Stratigraphy and development of the Late Miocene-Early Pleistocene Hawke's Bay forearc basin

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Abstract

A Late Miocene-Early Pleistocene mixed carbonate-siliciclastic sedimentary succession about 2 500 m thick in the Hawke's Bay forearc basin is the focus of a basin analysis. The area under investigation covers 3 500 km^2 of western and central Hawke's Bay. The stratigraphy of Hawke's Bay Basin is characterised by dramatic vertical and lateral facies changes and significant fluxes of siliciclastic sediment through the Late Miocene and Pliocene. This project aims to better understand the character and origin of the sedimentary succession in the basin. Geological mapping has been undertaken at a scale of 1:25 000, with data managed in an ARCINFO geodatabase, following the database model employed in the IGNS QMap programme.

Along the western margin of the basin there is progressive southward onlap of late Cenozoic strata on to basement. The oldest units are of Late Miocene (Tongaporutuan) age and the youngest onlap units are of latest Pliocene (Nukumaruan) age. Geological mapping of the basin fill places constraints on the magnitude (about 10 km) and timing (Pleistocene) of most of the offset on the North Island Shear Belt.

Lithofacies have been described and interpreted representing fluvial, estuarine, shoreface and inner- to outer-shelf environments. Conglomerate facies are representative of sediment-saturated prograding fluvial braidplains and river deltas. These units are dominated by greywacke gravels and record the erosion of the Kaweka-Ahimanawa Ranges. Sandstone facies typically comprise very well sorted, clean non-cemented units of 10-50 m thickness that accumulated in innershelf environments. Siltstone facies probably accumulated in relatively quiet, middle- to outer-shelf water depths, and comprise well-sorted, firm non-cemented units with occasional tephra interbeds. Limestone facies represent examples of continent-attached cool-water carbonate systems that developed in response to strong tidal currents and a high nutrient flux during the Pliocene. These facies are examples of mixed siliciclastic-bioclastic sedimentary systems. Of these facies the widespread distribution and thickness of sandstone and limestone units present the most potential for hydrocarbon reservoirs. Similarly, the distribution of siltstone and mudstone beds provides adequate seal rocks. Mangapanian limestone facies have already been targeted as potential petroleum reservoirs (e.g. Kereru-1). Geological mapping suggests that potential hydrocarbon reservoir and seal rocks occur extensively in the subsurface.

Introduction

The Hawke's Bay forearc basin is the principle forearc basin of the Hikurangi subduction margin in eastern North Island (Fig. 1). From a hydrocarbon viewpoint the basin is very lightly explored.

A basin analysis investigation is being undertaken of the Hawke's Bay forearc basin in eastern North Island. A major component of this work involves the establishment of a stratigraphic framework and the mapping of these stratigraphic units, leading to the development of a new geological map. The mapping is being undertaken at a scale of 1:25 000, with production of the final map at 1:50 000 scale. The study area is located between the Waikari River in the north and the Ngaruroro River in the south; the axial ranges form the western boundary and the coastline the eastern boundary (Fig. 2). Related investigations that will be incorporated in this analysis include the prior work by Bland (2001) and Graafhuis (2001), and concurrent work in preparation by Rachael Baggs and Sarah Dyer. The petrography and sedimentology of many of the Pliocene limestone units, particularly those exposed in the hill country south of Hastings, have recently been reported by Caron (2002).

The aim of this paper is to provide an introduction to the character and development of the sedimentary succession in the Hawke's Bay forearc basin. We briefly describe the stratigraphic units in the basin, outline some of the more important facies types, and structural elements of the basin, and conclude with a brief discussion regarding outcrop-subcrop correlations in the basin.

