The details of wells studied, core meterage, and seismic incorporated into the study are given in Table 1 and Appendix 2. In addition information from adjacent wells within the Canning basin has also been incorporated into the study, supplemented by available published descriptions of outcrops.

Collection of data was undertaken during three field seasons in Adelaide, South Australia. The core was examined at the Challanger Geological Services warehouse (Plate 1B), and also in the Adelaide office of Western Mining Corporation, at that time the base for the Canning Basin Exploration Group. All seismic and wireline log data were provided by Western Mining Corporation.

In order to assess geometry and lateral continuity of the sedimentary units encountered in the narrow diameter core, and allow a comparison with contemporaneous deposits described in the literature, a number of sections of the equivalent Permo-Carboniferous were examined. Selected outcrops of Permo-Carboniferous sediments were examined in South Australia, most notably the Hallett Cove section to the southeast of Adelaide. In addition sections from the equivalent Permo-Carboniferous Itarare Group from the Parana Basin in Brazil were viewed during the field trip run as part of the VII International Gondwanan Conference. (courtesy of Prof. Rocha Campos and J.R. Canuto of the University of Sao Paulo). Whilst this data does not form an integral part of the thesis, which is restricted to the Canning Basin, where appropriate, examples of equivalent facies at outcrop are presented as plates in comparison with the subsurface core data.

1.4.2 Core logging

The slim-hole continuous coring process produces core with a diameter of either 4cm or 6 cm depending on the hole size. The inherent problems of core interpretation, which are greater with narrow diameter core, are discussed in Chapter 6. Core from 15 wells was initially cleaned to remove the coating of drilling mud, reoriented and then visually inspected and logged. Where necessary selected areas were slabbed, although due to the extensive meterage of core and financial restrictions this was not the norm and the majority of core was examined unslabbed. Important features were photographed and samples taken from selected horizons for petrographic analysis in the UK. Samples from selected wells have also been processed for palynological and palaeontological studies by Dr. C B. Foster of Western Mining Corporation, Dr. J.B. Waterhouse of the University of Queensland and Dr. V. Palmieri of the Geological Survey of Queensland, details of which are outlined in this thesis.

Field logging was performed at a scale of 1:50. Subsequently, the forms were re-draughted at a scale of 1:200, and at the same time correlated with the geophysical logs (Appendix 1). At all times the geophysical log depths were regarded as true depths, and core depths have been adjusted to correlate where necessary..

1.4.3 Additional data integration and methodology

The logged sections were subdivided into a number of facies associations, based on lithology and wireline log character, and a series of correlations were constructed across the study area. At the same time selected seismic lines were interpreted to aid the correlation and provide information on regional structural controls on sedimentation. The seismic lines utilised were chosen to connect the study wells or act as link lines, thereby providing a series of regional loops. Detailed methods used in the analysis of the sedimentological, geophysical and seismic data are outlined in the respective chapters.

The resultant information from well correlations and seismic interpretation was used to construct a stratigraphic framework for the study area. Within this framework, core facies analysis formed the basis for the interpretation of depositional processes, environment of deposition, lateral continuity and relative location of the various facies. From this information it was possible to postulate the evolution in the style of, and controls on, sedimentation through time.

1.5 FORMAT OF THESIS

The thesis is organised in order to focus from a broad overview of Canning Basin and Gondwanan geology to the detailed description of the Grant Group recorded in cores from the Barbwire Terrace.

Chapter 2 provides the geological framework for the study. It includes; a general review of early exploration in the Canning Basin, the naming of the basin, structural subdivisions, stratigraphic framework, and a summary of the basin development. In addition, this chapter relates the Canning Basin to Gondwanan geology and discusses the late Palaeozoic glaciation.

Chapter 3 concentrates on the Grant Group, reviewing its sedimentology, lithostratigraphy and biostratigraphy from previously published research.

Chapter 4 introduces the results of current research undertaken as part of this thesis, presents a revised stratigraphic framework for the Barbwire Terrace and discusses the implications to the published stratigraphy for the basin.

Chapter 5 reviews the concepts of seismic stratigraphy and sequence stratigraphy, presents an interpretation of the regional seismic grid over the Barbwire Terrace, and proposes a seismic stratigraphic breakdown of the Grant Group.

Detailed sedimentological facies analysis of the cored sections from the Barbwire Terrace is presented in Chapters 6 to 9. Chapter 6 summarises the methods employed in the study and reviews some key aspects of glacial sedimentology. Chapters 7, 8 and 9 contain the detailed sedimentological descriptions of the Grant Group from the Barbwire Terrace, and present a classification of the sequence into a number of facies associations, for which possible depositional models are proposed. Finally the implications and conclusions of the study are reviewed in Chapter 10, together with recommendations for future work.

Figures, plates and enclosures are located in Volume 2, which also contains the facies logs for the study wells in Appendix 1, classified in alphabetic order. They are referred to constantly throughout the text by well name and depth. Appendix 2 comprises a set of data sheets for the study wells. Table 1 lists data for all the stratigraphic boreholes from the Barbwire Terrace.

CHAPTER 2

GEOLOGICAL FRAMEWORK

2.1 THE CANNING BASIN

2.1.1 Early Exploration

Initial geological investigations of the Canning Basin began in the early 20th Century. These reconnaissance studies are reviewed by Guppy *et al.* (1958) and Traves *et al.* (1956). In 1947 aerial photographing of the whole basin commenced, and in the 1950's the Bureau of Mineral Resources (BMR), with support of a number of oil companies, began regional geological mapping (Traves *et al.* 1956, Guppy *et al.* 1958, Veevers and Wells 1961).

The term 'Canning Basin' was introduced by Gentilli and Fairbridge (1951) in their work 'Physiographic regions of Australia', adopted from the Canning Stock Route, which had been established by the pioneer surveyor A.W.Canning in 1906.

Prior to this, early exploration along the Fitzroy River in the 1920's had sponsored the term 'Fitzroy Basin' (which is still in use for a distinct sub-basinal province, the Fitzroy Trough). More commonly the term 'Desert Basin' was used to describe the physiographic depression between the Kimberley Block to the north and the Pilbara Block to the southwest (Clapp, 1926)(Figure 3)

When the West Australian Petroleum Pty. Ltd. (WAPET) commenced exploration for hydrocarbons in 1953 they adopted the name Canning Basin, and this was formally accepted by the Bureau of Mineral Resources in 1956 (Casey and Nellingan 1956).

2.1.2 Basin Definition

The Canning Basin underlies an onshore area of 430,000 sq.km. and an offshore area of 165,000 sq.km. to the 200m bathymetric contour. In popular usage the term Canning Basin refers to the onshore, intracratonic basin between the Precambrian Kimberley and Pilbara blocks. It contains in excess of 10,000 m of Palaeozoic sediments beneath a thin Mesozoic and Tertiary cover (Figure 3).

The northeastern and southwestern margin of the basin is the unconformity between Phanerozoic sediments and the Precambrian rocks of the Kimberley and Pilbara Blocks respectively. The southern boundary with the Officer Basin is arbitrarily selected on the crest of the Warri Arch, also referred to as the 'Ankatell Regional Gravity Ridge' (Fraser 1976), which aeromagnetic and gravity interpretation suggest is an anticline within the Precambrian basement.

The boundary between the Canning and Amadeus Basins from early Permian onwards is the trace of the unconformity between Permian sediments and the older Amadeus sequences, defined from gravity data as an elongate northerly trending basement high. To the northwest the boundary of the offshore Canning Basin has not been defined, although Playford et al. (1975) and Gorter et al. (1979) have arbitrarily chosen the edge of the continental shelf as the northwestern margin.

2.1.3 Structural Subdivisions

The Canning Basin is subdivided into a number of structural units based on present day basement configuration (Figure 3 and 4). Regional seismic surveys and more detailed seismic programmes, in particular along the northern margin, together with gravity, magnetic and borehole data provide the bulk of the information. Very little structural information can be obtained from surface exposures (Towner and Gibson 1983).

The structure of the basin is dominated by a northwesterly trending graben, separated from two sub-basins by a broad arch (Figure 3). To the south a poorly delineated shelf (Gorter et al. 1979) laps around the north of the Pilbara Block and is divided into three parts, the Ankatell, Tabletop and Ryan Shelves. It is covered by a veneer of less than 700m of Late Palaeozoic and Mesozoic rocks. There is poor control in this area due to the absence of wells and seismic coverage and the validity of these structural subdivisions has been questioned (Towner and Gibson 1983).

The Kidson and Willara Sub-basins are two contiguous depressions, which seismic evidence would suggest are the result of gentle downwarping of the basement. Information from seismic, gravity and borehole data indicates a maximum depth to top basement (Precambrian) of 10,000m and 4,500m respectively.

The central Broome Arch and its southeastern correlative the Crossland Platform, is a broad area of shallow basement overlain by 1000 - 3000m of Palaeozoic and Mesozoic sediments.

To the north of the Broome Arch/Crossland Platform are the Jugurra and Barbwire Terraces, relatively narrow shelves marginal to the main graben. Separated from the Fitzroy Trough to the north by the Fenton Fault System, the southwestern boundary of the Jugurra and Barbwire Terrace is also delineated by faults, the Dampier Fault System for the Jugurra Terrace and the Dummer Range Fault System for the Barbwire Terrace. The eastern limit of the Jugurra Terrace is defined as the Camelgooda Transfer Zone (Begg 1987). Geophysical evidence suggests the terraces are the result of dominantly extensional block faulting, the major faults paralleling the northwest-southeast trending Fitzroy Trough and steeply dipping towards their downthrown side to the northeast. There is also evidence for a number of near vertical faults oriented normal to the strike of the Fitzroy Trough, which have undergone significant strike-slip movement (Figure 8, Begg 1987). Evidence from seismic, interpreted as part of this study, suggests that all the faults have long histories, with multiple phases of movement.

Palaeozoic and Mesozoic sediments on the Jugurra Terrace are between 2000m and 4500m thick, and on the Barbwire Terrace range from 1500m in the northwest to more than 4500m in the southeast (Towner and Gibson 1983).

The Fitzroy Trough is a northwest-southeast trending graben system, bounded by a series of major faults; to the southwest the Fenton Fault System and to the northeast the Beagle Bay, Pinnacle and Stansmore faults, themselves cut by a series of transfer fault sets. The southwestern boundary of the graben, the Fenton Fault System, is characterised by a steep gravity gradient and has an estimated maximum movement of about 4000m. The northwestern and southeastern ends of this fault system are poorly defined and seismic evidence suggests the displacement is taken up by monoclinal flexuring (Towner and Gibson 1983). The Fitzroy Trough contains a thick sequence of Palaeozoic and Mesozoic sediments, with basement depths generally of 8000m up to a maximum depth of 18,000m in the southeast (Figure 4).

The study area is located on the Barbwire Terrace, adjacent to the Fitzroy Graben (Figure 7). Regional bouguer gravity maps clearly display the area to be a terrace, marginal to the main graben (Figure 9), confirmed by seismic (Figure 10).

2.1.4 Stratigraphic Framework and Basin Development

This review of the stratigraphy and development of the Canning Basin draws on a wide selection of literature, primarily the product of research by the Bureau of Mineral Resources and the Geological Survey of Western Australia, as well as published oil company data. The history of research into the Grant Group of the Canning Basin and the main reference sources are cited in Chapter 3.2 or have been noted within the text. The generalised stratigraphy of the Canning Basin is summarised in Figure 11.

Deposition within the Canning Basin commenced in the Ordovician unconformably upon a gently downwarped surface of Precambrian rocks, following a long period of erosion or non-deposition. The Nambeet, Willara, Goldwyer and Nita Formations were deposited in a shallow epeiric sea and at this stage the basin can be regarded as an intra-cratonic sag.

Following a Middle Ordovician to Early Silurian hiatus, with uplift and erosion, downwarping in the southern Canning Basin initiated the formation of the Kidson and Willara Sub-basins. Thick deposits of evaporites - the Carribuddy Formation - accumulated in the resultant restricted marine environment, which appears to have extended over most of the present day Canning Basin. The Carribuddy is present on the Barbwire Terrace and inferred to be present at depth in the Fitzroy Trough, unless subsequently mobilised. The following 'Tandalgoo' red bed sequence, comprising a series of thick fluvial and aeolian sandstones, was deposited under arid continental conditions during the Early Devonian.

Middle Devonian movements along the Fenton, Dampier, Dummer Range, Beagle Bay and Pinnacle Fault Systems initiated the Fitzroy Trough, establishing unrestricted marine conditions in the area for the first time. The Fitzroy Trough extended by up to 60 km (Begg 1977) resulting in a great thickness of sediment in the trough compared to the adjacent terraces and the Broome Arch/Crossland Platform. At this time also a series of transfer faults developed (Begg 1987) at right angles to the strike of the major bounding structures of the basin. Middle to Late Devonian deposits include extensive carbonates, most notably the development of reefs in the Pillara and Nullara Limestone units, interbedded with shallow marine mixed clastics. Structural control on deposition during this time is well documented (Playford and Lowry 1966, Lehmann 1984, Begg 1987), with fault ridges producing bathymetric relief enhancing the growth of reef cycles.

By the Late Devonian active rifting had terminated, replaced by regional subsidence. As deposition continued, sedimentation rates eventually exceeded subsidence resulting in the infilling of the basin and deposition of predominantly shallow marine clastic sequences of the Early Carboniferous Fairfield Group.

During the Middle Carboniferous the rift phase fault systems were reactivated during the Alice Springs Orogeny, and the basin suffered massive uplift and extensive erosion. This uplift was possibly a triggering factor for the subsequent glaciation within the area. The peneplanation resulted in a widespread angular unconformity - the Base Grant Unconformity.

Renewed subsidence occurred during the Late Carboniferous throughout the basin (Figure 12), with the development of an asymmetry to the Fitzroy Graben due to differential subsidence along the Fenton Fault System and the resultant deposition and preservation of a thicker sequence on the southern side of the trough. The Grant Group glacial sediments were deposited throughout the basin. The base of the group is diachronous (clearly demonstrated within this study, see Chapter 4) and a basal Late Carboniferous section is restricted to the deeper parts of the Fitzroy Trough. Initial non-deposition on the marginal terrace and platform areas during the Late Carboniferous was probably a result of ice sheet location, deposition becoming more widespread during the early Permian. In total a sedimentary pile of over 4500m thick was deposited in the Fitzroy Trough consisting of the Grant Group, Poole Sandstone, Noonkanbah Formation, Liveringa Formation, Blina Shale and Ermine Sandstones of Permian and Triassic age.

A period of non-deposition and/or erosion followed from the mid-Triassic to mid-Jurassic. During the Late Triassic a right lateral wrench regime developed in the Canning Basin, as a result of the rifting along the 'proto margin' with India, which was a precursor to the ultimate breakup of

Gondwana in the Jurassic and Cretaceous (Figure 13, Veevers 1988). This right lateral wrench regime resulted in local inversion, a product of compression between the Canning Basin and the Halls Creek Province, with extensive uplift, faulting and erosion. Folding within the trough was probably assisted by salt movement and decollement at depth (Gorter et al. 1979). Wrench movements, concentrated along the main extensional faults, resulted in the development of large anticlines within the Fitzroy trough area, trending approximately 45' to the strike of the basin (Towner and Gibson 1983).

A number of structural styles developed on the Barbwire Terrace during the Jurassic and Cretaceous. Simple reactivation and reversal of the main Fenton Fault System occurred, while more complex compressional wrench-induced anticlines along the Dummer Range Fault System were produced by reversal of, and thrusting along, the existing normal faults. The differing structural styles and development of the compressional wrench related folds are thought to be associated with the location of the cross-cutting transfer zones (as yet still ill-defined) and the evaporitic Carribuddy Formation, the presence of 'plastic' evaporitic deposits enhancing the structuring (Figure 8, Begg 1987).

The overall tendancy since the Early Jurassic for regional downwarping resulted in deposition of the Wallal Sandstone, Alexander Formation, Jarlemai Siltstone and uppermost Broome Sandstone. Deformation of these sediments up to the present day is related to the subsequent separation of India and Australia, which began in the Cretaceous.

From the Late Cretaceous to Early Tertiary extensive weathering under humid conditions produced lateritic profiles up to 130m thick. This, together with subsequent silicification and development of extensive ferricrete and calcrete profiles, enhances the difficulties of mapping and makes detailing the limited surface exposures a complex task.

2.2 LATE PALAEOZOIC GLACIATION OF GONDWANALAND

2.2.1 Introduction

There is a wealth of evidence from the stratigraphic record to suggest that ice ages have occurred at intervals throughout geological time (Hambrey and Harland 1981). Global ice ages are recorded from about 2300, 900, 750, 600, 450, 300 million years ago and within the last 6 million years, with an approximate periodicity of 150 million years, the exception being the middle of the Mesozoic era. Recent research (Frakes and Francis 1988) indicates the presence of at least a small ice cap during the Cretaceous, and in reality the earth has probably experienced continuous glaciation since the Precambrian, with periods of ice advance and retreat. During the Late Palaeozoic, Gondwanaland, a major landmass comprising the present day continents of Australia, Africa, Arabia, India, South America and Antarctica, suffered extensive glaciation. (Crowell and Frakes 1971a and b, Frakes 1979, Crowell 1978; Hambrey and Harland 1981, Anderson 1983). Distribution of the glacial deposits plotted on a reconstruction of the Gondwanan landmass/ocean pattern form a grouping that would be expected from a large polar ice sheet, possibly covering an area almost twice as large as that of the present day Antarctic ice sheet.

2.2.2 Cause of glaciations

The causes of glaciations have been addressed by numerous authors including Milankovich (1969), Flint (1971), Hughes (1975), and it is clear that periods of glaciation are related to a complex interaction of many controlling factors. The instigation and eventual termination of large ice masses is the result of changes in energy input to the glacial system (Larsen and Barry 1974, Adam 1969, Sugden and John 1985), both endogenetic such as continental drift and mountain building, as well as exogenetic. Research suggests that no single factor controls the onset of glaciation, rather a combination of circumstances, including the interrelation between land configuration and altitude, ocean characteristics, polar position and features of oceanic circulation, which are all potential contributory elements, in addition to normal climatological interactions. Close to the threshold of glaciation, a combination of the above factors produces a positive feedback which triggers the growth of an ice sheet, whilst mechanisms such as the raising of albedo due to increased snow cover lead to reduced adsorption of solar radiation and produce an overall climatic cooling. The complexity of the variables that have a control on glaciation prevents a simple model for ice sheet expansion and degradation, or estimates of potential ice mass.

The actual growth of an ice sheet is produced by excessive precipitation within the glaciated area, and the failure of the glacial system to achieve an adequate throughput (ie. ice transport and melt). Storage of the resultant increase in ice volume is effectively achieved by a constant adjustment of the equilibrium profile and expansion of the ice sheet laterally. Once the ice sheet can dispose of all the precipitation it receives, a state of dynamic equilibrium is reached, subsequent minor variations reflecting small fluctuations in climatic conditions. There is a theoretical limit to the maximum size of an ice sheet, dependent on a multitude of variables, beyond which further growth alters the controlling environment and glacial retreat ensues. Such a scenario could be envisaged if, for instance, the ice sheet became so large and remote from the coast that precipitation reduced in the centre, or if climatic warming crosses a certain threshold (allowing for minor fluctuation in the ice sheet due to minor climatic fluctuations) resulting in rapid ice wastage and glacial retreat. The process of ice sheet disintegration probably also has the characteristic of a positive feedback loop, resulting in rapid and often catastrophic ice sheet downwasting (Sugden and John 1985).

Figure 14 portrays a model for the fluctuation of a continental ice sheet in space and time, demonstrating the retreat polewards of the ice margin during periods when the global climate is least suited to extensive ice cover. Fluctuations which occur frequently over the short term, between 100-10,000 years, reflecting local climatic variations, have a localised effect and may not be readily correlated over a wide area. Long term larger global variations with a periodicity in the range of 10,000 to over 100,000 years are low frequency and high magnitude events, the result of major climatic changes, which produce widespread glacial retreat or advance affecting vast areas (Figure 15). Clearly, mid-latitudinal areas (such as the predicted position of the Canning Basin) are those where climatic instability is most marked, with rapid ice sheet build up and wastage (Flint 1971, Bryson et al. 1969, Sugden and John 1985).

Small and large scale fluctuations in the ice sheet produce distinctive suites of sediment, although the sedimentary record is commonly complex and incomplete due to erosion following ice advance which removes previous deposits.

2.2.3 Permo-Carboniferous glaciation of Gondwana

Recent work by Powell and Veevers (1987) suggests that the Gondwanan glaciation started in the latest Devonian initially as local glacial centres in northern South America and Africa, expanding to affect southern South America and Australia during the Namurian (Late Carboniferous) and eventually covering the majority of Gondwanaland during the Permo-Carboniferous culmination (300-290Myr BP). (Figure 16). The record of Devonian and Late Carboniferous glaciation is still open to debate, with many workers sceptical of many of the supposed 'glacial' sediments (Dickens 1985). As reviewed in detail in Chapter 6, the positive identification of the 'glacial' affinity of many deposits is often difficult, and similar sediments are formed by non-glacial processes. Dickens (1985) suggests from global faunal and floral evidence that the Early Carboniferous had an equable climate , which emphasises the restricted nature of any early glaciation, if the reported glacial sequences are to be accepted.

During the Late Carboniferous distinct provincialism in the floras and faunas attests to a cooling climate, and deposits from mountain glaciation in eastern Australia and South America (although again not conclusive) would support this (Herbert 1980, Benson 1981, Dickens 1985). By the Early Permian the evidence for widespread glaciation is substantive, further enhanced if the glacial sediments of Stage 2 palynozone are accepted to be of Early Permian age (see Chapter 3).

The principal cause of the glaciation is speculative, but closure of the Palaeo-Tethys Ocean, which resulted in a reduced rate of subduction and attendant reduced atmospheric carbon-dioxide (producing the opposite of the 'greenhouse effect' by allowing increased radiation of heat from the planets surface), is postulated as the major contributory factor (Crowell 1978, Fischer 1984). It is also clear from calculated apparent polar wander paths (Schmidt et al. 1986, Scotese 1986) that Gondwana drifted across the south pole from Late Devonian times onwards, thus making it susceptible to glaciation (Figure 16 and 17). There is some discrepancy in the reconstructions and timing made by various authors although the overall pattern is similar. In addition, Powell and Veevers (1987) attribute regional orogenic uplift as a triggering mechanism for the onset of glaciation, and the restriction of early (Devonian) glacial deposits to regions that bordered tectonically active areas, with palaeo-latitudes as far north as 30'S in South America and parts of Africa, supports this. Only during the latest Carboniferous to Early Permian did the glaciation expand to cover the majority of Gondwanaland. At this time the glaciation was polar in Antarctica and the Canning Basin was located at between 60 - 70'S (Veevers 1984).

It is probable that the Gondwanan ice sheet was in reality made up of a series of ice domes like those described from the more recent Laurentide ice sheet (Sugden and John 1985) or the Antarctic ice sheet (Figure 18, Budd et al. 1971). The domes act as independent ice centres of accumulation and dispersal, responding differently to regional and local climatic variations. At times they would have coalesced to create a massive ice sheet, and at other times, during periods of retreat, become detached from each other. Ice marginal areas experience the most marked fluctuations, with resulting complex sedimentary record. Dickens (1985) suggests that even during the Permian the glaciation might have been restricted and dominated by 'valley' glaciers, however,the widespread occurrence and thickness of the deposits strongly favours a continental ice sheet. The scattered distribution of Permian glacial sediments can be explained primarily as a function of preservation potential, with only major Permo-Carboniferous basins yielding extensive suites of glacial sediments today. The evidence from widespread striated surfaces that the major shield areas have suffered extensive glaciation would suggest that the absence of glacial deposits in these areas is a function of subsequent erosion.

A major problem in the study and correlation of glaciogenic sequences deposited throughout the Gondwana continent is the lack of biostratigraphic control. With the exception of marginal areas, Gondwanan Permo-Carboniferous sequences are predominantly non-marine and thus correlation relies on micro-flora. Whilst affording a means for basin-wide correlation, inter-regional correlations are less secure, and the precise dating of these palynostratigraphic zones is often difficult (Anderson 1983). The age of the micro-floras can only be linked to the Euramerican faunas by way of rare Euramerican taxa along the margins of Gondwanaland. In particular the transition from the Carboniferous to Permian is uncertain, both because of poor correlation between marine faunas and non-marine palynofloras, and the paucity of micro-fauna and flora during the glacial maxima at this time, a reflection of the severity of the environment (Powis 1984).

Within Australia Kemp _et al_. (1977) and Balme (1980) originally concluded that the bulk of the glacial sequence, within the 'Stage 2' microfloral zone, belonged to the Carboniferous. However more recent research (Archbold 1982, Dickens 1985, Foster and Waterhouse 1988) indicates that the main deglaciation and associated deposition of glacial sediments occurred during the Early Permian. Further refinement of the biostratigraphic framework is not possible at present. This is discussed in more detail in Chapter 3.

The extensive suites of glaciogenic sediments deposited during the Late Palaeozoic glaciation are preserved in a number of major Gondwanan basins. Review papers for most of these deposits are to be found in the volume 'The Earth's pre-Pleistocene glacial record', edited by Hambrey and Harland (1981). These include the Dwyka Formation from the Karroo Basin of South Africa (Von Brunn 1980, Von Brunn and Stratten 1981, Visser 1982, 1983, 1985, Visser and Loock 1982); the Itarare Group from the Parana Basin of Brazil (Rocha Campos and dos Santos 1981, Gravenor and Rocha Campos 1983); the Pagoda Formation from Antarctica (Lindsay 1970, Miller 1989); the Al Khlata Formation from Oman (Braakman _et al_. 1982, Qidwai _et al_. 1988) and from numerous basins in Australia (Plate 2), including; the Merrimellia Formation of the Cooper Basin (Williams and Wild 1984); the Lyons Formation of the Carnarvon Basin (Condon 1967, Van de Graaff 1984); and the Wynyard Tillite of Tasmania (Banks 1984).

The gross glaciogenic sedimentary package recorded in these basins is remarkably similar, with a general trifold vertical division into a basal proximal glacial sequence, a middle fine-grained basinal sequence and an upper coarse clastic package. The middle fine-grained sequence is regarded by Dickens (1985) as evidence for a post-glacial eustatic rise in sea level, recorded throughout the continent, and this is supported by research undertaken in this thesis. The Lyons Group of the Carnarvon Basin, at over 1500m is one of the thickest sequences of Permo-Carboniferous glacial sediments in Australia, and contains marine fauna that provide valuable biostratigraphic control (Condon 1954, 1967, Archbold 1982). Five major glacial advance and retreat packages have also been recognised (Dickens 1985) within the glaciogenic section of Asselian to Lower Sakmarian age. The fauna suggests a comparatively consistently cold climate throughout, with no 'warm' interglacial periods as experienced during the European Pleistocene glaciation (Dickens and Thomas 1959, Dickens 1985, Archbold 1982), although this may in part reflect the locality of the sections close to the ice front even during 'interglacials'. Similar records of glacial advance and retreat sequences have been recorded from Antarctica (Lindsay 1970, Miller 1989), South Africa (Visser and Kingsley 1983), Brazil (Gravenor and Rocha-Campos 1983) and Oman (Braakman et al. 1982) which although not necessarily directly equivalent in age, do indicate periodic variations in the ice sheet position. Similar glacial advance and retreat sequences have now been recorded for the first time from the Grant Group.

2.2.4 Permo-Carboniferous deposits in Australia

Basins that contain Permo-Carboniferous glaciogenic sequences are shown in Figure 2. The majority of the Permo-Carboniferous section is to be found only in the sub-surface and it is thus relatively poorly recorded. The exceptions are areas where the sediments have economic potential as hydrocarbon reservoirs, such as the Cooper Basin of South Australia / Queensland, which have thus been sampled by numerous exploration boreholes with additional seismic and wireline log data. Where limited outcrop is available and accessible, such as the outcrops of the Troubridge Basin in South Australia, the distribution of the glacial sequences are well recorded although for the most part detailed sedimentological studies have not been carried out. Most basins have received only early reconnaissance studies, if any, which are restricted to description of the small number of exploration boreholes, often with rare core available for study, for example the Arkaringa or Polda Basins.

Outcrops of Permo-Carboniferous glacial sequences are to be found in South Australia, including the excellent exposures of laminites and dropstone facies of Hallett Cove. Many of these outcrops were among the first recognised as Permian glacial sequences by Prof. Howchin in the late 1800's (Howchin 1895). He noted striated pavements, tillites (boulder clay) and the presence of a relict glacial topography (Roche moutonee, glaciated valleys), and published the first detailed accounts of Permo-Carboniferous glaciation in Australia.

The basin framework in Australia which controlled the Permo-Carboniferous deposition originated during the Late Carboniferous when a number of major basins were initiated, or old basins rejuvenated, at the start of the Innaminka Regime (Veevers 1984). The Australian Innaminka tectonic regime lasted from the Late Carboniferous to the mid-Cretaceous and encompassed the development of the Gondwanan Series basins. This followed the Early Carboniferous Alice Springs regional deformation, uplift and resultant mid-Carboniferous lacuna (except the deeper parts of the Canning and Bonaparte basins), with non-deposition primarily due to the formation of a continent-wide ice sheet (Crowell and Frakes 1971a,b). Only following retreat of the ice, during the latest Carboniferous to Early Permian, did the Innaminka basins receive sediments, initially extensive glaciogenic sequences. From the distribution of glacial sequences and recorded striations from the exposed shield areas it is possible to make a tentative reconstruction of the ice sheet during the Permo-Carboniferous (Figure 19).

The Canning Basin probably has a complete conformable sequence in the deeper parts of the Fitzroy Trough (Towner and Gibson 1983), but the geology of the study area, on the Barbwire Terrace, records the initial Early Carboniferous uplift (Alice Springs Orogeny) followed by ice sheet formation and resultant erosion, with subsequent deglaciation and sedimentation during the Late Carboniferous-Early Permian.

CHAPTER 3

THE GRANT GROUP

3.1 PREVIOUS WORK

The term 'Grant Range Beds' was introduced by Talbot (1920) and Woolnough (1933) applied the term to sediments with a glacial affinity described from the Canning Basin. As a result of further study and the availability of borehole data Guppy et al. (1952,) renamed it the Grant Formation and defined the type locality as the Grant Range (Long. 124' 05"E., Lat. 18' 02"S.) .

The Grant Formation unconformably overlies PreCambrian to Early Carboniferous rocks and includes all the glacial and fluvioglacial sediments below the Poole Sandstone (Guppy et al. 1958). The glacial nature of the sediments was clearly recognised at an early stage, and Guppy et al. (1958) writes:

> 'All rock types of the Grant Formation are considered to be glacial or fluvioglacial in origin. Sediments resembling tillites, varves and morainic beds have been examined in the Poole Range, the central St. George Range and the central Grant Range. The deposits consist of unbedded blue-grey sandy siltstone containing glaciated boulders of many rock types, including granite, metamorphic quartzites, and Devonian Limestones'.

The majority of the Grant Formation is to be found only in the subsurface, and as such petroleum exploration boreholes provide the bulk of the available data. Exploration for hydrocarbons by the West Australian Petroleum Pty Ltd (WAPET) provided the first series of boreholes through the Grant Formation, which began with Grant Range 1 in 1955, followed by a number of other wells and a series of test holes drilled for the Bureau of Mineral Resources (BMR) during 1955-1956. A full review of the drilling activity is given in Towner and Gibson (1983).

Further exploration activity by WAPET and a number of other oil companies between 1966-1970 resulted in additional information being made available over various parts of the basin. During the period 1971-1974 WAPET drilled a further 15 holes, including the Lake Betty 1 well, and as a result of this new information they subdivided the Grant Formation into three informal subdivisions; the Lower Sandstone Unit, Middle Shale Unit and Upper Sandstone Unit.

They were also able to tentatively correlate the units between the scattered boreholes, based primarily on cuttings derived lithology and wireline log character. Very few cores were available from the Grant Formation and thus detailed lithological descriptions and hence facies interpretations were not possible.

In 1972 the BMR in cooperation with the Geological Survey of Western Australia (GSWA) began a major mapping exercise for the entire onshore Canning Basin, at a scale of 1:250,000. Mapping in the Canning basin is difficult, outcrops are widely separated and generally of poor quality. Because of the lack of marker beds and palaeontological control, correlations are difficult to establish. The extensive cover of surfical deposits such as laterite, silcrete and aeolian sands also add to mapping difficulties.

The results of this mapping project were published between 1975 and 1980, papers with relevance to the Grant Formation being: Yeates et al. (1975), Crowe and Towner (1976 a,b,c,), Towner et al. (1976), Crowe et al. (1978) and Towner and Gibson (1983). The study area is covered by the Noonkanbah Sheet SE51-16, published by the BMR in 1977 (compiled by Towner, Wyborn and Walton) and summarised in Figure 20. A large part of the map area was only interpreted from aerial photographs or helicopter traverses. The interpretation pre-dates the WMC stratigraphic borehole programme, and the summary map has been modified to account for this information.

Crowe and Towner (1976a) recognised the three subdivisions of the Grant section proposed by WAPET, and noted that a similar sequence had been encountered in the Continental St. George Range 1 well. In addition, as a result of the mapping, they defined part of the exposed section of the Upper Sandstone Unit as the Wye Worry Member and the Millajiddee Member.

Later that same year Crowe and Towner (1976c) upgraded the Grant Formation to Group status and formally defined three formations: the **Betty Formation** (equivalent of the Lower Sandstone Unit), **Winifred Formation** (formerly Middle Mudstone) and the uppermost **Carolyn Formation** (Upper Sandstone Unit), with its constituent **Wye Worry** and **Millajiddee Members** (Figure 21).

The most recent reviews of the geology of the Canning Basin have been undertaken by the BMR. Forman and Wales (1981) produced a review of the geological evolution of the Canning Basin, with access to information from recent petroleum exploration activities lodged with the BMR. Further field studies were not undertaken at this time. A series of regional stratigraphic correlations based on 240 geological control points (mainly exploration wells) were constructed and the various intervals mapped. An interpretation is only as good as the data it is based on, and with only 240 control points in a basin the size of France, the majority of which are old wells with no core, the intrerpretations are very broad ranging. The report has a tendency to treat the geology of the Canning Basin as simple 'layer cake' stratigraphy, identifying similar packages of sediments and correlating them over large distances. This must be treated with caution.

Towner and Gibson (1983) provide the most recent BMR review of the geology of the Canning Basin, their interpretations based on all the available data. Most recently, a symposium on the Canning Basin was held by the Geological Society of Australia in 1983, and the proceedings (Purcell 1984) contain a wide range of papers that are cited in this thesis. The volume includes a number of contributions from oil exploration companies, which represent some of the first instances of published release of the large amount of 'confidential' data collected by the said companies. (The BMR has access to a large proportion of this data, although it is restricted as to what it can publish).

The BMR are about to embark upon a major review of the geology of the Canning Basin, involving acquisition of seismic and additional field studies, a project that is planned to take 3-5 years.

3.2 DATING OF THE PERMO-CARBONIFEROUS SECTION

3.2.1 Introduction

As discussed briefly in Chapter 2, dating and correlation of the Permo-Carboniferous section throughout the Gondwanan continent is problematic Except for marginal areas the sequences are predominantly non-marine, and in Australia mainly found only in the subsurface. This precludes the routine use of invertebrate palaeontological dating. Palynology is therefore the only widely available method for biostratigraphic subdivision of the strata. Inter-regional correlation of palynological assemblages is however hampered by both a lack of detailed systematic studies and genuine differences in species composition and geological range from area to area (Foster and Waterhouse 1988).

It is not within the scope of this thesis to undertake a comprehensive review of the palynological research undertaken to date on the Permo-Carboniferous section, although the recent research relevant to the Canning Basin is summarised below.

3.2.2 Canning Basin Biostratigraphic Framework

Within Australia the palynostratigraphic scheme most widely applied is that presented in the review paper of Kemp *et al*. (1977). The Late Carboniferous and Permian sequences are zoned according to range-zones in Eastern Australia and assemblage-zones in Western Australia. The basal Grant Group of the Canning Basin has been assigned to Unit I of Balme's Western Australian zonation scheme, the bulk of the Grant section lying within Unit II and the uppermost section in Unit III (Balme 1980). The Permo-Carboniferous boundary was tentatively placed within Unit II (Figure 22).

Further work on the Grant Group by Powis (1979 unpub.) recognised four assemblage zones within the Permo-Carboniferous section;, *Spelaeotriletes ybertii, Potonieisporites novicus, Microbaculispora tentula and Diatomozonotriletes townronii.* Powis later redefined the *P. novicus* zone as the *Diatomozonotriletes birkheadensis* zone (Powis 1984), and assigned the *M. tentula* assemblage to Stage 2.

Powis (1984) attempted to unify his work with the range-zone and assemblage zone schemes of Kemp *et al* (1977) and proposed a revised zonation, in which Stage 1 equates with Unit 1, Stages 2 and 3a with Unit II and Stage 3a/b with Unit III (Figure 22). However the definition and age of the resultant stages is by no means unanimously accepted, and the taxonomic detail of many of the assemblages is still ill-defined and hence correlation is difficult (Foster 1989 pers comm.). Recent work on the Grant Group palynofloras by WMC (unpubl. internal reports) would suggest that a further revision of the palynostratigraphy is required (a detailed account of the problem is given by Foster and Waterhouse 1988).

A new palynological zone - the Granulatisporites confluens Oppel-zone has been identified from the extensively cored Grant Group on the Barbwire Terrace (Foster and Waterhouse 1988). Although it is not possible to establish with certainty its relationship with the previously defined Australian zones, Foster states that "the G. confluens zone can probably be equated with assemblages described by Powis (1984) as Stage 2 (Figure 22).

This newly defined G. confluens assemblage is significant because in Calytrix 1 it is associated with a marine fauna, which provides a date of earliest Permian (Asselian) age (Foster and Waterhouse 1988). In addition micro-palaeontological work undertaken on foraminifera recovered from Ficus 1, Eremophila 2, Dampiera 1A and Calytrix 1 analysed by V. Palmieri (pers comm.) further confirms an Asselo-Sakmarian age. This is in contradiction to the dates proposed by Powis (1984), who placed Stage 2 in the Carboniferous, although he had no independent faunal evidence to support this.

It should be noted that the identification and dating of the macrofauna by Waterhouse (Foster and Waterhouse 1988) is not unanimously accepted, and many workers, although in agreement that the fauna is of Early Permian age, would prefer a Tastubian/Early Sakmarian date (Dickens pers.comm. and Archibold pers.comm.).

Dickens et al. (1977) identified the only other Grant Group marine fauna from outcrops of the Wye Worry Formation (Crowe and Towner 1976) in the St George Range, and ascribed the sequence an age of Early Permian (Sakmarian).

Waterhouse (Foster and Waterhouse 1988) however, states that the fauna recorded from the Calytrix 1 well shows no firm correlation with the material recorded by Dickens (op. cit.). A cold water environment was inferred from the low diversity of the Wye Worry fauna described by Dickens, but in the Calytrix well the fauna is more diverse, which Waterhouse suggests could indicate a warmer climate and a different age. Dickens (pers. comm.) feels that the apparent difference in diversity should not at this stage be regarded as significant.

Clearly at present the identification and dating of the fauna is not of a precision to accurately solve this dilemma, and the apparent older age of the Calytrix fauna based on disputed faunal identification is not regarded as reliable. The stratigraphic position of the Wye Worry section is dealt with in detail in Chapter 4, and although the precise relationship is unclear due to lack of data, it is suggested that the Wye Worry section could equate with the Hoya and Calytrix Formations described in this thesis. Until further research has been carried out, it is therefore suggested that the fauna from the Wye Worry section is from part of a sequence equivalent to the Calytrix Formation.

