THE STRUCTURE, SEDIMENTOLOGY, SEQUENCE STRATIGRAPHY AND TECTONICS OF THE NORTHERN DRUMMOND AND GALILEE BASINS, CENTRAL QUEENSLAND, AUSTRALIA

Volume I

Thesis submitted by
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ABSTRACT

The Late Devonian-Early Carboniferous Drummond Basin and overlying Late Carboniferous-Middle Triassic Galilee Basin are extensive intracratonic basins with predominantly fluvial sediment infill. They are inferred to have developed on Proterozoic and Early Palaeozoic basement similar to the adjacent Charters Towers Province and Anakie Inlier. Depositional and structural architecture of the basins have been investigated through a combination of seismic, geophysical well log and gravity data sets with lithologic information obtain from well cores, surface mapping and sedimentary petrography.

Comprehensive interpretation of 750 km of seismic traverse resulted in the recognition of eleven seismic facies, several of which have distinctive internal signatures, separated by reflection boundaries that can be traced basin wide. Lithologic and geophysical logs from sixteen wells and boreholes can be matched to seismic stratigraphic units and allow the basinal infill to be described in terms of the lithostratigraphic frameworks already established in the literature. The construction of structure contours for unit boundary surfaces has identified extensional structures associated with rift phases of basinal development and the pattern of thrust and thrust fold features associated with basin inversion. Eleven new structural features that have continuity through the Drummond and Galilee Basins have been defined and other features noted in the literature have been reinterpreted based on evidence from seismic profiles. The construction of isopachs for each unit has allowed tracking of basinal infill thickness trends through time.

Analysis of geophysical and lithologic logs from petroleum wells and boreholes, augmented by sections documented from surface exposure has resulted in the recognition of some 16 discrete sequences, each based on a repeating pattern of three types of non-marine systems tract that mainly reflect basinal tectonics but also the influence of climate and eustatic sea level change. Both basins share a common style of sequence development that is not reflected in the current literature.

Provenance interpretation based on petrographic data from 121 thin sections representative of most of the Drummond Basin and all of the Galilee Basin suggests that

the majority of basin infill was derived from a recycled cratonic source, such as the Thomson Fold Bel to the west, and less material derived from an eastern volcanic arc than previously thought. However SHRIMP-derived U-Pb age data for zircon populations from two samples broadly representative of quartz arenites prominent in the basinal successions conflict with this view. Such data for a sample from the Mount Hall Formation of the Drummond Basin indicates that its source was largely from Early to Mid Palaeozoic igneous terranes like those represented in the Charters Towers Province to the north and inferred for the Thomson Fold Belt to the west. Zircon ages of a sample of Warang Sandstone of the Galilee Basin indicates a Late Palaeozoic igneous source, with derivation largely from an eastern magmatic arc.

The Drummond Basin commenced as a back-arc extensional basin, progressed through a thermal sag phase and ceased development during mild compression associated with a far-field expression of the Kanimblan Orogeny. Structural patterns show initial rift architecture, with compartments separated by newly defined transfer fault zones. Extensional faults between the transfer structures extend further through the basinal succession than previously thought. This basin developed a broad sag phase but the final stages show a foreland influence induced by Kanimblan thrust loading on its eastern margin. Basinal structure has been strongly modified by inversion in the Middle Triassic associated with the Hunter-Bowen Orogeny.

The Galilee Basin commenced as a foreland basin expressing continuity with the late-stage development of the underlying Drummond Basin from which its division is arbitrary and based on historical misconceptions of Kanimblan tectonism. Thermal subsidence related to the rift phase of the Drummond Basin continued as an influence in addition to foreland subsidence. Tectonic quiescence marks a mid-stage of basinal development reflected in a regionally developed paraconformity and deposition of a basinwide coal measure sequence related to eustatic sea level rise over a stable substrate. The upper part of Galilee Basin infill reflects a foreland phase of development and records two episodes of thrust loading on the eastern margin associated with the Hunter-Bowen Orogeny.

Ongoing crustal contraction during the Hunter-Bowen Orogeny resulted in inversion of the Drummond and Galilee Basins with the development of large-scale thrust dislocations and associated fault bend anticlinal structures. The Middle Triassic Clematis Group is the youngest unit that shows folding due to inversion. Much of the western parts of both basins remain relatively undisturbed apart from gentle regional pre-Middle Jurassic tilting that marked the final phase of Hunter-Bowen tectonism.

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1.0 INTRODUCTION

1.1 Research Objectives

The Late Devonian-Early Carboniferous Drummond Basin and overlying Late Carboniferous-Middle Triassic Galilee Basin are large intra-cratonic terrestrial basins in central Queensland, Australia (Figure 1.1). They comprise part of an active continental margin assemblage, inboard of the New England Orogen, which developed along eastern Gondwana in the Late Palaeozoic-Early Mesozoic. The stratigraphic framework of the Drummond Basin was first established on its southern margin by petroleum explorers. This framework and the developed structural fabric were extended over its eastern outcrop margin by a regional mapping programme undertaken by government agencies between 1964 and 1973. General syntheses of the Drummond Basin were undertaken by de Bretizel (1966) based on petroleum surveys and Olgers (1972) based on systematic regional mapping. The tectonic development of the Drummond Basin was evaluated by de Caritat and Braun (1991), Johnson and Henderson (1991) and Davis and Henderson (1996) but these contributions mainly concentrate on the seismic imaging and mapping of the basal stratigraphic interval of the basin. To date no detailed investigation has been undertaken of the subsurface structure and stratigraphy of the Drummond Basin. The Galilee Basin extensively overlies the Drummond Basin but outcrop is limited to its northern and southern margins. A broad overview of the structure and stratigraphy of this feature has developed from regional mapping associated with that of the Drummond Basin, seismic surveys and interpretation of key wells. The tectonic development of the Galilee Basin is discussed by Evans and Roberts (1980) and Veevers et al. (1982) but conclusions were based on limited data sets. Their research was carried out prior to the development of new seismic and sequence stratigraphic conceptual models (Payton 1977 ; Brown and Fisher 1980) that are now widely used to evaluate basinal development.

A multidisciplinary approach has been taken in this revision of the structure, lithostratigraphy and tectonic development of the northern part of the Drummond and Galilee Basins. A new seismic facies interpretation of relatively modern seismic profiles has been undertaken to determine the geometry of seismic units and detailed subsurface structure in the Drummond and Galilee Basins. This interpretation has been tied to a revision of the lithofacies determined from downhole electric logs and stratigraphic cores. No seismic sequences were defined as regional unconformities that bound these sequences were unable to be determined from seismic profiles that did not intersect regional basin margins. An interpretation of parasequence stacking patterns derived from geophysical well logs resulted in the development of a systems tract model of the depositional history of both basins. The order of these systems tracts defined depositional sequences bound by unconformities or hiatal surfaces. Petrofacies analysis of selected outcrop and core samples, reinforced by limited zircon age data, was undertaken to determine the provenance of the sediment infill of the basins. Synthesis of the seismic and lithologic data results in a new detailed tectonic model for the development of the northern Drummond and Galilee Basins.

This study hopes to achieve the construction of a new subsurface stratigraphic framework that can be linked to outcrop. The development of detailed structure contour maps will show the tectonic overprint of regional orogenic events, particularly the Kanimblan and Hunter-Bowen Orogenies. Construction of detailed isopach maps and undertaking of comprehensive provenance studies will result in the understanding of the stratigraphic relationships between the northern Drummond and Galilee Basins. The analysis of this structural and stratigraphic data will result in a new tectonic model of basinal development beyond that stated in the current literature.

1.2 Crustal Context of the Drummond and Galilee Basins

The Drummond and Galilee Basins are a broader basinal system that overlies Cambrian-Ordovician crystalline basement of the Thomson Fold Belt (Scheibner and Veevers 2000) to the west of penecontemporaneous magmatic arc systems of the New England Orogen (Figures 1.2, 1.3). The development of the Galilee Basin is partly synchronous with the formation and infill of the Bowen Basin.

1.2.1 Basement Terranes

The Thomson Fold Belt is part of the Tasman Orogenic Zone that accreted onto the Australian Proterozoic craton east of the Tasman Line during the early Phanerozoic. Although it is largely a subsurface feature, a northeast structural grain is indicated for it by basement topography, gravity and aeromagnetic trends and basement-related structures in the cover rocks (Murray and Kirkegaard 1978; Evans 1980). Fine-grained metasediments with radiometric dates spanning the Cambrian and Ordovician Periods were intersected in wells drilled to basement (Murray 1994; Scheibner and Veevers 2000).

Exposed portions of the Thomson Fold Belt occur in the Charters Towers Province of Henderson (1980) and the Anakie Inlier. Within the Charters Towers Province Late Mesoproterozoic-Cambrian metasedimentary terranes include the Cape River, Argentine and Running River Metamorphics which have similar psammo-pelitic protoliths with subordinate altered mafic rocks. The metamorphic grade for these units ranges from upper greenschist to upper amphibolite and their overall structural grain is northwest (Withnall and Hutton 1997). The structure of the Cape River Metamorphics developed in three deformation events occurring between 500 Ma and 460 Ma (Withnall et al. 1997). The main fabric, crS_2, initially had a shallow dip but is folded by crS_3 so that the dominant structural grain is NW/SE. The Cape River Metamorphics are cut by NE to E-directed faults.

The southern part of the Charters Towers Province is occupied by the Late Cambrian-Ordovician Seventy Mile Range Group. This unit contains a lower assemblage of immature terrigenous clastics succeeded by an upper assemblage of acid to intermediate volcanics and volcaniclastics associated with a continental back-arc basin (Henderson 1986). Metamorphic grade is sub-greenschist-pumpellyite facies with locally developed greenschist and hornsfels associated with emplacement of the Middle Ordovician-Silurian Ravenswood Granodiorite Complex (Berry et al. 1992). The structural grain of the Seventy Mile Range Group is easterly but the group has been dismembered and deformed by emplacement of the Ravenswood Granodiorite Complex. Three deformation events are recognised in the Seventy Mile Range Group (Berry et al. 1992) but the ages of thD_1, thD_2 and thD_3 are not precisely known. The dominant thS_2 foliations indicate that it, in general, is part of a S-facing limb of a thF_2 fold. Locally developed thS_3 foliations parallel NE and E/NE-trending faults that are prominent in the Seventy Mile Range Group (Henderson 1986).

The Anakie Inlier is dominated by the Anakie Metamorphic Group consisting of psammo-pelitic metasediments and mafic meta-igneous rocks that are multiply deformed (Withnall et al. 1995). The original age of the Anakie Metamorphic Group is uncertain but U/Pb age information for detrital grains indicates that it is probably Neoproterozoic to Middle Cambrian suggesting that continental crust of this age extended to the south of the Charters Towers Province (Withnall et al. 1996; Fergusson et al. 2001). The older age is associated with the Bathampton Metamorphics the protolith of which is interpreted as part of a passive margin eastward of a Grenville-aged craton (Fergusson et al. 2001). These rocks are correlated with the non-volcanic portion of the Adelaide Fold Belt and Wonominta Block in NSW. The younger age is associated with the Wynyard Metamorphics correlated by Crawford (1997) with volcanic successions in the Wonominta Block and related to Cambrian rifting. Three deformation events are recognised within the Anakie Metamorphics by Withnall (1995). The dominant foliation in the Anakie Metamorphic Group is regarded as D_2 trending NW/SW with D_1 fabrics represented as parallel to relict bedding. The age of D_2 is considered to be Cambrian, based on a K/Ar muscovite age of 510 Ma obtained by Withnall et al. (1996) who interpreted it to represent the Delamerian Orogeny that produced deformation in the Adelaide Fold Belt. The D_2 foliation was originally flat-lying but was folded in D_3 producing a set of NE-trending upright folds contemporaneous with large SE-trending faults that appear to be accommodation structures (Withnall 1995). The age of D_3 is unknown but Early Devonian cover sequences unconformable on the Anakie Metamorphic Group are also folded. The deformation is associated with the Tabberabberan Orogeny. Withnall (1995) argues that the predominant westerly dip, easterly vergence and southwest over northeast shear sense of the Anakie Metamorphic Group support thrust related deformation. Airborne geophysical and airphoto interpretation of the Anakie Inlier has produced two distinct lineament patterns for the Anakie Metamorphic Group. E/NE and E/SE trends are most prominent with subordinate northeasterly and southeasterly sets (Withnall 1995). To the east, in the adjacent Bowen Basin and basement terranes, E/NE-trending lineaments are corridors associated with transfer faults related to early half graben development in the Bowen Basin. These faults were later utilised as lateral ramps and tear faults during Triassic thrusting (Hammond 1987).

On the southern outcrop margin of the Anakie Inlier a linear zone of arenite, limestone and minor mafic volcanics comprise the Late Ordovician Fork Lagoon beds (Anderson and Palmieri 1977; Palmieri 1978). This unit has a complex set of tight folds and major bounding fault zones. The structural fabric within the Fork Lagoon beds is generally NE, parallel to the contact with the Anakie Metamorphic Group. Deformation of the Fork Lagoon beds may be Middle Devonian in age, associated with syntectonic emplacement of the adjacent Retreat and Taroborah Batholiths (Withnall 1995). Limited foliation and lineation measurements on the bounding faults suggest that the dominant movement may be strike-slip.

1.2.2 Late Palaeozoic Rocks

Rock assemblages of central Queensland in late Palaeozoic time reflect episodes of large-scale basin development. The Devonian Adavale Basin is a rift related, predominantly non-marine basin located inboard of a convergent plate boundary indicated by silicic volcanics in rocks of the New England Orogen (Remus and Tindale 1988; Scheibner and Veevers 2000). The present basin is an erosional remnant of a more extensive system (Passmore and Sexton 1984). It lies beneath the Galilee Basin and predates the subjacent Drummond Basin. Devonian intermediate volcanics and sediments, comprising the Theresa Creek Volcanics, Dunstable Volcanics, Ukalunda beds, Sedgeford Formation, Douglas Creek Limestone and Glendarriwell beds, within the Anakie Inlier represent remnant successions of a later back-arc basin (Henderson et al. 1995). The Belyando Basin, a rift-sag feature recognised from geophysics underlying the northern part of the Drummond Basin (Draper et al. 2004) and the Timbury Hills Formation on the Roma Shelf (Scheibner and Veevers 2000) may represent successions related to the Adavale Basin. A Middle Devonian compressive episode is evidenced by an angular discordance within the sequence of the Adavale Basin (Passmore and Sexton 1984; Remus and Tindale 1988). An episode of regional-scale plutonism overlaps with the formation of the Adavale Basin and related sequences. It is represented by the Retreat and Taroborah Batholiths that occupy the southern portion of the Anakie Inlier. This multi-phase intrusive complex contains calc-alkaline acidic to basic suites (Crouch et al. 1994). A K-Ar date of 352-379 Ma (Webb et al. 1963) and a Rb-Sr date of 366-385 Ma (Crouch et al. 1995) have been determined for the Retreat Batholith. The adjacent Taroborah Batholith has a K-Ar age of 372-374 Ma (Webb et al. 1963). Magnetic and topographic lineaments in the Retreat Batholith show two trends, a NW set and a NE set. The arcuate NW-trending Kettle Creek Fault that separates the Retreat Batholith from the Anakie Metamorphic Group shows about 3km of sinistral displacement (Withnall 1995). This direction is similar to N/NW extensional structures in the Adavale Basin. A Late Devonian (Frasnian-Fammenian) compressive episode, linked to Tabberabberan orogenesis, resulted in a regional unconformity in basinal elements of the New England Orogen and inverted the Adavale Basin (Passmore and Sexton 1984; Henderson and Davis 1998; Murray et al. 2003). An alternative view places the final deformation of the Adavale Basin at the same time as the Late Carboniferous inversion of the Drummond Basin (Remus and Tindale 1988; Scheibner and Veevers 2000). This compression induced folding of Early Devonian strata and local deformation of the Retreat Batholith in the Anakie Inlier (Murray 1986; Blake et al. 1995). The main deformation trends NE/SW within the Adavale Basin. This is similar to NE-trending lineaments that offset the Kettle Creek Fault in the Retreat Batholith.

The Emsian to Visean-?Namurian Burdekin Basin is a terrestrial and marine back-arc basin overlying basement of the Charters Towers Province. It developed as a result of back-arc extension with a transtensional component (Draper and Lang 1997). Initial rift infill was followed by a thermal relaxation phase in the Tournaisian and finally a renewed phase of rifting. In the Middle or Late Carboniferous, compression of the basin developed large scale, slightly asymmetric folds and normal faults, active during deposition, were reactivated and reversed. In the northern part of the basin the structural trends are E/NE with minor N/S trends, whereas in the southern part of the basin the folds and faults trend NW. In the Late Carboniferous-Early Permian calc-alkaline, I-type subduction-related igneous rocks intruded the basinal assemblage and represent the magmatic arc developed within the Northern New England Orogenic Zone (Henderson 1980).

The Late Devonian-Early Carboniferous Drummond Basin developed as an extensional back-arc basin within an active margin assemblage inboard of a westerly dipping subduction zone (Johnson and Henderson 1991; De Caritat and Braun 1992). The extensional phase of the Drummond Basin is controlled by NW-trending listric faults which are truncated by an E/W-trending northern margin and N/S trending eastern margin. (Johnson and Henderson 1991; De Caritat and Braun 1992; Henderson and Davis 1993; Davis and Henderson 1996). These authors interpret dislocations orthogonal to this trend as transfer faults. A Late Carboniferous deformation event, thought to be linked to the Kanimblan Orogeny, terminated sedimentation of the

Drummond Basin (Olgers 1972; Fenton and Jackson 1989; Johnson and Henderson 1991; Withnall et al. 1995). Folds within Drummond Basin strata appear to be strongly controlled by the orientation of the contact of the basin margin and the Anakie Inlier. In the northern region of the basin NE-oriented folds are associated with the Mt Elsie Fault Zone whilst south of the Scartwater Salient the trend is northerly. In the southern region fold axes are NW, parallel to the basin margin Chinaman Fault. To the south the folds trend NNE in the Bogantungan Embayment.

Johnson and Henderson (1991) and De Caritat and Braun (1992) marked the position of the related magmatic arc in the Northern New England Orogen as the Connors Arch but radiometric zircon dating by Allen et al. (1998) indicate that igneous rocks in the tract are largely of Late Carboniferous-Early Permian age. The Yarrol and Campwyn Terranes, to the east of the Connors Arch, have been interpreted as representing a forearc basin developed contemporaneously with the Connors Arch (Day et al. 1978; Fergusson et al. 1994; Murray et al. 2003) or a backarc basin related to crustal melting and extension associated with the opening of the Drummond Basin (Bryan et al. 2001). Holcombe et al. (1997) proposed that all the post-Early Carboniferous magmatic provinces of the Northern New England Orogen are associated with an eastwards rollback of the subduction zone and that all onshore basins developed in a backarc setting. U-Pb zircon analysis of silicic volcanics in the Campwyn Terrane produced dates of *ca* 360-350 Ma (Bryan et al. 2004) matching those of silicic volcanics in the Drummond Basin (Henderson et al. 1998). In the Campwyn Terrane the Early Carboniferous (Tournaisian) Edgecumbe beds comprise shallow marine sediments and acid volcanics (Brown 1963 ; Paine and Cameron 1972) east of a magmatic arc system.

The Early Permian-Middle Triassic Bowen and Late Carboniferous-Middle Triassic Galilee Basins are related features that also developed inboard of the New England Orogen. The Galilee Basin extensively overlies the Drummond Basin and has been variously considered to be a pull apart basin related to shearing along the eastern margin of the Drummond Basin (Evans and Roberts 1980), a pericratonic basin (Veevers et al. 1982) or a foreland basin (De Caritat and Braun 1992). To the west it onlaps early Palaeozoic basement of the Maneroo Platform and overtops the Beryl Ridge extending into the Lovelle Depression (Vine 1976; Evans 1980). In the south, the Galilee Basin has a fault controlled boundary with the Early Permian-Middle Triassic Cooper Basin and merges with the Early Permian-Middle Triassic Bowen Basin on the Springsure Shelf (Gray 1976). For the Bowen Basin three phases of tectonic development are recognised based on stratigraphic packaging, sediment dispersal patterns and sandstone petrology (Fielding 1990; Fielding et al. 1995). An Early Permian phase of extension and magmatic activity that resulted in the widespread deposition of volcanogenic sediments in eastern parts may have commenced as early as Late Carboniferous and be responsible for the Late Carboniferous-Early Permian igneous activity, such as the Bulgonunna Volcanics, widespread in the Northern New England Orogen. An early Late Permian episode of thermal subsidence and a Late Permian to Middle Triassic phase of foreland loading and contractional deformation followed. Inversion in the Middle Triassic resulted in tilting of the Galilee Basin (Evans 1980; Smart and Senior 1980), associated with the last stages of the Hunter-Bowen Orogeny that also affected the Bowen Basin.

1.3 Prior Studies of the Drummond and Galilee Basins

The Late Devonian-Middle Carboniferous Drummond and Late Carboniferous- Middle Triassic Galilee Basins are very large scale intracratonic systems collectively covering an area of 285,000 km^2 in central Queensland. They were both recognised from regional geologic studies in the early 1950's and knowledge of them has been progressively built by a number of subsequent studies. Both basins are poorly exposed on their eastern margins, the Drummond Basin being extensively overlapped by the Galilee Basin which in turn is extensively overlain by the Early Jurassic-Late Cretaceous Eromanga Basin. Broadscale definition of the Drummond and Galilee Basins has derived from regional mapping combined with interpretation of seismic profiles, well cores and downhole logs.

1.3.1 Drummond Basin

Drummond Basin lithostratigraphy was first described from outcrop in its southern part (Anon 1952). A comprehensive stratigraphic evaluation of the basin was first provided by de Bretizel (1966) based on regional surveys related to petroleum exploration. Systematic 1:250,000 scale regional geological mapping of central Queensland by Mollan (1967), Olgers (1969a; 1969b, 1970), Malone (1969), Clarke and Paine (1970), Exon (1970), Vine and Doutch (1972), Paine and Cameron (1972) and Senior (1973) instituted by the Australian Bureau of Mineral Resources and Geological Survey of Queensland greatly improved knowledge. A comprehensive compilation of the stratigraphy, facies architecture and basin morphology by Olgers (1972) followed the regional mapping program. Limited seismic interpretation of stratal continuity of the Drummond Basin was provided by Pinchin (1978) and Fenton and Jackson (1989). Subsequent studies centred on mineral exploration (Hutton 1989; Wells et al. 1989; McPhie et al. 1990; Oversby et al. 1990; Sennitt 1991; Goulevitch 1992; Bobis 1992; Bobis et al. 1995; Bolt 2001), structural analysis (Johnson and Henderson 1991; De Caritat and Braun 1992; Henderson and Davis 1993; Henderson and Davis 1995; Henderson et al. 1998) and specific basin studies (Bennedick 1993; Oversby et al. 1994; Alexander 1997; Goddard 2003).

1.3.1.1 Stratigraphy of the Drummond Basin

The Drummond Basin west of the Anakie Inlier can be divided into a northern and southern region based on stratigraphic differentiation and structural patterns (Figure1.4). Olgers (1972) recognised three cycles of basinal infill which he considered to be separated by minor epeirogenic events. No unequivocal evidence of disconformity between the cycles has been documented. Each cycle commenced with deposition of coarse sediments and ended with a fine grained facies. Cycle 1 is characterised by volcanic and volcaniclastic strata. Cycle 2 is characterised by quartzose sandstone and renewed tectonism with associated hinterland uplift and volcanism initiated Cycle 3, characterised by volcaniclastic sandstone and tuff.

(i) Northern Region

In the northern region the basal Cycle 1 sequence is complex and has local facies variations. The basal St Anns Formation, which unconformably overlies Ukalunda beds and older basement, can be subdivided into three parts, a basal conglomeratic unit, a unit of interbedded lithic sandstone, mudstone, chert and algal limestone and an upper sequence of acid tuff, algal limestone and pelite. Locally, such as an epithermal gold prospect at Yandan, andesite is included (Goulevitch 1992). Zircon dates obtained for the St Anns Formation were not useful due to inheritance but a review of biostratigraphic assemblages accords a Late Devonian-Early Carboniferous age. In the type area near St Anns Homestead the uppermost part of the St Anns Formation is separated as the Llanarth Volcanic Member.

Cycle 2 is characterised by quartzose sandstone and consists of the Scartwater and Mount Hall Formations. Units mapped as Raymond Formation by Olgers (1970) are reassigned here to the Mount Hall Formation based on seismic and outcrop continuity. The Scartwater Formation consists of fluvial feldspatholithic quartz sandstone interbedded with mudstone. Minor beds of algal limestone, conglomerate, tuff and lithic sandstone are also present. Early Carboniferous macroflora are present in the Scartwater Formation. The unit shows lateral facies variation and shows a gradational contact to the overlying Mount Hall Formation that comprises cross-stratified quartzose conglomerate and pebbly sandstone.

The basal Star of Hope Formation of Cycle 3 is basinwide in distribution except for a local absence in the southern region. The unit consists of varicoloured volcanolithic sandstone, quartz-pebble conglomerate and tuff. Near the northeast basin margin mudstone and siltstone are interbedded with sandstone (Alexander 1997) and in-situ fossil tree trunks have been reported (Olgers 1972). In the north, Cycle 2 and the Star of Hope Formation were interpreted by Olgers (1972) to onlap onto the basin margin. The Bulliwallah and Natal Formations complete Cycle 3. The former consists of interbedded feldspatholithic quartz sandstone and olive green mudstone with interbeds of tuff and volcanolithic sandstone. The latter consists of a monotonous sequence of interbedded feldspathic quartz sandstone and olive green siltstone and mudstone. Traces of fossil fish have been found in the Natal Formation (Turner and Cook 1999). Contacts between Cycle 3 units are conformable.

(ii) Southern Region

In the southern region of the Drummond Basin, Cycle 1 is represented by the Silver Hills Volcanics, comprising of acid flows, pyroclastics and lithic sandstone. This unit unconformably overlies the Anakie Metamorphic Group, the Retreat Batholith and the Dunstable Volcanics. Perkins et al. (1995) provided U/Pb SHRIMP ages from 351.2 ± 4.0 Ma to 357.4 ± 3.3 Ma from the Silver Hills Volcanics, at Twin Hills and Lone Sister, near the northern limit of their distribution. U-Pb zircon SHRIMP ages of 343.7± 5.3 Ma and 349.2 ± 7.1 Ma and a K-Ar age of 344 ± 3 Ma were obtained for the Silver Hills Volcanics by Henderson et al. (1998) in the Red Rock-Wynyard area. This data suggests that deposition of the volcanics and volcaniclastic sediments of the Silver Hills Volcanics took place over a short interval in the Late Devonian-Early Carboniferous.

The Telemon Formation commences Cycle 2 and comprises basal volcanolithic conglomerate and sandstone with finer-grained strata and thin algal limestone interbedded higher in the succession. Olgers (1972) considered the volcanic clasts of the conglomerate to be derived from the underlying Silver Hills Volcanics by erosion, rather than intraformational in character, and consequently considered the lower contact of the Telemon Formation to be disconformable. The Mount Hall Formation has a lithology similar to that found in the northern region. Deposition of the Raymond Formation completed Cycle 2. This unit consists of flaggy quartzose sandstone and mudstone and is little different in lithology from the Mount Hall Formation. The conchostracan *Leaia* has been described from the Raymond Formation by Tasch (1979) and dates the unit as Tournaisian or early Visean in age. The unit conformably overlies the Mount Hall Formation and where the latter is absent rests disconformably on older sediments.

The Star of Hope Formation and Ducabrook Formation comprise Cycle 3. The Star of Hope Formation in the southern region has a similar stratigraphy to the northern region except in the Springsure area where a hiatus between the Raymond Formation and uppermost Ducabrook Formation was recognised by Mollan (1967). The Ducabrook Formation comprises a thick unit of interbedded quartzose sandstone and mudstone with minor beds of acid tuff, reworked tuff, conglomerate and limestone. Abundant fish scales and a Visean tetrapod fauna have been documented from it by Thulborn et al. (1996).

1.3.1.2 Structure of the Drummond Basin

Previous regional evaluations have recognised a population of inversion structures for the Drummond Basin. The Bogantungan Embayment (Olgers 1972) comprises a series of open, dome and basin folds and flexures within the southern Drummond Basin succession (Figure 1.5). These folds have a N-NE trend. Fold structures that outcrop in anticlinal cores or have resistant dipping units are named because of their size and continuity. They are broadly symmetrical about their axes except the Telemon Anticline and the Mount Beaufort Anticline which are asymmetrical with a steeper eastern flank

(Mollan 1967; Exon 1970). The Mount Beaufort Anticline has a NE-SW axial trend. A similar trend is present in Galilee Basin structures overlying the Adavale Basin to the southwest.

Field mapping and interpretation of seismic data show that major listric faults bound the Drummond Basin to the west of the Anakie Inlier (Johnson and Henderson 1991; De Caritat and Braun 1992; Davis and Henderson 1996). The NW-trending Chinaman Fault is an example of these extensional faults. Dislocations of the extensional structural grain that trend NE-SW have been interpreted as major transfer faults (Johnson and Henderson 1991; Davis and Henderson 1996) inducing complex subsidence of fault blocks in the basinal floor. The Mt Elsie Fault, northwest of the Anakie inlier, is a possible transfer fault system. A gravity gradient, called the Belyando Feature (Vine 1972) extends in a N-NW direction from the Bogantungan Embayment and marks the western outcrop limit of Drummond Basin sediments. This gradient indicates that basin cover shallows to the east approaching the Anakie Inlier. Vine (1972) associated the Mingobar Monocline and White Mountains Structure further to the north as structural expressions of this gravity gradient. The Koburra Trough was interpreted by De Caritat and Braun (1992) as a series of extensional half-graben compartments. Johnson and Henderson (1991) showed that the northern end of the gravity gradient consists of a compressional block-fault structure, the Belyando Structure, which changes character to the north where it becomes a gentle monocline. As this fault was interpreted to extend into the basement it was considered to be a thick-skinned component of compressional deformation (Johnson and Henderson 1991). Some of the faults affecting the Drummond Basin, in particular the Belyando Structure, propagate into the overlying infill of the Galilee Basin. Structural elements east of the Belyando Feature trend north-northwest, parallel to the strike of the gravity gradient. Pinchin (1978) interpreted the Beresford Upwarp as an arch that is composed of a population of normal faults at depth that were synactive with Drummond Basin infill. He considered the associated Donnybrook Gravity High to be caused by a body of deep-seated dense rock. A westerly propagating, deep-seated thrust system to the west of the Beresford Upward affected only Drummond Basin infill.

Northward of the Beresford Upwarp the style of folding changes from simple, broad open structures to an arcuate belt of complexly folded and faulted sediments termed the

Scartwater Salient by Olgers (1972). Transform faults trending NE-SW were inferred at the northern and southern boundaries of the belt by Johnson and Henderson (1991). Fold trends drape around the projecting northwestern margin of the Anakie Inlier and follow its northern boundary. This pattern may be explained by relative dextral translation of the Charters Towers Province and Anakie Inlier basement blocks. Three structural domains were established by Olgers (1970) for the Scartwater Salient. Domain D_1 is a narrow zone adjacent to the Anakie Inlier where bedding generally dips west and has not been folded. Some clockwise rotation and upward displacement of strata along the St Anns Fault has occurred and may be a reflection of shearing strain associated with wrench faulting. This large fault was interpreted by Olgers (1972) as a left reverse oblique slip fault similar in style to the Chinaman Fault and is part of a larger structure, the St Anns Megashear. Domain D_2 is located west of the St Anns Fault and is characterized by tight dome-and-basin folding and extensive faulting. The folds are symmetric and chevron style with abrupt closures and amplitude decreases to the west. Domain D_3 to the west is characterized by gentle folding and extensive faulting. Here synclines are interpreted by Olgers (1972) as symmetrical whereas anticlines are asymmetrical with steeper western flanks. Fold axes trend N-NW and include the Bulliwallah and Blowhard Synclines and the Bingeringo and Hopkins Anticlines. One anticline was mapped as having an overturned western limb. Olgers (1972) considered that a décollement was developed at the base of the Drummond Basin infill west of the St Anns Fault with folding restricted to the thrust sheet above this structure.

1.3.2 Pretoria Basin

The Late Devonian and Early Carboniferous succession east of the Anakie Inlier was previously considered to be part of the Drummond Basin by Olgers (1972) but it has a different stratigraphic framework to the succession on the western margin of the Anakie Inlier. It is treated here as a discrete basin in its own right, and named the Pretoria Basin after Pretoria Hill, a prominent physiographic feature within it.

1.3.2.1 Stratigraphy of the Pretoria Basin

The Pretoria Basin has a stratigraphic succession different to the Drummond Basin (Figure1.6) and is physically separated from it by the Anakie Inlier. A NE trending basement ridge marks the northern limit. Its southern limit is unknown because it is covered by Bowen Basin sediments. Olgers (1972) considered basinal elements to be continuous to the southeast of the Anakie Inlier but there is no seismic or drill hole information supporting this view.

