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SEDIMENTARY LITHOFACIES, PETROGRAPHY AND DIAGENESIS OF THE KAPUNI GROUP IN THE KAPUNI FIELD, TARANAKI BASIN, NEW ZEALAND

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(2004)

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ABSTRACT

The reservoir architecture and quality of the Kapuni Group sandstones in seven wells (Kapuni-1, -3, -8, -12, Deep-1, 14 and -15) in the Kapuni Field are characterised using available core and digital geophysical log data. The study focused primarily on the Eocene Mangahewa Formation, but where limited core permits the older Kaimiro and Farewell formations are also examined.

Eleven lithofacies in the Kapuni Group, identified and defined in core on the basis of colour, lithology, bedding, texture and sedimentary structures, are interpreted to represent tidal sand bar, tidal-inlet channel, fluvial-tidal channel, spit platform, sand flat, shallow marine, tidal channel, meandering tidal channel, mud flat, swamp and marsh environments. Correlation of core lithofacies with geophysical log motifs enabled lithofacies identification where core data are not available. Log motifs representing each of the lithofacies were then extrapolated to uncored sections of the Mangahewa Formation in the Kapuni Field wells.

Interpretation of lithofacies in core and geophysical log motifs indicate that the Mangahewa Formation was deposited in an estuarine setting. During initial deposition of the Mangahewa Formation tide-dominated estuarine lithofacies were deposited. A major coal horizon, the K20 coal, in the field represents a period of maximum infilling. Above this coal core and log data indicate a wave-dominated estuary exhibiting a clearly-defined, "tripartite" (coarse-fine-coarse) distribution of lithofacies.

Provenance studies suggest that low-grade metamorphic and granitic rocks are the dominant source for the Kapuni Group sandstones. Minor input from sedimentary and acid volcanic source rocks are also identified. A volcanic source, however, is more important in sandstones from the Farewell Formation, than in the younger Kapuni Group formations. Probable sources include the low-grade metamorphic rocks of Lower Cambrian to Permian age, Permian to Carboniferous Karamea Granite, Triassic and Jurassic greywacke-argillite sediments, Upper Cretaceous Pakawau Group sediments and Pre Cambrian to Upper Cretaceous acid volcanics.

Reservoir quality variations in the Kapuni Group sandstones are directly related to environmental and diagenetic processes that have controlled porosity reduction and enhancement. Porosity has been reduced mainly by mechanical and chemical compaction, clay formation (predominantly kaolinite and illite in the Mangahewa and Kaimiro formations and smectite in the Farewell Formation), carbonate precipitation (primarily siderite and calcite), quartz and feldspar overgrowths and pyrite precipitation. While, porosity has been enhanced primarily by carbonate dissolution and subordinately by grain and clay dissolution and minor grain fracturing.

The Mangahewa Formation sandstone lithofacies of tidal sand bar and tidal channel environments exhibit the best reservoir characteristics. Future reservoir development in the Kapuni Field and exploration in the Kapuni Field should focus on identifying and exploiting these lithofacies.

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INTRODUCTION

1.1 BACKGROUND

The Kapuni Field is New Zealand's largest onshore gas/condensate field, located approximately 40 km south of New Plymouth in the southeastern part of the Taranaki Peninsula (Figure 1.1). Discovered in 1959 by Shell BP Todd Oil Services Limited (SBPT)[1], the field was brought into production in 1970. A total of 15 wells (Kapuni-1 to -15) and two side-tracks (Kapuni-3A and 15A) have been drilled[2]. Currently 11 production wells in the field produce gas and condensate from multiple sandstone reservoirs of the Eocene Kapuni Group. At 1 July 2001 total reserve estimates for the field stand at 62 million barrels (mmbbls) of condensate and 1322 billion cubic feet (bcf) of gas, with remaining reserves of 3.5 mmbbls of condensate and 421.4 bcf of gas (Crown Minerals, 2002).

1.2 PURPOSE AND SCOPE OF STUDY

The aim of this study is to characterise the reservoir architecture and reservoir quality of the Eocene Mangahewa Formation in the Kapuni Field. The older Kaimiro and Farewell formations, which along with the Mangahewa Formation complete the Paleocene to Eocene Kapuni Group succession, are also examined. Although, hydrocarbons are not produced from either of these deeper formations in the field, they do provide important reservoirs elsewhere in the Taranaki Basin[3]. This study is based only on those Kapuni Field wells where both core and digital geophysical logs are available for the Kapuni Group; namely: Kapuni-1, Kapuni-3, Kapuni-8, Kapuni-12, Kapuni Deep-1, Kapuni-14 and Kapuni-15.

Specific objectives of this study are to:

- Identify sedimentary lithofacies in core from the Kapuni Group and interpret their environments of deposition
- Relate sedimentary lithofacies in the Mangahewa Formation to their corresponding geophysical log patterns (log motifs) and then extrapolate to uncored sections in the wells

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[1] BP terminated its upstream activities in New Zealand in January 1991 as a result Shell BP Todd Oil Services (SPBT) changed to Shell Todd Oil Services (STOS).

[2] The Kapuni-13 well was named Kapuni Deep-1.

[3] The Kaimiro Formation provides the main producing reservoir sandstones 'D sands' in the Maui Field, whist the Kupe Field produces from sandstones of the Farewell Formation.

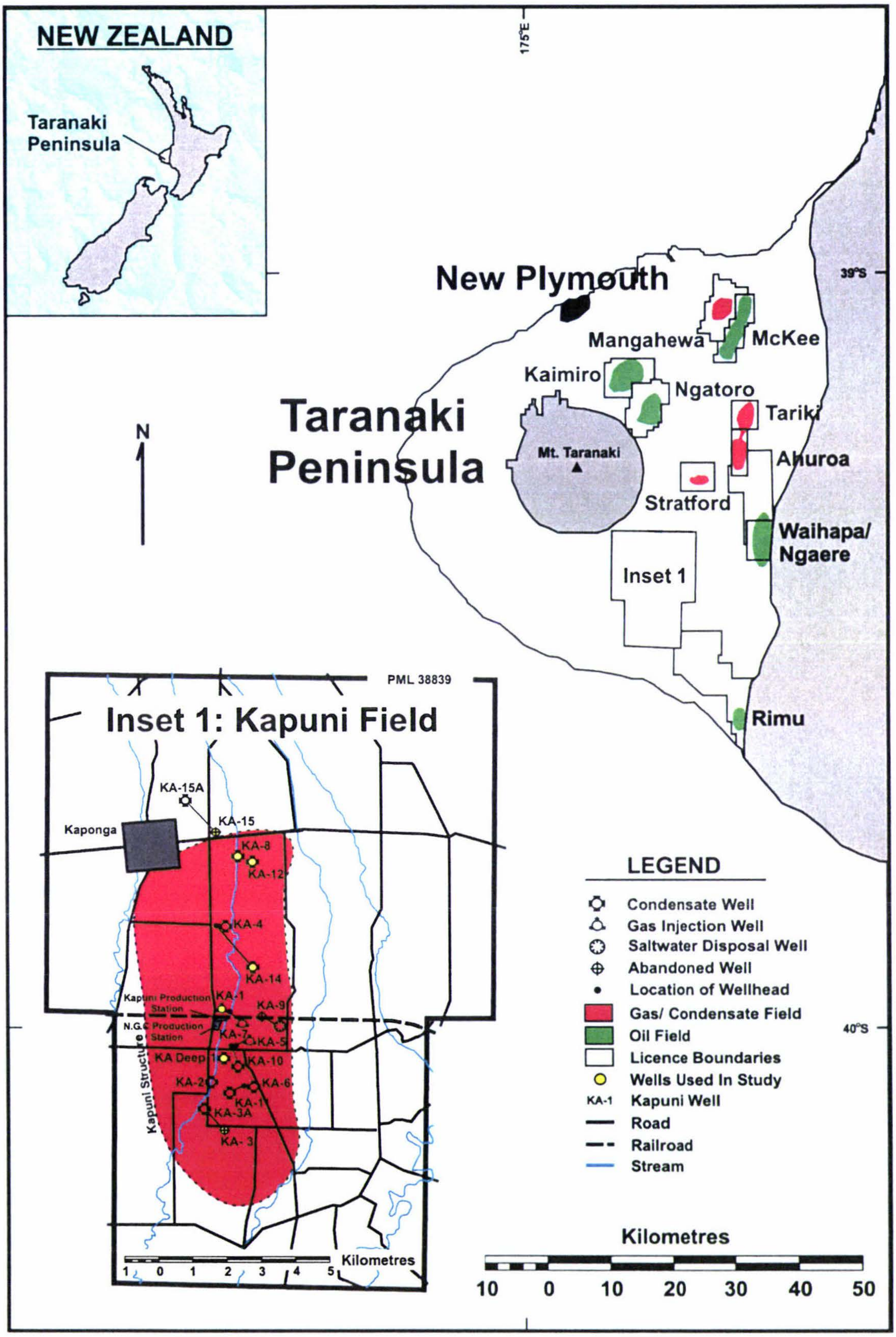

Figure 1.1: Location map of the Kapuni Field and wells

- Develop an environment of deposition model for the Mangahewa Formation based on lithofacies from core and log motifs
- Identify the composition, porosity, texture and classify sandstones in the Kapuni Group
- Elucidate the provenance for the Kapuni Group sandstones
- Identify the diagenetic processes in the Kapuni Group sandstones and determine how they have modified the original sandstone
- Establish the sequence and timing of diagenesis in the Kapuni Group sandstones.