The relationship of G. confluens to the previously established palynological zones has been determined using core data from the Bonaparte basin and Foster (WMC internal report unpubl.) states that it immediately succeeds the older D. birkheadensis zone defined by Powis (1984). The relationship to the 'Stage 1' assemblages cannot as yet be established, however Foster suggests that this assemblage may well represent a facies controlled restricted palynoflora.

The base of the Grant Group is taken as the boundary between the D. Birkheadensis and the Stage 1/ G.confluens assemblages. The D. birkheadensis flora displays a significantly more diverse palynofloral assemblage than the overlying Stage 1 / G. confluens (Stage 2) flora, and this is interpreted to indicate a change from a relatively mild pre-glacial climate to harsh conditions, following the onset of continental glaciation (Powis 1984). Over much of the Canning Basin the Stage 1 assemblage is absent due to non-deposition or erosion and the basal Grant Group commonly contains only G.confluens (Stage 2) assemblages.

The upper limit of the Grant Group is taken as the base of the Nura Nura Limestone member of the Poole Sandstone, where present, and on the Barbwire Terrace at the disappearance of the G. confluens assemblage, succeeded by Stage 3 palynofloras, commonly containing Diatomozonotriletes townrowii.

It is clear from the above review of current palynostratigraphic research that the dating and correlation of the Permo-Carboniferous Grant Group is still conjectural, however it is accepted for the purpose of this thesis that;

1. The Grant Group on the Barbwire Terrace can be assigned to the G. confluens palynological zone, as defined by Foster and Waterhouse (1988),

which is of earliest Permian age (Asselian/Tastubian).

2. The G. confluens zone could extend into the Late Carboniferous in the deeper parts of the basin.

3. The older Stage 1 assemblage is not recorded on the Barbwire Terrace, due either to non deposition or erosion, but could be present in the deeper parts of the basin.

4. The base of the Grant Group is taken as the D. birkheadensis to Stage 1 / G. confluens boundary (based on Powis 1984 and Foster & Waterhouse 1988), the age of which is still illdefined.

5. The Stage 1 assemblage, as defined by Powis (1984), could be the equivalent of the D. birkheadensis assemblage, in which case the D. birkheadensis / G. confluens boundary is the base of the Grant Group.

The G.confluens assemblage has been recognised and correlated in other Permo-Carboniferous basins in Australia. Preliminary correlations have also been made with Gondwanan palynofloras from South America, South Africa, Zimbabwe, India and Antarctica (Foster and Waterhouse 1988), which provide evidence for the contemporaneous nature of the glacial sequences (Plate 2).

3.3 PREVIOUSLY DEFINED GRANT GROUP LITHOSTRATIGRAPHY

3.3.1 Introduction

The Grant Group was formally named by Crowe and Towner (1978) who recognised three formations; the lower Betty Formation, the middle Winifred Formation and the upper Carolyn Formation, which can be further subdivided into a lower undivided section, overlain by the Wye Worry and Millajiddee Members (Figure 21). The formations have been correlated between widely spaced wells, primarily on the basis of wireline log character, supplemented where available by seismic data.

3.3.2 Betty Formation (Lower Sandstone Unit)

This formation occurs only in the subsurface. Crowe and Towner (1976a) identified the unit in the following wells: Mount Hardman 1, Esso

1, St George Range 1; and stated that it had a thickness of 406m in Lake Betty 1. Crowe et al. (1978) redefined the type section as between 1058m and 1657m in the WAPET well Lake Betty 1, Lat 19' 34' 10''S, Long 126' 19' 52''E. (This is not regarded as being an effective lithostratigraphic unit from either wireline log character or correlation with the Barbwire Terrace section, and an alternative top Betty Formation is proposed in Chapter 4). The unit has a maximum recorded thickness of 1714m in the WAPET well Grant Range 1 (Towner and Gibson 1983). The basal contact is described as both conformable and unconformable in various reports.

The lithology is described as mainly fine to coarse sandstone with minor siltstone and claystone. 'Lithic fragments' were recorded from Mount Hardman 1. A similar 'lithic conglomerate' (Crowe et al. 1978) was encountered near the base of the Grant section in Lake Betty 1 (described from cuttings), which was interpreted to be a possible 'tillitic' unit, although this could just as readily be a petromict conglomerate. The formation also contains carbonaceous siltstones, rare coals (possibly only carbonaceous material) and is recorded as being calcareous near the base.

The sequence is tentatively dated as Late Carboniferous on palynological evidence from the well Mount Hardman 1 (Crowe et al. 1978), and interpreted to be non-marine. Forman and Wales (1981) term the Betty Formation, Unit 4a, which they claim has a maximum thickness of 1654m in the Fitzroy Graben, and approximately 500m in the Kidson Basin. Forman and Wales (op.cit.) also interpret Unit 4a to be marine, but no supporting evidence is provided. The report places the unit within the palynological Stage 1 (Evans 1969), of Stephanian to basal Sakmarian age. Unit 4a is correlated by Forman and Wells (1981) from the graben onto the Barbwire Terrace.

3.3.3 Winifred Formation (Middle Shale Unit)

Crowe and Towner (1976a) describe the' Middle Shale Unit' in the subsurface from wells; Mt Hardman 1, Esso 27 and St George Range 1 with recorded thicknesses of;, 57m in Mt Hardman, 40m in Esso No 27, 225m in St George Range and 64m in Barbwire 1.

Towner and Gibson (1983) state that the formation is 278m in Sisters

1, and describe the lithology as consisting of; a dominantly fine grained sequence, comprising siltstones, mudstones and thin sandstones, occasionally carbonaceous and pyritic and containing rare crinoid and bryozoan fragments (identified in Sahara 1 from cuttings). The unit forms poor outcrops on scree covered hills near Mt Winifred, Lat. 22 52' 40"S Long 123 36' 20"E, recorded on the TABLETOP sheet. Towner and Gibson (op.cit.) suggest either a deep marine or lagoonal environment of deposition.

Forman and Wales (1981), term the Winifred Formation, Unit 4b, and state that it is thickest in the Willara Sub Basin. From this they infer that the Fitzroy Graben was stable at this time. The presence of marine fossils (not recorded in detail) is interpreted as indicating a warmer climate than unit 4a, with a more diverse microflora dated as belonging to Stage 2 (Evans 1969) The recorded presence of arenaceous foraminifera however, are taken to indicate a cold climate, and this apparent anomaly remains unresolved.

3.3.4 Carolyn Formation (Upper Sandstone Unit)

Crowe and Towner 1976(b) subdivided the Carolyn Formation into two upper members; the Wye Worry and overlying Millajiddee, which crop out, and a lower undivided section, which is only found in the subsurface.

The undivided Carolyn Formation consists of fine to coarse-grained, massive sandstone and minor siltstone, which conformably overlie the Winifred Formation and range in thickness up to 635m in St George range 1 (see Chapter 4 for a discussion as to the reliability of this figure).

The Wye Worry Member is defined from the type section, Lat. 18 46' 45" S Long. 125 18' 50" E located in the St George Range (Figure 23), and varies in thickness from 25-95 m (the thicknesses are estimates based on numerous small isolated exposures). The member comprises varve-like mudstones, which contain occasional scattered clasts that display striations and faceting (Figure 24). Tillitic units, conglomerate and sandstone lenses are also described from the Wye Worry section, which are commonly slumped and deformed.

Towner (1981) further subdivided the Wye Worry into four units, although again the descriptions are very brief. The basal two units comprise laminated mudrocks with striated pebbles and unsorted silty claystones with abundant boulders, presumably diamictites (refered to later in the same text as "tillitic units"). Above these basal glaciogenic units, Unit 3 is described as consisting of calcareous siltstones and Unit 4 of interbedded siltstone and very fine-grained sandstone. Marine macrofossils from within the middle of the Wye Worry Member give an Early Permian (Sakmarian) age (Dickens et al. 1977). Unfortunately neither Towner (1981), Crowe and Towner (1976b,c) or Dickens et al. (1977) describe the sections or the locality of the marine macrofossils in detail, Crowe and Towner (1976b) merely stating that the fauna was derived from the 'middle' of the member. The Wye Worry Member is interpreted to have a gradational and possibly interfingering upper contact with the overlying Millajiddee member.

The Millajiddee Member is defined from the type section at, Lat. 18 45' 00"S Long. 124 55' 25"E and crops out in the St. George and Poole Ranges (Figure 23), where it is at least 75m thick. It comprises dominantly medium-grained sandstone with large scale cross bedding, occasionally displaying ripple and flaser bedding (Figure 25). Wood fragments have also been recorded from certain outcrops. The unit is unconformably /erosionally overlain by the Poole Sandstone.

The stratigraphic position of the Wye Worry and Millajiddee members and their relationship to the section recorded from the Barbwire Terrace is not clear. There is a lack of data in the intervening area between the outcrops and the Terrace area and few publications on the outcrops themselves. Those publications that do exist are very general, providing only limited information.

It is clear from the above summary that the available information on the sedimentology of the Grant Group is limited. This is largely a function of the dominantly subsurface nature of the sequence, only the uppermost section forming outcrops, which are themselves generally of a poor quality. The subsurface data consists mainly of geophysical wireline logs and cuttings from wells of varying vintages, with only rare isolated cores. As a result, to date, it has only been possible to define generalised lithological subdivisions, and identification of sedimentary features diagnostic of the environment of deposition has not been achieved.

This study provides a detailed sedimentological description of the Grant Group and proposes a revised lithostratigraphic framework for the Barbwire Terrace area (see Chapter 4). A correlation between this stratigraphy and the composite stratigraphy for the 'Canning Basin' is proposed, although it is emphasised that it is only regarded as tentative at this stage.

CHAPTER 4

REVISED STRATIGRAPHIC FRAMEWORK

4.1 INTRODUCTION

Prior to the acquisition of continuous core coverage through the Grant Group on the Barbwire Terrace by Western Mining Corporation Ltd., no complete section was known. The previous stratigraphy of the Grant Group was based on a composite section made of information from scattered outcrops and isolated exploration boreholes, the majority of which are of variable quality and vintage and were not extensively cored (Figure 21, Crowe and Towner 1976a,c, Towner 1981).

The published subdivision of the Grant Group into a lower Betty Formation, middle Winifred Formation and upper Carolyn Formation has already been reviewed (Chapter 3). With the exception of the upper part of the Carolyn Formation, details of lithology and interpretations of the depositional environment are scarce to non existent for the majority of the Grant Group. Previous workers have assumed that the broad tripartite subdivision observed from the deep boreholes in the graben, can be correlated with the sequence recorded from the Barbwire Terrace. The section on the Barbwire Terrace can also be subdivided into three units, however, this study clearly demonstrates the invalidity of the assumption that these sections are equivalents, and evidence primarily from seismic and well correlations indicates that a large part of the 'Grant Group' is restricted to the deeper graben areas, and has no equivalent on the Barbwire Terrace.

It must be emphasised at this juncture however, that whilst the correlation and subdivision of the Grant Group is well controlled on the Barbwire Terrace, due to poor data coverage both within the Graben and linking the Graben to the Terrace, the interpretation away from the study area into the Fitzroy Graben is tentative at this stage.

The ability to examine field outcrops of the Grant Group was not available during the course of this study due to the inaccessibilty of the region and limitations on the length of field season in Australia. In addition, information from the deep wells was limited to proprietary reports obtained by Western Mining Corporation Ltd. and released wireline log data. The data from the deep wells is fragmented and of poor quality. Published information on the outcrops is also minimal. However, from the limited data available to this study, it has been possible to attempt a correlation between the Barbwire Terrace section and the nearest deep borehole Lake Betty 1. The correlation has been extended to St George Range 1, which is also the location of the type areas for the upper Carolyn section. It is the author's opinion that the published correlation between Lake Betty 1 and St George Range 1 is incorrect, and that the published formation tops are erroneously recorded in the BMR literature. Because of the doubt as to the exact correlation between the sequence observed on the Barbwire Terrace and the previously published stratigraphy, it was decided to erect a separate stratigraphic framework for the Barbwire Terrace area. At a later date, with additional data, it should be possible to produce a unified stratigraphic framework for the basin, however at this stage the compromise seems the most prudent solution.

4.2 BARBWIRE TERRACE STRATIGRAPHY

4.2.1 Introduction

Detailed sedimentological description of 15 fully cored boreholes, which comprise a total of over 3.5km of core through the Grant Group deposited on the Barbwire Terrace, has enabled three formations to be defined. This study divides the Grant Group on the Barbwire Terrace into a lower Hoya Formation, a middle Calytrix Formation and upper Clianthus Formation (Figure 26). The detailed sedimentological descriptions of these formations is provided in Chapters 7, 8 and 9 respectively, and shall thus only be summarised herein. All three formations are recognised throughout the Barbwire Terrace, and are interpreted to have equivalents in the deeper parts of the graben.

Correlation between Hoya 1, Calytrix 1, Clianthus 1, and Melaleuca 1 is presented in Figure 27, between Drosera 1, Caladenia 1, Halgania 1 and Melaleuca 1 in Figure 28, Eremophila 1, 2, 3, and Ficus 1 in Figure 29, and finally Kunzea 1, Drosera 1, Goodenia 1 and Aristida 1A in Figure 30. In addition, a more detailed correlation between Hoya 1, Calytrix 1 and Clianthus 1 is displayed in Figure 31, and between Eremophila 1, 2 and 3 in Figure 32, the latter to be viewed in conjunction with the section of seismic line 82-20 displayed in Figure 33. Sections of seismic line 82-24, which displays both the relationship of Drosera 1 to Caladenia 1, and Halgania 1 to Melaleuca 1 along with the key evidence for a lower Grant section not preserved on the terrace, are displayed in Enclosures 1 and 2.

4.2.2 Hoya Formation

The Hoya Formation rests with an angular unconformity upon folded and faulted Late Palaeozoic sediments. Over most of the Barbwire Terrace the subcrop is Early Devonian dolomitic limestones of the Nullara Limestone Equivalent. In addition the Early Carboniferous Fairfield Group underlies the Grant group to the east, adjacent to the main Fenton Fault System, and older Ordovician and Silurian sediments of the Carribuddy Formation and Goldwyer Formations underlie the Grant Group to the west of the Dummer Range Fault System (Figure 34).

The Hoya Formation comprises a complex suite of glacial diamictites, deposited as lodgement, subglacial and supraglacial melt-out tills, flow tills of various origins and debris flows, interbedded with fluvial and subaqueous mass flow sandstones and glacio-lacustrine and glacio-marine mudrocks. It varies in thickness from 25m to 150m, noticeably thinning onto palaeo-highs controlled by the underlying structure. The section between Eremophila 1, 2 and 3 demonstrates this (Figures 29, 32 and 33).

The sequence is highly variable and correlation of individual units across the terrace is generally not possible. The exception to this is the basal diamictite, which is laterally continuous and recorded from all wells on the Barbwire Terrace that encounter the Base Grant Unconformity. This is interpreted to be a lodgement diamictite released from the base of the retreating ice sheet. Drosera 1 and Kunzea 1, located to the southwest of the terrace, on the Crossland Platform, did not encounter a basal lodgement till, and in this area the unconformity is overlain by a package of fluvial sandstones. This suggests that either the lodgement till was not deposited on the Crossland Platform, implying the absence of grounded ice, or more likely the facies was subsequently reworked by the fluvial sequence.

Correlation of facies within the Hoya Formation is possible between relatively closely spaced wells. Between Hoya 1, Calytrix 1 and Clianthus 1, 5km apart respectively, in addition to the basal diamictite it has been possible to correlate the mudstone intervals and the muddy diamictite facies, both of which are interpreted to have been deposited as extensive 'blanket' deposits under marine or lacustrine conditions (Figure 31). The remaining sandstones and sandy stratified diamictites show no clear correlation between wells, inferring either that they are laterally discontinuous units, or the presence of multiple erosion surfaces between the wells. The basal sandstone is tentatively correlated between Hoya 1 and Calytrix 1, although the unit thickens appreciably towards Calytrix 1. The upper sandstone unit in Hoya 1 is inferred to be the lateral equivalent of a diamictite package in Calytrix 1. Based on possible depositional models it is suggested that the diamictites are primarily of subaqueous origin, and that the sandstone units are the deposits of large subaqueous fan systems which were coeval with diamictite deposition, and could be the lateral or distal equivalents. The mud-rich diamictite packages appear to be laterally continuous between wells, although individual units are not correlatable. It is notable that the gross character of the formation is similar in all three wells, as is the overall evolution of the sedimentary package from sandstones and diamictites into fine grained mudrocks.

Correlation between more widely spaced wells is limited to the gross section, and individual beds/units cannot be recognised as being laterally extensive. From seismic data it is apparent that the Hoya section is extremely heterogeneous, with a complex mounded and hummocky seismic character (see Chapter 5 for a more detailed description of the seismic facies). This supports the evidence from well correlations that individual units are not correlatable across the Terrace.

Away from the Barbwire Terrace, both seismic evidence and correlation suggests that section exists that is older than the Hoya Formation _sensu stricto_. To the southwest, beyond the Dummer Range Fault System, an extensive suite of glacio-fluvial sandstones are recorded in Drosera 1 and

Kunzea 1. These sandstones have no equivalent on the terrace, and seismic evidence suggests that the sequence onlaps the Barbwire Terrace, and as such underlies the Hoya Formation recorded on the terrace. (Enclosure 1). The thick sandstone sequence and its probable origin are dealt with in more detail in Chapter 5, however in terms of its stratigraphic importance, the section clearly demonstrates that deposition was taking place in the adjacent basins (the Crossland Platform is interpreted to have been a relative low area during the deposition of the Grant Group), whilst the Barbwire Terrace was an area of non deposition or erosion, possibly due to ice cover at the time. This is further confirmed by the eastern portion of seismic line 82-24 (Enclosure 1), which again clearly displays an older section, believed correlatable with the 'Betty' and 'Winifred' Formations, which onlaps the Barbwire Terrace and therefore has no equivalent on the Terrace. The basal section of Melaleuca 1 tags the top of the onlapping section, which is observed in the well to comprise a stacked series of mass flow sandstones. This section is dated as belonging to the G.confluens Oppel Zone, confirming it as the Grant Group (WMC in-house report).

For the present, the base Hoya Formation is defined as the Base Grant Unconformity (or its conformable equivalent in the deeper parts of the basin) and thus the Hoya Formation encompasses both the section recorded from the Barbwire Terrace and the section from the deeper basin areas. It is envisaged however, that with the acquisition of more data and with further study, a separate lower formation (or formations) will be divisible, that is not recorded over the Barbwire Terrace.

4.2.3 Calytrix Formation

The Calytrix Formation is characterised by mudrocks, which are laterally extensive and readily correlated throughout the Barbwire Terrace. In certain wells, most notably Calytrix 1, a marine shelf sandstone and calcareous mudstone facies were also recorded from the Calytrix Formation. These facies are restricted in their areal extent and not correlatable across the Terrace.

The base of the Calytrix Formation is defined in most wells as the gradation from a thin muddy diamictite into a thick mudrock sequence. The Calytrix Formation contains no direct evidence of 'glacial' input, and may also be thus defined as the first non-glacial mudrock sequence overlying the 'glacial' Hoya Formation. The formation has a uniform seismic character, displaying low amplitude laterally consistent reflectors. On wireline logs the formation is identified as a section with a moderately uniform high gamma reading. The base has a characteristic sonic peak, believed to be related to increased calcareous material in the section (see Figures 28 to 32). This is interpreted to represent a marine marker, that also defines the base of the Calytrix Formation. The marine section is best developed in Calytrix 1, where a thick sequence of fossiliferous sandstones is overlain by a 11.38m thick dark grey to black calcareous mudstone with abundant delicately preserved bryozoa. This marine sandstone and mudstone is not well developed in the remaining wells, but at the equivalent log marker isolated fragments of shelly debris were located in Hoya 1, Clianthus 1, Melaleuca 1 and Ficus 1 within a dark grey mudstone. Evidence from micropalaeontological studies undertaken as proprietary work for Western Mining Corporation Ltd. by V. Palmieri (pers.comm.) also indicates open marine conditions at the same stratigraphic location in Eremophila 2 and Ficus 1, as well as Calytrix 1.

The Calytrix Formation varies in thickness over the Barbwire Terrace. It attains a maximum thickness of 163.25m in Dampiera 1, and is thinnest in Aristida 1 where it is only 6.2m thick. The formation noticeably thins onto pre-existing structural highs and thickens into the basin. Between Hoya 1 and Calytrix 1, the formation increases in thickness from 68.9m to 78.5m and further thickens to 100m in Clianthus 1. The same pattern is displayed between the three Eremophila wells, which show an increase in thickness from 77m to 92m and 114m between Eremophila 1 to Eremophila 3. Further along the same trend, Ficus 1 contains a 142.20m thick Calytrix Formation.

The Calytrix Formation also thins from 124.55m in Halgania 1 to 73.5m in Caladenia 1. The Caladenia 1 well is located on the trend of the Dummer Range fault zone. This thinning suggests the surface expression of the Dummer Range fault was relatively positive during deposition of the Grant Group, implying syn-depositional growth of the reverse fault 'flower' structure clearly evident on the seismic (Enclosure 2). The Calytrix Formation also thins from 124.55m in Halgania 1 to only 47.5m in Melaleuca 1 (Enclosure 2, Figure 28). This thinning is more problematical, because it is counter to the regional trend whereby the section thickens toward the graben area. The seismic section also confirms the unusual thinning within this section. This feature is interpreted to be related to growth of the Fenton Fault System, which was active during the deposition of the Grant Group, resulting in the extremely thick Grant section and marked asymmetry to the Fitzroy Graben. The margins of the graben have suffered a degree of counter-rotation and associated footwall uplift. This effectively results in localised high areas adjacent to the main graben bounding fault, and thus the thinning of the Calytrix Formation toward Melaleuca 1. It is expected that the Formation will thicken appreciably into the graben area, away from these localised highs, following the trend displayed by Hoya 1 to Clianthus 1, although without detailed well control or regional seismic lines running into the basin this cannot as yet be confirmed.

4.2.4 Clianthus Formation

The Clianthus Formation rests with an abrupt base upon mudrocks of the underlying Calytrix Formation. It is the uppermost sequence of the Grant Group defined from the Barbwire Terrace, and overlain by the Poole Sandstone. The upper contact is recorded from field outcrops (Crowe and Towner 1976a,b,c) to be unconformable or disconformable, with a degree of folding/slumping prior to the deposition of the Poole Sandstone. This is not evident in the core, although only Clianthus 1 and Melaleuca 1 contain core coverage over this contact. Within these wells the base of the Poole Sandstone is observed to be abrupt and erosive.

The interpretation of the Clianthus Formation on seismic is difficult primarily because the data quality at shallow depths is poor. The upper 0.1 seconds of data is generally a transparent zone in which very little coherent information has been received. The characterless zone at the top of the seismic sections is also partially due to processing parameters selected by Western Mining Corporation Ltd. for optimum data quality between 0.2 to 1.5 seconds. Over much of the Barbwire Terrace the Clianthus Formation is at depths of between 0 and 150m (less than 0.2 seconds) and thus falls within this poor data zone. Where the formation is deeper, the discordant contact with the Poole Sandstone is observed, such as on seismic line 82-24 (Enclosure 1).

The Clianthus Formation is recognised throughout the Barbwire Terrace where core or wireline log data is available. It can be divided broadly into a lower sandstone package, interpreted in this study to be the product of a low sinuosity sand dominated fluvial system, and an upper heterolithic sequence interpreted to be deposited on a shallow marine shelf (Figures 27 to 32). These facies are recognised throughout the basin, testifying to laterally extensive depositional environments.

The Clianthus Formation has many similarities with the field descriptions of the upper part of the Carolyn Formation, recorded from the St George Range and defined as the Millajiddee Member by Crowe and Towner (1976c). Lack of adequate control between the study area and the described outcrops (some 100km to the north) prevents more than a tentative correlation (Figure 23).

4.3 RELATIONSHIP OF THE BARBWIRE SECTION TO THE PUBLISHED GRANT GROUP STRATIGRAPHY

4.3.1 Review and correlation of the Barbwire Terrace to the St George Range

At the outset of this study it was assumed, following a detailed literature review, that the formations defined from the 'composite' stratigraphic framework for the basin (Towner 1981) were present on the Barbwire Terrace. The published stratigraphy for the Grant Group defines three formations, the lower Betty Formation, the middle Winifred Formation and the upper Carolyn Formation (Figure 21). This 'composite' stratigraphy relies heavily on poor quality well data, of varying vintages drilled between 1955 and 1974. The well data is the exclusive source of information for the Betty and Winifred Formations, as they do not outcrop within the basin. Within these deep wells the Grant section is rarely cored, and lithological descriptions rely on cutting and wireline log interpretation. The wireline log data is inconsistent and of poor quality by modern logging standards.

Initial appraisal of the section from the Barbwire Terrace recognised a threefold division of the Grant Group, broad lithological analogues for the 'composite' stratigraphy, comprising a basal 'sandstone and diamictite' dominated sequence, a middle 'mudrock' dominated sequence and an upper mixed clastic sequence.

Dating and palynological zonation is extremely tenuous and crude within this Permo-Carboniferous section, as already discussed in Chapter 3, and offers little assistance in correlation. The section recorded from the Barbwire Terrace, where sampling has been carried out by Western Mining (Foster and Waterhouse 1988, and numerous confidential WMC in-house reports) is within the G.confluens zone of Asselo-Sakmarian age (Figure 22). The thick basinal section encountered in wells such as Lake Betty 1, and St George Range 1 (Foster pers. comm.) also contain G.confluens, but the lower age limit of this assemblage has not been verified and the section could extend into the Carboniferous.

Although the gross character of the published composite stratigraphy and the section recorded from the Barbwire Terrace is similar, a number of inconsistencies were apparent. It has not been possible to make a simple correlation between the threefold division of the Barbwire Terrace section and the published 'composite' stratigraphy defined for the graben. To overcome this uncertainty a separate stratigraphic framework was erected for the Barbwire Terrace.

The main criteria which suggest a simple correlation is not possible are:

1. The presence of diamictites and rhythmically bedded mudstones described from the Wye Worry Member of the Carolyn Formation, which by simple correlation would be the equivalent of the Clianthus Formation described above.

2. The identification of a 'diverse' bivalve and bryozoan fauna from the upper part of the Wye Worry/Millajiddee Member.

3. The clear evidence from seismic of 'onlapping' units, which have no equivalent on the Barbwire Terrace, and yet can be demonstrated to be of Grant Group age.

4. The marked thickness variation between the section recorded on the Barbwire Terrace, attaining a maximum thickness of 550m, and an

estimated maximum thickness in the Fitzroy Graben of in excess of 2.4km (Towner and Gibson 1983).

5. The wireline log correlation between Lake Betty 1 and the Barbwire Terrace.

The presence of diamictites and rhythmically bedded mudstones with 'dropstones' described from outcrops in the St George Range is the most problematical feature. On the Barbwire Terrace the section described from the extensive core data suggests that sediments with a clear 'glacial' affinity are confined to the lower part of the Grant Group, and can be restricted to the newly defined Hoya Formation. The presence of diamictites and glacially derived sediments in outcrop, and assigned to the upper Carolyn Formation allows for two possibilities:

A. The Carolyn, or part of the Carolyn Formation is the equivalent of the Hoya Formation, thus fulfilling the criteria that the glacial sediments are restricted to the Hoya Formation.

B. Glacial sediments were deposited some 150km to the north of the study area during the late stages of the Grant Group and that the Carolyn Formation is the equivalent of the 'Clianthus Formation'.

No evidence for glacial sediments can be discerned from the upper part of the Grant Group on the Barbwire Terrace (Clianthus Formation), and more importantly the abundance of plant debris suggests an amelioration of the climate during the deposition of the Clianthus Formation. The possibility that glacially derived sediments were being deposited in the St George Range area, whilst non glacial fluvial and shallow marine sediments were deposited on the Barbwire Terrace does exist, but the relatively short distance between sites, and the clear pattern recorded in the cores from the Barbwire Terrace of a major ice retreat at the end of the deposition of the Hoya Formation suggests a more likely explanation is that the lower Carolyn Formation at outcrop in the St George Range is the equivalent of the Hoya Formation.

The St George Range, in common with a number of high ground areas located along the Fitzroy Graben axis, is the result of wrench related anticlines. This is demonstrated in Figure 35, a diagrammatic representation of a regional seismic line running northeast to southwest across the main graben (the location of the line is to the north of the St George Range but it is believed the structure is analogous). This section clearly demonstrates the uplift of the Grant Group associated with the Late Triassic to Recent anticlinal folding, providing a mechanism by which the Hoya equivalent could have been uplifted and exposed within the graben.

The bivalve and bryozoan assemblages described by Dickens et al. (1977), have already been reviewed in Chapter 3, and to summarise, it is believed that the section in which the fauna was identified could be the equivalent to the Calytrix Formation.

From published information it is evident that the Wye Worry Member contains a lower section that contains diamictites and rhythmites, possibly the equivalent of the Hoya Formation, an upper section which is dominated by mudstones and from which a diverse fauna was collected, the possible equivalent of the Calytrix Formation. The Formation is overlain by the Millajiddee Member, which is lithologically similar to the Clianthus Formation described from the Barbwire Terrace.

The identification of onlapping sections (Enclosure 1), which have no correlative on the Barbwire Terrace, discussed above under the review of the Hoya Formation, also suggests that the 'layer cake' correlation of stratigraphic units onto the terrace from the graben is an over simplification. Evidence from seismic and well correlation supports the view that a large part of the Grant section present in the Fitzroy Graben, making up a total in excess of 2km (Towner and Gibson 1983), has no direct correlative on the Barbwire Terrace, and that deposition was taking place in the graben at a time when non deposition or erosion occurred on the terrace. It is likely that the terrace was ice covered during a large part of this time, evidenced by the 'glacially' eroded surface and development of a laterally extensive lodgement till.

4.3.2 Correlation between the Barbwire Terrace section and the adjacent wells.

The correlation of the formations defined from the Barbwire Terrace and the outcrops of the Carolyn Formation is valid for the St George Range area. However a complication arises because the correlation to the section recorded in St George Range 1, and especially correlation between St George

Range 1 and Lake Betty 1, the nearest 'deep' well to the study area, is not obviously apparent. As previously noted, St George Range 1 is a key well because it spudded just below the base of the Wye Worry Member outcrop. The BMR interpretation places the Wye Worry and Millajiddee Members within the Carolyn Formation, above the Winifred and Betty Formations which they recognise in St George Range 1. On log character alone the author finds it impossible to recognise a simple threefold subdivision of the Grant section in St George Range 1, and there is little to correlate between Lake Betty 1 and St George Range 1. Confusion arises in correlating the section defined from the Barbwire Terrace and that published for the deep wells primarily because;

1. The formations defined in Lake Betty 1 have different published thickness and tops in different BMR reports.
2. The top to the Betty Formation in Lake Betty 1 appears to be badly picked.
3. Despite the lack of comment in any published report, the correlation between St George Range 1 and Lake Betty 1 is <u>not</u> clear from wireline log or lithological data. (This may in part be due to a lack of data available to the author).
4. The author believes that the 'Carolyn Formation' as defined in by the BMR from Lake Betty 1 and the 'Carolyn Formation' defined from St Georges Range 1 are not equivalents and as such are incorrectly correlated in the published literature.

Both wells contain type sections, Lake Betty 1 for the Betty Formation and St George Range 1 (and the outcrop in the St George Range) for the Carolyn Formation. It is the authors opinion that the Carolyn Formation identified in St George Range 1 has been mis-correlated in the literature with a section termed 'Carolyn Formation' in Lake Betty 1.

The section from the Barbwire Terrace can be correlated on wireline log character with the section recorded in Lake Betty 1. An attempt has been made to extend this correlation to St George Range 1, based primarily on the outcrop descriptions and wireline log character. Figures 36A & B attempt to summarise the confusing mix of stratigraphic nomenclature. Figure 36A displays a correlation between the Barbwire Terrace stratigraphic framework and the previously defined stratigraphy for Lake Betty 1 and St George Range 1. Figure 36B shows a proposed revision, which is discussed below.

4.3.3 Correlation of the Barbwire Terrace sequence with Lake Betty 1

The Grant Group in Lake Betty 1 is subdivided into three formations. Crowe and Towner (1976) defined the Betty Formation from between 1249m to 1657m, giving a thickness of 406m. Crowe et al. (1978) stated the top as 1058m giving a thickness of 599m. However log character would suggest a more consistent pick, at the top of the 'massive' sandstone package would be 1343m, giving a thickness of 314m. The top Winifred Formation is at 867m, which using the revised top Betty Formation pick at 1343m, gives a thickness of 475m. From correlation with the Barbwire Terrace section it is further proposed that the Winifred section can be divided into a lower 'Hoya' equivalent from 1058m to 1343m (285m thick) and an upper Calytrix equivalent from 867m to 1058m (191m thick). On present definition the Betty Formation is also part of the Hoya Formation, although it is interpreted that due to onlap the Betty Formation is absent from the terrace. The top Carolyn Formation (base Poole Sandstone) is picked at 764m, providing a thickness of 104m.

From correlation with the Barbwire Terrace it is suggested that the Carolyn Formation of Lake Betty 1 is the equivalent of the Clianthus Formation, and that the upper section of the Winifred Formation is the equivalent of the Calytrix Formation. The lower section of the Winifred Formation, and by strict definition the Betty Formation, are thus the equivalents of the Hoya Formation. This relationship is displayed in Figures 36 and 37.

4.3.4 Correlation of Lake Betty 1 with St George Range 1

The correlation between Lake Betty 1 and St George Range 1 is problematical. The Carolyn Formation as defined in St George Range 1 is 635m thick (reported as 652m in the literature, but this does not equate to a reliable log pick), with an additional 150m of outcrop from which the Wye Worry and Millajiddee Members are defined. This compares with a section defined as 'Carolyn Formation' of only 104m thick in Lake Betty 1. The defined Winifred Formation in St George Range 1 however is only 220m thick compared to 475m in Lake Betty 1. The Winifred Formation from St George Range is of comparable thickness to the upper section of the Winifred Formation from Lake Betty 1 (the Calytrix equivalent), and a correlation is possible (Figure 36A). A number of critical problems arise however, if this correlation is accepted:

1. The Betty Formation in Lake Betty 1, as defined by Crowe et al. (1978), contains an upper section which has a similar wireline log character to the Hoya Formation found on the Barbwire Terrace. This wireline log character cannot be correlated with the Betty Formation defined in St George Range 1.

2. On the Barbwire Terrace, glacial sediments are restricted to the Hoya Formation, and there is abundant evidence that a rapid deglaciation occurred at the end of the Hoya Formation. Correlation between the Clianthus Formation and the Carolyn Formation of St George Range 1 would place glaciogenic units in the uppermost section of the Grant Group. There is no corroborative evidence for this from the abundant cored sections from the terrace.

3. The correlation suggests a massive increase in thickness of the Carolyn Formation between Lake Betty 1 and St George Range 1. Correlation between the Barbwire Terrace and Lake Betty 1 does not indicate major basin subsidence during this period. Correlation between Lake Betty 1 and the terrace does however indicate substantial growth during deposition of the basal Grant section.

Attempting to honour the information from outcrops, and the depositional history evident from analysis of the cored sections from the Barbwire Terrace, and assuming a relatively constant thickness for the Winifred and Carolyn Formations, an alternative correlation is proposed (Figure 36B). The Carolyn section in Lake Betty 1 is correlated with the Millajiddee Member defined from the George Range area, and not to the entire 'Carolyn Formation' previously defined from St George Range 1. The Winifred Formation in Lake Betty 1 would thus be the approximate equivalent of Wye Worry Member and the upper section of the undivided Carolyn

Formation from St George Range 1. Lithological descriptions for the upper part of the Wye Worry Member (see Chapter 3) resemble the Calytrix Formation defined from the terrace, and it is possible that this section is also found in outcrop and not recorded in St George Range 1. The presence of glaciogenic sediments that crop out in the St George Range would also suggest that at least part of the Hoya Formation 'equivalent' outcrops in the St George Range, and correlates with the lower part of the Wye Worry Formation (Figure 38).

The revised Betty Formation from Lake Betty 1, comprising massive sandstones, is correlated with the lower 'undivided' section of the Carolyn Formation, which has a similar log character and lithological description. This assumes a much thickened lower section in George Range 1 that is not recorded in Lake Betty 1 or on the Barbwire Terrace, indicating that initial deposition of the Grant Group was restricted to the deepest part of the Fitzroy Graben. The marked uplift of the section concurs with evidence from regional seismic coverage of major wrench related anticlines within the Fitzroy Trough..

Without further data to constrain the structural setting of St George Range 1 and its relationship to Lake Betty 1 and the Barbwire Terrace, this problem cannot be resolved with satisfaction.

4.3.5 Summary

To summarise, a tentative correlation between the section described from the Barbwire Terrace and that reported from Lake Betty 1 has been made, based on wireline log character and the limited lithological descriptions from cuttings. The Carolyn Formation as defined in Lake Betty 1 is interpreted to be the equivalent of the Clianthus Formation. The Winifred Formation in Lake Betty 1 can be correlated with the Calytrix and Hoya Formations. The revised Betty Formation has no equivalent on the Barbwire Terrace proper. It is also proposed that the Carolyn Formation as defined from St George Range 1 is the equivalent to the complete section recorded from the Barbwire Terrace. The Wye Worry Member and upper part of the undivided Carolyn Formation are the equivalent of the newly defined Hoya and Calytrix Formations, and the Millajiddee the equivalent of the Clianthus Formation.

If this correlation is verified, with additional data and further study of the regional implications, the naming of these units will require modification. It is emphasised however that the fully cored sections from the Barbwire Terrace offer the best data available in the area, and are much more reliable as type sections than scattered poor quality outcrops.

CHAPTER 5

SEISMIC STRATIGRAPHY

5.1 INTRODUCTION

Seismic data, integrated with core and wireline log information from the stratigraphic boreholes, provides control on the lateral distribution of the Grant Group within the study area.

The interpretation was undertaken on a number of key lines from Western Mining Corporation's recently acquired proprietary seismic data set, and was not intended to be a comprehensive mapping exercise, but designed to address specific questions and provide information to assist the sedimentological analysis. Lines selected either link the study wells, or act as tie lines to provide a regional grid to enable loop-tying.

The seismic data was examined in order to determine:

1. The nature of the basal Grant boundary.
2. The relative thickness of the Grant Group over the study area.
3. The character of the seismic, to provide additional information on lithology, which can be integrated into the sedimentary facies analysis.
4. The lateral continuity of the facies identified in the cored boreholes.
5. The stratigraphic framework for the study area, and the relationship between the Grant Group deposited on the Barbwire Terrace and that recorded from adjacent areas, in particular the thick Fitzroy Graben section.
6. Potential controls on sedimentation within the study area.
7. The evolution of sedimentation within the study area.

5.2 SEISMIC STRATIGRAPHIC PRINCIPLES

The study takes advantage of recent advances in the methodology of seismic interpretation brought about by the increasing quality and availability of seismic data, in particular techniques of seismic stratigraphy which have developed rapidly over the past decade since the pioneering work of Vail et al. 1977. The interpretation makes the assumption that location and character of a seismic reflection is primarily related to lithological variations, and that seismic reflectors are approximations to time lines (Badley 1985, Bally 1987). This principle forms the basis of seismic stratigraphy, which can be divided into two components; seismic sequence analysis and seismic facies analysis. Important contributions in this field of study have been made by Vail 1977, Vail 1987, Vail et al. 1977, Van Wagoner et al. 1987, Van Wagoner et al. 1988, Mitchum et al. 1977 among others, and many of the key papers appear in the AAPG Memoir 26 (Payton, 1977) and more recently in the SEPM Special Publication 42 (1988).