Units of the Pretoria Basin are poorly exposed and in general not well documented. In the south the basal Greybank Volcanics outcrop around a basement high at Fletchers Awl and comprise andesitic to dacitic volcanics, conglomerate and volcanolithic sediments that represent a brief marine transgression (Blake et al. 1995). Based on conodont morphology the Greybank Volcanics have a late Frasnian to early Famennian age and are older than the Mount Wyatt Formation (McKellar 1970; Blake et al. 1995). On the northern basin margin the basal Bimurra Volcanics comprise rhyolitic, andesitic, and trachytic lava, pyroclastics, sinters and volcaniclastics. Hutton et al. (1991) suggest that these sediments may represent the infill of a localised fault basin. The Bimurra Volcanics has a U/Pb (zircon) age of 356.2±2.9 Ma (Famennian) with inheritance at 400-370 Ma (Perkins et al. 1995). This unit is conformably overlain by paralic to shallow marine sediments and pyroclastics of the Mount Wyatt Formation. The unit lies unconformably on basement on the flanks of the Anakie Inlier and appears to be partly correlative with the Bimurra Volcanics (Hutton et al. 1998). A volcanic sequence comprising volcaniclastics, pyroclastics, ignimbrite and mafic-felsic volcanics appear to represent discrete volcanic centres. The stratigraphic position is uncertain but the sequence has a similar lithology to the Silver Hills Volcanics on the western margin. The volcanic sequence unconformably overlies basement on the Anakie Inlier and is concordant on the Greybank Volcanics at Fletchers Awl (Blake et al. 1995). The Mount Coolon Andesite, near the northern extent of the volcanic sequence, has a 347.0±2.9 Ma age (Perkins et al. 1995) which places it within the age range of the Silver Hills Volcanics. The Mount Rankin Formation disconformably overlies the volcanic sequence and comprises feldspatholithic sandstone, pelite, chert, intraformational conglomerate, tuff and minor andesite to dacite. This unit contains Early Carboniferous flora (Olgers 1972).

1.3.2.2 Structure of the Pretoria Basin

Scattered outcrop produces a disparate structural framework for the Pretoria Basin. On the northern margin Malone et al. (1966) and Hutton et al. (1991) noted that the structural trend of folds is NE which is different to the general N-NW fold trend of the majority of the Drummond Basin. Near the southern outcrop margin a faulted set of folds show a N-NW trend which is repeated in minor outcrop at Fletchers Awl.

1.3.3 Galilee Basin

Petroleum exploration led to the development of the Permian-Early Mesozoic stratigraphy in the region of the Springsure Shelf (Anon 1952). The term Galilee Basin was first used to describe an assumed Late Palaeozoic-Early Mesozoic depression west of the Drummond Basin by Whitehouse (1955). Subsequent reconnaissance mapping, seismic surveys and exploration wells proved the existence of the Galilee Basin and improved knowledge of its stratigraphy and structure. Various reports have outlined the stratigraphic and structural development of the Galilee Basin (Vine et al. 1964; Vine et al. 1965; Benstead 1973; Pinchin 1978; Nelson 1981) and were summarised by Vine (1976) and Evans (1980). Analysis and correlation of borehole logs and outcrop extended the stratigraphy of the Galilee Basin to the north and south and showed a relationship between Permian infill of the Galilee and Bowen Basins across the Springsure Shelf (Gray and Swarbrick 1975; Gray 1976; Gray 1977). Palynologic evidence (Evans 1966; McKellar 1977) indicates that the Bowen and Galilee Basins have similar Triassic sections.

1.3.3.1 Stratigraphy of the Galilee Basin

The Galilee Basin can be divided into a northern and southern region based on differences in lithostratigraphic succession (Figure 1.7). The boundary between these regions is in the vicinity of the northeast basement extrapolation of the Barcaldine Ridge extension of the Maneroo Platform (Figure 1.8). The lowermost unit of the Galilee Basin is the upper Carboniferous-Lower Permian Joe Joe Group which is divisible into three conformable formations. The basal Lake Galilee Sandstone comprises quartzose sandstone and minor conglomerate with argillaceous beds present in its upper part. This formation is not found in outcrop. The overlying Jericho Formation comprises pebbly mudstone interbedded with volcaniclastic sandstone and conglomerate. In outcrop in the southern region, tillite and fluvioglacial conglomerate have been recognised (Mollan 1967). The intervening Oakleigh Siltstone Member contains varved argillaceous strata and is widespread in distribution. The succeeding Jochmus Formation comprises a lower section of mainly volcaniclastic to feldspathic sandstone and an upper interval composed of fine to coarse-grained sandstone with minor mudstone and siltstone. Outcrop of the Jochmus Formation in the southern basinal region contains varves and tuff. In the northern region of the Galilee Basin, the three formations are only defined in the subsurface. They are all present in the Koburra Trough region (Figure 1.8), where the Jochmus Formation contains a middle section of pelite and tuff, called the Edie Tuff Member. In the Lovelle Depression the basal stratigraphic unit is the Jochmus Formation. The northern outcrop equivalent of the Jochmus Formation is termed the Boonderoo beds. This unit is composed of fluvioglacial conglomerate, sandstone and varved siltstone. The misnamed Aramac Coal Measures which conformably follow are restricted to the northern subsurface margin of the Barcaldine Ridge and the Lovelle Depression (Hawkins and Green 1993). It is composed of quartzose to labile sandstone, shale with minor occurrence of coal.

Palynology indicates that a hiatus is present between the Early Permian Aramac Coal Measures/Jochmus Formation and Late Permian strata (McKellar 1977). In the southern region of the Galilee Basin the Colinlea Sandstone, comprising quartzose sandstone and conglomerate with minor shale, unconformably overlies and onlaps the Joe Joe Group (Gray 1976). Over the Springsure Shelf, the fluvial Aldebaran Sandstone, marine transgressive Freitag and Ingelara Formations, marine regressive Catherine Sandstone and marine to paralic Peawaddy Formation, all of the southern Bowen Basin, interfinger with the Colinlea Sandstone. The conformably overlying Bandanna Formation comprises calcareous, lithic sandstone, siltstone and coal with minor tuff and oil shale. The marine Black Alley Shale of the southern Bowen Basin interfingers with the lower Bandanna Formation over the Springsure Shelf. In the northern region of the Galilee Basin the correlative of the Colinlea Sandstone and Bandanna Formation interval is termed the Betts Creek beds. This unit disconformably overlies the Boonderoo beds in outcrop and the Aramac Coal Measures in subcrop. The Betts Creek beds is composed of interbedded sandstone and conglomerate, siltstone, carbonaceous shale and low rank coal seams.

The stratigraphy of Triassic units in the Galilee Basin is generally continuous across the northern and southern regions. Labile sandstone and multicoloured argillaceous sediments of the Rewan Group conformably overlie the Betts Creek beds. In the northern region the Dunda beds are an outcrop facies variant of the uppermost Rewan Group characterised by a greater quartzose content and subordinate lutites. The contact between the Rewan Group and the Clematis Group varies from gradational in the centre of the basin (Olgers 1970) to erosional in the southern Galilee Basin (Exon 1970; Senior 1973). Limited paleocurrent directions for the Dunda beds show an easterly source whereas the Clematis Group has a predominantly WNW source (Vine et al. 1965). This suggests that an unconformable relationship or interfingering could occur between the two units. The Clematis Group consists predominantly of quartzose sandstone with minor interbeds of mudstone and siltstone. At the northern margin of the basin the Warang Sandstone is an outcrop correlative of the upper Clematis Group and shows an unconformable boundary with the Betts Creek beds. The uppermost unit of the Galilee Basin is the predominantly argillaceous Moolayember Formation. It shows a gradational contact with the Clematis Group and palynologic evidence (McKellar 1977) shows that the Warang Sandstone is partly a lateral facies equivalent of the Moolayember Formation.

1.3.3.2 Structure of the Galilee Basin

The Galilee Basin overlies part of the Maneroo Platform, an area of crystalline basement that is step-faulted with downthrows to the west (Vine et al. 1965). Extensions of the Maneroo Platform underlying the Galilee Basin are termed the Beryl Ridge and Barcaldine Ridge, the latter effectively dividing the Galilee and Drummond Basins into northern and southern regions (Figure 1.8). The NE-trending Warrego Fault and Pleasant Creek Arch are located near the southern boundary of the Galilee Basin (Vine 1973). These features extend into the underlying Adavale Basin. Remus and Tindale (1988) interpreted the Warrago Fault as a backthrust/forethrust couple but do not show it as affecting the Galilee Basin. The Pleasant Creek Arch is a fault-bend anticline developed above a thrust ramp. A series of anticlines and synclines, including the dominant Birkhead Anticline, parallel the Pleasant Creek Arch and have the same NE trend as the Mount Beaufort Anticline of the Drummond Basin. Exon (1970) interpreted units thinning over the Birkhead Anticline as suggesting this as a growth fold during deposition of the Galilee Basin with. However the thinning could also be due to post-tectonic erosion. The Canaway Fault separates the Galilee and Cooper Basins. This normal fault is downthrown to the east. It has a northerly trend and extends into the Maneroo Platform. The Canaway Fault only offsets Early Permian strata of the Galilee Basin with Late Permian-Early Triassic units having Cooper Basin correlatives over the Canaway Ridge (Wells and O'Brien 1989). The Canaway Ridge is also a significant feature in the underlying Adavale Basin where it separates the Warrabin and Barcoo Troughs from the Main Depression (Passmore and Sexton 1984). The Nebine Ridge and associated Springsure Shelf are basement highs that mark the eastern boundary of the Galilee Basin.

The NW-trending Hulton-Rand Structure and NE to E-trending Tara Structure are monoclinal features in the Galilee Basin, bordering the Barcaldine Ridge (Vine et al. 1965). They are probably basement faults at depth, suggesting that the ridge is a horst. The sedimentary succession across the Hulton-Rand Structure is much thicker on the downthrow side. This is evidence that this feature was a growth fault during infill of the Galilee Basin. Another NW-trending structure, the Dariveen Fault, has the Maranthona Monocline adjacent to its downthrow side. The NE-trending Tara Structure was interpreted as a reverse fault by Jackson et al. (1981) and Hawkins and Green (1993) but these contradictory interpretations have the footwall on different sides of the fault. In the northern Galilee Basin the Belyando Feature of the Drummond Basin is continued as the NW-trending Mingobar Monocline and White Mountains Structure that represent a zone of monoclinal folding. A structural depression, recognised by Benstead (1973) in the northeastern Galilee Basin, is termed the Koburra Trough. This trough parallels the trend of the Belyando Feature and contains the maximum preserved thickness of Galilee Basin sediments. Benstead (1973) determined that the presence of a thick, continuous sequence of Permian sediments in the trough indicates penecontemporaneous subsidence and deposition. A shallower trough, called the Lovelle Depression (Allen 1975), occurs on the northwest margin of the Galilee Basin. The Holberton Structure and the Elderslie Ridge flank the N-NE trending Cork Fault. These structures parallel the total magnetic intensity and Bouger gravity anomaly gradients of the Thomson Orogen that forms basement to the basin (Murray and Kirkegaard 1978). The Cork Fault is a major normal fault in the basement with downthrow to the west (Hawkins and Harrison 1978). Vine (1976) showed that the Cork Fault is a complex structure that was active in its northern part during early infill. The associated fault-related Holberton Structure and Elderslie Ridge were not active during sedimentation. The northerly trending Weatherby Structure parallels the Beryl Ridge extension of the Maneroo Platform. Major NE-trending fold structures found in the southern Galilee Basin are not evident in the northern region.

2.0 SEISMIC STRATIGRAPHY

2.1 Introduction

The application of seismic stratigraphy was first published in a series of papers that outlined the principles (Mitchum and Vail 1977; Mitchum et al. 1977a; Vail et al. 1977c), defined the concepts of depositional sequences (Mitchum et al. 1977b) and relative changes in sea level (Vail et al. 1977b; Vail et al. 1977a). The application of seismic facies parameters to describe depositional frameworks was undertaken for clastic marine environments (Sangree and Widmier 1977). In carbonate buildups the criteria for recognition of seismic facies requires the use of direct and indirect parameters (Bubb and Hatlelid 1977). The concepts were summarized and definitions expanded by Brown and Fisher (1980) and Brown (1985). Specific examples of the use of seismic stratigraphy in active and passive margins are given in AAPG Memoir 26 (Payton 1977) and AAPG Memoir 39 (Berg and Woolverton 1985).

Seismic data resolution has improved to the point that a seismic line resembles a geological cross section. Modern seismic acquisition and processing produce multi-fold CDP (common depth point) sections with reduced multiples. Seismic lines are generally low resolution tools, but they have much better lateral coverage than outcrops. Seismic data show gross geometry (within the limits of resolution) over large areas. Vertical exaggeration can be changed to reveal subtle angular relationships. A single seismic reflector is an isochron and can cross lithostratigraphic facies boundaries. An exception occurs where the reflection surface is an unconformity. Most unconformities are hiatal boundaries that represent lateral time-variable units due to either non-deposition or erosion.

Seismic sequence analysis involves the identification of relatively conformable successions of genetically related strata, known as depositional sequences that are separated by broad scale unconformities and their correlative conformities. These bounding discordances are called toplap, downlap, onlap, convergent onlap, lapout and erosional truncation. Correlative conformities are concordant (Figure 2.1). If onlap or downlap cannot be determined due to structural overprinting the term baselap is used for the basal termination. Toplap is a discordant seismic boundary in which inclined seismic strata laps out in a landward direction at the top of the unit, but the successive terminations lie progressively basinward (Mitchum 1977). This is a result of non-deposition with perhaps minor erosion. Downlap is a base-discordant relation in which initially inclined seismic strata terminate downdip against an initially horizontal or inclined surface (Mitchum 1977). An onlap is characterized by the regular and progressive pinching out of a seismic unit towards the margins of a depositional basin (Mitchum 1977). The boundary of each unit in the sequence is overstepped by the overlying unit. Onlap can be proximal or distal in relation to a reference point. Convergent onlap occurs when seismic strata rapidly thin towards a basin margin with progressive overstepping of overlying units. Lapout is defined by Mitchum (1977) as the lateral termination of strata at their depositional pinchout and includes toplap, onlap and downlap types. In this paper, lapout is redefined as a distinct seismic boundary that is characterized by rapid pinching out of the depositional unit towards the basin margin with no overstepping of the overlying unit. A concordant boundary reflector can be traced laterally from a truncation or lapout. Erosional truncation is the termination of seismic reflections interpreted as strata along an unconformity surface due to post-depositional erosional or structural effects. It occurs along the upper part of a sequence boundary. Generally in this study the seismic reflectors show concordance as the majority of the seismic lines do not intersect regions of tectonic change within the basins. Only the northernmost seismic lines intersect the basin boundaries. This general concordance made it difficult to determine a succession of seismic sequences within the Drummond and Galilee Basins.

Seismic facies analysis involves the recognition of units within a seismic sequence. A seismic facies is an areally definable 3D unit composed of groups of reflectors whose character differs from those of adjacent facies units. These units may be the seismic response of a lithofacies. The amplitude, frequency, continuity and reflection configuration of seismic reflectors can be qualitatively described. Amplitude is controlled by the velocity and density contrasts of individual interfaces. Optimum bed spacing in relation to frequency may result in amplifying lower energy reflectors producing a higher amplitude response. Fluid contrasts within the strata may also increase the normal rock velocity-density producing changes in amplitude. Frequency is a characteristic of the seismic pulse. It is related to the spacing of the reflectors, fluid content of the strata and lateral thickness changes. Continuity of reflectors is associated with the continuity of strata. Continuous reflectors suggest uniformly stratified deposits.

Lateral changes in amplitude, frequency and continuity, tied in with lithic well data, can be used to prepare lithofacies maps. Interval velocity is a quantitative value and can be compared to interval transit times derived from borehole logs. Internal reflector configurations occur within a seismic facies. They are at a smaller scale than the bounding relationships within a sequence and can take the form of: parallel/sub-parallel to divergent patterns with modifying configurations of even, wavy, hummocky, lenticular, disrupted or contorted form (Figure 2.2).

The external geometry of seismic facies may assist in the interpretation of the broad depositional environment, the tectonic setting of deposition and a probable source direction for sediment supply. The external boundaries may be identified by the termination of seismic reflectors against a common surface, by a conformable reflector that encloses a particular configuration or by an arbitrary boundary within a sequence across which there occurs a gradational change in seismic facies parameters. The limitations in the use of external geometry include the need for 3D seismic coverage and the necessity for sufficient lateral coverage to include the boundaries of the seismic facies unit. External geometries can be described as sheet, sheet drape, wedge, lens, mound, fan, channel fill, trough fill and basin fill (Figure 2.3).

2.2 Previous Interpretations

Early seismic interpretations of the research region were hampered by lack of energy penetration through the “P horizon” coal beds of the Galilee Basin and are summarized in Cundill et al. (1971). After the completion of exploratory wells a reinterpretation of available single to 12 fold CDP data determined “Top Middle Devonian” and “Base Middle Devonian” boundaries for the Drummond Basin (Hightower 1978). An error in correlating the Late Devonian-Early Carboniferous Drummond Basin with the Devonian Adavale Basin by Hightower (1978) lead to the conclusion that the Drummond Basin strata had a marine origin and included reefal structures in the seismic profiles. Pinchin (1978) interpreted four seismic profiles that were widely spaced over the whole Drummond Basin. In this investigation the boundaries between basement, Drummond Basin and Galilee Basin were determined. Where outcrop or tie-line wells were available Pinchin determined partial subsurface extent of Drummond Basin stratigraphy. The 1982 Carmichael Phase I seismic survey in the northern Drummond and Galilee Basins ties to four previously drilled wells and a subsequent 12 to 24 fold Phase II survey concentrated on trends in the Northern Drummond and Galilee Basins (Gillies 1983). These surveys identified the “P horizon” reflector in the Galilee Basin and Top Drummond, Lower Carboniferous, Top Devonian and basement reflectors in the Drummond Basin. Problems occurred with tieing the Drummond Basin profiles to outcrop in the Mt Gregory area and the Top Devonian reflector was mis-identified as marine and associated with the Ukalunda beds found in basement outcrop. A high quality 60 fold Campaspe seismic survey and subsequent corehole drilling program was undertaken over a very small area of the northern margin of the Drummond Basin (Fenton and Jackson 1989). This survey produced detailed seismic profile interpretations of Drummond Basin stratigraphy but incorrect interpretation of the lithologic logs created errors in the assignation of seismic units to the stratigraphy. The Campaspe seismic survey and some of the Carmichael seismic profiles were reinterpreted by Johnson and Henderson (1991) with a focus predominantly on structural interpretation. A basic subdivision of basement, Drummond Basin and Galilee Basin boundaries was undertaken. Limited subdivision of Drummond Basin seismic units with no correlation to lithostratigraphy was attempted for parts of two seismic lines from the Carmichael and Campaspe surveys.

2.3 Methodology

This investigation covers the northern Drummond Basin and the northern Galilee Basin. Seismic facies analysis has been undertaken using 750km of proprietary 12 to 24 fold and 60 fold CDP seismic data (Figure 2.4) used in previous interpretations by Gillies (1983) and Fenton and Jackson (1989). Complete interpretation of these seismic profiles can be found in the Appendix. Sixteen tie-line wells and boreholes, as well as limited outcrop associations, provide stratigraphic control between the seismic facies and lithostratigraphic facies. Although seismic facies units can be matched with confidence on the basis of key intervals and identical seismic attributes across the research region, seismic spatial coverage is unequal with traverses concentrated in northern and southern regions of the research area.

2.4 Seismic Stratigraphy of the northern Drummond Basin

In the northern Drummond Basin five seismic facies units are recognized, characterized by their internal characteristics and generally concordant stratal boundaries. This limits the determination of seismic sequences defined by broadscale unconformable boundaries. These seismic facies can be traced from outcrop on the Scartwater Salient to onlap onto basement or lapout at the western margin of the basin (Table 2.1, Figure 2.5a). The basal part of the northern Drummond Basin was not imaged in the seismic traverses. The lowest reflector that can be traced with confidence is the upper boundary of the Scartwater Formation with the underlying stratigraphy comprising Cycle 1 and the basal portion of Cycle 2 of the basin fill.

2.4.1 Seismic Facies D1 – Scartwater Formation

Only the upper boundary of the Scartwater Formation can be identified with confidence in the seismic records. Seismic facies D1 comes to near-surface subcrop at the eastern end of seismic line CS86-03 in the northern region associated with an isolated basement outcrop of the Seventy Mile Range Group. The parallel line CS86-05 has D1 at faulted depth on its eastern boundary. At the nearby Pajingo Mine the Scartwater Formation is intersected in deep drill holes (Goddard 2003). Its internal seismic pattern is similar to the overlying seismic facies D2 with the major difference being a lack of lateral continuity in the D1 reflectors. This suggests a greater lithological variation vertically and laterally in D1 compared with D2. Outcrop of the Scartwater Formation shows a broad variation in the basic quartz psammite lithology of Cycle 2 sediments. Often the internal reflectors are masked by strong multiples generated by the overlying D2 seismic unit. The boundary between D1 and the overlying D2 is commonly wavy and slightly incised near the eastern boundary of the basin. The eastern upper boundary of D1 shows rare toplap terminations and the overlying D2 shows onlap in places suggesting that a sequence boundary occurs at the top of D1. The boundary becomes concordant towards the basin centre and shows only minor incision over the western shelf. The toplap relationship indicates an erosional hiatus of a possible progradational facies whilst the onlap relationship can be caused by renewed extensional subsidence of rift infill.

2.4.2 Seismic Facies D2 – Mount Hall Formation

Seismic facies D2 and the overlying seismic facies D3 provide the most distinctive seismic facies of the Drummond Basin. Seismic facies D2 outcrops near the eastern end of seismic line CS86-05 which is associated with currently mapped outcrops of the Raymond Formation. The mapped outcrop more logically is a sandy facies of the Mount Hall Formation as it laterally ties with the seismic facies attributed to this formation. Near-surface subcrop in the eastern end of CAR83-57 is associated with outcrop of the Mount Hall Formation on Mt Gregory. The Raymond Formation, defined in the southern Drummond Basin, is not recognisable as a distinct seismic facies, well log facies or outcrop in the northern Drummond Basin. The internal configuration of D2 is hummocky with a disrupted seismic pattern or a contorted configuration. This is considered to reflect a complex fluvial architecture related to a braidplain origin determined from outcrop. Seismic facies D2 is distinguished from the overlying D3 by its uneven internal configuration. Towards the eastern basin margin it shows toplap beneath D3 but generally the upper boundary is concordant to slightly wavy. In the northern region of the Drummond Basin D2 shows a divergent geometry towards the eastern margin. This divergence is partially developed in the interpretable eastern end of CAR82-25. On the western margin of the Drummond Basin, D2 onlaps D1 or basement, indicating a sequence boundary at the base of this facies. In the southern region the western margin of D2 is block faulted but the seismic facies shows no divergence towards the hanging wall. This shows that subsidence of the basin block was greater on the eastern basin margin and that downthrow of the western margin occurred after deposition of D2. The minor toplap in the northern region suggests that some sediment input occurred from the eastern basin margin but the lack of downlap onto D1 shows that this input occurred towards the end of development of D2. A wavy upper boundary shows a slight erosional unconformity with D3. Generally the conformity of the geometry suggests that deposition of the fluvial facies associated with the seismic facies occurred parallel to the basin axis. In parts towards the eastern margin of the basin a seismic sub-facies, distinguished by a reflection signature of diminished amplitude, merges laterally with D2.

2.4.3 Seismic Facies D3 – Star of Hope Formation

Seismic facies D3 is distinguished from the underlying D2 by its high amplitude, even reflectors that have excellent lateral continuity. In the northern region D3 comes to near-surface subcrop in seismic lines CS86-03 and CS86-05 associated with the outcrop trend of the Star of Hope Formation. Seismic facies D3 has a concordant upper boundary with D4. The lower boundary is also generally concordant with a slightly wavy boundary towards the basin margins. Minor expressions of downlap occur and the seismic facies onlaps onto D2 and basement along the western basin margin indicating a sequence boundary between the D2 and D3. Seismic facies D3 shows a divergent geometry on the eastern margin in the northern and southern regions, similar to D2, showing that subsidence was rapid in these localities. In the southern region seismic D3 shows onlap infill of the downthrow fault blocks in D2. This shows that the fault blocks reflect an unconformable surface that developed on the western margin between D2 and D3. This unconformity is evidenced on the eastern margin by the erosional wavy lower boundary with D3. Minor downlap of D2 onto D3 suggests that some sediment was derived from the eastern margin but generally the sediment input was parallel to the basin margins. The relatively even boundary reflectors and the excellent internal configuration is evidence that seismic facies D3 generally developed under tectonic conditions of gentle subsidence with a greater rate of subsidence occurring on the eastern margin..

2.4.4 Seismic Facies D4 – Bulliwallah Formation

Seismic facies D4 is bounded by strong, high-amplitude reflectors that have excellent continuity. In the northern region D4 subcrops adjacent to the Cape River on seismic line CS86-03 but no surface verification is available. Along trend, on CS86-05 in the northern region, near-surface subcrop is associated with nearby outcrop that has been tentatively mapped as Natal Formation. This mapping is currently undergoing revision by the Geological Survey of Queensland. On the eastern end of CAR83-99 subcrop of D4 is associated with mapped outcrop of the Bulliwallah Formation along strike of the Hopkins Anticline. Both upper and lower boundary reflectors generally show concordant relationships with local toplap against the overlying D5 and local erosional truncation or downlap against the underlying D3. This indicates that sequence boundaries occur between D4 and the underlying D3 and overlying D5. This relationship shows that D4 accumulated under conditions of gentle subsidence with localized greater subsidence of basement blocks reflected in adjustment of the lower boundary by erosion or progradational infill. Where the overlying D5 is not present in the northern region, D4 has a concordant relationship with G1 of the overlying Galilee

Basin. On the western margin of the Drummond Basin D4 onlaps the underlying D3 and basement. Seismic facies D4 thins towards the eastern and western margins of the Drummond Basin showing that subsidence was generally basinwide during development of D4.

2.4.5 Seismic Facies D5 – Natal Formation

The seismic facies D5 has a similar seismic facies signature as the underlying D4. A strong reflector with an associated multiple marks the boundary between these two seismic facies and the internal reflectors of D5 have similar continuity than D4. In the northern region, on the eastern end of CAR82-13, subcrop of D5 is associated with mapped outcrop of the Natal Formation. Seismic facies D5 was not detected on the northern margin of the Drummond Basin. In general the upper and lower contacts of D5 are concordant. Toplap of the reflectors beneath the overlying G1 of the Galilee Basin is seen suggesting progradation from the east indicating an uplifted margin during deposition of D5. In the northern region very gradual onlap onto underlying D4 and basement marks the western basinal margin indicating a basal sequence boundary. In the southern region D5 thins and shows lapout onto the underlying D4 on the western margin of the Drummond Basin. The external geometry of D5 shows a generally uniform thickness that thins towards the western margin and is truncated by a thrust system towards the eastern margin of the Drummond Basin. These boundary relationships and external geometry of D5 show that subsidence was gentle during development of the seismic facies. The toplap on the eastern margin and lapout on the western margin suggests that the margins were higher due to flexural subsidence of the basin occurring along the line of the basin axis

2.5 Seismic Stratigraphy of the northern Galilee Basin

The northern Galilee Basin can be divided into six seismic facies characterized by their internal characteristics and stratal boundaries (Table 2.1, Figure 2.5b). The seismic facies are laterally very continuous, internally homogeneous, possess clear boundary reflectors and show concordant or local toplap relationships. On the eastern boundary the facies terminate along a line of inversion features, showing the current eastern edge of the Galilee Basin is structurally defined. Tie-line boreholes on the seismic lines show a correlation between lithostratigraphic subdivision and the seismic units. Original geophysical data tapes were not available and consequently no quantitative correlation using interval velocities can be made between the seismic units and depth data from boreholes.

2.5.1 Seismic Facies G1 – Jericho Formation

The boundaries of seismic facies G1 are generally concordant with the overlying G2 and underlying D5. Seismic facies G1 has never been found in outcrop. In the northern region, seismic profile CS86-03 shows outcrop of G1 where the seismic line crosses the Cape River. Drilling to the northwest of this seismic line encountered pebbly sediments, interpreted as Boonderoo beds, beneath the Tertiary laterite (Wecker 1978). On the Charters Towers geological sheet SF55-2 the surrounding area is mapped as Quaternary alluvium and Tertiary ferricrete with outcrop of Warang Sandstone and Betts Creek beds to the northwest (Clarke and Paine 1970). The Jericho Formation underlies all of these units and as they all have a general southwest dip it is logical that G1 would have nearsurface subcrop to the east of the mapped units. In the boreholes and wells the relatively thick Jericho Formation overlies the Natal Formation which is assigned seismic facies D5. Minor onlap of G1 onto D5 and a slightly wavy boundary between the two facies in the vicinity of inversion structures suggests that these structures were slightly active before development of seismic facies G1. Onlap onto D5 and basement occurs to the west over the Beryl Ridge showing that this boundary had gentle subsidence. The Lake Galilee Sandstone underlies the Jericho Formation in the wells Koburra-1, Lake Galilee-1 and Carmichael-1. The Lake Galilee Sandstone does not have a distinctive seismic signature compared to G1 and is thought to represent a local facies variant of the Jericho Formation. A high-amplitude laterally continuous reflector and its adjacent multiple is present approximately mid-way in G1. This strong reflector results from a marked velocity change at the boundary between the fine-grained sandstone of the upper Jericho Formation and the very fine-grained siltstone of the Oakleigh Siltstone Member. The boundary between the overlying seismic facies G2 and G1 is a low to moderate-amplitude, laterally continuous reflector and its adjacent multiple, representing a velocity change at a lithological boundary. Commonly this reflector is difficult to pick suggesting a gradual lithological change between G1 and G2. Seismic facies G1 shows great uniformity in thickness until truncated by a thrust fault system on its eastern margin suggesting that it was originally more continuous to the east. Seismic facies G1 gradually thins as it onlaps D5 and basement to the west.

2.5.2 Seismic Facies G2 – Jochmus Formation

Seismic facies G2 and underlying G1 show a similar seismic signature suggesting a corresponding lithology. The seismic facies G2 is not detected in outcrop, approaches subcrop on the Mingobar Structure and is not present east of this inversion structure. Seismic facies G2 is interpreted to represent the Jochmus Formation based on its stratigraphic position overlying the Jericho Formation in wells. The Jochmus Formation contains a fine-grained interval, the Edie Tuff Member, which is not seismically significant and is not detected as a subunit of G2. The basal surface of G2 is concordant with G1 showing that subsidence and infill was continuous with the lower facies. Its upper surface shows erosional truncation onto G3 as it thins onto the Mingobar Structure where it has been locally removed following inversion. To the west G2 progressively onlaps G1 reinforcing the continuous basin subsidence during the development of G1 and G2. Localised thickening of G2 over the Beryl Ridge extension of the Maneroo Platform relates to fill of incised valleys cut into basement. This indicates that the Beryl Ridge was a high before development of G2. This structural interpretation is reinforced by the development of the Jochmus Formation as the basal unit in the Lovelle Depression to the west of the Maneroo Platform. Laterally this seismic facies is very consistent in signature indicating basin wide uniformity in its fluvial facies mosaic.

2.5.3 Seismic Facies G3 – Betts Creek beds

The seismic facies G3 shows a distinctive seismic facies pattern of moderate-amplitude, high-continuity reflectors thought to be due to a carbonaceous content. Due to its stratigraphic position overlying the Jochmus Formation in wells and seismic profiles and its carbonaceous signature the seismic facies G3 is interpreted as the Betts Creek beds. Because of its distinctive seismic signature and lateral continuity the Betts Creek beds can be used as a very reliable marker within seismic profiles. The upper boundary is the seismic "P horizon" of earlier studies (Anon 1962; Preston and Hightower 1963; Anon 1966a, 1966b ; Anon 1967a, 1967b) and is concordant with the overlying G4. The lower boundary shows erosional truncation of underlying reflectors of G2 proximal to the Mingobar Structure. Further west the lower boundary is wavy suggesting minor erosional relief cut into the underlying G2. This shows an unconformable relationship occurs between the Jochmus Formation and the Betts Creek beds. This relationship is reinforced by the palynologic hiatus between the two units (Norvick 1974). The Betts Creek beds are continuous over the Beryl Ridge to the west. The Betts Creek beds show no evidence of onlap onto the Mingobar Structure in the northern and southern regions. Minor thinning of the seismic facies onto this structure represents structural thinning towards the basin margin east of the Mingobar Structure. This shows that uplift on the Mingobar Structure occurred between development of G2 and G3 and also post-development of G3.

2.5.4 Seismic Facies G4 – Rewan Group

Seismic facies G4 has a very variable seismic signature reflecting lateral facies changes. Seismic facies G4 comes to subcrop in the northern region on seismic lines CAR82-09 and CAR82-11 where it is represented by mapped Warang Sandstone on the surface. In the southern region on seismic lines CAR82-23 and CAR82-25 the subcrop is mapped on the surface as the Dunda beds. In both the northern and southern sectors of the study area G4 has concordant upper and lower boundaries. In the northern sector the amplitude of the seismic reflectors increases from low in the east to high in the west, corresponding to an increase in density of the seismic facies and reflecting a progressive change in the pelitic content. In the southern sector the group shows a similar rapid east to west amplitude change as well as a vertical division into two sub-facies reflected by an upward reduction in density. The Rewan Group shows no evidence of onlap onto the Mingobar Structure with thinning to the east due to post-inversion erosion. Seismic facies G4 is continuous to the west and shows a sheet-like external geometry. This shows that basin subsidence and infill was continuous between G3 and G4 and that post-depositional inversion along the Mingobar Structure occurred after deposition of G4.