Geological setting

Hawke's Bay is a major topographic depression extending NNE-SSW through inland eastern North Island, New Zealand (Fig. 2). Tectonically it corresponds to a forearc basin within the Hikurangi margin (Ballance 1993). The forearc basin, having a NE-SW structural grain in central to northern Hawke's Bay, formed during the Late Miocene (Tongaporutuan), and

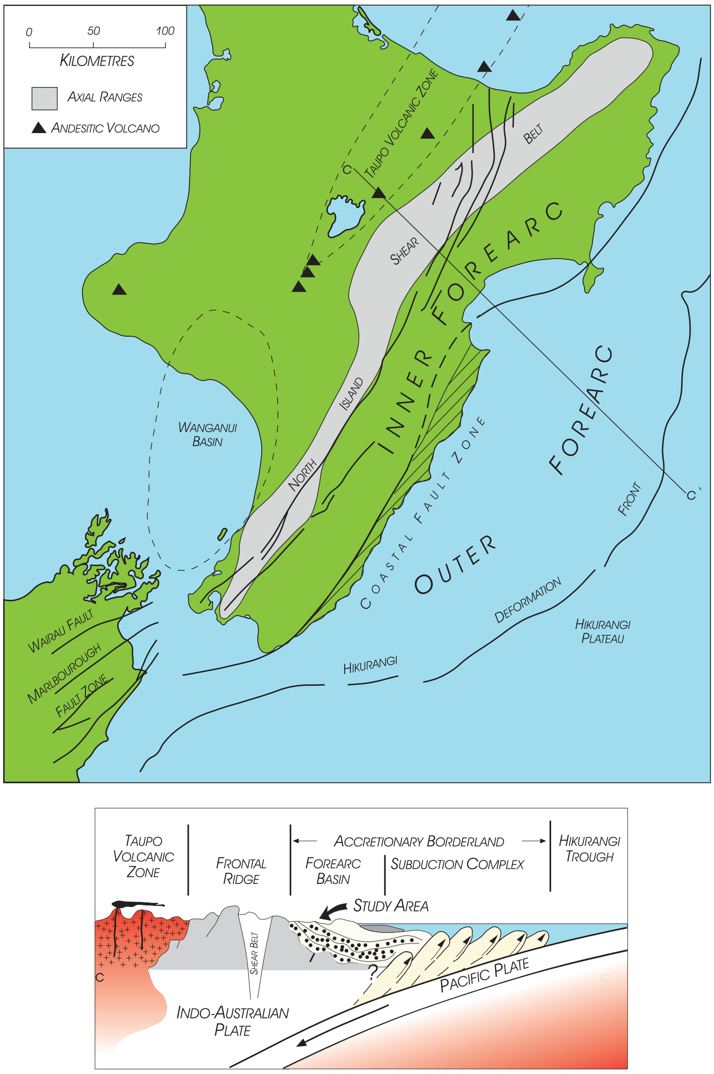

Figure 1. Tectonic setting of the Hawke's Bay forearc basin, eastern North Island, New Zealand.

overlies a terrigenous succession at least 5 km thick that contains Late Cretaceous through Miocene, mainly deep-water marine sediments. Basement rocks of Jurassic age underlie the axial ranges that bound the forearc basin on its western margin. The Pliocene – early Pleistocene succession in central part of the forearc basin forms a SE-dipping monocline, whereas to the north and south (southern Raukumara Peninsula and central Hawke's Bay) it forms broad synclines. In the vicinity of Mahia Peninsula and south of Cape Kidnappers the Pliocene-Pleistocene beds have been deformed and uplifted due to involvement in the growth of the modern accretionary prism (Pettinga 1982).

Sedimentary fill of the basin

The sedimentary fill exposed in the basin comprises a Late Miocene to Early Pleistocene (c 8.0-1.7 Ma) broadly regressive succession over 2500 m thick. In total the basin contains a Cenozoic fill up to 5 km thick. The basin fill is truncated by the Mohaka and Ruahine Faults, and the largely dip-slip Kaweka Fault (Fig. 3). Stratigraphic units typically crop out in broadly northeast-southwest striking belts that dip between 20-2° to the southeast.