Application of seismic stratigraphic interpretation techniques allows the subdivision of seismic reflections into packages. Seismic sequence analysis involves interpretation of these packages as depositional sequences (Mitchum et al. 1977), bounded by stratal surfaces -'sequence boundaries' that record major reorganisations in basin palaeogeography and separate major shifts or changes in the depositional system. Recognition of sequence boundaries and sequences enables the establishment of a chronostratigraphic correlation framework across the study area, which can be integrated with well and wireline log correlations. Analysis of the variations in seismic parameters within the seismic sequence allows an interpretation of the integral seismic facies, which can be related to the lithology of the section and integrated with detailed core analysis to provide valuable information as to the lateral distribution and relationship of the lithofacies.

The work of Vail (1984, 1988), Van Wagoner et al. (1987, 1988) and co-workers, has produced a myriad of terminology (see Van Wagoner et al. 1988 for a definitive review) a simplified form of which is used in this thesis. The basis of their 'Depositional Sequence' model is the interpretation of a sequence to be the product of deposition during a cycle of eustatic change. 'Sequence boundaries' are unconformities (or their correlative conformities) defined as erosive contacts produced by subaerial erosion resulting from relative sea level fall. A sequence records the gradual eustatic rise in sea level and resultant transgression, the 'transgressive surface' being the first marine flooding surface across the shelf. The sequence can be subdivided into 'parasequences', a relatively conformable succession of genetically related beds, which are bounded by 'marine flooding surfaces' which separate older from younger strata and represent abrupt increases in water depth (Figure 39).

Galloway (1989) suggests an alternative model, the 'Genetic Stratigraphic Sequence', proposing the maximum flooding surface as the natural boundary for the sequence (180 degrees out of phase from the Vail model) , although the basic tenet of his model is similar (Figure 40).

The depositional sequence model and idealised seismic configurations have been produced mainly from thick basin fill sequences along passive continental margins. In the limited section available in the study area, application of the basic concepts of the model is possible, but the idealised cycle cannot be fully recognised.

The main contentious aspect of the depositional sequence model as proposed by Vail and his co-workers is the belief in the dominance of eustatic control on the development of depositional architecture, an assumption questioned by many authors (Miall 1986, Galloway 1989), who emphasise that depositional patterns reflect a dynamic interplay of eustatic change with the rate of sediment supply and basin subsidence (dependant on the tectonic setting). Under glacial conditions the picture is likely to be further complicated by the role of glacial advance/retreat cycles and isostatic readjustments, which control both sediment input and relative sea level.

5.3 DATA BASE AND QUALITY

Seismic data quality in the Canning Basin is variable dependent on the line vintage. Older lines - pre-1980 - are of poor quality, with only the base Grant unconformity being a consistently identifiable reflector. Lines from six surveys: 1982, 1983, 1984, 1985, 1986 and 1987 were incorporated into the study.

The Grant Group section over the study area is present from near the surface to between 200 and 500 milliseconds TWT (in two-way time). It is overlain in the southern half of the study area by the Poole Sandstone and Noonkanbah Formations, and in the extreme north by Jurassic sandstones (Figure 20). In the central part of the study area the Grant Group is near the surface, covered by a thin veneer of Recent - Quaternary sediments (mainly aeolian sandstones) and does not form outcrops.

In general the upper 100 milliseconds comprises poor quality data in which no consistent reflectors can be identified, in part due to the processing parameters selected for optimum quality data at a deeper level, and as such the upper limit of the Grant is difficult to establish.

The other main data quality problem arises from large statics created by the irregular topography of the study area, notably sand dunes, which results in zones of poor quality data often breaking up what otherwise might be laterally consistent reflectors.

However, interpretation of key lines, controlled by the stratigraphic boreholes, does provide valuable information. Three key lines are presented which display a variety of features that have a significant input to the interpretation of the sedimentology and stratigraphy of the Grant Group.

5.4 METHODOLOGY.

The interpretation of seismic data is based on the assumption that the location and character of a seismic reflection is primarily related to lithological variations (Figure 41), and that seismic reflectors are approximations to time lines (Badley 1985, Bally 1987).

Key reflectors were picked, utilising the methodology advocated by Mitchum et al. (1977) and Badley (1985), paying particular attention to reflection relationships, terminations, configurations and geometry (Figure 42).

Initially the well data ~~was~~ were integrated with the seismic in order to identify the key horizons. Velocity surveys undertaken on the majority of the stratigraphic boreholes provide two-way times (TWT) at selected horizons, enabling a good correlation of seismic and well data. The results display a reasonable correlation between lithological horizons and the seismic data. In particular the base Grant horizon corresponds closely to its reflector due to the general high impedance contrast.

The reflectors were looped around the regional grid and correlated where possible with the well data. Laterally consistent reflectors which correlate with major changes in lithology are interpreted to indicate regional changes in depositional environment.

5.5 INTERPRETATION

5.5.1 Base Grant Reflector

Information from the stratigraphic boreholes suggests that over much of the study area the basal Grant section comprises sandstones, diamictites and mudstones, which rest unconformably upon Devonian dolomitic limestones or to the west the Carribbuddy evaporitic sequence. The resultant acoustic impedance contrast is strongly positive. The seismic sections are predominantly recorded with S.E.G. (European Geophysical Standard) phase and polarity, minimum phase and normal polarity, and the Base Grant was taken as the white trough produced by the positive reflection coefficient.

The base of the Grant Group is a strong consistent reflector, which separates folded and faulted older Palaeozoic sediments from the relatively flat lying Grant. Clear truncation of underlying reflectors and onlap of the basal Grant Group reflectors indicates the angular nature of the unconformity surface (Enclosures 1 & 2).

The Base Grant horizon, mapped in TWT over the study area (Figure 10, summarised from WMC regional mapping) clearly displays a marked northwest - southeast lineation. In the study area located on the Barbwire Terrace the depth to the Base Grant is between 200 and 500 milliseconds TWT (approximately 150 - 600m), bounded to the northeast by the Fenton Fault System, beyond which the base Grant rapidly increases in depth to over 1250 milliseconds (estimated base Grant depths in the Fitzroy Graben are up to 2.5 seconds TWT) and to the southwest by the Dummer Range Fault System, beyond which the base Grant increases to depths of between 400 and 500 milliseconds. The line of the Dummer Range Fault forms a regional structural high at the Base Grant Horizon, with a subsequent thin Grant Group sequence.

5.5.2 Structural Evolution of the Study Area.

With the exception of the major basin bounding faults, most other smaller faults that affect the older Palaeozoic section terminate beneath the Base Grant Unconformity. Occasionally the unconformity surface is displaced or folded over the trend of a major pre-Permian fault, implying minor reactivation.

Both the Dummer Range and Fenton Fault zones are a series of subparallel faults that have undergone a complex history of early normal growth, with downthrow to the northeast, followed by late reactivation and reversal during the Alice Springs Orogeny at the end of the Early Carboniferous, prior to the deposition of the Grant Group. The Grant Group thickens appreciably over the major bounding Fenton Fault System to the northeast indicating active syn-depositional fault growth. The asymmetry of the Fitzroy Trough originated during the Late Carboniferous (Towner and Gibson 1983, Begg 1987), with a thicker section present along the southern side of the trough due to differential subsidence along the Fenton Fault Zone.

Tilting of the Barbwire Terrace fault blocks during the major growth phase of the Fenton Fault is evident. Basal Grant Group reflectors on the margin of the Barbwire Terrace (Enclosure 1) have been tilted to the south west, with subsequent Grant units onlapping the relative high produced along the fault crest. This tilting is restricted to the lower Grant, with normal regional subsidence producing thickening into the basin during the upper Grant.

The Dummer Range Fault Zone displays spectacular 'flower structures' along the margin of the fault system produced by reactivation and reversal which was initiated during the Alice Springs Orogeny at the end of the Early Carboniferous, prior to the deposition of the Grant Group. Some late movement could possibly be coeval with the deposition of early Grant units, with periodic movements continuing until recent times. The reversal produced structural highs along the line of the Dummer Range fault, which resulted in a thinned Grant sequence, clearly displayed on the well correlations and seismic lines (Figure 28 and Enclosure 2).

Late Triassic to Jurassic compression within the basin, and the instigation of a right-lateral wrench regime (Begg 1987) resulted in minor reversal of the major bounding faults, tilting of the fault blocks in some areas and the development of divergent anticlines within the main graben, at 45 degrees to the strike of the basin. Figure 20 displays the solid geology of the extended study area and St. Jones Range 1 was drilled on the surface expression of one of the anticlines. The highground areas to the north of the study area, the Grant Range for example, in which the Wye Worry and Millajiddee type sections are to be found, are also related to anticlinal features (Plate 3, Figure 35).

5.5.3 Barbwire Terrace Seismic Sequences

UNIT 1 (Hoya Formation). Within the study area, the lower unit (parasequence) is confined by the basal unconformity (a sequence boundary), and an upper laterally continuous reflector that correlates to the near-base of the mudstone dominant section in the stratigraphic boreholes, interpreted to be a marine-flooding surface. Unit 1 correlates with the Hoya Formation identified in the core, although the upper limit as displayed on the seismic may appear low in some areas, due to the presence of mudstones interpreted to be part of the upper section of the Hoya Formation. The upper reflector, which marks the top of Unit 1, is present throughout most of the study area, and represents the first mappable laterally extensive reflector of the Grant Group.

Unit 1 consists of a highly variable seismic facies, comprising abundant mounded, hummocky and lenticular units producing a generally complex fill. The unit thins onto the structural highs, with common onlap onto the base Grant unconformity. Line 82-20A (Figure 33) displays the onlap of the basal Unit 1 onto a structural high, controlled by wells

Eremophila 1,2 and 3 (Figure 43 and 44). The near-top Hoya Formation can be correlated from Eremophila 3 to Eremophila 2, but the reflector merges with the base Grant reflector due to interference of the reflectors towards Eremophila 1, and becomes indistinct. From the well correlation it is evident that the Hoya Formation thickens towards the east from only 21.50m in Eremophila 1 to 51m in Eremophila 2 and 101m in Eremophila 3 (Figure 32). Reflectors within Unit 1 to the east of Eremophila 2 also onlap onto the base Grant unconformity, and display a complex internal geometry.

From well data it is evident that the Hoya Formation comprises diamictites, sandstones and thin mudstones, which are not readily correlated between adjacent wells. Seismic stratigraphic evidence confirms these facies have a irregular lateral distribution and are often lenticular or mounded. The top of the Hoya Formation is characterised by a change to mudstone deposited within a fairly deep water marine to restricted marine environment. The lateral continuity of the equivalent reflector would suggest a region-wide event interpreted to be a 'marine-flooding' surface.

UNIT 2 (Calytrix Formation). This unit comprises moderately parallel reflectors of low to moderate amplitude which have a good lateral continuity. This confirms ideas on the nature of the sediments from sedimentological analysis of the cores, that the facies is laterally persistent. The unit is bounded by the near top Hoya reflector at the base and an upper reflector, equivalent to the base of the Clianthus Formation, which represents a change to mixed clastic deposition from the basinal mudstones of the Calytrix Formation.

The upper limit of this unit is commonly poorly represented on the seismic section due its shallow nature. The unit displays regional variations in thickness, suggestive of differing subsidence rates associated with minor fault movements. Line 82-24, which runs west - east and links a number of stratigraphic boreholes, Unit 2 thins from Halgania 1 towards Melaleuca 1, before thickening again into the graben (Enclosure 1). This possibly reflects relative uplift of the footwall of the main Fenton Fault System, producing a structural high at the Melaleuca location.

UNIT 3 (Clianthus Formation) is the uppermost section of the Grant Group. Due to the lack of data in the upper 100 milliseconds of most seismic sections, Unit 3 is commonly not recorded. To the south and southeast of the study area where the Grant Group is deeper, Unit 3 comprises fairly consistent sub-parallel reflectors of low to moderate amplitude, sugesting a relatively laterally extensive and massive bedded sequence. The top of Unit 3, which marks the contact between the Grant Group and the Poole Sandstone, is interpreted to be a sequence boundary. Field descriptions of scarce outcrops near the study area (Towner et al. 1976, Towner and Gibson 1983, Crowe and Towner 1976 a,b & c) suggest an unconformable or disconformable relationship, and where the contact is recorded on seismic the Poole sandstone section often appears to cut down into the uppermost Grant section (Enclosure 1 & 2 and Figure 28).

5.5.4 Older sequences onlapping the Barbwire Terrace

The three units described above form the Grant sequence on the Barbwire Terrace, however it is apparent from the seismic that older sections of Grant Group have been deposited and preserved in adjacent areas. To the east along the margins of the Barbwire Terrace and within the Fitzroy Graben, and to the west in the Crossland Platform area units of Grant Group sediments clearly onlap the Terrace area, and have no age equivalent preserved on the Terrace.

Line 82-24 (Enclosure 1) runs in a west to east direction from the Barbwire Terrace to the margin of the Fitzroy Graben. Stratigraphic boreholes Halgania 1 and Melaleuca 1 provide control for the eastern margin. The section clearly displays onlap of units from the graben onto the Terrace high, with a lower Unit A and B not recorded in the main study area and a thickened Unit 1. Unit A rests upon the unconformity surface and has a very planar, laterally consistent upper reflector which correlates to the base of a mudstone in Melaleuca 1. The character of the reflector and its correlation with a change to mudstone deposition of possible marine origin is interpreted to represent a transgressive surface. The horizon is downlapped by reflectors from the west. Unit A has a complex internal character, comprising mounded and lenticular reflectors, with common onlap. A thin section of the Fairfield Group (encountered in Cassia 1 and projected from the south), is also preserved along the margin of the

Terrace.

The presence of onlap and older sections of Grant preserved in the Graben with no equivalent on the Terrace is significant. Although limited to only a few sections, which do not go very far into the Graben proper, the onlap suggests that a large section of the Grant Group present in the Graben, and recorded in wells such as Lake Betty 1 and St George Range 1, does not have an equivalent on the Terrace. The integration of the sedimentological analysis of the core (see Chapters 7 to 9) with the seismic would suggest that a large ice sheet was located on the Barbwire Terrace, with resultant non-deposition or erosion, at the same time that sediments were being deposited in the Graben.

The previous assumptions from earlier published reports, of a simple 'layer cake' stratigraphy for the Grant Group in the Canning Basin is again questioned, as in Chapter 4. The onlap of reflectors clearly demonstrates that the thinner sequence on the terrace cannot be dismissed as a condensed version of the basinal Grant Group, but rather there is a major portion of the Grant Group not present on the Barbwire Terrace.

5.5.5 The 'Drosera' mounded features

On the Crossland Platform to the south west another sequence is recorded on the seismic that has no equivalent on the terrace. Characteristic 'mounded' features are clearly displayed on the seismic, and well control from Drosera 1 and Kunzea 1 indicates the sedimentary fill comprises a thick suite of fluvial sandstones.

The western portion of line 82-24 (Figure 45) displays a high relief mounded feature located on the Crossland Platform, to the west of the Dummer Range Fault System at the margin of the Barbwire Terrace. The mounded feature has been cored by Drosera 1, and comprises a thick sequence of fluvial sandstones resting directly upon the Base Grant Unconformity. A similar fearure cored in the well Kunzea 1, which encountered a comparable sandstone package. The subcrop in this area comprises siltstones and remnant evaporites of the Silurian Carribuddy Formation. Correlation from the wells on the terrace, suggest the entire sandstone sequence is older than the main Hoya Formation encountered on the terrace.

The mounded features are interpreted to be related to initial rapid erosion of the evaporitic Carribuddy Formation, producing a thick broad 'valley fill' deposit of fluvial sandstones. Interpretation of the broad regional seismic grid suggest the mounds form linear features which trend away from the Barbwire Terrace towards the Kidson Sub-Basin (Figure 46). The present day mounded appearance is a result of later withdrawal/leaching of the adjacent evaporite section and also the effect of the different relative compaction of the sand dominant section associated with the mound and the adjacent mudstone dominated sequence (Figure 47). Similar features have been recorded from the Permo-Carboniferous section of Oman (Heward 1990), and termed 'turtle back' structures.

Reflectors which drape the sandstone features appear to onlap the high which forms the western margin of the Barbwire Terrace (Figure 49). Seismic suggests the western margin of the Barbwire Terrace has been uplifted subsequent to reversal along the main Dummer Range Fault System. The doming of the section suggests the development of a 'flower' structure caused by wrench related fault reversal (Enclosure 2). The timing of the reversal is difficult to establish. Certainly movement has occurred post Grant Group and Poole Sandstone deposition, with apparent uplift and erosion of these sections. However the Grant Group noticeably thins along the trend of the Dummer Range Fault, which also suggests uplift both prior to and possibly during Grant Group deposition. The presence of an area of positive relief along the Dummer Range fault trend is also suggested by the apparent onlap of section preserved on the Crossland Platform.

The section cored by Drosera 1 and Kunzea 1 is interpreted from seismic and lithostratigraphic correlation to be older than the main Grant sequence from the Barbwire Terrace. It is postulated that deposition of the sandstone packages recorded in these wells occurred in large low sinuosity braided outwash valley fills, originating from the ice sheet which was located on the Barbwire Terrace. Rapid erosion of the evaporitic subcrop aided the deposition of the thick fluvial packages along the linear valley trends.

5.6 SEQUENCE STRATIGRAPHIC ANALYSIS OF THE GRANT GROUP

Packages of genetically related sediments (sequences and parasequences - Vail et al. 1977a & b) can be recognised from the seismic data covering the Barbwire Terrace and margins of the Fitzroy Graben. The Grant Group can be defined as a sequence, bounded by the Base Grant unconformity and its correlative conformity in the axis of the Fitzroy Graben and the upper unconformity with the overlying Poole Sandstone. The sequence can be further subdivided into a number of parasequences or genetic units, which are related both to ice advance and retreat, and relative sea level.

The basal Grant, 'Betty Formation', is restricted to the deep Fitzroy Graben, and from seismic data an equivalent lower package is clearly observed to onlap the Barbwire Terrace. This is interpreted to represent a 'lowstand' unit, deposited during a period of relative low sea level and present only in the deeper parts of the basin. The relative lowering of sea level is interpreted to be related both to the growth of the Gondwanan ice sheet, which probably covered the Barbwire Terrace at this time, and the localised effect of rapid subsidence within the Fitzroy Graben, evidenced by the thickness variation over the Fenton Fault.

Seismic line 82-24-east (Enclosure 1) displays a strong reflector, which marks the top of the lowstand unit and the initial transgressive surface onto the Barbwire Terrace. The onset of transgression onto the terrace probably marks the initiation of the ice sheet retreat within the basin. Above this horizon, the seismic character on the margins of the Barbwire Terrace has a mounded and complex internal stratification, which suggests a complex and chaotic internal geometry to the sedimentary facies and could indicate the margins of the grounded ice deposit. This cannot be verified with core data as, unfortunately, Melaleuca 1 did not reach the Base Grant unconformity although the lower section cored does not contain extensive diamictites, and lies to the east of the proposed limit of the 'grounded ice facies'.

Over the majority of the Barbwire Terrace sedimentological evidence from the extensive core coverage confirms the basal section of the Grant Group contains extensive glaciogenic diamictite facies, with indications of multiple periods of ice advance and retreat before a final major retreat at end Hoya times. The seismic section equivalent to the Hoya Formation displays numerous onlapping surfaces and a complex internal geometry which supports the interpretation of deposition from a gradually retreating ice sheet. The retreat of the ice sheet would result in a concurrent rise in relative sea level. The seismic section equivalent to the Calytrix Formation has a laterally continuous uniform seismic character and is recorded over all the Barbwire Terrace. As such this is interpreted both from seismic character and the recorded facies from the core, to be a parasequence which represents the period of transgression and maximum flooding. The characteristic dominance of fine grained mudrocks which are laterally extensive is interpreted to reflect the release of large volumes of water from the rapidly declining ice sheet. (The term 'ice sheet' refers to the entire Gondwanan ice sheet, and is not restricted to localsed retreat in the Canning Basin area. Although the rate and timing of ice sheet decline may be expected to vary over the Gondwanan continent, the overall pattern of final ice sheet retreat recorded in the geological record and the rise in relative sea level is interpreted to be a global feature).

An interplay of isostatic uplift, basin infill and the emergence of large areas of hinterland to act as a major clastic source resulted in the gradual regression towards the top of the Grant Group and influx of fluvial and shallow marine conditions, finally culminating in the major fluvio-deltaic complexes of the Poole Sandstone (see Chapter 10 for a full review).

To summarise, formations defined from the Grant Group may be regarded as 'parasequences', within the Grant Group 'sequence' (Figure 49). The sequence can be viewed as a sedimentary package evolving primarily in response to relative sea level fluctuations controlled by climatic change, itself a result of the initial advance and eventual retreat of the Gondwanan ice sheet. This represents a simple model, which appears to reflect changes both in the depositional environment recorded in the cored section from the Barbwire Terrace, the lateral continuity and spatial distribution of the facies, interpreted from both well correlations and seismic interpretation, and the known Gondwanan ice sheet history as described in various published accounts from various continents (This is discussed in more detail in the conclusion Chapter 10).

The role of basin dynamics and regional tectonics is unclear. Certainly the Canning Basin was actively subsiding during the Permo-Carboniferous, evidenced by the deposition and preservation of the Grant Group section. And the active growth of the major bounding faults (or reversal in the case of the Dummer Range Fault) is apparent from thickness variations between the terrace and adjacent basins. The active and rapid growth of the Fitzroy Graben probably did have a controlling effect on facies distribution and the limitations of the grounded ice sheet. This is indicated both by the preservation of a low stand unit within the graben, and the postulated limit of the grounded ice facies on the terrace.

CHAPTER 6

INTRODUCTION TO SEDIMENTOLOGY

6.1 PREFACE

The acquisition of core by Western Mining Corporation Limited from wells on the Barbwire Terrace provides near complete sections through the Grant Group. The fully cored slim hole wells form part of Western Mining's exploration programme for hydrocarbons in the Canning Basin, and represent an innovative approach to obtain geological and in particular stratigraphic data in a remote and relatively unexplored part of the basin (Ashton 1984). In total 31 stratigraphic boreholes have been drilled by Western Mining. The boreholes were rotary drilled to between 25 to 100 metres, and then fully cored to total depth. Due to the stratigraphic position of the Grant Group most wells core the sequence and cut the basal unconformity. In addition, most of the wells were logged with a full suite of wireline logs and extensive seismic surveys have been conducted concurrently with the drilling programme.

The sedimentological analysis of the core was undertaken to determine the depositional processes and environment of deposition of the Grant Group sediments and to assist in producing a stratigraphic framework over the study area. The core was logged in detail (see Chapter 1), correlated with the wireline logs and then subdivided into facies and facies associations based on lithological character.

The concept of facies (Gressly 1838, Middleton 1973) and facies analysis is reviewed by Reading (1986), who states that "a facies should be a distinctive rock that forms under certain conditions of sedimentation, reflecting a particular process or environment". The facies may be subdivided into subfacies and also grouped into facies associations, which are groups of facies that are genetically or environmentally related.

6.2 FACIES ANALYSIS OF CORE

Within this thesis the term facies has been used in a purely descriptive sense, with subdivision based on physical properties of the sediments in order to identify a number of distinct lithofacies and facies associations. The wireline log character of the equivalent section has been incorporated as a 'physical' property of the sediment and used to supplement the lithofacies interpretation. It has not been separated as a distinct 'wireline log' facies. The facies and facies associations identified in the core have then been correlated with equivalent seismic facies.

Core provides discrete vertical profiles through the section, but virtually no control on the lateral variation, continuity and distribution of facies. As such vertical facies relationships and the context of a facies are of prime importance, and the principle of Walther's 'Law of Facies' (1894, see Middleton 1973), namely that facies occurring in a conformable vertical sequence were deposited in laterally adjacent environments, provides the main rationale for determining a wider palaeogeographic and environmental interpretation. The contact between facies is of prime importance in this case, as pointed out by Middleton (1973), since an erosive contact or major break in the succession may represent a considerable time gap and the passage of a number of environments whose products have subsequently been removed. The glacial environment is characterised by rapid changes of depositional environment and major erosive episodes due to ice advance and retreat, which only serve to further complicate the rock record making interpretation difficult.

Sedimentological analysis from core provides a wealth of data on the subsurface section not readily available by conventional drilling, wireline log interpretation or from seismic. However, core analysis has it~~'~~s limitations, primarily caused by the size restriction, and any interpretation is contingent upon these dimensional constraints. In this study narrow diameter cores provide the bulk of the data, ranging in size from 4.5cm to 6.5cm in diameter. Small scale sedimentary features, such as ripple-lamination , small scale cross-beds, bioturbation etc. are within the dimensional range to be fully recorded within a core of this size, however, larger features, such as low-angle erosive features, large-scale cross bedding, hummocky cross-bedding, boulder trains and large geomorphic features (eskers, channels etc.), are not as easily recognised or interpreted. In many cases the interpretation of a feature involves analogy with similar features described from outcrop, assuming a similar areal extent. Often sedimentary structures can be described only in general terms, such as 'cross-bedding' or 'soft-sediment deformation, where lack of exposure prevents a more detailed interpretation. Clast distribution and size range within the diamictites is not accurately recorded by one 4.5 cm core, which depending on the location could easily give vastly different results in such poorly sorted sediments. Palaeocurrent analysis is also beyond the scope of unoriented core, unless oriented by dipmeter data, which unfortunately could not be run at the time in such narrow diameter holes.

6.3 REVIEW OF GLACIAL SEDIMENTOLOGY

6.3.1 Identification of glaciogenic deposits.

Criteria for recognition of glacial deposits have been discussed in detail by numerous authors, eg. Harland *et al.* (1966), Flint (1971), Hambrey and Harland (1979, 1981). The main features characteristic of glacial environments are:

1. Abraded surfaces containing striations, grooves, chattermarks and roche-moutonee like forms.
2. Diamictites, with characteristic great range in size and shape of clast material
3. Facetted or striated clasts
5. Variable lithology of clast component and possible large incompetent and soft-weathering clasts
6. Clay sized particles (rock flour) in the matrix.
7. Boulder beds or concentrations of boulders, possibly with abraded upper surfaces.
8. Dropstones, rafted by icebergs calved from the ice sheet or glacier.
9. Varved mudrocks, produced by the seasonal variation of clastic input to the basin.

10. Morphological features, such as ice-wedges, drumlins, eskers, moraines.

Although many of the above features can be produced under non-glacial conditions, such as debris-flow diamictites or vegetation-rafted dropstones, the combination of a number of the above characteristics in sufficient quantity suggest a glacial environment of deposition.

A major problem in core analysis is the recognition of many of these criteria due the core size limitation. Striations on erosive surfaces, boulder beds, ice-wedges and large morphological features are beyond the scope of core studies. However, integration of outcrop and seismic data to som extent provides a method for overcoming these lateral limitations.

6.3.2 Evidence for glacial deposition of the Grant Group

Evidence for the glacial nature of the Grant Group comes from various sources; regional studies of the climatic conditions prevalent during the Permo-Carboniferous; comparison with similar deposits described from other Gondwanan basins; published information on outcrop in the Canning Basin area, and the character of the sediments encountered in core from the Barbwire Terrace area. The palaeogeography of the Gondwanan continent, climatic conditions during the Permo-Carboniferous and contemporaneous glacial sediments from other Gondwanan basins have already been discussed in Chapters 2 and 3.

Evidence from outcrops in the Canning Basin area include striated pavements on basement in the Kimberley and Pilbara Blocks (Towner et al. 1976), which are commonly overlain by diamictites which contain very-poorly sorted striated and facetted clasts, and are interpreted to be tillites of various types. Exhumed Permian topography is recorded from the margins of the Canning Basin, including incised valleys with diamictite fill (Towner and Gibson 1983). In addition, laminated mudrocks, possibly varved, with scattered dropstones of various lithologies, have been described from both the margins of the basin and from outcrops close to the study area in the Poole, Grant and St George Ranges (Crowe and Towner 1976a,b &c, Dickens et al. 1977).

The glaciogenic character of the sediments found in the core from the Canning Basin is discussed in detail in the following chapters. In summary, this data confirms evidence from elsewhere of a glaciogenic origin for the Grant Group. In addition, cold climatic conditions are inferred from palaeontological, micro-palaeontological and palynological studies, undertaken by Western Mining Corporation on both core and outcrop..

6.3.3 Terminology and classification of glaciogenic deposits

The most appropriate terminology and classification of glaciogenic deposits has been the subject of much discussion (Harland et al., 1966, Boulton 1976, Dreimanis 1976, Hambrey and Harland 1981, Gravenor et al. 1984, Brodzikowski and Van Loon 1987). Difficulty arises primarily from the need to adequately describe deposits which consist of large clasts floating in a matrix of massive or stratified, poorly sorted mud/silt/sandstone. Terms such as boulder clay, till (Giekie 1877), tilloid (Blackwelder 1931), pebbly mudstone (Crowell 1957), paraconglomerate (Pettijohn 1975) and diamictite (Flint et al. 1960a & b) have all been proposed, although their usage is not synonymous and not restricted in many cases to glacial sediments.

This thesis follows nomenclature proposed by Hambrey and Harland (1981) and utilises the terms till, tillite, diamict and diamictite. A brief summary of their definition in common usage follows:

1. Diamict / Diamictite

The term diamictite was proposed by Flint et al. (1960a&b) for lithified 'essentially non-sorted, non-calcareous, terrigenous deposits composed of sand and/or large particles in a muddy matrix'. The term is thus non-genetic and covers all sediments with scattered clasts in a fine-grained matrix. The term specifies a range of particle size, not the relative abundance of any or all size classes (Frakes 1979). A diamict is the unlithified equivalent of a diamictite.

The inherent problems of interpreting glacial sequences are enhanced when dealing with core, where the lack of lateral exposure precludes the identification of many of the features that indicate a 'glacial' origin for the sediment. As such, the non-genetic term diamictite is prefered in this thesis, with only tentative application of the term tillite applied in the interpretation.

2. Till / Tillite

The term till was first applied to 'stiff, unstratified clays containing angular, subangular and rounded blocks of rock' and is synonymous with boulder clay, both defined by Giekie (1877), as 'a deposit which owes its origin more or less directly to the grinding action of glaciers'.

A degree of disagreement as to the exact definition of the term is still evident, centred around the point at which dissaggregation of the till in water, flowage after initial deposition and/or resedimentation alters the original sediment. For example, Boulton (1976) defines a till as 'an aggregate whose components are brought together by the direct action of glacier ice, which though it may suffer deformation by flow, does not undergo subsequent disaggregation and redeposition'. This definition excludes deposition in water, such as material rafted by icebergs. Shaw (1985) proposed an even tighter definition of a till by excluding deposits which exhibit subsequent flow deformation.

However, there is a general consensus that a more liberal definition, which is less precisely limited genetically, should be adopted. Hambrey and Harland (1981) proposed the adoption of the definition ' a sediment in which the particles have been brought together by the direct agency of glacier ice and which has been deposited terrestrially directly by or from glacial ice, or waterlain from a glacier in a body of water'. This definition is adopted in this thesis.

Tillite, a term attributed to Penk who applied it in 1906 to the Dwyka Tillite, is the lithified equivalent of till. Its use is often broader ranging than till, including ice-rafted deposits in a marine or lacustrine sediment, not strictly a till in the above definition.

The limit at which the proportion of ice-rafted material is so low that the sediment is no longer a till/tillite has not been quantitatively defined. However, the term till/tillite is not extended to laminated sediments with partly sorted matrix and only rare outsize clasts/dropstones. In this thesis these deposits are referred to as glaciolacustrine or glaciomarine deposits.

A classification of tills into genetic units determined by the process of glacial transport and subsequent deposition was first recognised by Flint (1971). This initial twofold division into basal/lodgement till and ablation till has subsequently been revised by Dreimanis and Vagners (1971) and later Dreimanis (1974) who further subdivided till into subglacial, supraglacial and proglacial deposits, dependant on the location of deposition with respect to the ice. The three groups contain a number of facies differentiated by the process of deposition, such as melt-out, lodgement and flow. A separate group for waterlain till is also included. THe above provides the basis for the classification of proposed tillites in this thesis, with the addition of 'distal' ice-rafted glaciomarine and glaciolacustrine sediments (Hambrey and Harland 1981)(Figure 50).

However, for most pre-Pleistocene sediments lack of adequate exposure prevents a determination of the mode of deposition as precisely as outlined above. As already discussed, in the case of core studies this is further complicated because the many of the criteria used to determine the origin of a till are not within the resolution of narrow diameter cores. Nevertheless, the integration of core with seismic data and available outcrop information allows a limited interpretation of the origin of the diamictites and their classification following the scheme proposed by Hambrey and Harland (1981).

6.4 FORMAT OF SEDIMENTOLOGY CHAPTERS

The Grant Group on the Barbwire Terrace has been divided into three formations, based on lithological and seismic character. Each formation is described in detail in Chapters 7,8 & 9, wherin subdivision into a number of facies associations, facies and sub facies is proposed, based on the criteria previously discussed. Subdivision of the formations into facies allows a more thorough interpretation of the relationship and variations in the sedimentology of the sequence. Many of the facies and facies associations are gradational variants and as such transitional units exist, which are difficult to classify. In most cases these are described within both facies sections. For each facies, the description and interpretation are separated. Detailed facies logs for all the wells studied are to be found in Appendix 1 and selected examples for each facies are also displayed as figures with reference in the text.

The study has concentrated on the glacial Hoya Formation. The overall interpretation of the depositional environment, process of deposition, evolution, and distribution of the Hoya Formation is summarised in the synopsis at the end of Chapter 7. The sedimentology of the upper Formations is reviewed in Chapters 8 and 9, and the results from the sedimentological, stratigraphic and geoseismic research integrated within Chapter 10.

CHAPTER 7

SEDIMENTOLOGY OF THE HOYA FORMATION

7.1 INTRODUCTION

This chapter provides a description and interpretation of the facies defined from the Hoya Formation. The sequence is complex and records a period of gradual deglaciation, with rapid lateral and vertical facies changes and abundant erosion surfaces as a result of multiple phases of ice sheet advance and retreat.

The formation consists of three main lithologies; diamictites, mudrocks and sandstones, which can be classified into a number of distinctive and genetically significant facies associations. The facies associations are;

1. **Diamictite Facies Associations**

Basal Diamictite Facies	BD
Massive Sandy Diamictite Facies	DSm
Stratified Sandy Diamictite Facies	DSs
Massive Muddy Facies	DMm
Stratified Muddy Diamictite Facies	DMs

2. **Mudrock Facies Associations**

Massive Mudrock Facies	Fm
Bedded Mudrock Facies	Fl(1)

3. **Sandstone Facies Associations**

Sandstone Facies	S(1)

A coding system is employed, similar to that advocated by Eyles _et. al._ (1983) for use on facies logs and correlations. The first letter of the code defines the dominant lithology, D for diamictites, F for fine grained sediments/mudrocks, and S for sandstones/conglomerates. Subsequent notation does not follow any previously defined classification and is specific to this thesis. The diamictite associations are divided on dominant diamictite matrix type, 'sand' or 'mud', noted as the second letter, S or M respectively, and internal structure and bedding, either dominantly massive (m) or stratified (s) noted as the third letter code. A unique diamictite facies association, coded 'BD' is defined on its stratigraphic position. The fine grained mudrock facies are split into two broad types, either dominantly massive (Fm), or dominantly laminated (Fl). The fine-grained mudrock and sandstone facies are further subdivided numerically due to their great variety of facies types.

Throughout the text reference is made to the facies logs, which are all located in Appendix 1. Figure 51 displays the key to the facies log annotation, and this is duplicated in the Appendix.

7.2 DIAMICTITE FACIES ASSOCIATIONS

7.2.1 General

The diamictite facies recorded in the core are extremely variable, as might be expected from poorly-sorted sediments of glaciogenic origin. However, similar units are present in the various cores, and subdivision of the diamictites into a number of broad facies types is possible, based on the following criteria:

1. Matrix composition, which can be divided between dominantly sand-rich and mud-rich end members.
2. Clast composition; whether locally-derived intrabasinal or exotic extrabasinal: clast-rich or clast-poor: degree of roundness and size variation of the clasts

3. Sedimentary structures; whether massive or stratified (bedded, soft-sediment deformed, sandstone or mudstone lenses etc.)
4. Bedding; either massive or interbedded with mudstones, sandstones, or conglomerates.

In addition, the contact of the diamictites with adjacent units varies, and is diagnostic of the environment of deposition (see body of discussion).

Using the above criteria five facies association have been recognised;

1. Basal Diamictite (BD).
2. Massive Sandy Diamictite (DSm).
3. Stratified Sandy Diamictite (DSs).
4. Massive Muddy Diamictite (DMm).
5. Stratified Muddy Diamictite (DMs).

7.2.2 Basal Diamictite Facies (BD).

Description

The Basal Diamictite Facies (BD) is a laterally extensive unit, between 1-8 m thick. It is recorded in all the wells in the study area that reach the Base Grant unconformity, with the exception of Drosera and Kunzea. It is defined on the basis of its position, resting directly upon the basal unconformity, and also clast type and abundance, matrix composition and bedding (Figure 52).

Facies BD rests with a sharp erosive contact upon older Palaeozoic sediments, predominantly Late Devonian dolomitic limestones (Nullara Limestone Equivalent) and siltstones (Nullara Limestone Equivalent and Fairfield Formation) in the study area. The unconformity surface is irregular and weathered (Figure 53, Plates 6A). In Calytrix 1 and Hoya 1 below the sharp erosive base of Facies BD, the top 5m of the Devonian dolomitic limestone contains abundant large cavities. These are filled with diamictite of a similar composition to the basal unit of Facies BD, and thinly interbedded sandstones and mudstones. In larger cavities the diamictite occasionally displays irregular horizontal lamination, though it is more commonly massive or exhibits intense soft-sediment deformation.

The average composition of the diamictites is approximately 60% sand, 30% mud/silt with 10% clast material. The matrix is light grey to light brown in colour and very-poorly sorted. It comprises silt and sand grade dolomitic grains and additional mixed clays, quartz and lithic fragments (Plate 6B & C)).

Facies BD commonly comprises a lower light-grey to light-brown, massive and relatively clast-rich sandy diamictite, generally overlain by a series of similar sandy diamictites and thin interbedded sandstones. The bedded diamictites generally have sharp bases, and are massive. Occasional crude irregular bedding is picked out by darker or lighter coloured streaks, and the section is disturbed by intense soft-sediment deformation (Plate 6D).

The clast component is predominantly dolomitic limestone and siltstone, of a similar composition to the immediate substrate. Less common, although increasing in frequency towards the top of the unit, are igneous and metamorphic clasts, including granites, gneisses, volcanics and various metasediments (Plate 6C).

The dolomitic clasts are predominantly angular to subangular and range in size from a few millimetres to a maximum of 10cm. Due to the areal limitation of core, with a diameter of only 4cm, large clasts are only partially recorded, and true maximum clast size is probably in excess of this figure. The basement clasts are generally smaller, ranging in size up to 5cm, and display a higher sphericity and are more rounded than the dolomitic clasts. Overall the clast size of the dolomitic limestones decreases towards the top of the unit, away from the unconformity. The basement clasts show no apparent size trend.

Features such as surface striations and faceting were tentatively identified for a limited number of large dolomitic clasts. However due to the nature of the coring procedure, and the relatively small surface area visible on any isolated clast these features are regarded as questionable (Plate 7A). Rare striations were observed on clast surfaces not damaged by the coring procedure (ie. clasts removed from the core, such that the surface examined was in contact with matrix material).

In a number of wells, including Triodia 1, Eremophila 1,2,3, and Ficus 1, thin sandstones and clast-supported conglomerates are interbedded with the diamictites. The sandstones are massive to flat-bedded, fine to medium-grained and moderately well-sorted, commonly with sharp erosive bases and gradational upper contacts. They display intense soft-sediment deformation. The conglomerates comprise subangular to subrounded dolomitic limestones and rare basement clasts, with a medium to fine-grained sandstone matrix. They have sharp erosional bases and either grade rapidly into, or have a sharp upper contact with an overlying diamictite. The conglomerates are also found interbedded with the fine to medium grained sandstone.