2.5.5 Seismic Facies G5 – Clematis Group

The Clematis Group is represented by a thin seismic facies that exhibits a variable amplitude signature caused by porosity differences and expressing facies diversity. The frequency generally consists of a strong reflector and its multiple and a central moderate amplitude reflector. The central reflector is not always readily apparent due to facies variations. Seismic facies G5 is represented in the northern region by subcrop on the Mingobar Structure along seismic lines CAR82-9 and CAR 82-11 and subcrop in the southern region on seismic lines CAR82-23 and CAR82-25. This subcrop corresponds to mapped outcrop of the Warang Sandstone, a facies variant of the Clematis Group. The upper and lower boundaries are concordant with G4 and G6. The seismic facies G5 gradually thins onto the Mingobar Structure, but shows no onlap relationship, and is laterally continuous to the west over the Beryl Ridge and Maneroo Platform. Seismic facies G5 has a weakly expressed lens-like geometry, with little change in the seismic thickness across its distribution. Similar to G4 the seismic signature of G5 shows continuous basin infill before final inversion resulted in uplift and removal of its eastern margin.

2.5.6 Seismic Facies G6 – Moolayember Formation

The seismic facies G6 is distinguished by a stronger amplitude signal than the overlying seismic facies of the Eromanga Basin. Seismic facies G6 comes to nearsurface subcrop in the northern and southern regions equivalent to mapped outcrops of the Moolayember Formation. The upper boundary is diffuse and its relationship with the overlying Tertiary facies is difficult to determine. The lower boundary has a gentle rolling character against the underlying Clematis Group indicating an erosional unconformity. The seismic facies G6 shows onlap onto G5 on the Mingobar Structure showing that final inversion on this structure occurred before development of G6.

3.0 STRUCTURE

3.1 Introduction

The Late Devonian-Early Carboniferous Drummond Basin developed as a continental back-arc basin within an active margin assemblage developed inboard of a westerly dipping subduction zone. The related magmatic arc is represented by the Late Devonian-Early Carboniferous Connors-Auburn Volcanic Arc system and the fore-arc basin system includes the Campwyn Volcanics and Yarrol terrane (Day et al. 1978; Murray 1986; Fergusson et al. 1994; Murray et al. 2003). Drummond Basin development can be divided into two tectonic phases, an extensional rift phase and a subsequent thermal subsidence phase (Johnson and Henderson 1991; De Caritat and Braun 1992; Henderson and Davis 1993; Davis and Henderson 1996). Deformation of the Drummond Basin occurred in two widely spaced events. Henderson et al. (1998) described an angular discordance between rocks of the Drummond Basin and the overlying Late Carboniferous Bulgonunna Volcanic Group and De Caritat and Braun (1992) associated this deformation with the Kanimblan Orogeny. A contractional event in the Middle Triassic resulted in thrust-fault related monoclinal structures (Johnson and Henderson 1991). The development of the Late Carboniferous-Middle Triassic Galilee Basin has been variously considered by Evans and Roberts (1980) to be a pull apart basin related to shearing along the eastern margin of the Drummond Basin, by Veevers et al. (1982) to represent a pericratonic basin or by De Caritat and Braun (1992) to represent a foreland basin. Uplift in the Middle Triassic resulted in tilting of the Galilee Basin, associated with the last stages of the Hunter-Bowen Orogeny that also affected the Bowen Basin (Evans 1980; Smart and Senior 1980). Both the Drummond and Galilee Basins are extensively overlain by the intracratonic Jurassic-Early Cretaceous Eromanga Basin (Exon and Senior 1976; Smart and Senior 1980).

Regional-scale geological mapping has identified the structural character of the exposed part of the Drummond Basin. Olgers (1972) identified the Bogantungan Embayment and Scartwater Salient as discrete structural features of the Drummond Basin (see Figure 1.5). The Bogantungan Embayment shows a gentle folding pattern that changes strike from north-northeast in it southern part to northwest on its northern perimeter. Its southern sector shows a series of en echelon supratenuous folds with long sinuous axes whereas the northwesterly trending folds are sinuous and asymmetric with steeper western flanks. The Chinaman Fault marks the boundary of the embayment with the Anakie Inlier. This major fault is interpreted as a steeply dipping, margin-parallel, westerly downthrow extensional structure with transfer structures partitioning the basinal floor into compartments (Henderson and Davis 1995; Davis and Henderson 1996). Previous interpretations related the Chinaman Fault to basin inversion rather than extension (Olgers 1972; Johnson and Henderson 1991). Southwest of this fault the Drummond Basin infill has been interpreted by Henderson and Davis (1993) to have undergone thick-skinned thrusting and back thrusting, with basement exposed in the cores of the Nogoa and Telemon anticlines.

The Scartwater Salient has complexly folded and faulted sediments that drape around the northwest margin of the Anakie Inlier. Olgers (1970) divided the fold pattern in the Scartwater Salient into three well defined structural domains. Domain D_1 is located between the Anakie Inlier and the St Anns Fault, a major structure interpreted by Olgers (1972) as a curvilinear, sinistral reverse oblique slip fault. D_1 contains relatively thin, undeformed strata that generally dip west with some clockwise rotation and uplift along the St Anns Fault. Domain D_2, due west of the St Anns Fault, is characterised by tight folding and extensive faulting. Domain D_3 lies to the west of D_2 and is characterised by gentle folding and less extensive faulting. Within D_3 large-scale anticlinorium (Hopkins Anticline, Bingeringo Anticline) and synclinorium (Blowhard Syncline, Bulliwallah Syncline) plunge either to the north-northeast or south-southeast. The synclines are symmetrical but the anticlines are asymmetrical with steeper western flanks. Cores of the Hopkins and Bingeringo Anticlines are faulted and minor tight, second order folding had occurred on the crest of the Hopkins Anticline. These folds grade into the tighter structures of D_2. Fault orientations follow the fold trends or are oblique to this grain.

Major basin-bounding listric faults related to an inferred basal detachment surface, associated transfer faults that dislocate the NW-SE extensional structural grain and a population of reverse faults, that become more common towards the Anakie Inlier, were interpreted from seismic profiles of the Drummond Basin by Johnson and Henderson (1991). The basin floor/basement contact was contoured but these authors noted that this surface represents a marker horizon on the seismic profiles and may not coincide with true basement. Johnson and Henderson (1991) showed the Belyando Structure as a thrust-fault-related feature but described it as a monoclinal flexure. Thrust related monoclinal features, such as the Belyando Structure and the faulted eastern margin of the Drummond Basin, were considered to express easterly dipping fault orientations and were compared to similar thrust features in the Bowen Basin by Henderson and Davis (1993). Thin-skinned thrusting was associated with anticlinal structures in the Drummond Basin by Johnson and Henderson (1991) similar to thin-skinned thrust geometries shown by Fergusson (1990) and Korsch et al. (1992) for the Bowen Basin.

On its northeastern margin, Galilee Basin outcrop is confined to a linear topographic high, the Mingobar Structure, interpreted by Vine et al. (1965) as a monocline (see Figure 1.8). Located to the west of this structure, the Koburra Trough has been interpreted as a penecontemporaneous downwarp (Benstead 1973) or as a fault-controlled depression (Evans 1980). Outcrop of the Galilee Basin is present on the White Mountains Structure marking the northern basinal margin. Vine (1964) interpreted this structure as a monoclinal lineament.

To the south, a sharp gravity gradient, the Belyando Feature, was determined by Vine (1965) to be co-linear with the Mingobar and White Mountains Structures. Early seismic interpretation of Middle Devonian sediments underlying the northern Galilee Basin show the Koburra Trough, Mingobar Structure and linear normal fault features. These faults were reinterpreted by Hightower (1978) as possible thrust faults. Most of the structural features of the Galilee Basin have been recognised from seismic profiles, aeromagnetic surveys and gravity surveys as summarised by Hawkins (1982). The basinal structure shows northeasterly trends associated with basement lineaments and northwesterly trends restricted to the basin fill. Most of these structures are considered by Vine (1976) and Hawkins (1978) to have been active during basin development. Vine (1976) thought that some were inverted during Late Triassic compression to form the faulted major basement ridges of the Pleasant Creek Arch and the Canaway, Barcaldine, Beryl and Elderslie Ridges (see Figure 1.8). The development of an accepted stratigraphic subdivision by Gray and Swarbrick (1975) and Gray (1976) for the Galilee Basin allowed broad structural and isopach maps to be constructed by Vine (1976) and Wells (1989).

3.2 Methodology

This chapter re-examines the structure of the basinal assemblages at regional scale for the northern Drummond Basin and Galilee Basins. Seismic facies and structural analysis has been undertaken using 750km of modern 24 fold and 60 fold CDP seismic data from surveys undertaken by Canso Resources (Gillies 1983) and Shell Company of Australia (Anon 1987). These data are available only in hard copy form. Sixteen tie-line wells and boreholes, predominantly rotary air drilled, provide stratigraphic control (refer to Figure 2.4). Modern regional magnetic and gravity data assisted in structural interpretation.

Three previous seismic studies of the Drummond and Galilee Basins were of limited scope. Pinchin (1978) provided a very broad structural and stratigraphic interpretation of the these elements based on four short traverse lines that provided 6-fold CDP coverage with the seismic profiles tied to wells up to 60 km beyond the traverse terminations. A structural and tectonic interpretation of 60-fold CDP data was undertaken by Fenton and Jackson (1989) on a small area adjacent to basement outcrop on the northern margin of the Drummond Basin. Six short boreholes sited along one of the traverses controlled the stratigraphic interpretation. A broadscale seismic interpretation combined with regional magnetic and gravity data was undertaken over the northern Drummond Basin by Johnson and Henderson (1991). This study modified the structural interpretation of Fenton and Jackson and proposed the existence of transfer faults in the basinal system.

The stratigraphic subdivision and nomenclature used here for the northern Drummond Basin (see Figure 1.4) is that established by Olgers (1972), based on airphoto interpretation and limited ground traverses by numerous workers. Subdivision and nomenclature used in this study for the northern Galilee Basin (see Figure 1.7) is based predominantly on previous studies of electric logs from boreholes and wells by Gray and Swarbrick (1975), Gray (1976, 1977), Hawkins (1976) and Evans (1980) and limited outcrop mapping by various workers. This formal lithostratigraphic nomenclature can be matched to the seismic facies succession by subcrop and outcrop concurrence and correlation of lithofacies in boreholes.

The seismic facies of the northern Drummond and Galilee Basins show a distinctive set of internal reflection parameters, lateral relationships and upper and lower boundaries (refer to Table 2.1). Tie-line boreholes and outcrop on the seismic lines show a close match between lithostratigraphic subdivision and the seismic facies. Although seismic facies can be matched with confidence on the basis of key intervals and identical seismic attributes across the study region, seismic coverage is unequal with traverses concentrated in northwestern and southeastern sectors of the region. A series of structure contour maps were developed from the mapping of five seismic facies in the Drummond Basin and six seismic facies in the Galilee Basin. The basal part of the northern Drummond Basin sequence was not imaged in the seismic traverses. The lowest reflector that can be traced with confidence is the upper boundary of seismic facies D1, the Scartwater Formation, with the underlying stratigraphy comprising Cycle 1 of the basin fill.

Regional-scale structural features have been assessed by means of structure contour maps drawn for the upper surface of each seismic facies. Each of these maps is reviewed in ascending order to identify structural features that developed from extensional tectonics related to basin forming mechanisms and compressional tectonics related to inversion. Internal reflection characteristics with divergent patterns were used determine growth faults. Contorted or disrupted internal patterns with or without reflector offsets delineated compressional fault structures. Discussion of the structural features has been grouped where these features are common within seismic facies.

3.3 Structure of the northern Drummond Basin

3.3.1 Seismic Facies D1, D2 and D3 – Scartwater, Mount Hall and Star of Hope Formations

Seismic facies D1, D2 and D3 are cut by a listric normal fault system in the northern basin margin (Figure 3.1A, 3.1B, 3.1C). Thickening of the seismic facies towards these features show they were growth faults. NW-SE trending planar normal faults near the western margin do not propagate through D3 indicating that major extension in this part of the basin ceased during this time. Transfer faults are expressed as accommodation zones or kinks in the structure contours. The Mount Elsie Fault Zone was recognised by Johnson and Henderson (1991) whilst the Mount Janet, Moonoomoo and Moray Fault

Zones are newly recognised transfer faults. As a function of the small scale of the diagrams, dislocation of the structure contours is not apparent along these transfer faults. The extensional structures have been strongly altered by later inversion. The change in direction of inversion structures from north-south to northwest-southeast is a result of differential stress along these transfer fault zones.

Inversion structures dominate the structural pattern of the northern Drummond Basin. The Mingobar Structure of Vine et al. (1965) is bounded on its eastern margin by a linear anticlinal trend, newly defined as the Nunkumbil Anticline, that developed as a fault bend anticline associated with the blind thrusts situated within the Mingobar Structure. The accommodation ridge associated with the Moray Fault Zone lies along the trend of the Nunkumbil Anticline. Two synclines lie adjacent to the Numkumbil high, the newly defined symmetrical Buchanan and Aberfoyle Synclines. These synclines developed as inversion structures, the Buchanan Syncline as a fault bend fold in front of the Hopkins Thrust System and the Aberfoyle Syncline as a diastrophic depression. The tight set of structure contours aligned northwest-southeast represent the newly defined Hopkins Thrust System. The surface outcrop of this thrust system was called the Hopkins Anticline by Olgers (1970). This asymmetrical anticline has a faulted core. The northwest trending and plunging syncline, the Blowhard Syncline of Olgers (1970), separates the Hopkins Thrust System from a second thrust system to the east, newly defined as the Bingeringo Thrust System which is commonly represented by a duplex set of thrusts. The surface expression of this thrust system is the asymmetrical Bingeringo Anticline of Olgers (1970). The northwest plunging Bulliwallah Syncline mapped by Olgers (1970) lies to the east of the Bingeringo Thrust System. North-south trending closely spaced structure contours represent the newly defined Belyando Thrust that aligns with the Belyando Feature of Vine et al. (1965) on the southern boundary of the study area. The newly recognised Laglan Syncline developed as a fault bend fold in front of the Belyando Thrust, similar to the Buchanan Syncline. The new term, Ulcanbah Ridge, is an antiform developed within the Aberfoyle Syncline during differential inversion within discrete extensional rift compartments that are bounded by transfer faults. An undefined high, the Carmichael Structure, was recognised by Gillies (1983) in the region of the Ulcanbah Ridge. The Beryl Ridge is a basement structure that defines the western margin of the Drummond Basin.

Overlay of the Star of Hope structure contours on gravity contours shows a parallel relationship between gravity gradients and structure contours, particularly the Hopkins Thrust System and Belyando Thrust (Figure 3.2). This indicates a rapid change in density occurs along these features with an increase in values towards uplifted basement associated with the Anakie Metamorphics. The lowest Bouger anomaly is associated with the thickest preserved sediment infill of the Drummond and Galilee Basins. This occurs along the line of the Mingobar Structure and Aberfoyle Syncline.

3.3.2 Seismic Facies D4 and D5 – Bulliwallah and Natal Formations

The listric faults and graben structures on the northern margin are not apparent in seismic facies D4 or D5 (Figure 3.3A, 3.3B). The lack of normal fault propagation through the Bulliwallah and Natal Formations indicate that the extensional phase of basinal development had ceased prior to deposition. Facies D5 onlaps onto D4 and basement of the Beryl Ridge and has minor lapout onto D4 in the south. A gentle downwarp contour pattern from the east and the west is interpreted for the Bulliwallah Formation, with the depocenter derived from isopach contouring along the trend of the Mingobar Structure (see Figure 4.17). Similar to seismic facies D1 to D3 the structure apparent in D4 and D5 is predominantly due to post-depositional inversion. The depocenter for the Natal Formation (see Figure 4.21) coincides with the Buchanan Syncline indicating that inversion tectonics had some control on the infill at this time.

3.4 Structure of the northern Galilee Basin

The northern Galilee Basin can be divided into six seismic facies that relate to outcrop and borehole data (refer to Table 2.1). The seismic facies are laterally very continuous, internally homogeneous, possess clear boundary reflectors and show concordant or local toplap relationships. Most of the facies terminate along a line of inversion features, the Hopkins Thrust System, showing the eastern boundary of the Galilee Basin is structurally defined.

3.4.1 Seismic Facies G1 – Jericho Formation

Facies G1 shows a linear monoclinal feature coincident with the Mingobar Structure (Figure 3.4A). The Nunkumbil Anticline is expressed as a linear high that is the near surface expression of the domal closures found in the structure of the underlying

Drummond Basin. The structural expression of this anticline and the Ulcanbah Ridge has become subdued indicating that these had development during deposition of G1. The Aberfoyle and Buchanan Synclines are expressed as depressions, to the west and east respectively, of the Nunkumbil Anticline. Seismic facies G1 terminates against the Hopkins Thrust System but shows a fault-bend anticline on this thrust in the south indicating that the Jericho Formation extended further to the east before post-depositional inversion eroded the strata to its current extent. Structural control, during later inversion, along transfer faults developed in the syn-rift phase of the Drummond Basin is evident in the along the directional change along the Moray Fault Zone and the upthrust domal closure between the Mount Janet Fault Zone and the Mount Elsie Fault Zone.

3.4.2 Seismic Facies G2 – Jochmus Formation

Only the Mingobar Structure is apparent in the structure contours (Figure 3.4B). Isopach data (see Figure 4.29) shows thinning of facies G2 onto the Mingobar Structure indicating that this structure and its frontal Aberfoyle Syncline ceased growth during deposition of seismic facies G2. A gentle NW-SE fold pattern is evident to the west. The change in contour direction associated with the Moray Fault Zone is apparent indicating structural control by some transfer faults during inversion.

3.4.3 Seismic Facies G3, G4 and G5 – Betts Creek beds, Rewan and Clematis Groups

The structure contours show the Mingobar Structure present throughout all these facies (Figures 3.5A, 3.5B, 3.5C). The development of a broad northwesterly dip of these facies is associated with post-inversion uplift from the southeast. Broad, shallow folding with axial traces parallel to the northwest-southeast orientated Mingobar Structure has developed to the west associated with the Aberfoyle Syncline. The development of inversion structures decreases in the sequence from G4 to G5. The depositional hiatus, determined by McKellar (1977), is not apparent in the structure contours between G2 and G3. This indicates that the hiatus, if present, was not produced by tectonic changes in the basinal development. Inversion commenced during G4 time and was gradual through to G5 time. Isopach data for the Betts Creek beds (see Figure 4.31A) show a gradual thinning onto the Mingobar Structure indicating that this was a high during deposition of seismic facies G3. The Moray Fault Zone has some effect on the structure contours of G3 and G4 but has minimal influence on the development of G5 structures with uplift in the southeast producing a well developed synform and an overall northwestly dip.

3.4.4 Seismic Facies G6 – Moolayember Formation

Structure contours constructed on the upper contact of seismic facies G6 show only a faint expression of the northwesterly dip and shallow synclinal structure associated with facies G5 (Figure 3.6). The structural pattern and onlap of G6 onto G5 indicate that uplift ceased along the Mingobar Structure during the deposition of seismic facies G6. This indicates that compression and uplift occurred initially from the northeast forming the Hopkins and Bingeringo Thrust Systems, Bulliwallah and Blowhard Synclines, Mingobar Structure, Nunkumbil Anticline, Aberfoyle and Buchanan Synclines and Ulcanbah Ridge before compression from the southeast and uplift resulted in tilting of the basins to the northwest. Generally facies G6 is truncated by a very low dip to the southwest indicating that final uplift occurred from the northeast similar to the compression that developed the major inversion structures. This discordance marks the regional unconformity at the base of the overlying Jurassic-Cretaceous Eromanga Basin.

3.5 Discussion

3.5.1 Extensional Structures

Primary, curvilinear listric faults are developed along the northern edge of the Drummond Basin (Figures 3.7, 3.8). The near surface fault plane has an apparent dip of 48^0 shallowing to 10^0 with depth and appears to intersect with a deep seated detachment surface at approximately 3.25 sec two-way time. This intersection is equivalent to approximately 6500m (using an average interval velocity of 4000 $m.s^{-1}$). Fenton and Jackson (1989) did not interpret an intersection with basement for seismic profile CS86-01. A subsequent interpretation by Johnson & Henderson (1991) of this seismic line intersects basement at 2.8 sec two-way time, which supports the interpretation given here.

Thermal maturation data derived from Fenton and Jackson (1989) for boreholes located on seismic line CS86-01 (Figure 2.4) position the top of the Scartwater Formation at a depth of 2000m after completion of Drummond Basin infill. A measured section of

Cycle 1 sediments in the northern Drummond Basin show a thickness of more than 3000m (Henderson *et al.* 1998), implying that the Scartwater and underlying St Anns Formations provided up to half of the Drummond Basin infill at this location. A depth to basement of about 6500m derived from seismic interpretation is not unreasonable. Fault geometries on this profile indicate thin-skinned extensional architecture with a dislocation system located at shallow depths on the basement substrate to the basinal system.

The extensional geometry and syn-rift infill is predominantly the same for structures interpreted for seismic line CS86-01 (Figure 3.8), CS86-03 and CS86-05. The primary listric fault has two splays on the hanging wall. Poorly formed rollover structures are developed on splays distal to the master fault. The development of a rollover anticline in D3, associated with a splay fault adjacent to the easternmost master listric fault in CS86-01, suggests that the latest movement was associated with this structure. This rollover structure is poorly developed in CS86-03 and CS86-05. This suggests that growth faulting occurred at different times during development of the rift basin and at different rates in rift compartments that were separated by transfer faults. Curvilinear antithetic faults are likely to sole to the master listric fault but poor seismic resolution makes this inconclusive. The extensional geometry has been modified by later inversion reactivating movement on the antithetic faults producing doming of the strata. The extensional development is that of a listric fan with listric counter faults. Gibbs (1984) explained such patterns as a result of sequential propagation of external displacement on the faults, with movement first on the easterly structure and sequential displacement on faults to the west. Modeling by Rosenbaum et al. (2005) of over-thickened continental crust, which can be equivalent to the accretionary Thomson Fold Belt, indicates early development of upper crust detachment faults and exhumation of a metamorphic core complex. This extensional regime results in the development of two rift basins separated by relatively undeformed crust similar to the broad outline of the initial formation of the Drummond and Pretoria Basins separated by the Proterozoic Anakie Metamorphic Group. Wijns et al. (2005) attribute the formation of metamorphic core complexes to a large strength ratio between a weak lower crust and stronger upper crust. Stretching leads to low angle, high displacement faults. Isostatic compensation by the lower crust, due to thinned upper crust, results in the development of a metamorphic core complex. The tectonic quiescence stage of Rosenbaum et al. (2005) is represented by the initiation of thermal subsidence in the Drummond Basin. The wholesale rigid block faulting final stage, controlled by major cross-cutting faults, is not seen in the development of the Drummond Basin, where a mix of foreland and thermal subsidence controls the termination of basin development. The models of Rosenbaum et al. (2005) and Wijns et al. (2005) concentrated on thick-skinned, symmetrical extension which is counter to that of thin-skinned asymmetric extension evident in the Drummond Basin. McClay's (1995) modeling of extensional systems suggests that the extensional structural geometry seen on the seismic profiles can be the result of extension above a simple listric fault with a horizontal basal detachment. Listric faults concave to the primary fault are characterised as growth faults. High extension rate listric fault structures show steep, relatively planar antithetic faults distal to the primary listric fault. Therefore syn-rift infill sediments of the St Anns Formation and seismic facies D1 to D3 (Scartwater Formation to Star of Hope Formation) were deposited in a rift basin that developed above a thin-skinned detachment surface. A high extension rate developed a set of listric fans distal to the primary listric fault and the greater development of these fans reflects different extension rates. There is no thickening, listric fan development or rollover structures associated with the Hopkins and Bingeringo Thrust Systems to suggest that these were extensional structures before inversion of the basinal system.

Isopachs of seismic facies D2 show a thickening towards the easternmost primary listric fault in the northeast basinal sector showing that it was a growth fault during D2 time (see Figure 4.10). Thickening of D3 towards the primary listric fault is shown only on seismic line CS86-01 suggesting that extensional faulting was more limited at this time (see Figure 4.13).

No flower structures that are associated with the development of transfer faults were identified. However a difference in structural style of the extensional compartments recognised between CS86-01/03 and CS85-05 could be due to oblique-slip fault systems. These strike-slip faults were described by Gibbs (1987) as steeply dipping and deeply rooted in the crust. A steeply dipping reverse fault is evident on the seismic cross-line CS86-02 between CS86-03 and CS86-05 and is on the trend of the Mount Janet Fault Zone. This steep fault could be an inverted oblique-slip fault that acted as a transfer zone between two compartments. Zones of mineralisation are coincident with the trends of these transfer fault zones (Figure 3.7). Modeling of oblique and zig-zag rifting by McClay et al. (2001) resulted in symmetric graben structures with opposite polarity fault systems developed accommodation zones within sub-basins. In the zig-zag model linked rift-border faults developed kinked traces and relay ramps similar to that evident in the final extensional phase of the Drummond Basin. However, the McClay et al. (McClay et al. 2001) models used symmetrical extension that developed horst structures not evident in the Drummond Basin and the model did not develop strike-slip transfer faults interpreted as portioning rift sub-basins in the Drummond Basin.

The western edge of the Drummond Basin is characterised by a series of steeply dipping normal faults as shown on seismic lines CAR82-23 and CAR82-25 (Figure 3.9). The faults propagate into basement and only affect D1 and D2 seismic facies. A weakly developed rollover structure and thickening of isopachs of D2 towards the faults are evidence that they were active during the early phase of basin development during deposition of units below D3, the Star of Hope Formation. The most westerly member of the fault set shows abrupt termination of seismic facies D2 with no rollover. It is interpreted as a graben-bounding planar normal fault. Seismic facies D3 onlaps D2 along this profile where movement on the fault set has been minor or steps over fault planes that have experienced more substantial offset. The NW trend of these faults is matches the basin margin onlap pattern of seismic facies D2. This structural geometry is interpreted as a northwestward translation of basal rift graben faults into a hinge zone of a half graben rift. A pair of normal faults is interpreted in CAR83-84. These only propagate through D1, the Scartwater Formation, and through a basal portion of D2, the Mount Hall Formation. This structure represents a floor fault that was only active during the early stage of basin development.

3.5.2 Compressional Structures

Structure of the Galilee and Drummond Basin is dominated by slightly curvilinear, steeply dipping reverse fault systems (Figure 3.10). Three regional scale NW-SE trending thrusts are present, the Hopkins Thrust System, Bingeringo Thrust System and the Mingobar Structure. The Belyando Thrust is separated from similar features to the north by the Moray Fault Zone. It may represent continuation of the Hopkins Thrust System but this is uncertain. Regional scale synclines, the Bulliwallah, Blowhard and Buchanan Synclines separate the thrust structures. All of the thrust structures have fault bend anticlines, the Bingeringo, Hopkins and Nunkumbil Anticlines associated with them. This suggests that anticlinal features mapped between the Bingeringo Thrust System and the basin margin represent thrust structures.

Most of the apparent shortening of the basins took place along the Bingeringo and Hopkins Thrust Systems (Figure 3.11). The Hopkins Thrust is predominantly a single thrust with an antithetic fault on the hanging wall whilst the Bingeringo Thrust is a duplex thrust system with two dislocations in close proximity. Fault bend folds are commonly developed on the hanging wall of these reverse faults. These thrust systems have been mapped in outcrop on the Scartwater Salient as the Bingeringo Anticline and Hopkins Anticline respectively. The thrust faults are thin-skinned as they appear to flatten at depth and are inferred to join the detachment surface associated with the extensional tectonics. Movement along the individual thrust planes is not large with displacement averaging 400m, but the duplex form of the Bingeringo Thrust System produced an average uplift of 600m based on an average interval velocity of 4000 $m.s^{-1}$. The listric thrust faults show no ramp and flat geometries associated with thin-skinned compression as described by Coward (1983) and Williams et al. (1989). The steep thrust planes and lack of lateral transport by over thrusting is similar to contractional fault geometries determined by Korsch et al. (1992) for the Denison Trough in the adjacent Bowen Basin. These structures are considered to be reactivated extensional faults. The Hopkins and Bingeringo Thrust Systems are interpreted as reactivated large-scale antithetic faults, companion to splay faults sponsoring the extensional phase of the Drummond Basin. Lack of thickening of the isopachs from the east precludes these structures as reactivated primary listric faults. A greater thickness of sediment infill of D5 (Natal Formation) and G1 (Jericho Formation) accumulated in the depression west of the Hopkins Thrust System, compared to the Bingeringo Thrust System. D5 is also mapped as a thin cover in the Bulliwallah Syncline to the east of the Bingeringo Thrust System. As movement along these structures is comparable this indicates that the Hopkins Thrust System commenced development after the Bingeringo Thrust System and that an unrecognised older thrust system is located between the basin margin and the Bingeringo Thrust System.

Three bends in the structure contours are apparent in the Hopkins Thrust System and closely follow gravity contours (Figure 3.2). These bends reflect reactivation of the

Mount Janet, Moonoomoo and Moray transfer fault zones during compression of the basins. In the Scartwater Salient, a set of northeast trending faults mapped on the surface, adjacent to the St Anns Fault, are part of the Moonoomoo Fault Zone. Olgers (1972) interpreted the St Anns Fault as a thrust structure and this feature along with anticlinal features to the west represent reactivated antithetic faults distal to a previously unrecognised listric fault system on the eastern basin margin. The north-south trend of the Belyando Thrust south of the Scartwater Salient is coincident with the Belyando gravity gradient of the southern Drummond Basin. This gravity trend is due to a thin-skinned basement ramp thrust from the east coincident with the Hopkins Thrust and is unrelated to the Mingobar or White Mountains Structures as previously proposed by Vine (1965).

Steeply dipping blind thrusts, with brittle expression below seismic resolution, develop monoclines or anticlines with intervening synclines. These structures are defined as a dislocation that does not propagate to the surface and loses slip as well as stratigraphic separation upwards (Jackson 1997). Uplift due to such folding is similar to that of thrust dislocation, with an average value of 400m. The largest blind thrust is the NW-SE trending Mingobar Structure that contains all seismic facies except G6, the Moolayember Formation (Figure 3.12). It contains the Nunkumbil Anticline that has two domal closures. Their origin is conjectural and presumably relates to strain portioning within the basinal assemblage, possibly related to variable rates of compression of compartments separated by transfer faults. At the foot of the western limb a flexure, called the Aberfoyle Syncline, is developed. Its obvious presence up to G4 time (Rewan Formation) and lack of isopach thickening in this trough show that it is not a depositional feature (refer to Chapter 4). This structure is associated with the onset of the first basinal compressional event associated with the Kanimblan Orogeny. It developed due to compressive stress between the rising Mingobar Structure and basement of the Beryl Ridge. Minor folding of seismic facies G2 to G6 is due to compression associated with the Hunter-Bowen Orogeny that also reactivated uplift along all structures. The Buchanan Syncline is a narrow depression developed as a forefront fault bend fold to the Hopkins Thrust System. Isopachs of D5 (Natal Formation) and G1 (Jericho Formation) show that the Buchanan Syncline was a depositional depression developed during the Kanimblan Orogeny (refer to Chapter 4).

The change in trend of the compressional structures from north-south to northwest occurs at the position of the Moray Fault Zone. The St Anns Fault is associated with the Moonoomoo Fault zone and dextral rotation on this fault is a reflection of shear across this transfer fault zone.

There is no evidence of a major deformation event as proposed by Olgers (1972) affecting only Drummond Basin infill before deposition of the Late Carboniferous Galilee Basin. There is evidence for a minor compressional event occurring during deposition of the Natal and Jericho Formations shown by the onset of development of the Hopkins Thrust System, Buchanan Syncline, Ulcanbah Ridge and the pop-up structures on the Nunkumbil Anticline. Tectonically the Natal Formation is associated with development of the Galilee Basin rather than the Drummond Basin.

The northwest-southeast trending compressional structures of the Drummond and Galilee Basins ceased development during deposition of the uppermost unit of the Galilee Basin, the Moolayember Formation. Evidence for this is the concordance of underlying compressional structures in the Drummond and Galilee Basins and onlap of the Moolayember Formation onto these structures. The Moolayember Formation in this region has a palynologic date of Tr3a-d (Evans 1966) placing it in the Middle Triassic for Bowen Basin flora by Draper *et al.* (1990) and indicating that deposition took place during the Hunter-Bowen Orogeny associated with the last phase of foreland development of the Galilee and Bowen Basins (Doutch and Nicholas 1978; Elliott 1993; Fielding *et al.* 1995). Later broadscale regional uplift to the southwest is evidenced by the change in regional dip from northwest to southwest at the boundary of the Moolayember Formation with the overlying Eromanga Basin. The basal Hutton Sandstone of the Eromanga Basin contains a palynologic assemblage of upper J4 (Burger and Senior 1979) that Burger and Shafik (1996) equated with the Middle Jurassic, providing an upper age limit for Hunter-Bowen tectonism.