Progressive onlap of Neogene sediments on to basement is evident along the western margin of the basin. The oldest beds present in the study area are of Tongaporutuan (Late Miocene) age, and occur in the vicinity of the Napier-Taupo Highway. The youngest beds onlapping basement are of Nukumaruan (Late Pliocene) age, and crop out in the Ohara Depression adjacent to the northern Ruahine Range. In general the basin contains a mixed carbonate-siliciclastic succession, although the siliciclastic sediments of shelf origin are the dominant facies, particularly for the latest Miocene – mid Pliocene sediments. The Pliocene-Pleistocene portion of the stratigraphic column has a higher percentage of limestone beds. Late Pliocene beds include numerous prominent greywacke conglomerate beds that were sourced from the proto-North Island axial ranges. Uplift of the Ahimanawa Range area probably started during the late Pliocene (late Mangapanian), with the Kaweka Range being uplifting during the Nukumaruan (latest Pliocene) and the Ruahine Range during the Castlecliffian (Pleistocene).

Chronology

A number of key biostratigraphic datums have been identified in the basin. These allow for correlation between different facies and paleoenvironments across the basin, aiding the development of a paleogeographic model. A key marker horizon in the succession is the first occurrence of the Pliocene pectinid *Phialopecten triphooki*, a species whose arrival in the basin marks the beginning of the Nukumaruan stage (Late Pliocene) at approximately 2.28 Ma. This has subsequently allowed for a provisional correlation of Petane Group strata with the global oxygen isotope record. In southern parts of the study area (Ohara Depression and Kuripapango) Early Nukumaruan rocks contain the diagnostic basal Nukumaruan index scallop *Zygochlamys delicatula.* Other important age diagnostic species identified include the bivalves *Sectipecten wollastoni* (Kapitean), *Phialopecten marwicki* (Opoitian-Waipipian), *Mesopeplum crawfordi* (Opoitian-Waipipian), *Phialopecten thomsoni* (Mangapanian) and *Sectipecten mariae* (base Nukumaruan) and the gastropods *Struthiolaria dolorosea* (Opoitian) and *Pelicaria convexa* (Nukumaruan). Future dating of the succession in the study area will include radiometric dating of volcanic ash beds throughout the basin, and paleomagnetic analysis.

Formational nomenclature

There are three main stratigraphic units of group level. Late Miocene-Late Pliocene (Kapitean-late Mangapanian; e.Tk-l.Wm) sandstone-limestone parts of the fill form the **Mangaheia Group**. The part of this succession west of the Mohaka Fault is included within the **Makahu Subgroup**, while rocks of a similar age east of the fault are included in the **Maungaharuru Subgroup**. Formations included in the Mangaheia Group are the **Pakaututu** (Wo) and **Puketitiri Formations** (?Wo-?Wp) of the Makahu Subgroup, and the **Mokonui** (e.Tk-e.Wo), **Titiokura** (Wo-l.Wp), **Te Waka** (l.Wp-Wm) (Figs 4; 5A) and **Pohue Formations** (Wm) (Maungaharuru Subgroup). The Pakaututu Formation comprises an 8-15 m thick siliciclastic-rich limestone bed