Facies BD is overlain by a variety of lithologies, all with an abrupt upper contact (Plate 7B). In Hoya 1 and Eremophila 2 the basal diamictite is overlain by a thick package of sandy diamictites (DSm), which although of similar composition to the underlying diamictites, can be discerned as a separate units from their wireline log response. The Basal Diamictite Facies is also overlain by mudstones, both Facies Fl (Eremophila 3, Figure 54) and massive mudstones of Facies Fm (Aristida 1 and 1A, Caladenia 1), graded sandstones of Facies S5 (Halgania 1 and Ficus 1) and deformed sediments of Facies FL (Eremophila 1, Calytrix 1).

Interpretation

The stratigraphic position of the Basal Diamictite Facies and its facies relationship supports an interpretation of subglacial deposition. The sharp erosive contact between Facies BD and underlying older Palaeozoic sediments, mainly Devonian dolomitic limestones and siltstones, is interpreted to be a marked angular unconformity. This surface is clearly displayed on the seismic data (see Chapter 5, Enclosure 1), and separates an older folded and faulted sequence from the relatively undeformed overlying Grant Group, clearly indicating a period of uplift and erosion prior to deposition of the Grant. Within the study area the absence of the Lower Carboniferous section is also indicative either of a significant period of non-deposition or erosion.

It is postulated that the unconformity is a glacially eroded surface. The most convincing evidence for glacial erosion would be the recognition of striated surfaces. However, due to lack of outcrop and the size limitation of core, no striations on the surface of the unconformity could be identified in the study area. Striations have been recorded on outcrops of basement in the adjacent Kimberley and Pilbara Blocks. These are overlain by equivalent and comparable Permo-Carboniferous glacial sediments, attesting to the movement of ice sheets into the basin with erosion of the substrate and subsequent deposition during deglaciation (Towner and Gibson 1983)

In Hoya 1 and Calytrix 1 large cavities filled with sandy diamictite (of similar composition to the overlying BD facies) and thinly bedded sandstone/siltstone units within the Devonian dolomitic limestone subcrop are interpreted as solution features produced either by surface weathering prior to ice advance, or subglacially by meltwater. They have subsequently been infilled by massive diamictite deposited from the base of the ice sheet, and thinly bedded sandstone/mudstone deposited by meltwater percolating through the cavernous system.

The most compelling evidence for the unconformity surface being glacially eroded is the nature of the overlying sedimentary unit. Facies BD, which immediately overlies the erosional unconformity surface, consists of dominantly massive sandy diamictites. The overall massive aspect of facies BD is a feature common to basal tills (Boulton and Deynoux 1981, Dreimanis 1984, Anderson 1983). The gradual transition, evident in a number of cores, from a massive relatively clast-rich diamictite at the base to a series of irregularly bedded diamictites with thin interbedded sandstones is interpreted to indicate a change in depositional process. The lowermost diamictite, which rests directly upon the unconformity, is interpreted as a lodgement till deposited directly from the base of the retreating ice-sheet. The overlying diamictites with occasional sandstones and deformed bedding are interpreted as melt-out and possible supra-glacial flow tills (Shaw 1977, Boulton 1971).

The basal diamictite has a number of characteristics diagnostic of lodgement tills. Lodgement tills commonly rest on planar surfaces produced by glacial erosion (Shaw 1982, Boulton 1975, Brodsikowski and Van Loon 1987), and contain clasts of substratal sediment. They are dominantly massive and generally poorly sorted (Elson 1961, Boulton 1971,1972, 1975, 1976). The poor sorting, a feature of all tills, arises because ice does not exhibit the sensitive competence to transport sediment shown by running water and wind. Lodgement tills also tend to form continuous beds often of considerable thickness (Boulton 1975,1976, Kruger 1979, Eyles and Sladen 1981, Eyles and Miall 1983, Brodsikowski and Van Loon 1987).

Lodgement till is a deposit released from the sliding base of a dynamically active glacier by pressure melting and/or other mechanical processes (Figure 55). The process is gradual, with the release of clasts carried in the ice as frictional resistance between the ice and the bed causes the clast to lodge (Shaw 1985). The initial movement of the clast across the substrate creates striation on both clast and substrate, after lodging the upper surfaces of the clast may be abraded producing further striations and faceting (Kruger 1979).

Depositional rates of lodgement tills are probably highly variable, depending primarily on the rate of ice melt and the concentration of debris in the basal zone. Empirical studies suggest rates in the order of a few centimetres per year (Shaw 1982).

The transition to bedded diamictites, with crude stratification and occasional interbedded sandstones and conglomerates, is interpreted to indicate a change to dominantly melt-out deposition (Lawson 1979, Haldorsen and Shaw 1982, Ashley et al. 1985). Melt-out is the slow release of debris from glacier ice that is not sliding (Shaw 1982). The concept of melt-out was defined by Goodchild (1875) and observations of modern glaciers (Boulton 1971, Lawson 1979) confirm the formation of melt-out tills. Melt-out till is deposited by slow melting of stagnant ice and as such commonly retains some of the structure of the englacial debris from which it is derived, resulting in a crude bedding. It may be deposited on the surface of the melting ice (supra-glacial melt-out till) or at the base (subglacial melt-out till)(Figure 55). Melt-out till commonly has a high water content, which is only slowly evacuated from the fine-grained poorly-sorted tills with low permeabilities. This makes it potentially unstable and liable to flow (Boulton 1968, 1971, 1972, Boulton and Paul 1976). The resultant deposit can be termed a flow till (Hartshorn 1958).

Unfortunately there are no specific features that can be used to confidently differentiate between these deposits in the rock record. Preservation of crude bedding would suggest a melt-out origin, although both melt-out and flow tills can display intense soft-sediment deformation

(Shaw 1985).

An important part of the melt-out process is the accompanying release of large volumes of meltwater (Muller 1983). This meltwater deposits sorted sediments in temporary channels at the base, both englacially and on the surface of the ice mass (Eyles et al. 1983, Shaw 1977). With subsequent ice melt these sediments become interbedded with the tills, and commonly display intense soft-sediment deformation.

The clast component of the diamictites is of two distinct types, derived from either an intrabasinal or extrabasinal source. The most abundant clast type comprises intrabasinal lithologies, which are dominantly locally derived fragments of the substratum ripped up by the overriding ice sheet. The angular nature of these locally derived clasts indicates probable short transport distances. The abundance of clasts of dolomitic limestone (mainly of Devonian Nullara Limestone Equivalent), which forms the principal substrate upon which facies BD was deposited, indicates incorporation of locally derived material ripped up by the overriding ice sheet .

Many lithologies however are not found as major clast constituents although they do form the immediate substrate in certain areas. For example in Hoya 1 the immediate substrate consists of a greenish-grey siltstone (an interbedded lithology of the Nullara Limestone) and in Ficus 1 the substrate consists of thinly bedded sandstones, mudstones and limestones (Devonian Fairfield Formation). However, sandstones, siltstones and mudstones are not represented as a major constituent of clast type in the overlying diamictite. This is interpreted as a reflection of the relative competence of differing substrate lithologies, the softer lithologies more readily ground down and dissaggregating.

The presence of rare faceted faces and striations on occasional large dolomitic clasts is interpreted to be indicative of transportation in the traction zone of basal glacial ice (Flint 1971, Boulton 1978, Eyles, Sladen and Gilroy 1982). These features develop when a clast is trapped against bedrock and ground flat by moving ice. Such shaped and striated clasts are extremely difficult to identify in core, especially narrow diameter core. However, they have been tentatively identified in certain cores of Association BD.

Extrabasinally sourced lithologies, consisting of igneous and metamorphic clasts, were derived from the surrounding Precambrian shield areas. The direction of ice-sheet movement and hence clast transport is not known, as the cores examined were not oriented and thus no fabric analysis could be undertaken. However, potential source areas are the Kimberley Block to the northwest, the Pilbara Block to the southeast or other basement areas to the southwest, all of which imply transport for distances in excess of 150 km.

The greater roundness displayed by the extrabasinally sourced clasts indicates extensive subglacial or englacial glaciofluvial transport prior to incorporation in the diamictite. The lack of striations or marked faceting is possibly a refection of the hardness of the lithologies, a relationship noted from other diamictites. The lithology dependent nature of such features is well documented (Lindsay 1989, Eyles 1984, Kruger 1979).

Facies BD is followed by a variety of facies, which reflects the lateral variability and complex nature of the succeeding sedimentary succession. The widespread occurrence of an abrupt boundary followed by mudstone and heterolithic facies, interpreted as a subaqueous basinal deposit, suggests that the retreating ice sheet was rapidly inundated by marine or lacustrine conditions. In Hoya 1 the transition to thick massive sandy diamictites, of similar composition to the basal diamictite is more ambiguous, and these could be either subaerial or subaqueous melt-out or flow-tills.

7.2.3 Massive Sandy Diamictite Facies (DSm)

Description

Facies DSm is characterised by its apparent massive bedded nature (Figure 56). It consists of a light brown to medium grey argillaceous sandstone matrix, with additional randomly scattered larger clasts, ranging from coarse sand to large pebble and cobble grade (up to 15cm). The matrix is very poorly sorted, variably argillaceous, and contains abundant very fine to fine lithic grains (Plate 7C). Larger clasts, up to 10cm, are dominantly either light grey dolomitic limestone, or varicoloured and of igneous or metamorphic composition. The dolomitic clasts resemble the

Devonian dolomitic limestones which form the predominate subcrop upon which the Grant Group rests, whilst the igneous and metamorphic clasts are similar to Precambrian basement material, presently only exposed in the shield areas at the margins of the basin. Dolomitic clasts have a larger average size and are generally angular to subangular. The basement clasts are subangular to subrounded, and occasional rounded clasts were recorded.

The proportion of clast type within a diamictite is an important characteristic. Many diamictites within the study area contain abundant dolomitic clasts, such as facies DSm in Eremophila 2 between 185.40 - 198.20m, with relatively subordinate amounts of 'basement' clast material. Others contain no dolomitic clasts and only basement material. The latter are generally darker in colour, medium to dark grey, and have a lower density of clasts. Diamictites containing dolomitic clasts are commonly light brown to light grey in colour, reflecting the abundance of light coloured, fine grained dissaggregated dolomitic material in the matrix.

Although diamictites of facies DSm have an overall massive appearance, on closer inspection subtle variations in grain size and vague laminations are visible. A crude bedding is apparent, and this can be identified on the gamma-ray log over the interval. Occasionally thin silty wisps and lenses were also recorded.

The basal contact between facies DSm and adjacent facies is generally sharp. In Eremophila 2 at 219.40m it is characteristically sharp, resting upon a heterolithic sequence of sands and silts, which are heavily deformed. In Hoya 1 a massive sandy diamictite at 431.61m again displays a sharp lower contact, this time directly upon facies BD.

The upper contact between facies DSm and overlying facies may be either gradational or sharp. Facies DSm is commonly overlain by facies DSs, such as at 415.86m in Hoya 1. Generally the composition of the overlying diamictite Facies DSs is similar to that of the preceding Dsm facies, apart from an increase in the stratification and frequency of interbedded sandstones.

In Eremophila 2 both sharp and gradation upper contacts to diamictites are observed. An abrupt upper contact is observed at 186m between a sandy diamictite and an overlying medium-grey mudstone (Plate 7D). The upper contact of a similar sandy diamictite of facies DSm at 205.50m is gradational into a muddy diamictite, which in turn is gradational into laminated mudstones of facies Fl (Plate 8A). The sandy diamictite becomes increasingly mud-rich, and distinct mud-rich laminations become apparent, almost rhythmically interbedded with 'diamictite' beds. This increase in mud content continues over a 1m section with a gradual increase in thickness of mud-rich beds and a thinning/fining of the sandy diamictite beds until the coarser clast component is lost totally, to leave a laminated mudstone.

Interpretation

Sandy diamictites are well recorded both from studies of the rock record and recent deposits, and it is clear that the facies is not specific to one depositional process. Poor sorting discounts deposition by fluvial or bedload processes and also negates reworking or transport subsequent to deposition. The abundance of large outsize-clasts floating in an argillaceous sandy matrix suggests either deposition directly from the base of a melting ice sheet, supraglacial deposition and/or possible subsequent mass flow. The coarse grained nature of the facies establishes a proximal location to the ice sheet, the principal clastic source for the basin. The definition and processes involved in subglacial melt-out and supra-glacial melt-out deposition have been discussed in relation to facies BD and shall not be repeated herein.

Facies DSm commonly displays a sharp basal contact, indicative of a rapid change in depositional process. Underlying units often exhibit intense soft-sediment deformation, which is commonly attributed to sudden loading, causing slumping, convolution and dewatering (Walker 1984). Loading could be the result of ice sheet / iceberg grounding, or the sudden influx of sediment. The sharp basal contact together with the deformation noted in the underlying sediments suggest deposition either as 'melt-out' from the base of the ice, and/or subsequent remobilisation as 'flow till' or debris flows.

Diamictites resulting from mass flow processes at the terminus of a glacier/ice sheet are well recorded from modern and ancient examples (Hartshorn 1958, Boulton 1968, Lawson 1979). The release of large volumes of sediment from the ice, primarily by melt-out processes, produces unstable slopes and sediment masses which are liable to failure.

Resedimented diamictites resulting from mass movement form the bulk of many suites of glacial sediments. Debris flows/flow tills are usually stacked and commonly contain interbedded thin sandstones and stratified sediments, interpreted to be deposited on the surface of the flow from water expelled during transport and subsequent consolidation (Boulton 1968, Lawson 1979). Facies DSm is usually overlain by facies DSs, which does contain abundant stratified sandstone interbeds. Thin interbedded silts are recorded from Eremophila 2, however facies DSm is characterised by a massive or relatively massive nature, which implies that the flow units are large and possibly moving relatively short distances.

To summarise, the massive bedded nature associated with noted internal deformation, common sharp basal contact with underlying deformed sediments, and the gradational upper contact into facies DSs suggests that facies DSm was deposited initially as subglacial or possibly supraglacial melt-out and subsequently suffered a variable amount of resedimentation due to flow (Figure 55). The resedimentation has not resulted in significant dissaggregation or sorting, and as such the diamictites can be classified as melt-out and flow tills.

The observed gradation into muddy diamictites and laminated mudstones also indicates a subaqueous environment of deposition for some of the sandy diamictites. The gradual fining-upward of the sequence records a reduction in the availability of sand grade and coarse-clast component and may reflect a transition from ice proximal to ice distal conditions following a period of ice retreat.

7.2.4 Stratified Sandy Diamictite Facies (DSs)

Description

Stratified sandy diamictites (DSs) are normally associated with massive sandy diamictites (DSm) and stratified muddy diamictites (DMs). The gross composition of the diamictite is comparable with facies DSm, the differentiation in facies being determined by the relative increase in abundance of interbedded stratified sediments, and more intense internal deformation of the diamictite (Figure 56, Plate 8B).

The facies comprises beds of light grey to light brown sandy diamictite, interbedded with conglomerates, massive and normally graded sandstones, thinly laminated siltstones and sandstones and laminated mudstones. The diamictites have a very poorly sorted argillaceous sandstone matrix, commonly very fine to fine grained, with randomly scattered fine to cobble grade clasts. Large clasts over 0.5cm are not common, although scattered clasts up to 8cm were noted. The clasts are predominantly of igneous and metamorphic composition, interpreted to be basement material. They are generally angular to subrounded, some rare rounded clasts were observed. Less common subangular to angular dolomitic limestone clasts were observed, up to 6cm. The diamictites commonly display internal deformation, with folded and contorted bedding picked out by slightly siltier streaks, and thin silty wispy-laminae.

Interbedded with the diamictites are thin, massive and normally graded sandstones, ranging in grain size from very fine to medium grained. The sandstones commonly display intense soft-sediment deformation (Plate 8C). Thin silty laminations are contorted, folded and microfaulted (generally normal faults with less common reverse fault movement). Water escape pipes were noted. Many of the sandstones contain small pebble grade clasts, with no apparent orientation. The sandstones also contain small clay clasts and occasional small diamictite clasts, of similar composition to the interbedded diamictites.

Thin massive and laminated dark grey mudstones are also interbedded with the diamictites, generally completing an overall upward-fining sequence from diamictite, through stratified sandstone to silty mudstone and mudstone, such as occurs at 265.20m-266.50m in Eremophila 3.

In Calytrix 1 facies DSs has a gradational basal contact, marked by an increase from a massive muddy diamictite to thin bedded muddy diamictites, which gradually become increasingly sandy. This unit is overlain by a thick sandy diamictite, which is cut by a graded sandstone with abundant pebble clasts at the base (Plate 8D). Overall, Facies DSs in Calytrix 1 becomes increasingly sandy until within the top 1m where it rapidly grades into laminated mudstone of Facies Fl. The interbedded sandstones are both graded and massive, and soft sediment deformation is common, picked out by slightly siltier lenses. The facies has a slumped and deformed appearance.

In Hoya 1 a similar stratified sandy diamictite (DSs) rest with a sharp contact upon facies DSm at 415.86m. The diamictite is noticeably sandier with a much lower proportion of argillaceous matrix, clearly demonstrated by the sharp reduction in gamma-ray reading. Interbedded sandstones are commonly massive and like the example from Calytrix 1 display soft-sediment deformation, slumping, contorted bedding with thin wispy silty lenses, and occasional micro-faulting. Towards the top of the facies a 3m sandstone exhibits strong grading, from a conglomeratic base up to a medium to fine-grained top, capped by a thin sandy diamictite. The facies in Hoya 1 is overlain by a thick sequence of massive to graded sandstone, assigned to the sandstone Facies S5.

Interpretation

The stratified sandy diamictites (DSs) display many features in common with the massive sandy diamictite (DSm) and in general the process of deposition is believed to be similar. The character of the diamictites and the interpreted 'glacial' origin has already been reviewed at some length. The poorly-sorted texture and abundance of randomly scattered clasts, many of which are sourced from extra-basinal areas, suggest that the sediment was originally deposited directly from a melting ice sheet as a melt-out till. The poorly sorted character is common to all tills that are deposited directly from melting ice, a function of the glacier/ice sheets inability to sort sediment.

The abundance of deformation structures within the diamictites, common sharp basal contacts and the presence of interbedded stratified sandstones indicates that many of the diamictites have undergone mass flow. The association with thin sandstones, interpreted to be deposited from mass flows, and mudstones deposited from suspension indicates that the diamictite facies may have a subaqueous in origin.

Flow tills can occur under both subaerial and subaqueous conditions, and workers such as Boulton (1968, 1970, 1971) and Dreimanis (1975) have demonstrated that subaerial semi-plastic movement of tills is common in ice marginal locations. However the abundance of interbedded sandstones interpreted to be mass flow in origin and the upward transition into glaciolacustrine sequences would indicate that the bulk of facies DSs was probably deposited under subaquatic conditions.

Subaquatic flow tills have been described from numerous Pleistocene sections (Evenson et al. 1977), and they contain many features in common with Facies DSs described from the Hoya Formation. Many similar Pleistocene examples are interpreted to be the product of coherent mass flows of diamictite into an ice marginal glaciolacustrine /marine environment.

The depositional environment at the margins of a continental ice sheet is complex, with interfingering deposits of glaciolacustrine, glaciomarine and glaciofluvial origin. Mass flow is a common process, resulting from the rapid input of large volumes of sediment, the highly argillaceous nature of the sandstone and frequent loading and 'shock' due to minor ice advances, calving ice bergs etc. The interbedded character of the sediments and gradation from diamictites to conglomerates and stratified sandstones indicate a depositional environment in which flow velocities, sediment supply rates and source area are all highly variable.

7.2.5 Massive Mud-Rich Diamictite Facies (DMm)

The massive mud-rich diamictite (DMm) consists of a medium to dark-grey clay-rich matrix, with additional varying proportions of silt, sand and scattered large outsize clasts (Figure 56, Plate 9). An average composition is approximately 60% mud, 35% silt and sand, 5% clasts (greater than 2mm). It is massive, with only rare thin (.25mm - 1cm) silt to fine-grained sandstone lenses, which commonly display soft sediment deformation. The clasts are dominantly igneous, metamorphic and metasedimentary basement material, with only occasional clasts of dolomitic limestones in certain locations. They are rounded to subangular, rarely angular, and have a mean size of 1cm, but range from 2mm up to 10cm. The facies varies in thickness from 1m in Eremophila 1 up to 16.5m in Calytrix 1 (278.60 - 295.06m).

The contact between facies DMm and adjacent units is notably variable. Dependant on location both sharp and gradational contacts are displayed. In Eremophila 2, the cored section between 206-204m shows a gradual transition from massive muddy diamictite to massive mudstone, as the top of the diamictite gradually becomes thinly bedded, with alternating layers of mudstone and clast-poor muddy diamictite. The gradual reduction in thickness of the diamictite layers due to the loss of the sandy and coarse clast material, and accompanying increase in the thickness of the mudstone units continues until only mudstone is present. A similar transitional upper contact was also evident in Eremophila 3, Aristida 1 and 1A and Triodia 1.

In Hoya 1 the transition is very rapid, with no indication of bedding. The sand and coarse clast component rapidly disappears, leaving a mudstone of similar colour to the dominant matrix of the diamictite below. In Calytrix 1 facies DMm has a gradational contact with the overlying DMs and DSs facies.

The lower contact of facies DMm may also be either sharp or transitional. In Eremophila 1 between 174-177m there is a transition from rhythmically bedded mudstones and siltstones of Facies Fl to Facies DMm. Scattered clasts of similar composition to the matrix of Facies DMm and also rare lithic clasts of igneous and metamorphic basement material are present near the top of the laminated mudstone unit. The frequency of the clasts increases towards the top of the unit, and cm scale bedding becomes apparent, with thicker clast-rich layers (2.5mm - 1cm) and thinner (2mm) dark grey mud-rich layers. The bedded unit gradually gives way to a massive muddy diamictite. (The transition is described in more detail under Chapter 7.3 Facies Fl). In Hoya 1, however, (255-256m) a different basal contact is evident, the base of a DMm unit clearly displaying a sharp contact to the underlying mudstones of Facies Fm.

Interpretation

Facies DMm is characterised by its fine-grained nature, low clast content and massive appearance. These features together with the transition to subaqueous deposited mudstones of facies Fm and Fl (lacustrine or marine) suggests a waterlain origin. This interpretation is similar to that of Visser (1985), Deynoux (1985), Eyles and Eyles (1983) and Miller (1989) for analogous argillaceous diamictites.

A number of authors have dealt with the problem of distinguishing between muddy diamictites, most notably Crowell's paper on 'The origin of pebbly mudstone' (1957). A subdivision based on depositional process was proposed by Harland et al. (1966), with 'pebbly muds' originating either:

1. as orthotills - formed by the immediate release from melting ice i.e. subglacially

2. as paratills - a till formed by ice-rafting in a marine or lacustrine environment

3. as mass flows (debris flows).

More recently the term 'waterlain till' as defined by Dreimanis (1979) has been used to include diamictites deposited by several mechanisms, from grounded icebergs, subglacial melt-out and mass-flow. It is probable that Facies DMm sediments are the product of a combination of the above processes, together with ice-rafted 'rain-out' deposition (Eyles and Eyles 1983) into a glaciolacustrine or glaciomarine environment, which is not included in the definition of 'waterlain till'.

The difficulties of terminology have already been discussed (7.2.1). The qualification hinges on the point at which 'substantial dissagregation' of the sediment occurs, so that the 'till' ceases to be a 'till' and becomes a glaciolacustrine or glaciomarine deposit. Genetically waterlain till occupies the boundary between glacial and water deposited sediments (Boulton 1976, Dreimanis 1979). However, in most cases it is not possible to distinguish in core between true 'waterlain till' and ice rafted 'rain-out' deposits (Eyles 1983).

Rain-out diamictites are the product of normal deposition of muds and silts from suspension within a basinal setting, with the addition of coarse grade material from floating icebergs. In the strict definition of the term, these deposits do not constitute tills, because a large part of the sediment is not the product of 'direct' deposition from ice. Ice-rafted deposits generally have much finer textures than associated waterlain tills (Dreimanis 1979) but there is no critical limit which can be used to distinguish the environment of deposition. Both deposits could have transitional contacts with glaciolacustrine/glaciomarine sediments, or if remobilised as subaquatic flows, sharp contacts.

The main characteristics of Facies DMm are a fine-grained matrix, low clast content and massive appearance. The matrix consists predominantly of a dark-grey clay, of a similar character to adjacent lacustro-marine mudstones and is of a much finer texture than adjacent diamictites, interpreted to be of lodgement and subglacial melt-out origin (Chapter

7.2.). This suggests deposition in a more distal location away from the ice-sheet (the source of clastic input) with some degree of sorting.

The principal evidence for a subaqueous mode of deposition is the association of Facies DMm with mudstones of lacustrine or marine origin. The contact with clast-free mudstones is commonly transitional. The gradual inclusion of coarse clast material indicates a change in the depositional environment, the most likely mechanism for transportation of the clast component being floating ice.

In Eremophila 2 the transitional unit is a bedded sequence of alternating clast-rich and mud-rich layers, indicative of a periodic control on deposition (possibly annual). The presence of clasts of the massive muddy diamictite facies (DMm), within this bedded transitional unit (Plates 10 & 11), suggests that Facies DMm was deposited in a more proximal location. A possible transport mechanism might involve the freezing of clasts of DMm to the base of an ice mass, possibly by temporary grounding of the ice sheet, icebergs or seasonal pack-ice, which subsequently float to a distal location. The eventual upward-transition observed to massive diamictite suggests an increasingly proximal location closer to the ice sheet, possibly to a subglacial environment beneath the floating terminus of the ice sheet margin.

The clasts of diamictite are restricted to the bedded unit and appear to gradually disappear as the unit becomes more massive, with a increase in dispersed poorly-sorted sand grade material and scattered outsize lithic clasts. The control on 'diamictite' and mudstone-clast formation and transport is not clear, but presumably reflects the availability of grounded ice, assumed to be the principal agent for both entraining and transporting the clasts. Ovenshine (1970) recorded similar 'diamictite' pellets carried by icebergs in Glacier Bay, Alaska, and predicted the occurrence of such ice-rafted clast-rich units in the rock record.

A similar facies was observed from the Itarare Group of Brazil. The section, part of a large road-cutting, suggests these deposits are laterally extensive and gradational into massive muddy diamictites (Plate 11).

The transitional upper contact, exhibiting a gradual reduction in supply of the coarse component of the diamictite and a transition to mudstone, is interpreted as an ice retreat sequence, reflecting a gradual reduction in ice transported clasts. In this case the coarse clast component is not in the form of discrete mudstone or diamictite clasts, but as randomly scattered grains of sand and larger lithic clasts, similar to that which constitutes the main massive muddy diamictites. The transition is effected by a gradual reduction of coarse component within alternate layers, until the unit comprises soley of mudrock.

The lack of bedding and homogenous nature of muddy diamictites is well documented in both the rock record (Eyles and Eyles 1983, Eyles _et al_. 1985, Visser 1983, Visser and Loock 1982, Miller 1989) and from present day studies off Antarctica (Anderson _et al_. 1980, Kurtz and Anderson 1979) although the exact mechanism of formation is a matter of debate. It might be expected that 'rain-out' diamictites should display a crude bedding, since deposition in a glaciolacustrine or glaciomarine environment is usually associated with periodic changes in clastic input, resulting in a grain size variation. However, _massive_ diamictites interpreted as 'rain-out' have been described in the literature, and the contact between the diamictite and mudstone described above certainly suggest that the transitional unit is subaqueously deposited. As no distinct boundary exist between this transitional unit and Facies DMm, it may be assumed that the massive diamictite is also a deposited in a subaqueous basinal setting, possibly beneath the floating terminus of a glacier or ice sheet (Figure 55).

Examples of facies DMm with sharp basal contacts, could indicate an element of mass-flow subsequent to initial deposition, perhaps providing a mechanism for the destruction of primary stratification. Glacial margins are likely to be active sites for mass-flow generation, with large quantities of non-sorted sediments being delivered by ice sheets, and studies of recent sedimentation adjacent to the Antarctic ice sheet confirm this (Kurtz and Anderson 1979).

7.2.6 Stratified Mud-Rich Diamictite Facies (DMs)

Description

Stratified muddy diamictites are intimately associated with the massive muddy diamictites. The mud-rich diamictite is of similar composition to its massive counterpart, being medium grey in colour, and comprising approximately 60% mud, 30% silt to very fine-grained sand, with an additional 10% coarse clasts, up to boulder size. Stratification is present within the diamictite, commonly as fine silty wisps or laminations, which display intense soft-sediment deformation in places. Deformation within the diamictite is common, generally in the form of vague fold structures picked out by subtle changes in the diamictite composition. The clast content of the stratified muddy diamictite is comparable with that described for the massive muddy diamictite, comprising dominantly subrounded to subangular basement clast of igneous and metamorphic origin, with subordinate dolomitic material.

Interbedded with the diamictite are thin fine to medium grained sandstones, occasionally up to pebble grade. The sandstones are commonly massive with no internal stratification, although some thin graded sandstones have been recorded. The sandstones commonly have loaded bases and tops. In Aristida 1 and 1A, thin interbedded sandstones contain abundant intraclast material, mainly comprising muddy diamictite of similar composition to the surrounding diamictite (Figure 57). The clasts are large, up to 5cm, and angular. Each sandstone unit is intensely loaded by the surrounding muddy diamictite. Also interbedded with the diamictite are thin mudstone units, such as between 266m to 271m in Calytrix 1 (Figure 56).

In Calytrix 1, a massive muddy diamictite has been recorded with an upper gradational contact into a stratified diamictite, consisting of a similar muddy diamictite with interbedded thin sandstones. Slumping and soft sediment deformation is common. The diamictite gives way to thin sands, which in turn grade rapidly into a medium-grey laminated mudstone. The top of the mudstone is marked by the reappearance of the muddy diamictite as thin bedded units (20 - 30cm thick) interbedded with the mudstone. The colour of the mudstone and the diamictite are similar, the only difference being the additional coarse clast content in the diamictite. The base of each diamictite unit is commonly sharp, and possibly erosive. This section is overlain by a series of thin sandy diamictites of Facies DSs. The gradation into mudstone and thinly interbedded nature of the mudstones and diamictites provides important evidence for deciphering the environment of deposition.

The stratified muddy diamictite generally has a gradational lower contact with the massive muddy diamictite, such as at 278.40cm in Calytrix 1, or 329.70cm in Hoya 1. The upper contact is sharp, either overlain by a sandy diamictite or a sandstone. In Hoya 1 at 322m the stratified diamictite is erosionally cut by an upward-fining sandstone (Facies S7).

In Eremophila 1 a variant of the stratified muddy diamictite is observed. In this case the diamictite has a gradational lower boundary with a medium grey mudstone, and the stratification is in the form of thin interbedded laminae containing abundant 'diamictite' pellets and small mudstone clasts. Pellet abundance and frequency, and thickness of the laminations increases until the stratified diamictite eventually grades into a massive diamictite. The diamictite pellets are generally small, less than 0.5cm, and randomly oriented within a slightly siltier mudstone matrix.

Interpretation

The close association of facies DMs with facies DMm, and the common gradational contacts between the two facies, implies a similar depositional environment. Many of the criteria used to interpret the processes of deposition for the previously discussed massive mud-rich diamictite are equally valid for the stratified mud-rich diamictite. The evidence for a waterlain origin is apparent in both the abundance of interbedded sandstones, and the gradational contact with glacio-lacustrine or glacio-marine mudstones. The general abundance of soft sediment deformation suggest a certain degree of remobilisation and slumping of the diamictite subsequent to deposition.

However, the notable difference from the massive diamictites is the increased abundance of sandstone interbeds. These interbedded sandstones display both massive bedding and grading, with sharp or loaded bases. They show a rapid return to the diamictite or mudstone facies deposition, which suggests the sands were deposited rapidly into the basin. These features are characteristic of sands deposited by mass-flow processes, either by turbidity flows or combined grain flow/turbidity flows (Lowe 1976, Middleton and Hampton 1976, Ashley et al. 1982).

Grading resulting from the gradual decrease in velocity of the flow, and concurrent deposition of sand from suspension. In thin flows it is commonly the case that complete Bouma sequences are not developed, producing sandstones with a massive internal character (Walker 1984b). Subsequent later slumping and destratification due to fluidisation may also be responsible for the massive nature to some of these thin sands. The abundance of 'diamictite' and mudstone clasts within the interbedded sandstones recorded from Aristida 1 indicates that in part the flows were erosive, actively ripping up the substrate prior to deposition.

The increase in frequency of sandstone beds within facies DMs, suggests deposition took place in a more proximal environment than facies DMm. The upper contact of facies DMs with either sandstones or sandy diamictites is interpreted to display a continued increase in clastic material into the basin. This evolving sedimentary sequence displays a pattern indicative of increasing proximity to a clastic source. As the main clastic source into the basin is believed to be the run-off from the ice sheet, the gradually increase in coarse clastic component is indicative of a relative ice-sheet advance into the area of deposition.

In Eremophila 1 the silty mudstone containing abundant 'diamictitic' pellets suggest the presence of floating ice within a basinal environment.. The transportation of 'diamictitic' pellets by floating ice has been well documented by Ovenshine (1970) from Glacier Bay, Alaska. Similar stratified diamictites have been interpreted to be the result of seasonal/periodic fluctuations in ice cover, with periods of no ice movement resulting in mudstone deposition, and periods of abundant ice movement resulting in the pellet-rich laminations. The increased abundance of the pellets and thickness of the beds suggests an increased frequency of icebergs, which act as the main transport mechanism for the pellets. The gradation from massive mudstones through stratified mudstones/diamictites containing diamictitic pellets, to massive diamictite indicates a gradual increase in the availability of glacially derived coarser clastic material, and an increase in the frequency of floating ice This can also be interpreted to support a gradual ice sheet advance into the basin.

7.3 Mudrock Facies Association

The term mudrock is used in the sense proposed by Blatt et al. (1980), to include all sediment with a grain size of less than 0.0625 mm. Thus mudrocks comprise silt and mud as defined by Wentworth (1922). Blatt et al. also state that mudrocks can contain up to 15% sand grade material.

The mudrock facies association (F) is characterised by massive or bedded, light to medium-grey mudstones and siltstones and can be divided into two subfacies distinguished by their internal stratification; 1. a massive mudstone/silty mudstone facies (Fm), and 2. a stratified mudstone/siltstone facies (Fl). The stratified mudrocks can be further subdivided into a wide range of distinctive units, commonly interbedded with gradational contacts.

7.3.1 Massive Mudrock Facies (Fm)

Description

This facies is characterised by massive medium-grey mudstone to silty-mudstone with virtually no visible internal stratification and only rare thin lighter-coloured siltstone lenses. The gamma-ray log pattern over the interval commonly indicates minor changes in composition, with a number of upward-decreasing cycles possibly indicative of subtle upward-coarsening units. Bioturbation is present in a number of wells, although limited to certain horizons and dominated by small lozenge shaped '*Chondrites*' burrows. A marine fauna has been identified in Eremophila 2.

Although the facies varies in thickness, it is present at a similar stratigraphic position in a number of wells, indicating its extensive distribution.

Facies Fm displays both gradational and sharp contacts with adjacent units, the basal contact is commonly gradational with facies DMm or DSs and the upper contact sharp with overlying facies DSs.

In Hoya 1 the top of facies DSm gradually upward-fines to Facies DMm, which then rapidly upward-fines into Facies Fm (with a gradual loss of the coarse clast component, leaving the dominant muddy matrix). The facies is 13.5m thick and has a sharp upper contact with the overlying unit, Facies DMm.

From the gamma-ray log it is apparent that subtle changes in the composition of the mudstone are present, with upward reducing response indicating a development of crude upward-coarsening units. This change of grain size and texture is difficult to distinguish in the core, although occasional hints of bedding, picked out by subtle changes in colour and grain size were noted. Minor changes in grain size, from mud to silty mud, are gradational and no erosive or sharp contacts were observed. The overall appearance of the facies is massive.

A feature of Facies Fm restricted to Hoya 1 is intense brecciation near the base of the unit, which gradually decreases up section. Mudstone clasts, between 1-3cm in size, are supported in a mudstone matrix of similar composition. The clast are angular and a high proportion display interlocking faces, which indicates relatively little transport. Cross cutting at an angle of between 30-45' are thin 1-5mm wide zones of intense brecciation and shearing. The frequency of clasts gradually reduces up section until the mudstone becomes massive.

In Calytrix 1 between 308.94 - 295.06m a 6.5m thick unit of Facies Fm rests with an abrupt contact upon sediments of Facies DSs. The unit is dominated by massive silty-mudstone to mudstone, which contains occasional scattered fine to medium-grained sand grains. Although dominantly massive in appearance the unit displays subtle variations in the proportions of mud to silt. The massive mudstone can be subdivided into a number of large units of between 1-2m thick, each with gradational upper and lower contacts, producing a gamma-ray log pattern indicative of dominantly upward coarsening packages. Occasional thinly-bedded muds and silts are present within the overall massive mudstone, concentrated towards the top 3.5m of the unit. They contain small (less than 2.5mm) lenses of mudstone or silty mudstone, which have a sub-horizontal orientation and are concentrated on the siltier laminae. The lenses are normally darker than the surrounding silty-mudstone. These features are interpreted as small burrows, and their size, shape and distribution would suggest the trace fossil Chondrites. In Calytrix the Fm unit is overlain with a sharp contact by Facies DMm.

In Drosera 1 the base of a thick gradational unit from mudrock to a heterolithic facies association comprises massive mudstones. The massive medium-grey mudstones and silty-mudstones have a high proportion of scattered very-fine to fine-grained sand grains (up to 10%), and rest with an abrupt contact upon a stacked series of medium to coarse-grained sandstones (Sl). The massive appearance is deceptive, and on a large scale, 1-4m upward coarsening and upward-fining packages can be identified, although the change in grain size is very subtle. Rare outsize clasts occur scattered throughout the unit, generally less than .5cm in diameter and consisting predominantly of basement material.

In Aristida 1 and Aristida 1A a 5m section of Facies FM occurs between 195-190m and 193.52-188.60m respectively. The base of the unit shows a gradation from the underlying muddy diamictite (DMm) into massive medium-grey mudstones. The mudstones contain scattered subrounded to subangular sand grains, commonly concentrated along certain horizons, but comprising less than 10% of the unit. Rare pyritic nodules were also recorded. The upper contact is sharp and the unit is overlain by a muddy diamictite (DMm) of similar composition to the diamictite below the mudstone. The diamictite is the same colour as the underlying mudstone, comprising a muddy matrix with the addition of poorly-sorted sand grade and large clast material.

In Eremophila 2 a similar medium-grey mudstone with massive character is present between 204-198.50m. It has a gradational base from a massive muddy diamictite (DMm) and a sharp upper contact with a sandy diamictite DSm. The unit contains occasional scattered pyrite nodules. Small changes in colour pick out irregular internal structures which suggest soft-sediment deformation, but otherwise it is massive.

Samples from this unit (5 samples from 205-200m) were analysed by V. Palmieri (proprietry work for WMC), who identified a foraminiferal fauna represented by agglutinating hyperamminid, textulariid, ammondiscid and saccamminid forms, and also a rare crinoid fragment at 200m (Appendix 3). This faunal assemblage indicates marine conditions, restricted near the base and becoming more open marine to the top.