Inversion of the eastern Drummond Basin resulted in the removal of much of the basin fill and generally only the lower part of the basinal stratigraphy is preserved. Fenton and Jackson (1989), using vitrinite reflectance values and apatite fission track analysis, determined that the northern sector of the Drummond Basin underwent uplift of 2200m at the end of the Triassic. As Drummond Basin uplift due to thrusting and folding averages 1000m, subsequent regional uplift of the eastern margin of the basin must have occurred. Widespread deposition of the Eromanga Basin as covered the Drummond and Galilee Basins before renewed uplift and erosion lead to the extensive removal of these sediments from the eastern margin of the basin. Apatite fission track analysis of samples from the Lachlan Fold Belt and Hodgkinson Basin indicate that uplift and erosion of ≥2000m of overburden occurred in the mid to late Cretaceous (O'Sullivan *et al.* 1996; Marshallsea *et al.* 1998). This uplift may have been an expression of underplating inward of rifting that heralded the onset of continental extension prior to the opening of the Tasman Sea (O'Sullivan *et al.* 1995). Crustal dynamics related to subducted oceanic lithosphere beneath eastern Australia that stagnated in the mantle and is presently being drawn up by extension on the Southeast Indian Ridge (Gurnis et al. 1998) is an alternate explanation.

4.0 LITHOSTRATIGRAPHIC ARCHITECTURE, FACIES AND SYSTEMS TRACTS

4.1 Introduction

The formal stratigraphy of the Late Devonian-Early Carboniferous Drummond Basin is based on surface outcrop in its southern sector (Anon 1952) and is described in Chapter 1. Outcrop mapping in the northern sector and a regional mapping program produced separate stratigraphic nomenclature for the northern and southern basin successions (de Bretizel 1966; Olgers 1972). Exposure of Drummond Basin lithostratigraphy is poor and restricted to the eastern perimeter, adjacent to the Anakie Inlier. Drummond Basin fill has been grouped into three cycles by Olgers (1972) who considered them to be separated by minor epirogenic events. A related sedimentary succession east of the Anakie Inlier, previously assigned to the Drummond Basin, has been reassigned to the Pretoria Basin (refer to Chapter 1) and is not considered further in this discussion.

The Late Carboniferous-Middle Triassic Galilee Basin extensively overlies the Drummond Basin. Lithostratigraphic subdivision of the Galilee Basin is mainly based on well-log signatures (Vine et al. 1965; Gray and Swarbrick 1975; Gray 1976) and is discussed in Chapter 1. Different nomenclature for northern and southern regions applies with geographic division at the southern margin of the Maneroo Platform and its eastern extension, the Barcaldine Ridge. Most of the basin is covered by fluvial and marine strata of the Jurassic-Cretaceous Eromanga Basin. Tertiary duricrust and Quaternary colluvium, alluvium and lacustrine sediments are widespread in its eastern parts obscuring exposure.

Successions of the Drummond and Galilee Basins are almost entirely non-marine and biostratigraphic age control is poor. Macrofloras obtained from the Drummond Basin, mainly from the St Anns Formation, but also from the Scartwater, Star of Hope and Ducabrook Formations, indicate a Late Devonian to Early Carboniferous age (Tenison Woods 1883; McKellar 1964a, 1964b; White 1962, 1964, 1967, 1968, 1972; Rigby 1986). Palynological assemblages described by Playford (1977, 1978, 1988a, 1988b) placed the Star of Hope and Ducabrook Formations in the Visean and the Bulliwallah Formation across the Visean-Westphalian. Early Carboniferous palaeoniscoid and sarcopterygian fish are known from the Natal Formation (Turner and Cook 1999) and the Ducabrook Formation (Hill and Woods 1964; Turner et al. 2005). A Visean tetrapod fauna was described from the Ducabrook Formation (Thulborn et al. 1996) with mid-Visean *Gyracanthides* recorded from the same locality (Turner et al. 2005).

The Galilee Basin was one of several basins used by Evans (1967) to construct the east Australian Late Carboniferous and Permian palynological stages that were later revised by Kemp et al. (1977). Specific palynological studies of Galilee Basin cores include those of Evans (1966, 1967), Jones and Truswell (1992), Norvick (1974), Little (1976), McKellar (1977), Playford (1988a, 1988b), Powis (1980) and Price (1980a, 1980b). The Lower Jericho Formation is assigned to Stage 1 or Stage 2 of Price (1980a, 1980b), but palynomorph preservation is poor. The Lower Jericho Formation equates with Biozones A-B of Jones and Truswell (1992) which they assigned to the Namurian to Westphalian C. A tentative Stage 2 age was assigned by Price (1980b) to an assemblage in the upper Jericho Formation containing the Oakleigh Siltstone Member. Jones and Truswell (1992) assigned this assemblage to Biozones C-D and correlated it with Westphalian D to Late Autunian (early Asselian). The Jochmus Formation was assigned an Upper Stage 2 to Lower Stage 3 age by Little (1976) whereas the correlative Boonderoo beds were assigned a Lower Stage 2 age by McKellar (1977). These assemblages partly correlate with Biozones D-E of Truswell and Jones (1992) and equate with Westphalian D to early Sakmarian stages. McKellar (in Swarbrick and Wallin 1976) noted a Stage 3 assemblage in the Aramac Coal Measures. A basin wide hiatus during Stage 4 and Lower Stage 5 is indicated by the absence of fauna of this age but palynological age control is poor for Eastern Australian Permian fauna. McKellar (1977) placed the Betts Creek beds assemblage in Upper Stage 5 equivalent to the Kazanian-Tatarian interval. No palynologic age data are available for the Rewan and Clematis Groups in the Galilee Basin but Jensen (1975) noted a Tr1 (Early Triassic) assemblage for these groups in the Bowen Basin. The Moolayember Formation in the Bowen Basin contains a Tr3 (Anisian) assemblage (Balme and Foster 1996). Biostratigraphic age assignments for the Galilee Basin is summarised in Figure 4.1.

Radiometric age control is available for various volcanic units in Drummond Basin infill. SHRIMP U/Pb dates provide a formational age ranging from 350 Ma to 344 Ma for the Silver Hills Volcanics which equates to the Tournaisian (Perkins et al. 1995; Henderson et al. 1998). A K-Ar date of 342±6 Ma was obtained from volcanics associated with epithermal gold mineralisation at Pajingo (Perkins et al. 1995). Parks (2000) considered that these volcanics may have equivalents in the St Anns Formation. Termination of Drummond Basin deposition is constrained by the Late Carboniferous-Early Permian age of the Bulgonunna Volcanics that unconformably overlie the basinal succession and have a SHRIMP U-Pb age range of 304.7±3.2 M to 293.5±5.6 Ma (Black 1994).

No radiometric dates exist for stratigraphic units of the Galilee Basin. Volcanic rocks from the extensional phase of the Bowen Basin have produced K-Ar ages of 280, 270 and 234 Ma for the Lizzie Creek Volcanics (Webb and McDougall 1968) and a SHRIMP zircon age of 294.2±2.8 Ma (Allen et al. 1998) for the correlative Carmila beds. The difference between the K-Ar ages and the SHRIMP age is indicative of Ar loss from the samples. These volcanic units are biostratigraphically correlated with the Reids Dome beds of the southern Bowen Basin (Draper et al. 1990) which has a tentative palynological correlation with the Aramac Coal Measures of the Galilee Basin (Gray 1976).

4.2 Methodology

Sixteen rotary air drilled wells, variably cored boreholes and limited outcrop sections provide stratigraphic control in the research area (Figure 4.2). Well completion reports were used to provide lithologic information. All available drillcore has been evaluated with full logging of Campaspe-1 to 6a and Hughenden-3/4R and sporadic short core samples logged from Koburra-1, Lake Galilee-1, Towerhill-1 and Thunderbolt-1. Lithologic sections have been constructed from analysis of multi-suite down-hole geophysical logs that are available for all the wells and boreholes and cross checked with the lithologic logs. Isopach maps have been constructed from seismic facies analysis (refer to Chapter 2). Outcrop sections of the Scartwater, Mount Hall and Bulliwallah Formations of the Drummond Basin were measured and spot descriptions and paleocurrent measurements were taken for units of the Drummond and Galilee Basin.

The paucity of outcrop sections of Drummond and Galilee Basin strata has limited sedimentologic data for facies analysis. Basin analysis in this study relies on new data derived from vertical profile analysis of geophysical logs, lithofacies coding of core and sporadic measured sections as summarised in Table 4.1 and fluvial sequence stratigraphic analysis as established by Currie (1997) and Miall (2000). Vertical profile analysis is not precise because sporadic core sections do not allow detailed correlation of lithostratigraphic successions with geophysical logs.

As defined by Mitchum (1977) a depositional sequence is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities. These unconformities represent a significant hiatus that show evidence of erosion or non-deposition with obvious stratal terminations or a paraconformity recognised by biostratigraphic breaks. Van Wagoner (1988) defined a sequence boundary as an unconformity separating younger from older strata with a significant indicated hiatus, along which there is evidence of subaerial erosional truncation or subaerial exposure. Galloway (1989) thought that regional unconformity or hiatal boundaries were difficult to recognise and proposed instead genetic stratigraphic sequences bounded by maximum flooding surfaces. Embry (1993, 1995) suggested using the transgressive surface as a conformable surface which separates regressive strata below from transgressive strata above. This transgressive-regressive couplet forms a T-R sequence.

A major problem with these definitions is that the sequences cannot be traced into continental non-marine successions. Currie (1997) developed a general sequence stratigraphic model for non-marine rocks based on analysis of a foreland-basin system. This model related fluctuations in base level to readjustment of fluvial equilibrium profiles and changes in accommodation. In this model fluvial sequences are bounded by three types of unconformities; Type 1 develops after a major fall in base level and is characterised by valley incision; Type 2 forms during minor reduction of accommodation and develops widespread shallow erosion of a pre-existing alluvial plain; Type 3 forms after base level fall caused by local to subregional uplift within the basin and is characterised by extensive pedogenesis and/or erosional truncation of underlying depositional sequences.

Sequences can be subdivided into genetic systems tracts characterized by geometry, facies associations, types of bounding surface, parasequence set distribution and position within the sequence. Systems tracts are defined as a linkage of contemporaneous depositional systems, each composed of three dimensional assemblages of lithofacies (Brown and Fisher 1977). They are not genetically dependent upon eustasy or relative position of sea level but are a succession of strata confined to a time interval characterised by stability in position or with a regular trend in lateral translation of a set of depositional systems. Parasequences and parasequence sets are the stratal foundations of a sequence. Parasequences are a relatively conformable successions of beds and bedsets bounded by marine-flooding surfaces or their correlative surfaces (Van Wagoner et al. 1990). They typically show distinctive stacking patterns, called parasequence sets that are bounded by major marine-flooding surfaces and their correlative surfaces (Van Wagoner et al. 1990).

Parasequences are difficult to identify in non-marine successions because facies change related to depositional water depth is lacking but equivalents may be represented by fluvial avulsion cycles, coal beds on coastal plains and widespread overbank mudstones on alluvial plains. Shanley and McCabe (1993) used tidally influenced channel fills to indicate maximum flooding surfaces whereas Wright and Marriott (1993) used the development of paleosols to identify systems tracts. Various workers have used coal seams to indicate transgressive and maximum flooding surfaces (Arditto 1991; Aitken and Flint 1995; Flint et al. 1995; Hampson 1995). Stacking patterns of parasequence sets can be recognised as progradational where facies become more proximal in character upwards through the set, aggradational where facies characteristics remain relatively unchanged and retrogradational where facies characteristics become progressively more distal upward through the set.

As shown by Shanley and McCabe (1998) and Ethridge (1998) fluvial sequences show distinctive bedset stacking patterns that reflect the main influences on their accumulation, namely changes in base level, tectonism or climate (Figure 4.3). These three parameters can be entirely independent or somewhat dependent such that a change in one parameter will be reflected in one or both of the others. Beyond the influence of relative sea level rise, the tectonic effects of basin subsidence or source area uplift can cause a change in accommodation. Fluvial depositional systems directly respond to these changes in accommodation. Shanley and McCabe (1994) showed that a rapid fall in base level and negative accommodation leads to terrace formation, channel incision and reworking by low sinuosity, high gradient streams.

Currie (1997) developed these ideas of fluvial response to changes in accommodation into cycles of degradation and aggradation similar to the depositional model for cyclothems (Table 4.2). Relatively coarse-grained, low-sinuosity fluvial deposits contained within an incised valley or deposited as laterally amalgamated sand bodies form a degradational systems tract. McCarthy and Plint (1998) considered that interfluve areas in this setting may develop mature soils. This corresponds to the falling stage and lowstand systems tract of marine sequences. A transitional systems tract is the fluvial equivalent of an early transgressive systems tract of marine sequences as base level begins to rise. Fluvial styles undergo major change during local or regional base level rise. In this sense fluvial sequences maybe confined to single fluvial system or may cross major interfluves. A slow increase in accommodation causes channel systems to meander or avulse across valley floors producing stacked and laterally amalgamated channel fill deposits with little fine-grained floodplain sediment. A rapid increase in accommodation induces lateral and vertical channel migration. Törnqvist (1993) considered that a rise in base level, with a rapid increase in accommodation, favours avulsion and the formation of anastomosing channel facies. An aggradational systems tract is the fluvial equivalent to the late transgressive and highstand systems tract of marine association. Isolated channel fill deposits develop with thick accumulation of floodplain deposits.

However, the character of fluvial sequences is not due only to change in base level but also reflects climate. The main effects of climate change on river systems are changes in discharge and sediment supply. These are not in phase with base level fluctuation, complicating the sequence stratigraphy of fluvial deposits.

As summarised by Reading and Levell (1996) and Posamentier and Allen (1999), the stacking patterns of sedimentary packages may be determined from wireline logs (Figure 4.4). Such logs provide vital data for the interpretation of the basinal successions described here and the wireline logs available in this study are listed in Table 4.3.

Gamma ray logs measure radioactivity which is generally a function of clay content in sedimentary rocks and therefore a proxy for grainsize and depositional energy. Exceptions are anomalously high values given by organic-rich shales, clay-rich sandstones caused by diagenetic overprint and feldspar-rich arkosic sandstones. Low values characterise cemented horizons and coals but need to be calibrated against sonic logs. Gamma logging can discriminate at parasequence scale.

Resistivity logs measure bulk electric resistivity of the rock which is a function of porosity and pore fluid. Such logs are a good indicator of lithology provided the fluid content remains constant and generally discriminate parasequence sets. Similarly SP logs measure the difference in electrical potential between a subsurface horizon and the surface. It is sensitive to changes in permeability and can be used to differentiate between sands and shales. Such logs can also identify parasequence sets.

Sonic logs measure sonic transit time through a stratigraphic interval which is related to porosity and lithology. As such it can be used as a grainsize indicator but is affected by post-depositional cementation, compaction and the presence of fractures. Organic-rich condensed sections as found in coals or black shales produce anomalously long travel times.

The density-neutron log suite is an excellent indicator of lithologic and depositional trends. Density logs measure the electron density of a stratigraphic unit which is related to bulk density whereas neutron logs attempt measurement of porosity. In clean sandstones there is a small separation between these logs that becomes larger in the case of arkose. An increase in shale content is expressed as an increase in neutron values but a decrease in electron density values. The resulting cross-over and separation between the two curves can be a useful grain-size indicator and assist in the differentiation of parasequences. Coals are easily discriminated using density-neutron suite data. Density logs are affected by hole caving and by the incidence of heavy minerals such as pyrite and siderite. The presence of gas increases the neutron response.

Gamma-ray logs are commonly used to describe stacking trends of parasequence sets (Coleman and Prior 1980; Galloway and Hobday 1983; Cant 1984; Rider 1986; Emery and Myers 1996). Such trends may be observed as a change in the log reading or from shifts in the sand or shale base line (Figure 4.5). A cleaning-up trend (or funnel-shape) shows as a progressive upward decrease in the gamma log values. This is due to either a progressive change in the lithology or a gradual change in the proportions of thin interlayered pelitic units. It reflects an upward increase in depositional energy, upward shallowing of water depth in a marine sequence and upward coarsening. A cleaning-up trend may also be the result of a gradual change from clastic to carbonate deposition or a gradual decrease in anoxicity.

A fining-up trend (or bell-shape) shows as a progressive upward increase in gamma log values. This could be due to a change in bulk lithology or reduction in proportion of sandstone interlayers. Decrease in depositional energy is implied as expressed by meandering or tidal channel deposits. Large scale fining-up trends are found in successions of coarse fluvial deposits and estuarine fill. In shallow marine facies this trend corresponds with deepening water such as would be expected in a transgressive shoreline to shelf system. Fining-up successions may also form due to a gradual increase in anoxicity or a gradual change from carbonate to clastic deposition.

The boxcar trend (or cylindrical- shape) reflects a low-gamma unit with sharp upper and lower boundaries set within a higher gamma background interval. This suggests two contrasting depositional energies and an abrupt switching from one to the other. It is typical of fluvial channel sands where high bedload systems have a broad boxcar signature whilst mixed load systems have a narrower, serrated bell-shaped signature. Commonly turbidites, aeolian sands and evaporite units also show a box-car response.

The bow trend (or egg-shape) consists of an initial cleaning-up trend overlain by a dirtying-up trend of similar thickness with no sharp break between the two. It is generally the result of an increase and decrease of sediment load in a basinal setting unconstrained by changes in base level as in a fan system. Irregular trends show no systematic change in either the sand or shale baseline and lack the clean character of boxcar features. They represent aggradation of a shaly lithology and are typical of lacustrine successions, muddy overbank facies, marine offshore shelf and deepwater facies. An irregular trend can reflect subtle and systematic shifts in base line that only become apparent with change in the horizontal or vertical scaling of the log.

The non-marine systems tract model established by Currie (1997) is applied to log data in this study. Broad lithologic descriptions from borehole logs and detailed geophysical well logs allow the discrimination of coarse-grained basal degradational systems tract that fine upwards through a transitional system tract to an aggradational systems tract. These systems tracts can be correlated between wells and boreholes to produce a regional sequence interpretation. Bounding unconformities shown by erosional relief on seismic reflectors are rare for the Drummond and Galilee basinal infill. Hiatal surfaces are inferred where there is an abrupt boundary between fine-grained and coarse-grained successions.

4.3 Facies, Systems Tracts and Sequences of the northern Drummond Basin

Olgers (1972) divided the Drummond Basin succession into three lithologic cycles which he considered to be separated by minor epirogenic events. Cycle 1 contains volcanic and predominantly volcaniclastic sediments of the Mount Wyatt Formation, St Anns Formation and Silver Hills Volcanics. Cycle 2 is dominated by quartz arenites of the Mount Hall and Raymond Formations whereas Cycle 3 is characterised by volcanolithic sediments of the Star of Hope, Bulliwallah and Natal Formations. Hutton (1989) and Johnson and Henderson (1991) attributed Cycle 1 to a syn-rift assemblage whereas Cycles 2 and 3 were associated by these authors with a thermal sag phase in the development of the Drummond Basin. The Mount Wyatt Formation, a nearshore succession of volcaniclastic strata, outcrops on the eastern margin of the Anakie Inlier and has been reassigned to the Pretoria Basin in this study.

4.3.1 St Anns Formation

The basal package in the northern Drummond Basin is the Late Devonian St Anns Formation. It is not dealt with in any detail in this study as it is not profiled in the seismic sections. Details of Cycle 1 are provided by Bennedick (1993), Davis and Henderson (1996), Henderson et al. (1998) and Hutton et al. (1998). The unconformity between the St Anns Formation and the basement Anakie Metamorphics has been mapped near St Anns Creek, north of Scartwater homestead (P. Blake pers. comm.) and Olgers (1972) recorded a thick boulder conglomerate at the unconformable boundary. Outcrop of the St Anns Formation, confined to the eastern basin margin, indicates rapid lateral and vertical changes in lithology are characteristic of the unit. Henderson et al.

(1998) inferred a thickness of 1390m for the St Anns Formation estimated from scattered outcrop on the northeast basin margin.

Sections measured from surface outcrop of the St Anns Formation record a basal interval of conglomerate and conglomeratic sandstone, with clasts of metamorphic and granitoid origin, overlain by beds of cross-bedded pebbly volcaniclastic sandstone grading to siltstone, mudstone and algal limestone (Olgers 1972; Henderson et al. 1998). Mudcracks, plant impressions and *Serpulites* tubes are present in some beds. Ignimbrites and tuffs occur throughout as are sporadic sinter deposits (Sennitt 1991; Goulevitch 1992; Henderson et al. 1998). Olgers (1972) noted a massive conglomerate containing reworked clasts derived from underlying strata near the middle of the sequence.

The basal conglomerate and laterally equivalent pebbly sandstone developed as a degradational systems tract. Metamorphic and fossiliferous limestone clasts show a local derivation from the Anakie Metamorphics and Ukalunda beds respectively (Olgers 1972).

Overlying this systems tract are stacked upward-fining fluvial channel fill deposits grading from pebbly sandstone to siltstone. These represent a transitional systems tract formed when a rapid rise in base level developed an increase in accommodation. A siltstone horizon containing S*erpulites* tubes recorded by Henderson et al. (1998) at the top of this interval represents a maximum flooding surface and suggests that the shoreline was nearby during deposition of the transitional systems tract.

The upper part of the St Anns Formation consists of aggradationally stacked, thick bedded sandstones and cross-laminated siltstones containing plant fossils. This interval represents an aggradational systems tract. The presence of thin limestone beds suggests a paralic environment. The Llanarth Volcanic Member, a sequence of fine to medium-grained volcanolithic sandstone, pebbly sandstone, siltstone, chert with minor ignimbrite and tuff, represents the upper interval of the St Anns Formation in the vicinity of the St Anns homestead. This unit shows aggradationally stacked, thickly bedded sandstones and siltstones with plant fossils and likewise represents the aggradational systems tract.

The presence of ignimbrites at various levels within the St Anns Formation suggests that volcanic activity occurred nearby. The St Anns Formation is locally unconformably overlain by the Bulgonunna Volcanics (Henderson et al. 1998) near the northern margin of the basin. Olgers (1972) considered that a disconformity separated the St Anns and overlying Scartwater Formations.

4.3.2 Scartwater Formation (seismic facies D1)

The Scartwater Formation is predominantly interbedded quartz sandstone and mudstone with minor thin beds of limestone, conglomerate and lithic sandstone. Sporadic tuff interbeds indicate contemporaneous volcanism in the hinterland. The formation unconformably overlies the Ukalunda beds, St Anns Formation and unassigned acid volcanics (Olgers 1972). Olgers (1972) established a 1200m thick reference section from the eastern margin of the Scartwater Salient.

A measured section of part of the Scartwater Formation at Mountain Creek (20^{o}53’41”S 146^{o}45’45”E) comprises three high order sequences (Figure 4.6). Facies analysis for the Mountain Creek measured section shows that the degradational systems tract of Sequence A comprises medium to coarse-grained volcanolithic sandstone (Sh) that shows horizontal lamination. This represents an unchannelised sheet flood deposit with upper flow regime bedding forms. A green-grey tuff shows a pyroclastic overprint indicating regional volcanism. The transitional systems tract of Sequence A contains fine-grained, laminated sediments (Fl) that represents an outwash plain facies that developed during a faster increase in accommodation. The aggradational systems tract of Sequence A comprises predominantly fine-grained rhythmites (Fsu) containing a sandstone horizon (Sh) showing horizontal parting lamination. This is capped by a fine-grained horizon (Fsm) that is indurated and very thickly bedded. The planar bed forms show that deposition occurred in unchannelised sheet flow in a floodplain facies with a high sedimentation rate. The sandstone horizon represents fluvial channel fill in an avulsive environment. The sandstone and indurated siltstone lithofacies at the top of the systems tract reflects a pedogenic overprint.

The degradational systems tract of Sequence B comprises coarse-grained, green grey, quartz-lithic sandstone (St) that shows basal scour and trough cross bedding, planar cross bedding and angular rip-up mud clasts in the coarse horizons. Calcareous veining occurs in the sandstone. overlain by slightly finer grained sandstone (Sm) that is massively bedded. This couplet represents a sandy braided channel fill in an upper flow regime. An upper coarse-grained sandstone (Se) contains rip-up clasts and represents scour channel infill. In Sequence B no transitional systems tract is developed as a rapid rise in base level, compared to sediment load, caused the development of a transgressive surface of minimal deposition. The aggradational systems tract comprises upward fining fine-grained sandstone and siltstone beds (Spt) that exhibit poor sorting and planar cross-bedding. This interval is capped by fine-grained sandstone and siltstone (Fsu) that contains planar bed forms representing unchannelised sheet flood deposits.

A dislocation separates Sequences B and C. The degradational systems tract of Sequence C comprises coarse-grained, quartz-lithic sandstone (Sm) that is upward fining and shows massive internal bedding representing sheet flood facies developed on a lower gradient surface than Sequence B. The transitional systems tract is represented by a transgressive surface similar to that in Sequence B. The aggradational systems tract of Sequence C has predominantly massively bedded siltstone (Fsm) with interbedded fine-grained sandstone exhibiting horizontal lamination. This represents floodplain and abandoned channel fill deposits developed during a slow increase in accommodation sponsoring an avulsive fluvial environment. Red beds indicate sub-aerial pedogenic periods. The top of the measured section contains tuff beds indicating continued regional volcanism.

The three sequences represented in the Mountain Creek measured section reflect deposition that was largely controlled by changes in accommodation. Sequences A and C reflect slower rates of base level rise as evidenced by the avulsive nature of the aggradational systems tract whereas the anastomosing channel facies of sequence B suggests a more rapid base level rise. Each sequence is separated by a type 2 unconformity of Currie (1997) with limited valley incision and poor pedosol development.

Limited paleocurrent measurements show that the predominant paleoflow was to the south-southeast with a single reading to the northwest (Figure 4.7). A lack of isopach data impedes determination of depositional geometry. The predominance of fine to coarse grainsizes of the sediments and development of floodplain facies are evidence of a low gradient, high sinuosity sandy fluvial system that had an axial drainage pattern to the southeast.

4.3.3 Mount Hall Formation (seismic facies D2)

Due to its quartzose character and resistance to erosion, the Mount Hall Formation provides extensive outcrop along the eastern basinal margin. Here it is predominantly planar and trough cross-bedded quartzose sandstone, pebbly sandstone and quartzose conglomerate. A thickness of 2740-3000m is inferred by Olgers (1972) for the Mount Hall and Raymond Formations but no reference section has been mapped due to structural complications. A limited measured section obtained at Mt Gregory (20°04’14”S 146°42’25”E) in the southern part of the research area reflects the general character of the succession (Figure 4.8). Here trough cross-bedded, quartzose pebble-cobble conglomerate (Gt and Gh lithofacies) is interbedded with medium-coarse-grained quartzose sandstone (St and Sh lithofacies). The conglomerates have variable bedding thickness and are clast supported whereas the sandstones are thinly bedded or trough cross-bedded and poorly sorted. Scale limitation of the section makes a sequence stratigraphic analysis problematic but the interpreted low sinuosity braided channel facies is indicative of deposition in a degradational systems tract during a period of gradual base level rise after development of a sequence boundary. Sandstone characteristics seen in outcrop are variable over small areas due to rapid channel switching in a braided channel facies. Near Belyando Crossing (21°32’1”S 146°51’39”E) in the south, scattered outcrop consists of fine to medium-grained quartzose sandstone with discontinuous pebble bands whereas near Little Mt Bingeringo (21°29’46”S 146°27’48”E) outcrop consists of thinly bedded fine to medium-grained quartzose pebbly sandstone containing trough cross beds. Southwest of Dawson Vale homestead (21°20’32”S 146°31’26”E) a small outcrop of pebbly quartzose conglomerate shows imbrication and trough cross bedding. The coarse grainsize, poor sorting and fining upward trends of the Mount Hall Formation in outcrop are interpreted as longitudinal (Sh lithofacies) and transverse bars (Gt and St lithofacies) in low sinuosity rivers. There is no evidence of deposition of fine-grained floodplain sediments, or effusive volcanics, as found in the underlying Scartwater Formation. The Mount Hall Formation is not intersected in any of the wells or boreholes.

The Raymond Formation, characterized by finer grained, well bedded quartz sandstone and mudstone has been mapped in the southern part of the research area but is not recognised here. Isolated outcrops of very thinly bedded, very fine-grained quartzose sandstone displaying micro cross-beds and a fine to medium-grained, massive quartzose sandstone are considered to be fine-grained units within the general braided channel facies of the Mount Hall Formation. Sporadic coarse-grained beds, including pebble-cobble conglomerate are also represented in this tract of exposure.

Cross-bed measurements for outcrop mapped as Mount Hall Formation show two general paleocurrent trends, to the ENE and SE, with a minor component trending SW (Figure 4.9). The ENE paleocurrent trends in the Mount Hall Formation represent fluvial transport from the hanging wall of the extensional system with a structural grain of that trend similar to that recognised for Cycle 1 of the basin infill by Johnson and Henderson (1991) and De Caritat and Braun (1992). The SE directed paleocurrents represent the axial trend of overall basin subsidence which controlled the main drainage system. The paleocurrent trends are derived near the eastern margin of the basin and indicate little or no sediment input from the east. A major quartzose source to the east is not apparent, with the northern New England Fold Belt comprising predominantly volcanics and politic sediments, during the Mount Hall Formation depositional episode. Siliciclastic metasediments are noted in cores from the Thomson Fold Belt to the west (Murray 1994). Outcrop stacking patterns are not conclusive but suggest a fining upward pattern of coarse-grained, low sinuosity parasequence sets associated with a degradational systems tract. The regional scale change in lithology, fluvial processes and depositional style of the Mount Hall Formation from the underlying St Anns Formation indicates a substantial shift in sedimentary dynamics. Minimal initial accommodation in a degradational systems tract and a slow increase in this accommodation during Mount Hall Formation time produced deposition of coarse-grained sediments with transport of pelites through the basinal system.

Isopachs of seismic facies D2, recognised as the Mount Hall Formation, show four discrete depocenters separated by transfer faults that trend northeast-southwest (Figure 4.10). The depocenters are elongate in plan and generally show NW-SE trends. Isopachs nearest the northern basin margin show rapid thickening of the formation from the basin edge. To the west they show a gradual onlap onto the Beryl Ridge. The isopach pattern indicates that fault-induced tectonic subsidence was active during deposition, with compartments between the transfer faults subsiding due to displacement on normal faults that trend NW-SE. Progressive movement on this fault mosaic induced substantial differences in the thickness of the formation but its lateral continuity suggests that the depositional surface was largely undisturbed and related to a broad fluvial catchment draining to the SSE. An unknown factor is the amount of accommodation supplied by compaction of Cycle 1 syn-rift sediments (Henderson et al. 1998) and known to be to be variable in thickness (Hutton 1989). The isopach pattern suggests that the Drummond Basin at the time of deposition of the Mount Hall Formation had a relatively narrow transverse width of approximately 150km and an asymmetric infill geometry indicated by the easterly position of depocenters.

4.3.4 Star of Hope Formation (seismic facies D3)

The defining lithology of the Star of Hope Formation is the presence of varicoloured strata and pyroclastics. In the type area in the Star of Hope Syncline, south of Mt Gregory, it comprises slightly feldspathic pebbly quartz sandstone and pebble conglomerate similar to the underlying Mount Hall Formation (Olgers 1972). Further north, on the flanks of the Blowhard and Bulliwallah Synclines, it comprises acid tuff and tuffaceous and volcanolithic sandstone. A sequence of quartz-feldspathic sandstone and minor feldspathic tuff south of Mt Janet, near the northern margin of the basin, previously mapped as Star of Hope Formation by Clarke and Paine (1970), has been reassigned by Porter (1991) as the correlative Doongara Formation because of its distinctive lithologic character. Alexander (1997) recognised the Star of Hope Formation in the Burdekin Falls region as a variable succession of conglomerate, sandstone, mudstone and tuff. The Star of Hope Formation was examined in this study from isolated, scattered outcrop in the northern Drummond Basin. It generally comprises very fine to fine-grained, thinly bedded to ripple laminated, pale grey to grey quartzose sandstone with mudclasts and rare hard, cryptocrystalline, massive creamy grey tuff beds. Olgers (1972) showed thickness varying from 600m to 1800m in the northern Drummond Basin with thickest accumulation occurring on the northeast basin margin.

The Star of Hope Formation is intersected in Mogga-1 (2152-3620m), Campaspe-1 (84-550m) and Campaspe-2 (165-500m). In Mogga-1 the intersection generally revealed units of interbedded quartz-lithic sandstone, siltstone and minor tuffs (Lawrence 1984). The sandstone beds are fine to coarse-grained, have a silty matrix and an average thickness of 10m. Thicker bedsets of grey-green siltstone separate the sandstone units. The lithofacies in Mogga-1 can be divided into four intervals, SH1-4 (Figure 4.11). SH1 occurs from 3225-3620m and is characterised by varicoloured siltstones and minor very fine to coarse-grained quartz-lithic sandstone. From 3225m to 3453m siltstone is mainly red-brown, indicating a vadose depositional environment in a floodplain. This can develop when high availability of accommodation causes fluvial channels to avulse with the extensive deposition of overbank deposits. In Campaspe-1 a slightly fining upwards succession commences with four upward fining intervals from 360-550m. Each interval has a quartz-lithic conglomerate base that fines up to a planar cross-laminated, medium to coarse-grained quartz-lithic sandstone which in turn is overlain by a planar laminated or cross-laminated, fine-grained sandstone to siltstone. The conglomerate contains pebble-cobble clasts that are generally matrix supported and show poor imbrication. Rip-up clasts are also present. Bedding thickness is 0.5-1.0m but can range up to 8m and the beds commonly have a thin, cross-laminated sandy top. The base of each interval is abrupt. Sandstone cross-laminae commonly include carbonaceous silty layers. Siltstone shows microlamination some with carbonaceous flecks, but some horizons are oxidized and reddish in colour. The overlying interval, from 86-360m, is predominantly multicoloured micaceous siltstone with thin interbeds of fine-grained sandstone. Sporadic medium to coarse-grained sandstone beds are also present. The siltstone shows muddy wisps, rootlet traces and displays thick lamina of variable colour. Sandstone interbeds display planar cross lamination and rip-up clasts at the base. For Campaspe-1 the sedimentary pattern generally represents a meander stream channel facies with extensive development of floodplain sediments. It is comparable to SH1 of Mogga-1 but is conglomeratic, indicating a proximal location to the sediment source consistent with its position adjacent to the basin margin.