1.3 PREVIOUS WORK

Previous studies in the Kapuni Field have addressed various aspects of the stratigraphy, sedimentology, provenance, petrography and diagenesis of the Kapuni Group. Although, these studies have afforded a better understanding of the depositional and post-depositional process in the field most have focused on a limited number of wells and samples from the best producing reservoir intervals in the Mangahewa Formation. A discussion of previous work in the Kapuni Field is limited to published and unpublished reports, unpublished university theses and reports held on open file at the Ministry of Economic Development.

1.3.1 Stratigraphy and Sedimentology

Seismic surveys undertaken in onshore Taranaki from 1956 to 1957, led to the discovery of the Kapuni Field. The first stratigraphy and lithological descriptions of the Kapuni Group in the Kapuni Field were carried out by van der Klugt *et al.* (1959) following the drilling of the Kapuni-1 well. A glauconitic sandstone overlying a sequence of sandstones and coal beds with intercalations of calcareous siltstones and carbonaceous shales were identified. These strata were correlated with the thin sequence of similar sediments in North Taranaki recognised as the Mangaotaki Formation, first described by Glennie and Jaeckli (1956). In the Kapuni Field van der Klugt *et al.* (1959) informally subdivided the coal measure sequence into a sandstone-siltstone upper part, a middle interval of carbonaceous shales and a mostly sandstone dominated sequence in the lower part. Deposition of sediment in an overall fresh to brackish water environment was attributed to the formation.

After reviewing subsurface data from wells in the Kapuni Field and elsewhere in the Taranaki Basin Short (1962) recognised that the lithology, thickness and age of the Kapuni-1 coal measures were different from those described in the type section for the Mangaotaki Formation; and renamed the sequence the Kapuni Coal Measure Formation. He also suggested that during the Middle to Upper Eocene deltaic-lagoonal conditions prevailed across the Taranaki Basin and proposed that sediment was predominantly derived by one large river that drained into the basin from the north and east via a saddle in the Patea-Tongaporutu High.

Hicks (1962) and van Wijlen (1963) interpreted the seismic data along with data from logs, cores and cuttings from the first four wells (Kapuni-1 to -4) drilled. Hicks recognised major marker horizons based on 'microlog porosities' and named these the upper member comprising alternating shale, sandstone and coal, the "Main Sand" member composed of mainly sandstone with minor siltstone, shale and coal and the lower member composed predominantly of sandstone. The study by van Wijlen identifies and extensively describes the key marker beds in the Kapuni Formation. Further seismic surveys were carried out in 1971 and 1973 as 7 additional wells (Kapuni-5 to -11) and one appraisal outstep well (Kapuni-3A) were drilled. An interpretation of this seismic data was carried out by de Boer (1973).

A paleoecological study of the Eocene Mangaotaki Formation succession was carried out by Lutz (1964). The analysis focused on cores collected from the Kapuni-3 well in the Kapuni Field. Lutz assigned an Oligocene to Eocene age and interpreted the sequence penetrated as being deposited in a lower coastal plain environment.

To provide a geological basis for reservoir simulation studies Haskell (1975) undertook a geological review of the Kapuni Field, re-evaluating the seismic data and information available from the Kapuni-5 to -11 and Kapuni-3A outstep wells. Three major intervals were correlated between these wells and described as the K3, K2 and K1 intervals; revising the members previously described by Hicks (1962). The K3 interval extended from the base of the Mangahewa Formation to the K2 interval and was divided into the K3E, K3D, K3C and K3A sandstones. The K3E "Main Sands" occur at the base of the K3 interval and consist of a sequence of sandstone beds with overlying thin interbedded carbonaceous shales and coal (braided or meandering channel systems with surrounding mud flat and salt marsh environments). Above the "Main Sands" the K3C sandstone (channel system) and K3D sandstone (regressive beach) occur. The K3A "Upper Sands" occur at the top of the K3 interval comprising dominantly sandstone (redeposited from an emergent sandbar). The K2 interval comprising interbedded mudstones, shales and coals with localised silty sandstone beds (tidally exposed mud-flat and salt marsh environments) was recognised from the top of the K3 interval to the base of the Kap-20 coal (a thick coal that formed a prominent marker in each well, representing a period of widespread supralittoral swamp development). The K1 interval was reported to extend from the top of the Kap-20 coal to the top of the Kapuni Formation. The interval was subdivided into the K1C sandstone (channel system) and K1A sandstone (regressive beach deposit), while the remainder of the K1 interval was described as comprising shale and coal interbeds (tidally exposed mud-flat and salt marsh environments). In general the sequence penetrated in the Kapuni Field wells was interpreted by Haskell as lower coastal plain deposits comprising tidal channel, mud flat and salt marsh derived coals.

In a regional study of wells in the Taranaki Basin Harrison (1979) developed coal percentage and sandstone-shale ratio maps based mainly on gamma-ray, electric, induction-electric and sonic wireline logs. Five Kapuni Field wells (Kapuni-1, -2, -3, -4 and -8) were used in the study to examine the Upper Member of the Kapuni Formation in the Taranaki Basin. The highest percentage of coal in the basin was identified in the Kapuni Field wells, decreasing north and westward in the basin. On the basis of contour shape around the Kapuni Field and westward Harrison maintained that deposition of the Kapuni Formation occurred as part of a large delta complex prograding westward in the Taranaki Basin.

In a detailed study Hogan (1979) examined the stratigraphy and sedimentology of the Kapuni Formation from core obtained from eight onshore Taranaki wells, including two from the Kapuni Field (Kapuni-1 and -3). Hogan defined the type section of the Kapuni Formation in the Kapuni-1 well between 3245m and 3976m and divided the formation informally into four members (upper sandstone member, middle sandstone member, coal member and lower sandstone member) in which sandstone, shale and coal-bearing lithofacies were recognised. The subdivision varied slightly from those originally devised by Hicks (1962) and later redefined by Haskell (1975) as they were based on lithological variation, and spontaneous potential and resistivity logs. Hogan attributed marine to lagoonal or terrestrial environments of deposition to the Kapuni Formation.

Palmer (1980) provided a detailed description of core material from the Mangahewa Formation in eight onshore Taranaki wells. Two of these wells (Kapuni-1 and -3) were from the Kapuni Field. In the study stratigraphic columns were drawn for each core identifying colour, lithology, estimated grain size, siderite and level of bioturbation. A summary of the general lithology for each well was also given.

In 1983 the deepest well in the Southern Hemisphere Kapuni Deep-1 was drilled in the Kapuni Field to a depth of 5660.20 mahbdf[4]. Shell BP Todd Oil Services Limited (1984) presented a geological summary from the well based on information obtained from drill cuttings, sidewall cores, conventional cores and wireline logs. The Kapuni Formation was described as incorporating four regressive cycles defined as Cycles D, C, B and A. In reference to the reservoir intervals defined by Haskell (1975) Cycle D incorporated the K3A reservoir, Kap-20 coal and K1C sandstones; whilst Cycle C comprised the K3E reservoir. Cycle B represented the interval between seismic horizons A and B, incorporating the coastal sandstones which pass up into poorly developed coal measures

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[4] mahbdf (metres along hole below derrick floor)

(Kaimiro Formation). While Cycle A was defined to include a thick sequence of massive coastal sandstones (Farewell Formation), although drilling did not reach the base of this sequence.

In a later study, Palmer (1985) reviewed the stratigraphy and sedimentology of pre-Miocene sedimentary sequences in the Taranaki Basin. In the study the Kapuni Coal Measure Formation of Short (1962) was upgraded to the Kapuni Group to formalise the grouping of Paleocene to Eocene sandstone-coal measure sequence first encountered in the Kapuni-1 well. The Kapuni Group was subdivided into four formations by Palmer; from oldest to youngest they are the Kaimiro Formation, Omata Formation, Mangahewa Formation and McKee Formation.