Eremophila 3, between 279 and 272m, displays a more complex sequence with Facies Fm gradational into Facies Fl. The base of the association is transitional with an underlying muddy diamictite of Facies DM, in common with sequences described above. The diamictite grades into massive medium-grey mudstones, which contain thin lenses of diamictite and occasional siltstones. Rare clasts of lithic and diamict material are scattered throughout the mudstone, which also displays zones of soft-sediment deformation. The more massive mudstone grades into a thinly bedded to thinly laminated mudstone-siltstone unit of Facies Fl, which in turn rapidly grades into a muddy diamictite.

Melaleuca 1 has a massive mudrock unit between 329.50-361.70m. The basal 5m is dominantly a massive mudstone, initially very dark grey and fissile but becoming medium-grey and massive. The unit also contains rare clasts, up to 0.5cm, and thin lenses of silt and very fine to fine-grained sand. Bioturbation, small 1-5mm Chondrites burrows, is evident, concentrated along certain horizons. The unit grades into bedded silty-mudstones of Facies Fl.

Caladenia 1 has a 5m unit of Facies Fm between 113.11-118.30m. The basal contact of the unit is gradational from an underlying sandy diamictite (DSm). The basal 1.5m is a thinly bedded silty mudstone similar to Facies Fl, which displays intense soft-sediment deformation, slumping and resultant high-angle bedding. There is a gradual loss of silt and reduction in SSD to give a massive medium-grey mudstone. No bioturbation was recorded from this section.

Interpretation

Facies Association Fm is present in a number of wells and displays a uniform character and similar context with respect to adjacent units. The gradational basal contact with muddy diamictites indicates the glaciogenic nature of the facies. The upward-fining transition from muddy diamictite to massive mudstone is indicative of a glacial retreat sequence (Elverhoi et al. 1983, Miller 1989). As discussed in Chapter 7.2.5, the diamictite was deposited either from the base of a melting ice sheet (grounded or more likely floating), or from floating ice-bergs in the basin. The muddy nature of facies DMm suggests a basinal 'rain-out' origin, with the fine grained mud and silts deposited from suspension and the coarser sand grade and large outsize clasts released from either a floating ice shelf or icebergs. Ice sheet retreat is invoked as the primary cause of the facies change from diamictite to mudstones of Facies Fm. The loss of ice sheet cover or loss of contact between the ice sheet and the basin, prevented ice-berg formation, and removed the transport mechanism by which the coarser clast material entered the basin. The mud component continued to be transported into the basin, carried in suspension by melt-water from the ice sheet.

Close inspection of the otherwise massive mudstone reveals subtle changes in grain size. The gamma-ray log has proved useful in charting this compositional change, displaying an irregular pattern, in which broad upward coarsening packages can be determined. These variations in grain size are interpreted to indicate fluctuations in clastic input to the basin.

Occasional thin silt lenses interbedded in the mudstone are interpreted as the product of localised waning traction currents entering the basin. (Anderson et al 1980).

The presence of a foraminiferal fauna in samples analysed by V. Palmieri establishes a marine environment of deposition. The predominance of agglutinating foraminifera indicate cold water and possibly restricted marine conditions. This is consistent with the interpretation of a glacio-marine environment. Sampling of this facies is at present restricted to Eremophila 2, and thus any broad ranging interpretation must be somewhat tentative. However, the uniformity of the facies and its comparable stratigraphic position in a number of wells would favour a similar marine depositional environment for Facies Fm throughout the study area. The lack of internal stratification within Facies Fm is characteristic of marine mudstones, where flocculation of the clays in suspension results in rapid deposition (Obrien 1987).

The marine fauna identified indicates cold-water restricted marine conditions near the base, attributable to the proximity of an ice sheet with influx into the basin of large amounts of fresh water from the melting ice-sheet. This process is well documented from recent studies (Powell 1983, Ashley 1985), where close to the retreating ice sheet, large amounts of fresh melt-water dilute the water column, producing a fresh/brackish transitional zone. The often bedded nature of the basal section of facies Fm, comprising interbedded thin silts and muds, displays features characteristic of facies Fl, indicative of a proximal clastic source and possible fresh melt-water influx into the marine environment. The presence of thin silts and occasional diamict beds or lenses are interpreted to be the product of local underflows or mass-flows into the basin. Following ice-sheet retreat, conditions gradually became more open marine, with a resultant increasing diversity of fauna and concomittant change to a more massive nature to the mudstone.

A complete sequence is displayed in Eremophila 3, with a gradation from diamictite to massive mudstone, followed by bedded mudstones and siltstones of Facies Fl capped by another diamictite (Figure 54). The transition from Facies Fm to Facies Fl indicates an increase both in clastic input and variability of the discharge into the basin, producing characteristic graded beds in Facies Fl, interpreted to be underflow deposits (Ashley 1985). This change from massive to bedded units could also reflect a possible change from marine to restricted or freshwater conditions. The sequence records initial ice retreat and establishment of low-energy marine conditions, followed by a further ice advance into the basin, culminating in deposition of a diamictite indicative of proximal glacial conditions.

In a number of wells the facies displays bioturbation, concentrated along certain horizons and in small discrete populations. The burrows are small, oval shaped and resemble Chondrites , a three-dimensional branching system of burrows constructed by endobenthic deposit-feeding animals of unknown taxonomic affinity (Simpson 1956, Ekdale et al 1984). Chondrites is a wide ranging form and is not diagnostic of any particular depositional environment. However, bioturbation in these mudstones is not common and its restriction to certain horizons indicates a generally unfavourable environment, with only brief periods were the organism that generated the trace fossil flourished. Chondrites is recognised as a taxon that has the greatest tolerance for conditions of low oxygen concentrations (Bromley and Ekdale 1984, Ekdale et al. 1984). The occurrence of a monospecific assemblage of Chondrites would suggest dysaerobic or anaerobic conditions within the basin.

The upper contact of Facies Fm is commonly sharp and followed by a diamictite. This signifies a return to proximal glacial deposition indicative of ice advance into the basin. Evidence for grounded ice at this juncture, such as striated surfaces or boulder trains (Dreimanis 1976, Boulton 1976, Boulton and Deynoux 1981, Visser and Hall 1985) are not readily observed in core and thus the exact nature of the contact is unclear. However the contact is usually sharp (although not exclusively so, in Eremophila 3 the contact is gradational) indicating a rapid change in conditions and possible subglacial deposition.

The origin of the brecciated mudstone recorded from Hoya 1 is speculative, however any possible mechanism needs to address a number of critical features; 1/ gradation of the breccia up section into a massive mudstone, 2/ the 'in-situ' brecciation of the mudstone indicated by the character of the clasts and the presence of thin shear zones, and 3/ the context of the mudstone located between two glacial diamictites. The sharp upper contact of Facies Fm to a diamictite suggests a rapid change in depositional environment and ice advance into the basin. The brecciated zone may be a later fault plane cutting the section, but an alternative explanation is possible. The breccia could be produced by ice sheet or ice-berg loading during this ice advance, the resultant shear forces transmitted to the base of the unit causing in-situ brecciation. The process of brecciation could have been enhanced by freezing of the mudstone under periglacial conditions. Without lateral exposure it is difficult to more fully interpret this feature.

To summarise, the character and context of Facies Fm suggests deposition following retreat of the ice sheet and coincident rise in sea level. A foraminiferal fauna indicates marine conditions within the basin, and the presence of a restricted marine fauna and rare bioturbation is concurrent with an unfavourable cold climate environment. In certain areas ice-bergs were still present at irregular intervals during the deposition of facies Fm, introducing small amounts of ice-rafted debris (Ovenshine 1970). The massive mudstones were deposited under low energy conditions, with only rare bottom currents producing thin silt lenses. Higher energy conditions are often evident near the base and top of the facies, with increased clastic input and the presence of thin mass-flow deposits, a feature related to the increasing proximity of the ice sheet; interpreted to be the primary source of clastic material into the basin. Most units of Facies Fm have a gradational basal contact with waterlain diamictite, attributed to the gradual retreat of ice from the basin, and sharp upper contacts with a similar diamictite, indicating re-advance of the ice-sheet into the area. The presence of a brecciated zone in Facies Fm in Hoya suggests the possiblity of grounded ice at some localities.

7.3.2 Bedded Mudrock Facies

Description

The bedded mudrock facies is characterised by interbedded medium to light-grey mudstones and siltstones, with a variety of distinctive bedding types, reflecting variable processes of deposition. In general the bedding is irregular, however, a number of units exhibit rhythmic bedding with upward-fining cycles on various scales.

The section in Eremophila 1 between 189.60 and 175.25m displays the most diverse sequence of bedded mudrock types. It comprises a number of different bedded mudrocks, which commonly exhibit rhythmic bedding. These can be grouped into three main types.

Type 1 comprises upward-fining beds of light-grey siltstone to medium or dark-grey mudstones, characterised by a massive appearance to the silty layer (Plate 12A). Overall the bed gradually fines-upward from a light-grey silt to a medium-grey mud, without the more rapid change to mud noted in type 2. Individual beds are between 6 - 10cm thick, with the silt layer averaging between 75% to 80%, as above. The basal contact of each bed is sharp and not commonly loaded. Rare mudstone clast between 2.5mm to 5mm are present in the silty layer.

Type 2 mudstones are similar upward-fining beds of light-grey siltstone to medium or dark-grey mudstones. Each bed ranges in thickness between 10 - 15cm. The lower silty layer is between 75 and 80% of the total bed thickness and contains thin 1-5mm thick multiple-graded interbeds of coarser silt or occasionally very-fine grained sand (Plate 12b) The silty layer fines upward to a massive medium to dark-grey mud. The contact between the layers is gradational, but a rapid change to dark mud occurs near the top of the bed. The basal contact of each unit is sharp and occasionally loaded. A variant of type 2 found near the base of association F1 was also recorded from Eremophila 1. The overall character of the beds is as above, however the thin silty interbeds within the silt layer commonly contain small silty-mud clasts. In addition rare larger clasts of similar composition to the underlying diamictite are present randomly scattered within the silty layer. Beds in this section commonly display a loaded base.

Type 3 consists of multiple-graded units of thinly bedded siltstone and very-fine sandstone, fining upward to, and interbedded with, mudstones. Layers range in size from less than a 1mm to 0.5 cm (Plate 12c). The thin sand and silt layers clearly display individual upward fining, and rest with a sharp base upon either silt or mud. Layer thickness is not constant, although packages of between 5 or 10 layers have a similar thickness. The unit has a transitional upper contact with a muddy diamictite.

A transitional unit is briefly described below. The presence of abundant ice-rafted debris strictly classifies this unit as a bedded diamictite, and as such it has been discussed in detail under Chapter 7.2.5 and 7.2.6). The transitional unit is thinly bedded to thickly laminated, each bed comprises a lower silty mudstone layer fining upward to mudstone. Each bed is between 0.5 and 2cm thick, and commonly contains thin 1 - 2mm thick multiple-graded silt laminae within the lower silt layer. Scattered throughout the silt layer are small 1mm to 2cm angular to subrounded clasts of mud, silt and muddy diamictite matrix and occasional lithic composition. Overlying beds are commonly draped over larger clasts, and layers below clasts show compaction. Clasts are not evident in the thin darker mud layer.

Facies Fl also contains subordinate amounts of interbedded sandstones. These are massive to thinly bedded, fine to very-fine grained sandstones which upward-fine to silt or mudstone, and have sharp or loaded basal contacts. Rare very thick examples of graded sandstones were odserved in Hoya 1

Interbedded within Facies Fl in Eremophila 1 between 184.90m and 183.20m is a 1.70m thick sandstone unit comprising upward-fining fine to very-fine grained sandstones and thin interbedded mudstones. The basal sandstone is 50cm thick and has a marked erosive base. It consists of light-grey to light-brown fine to very-fine grained sand, with thin interbedded silty layers. The whole unit displays contorted or folded bedding produced by minor slumping and soft-sediment deformation. In part the sandstone appears homogeneous, again attributed to soft-sediment deformation and destratification. A thin 10cm mudstone unit caps the lower sandstone unit, which is overlain by a 65cm thick upward-fining fine to very-fine grained sandstone. This unit displays climbing ripple cross-lamination of Type A and Type B (Jopling and Walker 1968) in the lower 30cm, grading to thinly bedded to laminated very-fine sands and silts and eventually thinly laminated silts and muds. The sandstone is overlain by a 10cm thick mudstone, which is followed by three upward-fining units, a basal silty sandstone unit and two very-fine grained sandstones which upward fine to siltstones. The lower two units display loaded bases and are faintly flat bedded with occasional distortion of the bedding due to soft-sediment deformation. The upper unit has a flat base and is massive.

The whole package of sandstones is followed by a 2m thick sequence of mudstone to silty mudstone of Facies Fl which has abundant thin silty layers or lenses set in a muddy matrix. The silt beds are commonly loaded and deformed. This unit has an irregular bedded and soft sediment deformed character and the silt interbeds gradually reduce up section and the mudstone becomes more massive. By 181.70m the silty mudstone begins to display graded bedding of Facies Fl type 1.

Facies Fl commonly contains irregular and more complex bedded units, which exhibit intense soft-sediment deformation.

Caladenia 1 between 110.45 and 100.60m contains a 9.85m thick unit of interbedded mudstones and siltstones. The unit has a sharp basal contact with a sandy diamictite (DSs) and a gradational upper contact with a thin muddy diamictite (DMm). It is characterised by thin bedded mudstones and beds grading from siltstone to mudstone ranging in thickness from 1 to 6cm. The unit also contains thin siltstone to very fine sandstone interbeds, generally between 0.5 and 1cm thick.

Occasionally thicker bedded units are present and at 108.50m a thick (80cm) massive upward-fining silty-mudstone rests with a loaded basal contact upon deformed mudrocks. Soft-sediment deformation is pervasive, with intense folding due to slumping, and water escape features producing extremely complex structures, although the original graded or flat bedded nature can often still be deduced. Bioturbation was recorded in the upper 5m of the unit, restricted to certain horizons and consisting of small 1mm to 5mm oval shaped structures, interpreted as Chondrites.

The context of Facies Fl with relation to adjacent units is critical in determining the environment of deposition. It often occurs in gradational contact with other facies associations as part of a larger upward-fining or upward-coarsening package. For example in Halgania 1, an upward-fining package of sediments from 244.25m to 229.80m comprises a 4m thick massive sandstone at the base, followed by a 6m thick series of very-fine sandstones and siltstones. The graded beds of very-fine sandstone and siltstone have spectacular loaded and occasionally detached ball and pillowed bases, and gradually upward-fine to bedded mudrocks of facies Fl, culminating in a transitional facies of ice-rafted bedded diamictite (DMs) and finally a massive muddy diamictite (DMm).

The lower section of Facies Fl comprises thinly-bedded mudstones and siltstones, forming irregular upward-fining units from silt to mud of approximately 10cm thick. The light-grey silty layers, which are occasionally laminated and may contain thin silt and very-fine sand interbeds, display type A and B ripple cross-lamination and grade up into massive medium-grey mudstones. Above 231.50m the facies becomes more massive with only occasional thin silty laminae and interbedded thin (1-3cm thick) sandstones, which are internally massive and commonly display loaded bases. Soft-sediment deformation increases, with intense micro-faulting, slump-folds and water-escape features. A thicker sandstone unit is present at 231.30. Internally thinly laminated and ripple cross-laminated, the sandstone has a sharp basal contact and a gradational upper contact back into mudstones of Facies Fl (Plate 13).

Units comprising sediments with the characteristics of Facies Fl are also present as interbeds within the diamictite and sandstone facies associations, indicative of short lived depositional episodes. These are discussed within the relevant association.

In Hoya 1, a very heterolithic sequence is present between and , It is unusual in that it is heavily bioturbated, and contains a number of thick graded sandstones (up to 4.5m thick). It has a different character to Facies Fl from Calytrix 1 and Clianthus 1, which are not bioturbated.

Interpretation

The fine grained nature of Facies Fl, characterised by bedded mudstones and siltstones, and the style of internal stratification indicates deposition within a low-energy subaqueous environment. The close association with glacial diamictites and occurrence of out-size clasts indicates the glacial nature of the facies. The common rhythmic nature of the bedding and lack of any marine indicators suggests a glaciolacustrine setting.

The rhythmicity of the mudrocks in Facies Fl implies a periodic variation of sediment input and depositional processes. Rhythmic deposition is characteristic of ice-contact and glacier-fed lacustrine environments (Gustavson et al 1975, Ashley 1985), as a result of seasonal alteration in sediment supply beween a short-term ice-melt season and a period of reduced sediment input during the rest of the year.

However, there are several mechanisms for generating rhythmic deposits, not all of which imply an annual periodicity for the rhythm, for which the specific term 'varve' is restricted (DeGeer 1912). The process of deposition of rhythmites has been the subject of much study (Ashley 1975, 1985, Shaw 1977, Gilbert 1973, Gilbert and Shaw 1981, Gustavson et al. 1975, Sturm 1979) reviewed extensively by Ashley (1985). The overall upward-fining nature of individual beds indicates either a reduction in energy of the depositional process or a reduction in the supply of coarser grade material. The two extremes can be seen in graded beds deposited from slump generated surge currents and graded beds deposited from the seasonal fluctuations in sediment supply to the basin due to annual freeze and subsequent thaw in a glacial environment.

In a glaciolacustrine environment lake-water density stratification is critical to the mode of sediment dispersal, however the process of deposition and the dispersal mechanism ultimately dictate the nature of the deposit. Three main dispersal mechanisms have been defined by Ashley (1985), underflow, overflow-interflow and equal-density mixing. More commonly a combination of the above process are likely to be active at any one time within the basin. Ashley suggests that rhythmites deposited within a lake dominated by overflow-interflow are generally only thin (up to 1cm thick) and do not contain current induced structures. In this study the majority of rhythmites recorded within Facies Fl are between 1 to 15cm thick and commonly contain internal structures indicative of current activity, implying a dominance of underflow and/or combined flow deposition.

The presence of a multiple-graded silty layers in type 2 indicates deposition dominated by underflow processes, either of surge or quasi-continuous type, followed by overflow and interflow deposition of the upper silt to mud layer from suspension in the water column. The commonly loaded bases indicate initial rapid deposition, also confirmed by the small scale ripple structures which demonstrate current transport (Jopling and Walker 1968).

Bedded mudrocks of Type 1 are more enigmatic. They consists of a more massive silty layer, with a smooth gradation into a mud or silty mud. These features are more characteristic of slump-generated surge deposits which can be equated to turbidites (Bouma 1962), representing deposition over a period of minutes rather than annually. The apparent rhythmicity is in this case a factor of repetition of a randomly occurring process. However, there is a lack of stratification in the lower silty layer and type 2 mudrocks represent a gradational continuum with type 1.

Type 3 consists of thinly interbedded multiple-graded very-fine grained sand, silt and mud. The individual layers are much thinner than those of type 1 and 2, and the grain size contrast is greater. The coarse layers are the product of rapid deposition, with the general upward-fining nature of each layer the result of a gradual decrease in energy of the underflow and capacity to support the sediment. These units are analogous to distal turbidity deposits (Bouma 1962, Middleton 1976). The thin clay layer represents deposition, between succesive flows, from suspension over a much longer time period.

The bedded mudrock units in Eremophila 1,2,3 and a number of other wells grade into statified diamictite. This gradation is caused by the gradual addition of coarse clast material to the bedded mudstones. The coarse clast material is interpreted to be ice-rafted debris (Ovenshine 1970) indicating an ice advance into the basin. The process is transitional, with a gradual increase in the amount of clast material. The clast material is restricted to the silty layers, and is not common in the darker mud layers. This is probably indicative of ice-berg activity and associated release of entrained debris during the warmer summer period. This is also the period of greater clastic input to the basin resulting in association of the clast debris with the coarser silty layer. The clasts are commonly of a composition similar to the diamictite matrix, a feature noted by Ovenshine (1970) and repeated in numerous ancient glacial sequences.

The abundance of soft-sediment deformation within certain units of Facies Fl is ascribed to slumping and water escape. This reflects the unstable nature of the environment. Additionally, grounding of icebergs is a probable cause for some of the deformed sequences.

7.4 SANDSTONE FACIES ASSOCIATIONS

7.4.1 General

The Hoya Formation contains a complex suite of sandstone facies, with varying grain size, bed thickness, internal sedimentary structures and relationship to adjacent units. In total ten facies associations have been recognised. The facies are interpreted to be deposited in environments transitional between two end-members, fluvial and basinal. Thick sandstone sequences encountered in Drosera 1 and Kunzea 1 are interpreted to be fluvial in origin, deposited within a broad glacio-fluvial outwash plain/ valley fill. Thinner and more restricted fluvial sequences are also found in wells Calytrix 1 and Hoya 1, among others.

However, the bulk of the sandstones encountered in the Hoya Formation on the Barbwire Terrace are interpreted to be the product of a variety of mass flows into a subaqueous/basinal environment. The term 'basinal' is used as a general term to include both shallow and relatively deep marine and lacustrine conditions. The Sandstone Facies Associations are subdivided numerically; Facies 1-3 interpreted to be of fluvial origin, and 4-7 deposited under basinal conditions.

7.4.2 Sandstone Facies 1

In Drosera 1 the base of Facies 1 rests with a sharp erosional contact at 440.56m upon grey-green Devonian siltstones (Figure 58). The basal section comprises two 25cm thick clast-supported, massive-bedded conglomerates, which have sharp erosive bases. The conglomerates contain lithic clasts up to 5cm in diameter in a medium to coarse-grained sandstone matrix. The clasts are rounded to sub-rounded and composed of a variety of lithic material, predominantly of granitoid, gneissic and metasedimentary composition with rare dolomitic limestone and siltstone clasts (Plate 14A).

The basal conglomerates are overlain by a series of medium to coarse-grained sandstones and thin interbedded conglomerates. The sandstones are dominantly flat-bedded or rarely planar cross-bedded (Plate 14B). Many of the sandstones are pebbly, and comprise medium to coarse-grained sandstone with scattered lithic and mudstone clasts, up to 3cm in diameter. Individual units range in thickness fromn 10cm to 1m, and occasionally upward fine, from very coarse to medium-grained sandstone (Figure 59).

The sandstones are interbedded with conglomerates, predominantly matrix-supported but also clast-supported, similar to the basal conglomeratic units. A 61cm thick unit from 435.24m to 434.63m comprises flat-bedded medium-grained sandstone, with rare coarse to very-coarse lithic and mudstone clasts and occasional irregular thin silty drapes. It is overlain by two 20cm thick upward fining very-coarse to medium-grained sandstone units, with sharp erosive bases, followed by a 75 cm thick conglomeratic unit, which is dominantly massive and rapidly fines upward at the top to a very coarse-grained sandstone. The unit contains mudstone clasts that have small lithic clasts embedded into their margins indicating that the mudstone clasts were relatively soft during transport and deposition.

Above 434.20m a series of thin units, approximately 25cm thick, with abundant lithic and mudstone clasts up to 4cm in diameter at the base, fine upward to a medium-grained sandstone. Invariably the units have sharp, possibly erosive bases and are erosively overlain by the next upward-fining unit. Towards the top of the facies a series of thicker upward-fining units consist dominantly of massive clast-supported conglomerate at the base rapidly fining to very-coarse to medium-grained pebbly sandstones, which occasionally display planar cross-bedding, flat bedding and rare low-angle bedding in the upper medium-grained section. The units range in thickness between 15cm and 1m and have sharp erosive bases. Facies 1 is abruptly overlain at 470.86m by Facies 2.

The basal section of Kunzea 1 comprises sandstones and conglomerates of Facies 1. The facies rests with a sharp erosive contact upon red-brown and green-grey siltstones of the Carribuddy Formation. Unfortunately the section has abundant core loss which hinders the description and interpretation. The basal 2.50m comprises clast-supported petromict conglomerates with thin interbedded medium to coarse-grained sandstones. Although the basal conglomerate contains a very large 35cm clast of the underlying siltstone, it is dominantly composed of various lithic clasts of granitic, gneissic and metasedimentary composition with less common dolomitic limestone clasts. The conglomerates are mainly massive with occasional hints of flat bedding indicated by the horizontal alignment of clasts. A number of the conglomeratic units upward fine from a clast supported conglomerate to medium to coarse-grained pebbly sandstone.

Above 259m the section consists of isolated cores, the depth of which are ill-defined due to excessive core loss. A 5m section of core, from approximately 253 - 248m comprises a thick upward fining unit from a basal matrix-supported conglomerate to medium and fine-grained sandstone, capped by a silty sandstone. This is overlain by two upward-fining medium to fine-grained sandstone, which are thinly flat-bedded. The rest of the section comprises both matrix and clast-supported conglomerates, consisting of lithic clasts as below and occasional small mudstone intraclasts. Interbedded sandstones are medium to coarse-grained and dominantly massive or thinly flat-bedded, which are occasionally planar cross-bedded or indeterminately cross-bedded.

A core at approximately 213m contains a thin 15cm mudstone unit (base not seen), overlain by a massive upward-fining medium to fine-grained sandstone. The mudstone can be correlated with a high gamma reading between 212.75m and 213.50m. Similar gamma-ray character is present both above and below this point, indicating the possible presence of mudrock units, not recorded due to core loss. Overall the facies has a very irregular gamma-ray character, with thick blocky units separating intervals with an irregular and commonly upward increasing pattern. At 208m the character of the gamma-ray log becomes more uniform, indicative of a more massive lithological unit, and this is taken as the top of Facies 1. The gamma-ray log for the equivalent section in Drosera 1 is less irregular but shows a similar abrupt change to a massive characterless gamma-log at the transition to Facies 2.

Interpretation

Analysis of core, with its limited areal extent and subsequent lack of lateral control, does not facilitate the identification of large three dimensional structures, such as barforms or channels. However the depositional environment can be deduced from the vertical association of facies and the internal structures, as proposed by Rust 1975, Hein and Walker 1977, and Miall 1977.

The massive or crudely flat-bedded clast-supported conglomerates and massive, flat-bedded or planar cross-bedded sandstones indicate bedload deposition by unidirectional water currents. The conglomerates are the product of high-energy flows which facilitated the transport and deposition of the coarse clast component, followed by infiltration of the sand matrix during the subsequent lower flow stage. Unfortunately identification of cross-bedding or preferred lineation within the coarse conglomerates is virtually impossible in the narrow diameter cores.

The dominance of massive or weakly flat-bedded conglomerates suggest the gravels were deposited from high velocity flows as planar sheets in the form of low-relief longitudinal bars as part of a braided river drainage system (Smith 1970, Hein and Walker 1977, Steel and Thompson 1983, Rust 1977, 1984). The predominance of upper-flow regime conditions indicates deposition from frequent flood events, with high rates of aggradation. Common internal grading of the conglomerates and upward reduction in framework constituents is attributed to subsequent waning-flow velocities (Rust 1984, Thomas et al. 1985).

Interbedded flat-bedded sandstones, often with erosive basal contacts, are interpreted to be the product of upper-flow regime plane-bed deposition (Harms and Fahnestock 1965, Blatt et al. 1980, Harms et al. 1982, Figure 60). The presence or absence of primary current lineation could not be ascertained due to the lack of exposed bedding surfaces from the core. Formation of the lamination during high-flow velocity conditions is further confirmed by the presence of floating clasts in the interbedded flat bedded sandstones. Planar cross-bedded sandstones are less common in the section, although this could reflect the inherent problems of identification in core. Where identified the structures are interpreted to be the product of straight crested dunes, associated with the migration of transverse bars within the channel system (Rust 1977).

The association of planar cross-bedded and flat-bedded sandstones overlying massive conglomerates suggests sandstone deposition at the margins of longitudinal bars or bar-top aggradation during falling stage low-flow conditions, or deposition at the margins of the longitudinal bars as sand wedges (Rust 1984, Boothroyd and Ashley 1975). Overall the rapid vertical changes in grain size are consistent with deposition within a braided river system which has rapid discharge fluctuations (Rust 1972, Boothroyd and Ashley 1975, Thomas et al. 1985), a situation typical of glacial environments with periods of flood following ice melt.

Mudrocks are absent from the section in Drosera 1, although the sandstones and conglomerates contain abundant mudstone clasts, interpreted to be rip-up intraclasts, attesting to deposition of mudrocks in the area. Only partial lithification of the mudrocks prior to erosion and transport is indicated by the common inclusion of lithic clasts and grains along the margins of the intraclasts. Mudrocks recorded from Kunzea 1, although rarely preserved in the core, comprise massive or flat-laminated medium-grey mudstone and siltstone. The muds are interpreted to be suspension deposits from slow moving or standing water during waning stage conditions. This is supported by their position at the top of crude upward-fining sequences. The presence of the mudrock intraclasts and rare interbeds indicates fluctuations between high and low-stage deposition in the channel system, with deposition of muds in areas inactive during low flow periods . Subsequent channel migration during high-stage events and bank undercutting and erosion are the most likely mechanism for production of the intraclasts by reworking the mudrock component (Coleman 1969, Cant and Walker 1978). The overall lack of mudrocks in the sequence is attributed to the low preservation potential of fine-grained sediments under such high energy conditions, a feature common to gravel and sandy bedload systems (Rust 1984, Thomas et al. 1985)(Figure 61).

There is a notable lack of carbonaceous matter within the facies, indicative of a lack of vegetation within the immediate environment, and probably related to the harsh climatic conditions prevailing during this period.

The distribution of Facies 1 provides valuable additional information as to the mode of deposition. Facies 1 rests with a sharp erosive contact upon Silurian siltstones of the Carribuddy Formation. The marked unconformity is clearly erosive, and from seismic data it can be demonstrated that the conglomerate / sandstone sequence which has Facies 1 as its basal unit is restricted to linear mound-like features. The mounding is interpreted to be a combined effect of post-depositional compaction and related salt withdrawal from the underlying Carribuddy evaporitic sequence (see Chapter 5 for a full description). During deposition the facies was restricted to a series of broad linear depression, up to 2km wide and of illdefined length in excess of 10km. These valley-like features appear to be instigated by rapid erosion into the evaporitic Carribuddy Formation, enhanced by resultant salt dissolution.

The sequence onlaps the Barbwire Terrace and channel trend is to the west or southwest, towards the Kidson Sub-basin. Without palaeocurrent indicators from the core or clastic source information it is assumed from seismic evidence that the clastic material was sourced from the Barbwire Terrace, with flow towards the southwest. The glacially eroded surface on the Terrace which forms the base Grant unconformity, and the presence of an immediately overlying laterally extensive diamictite, interpreted as a lodgement till, indicates that a grounded ice sheet was located on the Terrace during this time.

The clast component in the conglomerates is predominantly of granitic and metamorphic composition, interpreted to be Precambrian basement material. However, the Barbwire Terrace has a Permian subcrop of Devonian mudstones and siltstones, and therefore the majority of clasts are not locally derived and must have been sourced from Precambrian basement areas on the margins of the Canning Basin, implying large transport distances. Transport of the clasts directly to the area by fluvial processes is unlikely due to structural and topographic constraints, indicating some element of glacial transport. A possible scenario invokes erosion and incorporation on or into the ice sheet in the basement areas, followed by transport onto the Barbwire Terrace, subsequent release during ice melt and deposition within a braided river system. The clasts could also be derived from diamictites originally deposited in the immediate vicinity and reworked by fluvial processes subsequent to ice sheet retreat.

7.4.3 Sandstone Facies 2

Description

Sandstone Facies 2 comprises a stacked series of flat and cross-bedded medium to coarse-grained sandstones, with occasional very-coarse grained and fine-grained interbeds (Figure 59). The facies has abrupt upper and lower boundaries and attains a thickness of 106m in Drosera 1 and 32m in Kunzea 1. Mudrocks are virtually absent from this sequence, represented only as a rare top to a fining-upward unit in Drosera 1. Mudstone intraclasts are also rare. Conglomerates, consisting of mainly lithic clasts, occasionally occur at the base of some sandstone units, resting on scoured bases. Vertical facies transitions show grading within sandstone units, from medium and coarse-grained sandstone to medium-grained sandstone, varying in thickness from 25cm to over 2m.

The base of Facies 2 in Drosera 1 is taken at 417.50m, which marks an abrupt change in the gamma-ray character from an irregular to a low-count relatively smooth massive unit. In core the contact is seen as a rapid transition from a 12m thick series of upward-fining conglomerates and medium-grained sandstones of Facies 1, to two 1m thick massive to flat-bedded medium-grained sandstones. These are followed by a 70cm upward fining very-coarse to medium-grained sandstone and two thin conglomerate units, the upper one reverse graded, overlain by a massive to planar cross-bedded medium-grained sandstone of Facies 2.

The bulk of Facies 2 comprises light brown medium-grained sandstone, dominantly massive to flat bedded and occasionally planar or trough cross-bedded. It is characterised by an overall grain size consistency and lack of interbedded mudrocks. Bedding varies from laminated, thinly or very thinly flat-bedded units between .25cm to 1cm, to more common flat bedding between 10 and 30 cm thick.

Individual sandstone units range from 25cm to over 2.5m thick, although many could represent amalgamated sandstones, their differentiation proving difficult because of the general grain size consistency and lack of obvious scoured bases or lag deposits. Nevertheless, the base of some units is marked by an erosive surface overlain by a thin conglomeratic lag, between 5 and 10cm thick, which then rapidly grade to medium or medium to coarse-grained sandstone. A number of sandstones contain scattered lithic pebble clasts, between 0.5 and 1cm in diameter. Low-angle bedding surfaces were occasionally recognised, primarily by preferential fracture of the core (Plate 12C). The top of Facies 2 in Drosera is a sharp erosive contact with a thick matrix-supported conglomerate of sandstone Facies 7, overlain by a sandy diamictite.

Very little core was recovered from this section in Kunzea 1. The limited small core fragments and dissaggregated sands available comprise light-brown medium to coarse-grained sandstone and less common pebble grade material. The lithic pebbles, between 2 - 4cm in diameter mainly comprise granitic, gneissic and various metamorphic clasts. The sandstone occasionally contains scattered small lithic clasts. The sandstones display planar cross-bedding and flat-bedding as well as massive bedded units. Much of the sandstone from the core had disintegrated, represented only by unconsolidated loose sand within the core trays. No sedimentary structures could be identified.

The boundary between facies 1 and facies 2 is less distinct in Kunzea 1 and the lack of core over most of the section prevents a detailed description. The core available can be used however to control the interpretation of the wireline logs to provide a limited description of the facies.

Above 207.50 the gamma-ray log becomes more massive, with a consistently low reading, comparable to the equivalent section in Drosera 1 and this is tentatively taken as the base of Facies 2. Immediately beneath this contact the gamma-ray indicates a possible mudrock unit, either mudstone or silty mudstone, similar to that tagged by a core at 212.75m.

Facies 2 comprises a lower 17.50m thick unit and an upper 8m thick unit, both of which have a blocky low gamma-ray character, interpreted to represent stacked medium to coarse-grained sandstones and rare conglomerates. The units are separated by a 1.50m thick unit with a higher gamma-reading, possibly a finer grained or argillaceous unit (not cored). The upper 5.75m of Facies 2 exhibits a more spiky character, with increasing and decreasing gamma readings, thought to represent graded, upward fining and upward-coarsening argillaceous or finer-grained sandstones. The top to facies 2 has been successfully cored, and comprises a sharp contact with medium grey-silty mudstones of Facies Fm, also cored.

Interpretation

The dominance of sandstone, only minor conglomeratic horizons, and a virtual absence of mudrocks, suggests deposition within an system that transported sand as the normal bedload. The stacked and amalgamated character of the sandstones, dominated by sedimentary structures such as flat-bedding and planar cross-bedding produced under high-energy conditions, indicate repeated flood events, with subsequent removal of any fine- grained sediments. Without lateral exposure it is difficult to assess whether deposition occurred within channels or as broad sheetflood events, although the presence of cross-bedding indicates some element of channelised flow.

Flat-bedding is interpreted to indicate a high-energy environment, produced under upper-flow regime plane-bed conditions (Harms and Fahnestock 1965, Rust 1984). The presence of poorly-sorted sandstones with occasional pebble clasts would support this inference, indicating rapid deposition. The thickness of the individual units and their coarse grain size precludes deposition under low-flow regime or by suspension settling. Occasional very thinly bedded and laminated sandstones could be the low-flow regime equivalent of ripples deposited under waning-flow, but these sandstones are not commonly preserved.

The presence of planar cross-bedding, formed by the migration of straight crested dunes, indicates unidirectional flow under moderate to high-energy conditions. It is interpreted to represent the migration of transverse bars within the shallow channels of a braided river system (Figure 61). Trough cross-bedding is uncommon, although this could be due to the difficulty of its recognition in core, but where present the structure indicates the migration of sinuous-crested dunes within channels, widely recorded from modern and ancient braided river systems (McKee et al. 1967)

Deposition during floods is indicated by the preponderance of upper-flow regime bedforms, and the lack of interbedded mudrocks. Mudrocks are susceptible to erosion either by channel migration or sheetfloods. Braided river systems generally display limited topographic variations, which results in repeated overbank flooding during peak discharge periods, removing any fine grained sediments and thus preventing the accumulation of mudrock sequences (Williams 1971, Picard and High 1972, Frostick and Reid 1977)). The absence of mudclasts within the facies implies that mudrocks were not deposited in the immediate vicinity.

Conglomerates, resting upon an erosive surface, commonly form the base to crude upward fining units. These are interpreted to be channel lags and the whole unit may be a deposit of a single flood event.

Facies 2 is similar to Facies 1, comprising deposition in a high-energy environment, the main difference being the nature of the bedload. The change from the coarse gravelly bedload of Facies 1 to the dominantly sandy bedload of Facies 2 could be the result of; a change in the clastic source; increasing distance from the source, the sandy facies being a relatively more distal or; a climatic control related to ice advance and reduction in melt-water supply.

The overall depositional environment envisaged for Facies 1 and 2 is that of a braided fluvial outwash, sourced by an ice sheet located on the Barbwire Terrace. From the seismic evidence (reviewed in Chapter 5) it would appear that a number of braided river systems of this type existed, restricted to topographic lows, which were produced initially by rapid erosion into the underlying Carribuddy evaporitic sediments, and possibly enhanced by continued subsidence due to salt leaching.

7.4.4 Sandstone Facies 3

Description

Facies 3 comprises a series of stacked sandstones, similar in character to Facies 2, but being dominantly medium to fine-grained, and containing a higher proportion of sedimentary structures (Figure 59). The facies is developed in Drosera 1 between 243.68 and 191.40m. It has an abrupt basal contact with a thick heterolithic sand/silt/mud sequence which contains interbedded diamictites of possible glacial origin.

The sandstones, predominantly light brown in colour, form crude upward-fining units between 20cm and 3m thick, although larger units could in fact be amalgamated sandstones whose individual boundaries are not apparent. They are commonly massive in appearance with no discernible bedding, but can also display both planar and trough cross-bedding, as well as flat-bedded and irregular wispy or wavy-bedded structures. Soft-sediment deformation is common, picked out as vague contorted structures within the otherwise massive sandstone.

Thick sandstones units, commonly massive at the base with a sharp lower contact, upward-fine from medium to fine-grained sandstone. The upper part of the sandstone exhibits thin silty laminations, often picking out vague wavy or rippled bedding, cut by the sharp base of the next unit.

Planar cross-bedding and trough cross-bedding become more common above 230m, although recognition is often tentative, due to the overall grain size consistency of the sandstones and the friable nature of much of the core.

Overall the facies is more thinly bedded than Facies 2, with a greater preponderance of graded beds and cross-bedding. Reactivation surfaces have been tentatively noted, displayed as low-angle erosive surfaces separating sandstone units. Flat bedding is less common than in Facies 2, and usually identified near the top of sandstone units, above a massive sandstone.

Apart from thin silty or muddy laminations towards the top of many sandstone units, discrete mudrock sequences are absent. The basal sandstones of Facies 3 contain small medium-grey mudstone intraclasts, and above 210m rare small dark-grey mudstone clasts were also noted, otherwise, mudstone clasts were not recorded. Rare fine carbonaceous fragments were also noted above 210m. The facies is overlain by a series of conglomerates and sandstones of Facies 1.