Interval SH2 in Mogga-1 extends from 2802m to 3225m and comprises carbonaceous siltstone and sandy siltstone units overlying subordinate sandy bedsets. From 3014m to 3121m the sandstone is pyritic, micaceous and slightly carbonaceous with siltstone intercalations that are decidedly carbonaceous. A limited exposure to oxidation in the vadose environment is indicated, implying a high water table associated with a rapidly rising base level. This interval represents a sandy braided channel facies that lacks coarser lithologies due to its distal location from the source. In Campaspe-2 a comparable section extends from 165-500m. It shows similar, but coarser grained, inter-layering as seen in Mogga-1. Each bedset contains a basal poorly sorted, medium to coarse-grained volcanolithic sandstone or pebble-cobble conglomerate bed that is abruptly overlain by interbedded fine-grained sandstone and siltstone. Basal beds display planar cross-lamination at their tops and commonly contain rip-up clasts. The siltstones display sporadic fine cross-lamination and are rarely red coloured. This sedimentary pattern represents an anastomosing braid plain channel system similar to the SH2 section in Mogga-1. The proximal coarsening of SH2 is evidenced in the conglomeratic facies of Campaspe-2 consistent with its position near the basin margin.

Section SH3 in Mogga-1 occurs from 2570m to 2802m. Calcareous to carbonaceous siltstone becomes predominant with thin beds of fine to coarse-grained sandstone. This suggests widespread floodplain development and poor development of fluvial channel systems during a period of rapid change in accommodation. This interval is not detected in the Campaspe wells.

Section SH4 in Mogga-1 occurs from 2152-2570m. The proportion of argillaceous strata is enhanced in this interval and some sandstone bedsets show an upward fining trend. In the interval from 2463-2570m the siltstone is multicoloured and has enhanced volcanolithic content. Associated thin tuffs indicate contemporaneous volcanic activity. This section indicates meander channel and floodplain facies development associated with a low gradient fluvial system.

Wireline log records from these three wells identify the same intervals apparent from the lithological logs and the interpretation of the stacking patterns has produced recognition of systems tracts with the identification of two discrete sequences (Figure 4.12).

The upper part of Sequence 1 is interpreted in Campaspe-1 and the basal succession of Mogga-1 between 3225m and 3620m. Seismic evidence shows that the concordant contact with the underlying Mount Hall Formation is relatively near the base of Mogga-

1. This indicates that this coarse-grained unit is the degradational systems tract of Sequence 1. In Mogga-1 wireline log shapes of Sequence 1 comprise slightly serrated, thick bell-shaped parasequence sets. The overall pattern indicates dominance of finer grainsizes and shows a fining up trend. This pattern has better resolution in the resistivity log as oxidation of the fine grained sediment has reduced the gamma response. This conforms to the pattern expected for high sinuosity fluvial channel facies that has experienced avulsion in a high accommodation aggradational systems tract matching lithofacies interpretation of interval SH1. The log pattern in Campaspe-1 is similar to this interval in Mogga-1.

Sequence 2 is composed of all three systems tracts. Between 2802m and 3225m the wireline log shapes in Mogga-1 are highly serrated with sporadic fine-grained intervals and an overall coarsening-up trend. This suggests a low sinuosity channel facies in an anastomosed fluvial style with rare intervals of floodplain development in a degradational systems tract. The log pattern in Campaspe-2 is consistent with the degradational systems tract of Mogga-1. In both cases, system tract interpretation from the geophysical records matches lithofacies assignment and interpretation.

The wireline log pattern in Mogga-1 from 2570m to 2802m shows a stacked series of bell-shaped and funnel-shaped parasequence sets. This indicates rapid changes in stream morphology during a period of increased rate of accommodation. Upward coarsening parasequence sets developed when the sediment supply exceeded accommodation whereas upward fining parasequence sets formed when the balance was reversed. A transitional systems tract of Sequence 2 is indicated but this is not represented in Campaspe-2 indicating non-deposition or removal by erosion of the equivalent interval on the northern margin of the basin where different depositional dynamics prevailed.

In Mogga-1 the log pattern between 2152m and 2570m comprises stacked, bell shaped parasequence sets with sporadic thick, serrated cylindrical parasequence sets that show an overall coarsening-up trend. This suggests a fluvial pattern of stacked and amalgamated channel facies that avulsed on a floodplain during a slow increase in accommodation. This pattern is indicative of an aggradational systems tract of Sequence 2. No matching interval is present in Campaspe-2, indicating that erosion or non-deposition of the upper portion of Sequence 2 occurred on the northern margin of the Drummond Basin caused by changes in the depositional dynamics.

Isopachs of the Star of Hope Formation (seismic facies D3) show four discrete depocenters (Figure 4.13) with the thickest succession developed in the northernmost of these. Depocenters are bounded by transfer faults identifying basinal compartments which experienced variable subsidence. A westward translation of two of the depocenters, compared with those mapped for the underlying Mount Hall Formation, indicates a changing pattern of fault related extensional subsidence. Accommodation was maximised further west than for the Mount Hall Formation implying enhanced movement on growth faults distal to the breakaway fault system on the basin margin and greater subsidence towards the basin axis. Thickness gradients show both NNW-SSE and ENE-WSW trends matching to the trends of the extensional fault fabric interpreted as controlling the deposition of Cycle 1 and the Mount Hall Formation. Depocenters along the central basin axis reflect a thermal subsidence phase whilst those along the basin margin reflect a tectonic subsidence phase. Both phases could have been operating throughout the development of the Star of Hope Formation. A more gradual westerly thinning is apparent than that shown by the underlying Mount Hall Formation indicating that subsidence of the Beryl Ridge slowed during the interval in which the Star of Hope Formation was deposited.

Limited paleocurrent data is available for the Star of Hope Formation. Olgers (1972) recognised a northwest paleoflow direction based on measurements of cross-lamination from exposures of the formation south of the region considered here. This probably reflects local transport as the axial trend of NNW-SSE is clear from the isopach pattern.

A thickness of 1468m of Star of Hope Formation strata intersected in Mogga-1 is comparable with Olgers (1972) maximum thickness of 1800m determined from outcrop. The basal boundary of Sequence 1 with the underlying Mount Hall Formation was not intersected but seismic evidence shows that the TD’s of Mogga-1 and Campaspe-1 are not to far above the contact. The uniformly coarse-grained character of the Mount Hall Formation suggests conformity with Sequence 1 of the Star of Hope Formation within a degradational systems tract. However the more fine-grained lithic nature and presence of tuffaceous horizons of the Star of Hope Formation indicate a change in hinterland character and sediment source from the west to the east.

Sequence 2 shows substantial development of all three types of systems tract suggesting that a slow increase in accommodation occurred. This pattern is consistent with the onset of the thermal phase of basin subsidence caused by cooling of the lithosphere as outlined by McKenzie (1978). However the Star of Hope Formation shows thickening towards listric faults on its northern boundary indicating that extensional tectonics was still in operation.

4.3.5 Bulliwallah Formation (seismic facies D4)

The Bulliwallah Formation is described by Olgers (1972) as a well bedded quartz sandstone, interlayered with lithic or feldspathic sandstone that is sporadically pebbly and thin beds of olive-green mudstone. Cross-bedding and ripple marks are common. A generalized section logged by Olgers (1972) has a thickness of 1800m.

A partial section of the Bulliwallah Formation was logged from outcrop along Paddy Creek (21^{o}29’51”S 146^{o}39’45”E) in the southern sector of the study region. It is composed of fine to coarse-grained quartz-lithic sandstone with thin interbeds of laminated siltstone (Figure 4.14). Sandstone is generally thickly bedded and contains trough cross beds (St lithofacies), minor planar cross beds (Sp lithofacies) and climbing ripples (Sr lithofacies) or is thinly bedded with parting lamination (Sh lithofacies). Siltstone is laminated and shows ripple marks (Fl lithofacies). The succession is interpreted as having formed from transverse and longitudinal bars related to low flow fluvial regime, sandy braided channel environment with minor fine overbank or abandoned channel deposits. The climbing ripples are evidence of a high sediment load in a fluvial channel (Bristow 1993). This succession is typical of a transitional systems tract which accumulated under conditions of slow increase in accommodation.

The Bulliwallah Formation is intersected in Lake Galilee-1 (3090-3400m), Mogga-1 (610-2152m), Campaspe-2 (52-165m), Campaspe-3 (85-500m), Campaspe-4 (280-500m), Campaspe-5 (462-550m) and Hughenden-3/4R (430-567m). In these wells and boreholes it generally consists of fine to medium-grained quartz-lithic sandstone interbedded with multi-coloured siltstone.

The formation is partially intersected in Campaspe-2, 4 and 5 whilst Campaspe-3 and Mogga-1 intersected the unit in full. In Mogga-1 thin tuff beds occur throughout with an ignimbrite horizon recognised at a depth of 1423m. Based on physical logging of the Campaspe wells and basic lithologic descriptions in the well completion report by Lawrence (1984) its succession can be divided into four intervals (Figure 4.15).

In the boreholes Campaspe-2 to 4, interval B1 is represented by stacked, upward fining, thick conglomerate beds contain quartzose and volcanic clasts and muddy rip-up clasts. The tops of the beds show planar cross-lamination. The conglomeratic bedsets are separated by siltstone containing red and green very thin beds and lamina, ripple laminations, calcareous nodules, bioturbation and carbonaceous streaks. Fine-grained sandstone in the upper part of coarse horizons shows planar cross-lamination, convoluted bedding, ripple cross-bedding and is sporadically pyritic. This suggests a low sinuosity braided channel facies with fining up sandy horizons indicating channel bars and the pelitic horizons representing abandoned channel fill. The lack of B1 in the well Mogga-1 could reflect the development of a bypass surface along the basin axis at this time. The lack of well defined chronologic data does not allow a more conclusive synthesis.

Interval B2 is represented in Campaspe-4 from 280m-454m and Campaspe-5 from 462m-530m as interbedded, fine-grained quartz-lithic sandstone and siltstone with carbonaceous laminations. Planar cross-bedding is common in the sandstone horizons. Ripple marks and bioturbation in the pelitic horizons suggest some ponding in this locality. This interval is present from 1289m-2152m in Mogga-1, consisting predominantly of thick bedded very fine to medium-grained, poorly sorted feldspatholithic quartz sandstone. Calcareous cement is characteristic. Subordinate coarse-grained beds occur sporadically. Commonly sandstone horizons fine up to siltstone that may be tuffaceous and some thick horizons of siltstone are also represented. These lithologies suggest deposition as a low sinuosity fluvial channel facies that has an anastomosing channel pattern and minor floodplain development. A similar lithofacies association is represented in the Paddy Creek measured section which probably represents a succession near the base of this interval. In Hughenden-3/4R a section is composed predominantly of green to red-brown, fine to coarsely stratified sandy siltstone with some beds showing convoluted lamination. Calcareous nodules and mud-infilled rootlet traces are common. Three tuffaceous beds occur within the siltstone. Fine to medium-grained quartz-lithofeldspathic sandstone interbeds are micaceous, contain muddy rip-up clasts and shows planar cross-lamination. The section in Hughenden-3/4R is assigned to the B2 interval of the Bulliwallah Formation on the basis of similarity with this interval in Mogga-1.

Interval B3, from 1091m-1289m in Mogga-1, comprises thin beds of very fine to medium-grained lithic sandstone interbedded with siltstone. Sandstone is commonly calcareous and both lithologies are pyritic. This interval suggests deposition in a floodplain facies.

The upper interval, B4, from 610m-1091m in Mogga-1, is composed predominantly of siltstone that is commonly pyritic and has traces of carbonaceous material. Minor horizons of very fine to medium-grained poorly sorted sandstone are intercalated. Sandstone is commonly calcareous. The well Lake Galilee-1 (3090-3406m) has a partial intersection of the Bulliwallah Formation in its basal part, represented by very fine to fine-grained feldspatholithic sandstone interbedded with carbonaceous shale. Sandstones show cross-lamination, scour and fill structures, mud cracks and are commonly pyritic and calcareous (Pemberton 1965) and is matched here to interval B4 of the formation. A continuation of predominantly a floodplain facies is suggested for B4 but the presence of carbonaceous traces, bioturbation, calcareous nodules and pyrite traces suggests that parts of B4 developed as a lacustrine facies.

The Bulliwallah Formation is conformably overlain by the Natal Formation in Mogga-1 and Lake Galilee-1 indicating a continuity of sedimentation in the centre of the basin. However on the northern basin margin the Early Carboniferous Bulliwallah Formation is overlain by the Late Carboniferous lower Jericho Formation of the Galilee Basin indicating a significant hiatus between the two units.

Sequence 3 is composed of three systems tracts that have variable development in different parts of the basin. The well logs of Campaspe-3 and parts of Campaspe-2 and 4 have a generally low gamma ray response that shows serrated cylinder shaped, funnel shaped parasequence sets separated by minor fine-grained units (Figure 4.16). These are interpreted as reflecting a low sinuosity conglomeratic braided channel facies and fine-grained overbank facies in a degradational systems tract. The floodplain siltstones were deposited episodically such that greenish horizons reflects residency in a reducing phreatic environment following deposition whereas red horizons express residency in an oxidizing, vadose environment. The lack of a degradational systems tract in Mogga-1 suggests that base level fall was minor and expressed as a surface of non-deposition.

In Hughenden-3/4R from 430m-553m, Campaspe-4 from 280m-500m, Campaspe-5 from 462m-550m and Mogga-1 from 1289m-2152m, finely stacked parasequence sets with few fine-grained cylinder block shapes represent a transitional systems tract. This pattern developed during an increase in the rate of change of accommodation.

From 610m-1289m in Mogga-1 the parasequence set stacking pattern evident in the geophysical logs is characterised by bell-shaped patterns and rare funnel-shaped patterns and an overall upward fining trend is indicated. Such a pattern suggests a high sinuosity fluvial channel facies with abundant overbank accumulation matching with the interpretation of lithofacies B3 and B4. Spikes in the gamma ray response reflect a tuffaceous input. Uncommon funnel-shaped parasequence sets that are capped with very fine-grained sediments possibly represent deltaic systems associated with ephemeral lacustrine environments. Successions of this type can develop in an aggradational systems tract where substantial accommodation space and a low gradient depositional surface encourage the lateral displacement of fluvial channels. The corresponding interval in Lake Galilee-1 has a finer lithology with fewer bell or funnel-shaped parasequence sets. This reflects high sinuosity fluvial channel deposition of predominantly floodplain association within an aggradational systems tract where a slow increase in accommodation and a high sediment input applied. Thin bell-shaped parasequences may represent crevasse splay deposits. The lack of an aggradational systems tract in the Campaspe wells and Hughenden-3/4R is a reflection of an erosional episode on the northern margin of the basin as indicated by the hiatal contact with the overlying Jericho Formation.

Isopachs of the Bulliwallah Formation, represented by seismic facies D4, do not show the broadscale compartmentalisation apparent for the Mount Hall and Star of Hope Formations (Figure 4.17). A distinctive thickening of the formation is apparent in a

NW-SE central linear zone of the basin, termed here the Yarromere Depocenter, where a large scale braided channel system was a long lived agent of deposition. The channel system splits into two tributaries to the NE indicating sediment supply from that direction and generally trends SSE down the axis of the basin. Northeasterly orientated thickening trends on the northern basinal margin of the basin suggest incised valley fill but the lack of a matched thinning pattern of the Star of Hope Formation precludes this. The pattern most likely reflects localised, fault-related subsidence during the thermal subsidence phase of the basin as a whole. A thinning trend towards the northern margin is coincident with the location of the Mount Janet Fault Zone and registers influence of this structure on the pattern of subsidence. A depocenter to the northwest of this fault zone suggests horst uplift associated with the transfer fault during the late onset of compression.

Thinning of the isopachs onto the Belyando Thrust in the SE indicates that compression from the east was occurring during deposition of the Bulliwallah Formation. Uplift of basinal hinterland to the east is reflected in the pattern of the Yarromere Depocenter. To the west facies D4 shows gradual onlap onto the Beryl Ridge. Paleocurrent measurements collected from the Scartwater Salient show a dominant transport vector from the west-southwest with minor input from the northeast (Figure 4.18). These vectors express localised transport from a high on the southern margin of the Scartwater Salient and fluvial input from a rising hinterland to the east.

The Bulliwallah Formation reflects a long term, slow increase in accommodation with well developed systems tracts. This slow accommodation increase can occur during the thermal subsidence phase of rift basin development. The axis of maximum subsidence is coincident with that of the underlying Star of Hope Formation. Sandy braided channel facies supplied substantial sediment from the hinterland that accumulated in floodplains with lacustrine facies developing with a reduction in grade. The Bulliwallah Formation reflects the commencement of compressional tectonics from the east associated with the Early Carboniferous Kanimblan Orogeny.

4.3.6 Natal Formation (seismic facies D5)

The Natal Formation was described by Olgers (1972) as consisting of a monotonous sequence of interbedded, fine-grained quartz-feldspathic sandstone, siltstone and mudstone. Ripple marks and fine scale cross-bedding are common. The maximum recorded thickness of the Natal Formation is 1200m. The Natal Formation has patchy outcrop in the Scartwater Salient. Near Washpool Bore (21^{o}34’43”S 146^{o}38’25”E) very fine to fine-grained sandstone is interbedded with laminated siltstone. Sandstone has thin planar bedding with macerated organic matter on the bedding planes. Siltstone contains abundant organic matter, calcareous nodules and shows ripple-related cross lamination. A bulldozed excavation (21^{o}33’05”S 146^{o}29’53”E) on Plain Creek Station uncovered silty sandstone and pebbly quartzose sandstone. The fine sandstone is laminated and contains silicified rootlets and mudcracks. Siliceous nodules within it have yielded fossil fish remains and plant fossils (Turner and Cook 1999). The coarse-grained sandstone has trough crossbeds and appears to have basal scour into underlying silty sandstone. These lithologies are indicative of a fluvial depositional environment with ephemeral development of standing water.

The Natal Formation is intersected in the wells Mogga-1 (2967-3259m), Lake Galilee-1 (2840-3090m), Carmichael-1 (2752-2850m) and Koburra-1 (2767-3259m) (Figure 4.19). In all the wells except Koburra-1 it consists predominantly of grey to brown calcareous siltstone and minor interbedded, grey, very fine-grained quartzose sandstone. In Mogga-1 a carbonate layer is found near the base and pyrite traces are common in the middle of the succession. In Lake Galilee-1 and Carmichael-1 the siltstones show traces of black carbonaceous material and the very fine-grained sandstones are micaceous. In Lake Galilee-1 pebbly sandstone becomes predominant towards the top of the formation. In Koburra-1 very fine to fine-grained, rarely medium-grained quartz sandstone is characteristic with subordinate calcareous, carbonaceous, micaceous siltstone. These lithologies are all indicative of fluvial systems with epilimnic shallow lake development. The carbonate and black organic layers in Mogga-1, Lake Galilee-1 and Carmichael-1 suggest tendencies towards deeper water hypolimnic facies development. The pyrite traces are evidence of a reducing environment in anoxic lake sediments possibly reflecting an increase in water depth. The enhanced fluvial influence in Koburra-1 shows an overall aggradational trend as expressed by the consistent stacking pattern of the bedsets.

The well logs of Koburra-1, Mogga-1, Carmichael-1 and Lake Galilee-1 intersect the Natal Formation (Figure 4.20). The overall stacking pattern in these wells shows parasequence sets that can be grouped into three sequences.

Sequence 4 has a thin basal sandy parasequence set with the lowermost serrated cylinder block shaped set representing a braided channel fill facies of a degradational systems tract. This tract is not recognised in Lake Galilee-1 suggesting that a bypass surface developed in this locality. It is overlain by funnel-shaped or bell-shaped parasequence sets of an aggradational systems tract with no evidence of floodplain facies. In Koburra-1 the parasequence sets of the aggradational systems tract are thicker and have a higher proportion of funnel-shapes. This is suggestive of fluvial channel fill in a progradational delta facies influenced by an increasing water depth in a lacustrine environment. In Mogga-1 and Lake Galilee-1 this interval is very fine-grained with a predominantly serrated pattern indicating deposition in a low energy fluvial or lacustrine environment affected by sporadic flood events and a gradual increase in the depth of standing water indicated by the development of hypolimnic facies.

The overlying Sequence 5 has a lower coarser grained funnel-shaped parasequence set representing the degradational systems tract characterised by a fine-grained braided channel facies. A succeeding aggradational systems tract interpreted in the wells developed as a very fine-grained lacustrine facies with a matching high gamma ray value in the wireline log that shows little influence from fluvial channel facies. An abrupt boundary separates sequence 5 from sequence 6 indicating a rapid change in facies possibly reflecting an erosional period during a fall in base level.

The classical sequence set of degradational, transitional and aggradational systems tracts makes up Sequence 6. A thin cylindrical parasequence set of the degradational systems tract indicates brief braided channel facies development, best expressed in Koburra-1. An overlying bell shaped parasequence set of the transitional systems tract represents anastomosing channel fill with a funnel shaped set in Koburra-1 suggesting an upward coarsening facies in this locality. A finely serrated pattern for the aggradational systems tract suggests deposition in a low energy environment with fine scale inter-layering of arenaceous and pelitic lithologies.

Isopachs of the Natal Formation show a basinal thickening in the Mirtna Depocenter with very gradual onlap onto the Beryl Ridge in the west (Figure 4.21). The eastern basin margin is defined by the Hopkins and Belyando Thrust Systems which were active during deposition. In the Scartwater Salient, slight thickening east of the Hopkins Thrust System and scattered outcrop show that a foreland depocenter was developing in front of the Bingeringo Thrust System. Uplift along the Belyando Thrust produced ponding of the sediments indicated by the closure adjacent to the thrust.

The short cycle sequence pattern for the Natal Formation relative to the underlying units reflect the onset of a compressional foreland phase in basin development. The lack of transitional systems tracts in Sequences 4 and 5 indicate the onset of rapid basin subsidence influenced by foreland loading. The patterns reflect a changing balance in the relative rates of sediment input and lacustrine base level rise. In a rapidly subsiding basin a fining upward trend develops when sediment input accumulation does not keep pace with an increase in accommodation. A coarsening upward trend develops when sediment accumulation outstrips accommodation and lake shorelines prograde.

4.4 Discussion of northern Drummond Basin Sequence Architecture

Cycle 1, represented by the St Anns Formation, comprises predominantly fluvial sequences developed during synrift infill of the northern Drummond Basin (Figure 4.22). Systems tract variation in the St Anns succession suggests variable accommodation space relative to sediment supply during deposition. High lateral variability of the formation suggests that infill occurred in discrete rift compartments bounded by transfer faults as proposed by Johnson and Henderson (1991) for the northern Drummond Basin. Ongoing proximal volcanic activity is indicated by pyroclastic horizons throughout the sequence.

Evidence of rift phase basin development that shapes infill patterns is more extensive than previously recognised. The suggested extensional architecture for Cycle 1 proposed by Johnson and Henderson (1991) and De Caritat and Braun (1992) persisted through Cycle 2 and the beginning of Cycle 3. Evidence is provided here for basinal compartments bounded by transfer faults throughout deposition of the Scartwater, Mount Hall and Star of Hope Formations. However the extensional dynamics and differential subsidence of compartments was insufficient to disrupt the lateral continuity of units. This phase of basinal dynamics was long lived extending over a period of some 25 m.y. for rift basin infill. The quartz-lithic Scartwater Formation of Cycle 2 has high order systems tracts that developed over a relatively short time period and the style of succession appears similar to that of Cycle 1 as documented by Henderson et al (1998) for the northern Drummond Basin. The presence of numerous tuff horizons indicates that volcanism was characteristic of the hinterland.

The Mount Hall and Star of Hope Formations contain lower order discontinuous sequences indicating that variable base level adjustment accompanied late stage rift infill evidenced by the compartmentalisation expressed in the isopach patterns. The systems tracts and sequences reflect the interaction of subsidence, base level fluctuation and sediment supply related to hinterland relief, climate and volcanic activity.

The quartzose Mount Hall Formation of Cycle 2 represents an unusual episode in the basinal dynamics. It represents a degradational systems tract developed as a coarse-grained braided channel facies from a cratonic hinterland source to the west. This requires ongoing uplift of the proximal hinterland during basinal extension to maintain an enhanced gradient of the depositional surface. The simple shear model of extension outlined by Wernicke (1985) and Coward (1986) produces a thin skinned extensional basin above a detachment fault with associated tectonic uplift of hanging wall basement block at the basin margin where thinning due to dislocation affects the lower crust and mantle. Coward (1986) calculated this uplift to be of the order of a few hundred metres. Schmidt and Clark (2000) position Australia in low latitudes during the Devonian to Early Carboniferous and a warm, moist climate may be inferred producing rapid weathering of the uplifted basement. The extensive development of this systems tract took place when sedimentary accumulation outstripped accommodation. Evidence of contemporary volcanism is lacking during this period.

Sequence 1 comprises the Mount Hall Formation and the lower part of the quartz-lithic Star of Hope Formation of Cycle 3 but the depositional dynamics returned to that characteristic of the Scartwater Formation. The aggradational systems tract of this sequence comprises quartz-lithic high sinuosity channel and floodplain facies. Sequence 2 contains low order systems tracts that have a similar style to higher order tracts in the

Scartwater Formation and show evidence of renewed volcanism in the hinterland. Isopachs for the Star of Hope Formation indicate the continued compartmentalisation of sediment infill developed as a continuation of the heterogeneous thinning of the lithosphere as outlined by Coward (1986). The broad onlap onto the Beryl Ridge and development of a NW-SE axial depocenter suggest that thermal subsidence characterised this basinal sector. Sequence 1 reflects the rapid subsidence of an extensional phase whereas Sequence 2 indicates the onset of slower subsidence probably associated with dominance of thermal subsidence. As noted by Coward (1986) the McKenzie model of pure shear lithospheric stretching and the Wernicke model of simple shear stretching on a major dislocation of lithospheric scale are end members of a range in crustal extensional models. Components of both types of extensional subsidence appear to have been applied to different basinal sectors during deposition of the Star of Hope Formation.

A change in the infill pattern for the remainder of Cycle 3, the Bulliwallah and Natal Formations, represents previously unrecognised complex tectonic drivers for the northern Drummond Basin infill. Quartz-lithic strata of Sequence 3 (the Bulliwallah Formation) comprise well developed fluvial systems tracts with pyroclastic input throughout indicating volcanic activity in the hinterland. The isopach pattern indicates broadscale basin infill along a NW axis marked by the Yarromere Depocenter. Gradual and continuous basinal subsidence controlled by thermal recovery is indicated. Minor influence by the Belyando and Hopkins Thrust Systems on the basinal geometry along its southeastern margin is apparent during deposition of the Bulliwallah Formation. It marks the commencement of contractional tectonics associated with the Kanimblan Orogeny

New evidence of active basin inversion during the Early Carboniferous is provided by Sequences 4, 5 and 6 and the isopach pattern of the Natal Formation. The set of small-scale sequences which lack transitional systems tracts indicate that subsidence was variable with pulses of rapidly enhanced accommodation space. The isopachs of the Natal Formation show the Mirtna Depocenter adjacent to an emerging Hopkins Thrust System with minor depocenters developing to the west of the Belyando Thrust and Bingeringo Thrust System. Modeling of foreland basin development by Flemings and Jordan (1989) indicated that a narrow foreland basin is developed during high thrust rates with slight development of a foreland bulge towards the hinterland. The quartz-rich nature of the sediments indicates that a cratonic hinterland was still the predominant sediment source and uplift was minor along the thrust belts. The broad onlap onto the Beryl Ridge and a general basin axis similar to that of the underlying Bulliwallah Formation suggest that thermal subsidence remained a major control on basinal subsidence. Lacustrine and deltaic strata represent the ponded infill of a complex foreland basin developed during minor loading along thrust belts. Such depositional environments are mainly controlled by tectonism and climate. Xue and Galloway (1993) determined that climatically driven lake fluctuations mimic sea-level changes and sequence stratigraphic patterns are similar but with differences reflecting higher periodicities and greater facies complexity as reflected in the small-scale sequence development of Sequences 4 to 6. Lake geometry, drainage area and gradient of inflowing streams that governs the texture and volume of supplied sediment were determined by tectonic controls. Minor uplift along the thrust fronts and generally low gradients of the hinterland and depositional surfaces is reflected in the fine-grained character of the Natal Formation.

4.5 Facies, Systems Tract and Sequences of the northern Galilee Basin

The lithostratigraphy of the Galilee Basin was formalised from outcrop mapping (Vine et al. 1964; Vine et al. 1965) and subsurface well log correlation (Gray and Swarbrick 1975; Gray 1976). The framework and relationships developed in these contributions is followed here with minor adjustments to some unit boundaries and modification of unit correlations based on seismic facies continuity. The Koburra Trough is renamed the Koburra Depocenter as it had no distinctive physiographic expression during deposition.

4.5.1 Lake Galilee Sandstone and Jericho Formation (seismic facies G1)

The Lake Galilee Sandstone is the basal formation of the Joe Joe Group and is succeeded by the Jericho Formation (Gray and Swarbrick 1975). Seismic facies recognition does not allow discrimination between these formations but they can be identified as individual units in borehole logs. The Oakleigh Siltstone Member is a recognisable division of the Jericho Formation registered as a basin-wide seismic event and also apparent in borehole logs. In the interests of matching seismic facies to formations, the three units are combined into seismic facies G1. None of these units are represented by outcrop in the northern Galilee Basin. In the southern Galilee Basin the Jericho Formation outcrops on the western margin of the Springsure Shelf and in the Bogantungan Embayment. Seismic profile CS86-03 in the northern Galilee Basin shows a near surface expression of seismic facies G1 adjacent to the Cape River beneath thin Cenozoic cover. This interpretation is supported by drilling to the north and northwest of the profile where stratigraphically overlying pebbly sediments were encountered, interpreted as Boonderoo beds by Wecker (1978) and Balfe (1980) but grouped here within the Jochmus Formation.

The Lake Galilee Sandstone is recognised in Mogga-1 (52.5-220m), Koburra-1 (2734-2767m), Lake Galilee-1 (2578-2840m) and Carmichael-1 (2465-2752m) (Figure 4.23a). It generally comprises a lower fine to coarse-grained quartz-lithic sandstone succession overlain by a siltstone to claystone interval and an uppermost unit of interbedded, fine-medium-grained quartz-feldspathic sandstone and siltstone. The mid-section argillaceous interval is not present in Lake Galilee-1. A coarse-grained unit in the lower section of Koburra-1 and Lake Galilee-1 was described by Pemberton (1965) as consisting of conglomerate with clasts of quartz, quartzite, chert and rare shale and limestone. A sub-bituminous coal seam and a carbonaceous band in the upper part of the Lake Galilee Sandstone are recorded in Carmichael-1 by Jessop (1995) and Koburra-1 by Pemberton and Brereton (1970).

The Jericho Formation is intersected in Koburra-1 (1920-2734m), Lake Galilee-1 (1815-2578), Carmichael-1 (1612-2465m), Hughenden-3/4R (158-415m), Campaspe-4 (75-280m), Campaspe-5 (53-460m) and Campaspe-6 (75-500m). In Lake Galilee-1, Carmichael-1 and Koburra-1 a discrete unit of the lower Jericho Formation overlies the Lake Galilee Sandstone (Figure 4.23a). It consists of interbedded, very fine to fine-grained quartz-feldspathic sandstone and carbonaceous siltstone. A thin coal seam is noted in the lithologic log of Carmichael-1 by Jessop (1995), confirmed by a sonic log spike over the interval.

This unit is succeeded by the Oakleigh Siltstone Member composed of interbedded siltstone, mudstone and shale. In Lake Galilee-1 (2025-2190m) it is thinly bedded with carbonaceous seams delineating the layering and some horizons grade to silty carbonates (Pemberton 1965). Two carbonaceous horizons near its upper contact are interpreted from the gamma and sonic logs. In Koburra-1 (2176-2310m) the Oakleigh Siltstone Member is more arenaceous with the proportion of interbedded, fine-grained quartz-feldspathic sandstone decreasing upward through the sequence. The sandstone contains red lithic grains that suggest a tuffaceous origin. Some siltstone horizons are calcareous. The upper Jericho Formation is lithologically similar to the lower part of the formation. Spikes in the sonic logs for this interval in Lake Galilee-1 and Carmichael-1 also show high gamma readings. Swarbrick (1974) suggested that they may represent tuffaceous beds. Jessop (1995) noted a few thin coal seams at the top of the formation in Carmichael-1.