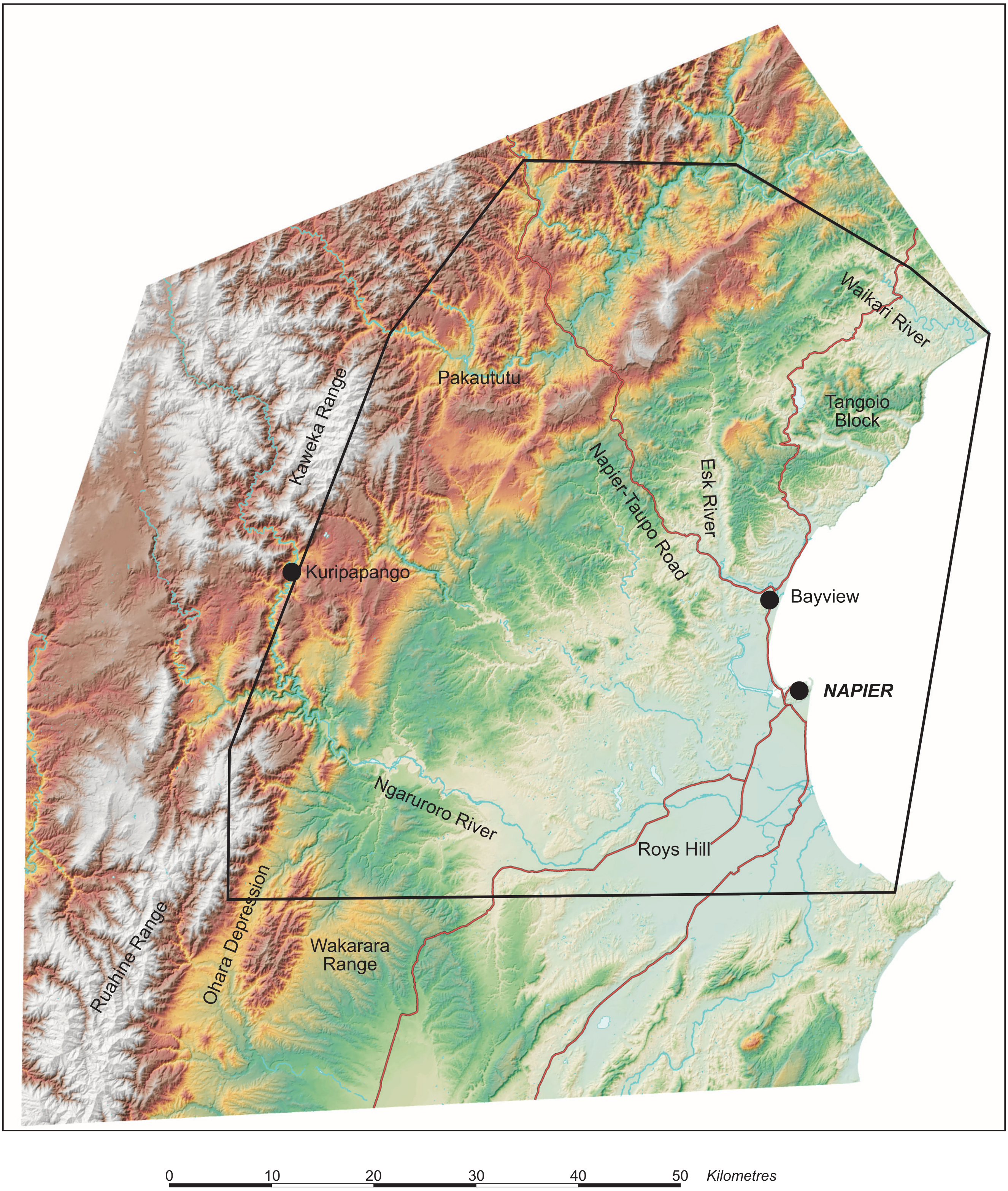

Figure 2. Location of the study area in the Hawke's Bay area, and names of localities mentioned in the text. The extent of the study area is depicted by the black polygon, and has been placed on a Digital Elevation Model (DEM). Note the prominent lineaments striking through the western part of the image that have developed due to the presence of the North Island shear belt.

that overlies either greywacke basement (west of Ruahine Fault) or thick (about 50 m) greywacke conglomerate and concretionary sandstone (Bland *et al.* 2003). Where present, the conglomerate and sandstone facies are included in the Pakaututu Formation. The Puketitiri Formation conformably overlies Pakaututu Formation and comprises massive to slightly laminated fine-grained siltstone to sandy siltstone. The Mokonui Formation consists of very well-sorted, fine to medium-grained sandstone unconformably overlain by the Titiokura Formation, a complex series of beds that crops out through central-northern parts of the basin. The Titiokura Formation consists of either a single mixed bioclastic-siliciclastic limestone bed in the south, or a series of siltstone/sandstone/limestone beds in the north (Bland *et al.* in review).