Interpretation

Facies 3 shows many similarities to Facies 2, comprising almost exclusively stacked sandstones exhibiting both planar and trough cross-bedding, as well as massive and flat-bedded units This suggests a similar environment of deposition by unidirectional currents of moderate to high energy, indicative of a sandy bedload dominated braided river system. Stacked fining-upward sandstone units indicate multiple flood events, with deposition of each graded sandstone from a single flood; producing a massive sandstone followed by cross-bedded and flat-bedded sandstone, capped by sandstone with laminated silts, often rippled, produced by subsequent waning-flow deposition. The lack of mudrocks also suggests a high-energy depositional environment, in which mudrocks were either not deposited or not preserved due to continual erosion. The lack of common mudstone intraclasts would support non-deposition within the immediate area.

High stage sheetflood or stream flood conditions resulted in massive or flat-bedded sandstone deposition, with planar and trough cross-bedding produced following flood peak recession under low-flow conditions, by the migration of straight or sinuous crested dunes within the shallow channel network of the braided river system. Finally rippled sandstone represents waning-flow deposition with silts eventually settling out by suspension from the slow moving or standing water to form drapes over the later bedforms.

The predominance of upper-flow regime bedforms, multiple scoured surfaces and amalgamated sandstones indicates that subsequent flood events commonly eroded the upper sections of these upward-fining sequences, to give the stacked sequence of massive or cross-bedded sandstones.

SANDSTONE FACIES 4,5,6, and 7

Sandstones of Facies 4,5,6 and 7 are commonly associated together, although not exclusively so. Interpretation of the depositional environment for each facies is dependant both on the internal features of the individual facies, but also the context of its relationship to adjacent facies.

7.4.5 Sandstone Facies 4

Description

A large proportion of the sandstones observed in the cores of the Hoya Formation display either no internal sedimentary structures, or only rare vague irregular wisps, streaks and indistinct colour variations. These sandstones are assigned to Facies 4. The sandstones are fine to medium grained, moderately sorted and commonly argillaceous. Small mudstone clasts up to 0.5cm are scattered throughout the sandstone, with no apparent preferred orientation (Figure 62).

The sandstones vary in thickness from tens of centimetres to over 12m (Drosera 1, 284.50-270.50cm), although the thicker beds may in fact be amalgamated units. Basal and upper contacts are characteristically sharp and occasionally loaded. Facies 4 sandstones are often associated and interbedded with sandstones that display internal sedimentary structures, assigned to Facies 5 and 6. These are interpreted to be the product of subaqueous mass flows. Thin units of massive sandstones are often interbedded with graded sandstones of Facies 5 and 6. Facies 4 is restricted to the development of thick (greater than 5m) developments of massive sandstones.

In Ficus 1 Facies 4 sandstones recorded from 375m to 424m are interbedded with massive sandy diamictite (DSm), graded sandstones of Facies 5 and 6 (S5,S6), and thin laminated mudstones (FL). The basal contact to the massive sandstone is loaded, and displays vague horizontal lamination in the lower 60cm before becoming dominantly structureless. Rare deformation structures are recorded from within the sandstone package, and from the gamma ray response it seems probable that the sandstones are in reality amalgamated units. The consistency of grain size and composition makes differentiation of individual beds largely impossible.

Interpretation

The origin of massive sandstones in the core is problematical and a number of interpretations are possible. The absence of lamination may be related to; the original mode of deposition; subsequent post-depositional soft-sediment deformation; or possible lack of recognition of structures due to the limited areal extent of the core or subsequent damage during the coring process (the softer sandstones are especially susceptible) must be emphasised. Although the latter is a strong possibility, in all cases the sandstones were thoroughly examined. Commonly they have a distinctive massive appearance, but vague contorted bedding, wisps, scattered mudstone clasts etc. are recognisable. This suggests that the 'massive' predominantly structureless nature is a primary or post-depositional feature and not a result of poor core preservation.

The lack of distinct bedding, either horizontal, cross-bedding or small scale rippling, suggests the sandstones were not emplaced by bed load mechanisms. The massive nature of the sands implies rapid deposition from a current with a high sediment concentration (Rust and Romanelli 1975). The deceleration of a heavily sediment-laden current results in rapid deposition without any significant bedload movement and is termed a sediment gravity flow.

The support mechanism for sand grains in sediment gravity flows involve either dispersive pressure, created by grain to grain collision, the 'grain flow' sensu stricto (Lowe 1976, Middleton and Hampton 1976), fluid turbulence, the turbidity flow (Hiscott and Middleton 1979) fluidisation, the fluidised flow (Middleton and Hampton 1976) or buoyant lift provided by a fine grained matrix, the density-modified grain flow (Lowe 1981)(Figure 63). A combination of a number of the above mechanisms is likely to have produced the thick massive sands observed in the core. The recognition of indistinct bedding may originate from the stacking of successive flows, of consistent grain size and composition. Randomly scattered mudstone clasts, commonly small and angular (less than 0.5cm), also support rapid 'freezing' of the sandstones.

Many of the 'massive' sandstones display vague contorted bedding, wisps of slightly cleaner sandstone and indistinct colour variations that suggest varying degrees of post-depositional soft sediment deformation. Liquefaction and dewatering are common features of mass flow deposits, resulting from rapid loading and common overpressuring of the sediments, especially where the sands have a high fine-grained matrix content.

The glacial environment is also characterised by common soft-sediment deformation due both to the high sedimentation rates and periodic loading by both the ice sheet or grounding of icebergs. The sandstones could also be the product of localised slumps as a result of rapid deposition and oversteepening of the sediment pile adjacent to the source of clastic input.

The context of facies 4 in relation to adjacent units is crucial in determining its mode of deposition. The association with sandy diamictites

(Ficus 1), graded sandstones of Facies 5 and 6, and thin laminated mudstones suggest deposition within a basinal setting, relatively proximal to the ice sheet. The massive nature indicates rapid deposition and/or post depositional deformation. The above criteria are compatible with deposition from a subaqueous fan system, fed by meltwater from the adjacent ice sheet. Sandstones of facies 5 and 6 represent progressively distal equivalents, or periods of reduced clastic input.

7.4.6 Sandstone Facies 5

Description

Facies 5 consists of a series of graded beds averaging 1.5m thick, with grain size decreasing from medium to fine-grained at the base to silt at the top (Figure 62). The base of the unit is commonly massive, although in common with Facies 4, the massive nature to the base of the sandstone units could be deceptive, and in reality the thick graded beds could represent a stacked or amalgamated series of thin graded units..

The base to each graded bed is commonly loaded or irregular, and possibly erosive. The sandstones are massive to flat-bedded at the base, and commonly display soft sediment deformation towards the top, with slump structures, water-escape features and microfaulting. Small, angular mudstone clasts are scattered throughout, occasionally displaying a vague preferred orientation and lineation sub-parallel to the bed. Concentrations of mudstone clasts at the base of sandstones is also apparent (Plate 15A). Stacked graded beds commonly show cyclicity with a progressive reduction in bed thickness, before being truncated by a succeeding thicker sandstone bed (Ficus 1 463.20 - 469m).

Interpretation

The graded sandstones are considered to be the product of mass flow processes within a lacustrine/shallow marine environment. Rapid deposition occurred from a turbulent suspension at the base of a turbidity current. The presence of stacked beds (both observed, and interpreted from the gamma ray response) which become finer grained and thinner upward suggest periodic deposition from pulsed flows which gradually decreased in velocity (Lowe 1982). The loaded basal contacts also support rapid deposition, as does the presence of mudstone rip-up clasts, commonly oriented sub-parallel to flow. The association of Facies 5 with Facies 4, 6 and 7 clearly demonstrates the transitional nature of the Facies.

7.4.7 Sandstone Facies 6

Description

Facies 6 comprises stacked series of thin (5cm to 1m) upward-fining sandstones, dominantly fine to very fine-grained, occasionally medium grained, which grade upwards to silt. The sandstones generally have a massive internal structure or display crude flat lamination, picked out by variations in the silt content. Interbedded thicker sandstones are thinly laminated, fine-grained, with thin siltstone/mudstone laminae. Ripple cross-laminationsn is rare, but is recorded from the top of some of the thicker sandstone beds. Soft-sediment deformation is abundant, both as general destratification, contorted/slumped beds and indistinct 'wispy' nature to the sands. Small scale micro-faulting is also common. Individual beds have sharp or loaded bases, occasionally displaying intensely flamed bases/tops. Sandstones of Facies 6 are commonly associated with sandstones of Facies 4, 5 and 7.

Interpretation

The association of thin graded sandstones, and laminated sandstones, siltstones and mudstones are characteristic of turbidity current deposits. Such sediment is deposited from suspension under conditions of decreasing velocity (Ashley et. al. 1985). The fine to medium grained, horizontally laminated sandstones are deposited during upper-flow regime conditions, with waning flow resulting in the development of ripples, culminating in settling of a fine silt/mud drape (Figure 64). The thin nature of the majority of the sandstone units suggests fairly weak or dilute currents, also supported by the general lack of ripple structures or complete Bouma sequence. Similar sequences have been recorded from the lower parts of glaciolacustrine delta-fronts (Gustavson et. al. 1975, Ashley et. al. 1982, Ashley 1975), and Pleistocene glacial lake sequences (Eyles and Eyles 1983) and are interpreted to be the product of turbid underflows associated with the influx of cold meltwater. Slumping of oversteeepened sediment piles adjacent to the site of clastic input, possibly triggered by ice sheet loading or iceberg grounding, may also be responsible for producing the stacked series of 'pulsed' flows. The thinly interlaminated mud/silt/sand sequences are interpreted to be the product of regular, thinner, more dilute currents.

7.4.8 Sandstone Facies 7

Description

Sandstone Facies 7 is recognised in Hoya 1, between 301.50m to 322m and comprises up to 9m thick upward-fining units, characterised by a basal intraclast conglomerates (Plate 15 B,C & D). The basal contacts to each bed are sharp and erosive. Intraclasts are dominantly medium to light grey mudstone, occasionally still displaying original fine lamination, muddy diamictites and rare sandstone laminae. The clasts are angular, normally elongate and display a marked bed parallel orientation. Rare petromict clasts are also present in the basal section, normally small (less than 0.5cm), angular to subrounded and of igneous or metamorphic composition. The matrix comprises a light brown to light grey, medium to fine-grained sandstone. The proportion of intraclasts rapidly reduces up section, grading into a medium to fine-grained sandstone, commonly capped by a thin silty sandstone, displaying fine lamination, minor soft-sediment deformation and micro-faulting. The sandstone is dominantly massive, but faint horizontal lamination is apparent in places.

Similar intraclast-rich graded sandstones are recorded from Facies 5, although these are much thinner, generally less than 1.5m, and are interbedded with fining-upward, clast-free sandstones.

Interpretation

The angular nature of the intraclast material suggests rapid erosion and deposition, without significant rounding during transport. The overall upward-fining of these large sandstone units suggest deposition from currents which gradually reduced in velocity (Figure 65, Walker 1984b). The basal erosive contacts are interpreted to indicate a channellised depositional setting, confining the flow and resulting in increased basal erosion . Initial erosion of the basin floor results in an abundance of mudstone rip-up clasts, which are subsequently deposited as the flow velocity reduces. The intraclast composition, that of basinal mudstones and diamictites supports a subaqueous depositional setting.

The association of Facies 7 with the previously described Facies 4,5 and 6, suggests that these facies are coeval, and represent lateral and distal/proximal facies equivalents.

Sandstone of Facies 4,5,6 an 7 show an intimate gradational association, and their context, with relation to adjacent units of mudrocks (FL and Fm) and various diamictites, suggest a depositional model with rapid lateral changes in depositional environment.

A model is proposed in which the sandstones were deposited by a subaqueous fan system, dominated by mass-flow processes, within an ice-proximal environment, fed by meltwater from the ice-sheet (Figure 66). Adjacent and contemporaneous deposition of muddy and sandy diamictites, and basinal mudstones is evidenced from the vertical facies transitions evident in the core. Lateral switching of the fan(s) would result in the interbedded nature of the sequence recorded from many wells.

7.5 SYNOPSIS

7.5.1 Depositional Model

Any broad model must incorporate the various depositional environments recognised from sedimentological analysis. The relationship of facies and their overall context is crucial to the development both of an integrated interpretation for each individual facies and a general depositional model for the formation. A summary depositional model outlined in Figure 67, incorporates the range of environments recorded in cored sections of the Hoya Formation and also attempts to reflect the interpreted lateral and vertical facies changes.

The Hoya Formation comprises a complex suite of diamictites, sandstones and mudrocks interpreted to be deposited under glacial conditions. Evidence for their glaciogenic nature comes from both the context of the formation and the style of sedimentation recorded from the cores. As noted previously, the basal contact of the Grant Group is a marked angular unconformity with folded and faulted older Palaeozoic rocks. This unconformity surface, at outcrop in the surrounding Precambrian shield areas, contains glacial striations indicative of grounded ice. Within the study area the presence of a basal diamictite, interpreted to be a lodgement till, together with the erosive and unconformable nature of the basal contact suggests that the Barbwire Terrace was also covered by a grounded ice sheet during the Late Carboniferous to Early Permian.

Above this basal unconformity the facies encountered in the Hoya Formation indicate fluctuations from ice proximal to ice distal conditions, and suggest deposition was predominantly into a subaqueous, variably marine and lacustrine setting. Proximal glacial conditions are evidenced by the abundance of diamictites, and the presence of mudrock facies containing ice rafted debris, whereas the distal conditions are characterised by laminated and massive mudrocks with no direct glacial input.

The depositional environment at the margins of a continental ice sheet is typically complex (Sugden and John 1985, Edwards 1978, Eyles and Eyles 1983, Brodsikowski and Van Loon 1987)(Figures 68, 69 & 70).

Extremely rapid changes in ice thickness, ice flow velocity, meltwater flow velocity and the resultant rate of clastic input are common, with highly variable energy conditions. Sedimentation rates on average are high, leading to unstable sediment profiles and common slope failure, and a resultant abundance of mass flow products. Soft sediment deformation is prevalent throughout the cored sections of the Grant Group, indicative of an unstable depositional environment (Plate 16).

In general, facies distribution in the cores are highly variable, both temporally and spatially, making interpretation of specific depositional environments extremely difficult.

Facies DSm, DSs and DMs are interpreted to be subglacial and supraglacial melt-out and flow tills. The extremely poorly-sorted nature of these sediments suggest deposition close to the ice sheet terminus as melt out tills, with localised remobilisation to produce flow-tills. These facies can occur in both subaerial and subaqueous conditions, and a variable environment with fluctuating sea/lake levels is anticipated. The common occurrence of soft sediment deformation due to slumping, water escape and liquefaction demonstrates the unstable environment of deposition, a characteristic feature of proximal glacial conditions (Dreimanis 1976, Evenson et al. 1977, Anderson et al. 1980, Boulton and Deynoux 1981, Powell 1983, Visser et al. 1984).

Interbedded sandstones are dominantly massive or graded, displaying internal stratification and a context which suggests deposition was dominated by mass flow processes. The thick stacked sandstone units interbedded with lacustrine/marine mudstones and diamictites are interpreted to be subaqueous fan deposits, sourced from a floating ice sheet (Figure 66 & 71a & b). Similar sequences have been recorded from the Quaternary of Canada (Rust and Romanelli 1975, Eyles and Miall 1984) and the Permo-Carboniferous Dwyka Formation of South Africa (Visser 1983, Visser et al. 1987).

The stacked sequence of fluvial sandstones encountered in Drosera 1 and Kunzea 1 are regarded as atypical for the Barbwire Terrace. Their distribution is restricted geographically (see Chapter 5 for a full discussion) and they are interpreted to be older than the main Grant Group deposited on the Barbwire Terrace. The relative abundance of stratification types suggests deposition within a sandy bedload dominant fluvial system (Boothroyd and Ashley 1985, Rust 1977). From seismic (see Chapter 5) the sandstones are observed to form linear features. These are interpreted to be valleys trending away from the Barbwire Terrace. The predominance of basement clasts, which are not locally derived, would support either reworking of earlier deposited diamictites, or that the fluvial system was sourced by meltwater issuing from an ice sheet located on the Barbwire Terrace, which was releasing entrained clasts transported from more distant basement areas. Plate 16 shows a similar modern day braided-outwash system sourced by a glacier by way of an approximate analogy.

Laminated and massive mudrocks are interpreted to be both marine and lacustrine in origin, reflecting possible changes in sea level and temporary restrictions (both ice damming and tectonic movements) creating freshwater conditions. The diluting effect of the release of vast amounts of freshwater into the marine environment can also create effective freshwater 'lacustrine' conditions near the terminus of an ice sheet (Powell 1983).

Laminated mudrocks, displaying rhythmically bedded units, suggest a relatively freshwater, lower energy environment with no wave action or current reworking. These units are interpreted to be the product of suspension and combined underflow, interflow and overflow processes (Ashley 1975, Ashley et al. 1985, Gustavson et al. 1975). More massive mudstones, commonly displaying small scale bioturbation are interpreted to be dominantly marine in origin, confirmed by micropalaeontological analysis undertaken by V. Palmieri (pers. comm.) No marine macro-fauna were identified from the mudrock sequences, possibly indicative of the extreme climatic conditions.

The mudrocks are often graded and interbedded with massive to stratified mud-rich diamictites, which are interpreted to be glaciomarine/glaciolacustrine 'rain out' deposits (Eyles and Eyles 1983, Eyles and Miall 1984, Eyles et al. 1985). The rain out deposits are interpreted to be the product of normal sedimentation of the fine-grained mudrock component from suspension, with the addition of coarse clasts as 'ice rafted debris'. The common gradation at the base and top of the DMm and DMs units supports a subaqueous depositional environment for the diamictites and also indicates that the ice sheet was in periodic contact with the water.

7.5.2 Evolution of the sedimentary package.

The Hoya Formation demonstrates an evolving depositional style common to the various scattered wells. Although detailed correlation between the widely spaced wells has proved impossible, the character of the formation and style of deposition is similar throughout the Barbwire Terrace, and an overall evolution from a subglacial to ice-proximal subaqueous and finally ice-distal subaqueous environments is discernible.

All the wells on the terrace encountered a sharp unconformable basal contact to the Grant, which is interpreted to be a glacially eroded surface. Above this a laterally extensive diamictite is interpreted to be a lodgement till indicating grounded ice. Overall the Hoya Formation displays a gradual reduction in glacially derived material and a change to dominantly marine conditions. This work proposes that the evolution of the sedimentary package reflects the gradual deglaciation of the Canning Basin, and a retreat of the ice sheet from the Barbwire Terrace. The deglaciation was not a single continuous process, but rather as recorded in the cores, a series of fluctuations or cycles of ice advance and retreat during a major deglaciation phase.

7.5.3 Ice advance and retreat cycles.

Ice advance and retreat cycles can be recognised from the sedimentary successions recorded in the Hoya Formation. In its simplest form the transition from glacially deposited diamictites, to mudrocks with ice rafted debris and eventually mudrocks or sandstones with no indication of direct glacial input, suggests a retreat of the ice sheet and a transition from an ice proximal to ice distal location. The reverse sequence, with gradual input of ice-rafted debris culminating in a diamictite is interpreted as an ice advance cycle. This pattern has been recognised within a number of other glaciogenic sequences, for example the Permo-Carboniferous Pagoda Formation of Antarctica (Miller 1989), the Permo-Carboniferous Dwyka Formation of South Africa (Theron and Blignault

1975, Visser and Kingsley 1982) and the Precambrian Smalfjord Formation of Northern Norway (Edwards 1975, 1984).

The most convincing retreat cycles culminate in the deposition of mudrocks with no ice rafted debris. The absence of ice-rafted debris suggests either the loss of contact between the ice sheet and the basin, thus preventing iceberg calving and iceberg transport, or a substantial retreat of the ice , resulting in considerable distance between the ice sheet and the deposition site, beyond the limit of maximum ice transport (Miller 1989). A further scenario could be envisaged, in which basin currents and dominant wind direction could prevent migration of the icebergs into an area. A major difficulty arises from the differentiation between true ice retreats/advances and lateral facies change.

The sequence recorded from the Barbwire Terrace contains numerous examples of transitions from diamictite to mudrock sequences, interpreted as an ice retreat sequence. However correlating the patterns between scattered wells proves difficult. The Eremophila wells, located only 5km apart, display the problem of correlation. Eremophila 1 contains a thinned section (21.30m) and is located on a structural high, interpreted to have been an area of positive relief during the deposition of the Grant Group. In this well, the Hoya Formation consists of a basal diamictite interpreted to be a lodgement till, deposited from the base of the retreating ice sheet. Above this the sequence contains some thin graded sandstones which rapidly give way to a thick sequence of laminated mudstones. The mudstones contain stratification which suggest deposition from combined flows within a lacustrine environment. No ice rafted debris is recorded from the sequence until the top 1m, where a rapid gradation occurs from laminated mudstones with rare diamictite clasts, to a massive mud-rich and eventually sandy diamictite. This upward transition into a diamictite, and the gradual increase in ice-rafted debris at the top of the unit is taken to indicate an ice advance into the basin. Thus, evidence from glacially derived material and the facies distribution, suggests an initial rapid ice retreat followed by a minor ice advance towards the top of the Hoya Formation; before final deglaciation of the basin.

Eremophila 2 contains a thicker Hoya Formation (51.16m). The basal diamictite association (BD) is overlain by a thick stacked series of sandy diamictites (DSm) and a thin mud-rich diamictite which grades rapidly into a massive mudstone. The significance of the stacked diamictites is unclear, and the possibility exists that the boundary between the Basal Diamictite and the overlying stacked sandy diamictite (and bed boundaries within the sandy diamictite) could be erosion surfaces representing multiple phases of ice advance and retreat. The alternative interpretation is that the whole sequence records a gradual ice retreat, with a gradation from subglacial lodgement, to subglacial/supra-glacial melt-out and flow tills and eventually a thin subaqueous 'rain-out' till. The mud-rich diamictite grades into a mudstone, which is only 6m thick, and is abruptly overlain by a massive sandy diamictite. The significance of the mudstone is difficult to establish. Either it represents a major period of ice sheet retreat and regional deposition of muds from suspension into a low-energy lacustrine (or possibly marine) environment, or alternatively the facies change represents a more localised lateral variation in depositional environment. Temporary fluctuations in ice movement direction or the isolation of the deposition site, due to ice damming or fluctuations in lake/sea level, could conceivably result in deposition of the thin mudstone unit.

The sandy diamictite in Eremophila 2 is overlain by laminated mudstones, comparable to the upper mudstones in Eremophila 1, although thinner. These rapidly grade into a muddy diamictite of similar composition to that identified in Eremophila 1. This suggests that the upper facies are laterally consistent, indicating a more regionally extensive depositional environment.

Eremophila 3 contains the thickest Hoya Formation at 102m, but has little in common with the section recorded in the other two wells. The basal diamictite is overlain by a massive sandstone and thin mudstone unit. This grades into a muddy diamictite which has an upper gradational contact back into a dominantly massive mudstone. The mudstone is 9m thick, contains scattered small clasts interpreted to be ice rafted debris, and has a gradational upper contact with a mud-rich diamictite. This sequence may record one or possibly two periods of ice advance and retreat under basinal condition, following the initial retreat of the grounded ice sheet. Again the significance of the first thin mudstone is hard to determine. Above this section, Eremophila 3 contains a complex suite of interbedded sandy diamictites and sandstone units, another thin laminated mudstone, and a 12m thick stacked sandstone package of possible fluvial origin. This upper section could represent a complex suite of sediments deposited close to the terminus of the ice sheet, with fluctuations in sediment supply and relatively small changes in ice sheet location, or a complex record of multiple phases of ice advance and retreat.

The top of the Hoya Formation in Eremophila 3 does correlate with the other Eremophila wells, containing a similar laminated mudstone, which grades into a thin mud-rich diamictite, overlain by the thick mudrock sequence of the Calytrix Formation. The upper diamictite has a similar character and stratigraphic location to the units described from Eremophila 1 and 2, which suggest that it is an equivalent and laterally extensive.

A similar facies to this is also recognised and can be correlated between most wells from the Barbwire Terrace. The lateral continuity of the unit and its gradational contacts with mudstones suggests that it was deposited in a basinal setting as a 'rain-out' deposit. It marks the top of the Hoya Formation and is succeeded by a thick sequence of mudstones interpreted to be deposited under marine conditions. The unit is generally thin, less than 2m thick, and it is postulated to results from a regional rise in sea level, which produced a short lived contact between the ice sheet and the basin, providing a brief period of abundant ice-rafted debris, prior to the final deglaciation, and loss of direct glacial input to the basin.

This example from the Eremophila area demonstrates the difficulty in distinguishing true ice advance/retreat cycles and is particularly problematic because of the lack of correlation between even closely spaced wells (Figure 72). This is interpreted to reflect the complex nature of the terminoglacial environment, with a wide its variety of facies types. Rapid lateral facies changes makes recognition of true ice retreat and advance cycles difficult, and many facies transitions can be explained by evoking lateral facies variations within a terminoglacial environment. However, the gradational contacts between muddy diamictites and thick basinal mudstones are interpreted to be fairly conclusive evidence for a glacial retreat recorded in a subaqueous basinal facies.

Although the Barbwire Terrace displays a complex pattern of facies relationships with no clear regional correlation, it is still possible to make an overall conclusion about the glacial history of the area as reflected in the cored sections of the Hoya Formation. Evidence suggests an initial ice advance into the basin, with a period of erosion, followed by an overall ice retreat punctuated by minor ice advance and retreat cycles.

CHAPTER 8

THE CALYTRIX FORMATION

8.1 INTRODUCTION

The Calytrix Formation comprises a mudrock dominant sequence that has a general upward-coarsening trend. The unit rests conformably upon the Hoya Formation, the boundary defined as a change from dominantly glaciogenic sedimentation to non-glacial marine facies. In most wells the boundary is located at the top of a thin diamictite unit, which is overlain by massive mudstone. The top of the formation is represented throughout the study area by the sharp erosional contact with the medium to fine-grained sandstones of the Clianthus Formation.

The Calytrix Formation has a characteristic seismic expression, with notable laterally continuous reflectors. The unit thins onto structural highs, in part related to syn-depositional fault movements. It also exhibits a distinctive wireline log character, with a high gamma-ray response reflecting the predominance of mudrock facies.

Four main facies associations have been recognised within the Calytrix Formation;

1. Sandstone Facies (S)
2. Calcareous Mudstone Facies (CM)
3. Mudrock Facies (M)
4. Heterolithic Facies (H)

These can be further subdivided into a number of subfacies.

The base of the Calytrix Formation contains a restricted development of marine sandstones, which yields a diverse fauna of bivalves, gastropods and bryozoa. These are best displayed in the well Calytrix 1 (Foster and Waterhouse 1988). The same well also cored an 11m thick calcareous mudstone, above the marine sandstones, which contains abundant delicately preserved bryozoa, either not recorded or represented only by a very thin fossiliferous mudstone at most other localities. Together these facies provide valuable faunal control for dating of the Grant Group on the Terrace (see Chapter 3).

The mudrock facies can be subdivided into a number of distinctive, although commonly gradational subfacies which show differences in internal structure and proportion of interbedded sandstones. These are indicative of varying controls on deposition within the basin. Limited microfaunal studies undertaken by V. Palmieri (pers. comm.) suggests the facies are predominantly marine to restricted marine, although with the exception of Calytrix 1, body-fossils are rare. In a number of wells, the mudrock association has an overall upward-coarsening trend and is gradational with the overlying heterolithic facies. The latter, at onset, contains mudrocks with abundant interbedded sandstones, which become more common upward such that the facies can then be described as sandstones with interbedded mudrocks.

The heterolithic facies is not represented throughout the study area, but where present contains sedimentary structures indicative of shallow marine shelf and possibly tidally influenced sedimentation.

8.2 SANDSTONE FACIES ASSOCIATION (S)

Description

Although the Calytrix Formation is characterised by a thick sequence of mudrocks, sandstone facies are developed locally. The well Calytrix 1 (from which the Formation takes its name) contains a stacked sequence of sandstones at the base of the Formation. The sandstone sequence is 18.20m thick and can be divided into five main facies based on lithology, grain size and sedimentary structures. The majority of these sandstones are absent from other wells in the area, which contain either a thin restricted sandstone sequence or non at all.

1. Sandstone Facies 1

Facies 1 is the basal sandstone facies of the Calytrix Formation and is present in most wells. In Calytrix 1 the sandstone facies rests with a sharp contact (223.40m) upon interbedded sandstones and mudrocks of the

Hoya Formation (see Calytrix 1 facies log - *Appendix 1*). The top of the facies is gradational with sandstones of facies 2 at 222.05m, giving a total thickness of 1.35m. Facies 1 comprises a poorly-sorted mud-rich fine to medium-grained sandstone, containing abundant lithic pebble clasts up to 1cm in diameter and common small (less than 0.5cm) mudstone clasts. Mudstone clasts commonly lie in a horizontal or sub-horizontal orientation, picking out an indistinct bedding lineation. Scattered carbonaceous debris is also recorded from certain bedding planes.

Poor sorting is probably in part due to bioturbation, which is suggested by an overall mottled appearance, although distinct burrows have not been observed. The unit is dominantly massive, with a homogenised and mixed character, with only rare hints of flat bedding.

The basal 32cm, and the upper 40cm of the Facies 1 in Calytrix 1 comprises a complex series of thinly bedded, fine to very fine-grained sandstones and silty mudstones. The sandstones are commonly finely laminated and display syn-sedimentary slumping and minor folding. Small tabular mudstone clasts are common along certain horizons, commonly parallel or sub parallel to the bedding. This bedded sequence is gradational with the massive poorly sorted muddy sandstone.

2. Sandstone Facies 2

Facies 2 comprises a thoroughly bioturbated fine to very fine-grained argillaceous sandstone (between 222.05m and 220.35m (1.70m) in Calytrix 1). Generally no distinct burrows are recognisable, rather an overall mottled or mixed character is apparent. However, along selected horizons numerous small oval burrow were recorded (approx. 0.5cm across). Small elongate clay clasts also occur at irregular intervals, and thin horizons rich in small fragments of black carbonaceous material. Above 220.56m the facies displays a crude stratification, mainly flat bedding, with alternate beds of fine-grained sandstones and bioturbated silty sandstone.

3. Sandstone Facies 3

This facies, developed between 219.60 and 218.40m (1.20m) in Calytrix 1, consists of thinly flat-bedded fine to medium-grained sandstones. The unit typically contains thin beds between 2 - 4cm thick, which are internally graded. The grading and variation in grain size is clearly demonstrated by the drilling mud invasion profile. The coarser, and hence more porous and permeable sand layers have a thick mud cake developed on their surface, whilst the finer sands have only a thin mudcake (Plate 18A). In general this sandstone (Facies 3) is significantly cleaner than the adjacent facies.

4. Sandstone Facies 4

Facies 4 forms the bulk of the sandstone sequence in Calytrix 1. It comprises a complex unit of thin bedded fine to very-coarse grained pebbly sandstones and muddy sandstones. The facies is initially present between 220.35m and 219.67m, where it is overlain with a sharp contact by facies 3. Facies 4 reappears above facies 3 again with a sharp contact at 218.40m and continues to its gradational upper contact with the calcareous mudrock facies at 205. 15m. The facies is dominantly flat bedded, with individual beds ranging in thickness from 2 - 10cm. Low-angle stratification is also present and possibly hummocky cross stratification is developed in places, although this bedding is difficult to accurately distinguish in core.

Occasional high-angle erosive surfaces are recorded. These commonly display sharp erosive contacts, which are overlain by medium to coarse-grained sandstone containing large mudstone clasts (2-4cm), lithic pebbles and abundant shelly debris. Individual beds are commonly graded, from coarse to medium-grained pebbly sandstone at the base up to fine to medium-grained muddy sandstone towards the top. The upper part of many beds are bioturbated, producing a resultant thoroughly mixed appearance to the sediment producing a poorly-sorted medium-grey argillaceous sandstone (Plate 18B). Although individual bed thicknesses are variable, the upward-fining nature is common and overall the facies displays a repetitive, almost rhythmic character. Fine carbonaceous material is present on certain bedding planes, as well as small clay clasts.

This facies is characterised by abundant shelly debris, including various small gastropods, bivalves and occasional bryozoa. The shelly material is commonly fragmented and concentrated in the coarser part of the graded beds. Details of the macrofaunal assemblage can be found in Foster and Waterhouse (1988).

The upper contact of Facies 4 displays a rapid transition to medium to grey calcareous mudstones (of the calcareous mudrock facies). The massive sandstone grades rapidly into mudstone with occasional thin sandstone lenses, which eventually over only a 50cm interval give way to a massive sand free mudstone.

The above descriptions are all taken from the well Calytrix 1, where the sandstone facies are best developed. The well Clianthus 1 displays only sandstones of Facies 2, which are overlain by a very thin calcareous mudstone. The adjacent well Hoya 1 contains sandstones ascribed to facies 2 between 214.96m and 207m and a sequence between 207m and 205.73m, which has no equivalent in Calytrix 1, described as Sandstone Facies 5 (below).

Of the more northerly wells, Melaleuca 1 is the only well to contain sandstones at the base of the Calytrix Formation. Sandstones of Facies 1 are recorded from between 263.22 and 261.66m, overlain by sandstones similar to Facies 4 from 261.66m to 249.09m, which are in turn overlain by a thin fossiliferous calcareous mudstone.

The remaining wells included in this study have not encountered the sandstone facies within the Calytrix Formation. Instead a rapid transition from a muddy or sandy diamictite to the mudstone facies of the Hoya Formation is noted.

5. Sandstone Facies 5

This facies comprises fine to medium-grained sandstone with common 1-2cm lithic pebbles. Virtually no shelly debris has been recorded. In Hoya 1 this facies is intensely bioturbated, and much of the original bedding is lost although some distinct high-angle irregular surfaces draped with clay are occasionally preserved. The sandstones of Facies 5 show a similar upper gradational contact to calcareous mudstone, although the calcareous mudstone in Hoya 1 is much thinner than in Calytrix 1 and contains only an impoverished fauna.

Interpretation

The Sandstone Facies Association (S) described above is noteworthy for its limited distribution and distinctive context, interbedded between sequences of interbedded mudrocks and sandstones of the Hoya Formation and overlain by a calcareous mudstone. The presence of a diverse macrofauna within sandstone Facies 4 indicates a marine environment of deposition. Overall the sequence displays a pronounced coarsening-upward profile, from its gradational basal contact with the bedded mudrocks of the Hoya Formation, through to bioturbated sandstone and mudstone, thin bedded sandstones and more complexly bedded and graded sandstones. This is clearly outlined by reference to the gamma-ray and sonic log character.

The sequence is interpreted as representing lateral progradation of a shoreline sequence, and shows certain similar features to sandstone units described from the Cretaceous Cardium Formation of Alberta (Walker 1983, Plint _et al_. 1986, Plint 1988, (Figure 73)). The gradational relationships between the four main facies described indicate a gradual shallowing, with coincident increase in the energy of deposition. However the sequence does not contain well developed upper shoreface or beach sandstones, or common high-angle cross stratification, which suggest that the complete progradation of the shoreface into the study area did not occur.

The abundance of mud in the lower part of the sequence suggest deposition in a relatively low-energy environment, below the fair-weather wave base (FWWB). This is further supported by the extensive bioturbation.

Facies 1, recorded in the well Calytrix 1, has a fairly sharp contact with the underlying bedded mudrock facies of the Hoya Formation, indicating an abrupt and erosive basal surface. The sandstones are argillaceous, with most primary structures lost due to bioturbation. Similarly the intensely bioturbated character of Facies 2 also suggests a relatively low-energy environment of deposition (Howard and Reineck 1979, Howard 1972). Any internal stratification of these muddy sandstone has been totally obliterated by bioturbation, although it can be inferred that the sequence may originally have contained thinly interbedded sandstones and mudstones. Comparison with the underlying bedded sandstones and mudstones of the Hoya Formation is important. In Hoya 1, Clianthus 1 and Calytrix 1 the underlying mudrock sequence is bioturbated, but contains discrete sandstone beds, which are not bioturbated and are interpreted to be rapidly emplaced as turbidites. The complete reworking of the sandstone of Facies 1 and 2 suggests a change to slow deposition, or increased bioturbation activity.

The preponderance of thin graded beds in Facies 4 suggests deposition was strongly episodic and dominated by storm processes on the shelf. The facies does not contain cross stratification, implying deposition was not by traction currents and occurred below wave base. The sandstones generally do not show any signs of modification or reworking by currents, which suggests rapid emplacent. The medium to coarse-grained pebbly sandstone at the base of each graded bed was most likely deposited during a high-energy storm, which swept the coarser debris out onto the shelf.

The gradation within beds from coarse up to muddy sandstones records the deposition of finer material from suspension, followed by intense bioturbation within the low-energy environment, prior to deposition of further coarse sandstone during the next storm event.

The importance of storm-generated turbidity currents has been discussed by Walker (1983), who concluded that turbidity currents were the primary mechanism for emplacement of sands and gravels into offshore environments. Similar sequences have been recorded from the Oxnard-Ventura area of California and Galveston Island offshore Texas (Howard and Reineck 1979).

Further evidence for high-energy flows comes from the presence of mudstone rip-up clasts along selected horizons. The marine fauna incorporated into the coarser sandstone fraction is interpreted as debris transported with the sand-grade material.

The sequence recorded in Calytrix 1 (Sandstone Facies 1-5) is interpreted to be the product of shoreface progradation, possibly related to an initial sea-level fall following a minor glacial advance. Initially bioturbated silty sandstones were deposited under low-energy marine conditions. The sequence coarsens upward with deposition of lower to upper shoreface parallel-laminated sandstones. Storm-surge deposition dominated, with rapid emplacement of fine to medium-grained sandstones during peak storm activity, followed by fine-grained sandstone and mudstone deposition during normal lower-energy conditions. Upper shoreface and beach facies are not recorded, and the rapid transition to mudstones deposited under low-energy marine conditions indicates a subsequent sea-level rise. This increase in water depth can be correlated throughout the study area and is considered to be related to the final deglaciation of the Canning Basin.

The absence of this thick sandstone sequence in the majority of adjacent wells suggest a discrete geometry for this sandstone body, controlled by basin topography.

8.2 CALCAREOUS MUDSTONE FACIES ASSOCIATION (CM)

Description

The Calcareous Mudstone Facies Association (CM) is best developed in Calytrix 1, where it is 11.38m thick. It is absent or only poorly developed in the remaining wells.

In Calytrix 1 the facies rests with a gradational contact upon sandstones of facies 4 in Calytrix 1. The transition is from medium to fine-grained argillaceous sandstones of Facies 4, which grade into thin lenticular bedded sandstones in a medium to dark-grey mudstone. The sandstone contain abundant shelly debris, and occasional pebbles up to 2cm in diameter. The sandstone lenses become less common until by 205.15m the sequence consists of massive medium-grey mudstone with only rare thin sandstone lenses.

The mudstone contains scattered delicately preserved bryozoa, lying parallel to bedding (Plate 18C). Other fauna include bivalves and small gastropods, although these are less common. Above 200.80m the mudstone contains thin horizons (3-4cm thick) which are light grey to white in colour and consist of concentrated shelly debris. These horizons have a relatively sharp base and top, and are followed by mudstone with scattered bryozoa and other shelly debris.

Above 196m the mudstone contains rare carbonaceous plant debris, up to 4cm in length. The upper section of the facies contains increasing amounts of sand, with often mixed and deformed bedding, possibly related to bioturbation although discrete burrows could not be identified. Bryozoa within this section are commonly brocken and fragmented, with a clear relationship between better preserved fauna and finer grained mud-rich beds.