In the Campaspe borehole set, a succession previously assigned to the Boonderoo beds and Natal Formation by Fenton and Jackson (1989) are reassigned here to the Jericho Formation based on seismic profile continuity (Figure 4.23b). A correlative of the lower Jericho Formation occurs in Campaspe-5 (435-460m) and Campaspe-6a (446-500m) composed of thin, graded beds of granule-pebble conglomerate interbedded with fine-medium-grained quartz-lithic sandstone and siltstone which is sporadically thickly bedded. Conglomerate clasts are volcanolithic and commonly imbricated. Sandstone beds show coarse and fine scale cross-lamination and convolute lamination whereas siltstone horizons show slump structures at the base of some beds, carbonaceous lamination, fine-scale cross lamination, bioturbation and rare red beds. An interval of interlaminated siltstone and fine sandstone containing a unit of medium to coarse-grained sandstone with pebble bands in Campaspe-5 (380-435m) and Campaspe-6a (377-446m) is a correlative of the Oakleigh Siltstone Member. Overlying this is a stacked set of fine to medium-grained lithic sandstone, rarely pebbly at the base and grey siltstone corresponding to the upper Jericho Formation. Tuffaceous bands occur in the upper Jericho Formation. In the Campaspe borehole set an overall coarser grainsize of the Jericho Formation indicates that the set reflects a proximal location to the sediment source. A similar interval in Hughenden-3/4R, previously assigned to the Boonderoo beds by Gray (1977), has been reassigned to the Jericho Formation based on lithologic and well-log correlation with the Campaspe boreholes. A thin coal bed is intersected at 279m in this borehole.

Records from Koburra-1, Lake Galilee-1 and Carmichael-1 show the Lake Galilee Sandstone to have sharp upper and lower boundaries on gamma and resistivity logs

(Figure 4.24a). The unit is predominantly slightly progradational with thin and finely serrated, cylinder-shaped parasequence sets that become broadly serrated in its upper part. It represents a degradational systems tract characterised by relatively coarse-grained sediment deposited in low sinuosity fluvial channels. The uppermost funnel-shaped and broadly serrated, parasequence sets in the Lake Galilee Sandstone indicate an anastomosing fluvial channel pattern. The abrupt basal contact with, but apparent absence of incision, into the underlying Natal Formation may represent an omission surface corresponding to the Type 2 unconformity of Currie (1997). The sharp upper boundary well log signature of the Lake Galilee Sandstone suggests an abrupt change in depositional regime to an aggradational systems tract.

The majority of the lower Jericho Formation is predominantly composed of stacked, bell to funnel-shaped parasequence sets that correspond to a fluvial meander channel facies with swampy floodplain development as evidenced by carbonaceous beds in Koburra-1, Lake Galilee-1 and Carmichael-1. Thicker fluvial channel parasequence sets and less rapid channel switching in Carmichael-1 and Lake Galilee-1 indicate low-energy stream morphology away from the basin margins. The Lake Galilee Sandstone and most of the lower Jericho Formation together represent a degradational and aggradational systems tract couplet that defines Sequence 7.

A coarser-grained parasequence set in the top interval of the lower Jericho Formation represents a fall in base level and the development of a degradational systems tract within a succeeding sequence. The same sequence is recognised in Campaspe-5 and Hughenden-3/4R based on superposition and association with the Oakleigh Siltstone Member. This interval has thick bell-shaped parasequence sets indicating sandy anastomosing fluvial channel facies.

The basin-wide, thick siltstones and minor sandstones of the Oakleigh Siltstone Member generally reflect lacustrine sedimentation as evidenced by silty carbonates recorded by Pemberton (1965) in Lake Galilee-1 and the presence of fine carbonaceous matter on bedding planes. This unit developed in response to a rapid increase in accommodation relative to sediment accumulation and represents an aggradational systems tract. Thick bell shaped parasequence sets within the Oakleigh Siltstone Member indicates a sporadic fluvial influence. Development of thin coal seams at the top of the Oakleigh Siltstone Member in Lake Galilee-1 indicates that lacustrine environments in some areas gave way to mires. The coarse-grained degradational systems tract of the uppermost interval of the lower Jericho Formation and aggradational systems tract comprising the Oakleigh Siltstone Member and a fine-grained lower interval of the upper Jericho Formation are grouped as Sequence 8.

An interval of the upper Jericho Formation above the Oakleigh Siltstone Member shows serrated cylinder shaped parasequence sets with minor funnel-shaped parasequence sets. These reflect a low sinuosity sandy braided channel facies with minor floodplain development as a degradational systems tract. The overlying interval shows bell-shaped and rare funnel-shaped parasequence sets that developed in an aggradational systems tract where slow increase in accommodation that produced fluvial meander channel and floodplain facies. The latter eventually developed mires represented by thin coal seams that are developed at the top of the upper Jericho Formation as recorded by Jessop (1995) in Carmichael-1. The degradational and aggradational systems tract couplet is recognised as Sequence 9. In Campaspe-4, 5, 6a and Hughenden-3/4R a corresponding coarse-grained degradational systems tract and upper fine-grained aggradational systems tract couplet is representative of Sequence 9 (Figure 4.24b).

Isopachs of this interval constructed in this present study from seismic facies G1 show a very gradual thinning onto basement to the west confirming the Beryl Ridge as a basement high (Figure 4.25). In contrast, the interval thins abruptly onto the Belyando and Hopkins thrusts which were active during deposition. The Jericho Formation thins over the Nunkumbil Anticline, an active feature during deposition and over a NW trending ridge, coincident with the Moray Fault Zone. Isopachs identify a thick section in the Koburra Depocenter, a foreland depression to the west of the Hopkins Thrust System with a second foreland depression adjacent to the Belyando Thrust. Vine (1976) constructed isopachs from well data of the Upper Carboniferous of the Galilee Basin that show a similar, elongate Koburra Depocenter. Onlap and thinning onto the Beryl Ridge represents the development of a foreland bulge on the hinterland side of an active thrust system.

4.5.2 Jochmus Formation (seismic facies G2)

The Jochmus Formation, the uppermost unit of the Joe Joe Group, is known only from the subsurface in the northern Galilee Basin and has not been recognised in outcrop of the Joe Joe Group in the southern Galilee Basin. Intervals of it are intersected in Towerhill-1 (1194-1489m), Aberfoyle-1a (1465-1495m), Koburra-1 (1498-1920), Thunderbolt-1 (1052-1611), Fleetwood-1 (1220-1236m), Lake Galilee-1 (1058-1815m) and Carmichael-1 (945-1612m). A representative section is shown in Figure 4.26. The formation comprises interbedded labile sandstone, siltstone and mudstone. Sandstone is fine to medium-grained, moderately to well sorted and locally conglomeratic whereas siltstone is argillaceous to sandy and carbonaceous. Mudstone is micaceous, carbonaceous and in places tuffaceous. Fine-grained units include varves.

The Jochmus Formation is divided into lower and upper intervals by the finer grained Edie Tuff Member that has wide basinal expression and is recognised by high gamma ray and low resistivity signatures (Gray and Swarbrick 1975). Exact definition of the upper boundary of the Edie Tuff Member is difficult for most intersections because geophysical logs show that the boundary is gradational. The lower Jochmus Formation is generally coarser in grainsize than the upper interval. The upper Jochmus Formation is not recognised in Towerhill-1 and has a thinned representation in Koburra-1. The “red tuff marker” of Cundill et al. (1971) defined as a reddish coloured siltstone horizon of the upper Jochmus Formation has no stratigraphic value. Such colouration and lithic content is known from various levels within the Edie Tuff Member and upper Jochmus Formation.

In Charters Towers-1, near Balfes Creek, a predominantly mudstone unit with minor siltstone, sandstone and very minor conglomerate, carbonaceous shale, probable tuff and calcareous claystone was assigned to the Boonderoo beds based on the presence of varved intervals by Balfe (1980). This succession has lithological similarities with the upper Jochmus Formation to which it is assigned in this study. The recognition of varved shale in the upper Jochmus Formation in Lake Galilee-1 by Pemberton (1965) and varved mudstone and tillite in the Boonderoo beds by Vine (1964) indicate a cold climate or glaciogenic influence on this interval. However, most of the Jochmus Formation logged in the wells comprises fine to medium-grained, moderately well sorted lithic sandstone and mottled argillite that show no glacial influence.

In wireline logs two sequences are represented in the Jochmus Formation (Figure 4.27). The lowermost of these, Sequence 10, commences with a basal cylinder shaped parasequence set that is coarse-grained with minor serration in the northern wells possibly reflecting a glaciogenic influence. This becomes finer grained to the south with highly developed serration indicating pelitic intercalations in Carmichael-1 and Lake Galilee-1. This represents a degradational systems tract with development of low sinuosity, sandy braided channel facies grading southwards to low sinuosity, anastomosing channel facies that display no lateral amalgamation. This interval is succeeded by a transitional systems tract composed of thick, bell shaped parasequences with fining upwards tendencies that represent a high sinuosity anastomosing fluvial channel facies with minor floodplain facies developed during a slow increase in accommodation. Sequence 10 is completed with an aggradational systems tract consisting of thick, bell shaped parasequence sets which represent a fluvial facies characterised by floodplain sediments with restricted, high sinuosity fluvial channel fill that fines upwards to fine-grained carbonaceous mudstone, carbonaceous siltstone and sandstone of the Edie Tuff Member.

Seismic profile CAR82-09 shows valley incision into basement in the region of Towerhill-1 on the Beryl Ridge (Refer to Chapter 3). Here the degradational systems tract of Sequence 10 was a bypass surface of enhanced elevation and an incised valley fill parasequence set of high sinuosity fluvial channels with increasing development of floodplain sediments represents the transitional and aggradational systems tracts.

Sequence 11 has a similar pattern to Sequence 10 but the reduced development of a transitional systems tract indicates a reduction of sediment supply during its emplacement. Sequence 11 is not represented, or poorly developed, on the northern margin of the basin indicating that basinal subsidence had largely ceased in this sector.

Isopachs of the Jochmus Formation (seismic facies G2) show the Koburra Depocenter as a continual depositional feature (Figure 4.28). Rapid thinning onto the Mingobar Structure and Belyando Thrust indicate that they were discrete, thrust-related geomorphic features of the eastern basinal margin during deposition of the Jochmus Formation. Overlap is apparent across the Beryl Ridge to the west and there is evidence of incised valley fill at the base of the formation on the western basinal margin. Isopachs of a Lower Permian sequence of the Galilee Basin constructed by Vine (1976) show the Koburra Depocenter in the northern Galilee Basin with onlap onto the Beryl Ridge and thinning over the Barcaldine Ridge into the southern Galilee Basin where sedimentation at this time was limited. A succeeding Mid-Permian isopach map of the Galilee Basin shows only a broad basinal infill of the northern Galilee Basin and no sedimentation in the southern Galilee Basin.

4.5.3 Betts Creek beds (seismic facies G3)

A basin-wide hiatus, indicated by a Stage 2 to 3a (late Asselian-early Sakmarian) age of the Jochmus Formation and an upper Stage 5 (Ufimian-Dzhulfian) age of the Betts Creek beds occurred in the Galilee Basin (Kemp et al. 1977). The Betts Creek beds outcrop near Pentland, where they onlap basement metamorphics along the White Mountains Structure. In the type locality the Betts Creek beds comprise a basal conglomerate overlain by *Glossopteris*-bearing mudstone, lithic sandstone and rare tuff interbeds (Vine et al. 1964). Measured sections in Porcupine Creek, White Mountains Creek and Betts Creek show that although conglomerate is typical in the lower part of the unit it largely consists of interbedded, kaolinitic, lithic sandstone and micaceous siltstone. Vine et al. (1964) considered coal and carbonaceous shale to be restricted to areas of low sedimentation rate. Beeston (1977) employed maceral and vitrinite reflectance analysis to classify the coal as non-coking sub-bituminous and sub-hydrous. Vitrinite reflectance measurements by Davis (1972) from the Betts Creek beds, Jochmus Formation and Jericho Formation in Koburra-1, Galilee-1, Towerhill-1 Thunderbolt-1 showed little variation in values and a broad relationship between present depth and reflectance. The data is consistent with a simple thermal history for the Galilee Basin as related to depth of burial.

The Betts Creek beds were intersected above the Jochmus Formation in the wells Towerhill-1 (1050-1194m), Aberfoyle-1a (1325-1465m), Koburra-1 (1330-1488m), Thunderbolt-1 (882-1048m), Fleetwood-1 (1040-1220m), Lake Galilee-1 (850-1058m) and Carmichael-1 (781-945m). In Hughenden-3/4R (50-158m) the Betts Creek beds have here been interpreted to overlie the upper Jericho Formation. Haworth (1968) reported a basal conglomerate, comprising predominantly quartz pebbles in Towerhill-1 whereas in Koburra-1, Thunderbolt-1, Lake Galilee-1 and Carmichael-1 upward fining coarse-grained sandstone occurs as the basal interval (Figure 4.29). In Hughenden 3-4R the basal interval is an upward-coarsening sublabile to quartzose sandstone. In Aberfoyle-1 and Fleetwood-1 carbonaceous shale is developed at the base of the unit, overlain by a thick sequence of upward fining labile sandstone.

The remainder of the Betts Creek beds comprises interbedded, fine to coarse-grained sandstone, coal, shale and carbonaceous siltstone. Jessop (1995) reported the presence of minor tuff in Carmichael-1 but neglected to note its position in the succession. The basal boundary of the Betts Creek beds shows in seismic profiles as a gently rolling discontinuity suggesting minor erosion preceded deposition. In a detailed study of the unit in Fleetwood-1 thirteen coal seams, varying in thickness from 0.2m to 3.0m, were recognised and correlated with twelve seams interpreted from the intersection in nearby Lake Galilee-1 (Anon 1993). Eight groups of coal horizons, ranging from 0.05m to 2m thick were logged in Aberfoyle-1a but these cannot be correlated with eight seams identified from neighbouring Koburra-1 (Anon 1994). Coals are predominantly durain with variable vitrain bands. Very minor fusain is reported in Aberfoyle-1a. A substantial argillaceous content is characteristic of the coals.

The Betts Creek beds have been correlated on palynologic evidence with the Colinlea Sandstone and Bandanna Formation (Gray 1976) that are identified in the southern Galilee Basin where they are separated by a marine transgression represented by the Peawaddy Formation and Black Alley Shale. This rise in sea level may have been the controlling influence on deposition of the Betts Creek beds as indicated on Figure 4.22.

In the wireline logs a coarse basal interval is represented by a thin funnel shaped parasequence set that represents a sandy braided facies deposited in the degradational systems tract of Sequence 12 (Figure 4.30). The thick overlying transitional systems tract contains stacked bell shaped parasequence sets that show an overall slightly upward coarsening signature. This represents an anastomosing channel facies with thin mire development in floodplain deposits. The coarsening trend reflects greater sediment input into the basin than the development of accommodation space.

The isopach map constructed for the Betts Creek beds shows that it is a thin sheet less than 200m thick that has remarkable continuity and consistency across the study area with rapid thinning to subcrop on the Mingobar Structure (Figure 4.31a). The pattern does not reflect prior basin morphology. The unit shows slight thickening to the south towards a shallow depocenter shown by Vine (1976) and a tract of slight thickening to the NW before thinning to outcrop. In detail the unit shows subtle, irregular thickness variations at the scale of less than 50m. This possibly reflects autogenic peat mound development in areas of low sediment input.

4.5.4 Rewan Group (seismic facies G4)

The Rewan Group is not represented in outcrop but is intersected in all wells in the northern Galilee Basin except Mogga-1, the Campaspe borehole set and the Hughenden boreholes. The Dunda beds, a facies variant of the Rewan Group, has limited extent in the northern Galilee Basin and outcrops on the southern margin of the study region. The Group consists of interbedded, labile, very fine to medium-grained, sporadically coarse-grained sandstone and varicoloured lutite that is rarely micaceous or carbonaceous (Figure 4.29). Red beds occur throughout the unit. The Rewan Group can be subdivided into three intervals based on changes in proportion of these two lithologies and stacking patterns. The lower interval (R1) is dominated by lutites, the middle interval (R2) has a substantial arenite component and the upper interval (R3) has thick horizons of sandstone and pelites but overall it is finer grained than the interval below.

In well logs interval R1 shows an aggradational to retrogradational pattern of bell shaped parasequence sets with the proportion of lutites increasing upwards (Figure 4.30). It represents a fluvial facies with high sinuosity channel fill and extensive floodplain sedimentation and marks the aggradational systems tract of Sequence 12 which commenced with the Betts Creek beds. The floodplain signature diminishes to the north where thick, bell shaped parasequence sets of high sinuosity avulsive fluvial channel facies association predominate in Koburra-1.

Interval R2 is a slightly coarsening upwards parasequence set that result in a serrated cylinder block log shape. It shows a distinctive series of positive spikes on the resistivity logs that reflect stacked channel fill. Interval R2 represents a fluvial facies with low sinuosity channels and minor floodplain sedimentation developed during a period of low accommodation as a degradational systems tract marking the commencement of Sequence 13. The uppermost interval, R3, is represented by predominantly bell shaped with minor development of funnel shaped parasequence sets, similar to R1. The pattern indicates a similar fluvial facies of high sinuosity channels and extensive floodplain sedimentation developed in an aggradational systems tract. The relatively thin degradational systems tract for Sequence 7, and lack of a recognisable transitional systems tract, indicates a period of rapid increase in accommodation as deposition of the sequence progressed. Koburra-shows enhanced development of channel sands suggesting a reduction in depositional gradient from north to south.

The Dunda beds, composed of quartz-labile sandstone and interbedded lutite, represent a transitional unit between the Rewan Group and the Clematis Group and mark the commencement of Sequence 14. Cross-bed measurements from the Dunda beds are variable but suggest a source from the east (Vine et al. 1965). The stacking pattern of Sequence 14 commences with a thin, serrated cylinder block shape overlain by a thin, generally fine-grained interval and an uppermost highly serrated bell shaped parasequence set. These three subdivisions correspond to degradational, transitional and aggradational systems tracts and a progression in fluvial facies from a sandy braided channel system to a low gradient meandering channel system with associated floodplain development.

Isopachs for the Rewan Group (seismic facies G4) identify thickening in the Koburra Depocenter, a very gradual thinning onto the Beryl Ridge and more rapid thinning towards the northwest and southeast (Figure 4.31b). The southeast thinning trend is associated with a northeast trending Moray Fault Zone that had a expression as a positive feature. The Rewan Group facies thins rapidly onto the Mingobar Structure suggesting that this feature marked the eastern basin margin during deposition of the group. The isopach pattern in this study is consistent with that constructed by Vine (1976) which likewise identified the Koburra Trough as a depocenter.

4.5.5 Clematis Group (seismic facies G5)

The Clematis Sandstone comprises the Clematis Group in the Galilee Basin which is considered to be correlative with the Clematis Group of the Bowen Basin (Mollan et al. 1969; Exon et al. 1972). It is represented in all boreholes and wells that intersect the uppermost part of the Galilee Basin succession in the region. In the northern transect it is recognised in Towerhill-1 (733-867m), Aberfoyle-1a (849-1090m) and Koburra-1 (818-1090m) whereas in the southern transect it occurs in Thunderbolt-1 (576-625m), Fleetwood-1 (540-652m), Lake Galilee-1 (345-463m) and Carmichael-1 (270-400m) (Figure 4.32). The Clematis Sandstone is predominantly moderately sorted, fine to coarse-grained quartzose sandstone with minor red siltstone and mudstone and rare conglomerate. Its outcrop correlative, the Warang Sandstone, occurs extensively in the White Mountains near Pentland on the northern margin of the Galilee Basin. According to Gray (1977) and McKellar (1977) the Warang Sandstone is correlative with the upper Clematis Sandstone and lower Moolayember Formation. Vine (1964) recorded this unit as disconformable on the Betts Creek beds and it occurs in Hughenden-1/2R (142/144-421m) where its upper boundary is not recorded but the interval it is similar in lithology to the Clematis Sandstone.

The Clematis Sandstone consists of two sequences that show best development in the northern sector of the region of study (Figure 4.33). Sequence 15 shows a basal finely serrated cylinder shaped parasequence set pattern with sharp upper and lower contacts. It represents a low sinuosity fluvial channel facies in a degradational systems tract during an interval of limited accommodation. A localised reduction in sediment input allowed the development of a carbonaceous interval evident in the sonic log of Lake Galilee-1. This sequence continues as a stack of thick bell-shaped parasequence sets that developed the aggradational systems tract with a very thin fine-grained unit representing a brief transitional systems tract. Such patterns develop when enhanced accommodation space is reflected by deposition from a meander stream pattern with some preservation of floodplain facies. The upwardly increasing pattern of serration suggests that avulsion and floodplain facies development became more dominant as sediment buildup lagged behind the increase in accommodation.

In the southern group of wells (Carmichael-1, Lake Galilee-1, Fleetwood-1, Thunderbolt-1) Sequence 15 is not developed indicating cessation of basin subsidence in this sector by the Middle Triassic. Sequence 16 commences with a cylinder shaped parasequence set that has sharp upper and lower boundaries similar to the degradational systems tract of Sequence 9. This systems tract is perhaps a subsurface correlative of the Warang Sandstone. The transitional systems tract is represented by a very thin finer grained facies whilst the aggradational systems tract comprises the overlying Moolayember Formation.

Paleocurrent measurements suggest a source from the northwest and west for the Clematis Sandstone (Vine et al. 1965). Stratigraphically equivalent units in the Bowen Basin show paleocurrents from the north flowing along the basinal axis with some input from the west in the upper part of the succession (Jensen 1975). From outcrop, in the southern Galilee Basin, the Clematis Group was considered by Vine (1965) to unconformably overlie the Rewan Group. This relationship is apparent in the northern basin with seismic profiles indicating a conformable relationship.

An isopach map for the Clematis Group (seismic facies G5) shows a broad, shallow depocenter west of the Mingobar Structure (Figure 4.34a). The group gradually onlaps the Beryl Ridge in the west and rapid thinning of the Clematis Sandstone onto the Mingobar Structure indicates that this feature continued expression as the basin margin. Vine (1976) identified a major fan-like depocenter for the Clematis Group adjacent to the White Mountains Structure with gradual thinning towards the south. Such interpretation is not supported in this study which indicates subdued thickness changes for this interval with a sediment source generally from the west.

4.5.6 Moolayember Formation (seismic facies G6)

Vine (1965) noted a gradational contact of this formation with the underlying Clematis Sandstone. It is logged in all wells that intersect the Clematis Group. In the northern sector it occurs in Towerhill-1 (563-733m), Aberfoyle-1a (380-849m) and Koburra-1 (320-818m) and in the southern sector it is present in Thunderbolt-1 (390-576m), Fleetwood-1 (147-540m), Lake Galilee-1 (125-345m) and Carmichael-1 (45-270m) (Figure 4.32). It comprises predominantly multicoloured lutites with labile sandstone and subordinate quartzose sandstone.

Wireline logs of the Moolayember Formation show a stacking pattern of thick bell-shaped parasequence sets separated by irregular fine-grained trends (Figure 4.33). Carbonaceous horizons are recorded in Thunderbolt-1, Towerhill-1 and Koburra-1. The stacking pattern suggests high sinuosity channel fill and floodplain fluvial facies marking the aggradational systems tract of Sequence 16.

Isopachs constructed for the Moolayember Formation (seismic facies G6) in this study show a thickening of the sediments in a rejuvenated Koburra Depocenter, gradual thinning onto the Beryl Ridge and rapid thinning onto the Mingobar Structure (Figure 4.34b), the same pattern as shown by all Galilee Basin units. The regional isopach map of the Moolayember Formation constructed by Vine (1976) has similar trends. It identifies the Koburra Trough with gradual thinning to the west and south.

4.6 Discussion northern Galilee Basin Sequence Architecture

The same style of systems tract development characterises sequences in the Drummond and Galilee Basins. It is built on the cyclicity of fluvial systems tracts with an irregular succession of degradational, transitional and aggradational elements (Figures 4.6, 4.12, 4.16, 4.20, 4.24a, 4.24b, 4.27, 4.30, 4.33). In some cases the succession is abbreviated with the transitional systems tract missing. The sequences have regional expression, essentially basin-wide for the study area. The succession of systems tracts that make up each sequence conforms to general practice in sequence stratigraphy. Sequences are separated by disconformities or correlative intervals in the sedimentary record where accumulation was minimal (Van Wagoner et al. 1988). Accordingly, degradational systems tract are taken here as the basal intervals of discrete successions, expressing reduced rates of sedimentation whereas the aggradational systems tract reflects enhanced rates of sediment accumulation as characterise highstand systems tract in marine successions. The approach is similar to that adopted by Shanley and McCabe (1993), Emery and Myers (1996), Cant (1996) and Currie (1997).

Sequences may have disconformable boundaries as is apparent for the paraconformity separating Sequences 11 and 12 and the incised valley development underlying Sequence 10. In general biostratigraphic control is too poor to identify hiatal surfaces and the resolution of seismic profiles and control from outcrop is likewise too poor to constrain erosional relief that may be present. Sequences developed during phases of foreland loading have a much smaller duration than those representing periods of thermal subsidence. This indicates that rapid changes in sedimentation take place during periods of active tectonics.

Models of foreland basin development proposed by Beaumont (1981) and Jordan (1981) generally show steady state subsidence. Flemings and Jordan (1989, 1990) modeled the effects of different flexural lithospheric rigidities and rates of thrust uplift on basin morphology and sediment supply during steady state subsidence. Low rigidity results in a wide but shallow basin, intermediate rigidity produces a narrower but deeper basin and high rigidity forms a wide and deep basin. Low thrust rates results in overfilled, deep basins. As the thrust rate increases the basin becomes progressively underfilled and narrow. Increasing sediment supply increases the volume of the foreland basin whereas enhanced transport efficiency increase the depositional area. These authors considered that their model has general application to non-steady state systems of foreland development. In general the Galilee Basin sequences record intervals of non-steady state foreland subsidence caused by episodic thrust displacement and the superposition of climate and sea level cycles on long-term progressive subsidence due to thermal recovery and thrust loading caused by contraction to the east. The sequence architecture is due primarily to basinal and hinterland tectonics with a subordinate climate signature.

The thick development of Sequence 7 and lack of a transitional systems tract indicates relatively rapid subsidence and high sediment load infill of the basin (Figure 4.22). The models of Flemings and Jordan (1989) indicated that moderate rates of thrusting and sediment supply are factors that produce basinal patterns as shown by isopachs of the Jericho Formation. The rapid thinning onto the Hopkins Thrust System and Belyando Thrust show that these features were active during deposition. Evidence occurs of contemporary uplift along the Bingeringo Thrust System suggests a series of piggy-back thrusts to the east were involved. The lack of forebulge shown in the model indicates continued influence of thermal subsidence on the basinal architecture. Red beds throughout the unit indicate a dry climate and the lack of conglomeratic facies suggests that sediment flux was low with a moderate transport coefficient. Petrofacies analysis (see Chapter 5) shows that the quartzose Lake Galilee Sandstone has a predominantly cratonic source whilst the Jericho Formation has greater input from proximal volcanic and thrust belt sources in the Anakie Inlier and Drummond Basin to the east. The dissimilar petrofacies of the Lake Galilee Sandstone indicates that it represents an axial drainage system in an underfilled basin that sourced the majority of its sediment load from an uplifted craton to the northwest. No evidence of contemporaneous volcanism is contained within Sequence 7 or by correlative foreland basin sediments in the adjacent Bowen Basin. During Sequence 7, broad-scale flexural subsidence of the foreland depocenter produces an accommodation that is filled by erosion of the thrust highland and platform hinterland. Similar but offset depositional trends for the underlying Natal Formation indicate tectonic comparability for these two intervals of the basinal succession. The hiatus suggested by previous authors (Olgers 1972; Day 1976; Gray and Swarbrick 1975; Gray 1976; Gray 1977; Draper 1997) is likely to be an artifact of imprecise biostratigraphic control.

Sequence 8 is less developed. The fine-grained lacustrine facies of the Oakleigh Siltstone Member that coarsens upwards to a fluvial facies of the upper Jericho Formation reflects a period of reduced thrust-derived loading with greater influence of thermal subsidence. The thick wedged infill developed during Sequence 7 changes to a thinner, broad lens-like infill that has basinwide continuity. A coarsening up trend indicates that the rate of sediment infill exceeded flexural subsidence.

Sequences 9, 10 and 11 reflect reduced thrust loading and consequential infill of the foreland trough. The Koburra depocenter is faintly apparent in the Jochmus Formation. The broad basinal infill shown by these sequences represents an overfilled basin developed during a period dominated by thermal subsidence. This slow rate of subsidence developed a complete set of systems tracts in the Jochmus Formation but no carbonaceous horizons are recorded indicating a persistent sediment supply. Petrofacies analysis (see Chapter 5) indicates that sediment derived from the thrust front was minimal with greater input from a westerly source. Valleys incised during uplift of the Beryl Ridge during the preceding episode of active thrusting were infilled by the Jochmus Formation. Flemings and Jordan (1989) suggested that this uplift developed as a result of thrust loading of a lithosphere of moderate rigidity.

Tuff horizons in the upper Jericho and Jochmus Formations indicate syndepositional volcanism which was coeval with emplacement of the Bulgonunna Volcanic Group in the eastern hinterland. Such volcanism was coincident with the onset of crustal thinning that formed the Bowen Basin to the east and the Lovelle Depression to the west. Basal infill of the Lovelle Depression is assigned to the Jochmus Formation by Hawkins and

Green (1993). The onset of this extensional phase is reflected in the cessation of foreland subsidence in the Galilee Basin.

Climate is considered to be a major influence on Late Carboniferous-Early Permian successions of the Galilee Basin, a period when icehouse conditions are thought to apply at a global scale (Veevers and Powell 1987; Veevers and Tewari 1995; Isbell et al. 2003). Late Palaeozoic Galilee Basin strata are thought to reflect glacial influences (Vine et al. 1964; Gray and Swarbrick 1975; Jones and Fielding 2004). Jones and Fielding (2004) described glacial diamictites of Namurian-Westphalian age in a generalized section of the Joe Joe Group in the southern Galilee Basin. Although the precise stratigraphic position of this section is questionable, the age assigned to it by these authors is consistent with that determined for the Jericho Formation. General indications of glacial facies include diamictite, striated erosional surfaces, striated and faceted stones, dropstones, till pellets, varves, ice/sand wedges and periglacial involutions. However some of these criteria are not restricted to deposits of glacial origin. Diamictites can be produced by debris flow mechanisms (Schermerhorn 1974), large stones can be rafted by plant debris and sand-wedge structures can be produced by soft-sediment gravity loading (Eyles and Clark 1985). Data presented here and in the discussion of the Drummond Basin indicates that no evidence of Carboniferous glaciation is apparent and glacial influence on sedimentation in the Galilee Basin was restricted to a short interval in the Early Permian.

The broad-scale logs presented in this study for the Jericho Formation are consistent with low sinuosity sandy braided channel facies fining upward to high sinuosity sandy channel deposits with moderate floodplain development. There is no representation of poorly sorted diamictitic sediments or striated pebbles in the succession. Banding recorded in the Oakleigh Siltstone Member shows no consistent seasonal colour variation making a glaciogenic origin unlikely for this lacustrine sediment. There is no apparent glacial influence on sedimentation of the Jericho Formation in the northern Galilee Basin.

Varves and striated pebbles in the Upper Jochmus Formation and correlative Boonderoo beds indicate a glacial influence on sediment source and transportation. Glacio-eustatic base level changes develop different responses in fluvial processes. Mol et al. (2000)

concluded a major period of incision occurs during climatic amelioration in periglacial regions because runoff increases whist sediment yield remains low. After the erosional phase, aggradation takes place due to erosional mobilization of regolith following removal of stabilizing permafrost. During the coldest glacial phase, braided river environments develop. The absence of vegetation and continuous permafrost leads to highly seasonal discharge and high sediment supply. This results in rapid aggradation on a highly unstable floodplain. In milder inter-glacial conditions meandering rivers develop. The coarse-grained strata in the Boonderoo beds and sandy braided channel facies to high sinuosity channel fill and floodplain facies of the Jochmus Formation represents end stages of glacial influence. The absence of permafrost resulted in relatively modest discharge fluctuations with seasonally continuous vegetation cover restricting sediment supply and promoting interchannel stability and restricting channel migration. Disparate biostratigraphic control indicates that this glacial period occurred in the Early Permian (Asselian) with the Boonderoo beds being reassigned based on lithologic compatibility with the Upper Jochmus Formation.

The extensive hiatus between the Jochmus Formation and Betts Creek beds represents a period of quiescence in the development of the Galilee Basin. Bowen Basin correlative strata are shown by Fielding et al. (1995) to represent the extensional and thermal subsidence phases of its tectonic development. Extension in the Bowen Basin induced uplift of the western basinal margin hinterland reflected in a period of non-deposition and possibly erosion of the Galilee Basin succession. The Aramac Coal Measures, which are outside the research area, represent localised mire formation in depressions associated with this uplift. Fielding et al. (1995) showed that sediment input into the Bowen Basin during this period was derived predominantly from the west.