In an attempt to standardise the nomenclature and dating of lithologic units King (1988a; 1988b) revised the stratigraphy in the Taranaki Basin. An investigation of key wells in offshore Taranaki lead King (1988a) to expand the Kapuni Group to incorporate the Farewell Formation of Paleocene age, which was originally assigned by Suggate (1956) to the Pakawau Group. This reassignment, however, created difficulties in subdividing similar coarse-grained rocks outcropping in northwest Nelson. Nevertheless, the subsequent identification of marine sediments in the Pakawau Group, reclassification of the late Cretaceous interval by Thrasher (1992) and discovery by Bal (1994) of an unconformity at the top of this interval added further support for inclusion of the Farewell Formation into the Kapuni Group.

Shell BP Todd Oil Services Limited (1988) undertook a geological and petrophysical analysis of core from the Kapuni-14 well. The study was based on 89m of core cut through the Mangahewa Formation K3E reservoir with the main objective to provide detailed lithological descriptions, a sedimentological model and petrophysical analyses to supplement K3E core from the Kapuni-3 well. In the study 5 lithological facies and 11 subfacies were distinguished on the basis of sedimentary structures and grain size. Subfacies were interpreted to represent tidal channel, tidally influenced distributary channel, mouth bar, lagoonal and/or tidal flat and floating peat swamp environments. The overall depositional environment was considered to be an upper deltaic plain to lower deltaic plain setting.

Structural influences on sandstone depositional systems and hydrocarbon accumulations in the Kapuni Field were investigated by Haskell (1989). The Kapuni Group sequence was interpreted to be deposited under regional lower coastal plain conditions. In particular Haskell elucidates to lacustrine, lagoonal and estuarine settings with fluvial to tidally influenced fluvial channels, tidal channels, sand and mud flat and swamp environments. He also noted that it was not possible to provide bed by bed correlation across the field, but refers to the sequence of units previously identified by Haskell (1975) comprising the K3, K2 and K1 reservoir intervals.

A major review of the Kapuni Field was initiated in 1989 with the acquisition of 3D seismic data covering the entire petroleum mining licence. Voggenreiter (1991) provided an interpretation of the data, and asserted that amplitude patterns of the K1 interval near the top of the Kapuni Group reflected lithologic changes diagnostic of fluviatile meandering channel features. Along with well data the work by Voggenreiter formed the basis for reservoir simulation studies of the Mangahewa Formation by Bryant and Bartlett (1992). Bryant and Bartlett developed a 3D reservoir model based on correlatable coals and associated mudstones across the field, subdividing the stratigraphic succession into nine layers. These layers, their boundaries and incumbent geology are examined in more detail later as they form the basis for current reservoir understanding in the Kapuni Field.

Shell Todd Oil Services Limited (1992) provided a lithological description and sedimentological interpretation of 18.60m of core cut from the K1A reservoir interval in the Kapuni-15 well. The K1A sandstones were originally interpreted as deposits of a low sinuosity distributary channel, although on the basis of tidal cross-bedding and *Ophiomorpha* trace fossils the interval was refined by Brekelmans *et al.* (1991) and Bryant and Bartlett (1992) to represent vertically stacked tidally-influenced channels. Sandstones in the K1A reservoir were also recognised as similar to those identified in core from the Kapuni-12 well, which form part of a coarsening upward shoreface body.

Flores *et al.* (1993) studied the sedimentology of the Kapuni Group reservoir system using almost 1,000m of core from nine wells in the Taranaki Basin. In the Kapuni Field, reservoir sandstones in the Mangahewa Formation were described in general as stacked fluviotidal facies, bounded by major truncations. These facies were interpreted to be deposited in predominantly tidal-creek and fluviotidal channels and subordinate tidal-inlet channel environments.

In the most comprehensive study of the Taranaki Basin to-date, King and Thrasher (1996) examined the Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin. In this study the Paleocene to Eocene Kapuni Group was subdivided into the Farewell, Kaimiro, Mangahewa and McKee formations. This reclassification also lead King and Thrasher to redefine the Kaimiro Formation which was originally assigned by Palmer (1985) to predominantly sandy, unfossiliferous strata encountered beneath early to middle Eocene marine mudstones of the Omata Member in the Taranaki Peninsula; to include all strata of Early Eocene age throughout the basin.

1.3.2 Geophysical Log Signatures (Log Motifs)

Log signatures have been used extensively used in the Kapuni Field wells to define cyclothems and reservoir intervals, however, limited work has been done on identifying individual units or lithofacies. The only analysis of log signature response at this scale was completed by Shell BP Todd Oil Services Limited (1988) on core from the Kapuni-14 well. The study found that when correlating the gamma-ray log to core, a cut off value of 60 API units separated the cross-bedded sandstones from the heterogeneous sandstones. The lithodensity/compensated neutron logs (LDL/CNL) was found to display good separation in the cross-bedded sandstones in the gas zone, heterolithic lithofacies demonstrated negative separation in the gas bearing section and positive separation in the lower water bearing zones. Whilst pronounced positive separation occurred in the mudstones and extreme positive separation coincided with sideritic intervals. The photoelectric factor log (PEF) was used to define the cross-bedded sandstones at 1.8 to 2.2 PEF units, heterogeneous sandstones at 2.1 to 2.5 PEF units, heterolithic at 2.0 to 2.7 PEF units and mudstones at 2.5 to 3.0 PEF units. PEF values over 2.6 units corresponded to intervals in which plant debris and/or pyrite were volumetrically important. The resistivity logs generally demonstrated a marked separation between MSFL and LL in the cross-bedded, heterolithic and heterogeneous lithofacies. On the raw resistivity curves, the heterogeneous sandstones were described as exhibiting a typically smooth trace for the heterolithic sandstones and cross-bedded sandstones; while the mudstones were considered easily identifiable by their uniform profile. Sonic transit times for the sonic (long spaced) log (SLS) were defined for the cross-bedded sandstones from 79 to 93 microseconds/ft, heterogeneous sandstones from 74 to 85 microseconds/ft, heterolithic from 64 to 87 microseconds/ft and mudstones from 63 to 82 microseconds/ft.

1.3.3 Provenance

Provenance in the Kapuni Field was first investigated by Hogan (1979). Modal analysis studies, particularly with respect to the undulose extinction and polycrystallinity of quartz grains lead Hogan to maintain that sandstones of the Kapuni Formation were predominantly derived from a low-grade metamorphic source, with sediment input also from plutonic and reworked sedimentary rocks. These findings along with sedimentological and stratigraphic evidence led Hogan to propose that that the formation was sourced from the Triassic and Jurassic greywacke-argillite metasediments, Pakawau Group sediments and Tasman Intrusives.

In studying the petrography of sandstones from the K1A reservoir interval in the Kapuni-12 well Challis and Mildenhall (1986) concluded on the basis of rock fragments, pebbles and detrital minerals, that the sandstones were derived almost entirely from a granitic source. Based on the identification of microcline, perthite and oligoclase feldspars, and the abundance of muscovite and biotite they suggested derivation from a two-mica granite. A change from muscovite to biotite or its alteration products in the well was thought to indicate a slight change in the composition of the source rocks. In reference to earlier studies, Challis and Mildenhall noted that most New Zealand granites contain shear zones in which undulatory quartz is abundant and considered the strain of quartz grains not to be an important provenance indicator. Instead, the apparent scarcity of sphene, epidote, and magnetite and abundance of microcline and oligoclase was used as evidence to suggest the Karamea Granite as the probable source.

Shell BP Todd Oil Services Limited (1988) investigated the provenance of sandstones from the Mangahewa Formation K3E reservoir interval primarily in the Kapuni-14 well, but also included samples from the Kapuni-3 well. On the basis of abundant quartz, scarcity or unstable minerals and rock fragments, and moderate grain rounding they suggested that sandstones were at least partly derived from a sedimentary source, and named the quartzose sediments of the Late Cretaceous Pakawau Group as a likely candidate. However, the dominant source rocks for the Kapuni Formation were considered to be granitic. Due to the absence of sphene and epidote, scarcity of magnetite and presence of K-feldspar the granitic source was identified as the Karamea Granite. They also suggested that a difference in the percentage of undulose and polycrystalline quartz and clay type and abundance between the Kapuni-3 and Kapuni-14 wells may indicate a slightly different source for the sediments.

In a petrographic summary of Taranaki petroleum reports Smale (1996) noted in the Taranaki Basin that the composition of the Kapuni Group was mainly granitic, with minor schist and altered acid volcanic rocks. Karamea type granite was identified as a provenance for the Kapuni Group in the Kapuni Field. Although volcanic rock fragments were noted to exceed granitic, the granitic provenance was still considered dominant.