Overlying the Calcareous Mudstone Association at 193.77 is a thin fractured sandy mudstone, followed by medium to light grey mudstone of the Mudrock Facies Association.

The calcareous mudstone facies is present as a very thin unit in most other wells in the study area, or not recorded at all. The well Hoya 1 contains a thin fossil rich mudstone between 205.73m and 205.58m which possibly extends up to 197.30m although this upper section contains only rare poorly preserved fauna. The basal 15cm is extremely rich in shelly debris and bryozoa and comprises a white to light-grey condensed sequence. The upper section is a medium to dark-grey mudstone with rare scattered shelly fragment. The mudstone is bioturbated throughout, commonly with a general mottled appearance with occasional lozenge shaped burrows up to 1cm in diameter. A similar sequence was recorded from Clianthus 1.

Of the more northerly wells, only Melaleuca 1 contains a thin fossiliferous silty mudstone between 249.09m and 248m (the top is not seen due to core loss). The medium grey silty-mudstone contains thin lenses of concentrated fossil debris, comprising bivalves, gastropods and bryozoa similar to those recorded from the well Calytrix 1. The facies was not recorded from any of the other wells in the study area.

Interpretation

The abundance of macrofauna indicates a marine environment of deposition. The fine grained nature of the sediment and associated preservation of extremely delicate bryozoa would suggest a dominantly low energy environment of deposition. Similarly a lack of sedimentary structures indicative of traction currents suggests that the mudstone was deposited from suspension, with only rare localised bottom currents introducing sandstone into the restricted environment.

Thin horizons comprising almost exclusively of shelly debris suggest intermittent high-energy conditions. The concentration of fossil debris within these horizons produced by winnowing of the mudstone during periodic storm events. The common fragmentation of the bryozoan and bivalve material in these fossil rich horizons further indicates brief periods of high energy conditions. The upper limit to the calcareous mudstone is fractured and has a weathered appearance, possibly indicating subaerial exposure prior to deposition of the thick mudrock facies.

8.3 MUDROCK FACIES ASSOCIATION (M)

Description

The Mudrock Facies Association (M) is the dominant facies of the Calytrix Formation, which imparts the formation's characteristic seismic and gamma-ray response. It comprises both massive and bedded units, with variable proportions of interbedded sandstones.

The facies is dominated by medium grey, massive, silty-mudstones. They commonly display bioturbation, both in the form of small lozenge shaped burrows, and more pervasive mottling of the sediment. The burrows are identified as dominantly Chondrites with subordinate Planolites and rare Zoophycus forms.

Rare marine macrofauna was also identified from this facies, most notably a well preserved bivalve (not specifically identified at present) at 303.10m in Ficus 1, indicating marine or restricted marine conditions of deposition. Samples from between 209-305.6m analysed for microfaunal content by V. Palmieri (WMC internal report, summarised in Appendix 3) contain immature brachiopods (Chonetes) and gastropods (Warthia and Paraplatyschisma) as well as a diverse assemblage of agglutinating foraminifera, both textularid and verneulinid forms.

The massive mudstone also contains fragments of organic matter. In Ficus 1 the mudstone facies contains large woody fragments , typically up to 1.5cm long, that are brown to brown-black in colour and lie scattered on bedding planes. Oxidation of this organic material has produced a brown mottling to the mudstone, with patches or 'haloes' surrounding larger fragments. Associated with the organic material are small pyritic aggregates, occasionally replacing the organic matter.

Where the facies appears more massive, a vague mottling suggests possible pervasive bioturbation, although the massive nature is primarily a feature of the consistency of the grain-size. The facies commonly rests upon a muddy diamictite, which is present in most wells in the study area and taken as the top of the Hoya Formation. The top of facies 1 is the transition to the bedded mudrock facies 2.

The massive mudstone is gradational with bedded facies, which display upward fining units from silt to mud. The beds vary from 2cm to 5cm in thickness, and are bioturbated by discrete small burrows (Plate 18D).

Interbedded with the mudstone facies are subordinate sandstones and silty sandstones. These are not recorded throughout the section, or in every well. They vary from small isolated sandstone wisps and starved ripples, to thin upward-fining sandstones, grading from fine to very fine-grained sandstone. The sandstones are mainly massive, with sharp bases and gradational tops fining back into the silty mudstone. Occasionally thicker sandstones display ripple cross-lamination and parallel lamination. Bioturbation is generally absent from the thicker sandstone interbeds, or affects only the upper few centimetres of the bed. Burrows are small and mostly suggest an origin by horizontal motion.

The gamma-ray log displays a moderately irregular character, indicating subtle changes in grain size and crude upward-fining and upward-coarsening units which are difficult to establish in the core due to the overall grain size consistency.

In a number of wells (Hoya 1, Eremophila 2, Eremophila 3) the mudstone facies has a gradational upper contact with the heterolithic facies, reflecting the increasing proportion of sands interbedded with the mudstone.

Interpretation

The mudrock facies is interpreted to be deposited within a low-energy basinal environment. The sequence is characterised by mud and silt deposited from suspension. The massive mudrock has no visible bedding, although the gamma-ray log over the interval suggest there are variations in composition. In part the massive nature could reflect intense bioturbation. It has a very uniform character, with few sandstone interbeds, suggesting a distal location away from any clastic source.

The basal contact of the mudstone facies is commonly abrupt or gradational with a thin muddy diamictite. However, the mudstone facies contains no coarse clasts (dropstones), which suggests that the basin did not have floating ice. This indicates a rapid retreat of the ice sheet so that it was no longer in contact with the basin, or so far removed that the study area was beyond the maximum distance for floating icebergs.

The bedded mudstones display graded bedding from silt up to mud, which indicates periodic variations in the clastic input to the basin, possibly seasonal. Thin fine to very-fine grained sandstone interbeds are interpreted to be the distal tails of turbidity flows (Walker 1984b). The thicker sandstones display ripple lamination and parallel lamination, characteristic of waning flow (Figure 64A & B). The sands have sharp bases and are not normally bioturbated in their lower section, again suggesting rapid emplacement from mass-flow processes. Bioturbation is present throughout this section, although never intense.

The transitional nature of the bedded and massive mudstones is interpreted to reflect periodic shallowing of the basin, and also variable clastic input. The bedded mudstones, containing a higher proportion of interbedded sandstones are interpreted to represent shallower, higher energy conditions. In a number of wells an overall regressive pattern is evident towards the top of the Calytrix Formation, culminating in gradation to the heterolithic facies.

8.5 HETEROLITHIC FACIES ASSOCIATION (H)

Description

The Heterolithic Facies Association comprises interbedded mudstones, siltstones and sandstones. It is not recorded from all the wells in the study area, but where present forms the upper section of the Calytrix Formation. It has a gradational lower contact with massive or bedded silty mudstones of the mudrock facies, and is overlain by the sandstone facies of the Clianthus Formation. The Heterolithic Facies has a complex bedded nature, with a wide variety of stratification types. Thin sandstone beds, displaying massive bedding, ripple lamination and parallel lamination, are interbedded with massive mudstones and laminated siltstone and mudstones. The whole section is bioturbated, often with an intensity that makes the recognition of primary bedding structures difficult. The trace fossil type is usually difficult to discern in the narrow diameter cores, but examples of Chondrites, Planolites and Zoophycus were noted.

The proportion of sandstone increases up section, although the thinly bedded nature prevails.

Interpretation

The Heterolithic Facies Association is interpreted to be a marine shelf sequence (Figure 76). The gradational lower contact with massive and bedded mudstones suggest that the heterolithic facies represent a regressive suite of sediments related to a gradual shallowing of the basin. The increase in sandstone content indicates an increased clastic input and relative proximity to the clastic source. The character of the facies, the presence of thinly bedded graded-sandstone and the abundance of bioturbation supports a shallow-marine shelf depositional environment (Tillman *et al*. 1985).

Shelf sequences are dominated by storm process, and the generation of mass-flows, which effect transport of the sands to the open shelf (Walker 1984). The preservation of the thin graded beds and the retention of their characteristic internal structures requires sedimentation below storm wave base. Abundant bioturbation also supports a low-energy shelf environment. The abrupt upper contact with the erosively based sandstones of the Clianthus Formation indicates a major regressive episode, with the advance of a fluvial system into the basin.

CHAPTER 9

THE CLIANTHUS FORMATION

9.1 INTRODUCTION

The Clianthus Formation is the uppermost formation of the Grant Group on the Barbwire Terrace. It is characterised by a basal sandstone facies, which is overlain by a heterolithic facies of mudstones, siltstones and sandstones.

The basal contact with the underlying Calytrix Formation is generally sharp and commonly erosive. It marks an abrupt change from dominantly fine grained mudrock deposition to coarse clastic deposition. The upper contact with the overlying Poole Sandstone is also sharp and erosive, and is recorded from field outcrops to be locally unconformable or disconformable (Crowe and Towner 1976b).

The Clianthus Formation is absent or only partially preserved in the northern part of the study area, and also along the Dummer Range Fault Zone, due to uplift and erosion. In addition, the extremely deep weathering profile in the Canning Basin, with extensive leaching and development of lateritic and silcrete profiles, makes recognition of the Clianthus Formation and also its differentiation from the overlying Poole Sandstone and Jurassic sandstones extremely difficult.

The Clianthus Formation is poorly imaged on seismic, primarily due to data acquisition and processing problems at such shallow depths (statics). Core coverage is also relatively sparse due to its shallow depth. Conventional drilling was normally carried out to a depth of 50m to 100m before coring commenced, and consequently a large part of the section can only be described from cuttings and wireline log response.

From the available data two main facies associations have been established (Figure 74);

1. Sandstone Facies
2. Heterolithic Facies

Both facies are recorded throughout the Barbwire Terrace.

9.2 SANDSTONE FACIES ASSOCIATION

Description

The sandstone facies comprises light brown, medium to fine-grained moderately well-sorted sandstones. The facies is characterised by stacked sandstone beds, which are massive, upward-fining and rarely upward-coarsening. Flat bedding is the most common stratification type recognised. Low-angle plane beds and cross bedding also occur. Cross bedding is of both planar and trough cross-bedded forms, although the difficulty of recognition in core relegated a large percentage as indeterminate. This problem is compounded in the case of the Clianthus Formation because the shallow depth of the cored section results in sands that are relatively soft and susceptible to core damage.

Disseminated carbonaceous material is abundant, commonly either as large coal clast lag-deposits, or laminations of fine carbonaceous 'hash' capping the upward-fining units.

The base of the sandstone facies is commonly erosive, marked by an intraclast conglomerate. The gamma-ray log character over the interval clearly illustrates this sharp basal contact. The remainder of the interval displays a fairly massive low gamma-ray reading. However, some variations are apparent, and both upward fining and upward-coarsening packages can be identified.

Cored sections vary in thickness from 45.30m thick in Hoya 1, through 35.90m thick in Fucus 1 and 32.20m thick in Calytrix 1 to 24.80m thick in Melaleuca 1. The cored sections from Ficus 1 and Melaleuca 1 are badly damaged and often unconsolidated, mainly due to the very soft nature of the sandstone. As a result, stratification is very poorly preserved, although over certain intervals flat bedded and cross-bedded units were observed. However, the grain size, texture and character of these sequences suggests a similar facies to the sandstones described from Calytrix 1, Clianthus 1 and Hoya 1.

In all the cored sections the facies has a conspicuous absence of mudrocks, comprising virtually exclusively stacked medium to fine-grained sandstones.

Interpretation

The facies is characterised by uniform medium to fine-grained sandstones with an absence of mudrocks, indicative of deposition within a system that transported sand as the normal bedload. The stacked nature of the sandstones, and predominance of flat bedding and cross bedding establishes that deposition occurred under high-energy conditions. The association of flat bedding, trough and planar cross-bedding within a relatively homogeneous sandstone sequence is characteristic of bedload dominant low-sinuosity channel systems. Experimental studies have shown that flat bedding in medium to fine-grained sands occurs under upper-flow regime conditions (Harms and Fahnestock 1965, Bluck 1974). Stratification is produced primarily by within-channel bar and dune migration. The homogeneous character of the sandstones is ascribed to bed accretion of low-amplitude medial bars leading to stacking of the sandstones units (Campbell 1976, Williams and Wild 1984). The sandstone facies is similar to facies S2 described from the Hoya Formation.

The erosive lower contact with the underlying Calytrix Formation mudstones and heterolithic units suggests a rapid influx of coarse clastic material into the basin. This is supported by the character of the sandstones, which commonly contain mudstone intraclasts, ripped up from the underlying Calytrix Formation. In addition, in Calytrix 1, Hoya 1 and Clianthus 1 the lower sandstones commonly contain abundant coaly/ carbonaceous debris both as larger clasts in basal lags or 'floating' in the sandstones. The sandstones often fine upward, and contain fine carbonaceous 'hash' deposited towards the top of the unit, indicating deposition from suspension during the waning stages of flow. This is interpreted as representing preserved bar-top, or channel-abandonment facies.

The abundance of carbonaceous material indicates that a significant proportion of plant material was transported with the sandstones. This reflects the gradual amelioration of climatic conditions following (and causative of) glacial retreat. Conditions were more favourable for the growth of vegetation, both as a result of gradual infilling of the basin and concurrent retreat of the ice sheet providing an increase in exposed land areas, and the associated 'warming' of the climate.

The Hoya Formation has no recorded plant debris, suggesting a much harsher environment that was not conducive to vegetation. This reflects both the dominant marine/lacustrine conditions interpreted from the facies, and the extreme climatic conditions associated with the maximum stage of a continental ice sheet. These two factors prevented the establishment of vegetated areas.

In summary, the sandstone facies of the Clianthus Formation is interpreted to have been deposited in the distal part of a high-energy, low-sinuosity, braided fluvial system. The predominantly fine-grained nature of the sandstones and lack of coarse-grained material or conglomeratic material supports a downstream marginal location, which is also indicated by the rapid upward transition to the shallow marine heterolithic facies described below.

9.3 HETEROLITHIC FACIES ASSOCIATION

Description

The heterolithic facies association is characterised by a complex suite of interbedded mudstones, siltstones and sandstones. The facies has a rapid, although gradational, basal contact with the underlying sandstone facies. Three main facies are recognised within the association:

1. Laminated mudstones, siltstones and sandstones
2. Thinly bedded sandstones and mudstones
3. Sandstones

1. Laminated mudstones, siltstones and sandstones.

This facies comprises dark-grey mudstones laminated with light-grey to brown siltstones and very fine-grained sandstones. The sandstones form graded laminae from a few millimetres to a few centimetres thick. In Calytrix 1, Hoya 1 and Clianthus 1 these interlaminated mudstones, siltstones and sandstones display both wave and current ripple cross-lamination. The ripples commonly have a symmetrical form, show undulatory bases and a crude bundled-upbuilding. Flaser and lenticular bedding are associated with the more argillaceous sections, and better developed in Melaleuca 1 and Halgania 1, where starved ripples are also common within this facies.

Bioturbation is present, generally in the form of small isolated burrows. Soft-sediment deformation is common, although restricted to certain discrete zones. Both syneresis cracks and water-escape pipes are recorded throughout this facies, commonly ptygmatically folded due to subsequent compaction. Zones of more intense deformation are ascribed to localised slumping of the section.

2. Thinly bedded sandstones and mudstones.

The laminated mudstones, siltstones and sandstones described above are commonly overlain by a sequence of thinly-laminated sandstones interbedded with mudstones or silty mudstones. The sandstones are fine to very fine-grained, although generally argillaceous, with silt or mud laminations. Abrupt, angular and erosive reactivation surfaces are evident, overlain by coarser-grained sediments.

Thicker sandstone units, in excess of 5cm, often exhibit preserved parallel lamination, and occasional wave and current-ripple lamination. Some sandstone units appear to be massive internally, ranging up to 10cm thick, and are separated by silt or.mudstone drapes. Other thicker units, up to 25cm, contain abundant ripple and climbing ripple cross-lamination, have abrupt bases and rapid gradational tops back into the silty mudstone.

Bioturbation is common throughout the sequence, but not normally present within the lower parts of the thicker sandstones. It does affect the upper section individual sandstone units and the overlying silty mudstones. The bioturbation varies in scale from small (less than 2mm) isolated burrows identified as '<u>Chondrites</u>' forms, to larger isolated burrows tentatively ascribed as <u>Zoophycus</u> and possibly <u>Planolites</u> forms. Conclusive identification of the trace fossil type is difficult in narrow diameter cores. This facies is considerably more heavily bioturbated than others of the heterolithic facies association and also commonly displays soft-sediment deformation structures in the form of localised slumping and water escape.

The facies is widespread and has been recognised in Calytrix 1, Hoya 1, Clianthus 1, Melaleuca 1, Ficus 1 and Halgania 1.

3. Sandstones

Interbedded with the above heterolithic sequences are thick bedded sandstone units. These comprise both clean, moderately well-sorted, fine to very fine-grained sandstones and more argillaceous, laminated, fine to very fine-grained sandstones.

The sandstones range in size from 50cm up to 5m thick. They display abundant flat lamination, ripple cross-lamination and occasional small scale cross bedding. Some examples of low-angle cross lamination is tentatively interpreted as hummocky cross-stratification, although identification of such structures in narrow diameter core is difficult. Both upward-coarsening and upward-fining examples are recorded from the section. Upward-fining sandstones, up to 50cm thick, have sharp bases and comprise parallel laminated to cross-laminated sandstone which rapidly upward fines at the top to a silty mudstone and eventually a mudstone. The upward-fining sandstones are commonly stacked. Finer-grained upward-fining sandstones display abundant climbing ripple or ripple-drift cross lamination at the base, again with a sharp basal contact, rapidly upward-fining to a silty mudstone.

The thicker sandstone packages, greater than 2.5m, are generally slightly coarser grained, from fine to rarely medium-grained, and characteristically upward coarsen to a sharp top capped by a laminated mudstone or a lenticular bedded heterolithic sequence of mudstones and siltstones. The top to the sands occasionally have laminations of fine carbonaceous material.

Bioturbation is recorded from the sandstones, although commonly not pervasive but restricted to certain intervals. The bioturbation type in the cleaner sandstones is distinct from that recorded from type 1 and 2 facies of the Heterolithic association. The thick cleaner sandstones contain an increased proportion of large vertical burrows, compared to more common small horizontal burrows within the more argillaceous units.

Micropalaeontological and palynological work on selected samples from Ficus 1 by V Palmieri (pers. comm.) identified abundant plant spores within the heterolithic section, and he attributed the facies to a restricted marine environment.

The top of the Clianthus Formation is marked by an abrupt return to coarse clastic deposition. The clean, medium to coarse-grained, commonly flat bedded, planar and trough cross-bedded sandstones are assigned to the Poole Sandstone.

Interpretation.

The heterolithic facies association is characterised by thinly laminated mudstones, siltstones and sandstones. The wide range in grain size within this facies indicates a depositional environment with fluctuating energy conditions (Reineck and Singh 1981). Three facies types have been recognised, in close association, all containing laminated mudstones, siltstones and sandstones. These represent a continuum of lithotypes reflecting the varying proportions of sand to mud. With increasing sand content, stratification grades from linsen, flaser and lenticular bedding types to laminated sandstones displaying ripple cross-lamination interbedded with thin massive silty mudstones. This progression is interpreted to reflect both increasing energy conditions and an increasing sand supply within the environment (Reineck 1972, Reineck and Singh 1981, Reineck and Wunderlich 1968) The ripple lamination is of two distinct types; wave ripples, identified by their characteristic undulatory bases, bundled upbuilding structures and roughly symmetrical form (De Raaf et al. 1977. Figure 75), and unidirectional current-ripples, which have a much simpler internal structure and general asymmetrical form. Commonly the current ripples form as isolated or 'starved' forms within the dominantly silty mudstone. The presence of both current-generated ripples and wave ripples suggests mixed wave and current processes. The overall laminated character of this facies suggests transportation and redistribution of sands by intermittent weak currents, with thick mudstone units produced from suspension during relatively quiet periods.

Thick interbedded sandstones appear to be either structureless or exhibit crude parallel-lamination. This suggest that these sands were deposited rapidly from suspension and not subsequently reworked by current activity or wave processes. Common to all sandstones of the heterolithic facies association are abrupt bases, which indicate sudden and often erosive emplacement by mass flows (Walker 1983a&b). Graded bedding indicates waning flows, further supported by the distribution of sedimentary structures. Deposition was periodic, probably associated with high-energy storm events, with limited periodic storm-wave reworking (Banks 1973). Background deposition of siltstones and mudstones continued during the quiescent periods. The thicker laminated and rippled upward-fining sequences observed in Ficus 1 and Melaleuca 1 indicate periodic larger flows and the upward-fining gradation suggest waning velocities as the sand was deposited.

A basin margin, shallow marine shelf setting is proposed, with intermittent restriction and development of lagoonal or brackish water conditions indicated by the abundance of syneresis cracks in the wave rippled type 1 facies identified from Hoya 1, Calytrix 1 and Clianthus 1 (Figure 76). A possible tidal influence to sedimentation could be invoked from the presence of flaser and linsen bedding types, and the abundance of mud drapes, but it is not conclusive.

The abundance of wave and current ripples and less common cross bedding, provides evidence for reworking of the sandstones by wave and current action, further suggested by the preponderance of vertical burrows in the thicker type 3 sandstones. It is proposed that the thick, clean type 3 sandstones represent relative shallowing of the shelf / basin margin area, allowing storm and normally wave activity to rework the sediment. This is further supported by the tentative recognition of hummocky cross stratification (Walker 1985). Sharp-based sandstones, which coarsen upward and have sharp tops may be deposited within channels cut by storm-surge ebb currents and filled as the storm subsides (Banks 1973, Walker 1983 a&b, 1985).

CHAPTER 10

SUMMARY AND CONCLUSIONS

The Canning Basin is one of the largest Permo-Carboniferous sedimentary basins in Australia, and yet, at the onset of this research, relatively little was known of the Permo-Carboniferous Grant Group. Access to extensive core coverage and additional seismic and wireline log data has allowed the integrated study of the Grant Group deposited on the Barbwire Terrace.

1. Stratigraphy

The Grant Group is dated as Early Permian, Asselo-Sakmarian in age, within the G. confluens palynological zone (Foster and Waterhouse 1988). This study recognises an older section, restricted to the deeper parts of the Fitzroy Graben, which could be of Late Carboniferous age.

The stratigraphic framework for the Grant Group of the Canning Basin was defined by Towner (1981). Following appraisal of the cored sections recorded from the Barbwire Terrace, it became apparent that a simple correlation with this 'composite' stratigraphy could not be made, and as such a new stratigraphic framework is proposed for the Barbwire Terrace.

The Grant Group deposited on the Barbwire Terrace has been divided into three formations; the lower Hoya Formation, the middle Calytrix Formation and the upper Clianthus Formation. These formations have distinct lithological, seismic and wireline log character and are interpreted to be parasequences, bounded by major changes in depositional style.

Whilst the correlation and subdivision of the Grant Group is well controlled on the Barbwire Terrace, the interpretation away from the study area is tentative at this stage. Correlation of the Barbwire Terrace section to the published stratigraphic framework for the Canning Basin has proved difficult. This is primarily because the published stratigraphy is based on sparse, scattered outcrops and isolated deep boreholes, which are not cored, providing little data to assist a conclusive correlation. However, an attempt has been made to correlate the Barbwire Terrace section with the published stratigraphic units of the deep well Lake Betty 1, namely the lower Betty Formation, middle Winifred Formation and upper Carolyn Formation. From that correlation it is proposed that the Hoya Formation equates with the lower part of the Winifred Formation found in Lake Betty 1. The upper section of the Winifred Formation correlates with the Calytrix Formation, and the Carolyn Formation from Lake Betty 1 correlates with the Clianthus Formation defined from the terrace.

Correlation to the outcrops in the St George Range, located to the north of the study area, has also been attempted. A revised interpretation is proposed, in which the upper Millajiddee Member is correlated with the Clianthus Formation, and the Wye Worry Member correlated with the Calytrix and part of the Hoya Formation. Both of these units form outcrops in the St George Range. Difficulty arises because the published stratigraphic division of the well St George Range 1, spudded just below these outcrops, is believed to be incorrect.

In St George Range 1, the lower part of the Carolyn Formation is believed to equate with the Betty Formation defined in Lake Betty 1. This is supported by evidence from the wireline log correlations and available seismic data, which indicates that there is a large basal section of the Grant Group preserved within the Fitzroy Graben, that has no equivalent on the Barbwire Terrace.

2. Sedimentology

From a detailed sedimentological analysis of 15 wells from the Barbwire Terrace, comprising in total over 3.5 km of core, a number of facies have been recognised.

The Hoya Formation contains a complex suite of interbedded diamictites, sandstones and mudrocks. It is characterised by substantial thickness of diamictites, interpreted to be of glacial origin.

A regionally extensive basal diamictite, interpreted to be a lodgement and subglacial melt-out till, rests on the basal unconformity with older folded and faulted Palaeozoic rocks. This is overlain by thick packages of diamictites, displaying features indicative of melt-out tills, flow tills and rain-out sediments, deposited from the retreating ice sheet and floating icebergs.

Interbedded with the diamictites are bedded and massive mudrocks, of both marine and lacustrine origin, many of which do not contain any indication of deposition within an ice-contact basin. The presence of basinal mudrocks that do not contain glacial inicators, such as dropstones, is taken to indicate periods of ice retreat from the margins of the basin. The apparent fluctuation from marine to non-marine conditions reflects both global variations in sea level and local restricted changes in the depositional environment, caused primarily by the the relative proximity of the ice sheet. It is also possible that due to its intra-cratonic nature, the Canning Basin may well have been isolated from marine influence during periods of Grant Group deposition

Sandstones are also recorded from the Hoya Formation. Thick sequences of stacked cross-bedded and flat-bedded sandstones and conglomerates were encountered by Drosera 1 and Kunzea 1. From seismic it is evident that these sandstones are restricted to unusual linear 'mounded' features, trending away from the Barbwire Terrace. They are interpreted to be valleys, filled with braided fluvial outwash sourced by the ice sheet, which was possibly grounded at the time on the Barbwire Terrace. The origin and location of the valleys reflect control by leaching of the evaporitic subcrop, which, together with later compaction effects, resulted in the mounded character of the sequence.

However, the majority of the sandstones recorded from the Barbwire Terrace display features indicative of a mass-flow origin. The stacked nature of these sandstones, together with their context, interbedded with marine and lacustrine mudstones and a variety of diamictites, suggest a basinal setting. It is suggested that they were deposited from subaqueous fan complexes fed by meltwaters from the ice sheet. In addition, many thin sandstones interbedded with the mudrock and diamictite facies are interpreted to be isolated mass-flow deposits, reflecting the unstable nature of the glacial environment.

The Hoya Formation contains all the glaciogenic sediments. It is overlain by a mudrock dominated sequence, the Calytrix Formation.

The Calytrix Formation contains sandstones, which are best developed in Calytrix 1, that have yielded a diverse marine fauna. Above the sandstones a thin calcareous mudstone, rich in delicately preserved bryozoa, was also recorded in Calytrix 1. Both the sandstone and calcareous mudstone facies have been recognised in other wells on the terrace, although they are poorly developed. The Calytrix Formation is characterised by a thick sequence of mudrocks, which can be correlated throughout the Barbwire Terrace, and into the Fitzroy Graben. The mudrocks are bioturbated and were deposited within a low-energy basinal (probably marine) environment.

The Calytrix Formation is overlain by coarse clastics of the Clianthus Formation, which are interpreted to be low-sinuosity fluvial deposits. The upper part of the Clianthus Formation comprises a complex suite of heterolithic sediments, containing abundant wave and current-rippled horizons, flaser and lenticular bedding and interbedded thicker cross-bedded sandstones. This is interpreted to be a shallow marine shelf sequence. The top of the Grant Group is taken as the base of a thick package of fluvio-deltaic sandstones, assigned to the Poole Sandstone.

3. Depositional History

The Grant Group recorded in the cored sections from the Barbwire Terrace, displays an evolving depositional style, which reflects the dynamics of the ice sheet. The sedimentary fill of any basin is a controlled by a combination of factors; climate, sea level change, clastic input, subsidence and tectonics. However, the style and evolution of a sedimentary package within a basin fed by major ice sheets will reflect more closely the state and position of that ice sheet.

The evolution noted within the Grant Group from a basal glaciogenic suite of sediments, to a mudrock dominated sequence capped by a regressive sequence of fluvial sandstones and shelf deposits, is interpreted to reflect the deglaciation of the Canning Basin (Figure 77).

The basal unconformity surface on the Barbwire Terrace is believed to be a glacially eroded surface, and the glacial package at the base of the Grant Group records the initial ice maxima and subsequent deglaciation of the area. The basal glaciogenic Hoya Formation records fluctuations in the ice sheet dynamics, within an overall retreat sequence. The deposition of thick deep-water low-energy marine mudrock sequences of the Calytrix

Formation are interpreted to reflect the global rise in sea level subsequent to the final stages of deglaciation. Finally an interplay between isostatic readjustments, basin fill, and the increased clastic supply resulting from the exposure of vast source areas following final deglaciation, results in the upward regressive package of the Clianthus Formation.

Ice sheet retreats commonly appears to be cyclical, in that, the overall retreat sequence comprises a number of minor ice advance and retreat cycles. Within the basal Hoya Formation recorded from the Barbwire Terrace a number of glacial advance and retreat sequences can be recognised, within an overall retreat package.

The final retreat of the Gondwanan Ice Sheet may well have been rapid, almost catastrophic in geological terms. The Laurentide Ice Sheet retreated in only a few thousand years, and offers a good example of the rate at which deglaciation may occur (Figure 78). It is possible to speculate that it may be feasible to correlate the sedimentary packages recorded in a number of Gondwanan basins with a major, and possibly the final retreat of the Gondwanan Ice Sheet. It is accepted that the Gondwanan Ice Sheet was a dynamic mass and not necessarily prevalent throughout Gondwana at any one time. However, the evolving sequence from a basal glaciogenic package, overlain by a mudrock dominated unit and finally a regressive sequence of coarse clastic and shallow marine shelf deposits is not unique to the Canning Basin. This evolving depositional style is common to many Permo-Carboniferous glacial deposits recorded from Gondwana basins; such as the Dwyka Formation from the Karoo Basin of South Africa, the Pagoda Formation of the Antarctic, the Itatrare Group of the Parana Basin, Brazil.

Without more detailed dating of the sections, the age equivalence is uncertain. However, the common style of sedimentary package and evolution is believed to directly reflect the dominant control the ice sheet has on sedimentation within these basins. The basal glaciogenic sequence records fluctuations in the ice sheet dynamics, within the overall retreat sequence. The final stages of ice retreat results in a global rise in sea level, and the concurrent deposition of thick deep-water mudrock sequences. Finally an interplay between isostatic readjustments, basin fill, and the increased clastic supply following final deglaciation, results in a regressive package of sediments.

4. Ice Sheet Distribution

Evidence from the distribution of glacial deposits from the Canning and Bonaparte Basins (the author's examination of cores for WMC, internal report), together with the recorded presence of striated surfaces, suggest that both the Pilbara and Kimberley Blocks were major ice accumulation centres during the Permo-Carboniferous. This is further supported by the abundance of basement clasts found in the diamictites and sandstones, believed to be sourced from the surrounding shield areas. The ice sheet was grounded at some point on these shield areas, and this study suggests that it extended onto the Barbwire Terrace, possibly covering the entire Canning Basin at its maximum extent.

A comparison can be drawn with the Antarctic ice sheet, the only modern day example of a major continental ice sheet. It must be emphasised that the setting of the Antarctic ice sheet is quite different from that envisaged for the Canning Basin. The Canning Basin was at between 60 to 70 degrees south during the Permian and as such glaciation was by a temperate ice sheet. In contrast, the Antarctic ice sheet is polar, and builds out directly into the ocean, and not an intra-cratonic basin. However a size comparison with the Ross ice-shelf (Figure 79 and 80) gives an idea of the dimensions of continental ice sheets.

Figure 81 display a model for the distribution of the ice sheet, during its maximum stage, within the Canning Basin area. It is clearly possible that the entire basin was covered by the ice sheet during the maximum stage of ice advance, and potentially by an ice shelf similar in style to the Ross ice shelf. However, whether the Fitzroy Graben had grounded ice is uncertain due to lack of data.

5. Summary

To conclude, this study has produced a detailed description of the Grant Group sediments deposited in the study area. Three new formations have been defined, which can be correlated by lithological composition, sedimentological facies, wireline log response and seismic character throughout the study area. A series of models for the depositional environments indicated by the sedimentary sequence have been presented, and the controls on the overall evolution in style of deposition assessed.

The combination of a stratigraphic framework, and detailed understanding of the Grant Group sediments provides valuable information in attempting to asses the distribution of facies which may act as hydrocarbon reservoirs. Certainly, the Grant Group contains abundant sandstones sequences, of subaqueous fan and fluvial origin, which have excellent reservoir characteristics and are intimately associated with sealing mudrocks and diamictites.

6. Further Work

This study has opened a Pandora's box of questions and problems that will require extensive further study.

The Grant Group covers a vast area, and the degree of lateral facies changes and correlation of units encountered on the terrace needs to be determined by further study in areas adjacent to the current study area. Provenance studies to address the source areas for the varied clasts recorded from the diamictites would determine the direction of ice transport into the basin. However, the potentially vast (and poorly documented) areas from which the clasts may have been derived makes this a difficult task.

Dating of the section is a major problem, and a concentrated detailed analysis should be undertaken to provide additional palynological zonation, which is crucial to control the lithological correlations. This has been done with some apparent success by Shell on equivalent glaciogenic sequences of Oman.

Finally, in the light of this study, it is clear that a clarification of the stratigraphy of the Grant Group in the Canning Basin is required. This would involve the re-assessment of the old well data, and re-examination of the limited core data to accurately determine its relationship to the Barbwire Terrace sequence. The existence of a lower Grant Group section not recorded on the Barbwire Terrace needs to be further addressed, and the imminent acquisition of a number of regional seismic lines by the BMR may well help to resolve this.

REFERENCES

REFERENCES

ADAM, D.P. 1969. Ice ages and thermal equilibrium of the earth II. Quat. Res., v. 5(2), p. 161-171.

ALLEN, J.R.L. 1970. Physical Processes of Sedimentation. Allen & Unwin, London, 248p.

ALLEN, J.R.L. 1971. A theoretical and experimental study of climbing-ripple cross-lamination, with a field application to the Upsala esker. Geogr. Ann., v. 53A, p. 157-187.

ALLEN, J.R.L. 1983. Sedimentary structures: their character and physical basis. Elsevier, Amsterdam, 254p.

ALLEN, J.R.L. 1983. Studies in fluvatile sedimentation: bars, bar-complexes and sandstone sheets (low sinuosity braided streams) in the brownstones (L.Devonian), Welsh Borders. Sedimentary Geology, v. 33, p. 237-293.

ANDERSON, J.B. 1983. Ancient glacial-marine deposits: their spatial and temporal distribution. In: Molnia, B.F. (Ed.). Glacial-marine sedimentation. Plenum Press, New York, p. 3-94.

ANDERSON, J.B., KURTZ, D.D., DOMACK, E.W., & BALSHAW, K.M. 1980. Glacial marine sediments of the Antarctic continental shelf. Journal of Geology, v. 88, p. 399-414.

ARCHBOLD, N.W. 1982. Correlation of the early Permian faunas of Gondwana: implications for the Gondwanan Carboniferous - Permian boundary. Jour. Geol. Soc. Aust. v. 29, p. 267-276.

ASHLEY, G.M. 1975. Rhythmic sedimetation in glacial Lake Hitchcock, Massachusetts-Connecticut. In: Jopling, A.V., & McDonald B.C. (Eds.). Glaciofluvial and glaciolacustrine sedimetation. S.E.P.M. Spec. Pub. v. 23, p. 304-320.

ASHLEY, G.M., SHAW, J. & SMITH, N.D. 1985. Glacial sedimentary environments. S.E.P.M. Short Course No. 16 Lecture Notes, 246p.

ASHLEY, G.M. 1985. Proglacial lacustrine environment. In: Ashley, G.M., Shaw, J. & Smith, N.D. (Eds.). Glacial sedimentary environments. S.E.P.M. Short Course No. 16 Lecture Notes, p. 135-216.

ASHTON, S.M 1984. Slim Hole Drilling in the Canning Basin. Philosophy and Application. In: Purcell, P.G. (Ed.). The Canning Basin, W.A.: Proceedings of the Canning Basin Symposium, Perth, 1984. Geological Society of Australia and Petroleum Exploration Society of Australia. p. 521-531.

BADLEY, M.E. 1985. Practical Seismic Interpretation. International Human Resources Development Corporation, Boston. 266p.

BALLY, A.W. 1987. (Ed.) Atlas of Seismic Stratigraphy. A.A.P.G. Studies in Geology, 27. 148p.

BALME, B.E. 1980. Palynology and the Carboniferous-Permian boundary in Australia and other Gondwanan continents. Palynology, v. 4, p. 43-55.

BANKS, N.L. 1973. Tide dominated offshore sedimentation, Lower Cambrian, *North Norway*. Sedimentology, v. 20, p. 213-228.

BANKS, M.R. 1981. Late Paleozoic tillites of Tasmania. In: Hambrey, M.J., & Harland, W.B. (Eds.) Earth's Pre-Pleistocene glacial record. Cambridge University Press, Cambridge, 1004p.

BEGG, J. 1987. Structuring and controls on Devonian Reef development on the north-west Barbwire and adjacent terraces, Canning Basin. Australian Petroleum Exploration Association, p. 131-151.

BENSON, J.M. 1981. Late Carboniferous and Early Permian tilllites of Newcastle, New South Wales. In: Hambrey, M.J., & Harland, W.B. (Eds.) Earth's Pre-Pleistocene glacial record. Cambridge University Press, Cambridge, 1004p.

BLACKWELDER, E. 1928. Mudfloes as a geological agent in semi arid mountains. Bull. Geol. Soc. Amer., v. 39, p. 465-480.

BLACKWELDER, E. 1931. Pleistocene glaciation in the Sierra Nevada and Basin Ranges. Bull. Geol. Soc. Amer., v. 42, p. 865-922.

BLATT, H., MIDDLETON, G., & MURRAY, R. 1980. Origin of sedimentary rocks. Prentice-Hall, New Jersey.

BLUCK, B.J. 1974. Structure and directional properties of some valley sandur deposits in southern Iceland. Sedimentology, v. 21, p. 533-554.

BOOTHROYD, J.C., & ASHLEY, G.M. 1975. Process, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska. In: Jopling, A.V., & McDonald B.C., (Eds.). Glaciofluvial and glaciolacustrine sedimetation. S.E.P.M. Spec. Pub., 23, p. 193-222.

BOOTHROYD, J.C. & NUMMEDAL, D. 1978. Proglacial braided-outwash: a model for humid alluvial-fan deposits. In. Miall, A.D. (Ed.). Fluvial Sedimentology. Canadian Society of Petroleum Geologists, Memoir 5, p. 641-668.

BOULTON, G.S. 1968. Flow tills and related deposits on some Vestspitsbergen glaciers. Jour. Glaciology, v. 7, p. 391-412.

BOULTON, G.S. 1971. On the deposition of subglacial and meltout tills at the margins of certain Svalbard glaciers. Jour. Glaciology, v. 9, p. 231-245.

BOULTON, G.S. 1971. Till genesis and fabric in Svalbard, Spitsbergen. In: Goldthwaite, R.P., (Ed.). Till a symposium. Ohio State University Press, Columbus, p. 41-72.

BOULTON, G.S. 1972. Modern Arctic glaciers as depositional models for former ice sheets. Jour. Geol. Soc., v. 7, p. 391-412.

BOULTON, G.S. 1975. processes and patterns of sub-glacial sedimentation: a theoretical approach. In: Wright, A.E., & Moseley, F. (Eds.). Ice Ages: Ancient and Modern. Geol. Jour. Spec. Iss., 6, p. 7-42.