Sequence 12 has a different depositional signature with extensive development of relatively thin coal seams of the Betts Creek beds over the northern Galilee Basin. A coarse-grained interval represents the degradational systems tract whereas peat mires formed the transitional systems tract with extensive floodplain development in the aggradational systems tract occurring within the lower Rewan Formation. No foreland depocenter is evident in the isopachs of the Betts Creek beds showing that compressional tectonics were inactive at this time. Tuffs in the paludal strata indicate active volcanism in the hinterland. Petrofacies analysis (see Chapter 5) indicates that the majority of sediment in Sequence 12 was derived from a westerly recycled orogen source similar to the underlying sequences.

Correlatives of Sequence 12 in the southern Galilee Basin are the coarse-grained Colinlea Sandstone, lacustrine to paludal Bandanna Formation and part of the undifferentiated Rewan Group which Grech (2001) associated with the regressive Sagittarius Sandstone. These units contain a transgressive-regressive marine cycle that overall represents the transitional systems tract of Sequence 12. Bohacs and Suter (1997) proposed that thin paralic coaly rocks with a retrogradational stacking pattern develop during the time of greatest increase in accommodation in a transgressive systems tract. This is a similar scenario to the fluvial transitional systems tract of Sequence 12 proposed for the formation of the coal bearing parasequence sets of the Betts Creek beds. In a sequence stratigraphic analysis of the Illawarra Coal Measures Arditto (1991) concluded that thin, dirty discontinuous coal units developed during a highstand progradational phase in contrast to thick, laterally continuous coals which developed during the commencement of the transgressive phase. However these coastal plain coals were influenced by proximal changes in relative sea level. The coals in the Betts Creek beds are distal to the shoreline indicating that different depositional dynamics were operating. Fielding et al. (1995) noted that foreland thrust loading and associated volcanism commenced during the Late Permian in the Bowen Basin, a proposition partly supported by Michaelsen and Henderson (2000). This is not supported by evidence in the Galilee Basin where depositional facies of Sequence 12 appear to be mainly controlled by relative changes in sea level.

Bohacs and Suter (1997) indicated that moderately thick, restricted peat production should occur in the early stage of an aggradational systems tract, becoming thinner but more extensive in the later stage of the systems tract deposition. The thick development in Sequence 12 of the aggradational systems tract, comprised of the upward fining R1 interval of the Rewan Group, indicates that the rate of increase in accommodation and accumulation of clastics decreased with time. Therefore the conditions for peat preservation should improve towards the top of the aggradational systems tract. The lack of evidence for any coal seams in R1 indicates that the groundwater level necessary for peat production was low during deposition. In fluvial regions the groundwater table is controlled by topography, sediment morphology and climate, particularly the precipitation/evaporation ratio. As the stacking pattern indicates an extensive floodplain with fluvial meander channels the gradient was low and the sediment input relatively consistent. Therefore climate must have been a controlling factor. Red beds in the Rewan Group indicate pedosol oxidation during dry climatic phases and low water table levels.

Sequence 13, consisting of the R2 and R3 intervals of the Rewan Group, shows rapid changes in accommodation suggesting that this part of the Rewan Group was affected by renewed foreland thrust loading. This is supported by evidence from Grech (2001) of a rapidly subsiding southern Bowen Basin during development of the Arcadia Formation and continued thrust loading outlined by Fielding et al. (1995). Petrofacies of the Rewan Group (see Chapter 5) show a predominantly recycled orogen source from the west with enhanced volcanolithic input indicating some derivation from a dissected magmatic arc to the east. This is comparable to paleoflow directions provided by Grech (2001) for the Bowen Basin which range from northwest to southwest for the western depositional margin and are from the east for the eastern depositional margin. Isopachs show a broad depositional depocenter indicating that the basinal downwarp was controlled by slow thrust uplift with high sediment input developing an overfilled basin. The presence of red beds indicates the continuation of the dry climatic phase which commenced in Sequence 12.

Sequence 14 (Dunda beds) comprises a complete set of systems tracts. This shows that sediment input and basin subsidence was matched and represents a local response to the foreland uplift that developed Sequence 13. Derivation of fluvial sediments of cratonic origin from the east indicates that the Anakie Inlier intrusives were an emergent high during the Early Triassic. Fielding et al. (1995) show a similar Anakie Inlier source for the Upper Rewan Group and Clematis Group of the Bowen Basin.

Sequence 15, represented by the majority of the Clematis Group, has a strong cratonic source signature. The main differences from Sequence 14 are predominant derivation from the west and northwest and lack of a transitional systems tract. Isopachs of the Clematis Group indicate a broad infill of the foreland trough and formation of an overfilled basin. This represents a quiescent phase in basin subsidence with high sediment accumulation proximal to the thrust front. In the adjacent Bowen Basin, Fielding et al. (1995) showed equal derivation of sediments in the Clematis Group from the Anakie Inlier to the west and an uplifted active volcanic arc in the east. In the northern Galilee Basin sediment was primarily sourced from a westerly hinterland indicating that there is only a superposition correlation of this Group between the Galilee and Bowen Basins.

Sequence 16 commences with the quartzose Warang Sandstone representing the degradational systems tract with the thick section of the Moolayember Formation representing the aggradational systems tract. The re-emergence of the Koburra Depocenter and the continued presence of the Mingobar Structure on the eastern basin margin indicate renewed thrust loading in the east. The narrow trough development associated with the aggradational systems tract indicates rapid thrust loading. The Warang Sandstone paleocurrents of Vine et al. (Vine et al. 1964) and petrofacies analysis (see Chapter 5) show cratonic derivation from the north with fluvial transport along the axis of the developing foreland basin.

The presence of the Mingobar structure as a basin margin high, the narrow Koburra Depocenter and continuance of sedimentation to the west indicates that the Moolayember Formation represents the overfilled basin phase of the thrust loading comenced at the beginning of Sequence 16. Petrofacies analysis (see Chapter 5) indicates a recycled orogen source. These circumstances are consistent with rapid thrust rate and high sediment transport coefficient models of Flemings and Jordan (1989). Following rapid uplift of the thrust front that controlled deposition of the Warang Sandstone the low gradient, high sinuosity fluvial facies of the Moolayember Formation show that uplift during deposition its was minimal. Thinning along a northeast trending ridge is associated with the Moray Fault Zone, a reactivated transfer fault of Drummond Basin association. Episodic reactivation of such transfer faults occurred during the Hunter-Bowen compressional orogeny that produced the late foreland phase of the Galilee Basin. In the Bowen Basin, Fielding et al. (1995) identified an eastern dissected volcanic arc as the main sediment source for the Moolayember Formation with westerly transports vectors. Sporadic volcanism occurred during deposition. This evidence is not supported by data for the Moolayember Formation in the northern Galilee Basin where sediment has a predominantly westerly orogenic source.

5.0 PETROFACIES AND PROVENANCE

5.1 Introduction

Petrofacies of clastic rocks are predominantly related to provenance and climate. Detrital composition is also controlled by transport history and depositional environment. A ternary classification of arenites was established by Folk et al. (1970). This was based on the main framework grains, between coarse silt and granule size, of quartz (Q), feldspar (F) and rock fragments (R). The Q pole includes monocrystalline and polycrystalline forms but excludes chert; the F pole contains all monocrystalline feldspar and the R pole groups all igneous, metamorphic and sedimentary lithic grains including chert. Folk et al. (1970) recognised five primary arenite fields and nomenclatural dissection is achieved by appending the most common rock fragment to one of the five primary arenite fields.

Dickinson (1970) proposed a similar ternary scheme, modified by Dickinson and Suczek (1979) and Dickinson (1985), based on framework grain contributions of quartz (Q), total feldspar (F) and unstable lithic rock fragments (L) specifically to evaluate provenance. The lithic content can be split into four categories: volcanic, clastic, metamorphic and microgranular. The classification ignores the matrix, carbonate minerals and minor constituents such as mica and heavy minerals. These authors identified a correlation between the ratios of these grain parameters and the provenance from which they were derived. This approach and interpretation has been very widely applied in literature on sedimentary petrography over the last two decades. McBride (1985) showed that diagenetic changes can distort the composition of sediments over time. Replacement of detrital grains by carbonate, the kaolinisation of feldspar and mica, the albitization of feldspars and the dissolution of detrital grains are factors that must be taken into account in order to deduce original compositions. Shanmugam (1985) found that secondary intragranular porosity must be counted as part of enclosing grains as the degree of grain dissolution can modify the original composition of sandstones.

A genetic classification of provenance of quartz types based on optical extinction, type of inclusions and grain shape was established by Krynine (1950). An empirical classification of quartz type based on six different styles of extinction and four different types of inclusion populations was introduced by Folk (1957) and related to a provenance. Blatt and Christie (1963) showed that undulosity and polycrystallinity of quartz in sedimentary rocks cannot be used determine the provenance of the quartz grains. However, a study of medium sized quartz grains (0.25-0.50mm) by Basu et al. (1975) showed that undulosity and polycrystallinity of quartz grains from immature arenites can differentiate metamorphic from plutonic sources when plotted on a doubled triangular diagram with poles for both polycrystalline and monocrystalline quartz.

The optical properties of plagioclase and K-feldspar are well known and grains of these minerals can be easily discriminated by optical means. Ease of identification can be improved by acid etching and staining. Distinguishing different varieties of plagioclase or K-feldspar in sedimentary thin sections is problematic due to similar optical properties and chemical alteration. Polysynthetic twinning in microcline is diagnostic but not always present. The recognition of different categories of lithic grains is based mainly on textural criteria.

Sedimentary grain types have clastic textures whereas regional metamorphic grain types have a schistose or semi-schistose fabric. Volcanic grain types can be subdivided into those consisting of a felsitic anhedral, microcrystalline mosaic, those with subhedral to euhedral feldspar crystals as microlites, those with plagioclase laths arranged in intergranular and interstitial textures, vitric to vitrophyric grains and shards. Microgranular grains with roughly equant crystalline domains can be igneous, metamorphic or sedimentary in origin and are commonly placed as indeterminate.

Petrofacies studies can help determine the tectonic setting of detrital sediments. The provenance signature in a stratigraphic succession may indicate tectonic events in the hinterland. Relationships have been established between detrital modes of sandstones, plotted on ternary diagrams, and different generic types of source area (Dickinson and Suczek 1979; Dickinson 1985). Employing this scheme, grains larger than 0.0625mm are categorised as monocrystalline (Qm) or polycrystalline (Qp) quartz, total feldspar (F), volcanolithic/metavolcanic lithics (Lv), sedimentary lithics (Ls), metasedimentary lithics (Lm). Some ternary diagrams total all lithics (Lt) or combine sedimentary and metasedimentary lithics (Lsm). The ratio of plagioclase to K-feldspar (P/K) can assist in determining a volcanic or plutonic source provided diagenetic alteration has not prejudiced the original composition. Five main petrofacies groups were identified by Dickinson (1988): quartzose (Qm>Qp & F); volcaniclastic (Lv>F); arkosic (F & Qm); volcanoplutonic (Qm, Qp, F & Lv>Ls) and quartzlithic (Qm, Qp, Ls>F & Lv). Each group is closely linked to the tectonic setting of the depositional basin and the source terrain from which the sediment was derived (Table 5.1).

Dickinson (1988) concluded that where sediment transport paths between orogenic source terrains and depositional basins are short and direct, sandstone petrofacies can be used to determine the tectonic evolution of the orogen. Mixed petrofacies reflect multiple sources and complex paleogeographic and paleotectonic relationships for the basins concerned. Collisional orogenic zones commonly produce foreland basinal petrofacies of this type (Dickinson and Suczek 1979). Other geologic perspectives are required to constrain the petrographic evidence, such as petrofacies trends reflecting changes in the tectonic setting over time. Modern dispersal paths of major continental rivers draining regions of different tectonic signature can be used as a basis for the interpretation of mixed provenance sedimentary assemblages observed in the stratigraphic record.

5.2 Method of Analysis

Thin sections were prepared from 61 drill core and outcrop samples representing all lithologic units in the northern Galilee Basin and 60 samples from drill core and outcrop representing all Cycle 2 and Cycle 3 units in the northern Drummond Basin (Figures 5.1, 5.2). Few thin sections were prepared from the Betts Creek beds and Natal Formation as the grainsize of samples available from these units is generally too fine-grained for analysis. In addition to framework grain determination, accessory minerals were determined through optical properties and sorting and textural maturity in each slide was calculated by gridding and roundness.

The framework grain analysis of each slide was undertaken using the Gazzi-Dickinson point counting method (Ingersoll et al. 1984; Suttner and Basu 1985; Decker and Helmold 1985). Three hundred points were counted per thin section and normalised in a spreadsheet database. Data for matrix, cement, mica, equant microgranular grains and secondary minerals were disregarded. The data were plotted on ternary charts using Ternplot, a freeware program. The charts were overlain on templates of compositional fields indicative of detrital nomenclature (Folk et al. 1970) or provenance type (Dickinson 1985). The separation of lithic fragments into volcanogenic (Lv), metasedimentary (Lm) and sedimentary (Ls) catagories was based textural attributes.

To assist in the resolution of provenance a representative quartz-rich sandstone sample from each of the northern Drummond and Galilee Basins were analysed for detrital zircon SHRIMP U-Pb age spectra. Discussions of this analytical technique are provided by Claoue-Long et al. (1995), Black and Kamo (2003) and Davis and Williams (2003).

5.3 Petrofacies of the northern Drummond Basin

Little petrofacies analysis has been undertaken on sediment infill in the Drummond Basin. Olgers (1972) recognised three discrete sedimentary cycles to which he ascribed petrographic significance. Cycle 1 was characterised by volcanic and volcaniclastic strata, Cycle 2 by basal units of feldspathic quartz arenite with minor chert, calcarenite and tuff and upper units of predominantly quartz arenite, and Cycle 3 by feldspathic quartz arenite, volcaniclastic strata and tuff (refer to Figure 1.4). The units that comprise Cycle 1 are outside the scope of this study but petrographic data were provided by Bennedick (1993) and Henderson et al. (1998). Cycle 2 samples of the Scartwater and Mount Hall Formations were obtained from scattered outcrop near the inferred eastern basin margin. Samples of Cycle 3 sediments, Star of Hope, Bulliwallah and Natal Formations, were derived from outcrop, wells and boreholes. Samples of the Natal Formation were generally finer grained than the 0.0625 mm cut-off size suitable for point counting.

5.3.1 Cycle One

General petrographic descriptions are given by Hutton et al. (1991), Goulevitch (1992) and Bennedick (1993) with framework grain composition Q/F/L plots provided by Bennedick (1993) and Henderson et al. (1998). Replotting these data on a Q/F/R diagram shows that Cycle 1 sediments are predominantly a mix of litharenite and feldspathic litharenite with low quartz content (Figure 5.3). Two samples from the Llanarth Volcanic Member plot in the lithic feldsarenite field and two others from the St

Anns Formation plot as feldsarenite. Henderson et al (1998) noted that lithic grains in the samples studied by these authors were exclusively volcaniclasts.

Bennedick (1993) described Cycle 1 sandstones from the Pyramid area in the northeastern extremity of the basin from an interval now regarded as the lower part of the St Anns Formation (see Henderson et al. 1998). They are characterised by framework grains of poorly sorted sub-rounded quartz and plagioclase feldspar with accessory biotite. Lithic grains of siltstone and devitrified volcanics were noted in outcrop but not described from thin section. The feldspar shows diagenetic alteration, mainly carbonate replacement. Samples from higher in the St Anns Formation have framework components of sub-angular to angular quartz, pink feldspar and lithics of mudstone and volcanic glass shards. Abundant diagenetic alteration has occurred, particularly carbonate replacement of the feldspar, resulting in increase of quartz content.

5.3.2 Cycle Two

The petrofacies of Cycle 2 is predominantly quartz-rich sublitharenite with a minor litharenite representation (Figure 5.4). Sorting ranges from very poorly sorted to well sorted. Monocrystalline and polycrystalline quartz grains show straight to undulose extinction with rare inclusion trails. In some samples the quartz grains have rare overgrowths indicating post-depositional addition. Lithic grains are predominantly of silicic to intermediate volcanic origin with a minor component of phyllitic to schistose grains of metamorphic origin (Figure 5.5). The volcanolithics are commonly degraded. Mica, mainly muscovite, is the main accessory mineral and isotropic lath-shaped grains, possibly zircon, are also common. The feldspar content is very low and is predominantly plagioclase.

5.3.3 Cycle Three

Cycle 3 samples included in the present study range from a quartz-rich sublitharenite to litharenite (Figure 5.6). An earlier study of the Star of Hope Formation in the northeast margin of the Drummond Basin by Alexander (1997) showed this unit as containing a mix of lithic feldsarenite and feldspathic litharenite with a low quartz content. Monocrystalline quartz with generally straight extinction and rare inclusion trails is dominant. Samples from the Campaspe borehole set on the northern margin of the basin generally have lower quartz content. Plagioclase dominates the subordinate feldspar population. The lithic content of Cycle 3 is predominantly of silicic volcanic or schistose metamorphic origin with an enhanced metamorphic component in the Bulliwallah Formation (Figure 5.7). One sample from the Bulliwallah Formation shows an appreciable lithic content of sedimentary origin. Mica, mainly muscovite, is the predominant accessory grain and volcanolithic grains are commonly degraded. Some samples have a high content of isotropic glass shards indicating a tuffaceous source. Alexander (1997) noted in his study of the Star of Hope Formation that quartz grains are generally monocrystalline, plagioclase laths are common with some showing partially developed pericline twinning or zoning and lithic clasts include fine grained lithologies of uncertain origin, mafic volcanics and devitrified perlitic and spherulitic silicic volcanics.

Cycle 3 has reduced quartz content relative to Cycle 2 particularly in the Natal and Bulliwallah Formations. This indicates a general decrease in the influence of a cratonic source. The lithic content has a much higher proportion of grains derived from a metamorphic origin whilst tuffs indicate a greater volcanogenic input. A subarenite population was derived from a sedimentary source. The more labile character of the Cycle 3 assemblage, relative to that of Cycle 2, suggests that a climatic shift, with reduced chemical weathering, may have had a partial influence on the sediment provenance.

5.4 Overview of Source Areas for Drummond Basin Infill

The Neoproterozoic-Early Devonian Charters Towers Province lies adjacent to the Drummond Basin on its northern margin. It contains the Cape River Metamorphics, a volcano-sedimentary assemblage of the Mt Windsor Subprovince and granitoids in the Lolworth and Ravenswood Batholiths (Figure 5.8). The Anakie Inlier lies on its eastern margin. This mainly comprises Neoproterozoic-Cambrian Anakie Metamorphics and the Middle Devonian Retreat Batholith. It also contains minor sedimentary and volcanic units of Devonian age.

The Thomson Fold Belt lies to the west and south of the basin and is entirely concealed beneath Late Palaeozoic and Mesozoic intracratonic basins. The content of this tract is known only from basement core samples and gravity trends. Murray and Kirkegaard (1978) and Murray (1994) considered it to represent an Early Palaeozoic orogen. However, Draper (2006) suggested that much of the orogen may be Neoproterozoic in age. The Nebine Ridge, a subsurface high of the Thomson Fold Belt, is located near its eastern margin. It is overlain by the Early Devonian Adavale Basin and metasedimentary rocks and granitoid intrusives of equivalent age grouped as the Roma Shelf (Murray 1994). To the west, the Thomson Fold Belt abuts cratonised Proterozoic crust along the Tasman Line (Scheibner and Veevers 2000; Direen and Crawford 2003). These Proterozoic terranes include the Arunta and Musgrave Blocks and Mount Isa Inlier. Proterozoic terranes are also represented in northeastern Queensland, such as the Georgetown Inlier, to the north of the Drummond Basin.

The Northern New England Orogen lies to the east of the Drummond Basin. It consists of forearc assemblages represented by the Campwyn and Yarrol terranes and an accretionary subduction complex of the Wandilla and Shoalwater terranes that broadly overlap in age with the Drummond Basin. The Marlborough terrane represents an Early Palaeozoic mafic-ultramafic assemblage with the Northern New England Orogen (Henderson et al. 1993).

5.5 Provenance of the northern Drummond Basin Sediment Infill

5.5.1 Cycle One

The northern Drummond Basin Q/F/L petrofacies associations indicate that sediment infill was predominantly derived from a magmatic arc, with subordinate input from a recycled orogenic source that included continental basement (Figure 5.9). The high proportion of volcanolithic sediment in Cycle 1 clearly indicates a mainly volcanic source. The ternary plot shows three general source populations of undissected arc, transitional arc and recycled orogen. The more feldspathic samples are consistent with some unroofing of the magmatic source. No palaeocurrent measurements are available for Cycle 1 infill.

The early phase of Drummond Basin development, reflected by Cycle 1 infill, is syndepositional with a number of Late Devonian-Carboniferous basinal systems distributed along the coastal sector of north Queensland (Figure 5.8). Several of these elements are similar to the Drummond Basin in being developed on cratonised Early to Mid Palaeozoic orogenic basement. The Gilbert River, Clarke River, Pascoe River and Bundock Basins are of this type. Their sedimentary petrography has not been studied in detail but preliminary data suggests a mostly recycled orogenic provenance (Edwards 1977; Withnall et al. 1980; Wyatt and Jell 1980; Scott and Withnall 1987). The easternmost element, the Burdekin Basin, has mixed volcaniclastic and reworked cratonic infill (Draper and Lang 1994) similar in character to Cycle 1.

A near coastal linear basinal tract, composed of the Late Devonian-Early Carboniferous Yarrol and Campwyn terranes, is an important element of the Northern New England Orogen. The petrofacies of the Yarrol Basin has not been studied in detail but reconnaissance work show that it is characteristically volcaniclastic in character (Bryan et al. 2001). A more comprehensive dataset for the Campwyn terrane show that it is dominated by volcaniclastic and volcanic strata (Paine et al. 1974; Fergusson et al. 1994; Bryan et al. 2003). It has generally been considered as a forearc system complimentary to the Drummond Basin as a backarc element (Fergusson et al. 1994; Leitch et al. 1994; Murray et al. 2003). Its infill broadly overlaps in age with Cycle 1 of the Drummond Basin. Bryan et al. (2001, 2003) took a contrary view and considered this system to be also of backarc association, a construct that presents a problem of sediment delivery from the same source across the Yarrol and Campwyn depocenters to supply the Drummond Basin. A subduction complex assemblage of the Late Devonian-Early Carboniferous Wandilla terrane, located immediately to the east of the Yarrol terrane is also volcaniclastic in character and derived from a magmatic arc (Leitch et al. 2003).

5.5.2 Cycle Two

Q/F/L and Qm/F/Lt ternary plots of Cycle 2 show a quartz-rich recycled orogenic provenance (Figures 5.10, 5.11). The magmatic arc source prominent for Cycle 1 sediments has very minor expression for Cycle 2. Murray (1994) found a similar character for his petrographic study of Cycle 2 sediments from Drummond Basin core samples. The higher lithic content of the Scartwater Formation marks a transitional stage between the volcanic arc provenance of Cycle 1 and a continental orogenic source. This conclusion is supported by the Qp/Lv/Lsm ternary plot (Figure 5.12) which also identifies a mixed orogen/arc orogen source suggesting that an easterly magmatic arc had continuing influence.

The quartz-rich sands of the Mount Hall Formation component may have been derived from a near-field uplifted quartzose source. A substantial compliment of polycrystalline quartz grains with metamorphic mortar textures in several samples supports this interpretation. Murray (1994) noted siliciclastic meta-sandstones from nearly all cores penetrating the Thomson Fold Belt. He considered that a quartz-rich turbidite assemblage, like that of the Lachlan Orogen to the south, may be widely developed in the Thomson Fold Belt.

Alternatively the Mount Hall Formation may reflect the effects of climate. Basu (1985) showed that QFR data can be used to determine the climatic regime of first order stream sand derived from plutonic or metamorphic sources but determined that steep slopes exceeding the angle of repose can obscure climatic effects on first order cycle sand composition. Employing Basu’s method of analysis, Cycle 2 sandstones plot in or near to the field in which a metamorphic source terrain was influenced by a humid climate (Figure 5.13). This is consistent with a westerly provenance from low grade siliclastic metamorphics as suggested by Murray (1994) to be widespread in the Thomson Fold Belt. A high stream flow regime indicated by the coarse grain sizes, typical of the Mount Hall Formation, was of little effect in obscuring the climatic overprint. A lack of feldspar indicates that no sediment derived from an easterly magmatic arc source. However, the SHRIMP zircon provenance data suggests that a magmatic arc was a significant source of sediment during the deposition of the Mount Hall Formation.

Palaeocurrent measurements, mainly from the Scartwater Salient region, were obtained for the Mount Hall Formation (refer to Chapter 4). They show predominant transport from the northwest and southwest with minor input from the north-northeast. This indicates derivation of the Mount Hall Formation from a westerly Thomson Fold Belt source with some input from the Charters Towers Province to the north. The data is entirely consistent with provenance interpretation derived from petrographic analysis.

The Shoalwater terrane is a subduction complex that lies outboard of the Wandilla terrane well to the east of the Mount Hall Formation. It is likely to be of Early-Mid

Carboniferous age, and may be a correlative of the Mount Hall Formation. It is dominated by quartzose sandstone for which Leitch et al. (2003) documented derivation from a recycled orogen source. A provenance similar to that of the Mount Hall Formation is indicated. The location of the Shoalwater terrane suggests that the Thomson Fold Belt lies beneath the Permian-Triassic Bowen Basin providing a similar recycled orogenic source during the Carboniferous.

5.5.2.1 Cycle 2 Detrital Zircon Ages

In this study a single sample (DP11) of medium-grained quartz sandstone from the Mount Hall Formation was obtained in the Scartwater region ($20^{o}55'50''$S $146^{o}40'13''$E) on the eastern margin of the Drummond Basin. Its stratigraphic position within the unit is unknown due to structural complexity and poor outcrop continuity. A Tera-Wasserburg concordia plot was obtained from 62 grain spot analyses and a relative probability plot of the ^{207}Pb corrected $^{206}Pb/^{238}U$ age produced using the method of Sambridge and Compston (1994).

The data shows four main zircon age populations indicative of provenance (Figure 5.14). The total population spans from Neoproterozoic to Carboniferous with no indicated source from a westerly Mesoproterozoic craton. Most of the age spectrum identifies episodes of silicic igneous activity that are well known from the northern Tasman Orogenic Zone. Grains ranging in age from 500-620 Ma are consistent with the ages of metasediments in the Charters Towers Province (Fergusson et al. 2005) and the age of metasedimentary tracts of the Thomson Orogen inferred by Draper (2006). The 470-490 Ma population is correlative with the Macrossan Igneous assemblage of Hutton et al. (1997a) that is well represented in the Charters Towers Province by older phases of the Ravenswood and Lolworth Batholiths and volcanics in the Mt Windsor Subprovince. Igneous rocks of this age are also represented in the Thomson Fold Belt (Murray 1994; Draper 2006). The 390-410 Ma population is correlative with the Pama Igneous assemblage recognised by Hutton et al. (1997b). This assemblage is widespread in northeastern Queensland and is represented in the Charters Towers Province by the younger phase of the Ravenswood and Lolworth Batholiths. Volcanics of this assemblage are represented in the basal Adavale Basin (Draper 2006) and the Anakie Inlier (Blake et al. 1995). The 350-360 Ma population matches to the age of the Retreat

Batholith in the southern Anakie Inlier and the age of subsurface granitoids from the correlative Roma Shelf to the south (Crouch et al. 1994; Murray 1994).

The youngest age group at 320-340 Ma age represents igneous activity broadly coeval with development of the Drummond Basin. The Yarrol and Wandilla terranes to the east which were largely inferred from recycled primary volcanic rocks indicates that an easterly volcanic arc was shedding sediment to both forearc and backarc basins during the Early Carboniferous.

In conclusion, the coincidence of age data with igneous episodes suggests that Palaeozoic igneous rocks contributed most of the detritus represented in the Mount Hall Formation. This suggests that unroofed plutonics were widely represented in the source areas contributing siliciclastic sediments to Cycle 2 of the Drummond Basin. The Charters Towers Province, to the north, represents such a source but it is of limited areal extent. It appears likely that igneous rocks matching the ages of those in the Charters Towers Province, as proposed by Draper (2006), are extensively represented in the Thomson Fold Belt. The age data thus imply a westerly magmatic arc and metamorphic basement source, rather than a recycled orogen, with the quartz domination due to climatic overprint rather than bedrock source.

5.5.3 Cycle Three

Q/F/L and Qm/F/Lt plots of Cycle 3 sandstones imply a recycled orogenic source that ranges from quartzose to transitional (Figures 5.15, 5.16). The Qp/Lv/Lsm plot suggests sediment derivation from both a fold-thrust belt and magmatic arc (Figure 5.17). The more dominant volcanolithic content for some Bulliwallah Formation samples and higher feldspar content, predominantly plagioclase, of the Natal Formation indicates enhanced influence of a magmatic arc in the younger part of Cycle 3.

Palaeocurrent directions for the Bulliwallah Formation obtained in this study (refer to Chapter 4) indicate a predominate source from the southwest with lesser input from the northeast and northwest consistent with a mainly westerly cratonic source suggested by petrographic interpretation.

The analysis presented here indicates derivation from the cratonic Thomson Orogen to the west with some influence from an easterly magmatic arc, a similar conclusion to that reached for Cycles 1 and 2. The minor but persistent magmatic arc signature is indicated by the volcaniclastic population and presence of tuff horizons. The less quartzose nature of Cycle 3 reflects either a tectonic or climatic change sponsoring an enhanced labile content. The influence of an emergent proximal thrust belt during the development of late stages of Cycle 3 (Chapters 3 and 4) argues for a tectonic explanation. Provenance of the Star of Hope Formation involved a substantial volcanic component, similar to Cycle 1, a conclusion also reached by (1997).

5.6 Petrofacies of the northern Galilee Basin

Arman (1964) provided brief petrographic descriptions of strata from the northern margin of the Galilee Basin and Hawkins (1976; 1978) undertook a paleogeographic reconstruction and provenance evaluation for the Carboniferous succession and Early Permian Betts Creek beds of the northern Galilee Basin. Based on the petrography of selected core samples Hawkins and Carmichael (1987) considered that monocrystalline and polycrystalline quartz, volcanic and volcanolithic grains, minor feldspar as mainly K-feldspar and minor mica were the main components of sandstone in the Galilee Basin. They noted that accessory minerals were consistent with derivation from igneous and metamorphic sources.

In this study the thin sections on which petrofacies analysis of the northern Galilee Basin was based are predominantly from borehole samples. No suitable samples were obtained for the Oakleigh Siltstone Member and some sandstone samples from coal measures of the Betts Creek beds were too fine grained for petrographic analysis. The petrographic data support separation into lower and upper petrofacies groups based on differences in quartz, feldspar and lithic contents.

5.6.1 Lower Petrofacies Group

Samples from the Late Carboniferous-Early Permian Joe Joe Group composed of the Lake Galilee Sandstone, the Jericho Formation and the Jochmus Formation are similar in character (refer to Figure 1.7 for stratigraphic succession). They consist mainly of monocrystalline quartz with secondary overgrowths, volcanolithics and minor mica, feldspar and lithic grains of metamorphic origin. A micaceous matrix comprises generally no more than a small component of the thin sections. Subordinate petrofacies L1, L2 and L3 are apparent.

5.6.1.1 Petrofacies L1.

The Lake Galilee Sandstone and Edie Tuff Member of the Jochmus Formation comprise petrofacies L1 for which quartz-rich sublitharenite is characteristic with a high proportion of volcanolithic grains (Figures 5.18, 5.19). No primary pyroclastic shards were noted in the Edie Tuff Member samples indicating that deposition from volcanic sources was localised. The Lake Galilee Sandstone is well sorted relative to the Edie Tuff Member. A substantial feldspar content, mainly K-feldspar and microcline, noted by Hawkins and Carmichael (1987) is not supported by this study as their sample was derived from a mudstone interval for clay analysis and reflects a very fine grained volcanogenic influence. Accessory minerals included pyroxene, garnet and opaques.

5.6.1.2 Petrofacies L2.

Sandstones of the Jericho Formation are grouped as petrofacies L2 which is distinguished by a relatively high feldspar content. Most samples are litharenite and feldspathic litharenite with minor lithic feldsarenite and sublitharenite (Figure 5.18). Lithic components are variable (Figure 5.19) but many samples show a high proportion of volcaniclastics. Potassium feldspar is noted in some samples. Hawkins and Carmichael (1987) noted the composition of the Jericho Formation as consisting of strained monocrystalline quartz, rare volcanic quartz and minor feldspar, mainly K-feldspar, consistent with the observations recorded here. In general the samples are texturally immature with poor to very poor sorting, which improves up-section as indicated by samples from the Campaspe borehole set.

5.6.1.3 Petrofacies L3.

This petrofacies is represented by the Jochmus Formation which is mainly composed of sublitharenite and litharenite showing a wide range in quartz content (Figure 5.18). A micaceous muddy matrix is characteristic, variably silicified. The lithic content is predominantly volcanolithic (Figure 5.19). Samples range from well sorted to poorly sorted.

Jochmus Formation samples studied by Hawkins and Carmichael (1987) contained strained and volcanic quartz with minor feldspar in the form of K-feldspar and plagioclase. A thin section of the Boonderoo beds analysed by these authors comprised strained monocrystalline quartz, minor K-spar with traces of plagioclase and polycrystalline quartz.