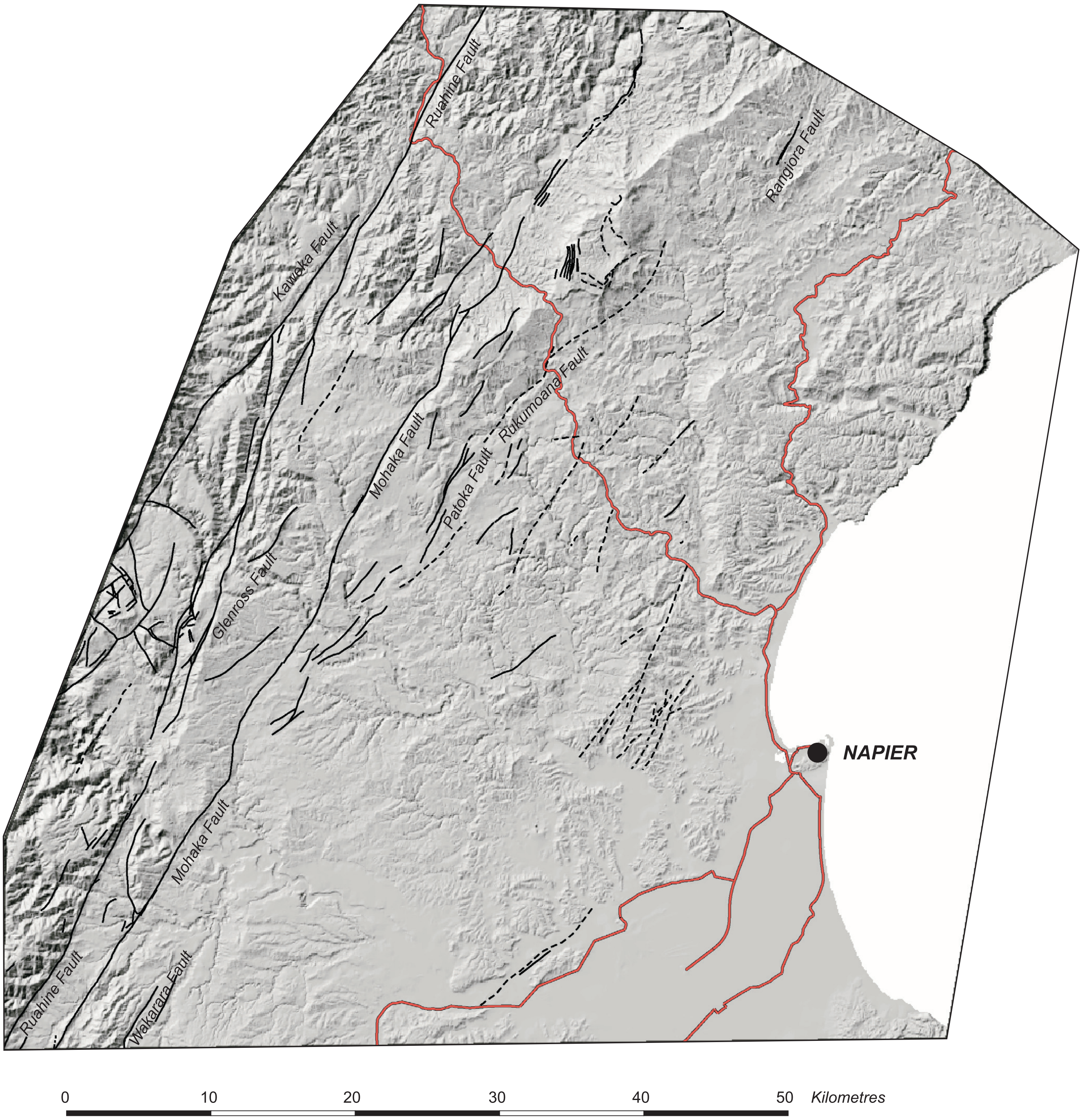

Figure 3. Faults in the study area shown on a hillshade model. Note how most structures are concentrated in western parts of the study area as part of the North Island shear belt. Accurately placed faults are represented by solid lines and inferred faults by dotted lines. No distinction has been made between active and inactive faults.