BOULTON, G.S. 1976. A genetic classifiaction of tills and criteria for distinguishing tills of different origin. In: Stankowski, W. (Ed.). Till: its genesis and diagenesis. Geogr. v. 12, p. 65-80.

BOULTON, G.S. & DEYNOUX, M. 1981. Sedimentation in glacial environments and the identification of tills and tillites in ancient sedimentary sequences. Precambrian Research, v. 15, p. 397-422.

BOULTON, G.S., & PAUL, M.A. 1976. The influences of genetic properties on some geotechnical properties of glacial tills. Quarterly Journal Engineering Geol., v. 9, p. 159-194.

BOUMA, A.H. 1962. Sedimentology of some flysch deposits. Elsevier, Amsterdam, 168p.

BRAAKMAN, J.H., LEVELL, B.K., MARTIN, J.H., POTTER, T.L., & van VLIET, A. 1982. Late Paleozoic Gondwanan glaciation in Oman. Nature, v. 299, p. 48-50.

BRODZIKOWSKI, K. & VAN LOON, A.J. 1987. A systematic classification of glacial and periglacial environments, facies and deposits. Earth Science Reviews, v. 24, p. 297-381.

BROMLEY, R.G. & EKDALE A.A. 1984. <u>Chondrites</u> : A trace fossil indicator of anoxia in sediments. Science, v. 224, p. 872-874.

BRYSON. R.A., WENDLAND, W.M., IVES, J.D., & ANDREWS, J.T. 1969. Radiocarbon isochrones on the disintergration of the Laurentide ice sheet. Arctic and Alpine Research, v. 1, p. 1-13.

BUDD, W.F., JENSENN, D., & RADOK, U. 1971. Derived physical characteristics of the Antarctic icesheet. Univ. Melbourne, Meteorol. Dept. Pub., 18, 178pp.

CANT, D.J. 1984. Development of shoreline-shelf sandbodies in a Cretaceous epiric sea deposit. Journal of Sedimentary Petrology, v. 54,p. 541-556.

CANT, D.J., & WALKER, R.G. 1978. Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada. Sedimentology, v. 25, p. 625-648.

CAMPBELL, C.V. 1976. Reservoir geometry of a fluvial sheet sandstone. AAPG. Bull., v. 60, p. 1009-1020.

CASEY, J.N., & NELLIGAN, P.F. 1956. Land classification and new geological names in northeast part of the Canning Basin. B.M.R. Rec. 1956/106 (unpub.)

CLAPP, F.G. 1926. Oil prospects of the Desert Basin of Western Australia. A.A.P.G. Bull. 10, p. 1118-1135.

COLEMAN, J.M. 1969. Bramaputra River - channel process and sedimentation. Sedimentary Geology, v. 13, p. 129-239.

COLEMAN, J.M., & PRIOR, D.B. 1982. Deltaic environments of deposition. In: Schole, P.A., & Spearing, D. (Eds.). Sandstone Depositional Environments. A.A.P.G. Mem. 31, p. 139-178.

CONDON, M.A. 1954. Progress report on the Stratigraphy and structure of the Carnarvon Basin, Western Australia. Aus. Bur. Miner. Resour. Geol. Geophys., Report 15.

CONDON, M.A. 1967. The geology of the Carnarvon Basin, Western Australia. Part 2: Permian Stratigraphy. Aus. Bur. Miner. Resour. Geol. Geophys. v. 77 191p.

CROWE, R.W.A., & TOWNER, R.R. 1976a. Permian Depositional History of the Noonkanbah 1:250,000 Sheet area, W.A.; Bur. Miner. Res. Aust., Record 1976/24.

CROWE, R.W.A., & TOWNER, R.R. 1976b. Environmental interpretation of the Permian Nura Nura Member of the Poole Sandstone, Noonkanbah Sheet Area, Canning Basin; a gradation between fluvatile and shallow water marine facies. Geological Survey of Western Australia, Annual Report for 1975, p. 103-106.

CROWE, R.W.A., & TOWNER, R.R. 1976c. Definitions of Some New and Revised Rock Units in the Canning Basin: Geological Survey of Western Australia, Record 1976/24.

CROWE, R.W.A., TOWNER, R.R., & GIBSON, D.L. 1978. Permian and Mesozoic geology of the Derby and Mount Anderson 1:250,000 Sheet Areas, Western Australia. Bur. Miner. Res. Aust., Record 1978/8.

CROWELL, J.C. 1978. Gondwanan glaciation, cyclothems, continental positioning and climatic change. American Journal of Science, v.278, p. 1345-1372.

CROWELL, J.C. 1957. The origin of pebbly mudstones. Geol. Soc. America Bull., v. 68, p. 993-1009.

CROWELL, J.C. & FRAKES, L.A. 1971a. Late Palaeozoic glaciation of Australia. Jour. Geol. Soc. Aust., v. 17, p. 115-155.

CROWELL, J.C. & FRAKES, L.A. 1971b. Late Paleozoic glaciation: Part IV, Australia. Geol. Soc. Amer. Bull., v. 82, p. 2515-2540.

DeGEER, G. 1912. A geochronology of the last 12,000yrs. Int. Geol. Congr. , Stockholm 1910, Compte Rendu, v. 1, p.241-258.

DE RAAF, J.F.M., BOERSMA, J.R., & VAN GELDER, A. 1977. Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland. Sedimentology, v. 24, p. 451-483.

DEYNOUX, M. 1985. Terrestrial or waterlain glacial diamictites? Three case studies from the Late Pre-cambrian and Late Ordovician glacial drifts in West Africa. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 51, p. 97-141.

DICKENS J.M. 1985. Late Palaeozoic glaciation. Bur. Miner. Res. Jour. Aust. Geol. Geophys., v. 9, p. 163-169.

DICKENS, J.M., & THOMAS, G.A. 1959. The marine fauna of the Lyons Group and the Carrandibby Shale of the Carnarvon Basin, Western Australia. Bur. Miner. Res. Jour. Aust. Geol. Geophy., v. 38, p. 65-96.

DICKENS, J.M., TOWNER, R.R., & CROWE R.W.A. 1977. A Permian cold water marine fauna in the Grant Formation of the Canning Basin, Western Australia. Journal of the Palaeontological Society of India, v. 20, p. 275-278.

DREIMANIS, A. 1974. Till and tillite. In: Fairbridge, R.W., & Bourgeois, J. (Eds.). Encyclopedia of Sedimentology. Hutchinson and Ross, New York.

DREIMANIS, A. 1976. Tills: their origin and properties. In: Legget, R.F. (Ed.). Glacial Till, an Interdisciplinary Study. R. Soc. Can. Spec. Pub., v. 12, p. 11-49.

DREIMANIS, A. 1979. The problems of waterlain tills. In: Schluchter, A., (Ed.). Moraines and Varves, A.A. Balkema, Rotterdamm, p. 167-177.

DREWRY, D.J. & COOPER, A.P.R. 1981. Processes and models of Antarctic glaciomarine sedimentation. Annals of Glaciology, v. 2, p. 117-122.

EDWARDS, M.B. 1975. Glacial retreat sedimentation in the Smalfjord Formation, Late Precambrian, North Norway. Sedimentology, v. 22, p. 75-94.

EDWARDS, M.B. 1978. Glacial sedimentary environments. In: Reading, H.G. (Ed.). Sedimentary environments and facies. Blackwell Scientific Publications, Oxford, p. 416-438.

EDWARDS, M.B. 1984. Sedimentology of the Upper Proterozoic glacial record, Vertertana Group, Finmark, North Norway. Norges Geologiske Undrsokelse Bull., v. 394, 76pp.

EKDALE. A.A., BROMLEY, R.G., & PEMBERTON, S.G. 1984. Ichnology. The use of trace fossils in sedimentology and stratigraphy. S.E.P.M. Short Course No. 15.

ELSON, J.A. 1961. The geology of tills. In: Penner, E., & Butler, J. (Eds.). Proceedings 14th Canadian Soil Mechanics Conference, N.R.C., Canada. Assoc. Comm. Soil and Snow Mech., Tech. Mem. 69, p. 5-36.

ELVERHOI, A., LONNE, O., & SELAND, R. 1983. Glaciomarine sedimentation in a modern fjiord environment, Spitsbergen. Polar Res.,v. 1, p. 127-149.

EVANS, P.R. 1969. Upper Carboniferous and Permian palynological stages and their distribution in eastern Australia. 1st Gondwanan Symposium, I.U.G.S., p. 41-54.

EVENSON, E.B., DREIMANIS, A., & NEWSOME, J.W. 1977. Subaquatic flow tills: A new interpretation for the genisis of some laminated till deposits. Boreas, v. 6, p. 115-133.

EYLES, C.H. & EYLES, N. 1983 Sedimentation in a large lake: a reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada. Geology, v. 11, p. 146-152.

EYLES, N., & SLADEN, J.A. 1981. Stratigraphy and geotechnical properties of weathered lodgement till in Northumbria, England. Quart. Jour. Eng. Geol., v. 14, p. 129-141.

EYLES, N., EYLES, C.H., & MIALL, A.D. 1982. Lithofacies types and vertical profile analysis; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. Sedimentology, v. 30, p. 393-410.

EYLES, C.H., EYLES, N. & MIALL, A.D. 1985. Models of glaciomarine sedimentation and their application to the interpretation of ancient glacial sequences. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 51, p. 15-84.

EYLES, N., & MIALL, A.D. 1984. Glacial facies. In: Walker, R.G. (Ed). Facies Models. Geoscience Canadian Reprint Series 1, p. 15-38.

EYLES, N., SLADEN, J.A., & GILROY, S. 1983. A depositional model for stratigraphic complexes and facies superimposition in lodgement till. Boreas, v. 11, p. 317-333.

FAIRBRIDGE, R.W. 1967. The encyclopedia of atmospheric sciences and astrogeology. Rhienhold, New York, 1200p.

FAIRBRIDGE, R.W. 1982. The fracturing of Gondwanaland. In: Scrutton, R.A., & Talwani, M. (Eds.). The Ocean Floor. John Wiley & Sons, New York, p. 229-235.

FLINT, R.F. 1971. Glacial and Quaternary geology. Wiley, New York. 892

FLINT, R.F., SANDERS, J.E., & RODGERS, J. 1960a. Symmictite: A name for nonsorted terrigenous sedimentary rock that contains a wide range of particle sizes. Geol. Soc. America. Bull., v. 71, p. 507-510.

FLINT, R.F., SANDERS, J.E., & RODGERS, J. 1960b. Diamictite: A substitute term for symmictite. Geol. Soc. America. Bull., v. 71, p. 1809-1810.

FORMAN, D.J. 1960. Glaciated pavement in the Ripon Hillss, Western Australia. Journal of the Royal Society of Western Australia, v. 43, p. 123-125.

FORMAN, D.J. & WALES, D.W. 1981. Geological Evolution of the Canning Basin, Western Australia: Bur. Miner, Res, Bull., 210.

FOSTER, C.B. & WATERHOUSE, J.B. 1988. The Granulatisporites confluens Oppel-zone and Early Permian marine faunas from the Grant Formation on the Barbwire Terrace, Canning Basin, Western Australia. Australian Journal of Earth Sciences, v. 35, p. 135-157.

FRAKES, L.A. 1979. Climates through geologic time. Elsevier, Amsterdam 310 p.

FRAKES, L.A., & FRANCIS, J.E. 1988. A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous. Nature, v. 333, p. 547-549.

FRASER, G. 1976. Gravity provinces and their nomenclature. Bur. Miner. Res. Jour. Aust. Geol. Geophy., v. 1(4), p. 350-352.

GALLOWAY, W.E. 1989. Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding-surface bounded depositional units. A.A.P.G. Bull., v. 73, p. 125-142.

GENTILLI, J. & FAIRBRIDGE, R.W. 1951. The Physiographic Regions of Australia. Geographic Press, New York.

GIEKIE, J. 1877. The Great Ice Age. Dalby, Isbister & Co., London, 854p.

GILBERT, R. 1973. Processes of underflow and sediment transport in a British Columbia mountain lake. Proc. 9th Canad. Hydrology Symposium, Nat. Res. Council Canada, p. 493-507.

GILBERT, R., & SHAW, J. 1981, Sedimentation in a proglacial Sunwapta Lake, Alberta. Can. Jour. Earth Sci., v. 18, p. 81-93.

GLOPPEN, T.G. & STEEL, F.J. 1981. The deposits, internal structure and geometry in six alluvial fans - fan delta bodies. (Devonian, Norway) - a study in the significance of bedding sequence in conglomerates. In: Etheridge, F.G., & Flores, R.M. (Eds.). Recent and ancient non-marine depositional environments: models for exploration. S.E.P.M. Spec. Pub. 31, p. 64-69.

GOODCHILD, J.G. 1875. The glacial phenomena of the Eden Valley and the western part of the Yorkshire-Dale district. Geol. Soc Lond. Quart. Jour.,v. 31, p. 55-99.

GORTER, J.D., RASIDI, J.S., TUCKER, D.H., BURNE, R.V., PASSMORE, V.L., WALES, D.W., & FORMAN, D.J. 1979. Petroleum Geology of the Canning Basin. Bur. Miner. Res., Record, 1979/32.

GRAVENOR, C.P. & ROCHA-CAMPOS, A.C. 1983. Patterns of Late Paleozoic glacial sedimentation on the southeast side of the Parana Basin, Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 43 (1), p. 1-39.

GRAVENOR, C.P., VON BRUNN, V., & DREIMANIS, A. 1984. Nature and classification of waterlain glaciogenic sediment, exemplified by Pleistocene, Late Palaeozoic and Late Precambrian deposits. Earth Science Reviews, v. 20, p. 105-166.

GRESSLEY, A. 1838. Observations geologiques sur la Jura Soleurois. Neue Denkshr. allg. schweiz. Ges. ger. Naturw. V.2, p.1-112.

GUPPY, D.J., LINDNER, A.W., RATTIGAN, J.H., & CASEY, J.N. 1952. The stratigraphy of the Permian and Mesozoic Sediments of the Desert Basin, Western Australia. Nineteenth International Geological Congress, Algeria, Gondwana Symposium, p. 101-114.

GUPPY, D.J., LINDNER, A.W., RATTIGAN, J.H., & CASEY, J.N. 1958. The Geology of the Fitzroy Basin, Western Australia. Bur. Miner. Res. Bull., v. 36.

GUSTAVSON, T.C., ASHLEY, G.M., & BOOTHROYD, J.C. 1975. Depositional sequences in glaciolacustrine deltas. In; Jopling, A.V., & Macdonald, B.C. (Eds.). Glaciofluvial and glaciolacustrine Sedimentation, S.E.P.M. Spec. Pub. No. 23, p. 264-280.

HALDORSEN, S., & SHAW, J. 1982. The problem of recognizing melt-out till. Boreas, v. 11, p. 261-277.

HAMBREY, M.J., & HARLAND, W.B. 1979. Analysis of Pre-Pleistocene glacial rocks: aims and problems. In: Schluchter, C.H. (Ed.). Moraines and Varves. A.A. Balkema, Rotterdam. p. 271-275.

HAMBREY, M.J., & HARLAND, W.B. 1981 (Eds.). Earth's Pre-Pleistocene glacial record. Cambridge University Press, Cambridge, 1004p.

HAMPTON, M.A. 1972. The role of subaqueous debris flow in generating turbidity currents. Journal of Sedimentary Petrology, v. 49, p. 775-793.

HARLAND, W.B., HEROD, K.N., & KRINSLEY, D.H. 1966. The definition and identification of tils and tillites. Earth Science Reviews, v. 2, p. 225-256.

HARMS, J.C., & FAHNESTOCK, R.K. 1965. Stratification, bedforms and flow phenomena (with examples from the Rio Grande). S.E.P.M. Spec. Pub., 12, p. 84-115.

HARTSHORN, J.H. Flow till in southeastern Massachusetts. Geol. Soc. Amer. Bull., v. 69, p. 477-482.

HERBERT, C. 1980. Evidence for glaciation in the Sydney Basin and Tamworth Syncline Zone. In: Herbert, C., & Helby, R. (Eds.). A guide to the Sydney Basin. Geol. Soc. New South Wales, Bull. 26, p. 274-293.

HEWARD, A.P. 1990. Salt removal and sedimentation in Southern Oman. In: Robertson, A.H.F., Searle, M.P. & Ries, A.C. (Eds.) The geology and tectonics of the Oman Region. Geol. Soc. Spec. Pub. 49, p. 637-652.

HOWARD, J.D. 1972. Trace fossils as criteria for recognising shorelines in the stratigraphic record. In: Rigby, J.K., & Hamblin, W.K. (Eds.). Recognition of ancient sedimentary environments. S.E.P.M. Spec. Pub. 16, p. 215-225.

HOWARD, J.D., & REINECK, H.E. 1979. Sedimentary structures of 'high energy' beach to offshore sequence; Ventura-Port Hueneme area, California. A.A.P.G. Bull., v.63, p. 468-469.

HOWCHIN, W.K. 1895. New facts bearing on the glacial features of Hallet's Cove. Trans. R. Soc. S. Aust., v.19, p. 61-69.

HOWCHIN, W.K. 1910. Description of new and extended area of Permo-Carboniferous glacial deposits in South Australia. Trans. R. Soc. S. Aust., v. 10, p. 1-12.

HUGHES, T. 1975. The west Antarctic ice sheet: instability, disintergration and initiation of Ice Ages. Rev. Geophys. and Space Phys., v. 13(4),p. 502-526.

JOPLING, A.V., & WALKER, R.G. 1968. Morphology and origin of ripple-drift cross-lamination, with examples from the Pleistocene of Massachusetts. Journal of Sedimentary Petrology, v. 38, p. 971-984.

KEMP, E.M. 1975. The palynology of the Late Palaeozoic glacial deposits of Gondwanaland. In: Campbell, K.S.W., (ed.) Gondwana Geology. Canberra, Australia, Australian National University Press, p. 397-413.

KEMP, E.M., BALME, B.E., HELBY, R.J., KYLE, R.A., PLAYFORD, G., & PRICE, P.L. 1977. Carboniferous and Permian palynostratigraphy in Australia and Antarctica: a review. Bur. Min. Res. Jour. Aust. Geol. Geophy., v. 2, p.177-208.

KRUGER, J. 1979. Structures and textures in till indicating subglacial deposition. Boreas, v. 8, p. 323-340.

KURTZ, D.D., & ANDERSON, J.B. 1979. Recognition and sedimentological description of recent debris flow deposits from the Ross and Weddell seas, Antarctica. Journal of Sedimentary Petrology, v. 49, p. 1159-1170.

LARSEN, J.A., & BARRY, R.G. 1974. Palaeoclimatology. In: Ives, J.D., & Barry, R.G. (Eds.). Arctic and Alpine environments, Methuen, London, p.253-276.

LAWSON, D.E. 1979. Sedimentological analysis of the western terminus region of the Matanuska Glacier, Alaska. Jour, Geol., v.90, p.279-300.

LEHMANN, P.R. 1984. The stratigraphy, palaeogeography and petroleum potential of thr lower to upper Devonian sequence in the Canning Basin, W.A. In: Purcell, P.G. (ed.) The Canning Basin, W.A., Proceedings of the Geological Society of Australia, Petroleum Exploration Society of Australia Symposium, Perth, 1984, p. 253-275.

LEVELL, B.K., BRAAKMAN, J.H., & RUTTEN K.W. 1988. Oil bearing sediments of Gondwanan glaciation in Oman. Bull. A.A.P.G. v.72, p. 775-796.

LINDSAY, J.F. 1970. Depositional environment of Palaeozoic glacial rocks in the central Transantarctic Mountains. Geol. Soc. America. Bull., 81, p.1149-1172.

LINDSAY, J.F. 1989. Depositional controls on glacial facies associations in a basinal setting, Late Proterozoic, Amadeus Basin, Central Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 73, p. 205-232.

LOWE, D.R. 1976. Subaqueous liquified and fluidised sediment flows and their deposits. Sedimentology, v. 23, p. 285-308.

LOWE, D.R. 1981. Sediment gravity flows: II, Depositional models with special reference to the deposits of high density turbidity currents. Journal of Sedimentary Petrology, v. 52, p. 279-297.

McKEE, E.D., CROSBY, E.T., & BERRYHILL, H.L., Jr. 1967. Flood deposits, Bijou Creek, Colorado, June 1965. Journal of Sedimentary Petrology, v. 37, p. 829-851.

MIALL, A.D. 1977. A review of the braided-river depositional environment. Earth Science Reviews, v. 13, p. 1-62.

MIALL, A.D. 1982. Analysis of fluvial depositional systems. American Association of Petroleum Geologists Education Course Notes Series, 20.

MIALL, A.D. 1983, Glaciomarine sedimentation of the Gowganda Formation (Huronian), Northern Ontario, Canada. Journal of Sedimentary Petrology, v. 53, p. 477-491.

MIALL, A.D. 1986. Eustatic sea level changes interpreted from seismic stratigraphy: a critique of the methodology with particular reference to the North Sea Jurassic record. A.A.P.G. Bull., v. 70, p. 131-137.

MIDDLETON, G.V. 1969. Turbidity currents and grain flows and other mass movements downslope. In: Stanley, D.J. (Ed.) The new cocepts of continental margin sedimentation. GM-A-1 to GM-B-14 Am. Geol. Inst.Short Course Notes.

MIDDLETON, G.V. 1973. Johannes Walthers law of correlation of facies. Bull. Geol. Soc. Amer., v. 84, p. 979-988.

MIDDLETON, G.V., & HAMPTON, M.A. 1976. Subaqueous sediment transport of deposition by sediment gravity flows. In: Stanley, D.J. & Swift, D.J.P. (eds.) Marine Sediment Transport and Environment Management. New York, Wiley, p. 197-219.

MILANKOVICH, M. 1969. Canon of isolation and the ice age theory. Israel Prog. Sci. Trans., Jerusalem. 484 p.

MILLER, J.M.G. 1989. Glacial advance and retreat sequences in a Permo-Carboniferous section, central Transantarctic Mountains. Sedimentology, v.36, p. 419-430.

MILLS, P.C. 1983. Genesis and diagnostic value of soft-sediment deformation structures-a review. Sedimentary Geology, v. 35,p. 83-104.

MITCHUM, R.H., VAIL, P.R., & SANGREE, J.B. 1977. Seismic stratigraphy and global changes in sea level: Part 6, Stratigraphic Interpretation of seismic reflection packages and patterns in depositional sequences. In: Payton, C.E. (Ed.) Seismic Stratigraphy-applications to hydrocarbon exploration. A.A.P.G. Mem. 26. p. 133-177.

MULLER, E.H. 1983. Dewatering during lodgement of till. In: Evenson, E.B., Schluchter, C.H., & Rabassa, J., (Eds.). Tills and Related Deposits. Balkema, Rotterdam, p. 13-18.

MUSTARD, P.S., & DONALDSON, J.A. 1987. Early Proterozoic ice-proximal glaciomarine deposition: The lower Gowganda Formation at Cobalt, Ontario, Canada. Geol. Soc. Amer. Bull., v. 98, p. 373-387.

O'BRIEN, P.E. 1987. Stratigraphy and seimentology of the Late Palaeozoic sediments beneath the Murray Basin, and their palaeogeographic and palaeoclimatic significance. Bur. Min. Res. Jour. Aust. Geol. Geophy. v.10, p. 53-63.

OVENSHINE, A.T., 1970. Observations of iceberg rafting in Glacier Bay, Alaska and the identification of ancient ice-rafted deposits. Geol. Soc. America Bull., v. 81, p. 891-894.

PAYTON, C.E. 1977. (Ed.) Seismic Stratigraphy-applications to hydrocarbon exploration: A.A.P.G. Mem 26. PETTIJOHN, F.J. 1975. Sedimentary Rocks. (3rd, Edn.) Harper, New York.

PICARD, M.D., & HIGH, L.R. 1972. Criteria for recognising lacustrine rocks. S.E.P.M. Spec. Pub. 16, p. 108-145.

PICARD, M.D., & HIGH, L.R. 1981. Physical stratigraphy of ancient lacustrine deposits. S.E.P.M. Spec. Pub. 31, p. 233-259.

PLAYFORD, P.E, & LOWRY, D.C. 1966. Devonian Reef Complexes of the Canning Basin, Western Australia. Geol. Surv. Western Aust. Bull. 118.

PLAYFORD, P.E., COPE, R.N., COCKBAIN, A.E., LOWE, G.H., & LOWRY, D.C. 1975. Canning Basin,. In: The Geology of Western Australia. Geol. Surv. W. Aust. Mem. 2,, p. 319-368.

PLINT, A.G. 1988. Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: Their relationship to relative changes in sea level. S.E.P.M. Special Pub., 42, p. 357-370.

PLINT, A.G., & WALKER, R.G. 1987. Cardium Formation 8. Facies and environments of the Cardium Formation shoreline and coastal plain in the Kakwa Field and adjacent areas, northwestern Alberta. Bull. Canadian Petroleum Geology, v. 35, p. 48-64.

PLINT, A.G., WALKER, R.G., & BERGMAN, K.M. 1986. Cardium Formation 6. Stratigraphic framework of the Cardium in subsurface. Bull. of Canadian Petroleum Geology, v. 34, p. 213-225.

POWELL, R.D. 1981. A model for sedimentation by tidewater glaciers. Annals of Glaciology, v. 2, p. 129-134.

POWELL, R.D. 1983. Glacial marine sedimentation processes and lithofacies of temperate glaciers, Glacier Bay, Alaska. In: Molnia, B.F., (Ed.) Glacial-marine sedimentation, Plenum Press, New York, p. 185-232.

POWELL, R.D., & VEEVERS, J.J. 1987. Namurian uplift in Australia and South America triggered the main Gondwanan glaciation. Nature, v. 326, p.177-179.

POWIS, G.D. 1979. Palynology of the Late Palaeozoic glacial sequence, Canning Basin, Western Australia. Ph.D. Thesis U.W.A. (unpub.)

POWIS, G.D. 1984. Palynostratigraphy of the Late Carboniferous sequence, Canning Basin, W.A. In: PURCELL, P.G. (ed.) The Canning Basin, W.A.: Proceedings of the Canning Basin Symposium, Perth, 1984. Geological Society of Australia and Petroleum Exploration Society of Australia, p. 429-438.

PURCELL, P.G. 1984, (Ed.) The Canning Basin, W.A.: Proceedings of the Canning Basin Symposium, Perth, Geological Society of Australia and Petroleum Exploration Society of Australia, p. 429-438.

QIDWAI, H.A., KHALIFA, M.I., BA-MKHALIF, K.A. 1988. Evidence of Permo-Carboniferous glaciation in the basal Murbat Sandstone Formation, Southern Region, Sultanate of Oman. Journ Petrol. Geol., v. 11(1), p. 81-88.

RAINBIRD, R.H., & DONALDSON, J.A. 1988. Nonglaciogenic deltaic deposits in the early Proterozoic Gowganda Formation, Cobalt Basin, Ontario. Canadian Journal of Earth Sciences, v. 25(5), p. 710-724.

READING, H.G. 1978. (Ed.) Sedimentary Environments and Facies. Blackwell Scientific Publications, Oxford.

REINECK, H.E. 1972. Tidal Flats. In: Rigby, J.K. & Hamblin, W.K. (Eds.) Recognition of ancient sedimentary environments. S.E.P.M. Spec. Pub. 16, p. 146-159.

REINECK, H.E., & SINGH, I.B. 1981. Depositionairy sedimentary environments. Springer-Verlag, Heidelberg.

REINECK, H.E., & WUNDERLICH, F. 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, v. 11, p. 99-104.

ROCHA-CAMPOS, A.C., & Dos SANTOS, P.R. 1981. The Itarare Subgroup, Aquidauana Group and San Gregorio Formation, Parana Basin, southeastern South America. In: Hambrey, M.J., & Harland, W.B. (Eds.) Earths Pre-Pleistocene Glacial Record, Cambridge University Press, Cambridge, p. 842-852.

RUST, B.R. 1975. Fabric and structure in glaciofluvial gravels. In: Jopling, A.V., & McDonald, B.C. (eds.) Glaciofluvial and Glaciolacustrine Sedimentation. S.E.P.M. Spec. Pub., 23, 238-248.

RUST, B.R. 1977. Mass flow deposits in a Quaternary succesion near Ottawa, Canada: diagnostic criteria for subaqueous outwash. Canadian Journal Earth Science, v. 14, p. 175-184.

RUST, B.R. 1978. Depositional models for braided alluvium. In: Miall, A.D. (ed.) Fluvial sedimentology. Canadian Society of petroleum Geologists, Memoir 5, p. 602-625.

RUST, B.R., & ROMANELLI, R. 1975. Late Quaternary subaqueous outwash deposits near Ottowa, Canada. In: Jopling, A.V., & McDonald B.C., (eds.) Glaciofluvial and Glaciolacustrine Sedimetation. S.E.P.M. Spec. Pub., 23, p. 304-320.

RUST, B.R. 1984. Proximal braid plain deposits- the Middle Devonian Malbaie Formation of eastern Gaspe, Canada. Sedimentology, v. 31, p. 675-695.

SCHLUCHTER, C.H. 1978. (Ed.) Moraines and Varves. A.A. Balkema, Rotterdam.

SCHMIDT, P.W., EMBLETON, B.J.J., CUDAHY, T.J., & POWELL, C. McA. 1986. Prefolding and premegakinking magnetizations from the Devonian Comerong Volcanics, New South Wales, Australia, and their bearing on the Gondwana Pole Path. Tectonics, v.5, p. 135-150.

SCOTESE, C.R. 1986. Phanerozoic reconstructions: a new look at the assembly of Asia. University of Texas, Institute for Geophysics Technical Report 66.

SHANNON, P.H., & HENDERSON, S.W., 1966. St Georges Range No. 1 Well completion report. Unpub. Report for Continental Oil Co.

SHAW, J. 1982. Melt-out till in the Edmonton area, Alberta, Canada. Canad. Jour. Earth Sci., v. 19, p. 1548-1569,

SHAW, J. 1977. Sedimentation in an alpine lake during deglaciation, Okanagan Valley, British Columbia, Canada. Geografiska Annalers, v. 59A, p. 221-240.

SHAW, J. 1985. Subglacial and ice-marginal sediments. In: Ashley, G.M., Shaw, J. & Smith, N.D. (Eds.). Glacial sedimentary environments. S.E.P.M. Short Course No. 16 Lecture Notes, 246p.

SHAW, J. 1987. Glacial sedimentary processes and environmental reconstruction based on lithofacies. Sedimentology, v. 34, p. 103-116.

SIMPSON, S. 1956. On the trace fossil Chondrites. Quaterly Journal of the Geol. Soc., v. 448, p. 475-499.

SMITH, N.D. 1970. The braided stream depositional environment: comparison of the Platte River with some Silurian clastic rocks, north-central Appalachians. Bull. Geol. Soc. Amer., v. 81,p. 2993-3014.

STEEL, R.J. & THOMPSON, D.B. 1983. Structures and textures in Triassic braid stream conglomerates ('Bunter' Pebble Beds) in the Sherwood Sandstone Group. North Staffordshire, England. Sedimentology, v. 30, p. 341-167.

STURM, M. 1979. The origin and composition of clastic varves. In. Schluchter, C.H. (Ed.) Moraines and Varves. A.A. Balkema, Rotterdam, p. 281-285.

SUGDEN, D.E., & JOHN, B.S. 1985. Glaciers and Landscape. Edward Arnold, London

THERON, J.N. & BLIGNAULT, H.J. 1975. A model for the sedimentation of the Dwyka glacials in the Southern Cape. In; Campbell. R.S.W. (Ed.) Gondwanan Geology, Canbera University Press, p. 347-701.

THOMAS, G.S.P. 1984. A late Devensian glaciolacustrine fan-delta at Rhosesmor, Clwyd, North Wales. Geology Journal, v. 19, p. 125-141.

TILLMAN, R.W., SWIFT, D.J.P, & WALKER, R.G. 1985. Shelf sand and sandstone reservoirs. S.E.P.M. Short Course 13, 708p.

TOWNER, R.R. 1981. Derby, Western Australia - 1:250,000 Geological Series. Bur. Min. Res. Explanatory Notes SE/51-7.

TOWNER, R.R. 1981. Late Palaeozoic tillites of the Canning Basin, Western Australia. In: Hambrey, M.J., & Harland, W.B. (Eds.) Earths Pre-Pleistocene Glacial Record. Cambridge University Press, Cambridge, p. 449-452..

TOWNER, R.R., CROWE, R.W.A., & YEATES, A.N. 1976. Notes on the geology of the southern part of the Canning Basin. BMR. Record 1976/95.

TOWNER, R.R., & GIBSON, D.L. 1983. Geology of the Onshore Canning Basin, Western Australia. BMR. Bulletin 215.

TRAVES, D.M., CASEY, J.N., & WELLS, A.T. 1956. The geology of the south-western Canning Basin, Western Australia. BMR. Report 29.

VAIL, P.R. 1987. Seismic stratigraphyinterpretation using sequence stratigraphy. Part I: Seismic stratigraphy interpretation procedure. In: Bally, A.W. (Ed.). Atlas of Seismic Stratigraphy. A.A.P.G. Stud. Geol. v. 27(1), p. 1-10.

VAIL, P.R., MITCHUM, R.M. jr. & THOMPSON, S. 1977. Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap. In: Payton, C.E. ed. Seismic Stratigraphy - applications to hydrocarbon exploration. A.A.P.G. Mem. 26, p. 63-81.

VAIL, P.R., TODD, R.G., & SANGREE, J.B. 1977. Chronostratigraphic significance of seismic relfectors. In: Payton, C.E. (Ed.) Seismic Stratigraphy- applications to hydrocarbon exploration : A,A.P.G. Mem. 26, p. 94-116.

VAN WAGONER, J.C., MITCHUM, R.M., POSAMENTIER, H.W. & VAIL, P.R. 1987 Seismic stratigraphy interpretation using sequence stratigraphy. Part 2: Key definitions of sequence stratigraphy. In: Bally, A.W. (ed.) Atlas of Seismic Stratigraphy. A.A.P.G. Stud. Geol., 27(1), p. 11-14

VAN WAGONER, J.C., POSAMENTIER, H.W., MITCHUM, R.M., VAIL, P.R., SARG, J.F., LOUTIT, T.S., & HARDENBOL, J. 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. S.E.P.M. Spec. Pub. 42, p. 40-45.

VEEVERS, J.J. 1984. Phanerozoic earth history of Australia. Clarendon, Oxford, England. 418 p.

VEEVERS, J.J. 1988. Morphotectonics of Australia's Northwestern Margin: A Review. In: Purcell, P.G. & R.R (Eds.) The North West Shelf, Australia. Proc. Pet. Expl. Soc. Aust. Symp. Perth.

VEEVERS, J.J. & POWELL, C. McA. 1987. Late Paleozoic glacial episodes in Gondwanaland refected in transgressive-regressive depositional sequences in Euramerica. Geol. Soc. America. Bull., v. 98, p. 475-487.

VEEVERS, J.J., & WELLS, A.T. 1961. The geology of the Canning Basin, Western Australia. B.M.R. Bulletin, 60.

VISSER, J.N.J. 1982. Upper Carboniferous glacial sedimentation in the Karoo Basin near Prieska, South Africa. Palaeogeography, Paleaoclimatology, Palaeoecology, v. 38, p. 63-92.

VISSER, J.N.J. 1983. Glacial-marine sedimentation in the Late Paleozoic Karoo Basin, Southern Africa. In: Molnia, B.F., (ed.) Glacial-marine sedimentation. New York Plenum Press, p. 667-702.

VISSER, J.N.J. 1983. Submarine debris flow deposits from the Upper Carboniferous Dwyka Formation of the Kalahari Basin, South Africa. Sedimentology, v. 30, p. 511-523.

VISSER, J.N.J., COLLINSTON, W.P., & TERBLANCHE, J.C. 1984. The origin of soft-sediment deformation structures in Permo-Carboniferous glacial and proglacial beds, South Africa. Journal of Sedimentary Petrology, v. 54, p. 1183-1196.

VISSER, J.N.J., & HALL, K.J. 1985. Boulder beds in the glaciogenic Permo-Carboniferous Dwyka Formation in South Africa, Sedimentology, v. 32, p. 281-294.

VISSER, J.N.J., & LOOCK, J.C. 1982. An investigation of the basal Dwyka Tillite in the southern part of the Karoo Basin, South Africa. Trans. Geol. Soc. South Africa., v. 85, p. 179-187.

VISSER, J.N.J., & KINGSLEY, C.S. 1982. Upper Carboniferous glacial valley sedimentation in the Karoo Basin, Orange Free State. Trans, Geol. Soc. S. Africa, v. 85, p.71-79.

VON BRUNN, V. 1980. Sedimentary facies related to the Late Paleozoic (Dwyka) deglaciation in the eastern Karroo Basin, South Africa. Fifth International Gondwana Symposium, Wellington, New Zealand, p. 117-123.

VON BRUNN, V., & STRATTEN, T. 1981. Late Palaeozoic tillites of the Karoo Basin of South Africa. In: Hambrey, M.J., & Harland, W.B. (eds). Earths Pre-Pleistocene Glacial Record,. Cambridge University Press. p. 71-79.

WALKER, R.G. 1983a. Cardium Formation 2. Sand-body geometry and stratigraphy in the Caroline-Garrington area, Alberta - The "ragged blanket" model. Bull. Canadian Petroleum Geology, v. 31, p. 14-26.

WALKER, R.G. 1983b. Cardium Formation 3. Sedimentology and stratigraphy in the Caroline-Garrington area, Alberta. Bull. Canadian Petroleum Geology, v. 31, p. 213-230.

WALKER, R.G. 1984a. Facies models. Geoscience Canada, Reprint Series 1

WALKER, R.G. 1984b. Turbidites and associated coarse clastic deposits. In: Walker, R.G. (Ed.). Facies models. Geoscience Canada, Reprint Series 1, p. 171-188.

WALKER, R.G. 1985. Cardium Formation at Ricinus Field, Alberta: A channel cut and filled by turbidity currents in Cretaceous Western Interior Seaway. A.A.P.G. Bull.,v. 69, p. 1963-1981.

WENTWORTH, C.K. 1922. A scale grade and class terms for clastic sediments. Jour. Geol. Soc. v. 30, p. 377-392.

WILLIAMS, B.P.J. & WILD, E.K. 1984. The Tirrawarra Sandstone and Merrimelia Formation of the southern Cooper Basin, South Australia - the sedimentation and evolution of a glaciofluvial system. Journal of the Australian Petroleum Exploration Association, v. 24, p. 377-392.

WILLIAMS, G.E. 1971. Flood deposits of the sand-bed ephemeral streams of Central Australia. Sedimentology, 17, 1-40.

WOPFNER, H. 1981. Development of Permian intracratonic basins in Australia. In: Cresswell, M.M., & Vella, P. (Eds.) Gondwana Five. A.A. Balkema, Rotterdam, p. 185-190.

WOOLNOUGH, W.G. 1933. Report on aerial survey operations in Australia during 1932. Aerial geology geophysics survey, North Australia, Canberra.

YEATES, A.N., CROWE, R.W.A., TOWNER,R.R., WYBORN, L.A., & PASSMORE. V.L. 1975. Notes on the geology of the Gregory Sub-basin and adjacent areas of the Canning Basin, Western Australia. B.M.R. Record 1975/77.

YEATES, A.N., GIBSON, D.L., TOWNER, R.R., & CROWE, R.W.A. 1984. Regional geology of the onshore Canning Basin. In: PURCELL, P.G. (ed.) The Canning Basin, W.A.: Proceedings of the Canning Basin Symposium, Perth, 1984. Geological Society of Australia and Petroleum Exploration Society of Australia, p. 521-531.