5.6.2 Upper Petrofacies Group

The upper group can be divided in petrofacies U1, comprising the Betts Creek beds, Rewan Group and the Moolayember Formation and petrofacies U2 consisting of the Clematis Group and the Warang Sandstone (refer to Figure 1.7 for stratigraphic succession). Most samples examined are from core but the Moolayember Formation and Warang Sandstone provided samples from outcrop. The most obvious signature of the upper petrofacies group is the lack of feldspar (Figure 5.20). Clear monocrystalline quartz with variable polycrystalline quartz content is dominant. The monocrystalline quartz grains have straight extinction and sporadic inclusion trails consistent with a volcanic source. The Betts Creek beds, Clematis Group and Warang Sandstone have the greatest polycrystalline quartz content. Mica, predominantly muscovite, is the main accessory mineral with biotite appearing in the upper Clematis Group and Moolayember Formation. A minor volcanolithic compliment is characteristic of the group with its proportion inversely proportional to the quartz content. A mud matrix, with a micaceous component, is typical. The samples were generally poorly sorted but some samples from the Moolayember Formation and Rewan Group are texturally more mature.

5.6.2.1 Petrofacies U1

Petrofacies U1 is characteristically a sublitharenite (Figure 5.20) with a single sample falling into the litharenite field. Volcanolithics are the dominant lithic element (Figure 5.21). Mica, predominantly muscovite, is best represented in the Rewan Group. Hawkins and Carmichael (1987) described strained quartz and rare K-spar in the Betts Creek beds and Rewan Group from argillaceous lithologies of petrofacies U1.

5.6.2.2 Petrofacies U2

Quartz-litharenite is characteristic of petrofacies U2 with minor representation in the sublitharenite field (Figure 5.20). A lack of feldspar and a low lithic content is typical.

The minor lithic content was exclusively derived from volcanogenic sources (Figure 5.21).

5.7 Overview of Source Areas for Galilee Basin Infill.

The Late Carboniferous-Middle Triassic Galilee Basin is part of an extensive basinal system that includes the Cooper Basin to the southwest and Bowen Basin to the east (Figure 5.22). In addition to the source areas identified for the Drummond Basin, late Palaeozoic assemblages developed to the east by this time are also a potential source. In particular, the Early Carboniferous to Early Permian Kennedy Province (Mackenzie and Wellman 1997) is represented by extensive volcanic fields including the Combarngo Volcanics unconformably developed on the Roma Shelf, the Bulgonunna Volcanic Group and the Urannah Suite.

5.8 Provenance of the Northern Galilee Basin Sediment Infill

5.8.1 Provenance of the Lower Petrofacies Group

A Q/F/L plot (Figure 5.23) of samples from the Joe Joe Group shows that the lower petrofacies group was predominantly derived from a recycled orogen with one sample of the L2 grouping indicating a magmatic arc source. The Qm/F/Lt plot (Figure 5.24) indicates that petrofacies L1 and L3 had a predominantly quartzose orogenic source whereas petrofacies L2 was mainly derived from a quartzose orogen with a minor dissected magmatic arc source. This is supported by the Qp/Lv/Lsm lithics plot (Figure 5.25) which shows a mixed orogenic source for petrofacies L1 and L3 and a greater influence of magmatic arc and thrust belt sources in L2. No palaeocurrent data are available for the Lake Galilee Sandstone, Jericho or Jochmus Formations.

The recycled orogenic source regions of the lower petrofacies group are likely to be basement terranes of the Thomson Fold Belt encountered in wells on the Maneroo Platform and Nebine Ridge at the western and southern margins of the Galilee Basin (Vine 1970; Murray 1994). The quartzose orogenic sediment source evident for the Lake Galilee Sandstone and Jochmus Formation, could have been derived from siliciclastic metasediments noted by Murray (1994) in the Thomson Fold Belt. The volcanolithic content of the Jericho Formation in the northern Galilee Basin is likely to have been derived from the contemporaneous Kennedy igneous association of

Mackenzie and Wellman (1997) which extended along the north and central Queensland coastal regions from Cape York to south of Rockhampton. The input of some sediment from a fold-thrust belt indicates a local source from uplifted Drummond Basin strata on the eastern margin of the Galilee Basin and adjoining sections of the New England Orogen (refer to Chapter 4). This suggests that sediment input for the lower petrofacies group was derived mainly from the west but the Jericho Formation had input from all sectors of the basin margin.

5.8.2 Provenance of the Upper Petrofacies Group

All samples from the Betts Creek beds, Rewan and Clematis Groups, Warang Sandstone and Moolayember Formation are tightly clustered in the upper sector of recycled orogen and quartzose recycled orogen fields of the Q/F/L and Qm/F/Lt ternary plots (Figures 5.26, 5.27), a conclusion supported by the Qp/Lv/Lsm plot mixed orogen source (Figure 5.28). The recycled orogen provenance for petrofacies U1 is consistent with an uplifted Thomson Fold Belt westerly source as determined for petrofacies L1 and L3. However petrofacies U1 has a higher content of volcanolithics suggesting greater sediment input from the Kennedy igneous association in the east during this time. Limited palaeocurrent measurements obtained by Vine et al. (1965) for the Colinlea Sandstone, a southern Galilee Basin correlative of the Betts Creek beds, show a general south-southeast transport direction and the Dunda beds, a facies variant of the upper Rewan Group, show a source from the east-northeast.

Grech (2001) determined a mixed Thomson Fold Belt and volcanic arc source for the Rewan Group in the southern Bowen Basin with the quartzose content increasing to the west. For most of the Permian, Fielding et al. (1995) interpreted a predominant sediment source from the west for the Bowen Basin consistent with the interpretation presented here for petrofacies U1 of the Galilee Basin.

For the correlative interval of petrofacies U1 in the northern Bowen Basin, represented by the Back Creek and Blackwater Groups, Michaelsen and Henderson (2000) determined two distinct petrofacies, A and B. Petrofacies A is associated with the Lower to mid-Upper Permian Back Creek Group which is a correlative of the lower Betts Creek beds of the Galilee Basin. Like petrofacies U1 of this study petrofacies A is quartz rich and has a predominant orogenic basement provenance from the west.

Martini and Johnson (1987) interpret this interval to reflect a cold to cold-temperate climate in the region.

Petrofacies B of the Bowen Basin is volcanolithic and is divided into two subfacies based on quartz content. Petrofacies B1 with lower quartz content is assigned to the Upper Permian Blackwater Group which is a correlative of the upper Betts Creek beds of the Galilee Basin. Fielding et al. (1995) interpreted the onset of volcanism and associated tectonic uplift for the Northern New England Orogen during this interval. This volcanic influence marks the boundary between the Back Creek Group and Blackwater Group in the Bowen Basin where minor input was still drawn from the west but a general switch in the drainage pattern resulted in the bulk of sediment being derived from the east. This abrupt switch in provenance is not recorded in the Galilee Basin where the bulk of sediment was consistently derived from a westerly quartzose orogenic source. A subdued volcanolithic signature is apparent for some samples from the Betts Creek beds reflecting distal volcanism during its deposition.

Petrofacies B2, with a higher proportion of quartz, is associated with the Lower Triassic Rewan Group in the Bowen Basin. Petrofacies B was determined by Michaelsen and Henderson (2000) to have originated from an undissected to transitional magmatic arc provenance located in the New England Orogen to the east. The increase in quartz content of B2 was attributed to a climatic change and shift in paleotemperature at the Permian-Triassic boundary by these authors.

A sample from the correlative Rewan Group in the northern Galilee Basin has a similar framework grain composition but has greater quartz content. Red beds in the Rewan Group indicate that climate change in the Triassic may have enhanced quartz content of the correlative facies in the Galilee Basin.

An arc origin is not reflected in the Rewan Group petrofacies U1 of the northern Galilee Basin where the low volcanolithic content indicates a continued westerly orogenic source, an interpretation supported by the finding of Grech (2001) for the Rewan Group in the southern Bowen Basin. In contrast, Fielding et al. (1995) identified an easterly sediment source for the Rewan Group in the Bowen Basin with axial drainage and minor eastward drainage from the Anakie Inlier. In the Dunda beds, a subfacies of the

Rewan Group in the Galilee Basin, paleocurrent measurements by Vine et al. (1965) show a general trend from the east, which together with some volcanolithic content, indicate that some sediment was derived from an easterly magmatic arc with the lithic content in the Galilee Basin reduced by climate and distance from source.

The Moolayember Formation samples grouped within petrofacies U1 show a continuation of the quartzose recycled orogen trend. This differs from the Moolayember Formation of the Bowen Basin for which Fielding et al. (1995) documented derivation from an easterly dissected volcanic arc. This indicates source partitioning with separation of the basins during Moolayember Formation time. Petrofacies U1 of the Galilee Basin had little influence from easterly uplift that infilled the adjacent Bowen Basin. The majority of U1 was derived from a similar westerly Thomson Fold Belt source as interpreted for the lower petrofacies group of the Galilee Basin.

The high monocrystalline quartz content of petrofacies U2, comprising samples from the Warang Sandstone and Clematis Group, were derived from an orogenic source and this petrofacies shows a very low volcanolithic input. Palaeocurrent measurements by Vine et al. (1964, 1965) for the Clematis Group in the southern Galilee Basin show a predominant source from the west with minor input from the east and the Warang Sandstone in the northern Galilee Basin shows a southerly transport direction with a minor easterly component. The provenance for the Clematis Group of the Galilee Basin was the Thomson Fold Belt and Charters Towers Province with a very minor input from an easterly magmatic arc. This is consistent with the Bowen Basin paleogeographic map for the Clematis Group constructed by Fielding et al (1995) that shows renewed sediment input from the west over the Anakie Inlier with continued sediment input from a dissected mountain range in the east and southerly transport along the basin axis.

5.8.2.1 Petrofacies U2 Detrital Zircon Ages

In this study, a single sample (OX1) of medium-coarse grained quartz sandstone from the Warang Sandstone was obtained in the Oxenhope region (21^0 07’ 52.7”S 145^0 38’ 33.5”E) of the northern Galilee Basin. Its stratigraphic position within the unit is unknown due to poor outcrop continuity. A Tera-Wasserburg concordia plot was obtained from 50 grain spot analyses and a relative probability plot of the ^{207}Pb corrected ^{206}Pb/^{238}U age produced using the method of Sambridge and Compston

(1994). This data shows five significant zircon populations related to provenance ages (Figure 5.29).

The populations spanning 410-430 Ma and 470-480 Ma have a similar source signature as that determined for Cycle 2 of the Drummond Basin. This corresponds to the Pama and Macrossan igneous assemblages of Hutton (1997b; 1997a) and intrusions within the Thomson Fold Belt (Draper 2006). A small population at 365 Ma represents a late phase of the Retreat Batholith as interpreted by Crouch et al. (1994). The main populations spanning 320-340Ma and 295 Ma corresponds to the Kennedy igneous association. This association is extensively represented by volcanic fields and plutons in northeastern Australia and represents a major element of the regional geologic framework. The earlier age is represented by the Silver Hills Volcanics (Henderson et al. 1998) in the Drummond Basin and basic flows and pyroclastics of the Glenrock Group in the upper strata of the Burdekin Basin to the north (Draper and Lang 1997). The youngest population corresponds with SHRIMP ages of 305-294 Ma obtained by Black (1994) for the nearby Bulgonunna Volcanic Group and 306-286 Ma for the correlative Urannah Suite obtained by Allen et al. (1998).

The zircon age data for the Warang Sandstone indicates that significant input occurred from magmatism represented by the Kennedy Province with the Thomson Fold Belt and Charters Towers Province also sediment sources. No sediment was derived from Proterozoic cratons such as the Georgetown, Mount Isa, Arunta and Musgrave terranes at this time. However, the volcanolithic source indicated for the Warang Sandstone from zircon data is not reflected in the provenance plots. This suggests a strong climatic signature reflected in the petrofacies of U2 that removed labile feldspar and lithics from erosional debris. This climate is a continuation of that interpreted to have prevailed during deposition of the Rewan Group and indicates an extensive period of deep chemical weathering in the region.

In contrast the Triassic Hawkesbury Sandstone of the Sydney Basin, well to the south, has a quartzose petrofacies of cratonic orogen similar to the Clematis Group. Veevers (2000) indicated the detrital zircon age population of the Hawkesbury Sandstone has a peak in the Neoproterozoic and a Proterozoic Beardmore-Ross provenance in the Trans-Antarctic Mountains. The similarity of petrofacies, but a cratonic orogen source for the

Warang Sandstone and a recycled orogenic source for the Hawkesbury Sandstone, of the two units suggests a broad climatic signature affected Eastern Australia in the Triassic.

5.9 Summary of Provenance for the northern Drummond and Galilee Basins

Previous studies of the Drummond Basin focussed on petrographic differences in sedimentation patterns (Olgers 1972; Hutton et al. 1991; Goulevitch 1992; Bennedick 1993; Henderson et al. 1998) but none attempted to determine the source of these sediments. Olgers (1972) divided these patterns into Cycles 1, 2 and 3 depositional episodes. This present study shows that Cycle 1 sediments have a predominant derivation from a dissected to transitional dissected volcanic arc with minor input from a recycled orogenic source. The presence of feldspar indicates that some unroofing of the magmatic source occurred. The Drummond Basin Cycle 1 relationship is similar to infill in the Burdekin Basin to the north and Yarrol and Campwyn terranes to the east. This indicates that the Drummond Basin commenced as a backarc basin, similar to conclusions by Fergusson et al. (1994), Leitch et al. (1994) and Murray et al. (2003). The Thomson Fold Belt to the west and south of the Drummond Basin is a probable source of the recycled orogenic grain content. A lack of paleocurrent data precludes a definite provenance conclusion for Cycle 1.

Cycle 2 sediments of the northern Drummond Basin show an initial transitional mixed provenance of an easterly volcanic arc provenance and a recycled orogen provenance in the west to a final predominant recycled orogenic source in the west. This recycled orogenic source is represented by the Thomson Fold Belt. Zircon age data indicates that a magmatic source also exists within the Thomson Fold Belt, similar to a conclusion by Draper (2006).

Cycle 3 sediments continue the predominant recycled orogenic source evident in Cycle 2. An easterly magmatic arc provenance is initially subordinate, limited to pyroclastic deposits. An increase in volcanolithics through the Bulliwallah and Natal Formations indicate an increasing influence from the magmatic arc to the east.

Limited petrographic information is available for Galilee Basin sediments and provenance determination has been undertaken only on the Betts Creek beds (Arman 1964; Hawkins 1976; Hawkins 1978; Hawkins and Carmichael 1987). This current study shows that the lower units of the northern Galilee Basin, the Joe Joe Group, had a predominantly recycled orogenic source derived from the westerly Thomson Fold Belt with a variable easterly magmatic arc provenance. The upper formations of the northern Galilee Basin all show a mixed recycled orogenic and volcanic arc source consistent with derivation from the westerly Thomson Fold Belt and easterly igneous associations. This is counter to the correlative units of the Bowen Basin, that Fielding et al. (1995) determined had a predominantly volcanic arc source from the east. Detrital zircon ages from the Warang Sandstone show a magmatic source within the Thomson Fold Belt comparable with Cycle 2 sediments of the Drummond Basin, with a volcanolithic influence from the east indicating a climatic influence on deposition.

6.0 Tectonic Development of the Drummond and Galilee Basins

6.1 Drummond Basin

Evidence provided by Hutton (1989), Johnson and Henderson (1991) and Henderson and Davis (1993) show that the Late Devonian-Mid Carboniferous Drummond Basin resulted from back-arc extension developed inboard of a coeval active margin assemblage within the New England Orogen. Back-arc rift basins are commonly short and wide (Williams and Eubank 1995). The Drummond Basin, showing a 500km length and 150km width, conforms to this description. Scheibner and Veevers (2000) proposed that extension was due to a steepening of a descending oceanic slab but it is unknown whether this was due to the influence of gravity (Dewey 1980) or shear stress caused by differential motion of the lithosphere with respect to the underlying mantle (Doglioni 1992). Wernicke (1985) proposed that regional extension may be facilitated by a single low angle shear zone that cuts a significant part of the crust and may extend to the asthenosphere. This shear zone can be associated with shallow subduction that undergoes rollback. This results in basinal asymmetry and tectonic uplift of the hanging wall hinterland as evident for the Drummond Basin. It is probable that the pre-existing NE structural fabric of the Thomson Fold Belt, which underlies the basin, exerted a strong control on rift partitions and the orientation of transfer zones. Evidence provided here indicates that the Drummond Basin developed as a passive rift in response to lithospheric thinning caused by a backstepping subduction zone in the east (Figure 6.1). A significant volume of magma found in the basin floor was produced due to decompressive partial melting.

Olgers (1972) described three large-scale sediment cycles for infill of the Drummond Basin. Johnson & Henderson (1991) and De Caritat & Braun (1992) recognised that Cycle 1 was associated with active back-arc crustal extension, reflected by a rift architecture of the basin floor. These authors recognised syn-rift growth faulting, shown by a thickening of seismic facies interpreted as Cycle 1 basin infill, towards a population of listric faults on the eastern basinal margin. The detail of extensional fault architecture was recognised by surface mapping of the Silver Hills Volcanics in the southern region of the Drummond Basin where the extensional fault geometry is partitioned into compartments by transfer faults (Davis and Henderson 1996). A thermal subsidence phase for the Drummond Basin was recognised by De Caritat & Braun (1992) as being associated with Cycles 2 and 3.

The extensional architecture of the Drummond Basin is endorsed in this study. However, the growth fault geometries extend much higher into the basin fill than previously recognised. Thickening of the seismic facies against listric faults as seen in seismic facies D1 to D3 indicate that these structures were active up-to and including deposition of the Star of Hope Formation at the base of Olgers's Cycle 3 (Figure 6.2, Section 1). Deflections in the structure contours related to these seismic facies represent the reactivation by Hunter-Bowen orogenic compression of transfer faults that were part of the extensional fabric. Depocenters for the Mt Hall and Star of Hope Formations as indicated by isopachs for these units are located between transfer structures indicating that they defined discrete compartments in rift architecture. The coarse-grained character of the Mount Hall Formation is attributed to relief generated by hanging wall uplift on a large-scale detachment fault system dipping west as modeled by Wernicke (1985) and Coward (1986) (Figure 6.1). Provenance plots indicate that Cycle 1, 2 and 3 sediments have a recycled orogen source such as the Thomson Fold Belt with variable input from a magmatic arc source. This conclusion conflicts with the zircon age data of the Mount Hall Formation that show a stronger influence of a magmatic arc. However, ages of granites in the Thomson Fold Belt (Draper 2006) associated with the Pama and Macrossan igneous assemblages and granites in the Roma Shelf associated with the Retreat Batholith indicate that igneous sources related to Early Palaeozoic magmatism are present to the west and south of the Drummond Basin. The quartz domination of the Mount Hall Formation is due to a climatic overprint whilst the increased labile content of the Natal Formation is a reflection of compressional tectonics.

During the Late Devonian-Early Carboniferous a thick sequence of volcaniclastic strata accumulated within the basinal successions of the Yarrol and Campwyn terranes (Fergusson et al. 1994; Murray et al. 2003) and the Wandilla subduction complex.(Leitch et al. 2003). A magmatic arc, the Connors Arch, between these elements and the Drummond Basin has been widely proposed (Murray et al. 1987; Henderson and Davis 1993; Henderson et al. 1993). This volcanic episode is represented by tuffaceous intervals within the Star of Hope and Bulliwallah Formations. Evidence of it, in terms of outcropping igneous suites is however sparse (Allen et al.

1998). This suggests that its expression was volcanic with an almost complete removal by erosion.

A localized sub-basin in the extensional mosaic developed near the Pajingo Mine on the northern basin margin and shows a discrete history (Fellows and England 2000; Goddard 2003). Here Drummond Basin units older than and including the Star of Hope Formation were tilted by fault rotation and were subsequently unconformably overlain by a sedimentary package that is equivalent to the Bulliwallah Formation of the Drummond Basin.

Down-stepping normal faults on the western basinal margin offset all the strata below the Star of Hope Formation (Figure 6.2, Section 2). They were not active as rotational growth faults as evidenced by the lack of thickening of the Mt Hall Formation against them. Drape fold structures in the Star of Hope Formation above these faults suggest they were active towards the end of syn-rift infill.

Thermal subsidence of the Drummond Basin occurred in the Early Carboniferous subsequent to deposition of the majority of the Star of Hope Formation. The basinal infill of fluvial Bulliwallah Formation and predominantly lacustrine Natal Formation show that this was a significant episode in the basinal history (Figure 6.1). The 2km thickness of these formations accumulated during the Visean, over a period of approximately 20 M.y. This relatively slow rate of subsidence suggests that lithospheric thinning, upwelling of the mantle and lithosphere thermal perturbation sponsored during the rift phase was relatively modest.

6.2 Kanimblan Inversion of the Drummond Basin

Extensional basins developed on the upper plate of subduction systems are zones of weakened lithosphere and highly likely to be affected by later inversion. The structure contours and isopach patterns of the northern Drummond Basin identify major thrust features indicating inversion of the basin during the final stages, and after, basin infill.

Previous studies recognised a deformation event, resulting in folding and inversion of the Drummond Basin linked to the Mid-Carboniferous Kanimblan Orogeny (Olgers

1972; Doutch and Nicholas 1978; Veevers et al. 1982; Fenton and Jackson 1989; Hutton 1989; Johnson and Henderson 1991; Withnall et al. 1995). De Caritat and Braun (1992) considered that Kanimblan orogenesis resulted in only relatively mild deformation.

The results of the present study show evidence of minor crustal shortening structures affecting the Drummond Basin prior to development of the overlying Late Carboniferous-Middle Triassic Galilee Basin. Evidence for Kanimblan contraction is shown by the foreland depocenter developed in the Early Carboniferous Natal Formation. An angular discordance between Drummond Basin strata and the Late Carboniferous Bulgonunna Volcanics has been mapped in the northeast of the basin (Henderson et al. 1998) and in its southern sector a similar discordance separates Drummond Basin strata and the Early Permian Colinlea Sandstone (Mollan 1967). Downlap of the Late Carboniferous Jericho Formation onto the Natal Formation west of the Mingobar Structure indicates a locally disconformable relationship between the two units. Minor onlap of the Jericho Formation onto the Natal Formation occurred on the Hopkins Thrust System, indicating that this feature was emergent in the Late Carboniferous (Figure 6.2, Section 2). Based on palynomorph data from Jones and Truswell (1992), a Late Carboniferous lacuna of some 10 Ma was considered by Scheibner and Veevers (2000) to separate the Ducabrook Formation of the Drummond Basin and the Lake Galilee Sandstone of the Galilee Basin.

It is now clear that the Kanimblan Orogeny had little effect on the Drummond Basin. There is no evidence of a regionally developed unconformity on the contact separating Drummond and Galilee Basin assemblages. Generally stratal relationships across this boundary are concordant, with only locally developed downlap and onlap (Figure 6.2). The Natal Formation represents the onset of foreland basin development induced by the Kanimblan Orogeny. However basinal development was more strongly influenced by the thermal subsidence phase represented by the Bulliwallah Formation. Localised onlap of the Jericho Formation onto the Nunkumbil Anticline shows that this structure was a minor topographic high at the inception of the Galilee Basin. This and other expressions of Kanimblan contraction are considered to be of only local-scale significance and not indicative of regional tectonism. There is no evidence of megashears, as postulated by Olgers (1972), producing sinistral shear deformation of the Drummond Basin. In contrast to earlier interpretations the population of broad, open upright folds mapped for the exposed eastern margin of the Drummond Basin is regarded here as Late Permian-Middle Triassic Hunter-Bowen orogenic structures unrelated to Kanimblan tectonism.

6.3 Galilee Basin

The initiation of the Late Carboniferous-Middle Triassic Galilee Basin is regarded here as reflecting an increasing rate of crustal convergence that commenced during the Kanimblan Orogeny (Figures 6.1, 6.3). The suggestions that subsidence was induced by a north-northwesterly trending sinistral shear couple (Evans and Roberts 1980) or a pericratonic downwarp adjacent to the Sydney-Bowen foreland basin (Veevers et al. 1982) are not supported by the compilation presented in the current study. The geometry of the Jericho Formation reflects a foreland regime. This unit expresses a longitudinal depocenter along the trend of the Hopkins Thrust System and a similar thickening appears to have been developed along the western margin of the Bingeringo Thrust System, although it cannot be recognised with certainty due to post-inversion erosion (Figure 6.2). These structures probably represent a piggy backed foreland basin couple and imply that related thrust systems were developed within Drummond Basin strata to the east. The underfilled nature of the basin at a time of high sediment influx suggests that thermal subsidence continued as an influence during this stage of basin evolution.

The Jochmus Formation is regarded as marking the waning of foreland basin development (Figures 6.1, 6.3). The development of thrust belt depocenters is not evident and the unit shows gradual thickening towards the basin axis suggesting that thermal subsidence was the principal mechanism controlling basin infill. Tectonic quiescence at the close of the Jochmus Formation is suggested by deposition of the Aramac Coal Measures as ephemeral mire accumulations patchily developed on the Jochmus Formation in the Northern Galilee Basin.

Early Permian extension in the adjacent Bowen Basin is well recognised (Hammond 1987; Fielding 1990; Elliott 1993; Holcombe et al. 1997b). An extensional geometry related to deposition of the basal Reids Dome Beds has been documented for the western part of the Bowen Basin (Figure 6.3). This unit was interpreted as fault bounded graben and half-graben infill associated with active crustal extension by Paten (1979), Draper & Beeston (1985) and Ziolkowski & Taylor (1985). The Lizzie Creek Volcanics that floor the basin in its eastern part are also considered to reflect this extensional episode (Henderson and Davis 1993). An extensional regime has been generally recognised as applying throughout the New England Orogen for this time (Fergusson and Leitch 1993) as reflected in the regional development of an Early Permian dyke swarm in its northern part (Stephenson 1990). Predominantly an omission surface and hiatus represents this extension in the Galilee Basin.

A hiatus marked by a disconformity below the Late Permian Betts Creek Beds signals cessation of extension in the Bowen Basin. The onset of the thermal relaxation phase recognised by Fielding et al. (1990; 1995) in the Middle to early Late Permian infill of the Bowen Basin, represented by the Cattle Creek to lower Aldebaran Sandstone stratigraphic interval of the Back Creek Group, has no apparent representation in the Galilee Basin. The Aramac Coal Measures may reflect this period but age associations require revision.

A disconformity is present at the base of the Colinlea Sandstone in the Galilee Basin and is also represented within the Aldebaran Sandstone of the Bowen Basin (Staines and Koppe 1979; Elliott 1993). This hiatus is synchronous with an uplift event recognised in the New England Orogen (Holcombe et al. 1993) and represents a far-field expression of an early phase of Hunter-Bowen orogenesis that had an influence on relative sea level change in the Galilee and Bowen Basins (Figures 6.1, 6.3). The Betts Creek beds and correlatives show influence of transgressions and regressions in their depositional pattern. These units and a small portion of the Rewan Group in the Galilee Basin are broadly correlative with a thermal subsidence phase recognised by Fielding et al. (1995) in the Back Creek Group of the Bowen Basin.

The upper part of the Galilee Basin succession represents a mild foreland phase of basinal development, matching the history interpreted for the Bowen Basin (Fielding et al. 1995). The Galilee and Bowen Basins have closely comparable stratigraphic signatures (Figures 6.1, 6.3). The Late Permian-Middle Triassic Rewan Group, Clematis Group and Moolayember Formation are thought to be common to both basins (Vine

1976) whilst the Blackwater Group of the Bowen Basin reflects an abrupt switch in provenance from a westerly cratonic source to an easterly magmatic arc source (Michaelsen and Henderson 2000). In the Galilee Basin far-field effects of this basinal phase driven by orogeny to the east was slight, as evidenced by the thin, conformable, laterally extensive formational architecture of the basin fill shown by the isopachs. This conclusion is supported by provenance evaluation for these units that show the majority of detritus derived from a westerly cratonic source that had a climatic overprint.

For the crustal sector embracing the Bowen and Galilee Basin's compressive deformation was at a climax in the Middle-Late Triassic age. In this stage of basin inversion, syn-tectonic folding and thrusting developed the majority of structures in the Galilee and Drummond Basins (Figure 6.2). The structural style of these basins is similar to that found in the Bowen Basin, but on a smaller scale. The structural pattern of the tight folds in the eastern Drummond Basin, dying out to the west towards the Beryl Ridge platform, is mirrored by the Bowen Basin with the eastern Gogango Overfolded Zone flanking the western undeformed Collinsville Shelf and Comet Platform.

6.4 Hunter-Bowen Orogenesis

The Hunter-Bowen Orogeny produced intense folding and thrusting in the New England Fold Belt and deformed parts of the adjacent Bowen and Sydney Basins (Murray 1986; Fergusson 1991; Veevers 2000). Deformation of the New England Orogen commenced in the Mid-Permian, as shown by the radiometric ages of metamorphism for subduction complex assemblages (Leitch and McDougall 1979; Leitch et al. 1993). Pulses of contractional deformation occurred in the northern New England Fold Belt from the Late Permian to late Middle Triassic (Fergusson and Leitch 1993; Holcombe et al. 1997a). Migration of the deformation front westward with time is recognised for the southern New England Orogen (Collins 1991; Fergusson and Leitch 1993). In the Late Permian, intense deformation associated with thrusting affected Early Permian strata in the Gogango Overfolded Zone and mid-Permian strata in the folded zone of the eastern Bowen Basin (Fergusson 1991; Fielding et al. 1995). This deformation had minimal effect on the western Bowen Basin. Both the northern New England Orogen and eastern Bowen Basin experienced thin-skinned thrusting and shearing in the Mid-Triassic

(Korsch et al. 1986; Fergusson 1991). Mid-Triassic deformation of the eastern portions of the Gunnedah Basin and Sydney Basin was due to reactivation of thin-skinned thrust systems (Hamilton et al. 1988; Glen and Beckett 1989). Elliott (1993) recognised an Early Triassic event which developed high angle thrusts in the Taroom Trough whilst in the Mid-Triassic folding occurred in the Bowen Basin. Fergusson (1991) considered that Hunter-Bowen deformation of the Bowen Basin was an ongoing event. Cross-cutting relationships on the eastern margin of the Drummond Basin suggest that the Anakie Inlier was uplifted along the St Anns Fault (Figure 6.2, Section 2) and movement may have occurred throughout the Hunter Bowen Orogeny as shown by zircon grain occurrence in the Early Triassic Warang Sandstone derived from the Retreat Batholith situated in the Anakie Inlier.

The mid-Triassic end-phase of the Hunter-Bowen Orogeny inverted and deformed the northern Drummond and Galilee Basins. This episode post-dated deposition in the Galilee Basin and is represented by a population of thrust faults and folds that were propagated through the entire stratigraphy of the Drummond and Galilee Basins (Figure 6.2). Deformation is limited to the eastern margin of the basins but late-stage uplift and regional tilting to the west produced the unconformity at the base of the overlying Eromanga Basin. Structures developed throughout the Hunter-Bowen Orogeny typically have a north-northwesterly trend (Fergusson and Leitch 1993). The northwesterly-orientated Mingobar and White Mountain Structures reflect this structural trend. Northwesterly trending structures such as the Hulton-Rand Structure, Darriveen Fault and Maranthona Monocline recognised on the western margin of the Galilee Basin represent part of the compressional fabric. Broad-scale dextral shear is inferred for the late stages of the Hunter Bowen Orogeny (Fielding 1990; Collins 1991). No rotation to the right is evident in the structural fabric of the Galilee Basin.

Two newly recognised NW-SE orientated en-echelon thrust systems and numerous blind thrusts are present in the northern Drummond and Galilee Basins. The surface expression of these major thrusts was previously mapped as the Bingeringo Anticline and the Hopkins Anticline (Olgers 1970). The seismic profiles show that the anticlines represent fault-bend folds above thrust ramps and these structures are renamed here as the Bingeringo and Hopkins Thrust Systems (Figure 6.2). Each involves only a small thrust displacement (0.2 second two-way time, approximately 400m) but the thrust population is stacked in piggy-back style. The structures flatten with depth, suggesting a thin-skinned style and in places show an antithetic association with basin margin listric faults. These structures are offset by reactivated transfer faults originally developed in the extensional phase of the Drummond Basin with NE-SW movement shown by dislocations in the structure contours.

The Mingobar Structure of Vine et al. (1965) or Mingobar Moncline of Olgers (1970) is part of a broad anticlinal feature, named the Nunkumbil Anticline, associated with a large blind thrust . The co-linear White Mountains Structure of Vine et al. (1964) represents the northern extension of the Mingobar Structure. The thrust to which these two features relate extends over 200 km and it commenced development during deposition of the Middle Triassic Clematis Group. The Aberfoyle Syncline is a very broad synform associated with uplift along the Mingobar Structure. It has no relationship with the Koburra Depocenter which is a depositional feature associated with the pre-deformation paleogeography of the Galilee Basin.

A sharp gravity gradient, referred to as the Belyando Feature in the Southern Drummond Basin, was interpreted as a major structural discontinuity between the Drummond and Galilee Basins by Vine (1965). This study shows the Belyando Feature to be an inversion structure related to the Hunter-Bowen Orogeny. The Belyando Feature in the Northern Drummond Basin is coincident with the structure contour expression of the Belyando Thrust.

7.0 References

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