1.3.4 Petrography and Diagenesis

The petrography and diagenesis of the Kapuni Formation in the Kapuni Field was first described by Hogan (1979). Petrographic microscopy, cathodoluminescence, infra-red spectrometry, x-ray diffractometry and scanning electron microscopy studies were conducted. Hogan concluded that the Kapuni Group sediments had been considerably modified by post-depositional processes. Quartz cementation and dissolution, formation of styolites, feldspar alteration, clay precipitation, carbonate cementation, pyrite precipitation and coalification of organic matter were identified as important diagenetic processes. Quartz cementation, feldspar alteration and kaolinite formation were deemed early diagenetic features, while quartz solution, illite formation, carbonate cementation (mainly siderite with some calcite) and pyrite precipitation were considered late diagenetic features.

Challis and Mildenhall (1986) conducted an investigation into the petrography and diagenesis of sandstones in the Kapuni-12 well. The sandstones were described as moderately to poorly sorted, fine- to medium-grained feldsarenites and subfeldsarenites. Compaction and the formation of authigenic kaolinite, illite, glauconite and carbonates (mainly dolomite, with less common calcite and siderite) and pyrite were identified as diagenetic processes reducing reservoir quality. In particular an increase in the proportion of mica and the transition from muscovite to biotite were considered to attribute to low porosity in the upper part of the K1 sequence in the Kapuni-12 well. Secondary quartz overgrowths were identified as the first stage in the diagenetic history of the sediments. Detrital kaolinite was considered to form the early cement, whilst carbonate was generally considered to be a late diagenetic mineral.

Shell BP Todd Oil Services Limited (1988) examined core from the K3E reservoir interval from the Kapuni-14 and -3 wells. The sandstones were described as fine- to medium-grained, moderately- to well-sorted subfeldsarenites. Kaolinite was identified as the main clay mineral with minor illite and mixed-layer illite-smectite. Petrographic studies indicated that syntaxial quartz overgrowths were not common, while the identification of carbonates included ankerite and siderite. The diagenetic history was considered to firstly involve the recrystallisation of original sedimentary clays to form well-crystallised kaolinite and mixed-layer illite/smectite. Next the dissolution of original calcite or dolomite cements occurred by organic acids creating considerable secondary porosity. Finally, late precipitation of ankerite and siderite reduced porosity in some sandstones.

A study by van der Lingen *et al.* (1988) provided the first comprehensive overview of diagenetic features in the Kapuni Group sandstones in the Taranaki Basin. Diagenetic processes adversely affecting reservoir quality of the sandstones in the Kapuni Field were namely; compaction, pressure solution, clay neoformation, quartz overgrowth formation and carbonate neoformation. Secondary porosity development was considered to enhance reservoir quality; through the dissolution of earlier (corroding) carbonate cements, dissolution of calcic plagioclase, quartz dissolution and grain fracturing. Progressive diagenetic stages in the Kapuni Group were identified. Early diagenetic features were recognised as plagioclase corrosion and kaolinite neoformation. Pressure solution and compaction were also recognised as early diagenetic processes, but thought not to be important until after carbonate cement dissolution. Carbonate cementation and dissolution were interpreted to occur at any depth. Whilst, dissolution of staurolite, garnets and quartz overgrowths were interpreted as late diagenetic processes.

Diagenetic controls on the porosity and permeability of the Kapuni Group sandstones in the Taranaki Basin were investigated by Collen (1988). In the study which concerned sandstones from two wells (Kapuni-1 and -3) in the Kapuni Field and the Ingleweood-1 well; mechanical compaction and the precipitation of silica, carbonate cements (predominantly calcite, less common siderite and rare dolomite and ankerite) and authigenic clays (kaolinite, illite and chlorite) were identified as the most important factors reducing reservoir quality. The dissolution of carbonate (particularly calcite) was considered the most important process for creating secondary porosity. Other less important processes in secondary porosity development were the dissolution of detrital grains and authigenic cements and the fracturing of rock and grains. Precipitation of silica was identified as an early cement which accompanied or closely followed precipitation of kaolinite and the dissolution of feldspar and other detrital grains. The crystallisation of illite and chlorite and successive deposition of cementing and replacive carbonates (mainly calcite, but also siderite, dolomite and ankerite) occurred next. The latest diagenetic processes included the dissolution of carbonates and feldspar, precipitation of kaolinite and the emplacement of hydrocarbons.

Smale (1996) provided a review on sandstone diagenesis in the Taranaki Basin summarising petroleum reports and the literature, in an attempt to unravel diagenetic sequences in the Maui, Kupe South and Kapuni Fields. Two main diagenetic sequences were distinguished in the basin. They were the 'Maui sequence' incorporating the Western Platform and adjacent areas and 'Kupe South sequence' representing onshore Taranaki. The Maui sequence was found to contain both late and early carbonate deposition around the middle of the sequence, while the Kupe South sequence (incorporating the Kapuni Field) was characterised by late quartz overgrowth development followed by carbonate dissolution.

The most extensive petrographic study in the Kapuni Field was conducted by Yunalis and Izhan (1995) primarily to assess potential reservoir problems related to sandstone mineralogy. The study involved a petrographic analysis of samples from the K1A, K3A, and K3E reservoirs in the Kapuni-3, -12, -14 and -15 wells. The mineralogical components (framework grains, clay matrix, and cements), texture and porosity of the samples, sequence and timing of diagenetic events and controls on the development of porosity and permeability were identified. The Mangahewa Formation sandstones were described as mostly quartz-rich with small but variable percentages of feldspar and lithics. Quartzarenite, subarkose and arkose sandstone were identified. Intragranular dissolution pores were recognised as the main porosity type with total visible porosity ranging from negligible (<0.4%) to good (19.6%). Of the diagenetic processes compaction, precipitation of pyrite and siderite, quartz overgrowth development, precipitation of ankerite, dissolution of feldspar/unstable grains and cements, and the formation of kaolinite represented the paragenetic sequence of diagenetic events and were considered the most important in determining sandstone reservoir quality.

The latest work on diagenesis in the Taranaki Basin is that of Smale *et al.* (1999) who studied the sandstone diagenesis of the Kapuni Group in the Kapuni Field and other onshore Taranaki wells. All three Kapuni Group formations (Farewell, Kaimiro and Mangahewa) were examined. The Farewell Formation comprised mainly feldsarenite sandstones. In the Kaimiro Formation feldsarenites and lithic feldsarenites predominated. While, the Mangahewa Formation sandstones are mainly feldspathic litharenites. In the study sandstones from the Farewell Formation were found to be more feldspathic than the younger Kapuni Group sandstones. Porosity was identified as variable (1.9% - 12.3%) in the Mangahewa and Kaimiro Formations and negligible (<1.9%) in the Farewell Formation. The diagenetic processes and sequence was largely consistent with the study by Collen (1988), although no evidence for early quartz cementation was found in the Kapuni Field. Kaolinite development was considered to be early; occurring before or during feldspar dissolution, whilst illite and chlorite were considered to form instead of kaolinite as a result of deeper burial. The main phase of quartz and feldspar overgrowth development occurred after clay mineral deposition. Carbonates (dolomite, ankerite, siderite and calcite) were thought to be late diagenetic features.

1.3.5 General Studies

Not withstanding the studies previously mentioned, a number of authors have provided either a general overview of the sedimentology, stratigraphy, provenance, petrography or diagenesis of the Kapuni Group in the Kapuni Field or make references in wider regional studies. McBeath (1976; 1977) was the first to provide a summary of the Kapuni Field, amongst other Taranaki Basin gas/condensate fields. Kear (1967) summarised the literature and presented a case study of the Kapuni Field. While more recently, Abbott (1990) presented an overview and classification of the Kapuni Field, mentioning the stratigraphy, trapping and reservoir systems.

A number of studies review or cite the Kapuni Group in the Kapuni Field as part of regional work on the Taranaki Basin. Some of the more important studies are summarised. The first notable studies of this type were provided by van der Sijp (1958a; 1958b; 1959) who described the Taranaki geology. Katz (1968; 1971; 1973; 1974; 1975a; 1975b; 1976a; 1976b) comprehensively discussed the oil potential in the Taranaki Basin focusing on the Kapuni Formation, which he described as being deposited in a lagoonal to deltaic environment. McLernon (1972; 1976; 1978) provided brief stratigraphic descriptions of the Kapuni Formation in Taranaki wells. Pilaar and Wakefield (1978) reviewed the stratigraphy of the Kapuni Formation in conjunction with the structural controls in the Taranaki Basin. A geological map of the Manaia area was published by Neall (1979). King and Cook (1987) presented a summary on the petroleum geology of onshore Taranaki. King and Robinson (1988) provided an overview of the Taranaki regional geology, while Robinson and King (1988) discussed hydrocarbon reservoir potential in the Taranaki Basin. Later, King (1990; 1991; 1994) described the changes in sedimentary and structural style in the Taranaki Basin in a number of papers. King and Beggs (1991) detailed the geological controls on oil and gas occurrence in the Taranaki Basin. Geosearch (1991) presented a summary of the exploration development in the Taranaki Basin including a review of the Mangahewa Formation stratigraphy and reservoir intervals in the Kapuni Field. Palmer and Bulte (1991) discussed the stratigraphy of the Taranaki Basin in relation to its active margin setting. Smale (1992) examined the provenance of sediments in the Taranaki Basin based on heavy mineral assemblages. Robinson *et al.* (1986a; 1986b; 1986c) examined the depositional history of the Eocene to Oligocene sediments. Palmer and Andrews (1993) discussed the Cretaceous to Tertiary sedimentation and structural evolution in the Taranaki Basin. McAlpine and Bussell (1994) summarised the literature on the Kapuni Field along with other onshore Taranaki fields in a field guide on Taranaki's hydrocarbon accumulations and facilities. As previously mentioned, in the most detailed study of its kind, King and Thrasher (1996) compiled a monograph synthesising the Cretaceous to Cenozoic geology and petroleum systems of the Taranaki Basin from industry information along with other published and unpublished studies. Aside from redefining the Kapuni Group; they reviewed the distribution, deposition setting and provenance of the Kapuni Group, making reference to the Kapuni Field. They also discuss the reservoir system including porosity trends and diagenesis in the Taranaki Basin. More recently, Crown Minerals (2000; 2001; 2002; 2003) provide a geological overview of the Taranaki Basin in their annual petroleum publications.