East of the Mohaka Fault the Titiokura Formation is conformably overlain by the Te Waka Formation, a unit that consists of limestone and sandstone beds of varying thickness (Fig. 5A). West of the Mohaka Fault the Te Waka Formation unconformably overlies the Puketitiri Formation. No Titiokura Formation occurs west of the Mohaka Fault. The Pohue Formation conformably overlies the Te Waka Formation and consists of alternating packages of siltstone and sandstone 10-80 m thick.

The Mangaheia Group is conformably overlain by the Late Pliocene (late Mangapanian- Late Nukumaruan; l.Wm-l.Wn) **Petane Group** (Fig. 4). This group is up to 700 m thick and is distinguished from underlying strata by its prominent cyclothemic character and the presence of distinctive greywacke conglomerate beds. The Petane Group comprises a series of siltstone/sandstone and conglomerate/limestone packages, the differing lithofacies comprising various systems tracts within sequences (Fig. 5D). The basal formation of the group is the **Matahorua Formation** (Fig. 5B), a series of siltstone-sandstone-greywacke conglomerate cyclothems that contain the Mangapanian-Nukumaruan boundary. Overlying formations are the **Waipunga, Esk, Tutira, Aropaoanui, Darkys Spur, Mairau, Tangoio, Te Ngaru, Waipatiki** (contains the Pliocene-Pleistocene boundary), **Devils Elbow** and **Kaiwaka Formations**. The

Waipunga Formation consists of interbedded sandstone and siltstone units 10-40 m thick and is restricted in outcrop to the Tangoio area. The Esk, Aropaoanui, Mairau, Te Ngaru and Devils Elbow Formations comprise slightly- to moderately-fossiliferous siltstone beds that coarsen up-section into fine-grained sandstone. The Tutira and Darkys Spur Formations comprise non- to densely-fossiliferous sandstone interbedded with thick (up to 15 m thick) greywacke conglomerate. The Tutira Formation is capped by a distinctive volcanic ash/ignimbrite bed up to 8 m thick. The Tangoio, Waipatiki and Kaiwaka Formation comprise sandstone interbedded with limestone and more rarely greywacke conglomerate. The limestone facies vary in composition across the study area, but are distinguished from older (Late Miocene-Early Pliocene) beds by their increased aragonitic infaunal bivalve content. These limestone beds typically pass from siliciclastic-rich to siliciclastic-poor beds in a down-dip (eastward) direction.

In southwestern parts of the study area (Ohara Depression-Kereru) an eastwards-younging conformable Late Pliocene – Middle to Late Pleistocene (Mangapanian-Castlecliffian; Wm-Wc) succession crops out, and is referred to as the Poporangi Group. Formations in the **Poporangi Group** include the **Kaumatua, Sentry Box, Whanawhana, Ohara¸ Mount Mary, Kereru, Okauawa** and **Poutaki Formations** (Fig. 4). Capping the succession in this area is a thick package of interbedded gravels, sands and pumiceous units of Castlecliffian age. The Kaumatua Formation (Wm) consists of interbedded sandstone, pebbly grainstone and conglomerate beds, and is possibly a southern equivalent of the Te Waka Formation based on lithological similarities. The latest Pliocene Sentry Box Formation (Early Nukumaruan; lower Wn) conformably overlies Kaumatua Formation and comprises packages of pebbly barnacle grainstone with common pecten valves. The Sentry Box Formation is rapidly overlain by bathyal mudstone facies (Beu 1995) of the Ohara Formation (early to middle Nukumaruan). Mount Mary Formation (early to middle Nukumaruan) comprises at least three sets of interbedded conglomerate and grainstone beds that unconformably overlie Torlesse basement (Erdman and Kelsey 1992). Mount Mary Formation grades into, and interfingers with Ohara Formation. Mount Mary Formation is absent where Ohara Formation directly overlies Torlesse basement (Erdman and Kelsey 1992). Kereru Formation comprises Late Nukumaruan dense pebbly limestone to sandy oyster beds cropping out along eastern margins of the Ohara/Kereru area (Erdman and Kelsey 1992). The Okauawa Formation (Late Nukumaruan) conformably overlies Kereru Formation and comprises densely fossiliferous massive mudstone and sandstone beds with thick, shelly greywacke conglomerate beds near the base of the formation (Beu 1995). Okauawa Formation is in turn conformably overlain by coarse-grained pumiceous sandstone, pumice granule to cobble conglomerate, medium-grained sandstone and massive mudstone of the Poutaki Formation (Kelsey *et al.* 1993). Whanawhana Formation (Early Nukumaruan; lower Wn) crops out in a small area north of the Ngaruroro River near Whana Valley and consists of up to 5 m of coarse, well-cemented shelly limestone. In this area the Whanawhana Formation conformably overlies Te Waka Formation.