1.4 GEOLOGICAL SETTING

1.4.1 Regional Geological Setting - Taranaki Basin

The Taranaki Basin, New Zealand's only commercial oil and gas producing region is located on the western coast of the North Island of New Zealand (Figure 1.2). This late-Cretaceous to Recent sedimentary basin comprises many interconnected sub-basins and depo-centres which collectively constitute an area of around 100,000 km^2 (King, 1994). The Taranaki Basin is primarily an offshore subsurface feature, but also includes the onshore areas of the Taranaki Peninsula and areas along the western margin of the North Island north of the peninsula and in the northwestern South Island (King and Thrasher, 1996).

All boundaries encompassing the Taranaki Basin are arbitrarily defined, due to the complex evolution of the basin (King and Thrasher, 1996). The eastern margin of the basin is defined by the north-south trending Taranaki Fault which bounds the subsurface Patea-Tongaporutu (basement) high and truncates the Cretaceous to mid-Tertiary

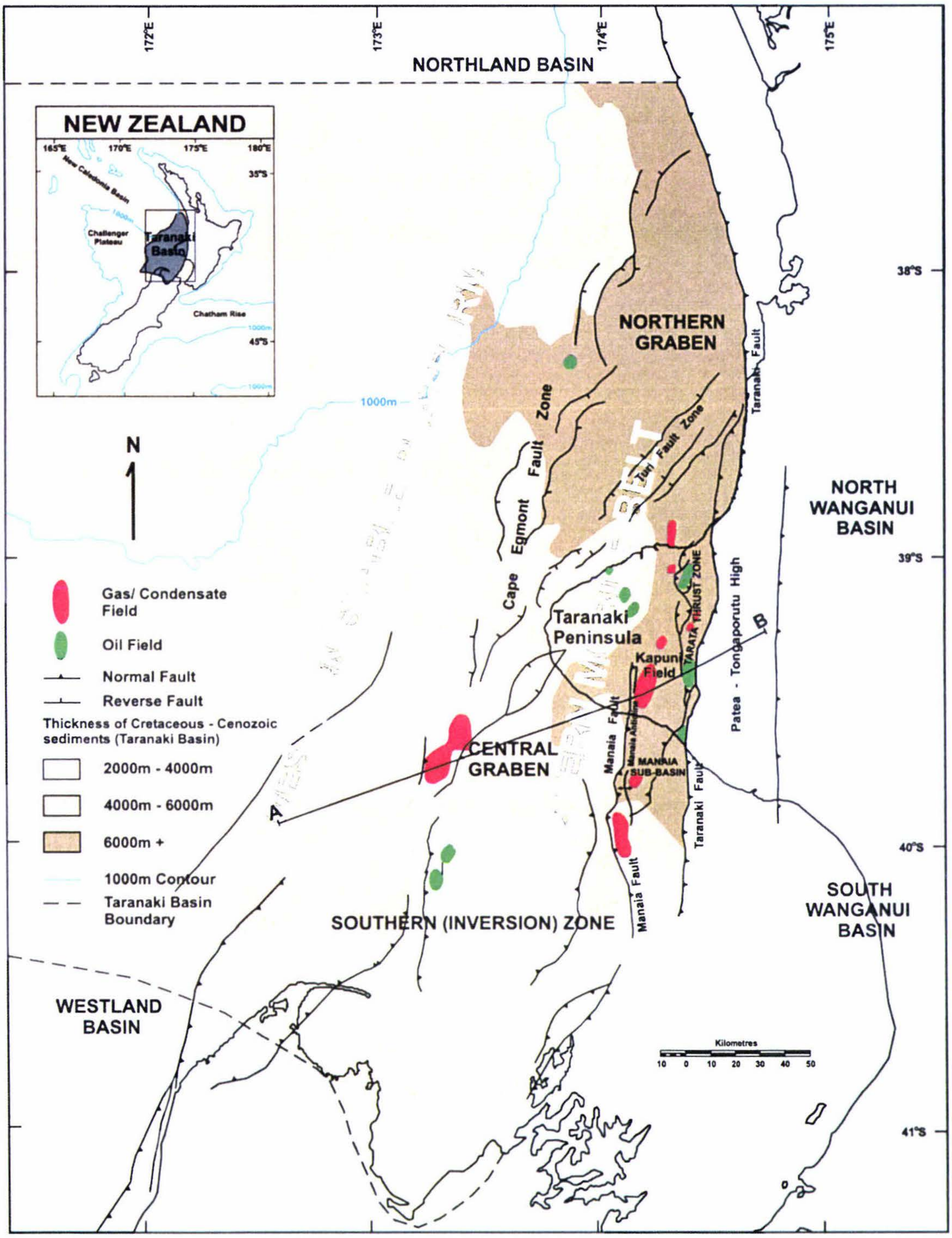

Figure 1.2: Taranaki Basin location map and main structural elements (Modified after King and Thrasher, 1996)

succession in the Taranaki Basin from the younger Neogene to Quaternary rocks in the adjacent north and south Wanganui Basins. Directly to the west the basin extends out beyond the present day continental shelf margin, in the southwest Neogene sediments onlap the Challenger Plateau, while in the northwest the seafloor descends into the New Caledonia Basin (King and Cook, 1987). In the south, the Taranaki Basin extends to onshore areas northwest of Nelson in the South Island (Palmer and Bulte, 1991). The northern limit of the basin has been defined as approximately the latitude of Auckland at 37°S where the Taranaki Basin adjoins the Northland Basin (Pilaar and Wakefield, 1978; Katz, 1976b; Isaac *et al.*, 1994). The boundary between the Taranaki Basin and Northland Basin is somewhat arbitrary and poorly defined offshore, and the two basins could in fact be contiguous (Palmer and Andrews, 1993; King, 1994; King and Thrasher 1996).

The Taranaki Basin comprises two main structural provinces; the Eastern Mobile Belt and the Western Stable Platform (Figures 1.2 and 1.3). The Eastern Mobile Belt, previously known as the Taranaki Graben, is composed of the Northern Graben and Central Graben in the northern sector and the Tarata Thrust Zone and Southern (Inversion) Zone in the southern sector of the basin. Collectively these sub-provinces represent a broad zone of deformation associated with progradation of the Australian-Pacific plate boundary through New Zealand that occurred in the Neogene (King and Thrasher, 1996). The western limit of this zone of deformation is delineated by the Cape Egmont Fault Zone. The Western Stable Platform extends from the upthrown side of the Cape Egmont Fault Zone to beyond the present day continental shelf, and in contrast to the Eastern Mobile Belt exhibits a relatively simple structure as the platform was largely unaffected by tectonic activity for much of the Cenozoic (Pilaar and Wakefield, 1978; Palmer and Bulte 1991; Palmer and Andrews, 1993).

1.4.2 Local Geological Setting - Kapuni Field

The Kapuni Field is situated along the productive Manaia Anticline which also contains the Kupe Field and Toru accumulations. The anticline is a significant inversion structure that strikes roughly north in the southeast of the basin (King and Thrasher, 1996). Structural contour maps generated by Haskell (1975) at the top of the Kapuni Group in the Kapuni Field indicate a c.18km long and 8km wide feature with four-way dip closure (pericline). The structure is bounded to the west by the Manaia Fault, a major east-heading, steeply dipping reverse fault in the basin. Along its length the anticline is truncated by a major angular unconformity (King and Thrasher, 1996). In the Kapuni Field, this unconformity is present just beneath the Miocene-Pliocene boundary.

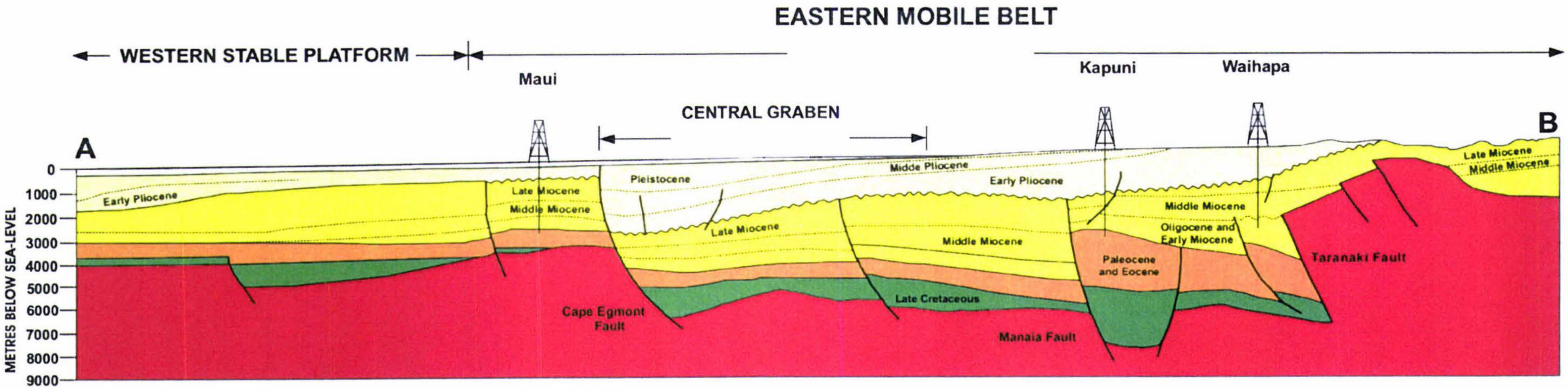

Figure 1.3: Cross-section through the Taranaki Basin showing the main structural elements (Modified after King and Thrasher, 1996)

Voggenreiter (1991; 1993) was the first to provide a detailed interpretation of faulting in the Kapuni Field from seismic data. In this study faults were interpreted as upward branching fault complexes attributed to wrench deformation. However, a review of the 3D seismic data by Holstege and Bishop (1998) reinterpreted the geometry and timing of faulting in the Kapuni Field (Figure 1.4). Planar normal faults, listric growth faults, thrust faults and reverse/reactivated faults were all recognised and three phases of faulting identified. Pre-late-Eocene extension and transtension resulted in listric and normal planar faults. Late-Eocene to Oligocene and mainly Miocene compression/inversion resulted in reactivation of the Manaia Fault. The final phase involved Plio-Pleistocene back-arc extension, manifested in small low angle thrust faults that accommodated crustal shortening.

1.5 STRATIGRAPHIC SUBDIVISION

1.5.1 Stratigraphic Subdivision in the Taranaki Basin

The Taranaki Basin contains a thick sequence (more than 7000m) of Late Cretaceous to Recent sedimentary rocks overlying varied Paleozoic and Mesozoic basement rocks (Figure 1.5). Stratigraphic subdivision in the basin is based on four 'megasequences' or groups, defined by seismic reflection character, age and lithology (King and Thrasher, 1996). They include the Late Cretaceous Pakawau Group, Paleocene-Eocene Kapuni Group and Moa Groups, Oligocene to Miocene Ngatoro and Wai-iti Groups and the Plio-Pleistocene Rotokare Group.

1.5.2 Stratigraphic subdivision of the Kapuni Group in the Kapuni Field

The Paleocene to Eocene Kapuni Group in the Taranaki Basin is distinguished by several marker horizons including major unconformities, marine flooding surfaces, and sequence boundaries, which are essentially time-line separating the Kapuni Group into formations (King and Thrasher, 1996). In the Kapuni Field the Kapuni Group comprises the Farewell, Kaimiro and Mangahewa formations.

i. Farewell Formation

The Farewell Formation, the basal formation of the Kapuni Group, is now considered to be Paleocene in age (Raine, 1984; King, 1988b). The Farewell Formation in the Kapuni Field is defined by the Cycle A seismic interval (Shell BP Todd Oil Services Limited, 1984). In Kapuni Deep-1, the only Kapuni well to penetrate the Farewell Formation, mainly coarse- to medium-grained sandstones and mudstones were identified. These were interpreted as deposits of coastal and lower coastal plain environments (Shell BP Todd Oil Services Limited, 1984). In the Kapuni Field and other wells in the Manaia

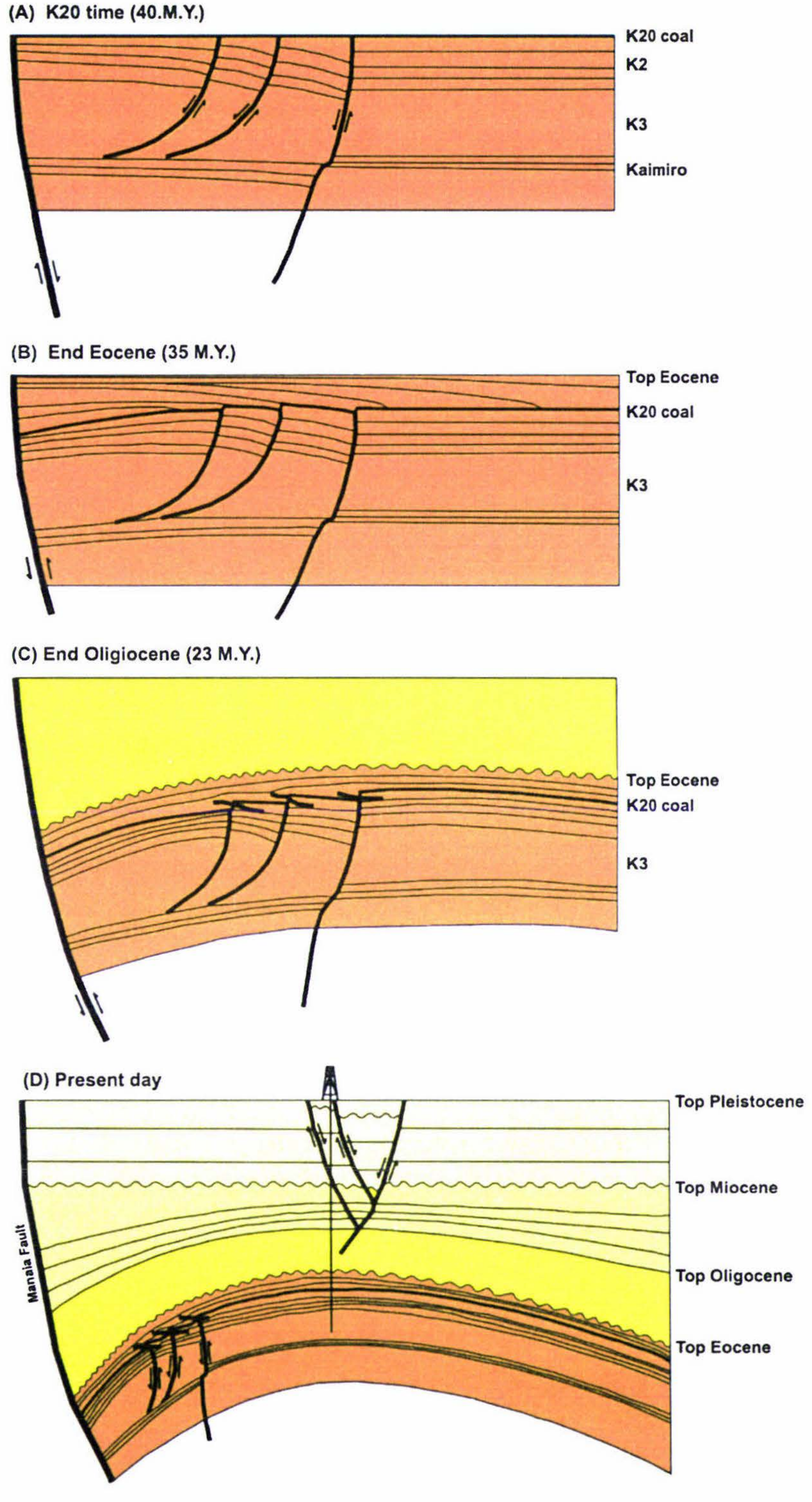

Figure 1.4: Idealised cross-sections showing the various stages in the evolution of the Kapuni anticline in the Kapuni Field. (A): basin transtension caused listric and planar normal faults – soft sediment deformation in coal/shale lithologies: (B): transition from transtension to compression (listric faults no longer active, Manaia transtensional fault beginning to reverse) with (C): main compressional/inversion phase (note thrust faults forming at pre-existing areas of weakness); (D): present situation with Plio-Pleistocene extension due to backarc extension/crustal downwarping (Modified after Holstege and Bishop, 1998).

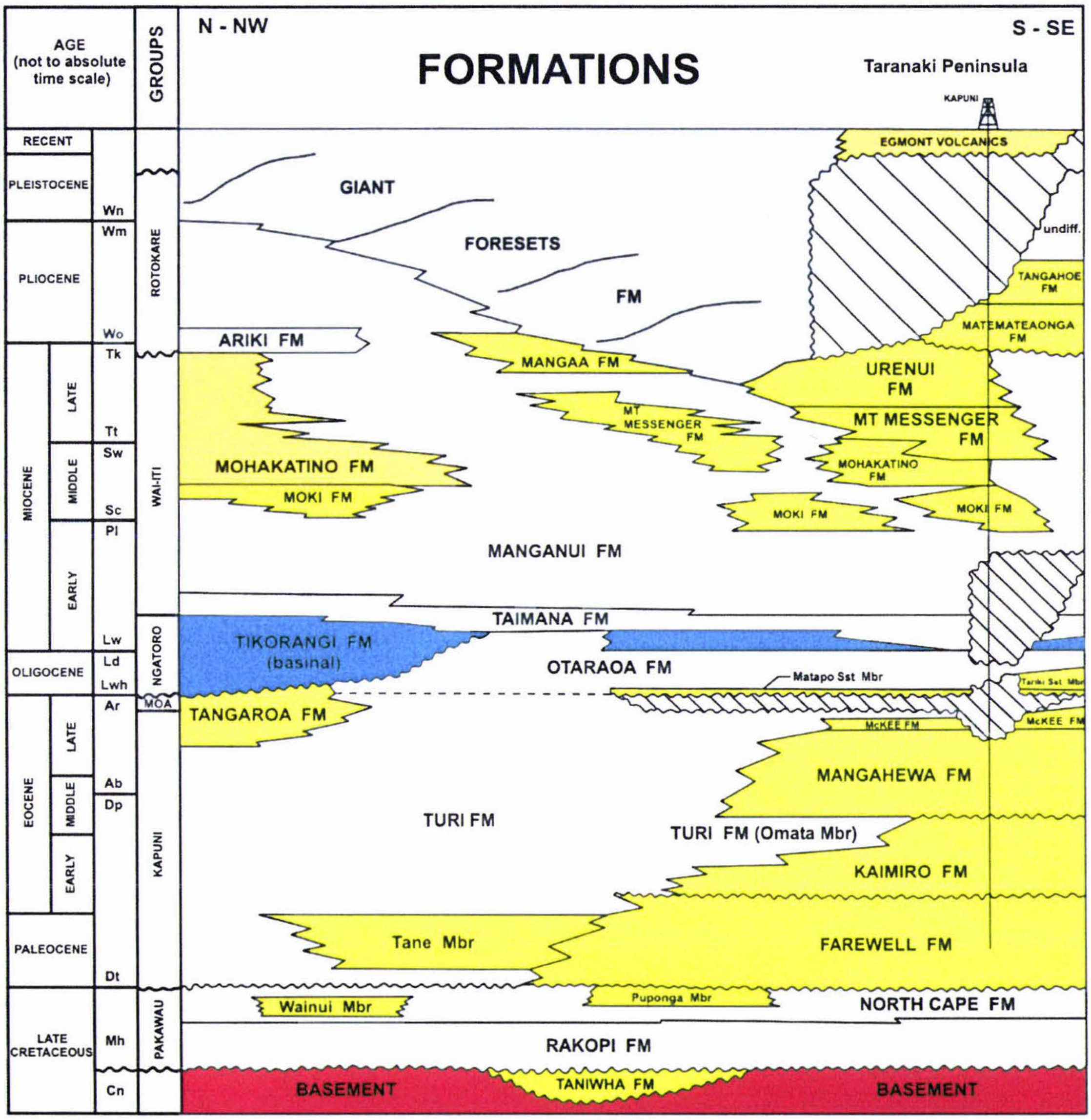

Figure 1.5: Cretaceous-Cenozoic stratigraphic framework for the Taranaki Basin (Modified after King and Thrasher, 1996)

sub-basin the top of the Farewell Formation is marked by an angular unconformity that relates to tilting in the Eocene (King and Thrasher, 1996).

ii Kaimiro Formation

The Kaimiro Formation in the Taranaki Basin corresponds to approximately the base of the Eocene (top Farewell Formation) up to the Omata Member, or where it is absent, such as in the Kapuni Field, an unconformity at the top of the Heretaungan stage - base Mangahewa Formation (King and Thrasher, 1996). In the Kapuni Field Shell BP Todd Oil Services Limited (1984) define the Kaimiro Formation as Cycle B, comprising primarily sandstone, siltstone, mudstone and less commonly coal deposited in terrestrial, upper coastal plain and swampy settings.

iii. Mangahewa Formation

The Mangahewa Formation includes all marginal marine and terrestrial lithofacies of middle to late Eocene age. Cycles C and D were defined by Shell BP Todd Oil Services Limited (1984) to characterise the Mangahewa Formation in the Kapuni Field. In the Kapuni wells the formation consists of alternating cycles of sandstones, capped by coals and mudstones that were deposited in fluvio-tidal environments (King and Thrasher, 1996). As previously mentioned the Mangahewa Formation has long been grouped informally into reservoir intervals for reservoir simulation studies. These subdivisions were originally based on major marker horizons identified through the Kapuni Field by Hicks (1962), van Wijlen (1963) and expanded on by Haskell (1975). A later study by Bryant and Bartlett (1992) supported these subdivisions but identified further correlatable coal and mudstone units across the field, allowing refinement of the subdivisions and the identification of nine reservoir layers (Figure 1.6). The following discussion reviews the reservoir layers defined by Bryant and Bartlett (1992), which they interpreted as characterising a tide-dominated estuarine environment.

The K3 interval comprises the main producing reservoir sandstones of the Mangahewa Formation in the Kapuni Field. At the base of the Mangahewa Formation the K3E3 and overlying K3E2 layers comprise estuarine sandstones with subordinate shale and coal. The K3E1 layer is composed of estuarine and fluvial channel sands with subordinate shales and thin coals. The K3U layer incorporates the interval between the 'Main Sands' and 'Upper Sands', comprising predominantly shales and coals with thin sheet and rare channel fill sands. The K3A layer 'Upper Sands' is composed of stacked channel-fill sands with subordinate shales and coals.

The K2 interval lies from the top of the K3 interval to the base of the K20 coal. The K2 interval lacks any significant sandstone units, and is primarily composed of shales, and coals with confined thin sheet and rare channel fill sands. The topmost part of the K2

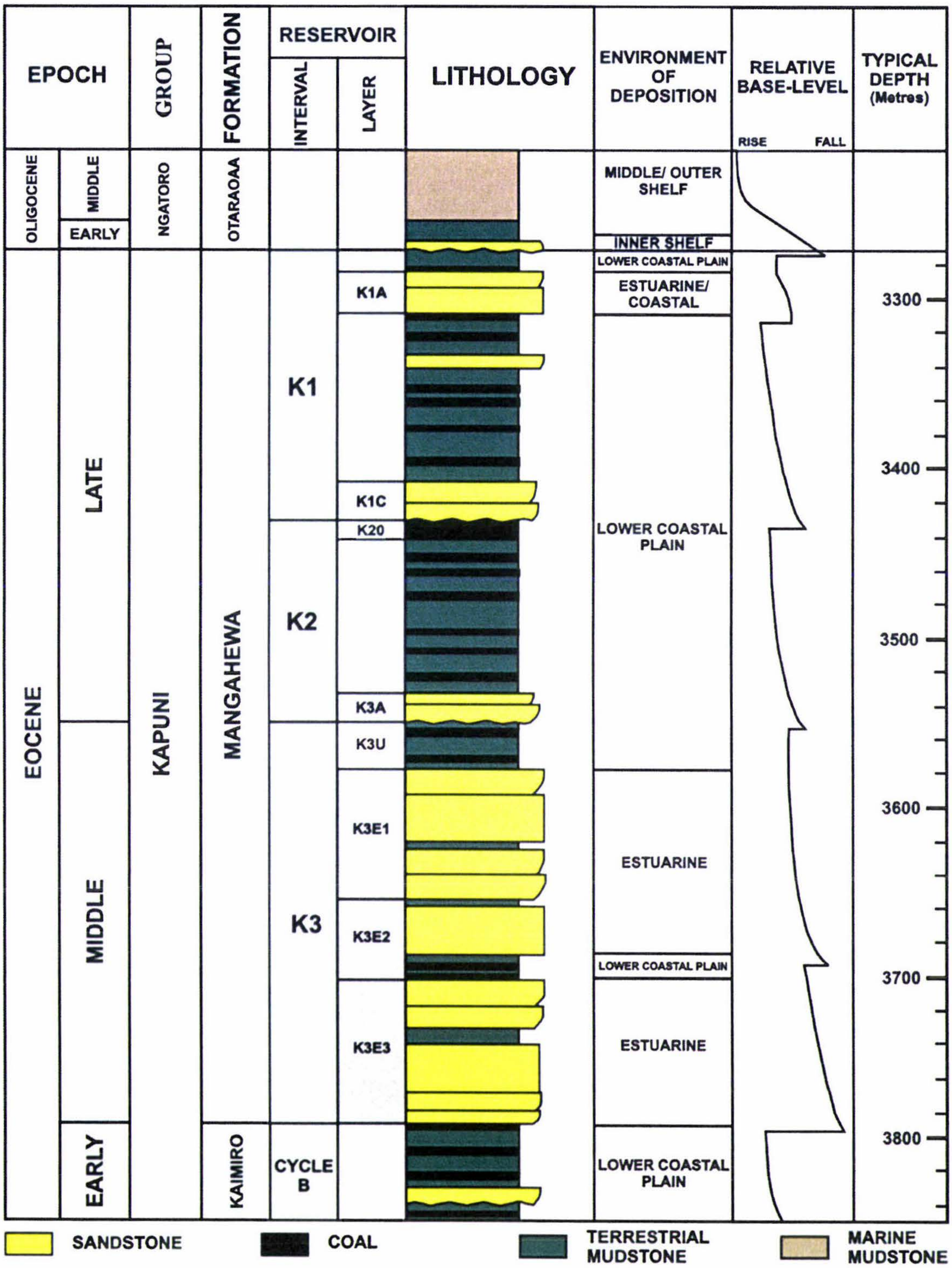

Figure 1.6: Schematic stratigraphy of the Mangahewa Formation in the Kapuni Field (Modified after Bryant and Bartlett, 1992)

interval is the K20 coal. The K20 coal is the only field wide marker bed that can be correlated with any certainty between the Kapuni wells, and represents a period of extensive swamp development in the Taranaki Basin[5] (Bryant and Bartlett, 1992).

The K1 interval extends from the top of the K20 coal to the top of the Mangahewa Formation. Overlying the K20 coal is the K1C sequence comprising stacked channel-fill sandstones with subordinate shales and coals. The K1 layer lies directly above the K1C sequence, consisting of laterally extensive coals and shales with thin sheet sandstones and rare channel-fill sandstones. The K1A layer, only present in the northern part of the field (Kapuni-8, -12 and -15 wells), comprises a wedge of paralic sandstones.

1.6 GEOHISTORY

The Taranaki Basin is a composite basin, exhibiting multiple phases of structural evolution and depositional fill (King and Thrasher, 1996). The geological history of the Taranaki Basin is reviewed in relation to structural, stratigraphic and paleogeographic developments that effected the Taranaki Basin throughout its development, with particular attention to events that occurred or impacted on the Manaia sub-basin where the Kapuni Field is located.

1.6.1 Late Cretaceous and Paleocene

Taranaki Basin development began in the late Cretaceous in response to the break-up of Gondwanaland and spreading in the Tasman Sea (Bulte, 1988). From the late Cretaceous to Paleocene the basin evolved as a series of rift grabens and normal faulted sub-basins; collectively constituting the Taranaki Rift (Thrasher, 1990; 1992). In the Manaia sub-basin rapid subsidence was controlled by the north- and northeast-striking Manaia Fault (King and Thrasher, 1996). Late Cretaceous paleogeographic reconstructions by King and Robinson (1988) indicate a block faulted subdued basin and range topography existed, where drainage systems flowed northwards off a southern hinterland. Terrestrial sediments of the Pakawau Group, comprising mostly conglomerate and sandstone lithofacies with subordinate carbonaceous mudstones were the main deposits (King and Thrasher, 1992). During the latest Cretaceous a widespread marine transgression inundated the Taranaki Basin from the north and west (Thrasher, 1992). Submergence of the former rift landscape resulted in the formation of complex tidal embayments.

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[5] The K20 coal is also referred to as the Kap 20 coal in the Kapuni Field and recognized as the Toko Member (Palmer, 1985) in onshore wells in eastern parts of the Taranaki Basin

1.6.2 Paleocene to Early Oligocene

The Paleocene was a period of waning tectonic activity in the Taranaki Basin, as it became increasingly distal to the spreading centre and the rate of crustal cooling diminished (King, 1994). Only a few major late Cretaceous faults exhibited continued subsidence, most notably for this study the Manaia Fault (King and Thrasher, 1996). By the end of the Paleocene spreading in the Tasman Sea had ceased (Bulte, 1988), placing the Taranaki Basin in a passive margin during much of the Eocene. Repeated marine advances and retreats from the Paleocene to Eocene resulted in the paleoshoreline migrating back and forth across a low-lying coastal plain. Thick sequences of sandstones, mudstones and coals of the Kapuni Group were deposited in a coastal system generally aligned NW-SE through the middle of the basin. In the late Eocene the structural regime changed to compressional, in response to progressive convergence along the Australian Pacific plate boundary (Palmer and Andrews, 1993). The tectonic changes at this time manifested in the separate development of the Western Stable Platform and the Eastern Mobile Belt. Throughout the tectonic transition the marine transgression continued unabated; and by earliest Oligocene the basin was completely inundated. Shallow marine siltstones and mudstones of the Turi Formation were deposited during this time. The regional marine transgression reached a maximum in the mid to late Oligocene. Geohistory curves by Hayward (1987) and Hayward and Wood (1989) of the mid Oligocene indicate that the rate of subsidence significantly increased causing the whole basin to deepen. Subsidence and inundation of hinterland to the south and southeast reduced sediment supply and widespread bioclastic limestones of the Tikorangi Formation were variably deposited in what was predominantly a sediment starved deep-water basin. However, deposition of terrigenous mudstones and siltstones of the Otaraoa Formation, sourced from east of the Taranaki Fault dominated in proximal eastern and southern central areas (King, 1994).

1.6.3 Miocene

The earliest Miocene marked renewed tectonism as the full effect of a major reorganisation in the plate tectonic configuration of the Southwest Pacific impacted on the Taranaki Basin. Walcott (1987) contends that the instantaneous pole of rotation moved away from New Zealand causing accelerated plate convergence along the Australian-Pacific plate boundary. Convergence initiated a major phase of compression and tectonic uplift in the east and south of the basin. In the east overthrusting of the Taranaki Fault occurred and the associated Tarata Thrust Zone developed. The early Miocene also coincides with the onset of uplift and formation of the Southern Alps and modern Alpine Fault system in the South Island (Palmer and Andrews, 1993). The concurrence of increased convergence rates on both the Alpine Fault and Taranaki Fault lead Knox (1982) to propose that the Taranaki Fault was a splay off the Alpine Fault.

However, King and Thrasher (1996) challenged this assumption contesting that although the Taranaki Fault may have been an integral part of an early transform system, it was probably never physically connected to the Alpine Fault *per se*. In the late Miocene - Pliocene a broad region of contraction occurred in the southern Taranaki Basin (Southern Inversion Zone). In the Manaia sub-basin east-west directed compression resulted in reverse movement on the Manaia Fault and growth of the Manaia Anticline (Pilaar and Wakefield, 1978; Knox, 1982; Schmidt and Robinson, 1990). Most of the basin remained at bathyal depth until the early Miocene. In the mid Miocene increasing uplift in the hinterland to the south and east resulted in sediment supply exceeding subsidence in the basin. This influx of terrigenous sediment marked the onset of a major regressive sedimentary phase in the mid to late Miocene as mud dominated turbidite deposits of the Wai-iti Group denote the beginning of the modern continental shelf.

1.6.4 Plio-Pleistocene

Plate boundary deformation continued to impinge on the eastern margin of the Taranaki Basin throughout the Plio-Pleistocene. Compression persisted in the south while extension influenced the northern regions of the basin; meanwhile the Western Stable Platform remained quiescent. Plio-Pleistocene uplift in the southern hinterland and possibly inversion structures in the basin provided vast amounts of terrigenous material to the basin (King and Thrasher, 1996). Several kilometres of Rotokare Group fine-grained sediment accumulated during this time, overfilling tectonically controlled depocentres in the east and eventually spreading out as a northwestwardly prograding sedimentary wedge onto the Stable Western Platform (King and Thrasher, 1992). Latest Miocene and Pliocene sedimentation is represented by the Matemateaonga and Tangahoe formations in the south and east of the basin. The most Recent sediments in the basin include the andesitic Egmont Volcanics that have preserved the underlying sedimentary sequences from erosion.