Formations in the study area unassigned to a lithostratigraphic group include the **Te Haroto** (Fig. 5C), **Waitere, Blowhard** (Fig. 5E), **Mangatoro, Makaretu, Mason Ridge and Scinde Island Formations**. The Te Haroto Formation (Tongaporutuan; Tt) crops out in the vicinity of the Napier-Taupo Highway and comprises densely fossiliferous concretionary sandstone that unconformably overlies Torlesse basement. Up section the formation passes into fine-grained sandy siltstone. In the study area the Waitere Formation (Early Tongaporutuan – Early Kapitean; e.Tt-e.Tk) is dominated by massive, slightly concretionary fine-grained siltstone that is unconformably overlain by the Mokonui Formation. The relationship between the Te Haroto and Waitere Formations is uncertain. The Blowhard and Mangatoro Formations crop out in the vicinity of Kuripapango in the central part of the Kaweka Range (Browne 2003). The Blowhard Formation comprises differentially cemented sandstone beds with occasionally non- to slightly-fossiliferous concretionary horizons and unconformably overlies Torlesse Greywacke basement. In topographic lows the base of the formation is marked by the presence of up to 100 m of very poorly to moderately-sorted greywacke conglomerate (Browne 2003). The occurrence of the pectinid *Sectipecten wollastoni* confirms a Kapitean age for the formation. Mangatoro Formation comprises Early Pliocene (Opoitian; Wo) sandstone and siltstone facies. In the Kuripapango area the formation is dominated by fine-grained muddy sandstone to sandy mudstone. The Makaretu and Mason Ridge Formations crop out south of the Ngaruroro River on what is locally known as “Mason Ridge”, and the Raukawa Range. The Makaretu Formation is a late Mangapanian mudstone-dominated unit, and is conformably overlain by the Mason Ridge Formation, a series of interbedded limestone, siltstone and sandstone beds of early Nukumaruan age (Beu 1995; Dyer in prep). The Scinde Island Formation comprises a series of interbedded limestone, shellbed and calcareous sandstone facies of lower Nukumaruan age. The Scinde Island Formation is time equivalent to the Matahorua, Sentry Box, Mason Ridge and Whanawhana Formations exposed further inland, and appears to have developed as a separate depositional system to other nearby Nukumaruan limestone facies.

Character of the basin fill

Coarse-grained skeletal limestones, frequently referred to as “Te Aute” limestone, are a distinctive part of the sedimentary fill of the Hawke’s Bay region. These beds have been a target for petroleum exploration in wells such as Mason Ridge-1 and Kereru-1. While limestone beds have accumulated on both margins of the forearc basin since the Kapitean (Late Miocene), it is important to note that these beds do not correlate through the subsurface (Fig. 6). Rather, they are the products of separate depositional systems. Limestone facies on the western margin of the study area (e.g. Titiokura and Te Waka Formations) are typical examples of cool-water “continent-attached” limestone units as characterised by Caron *et al.* (in prep). These beds contain abundant clasts of greywacke derived from an adjacent basement hinterland. The relatively high siliciclastic content of these units is also indicative of this depositional setting.

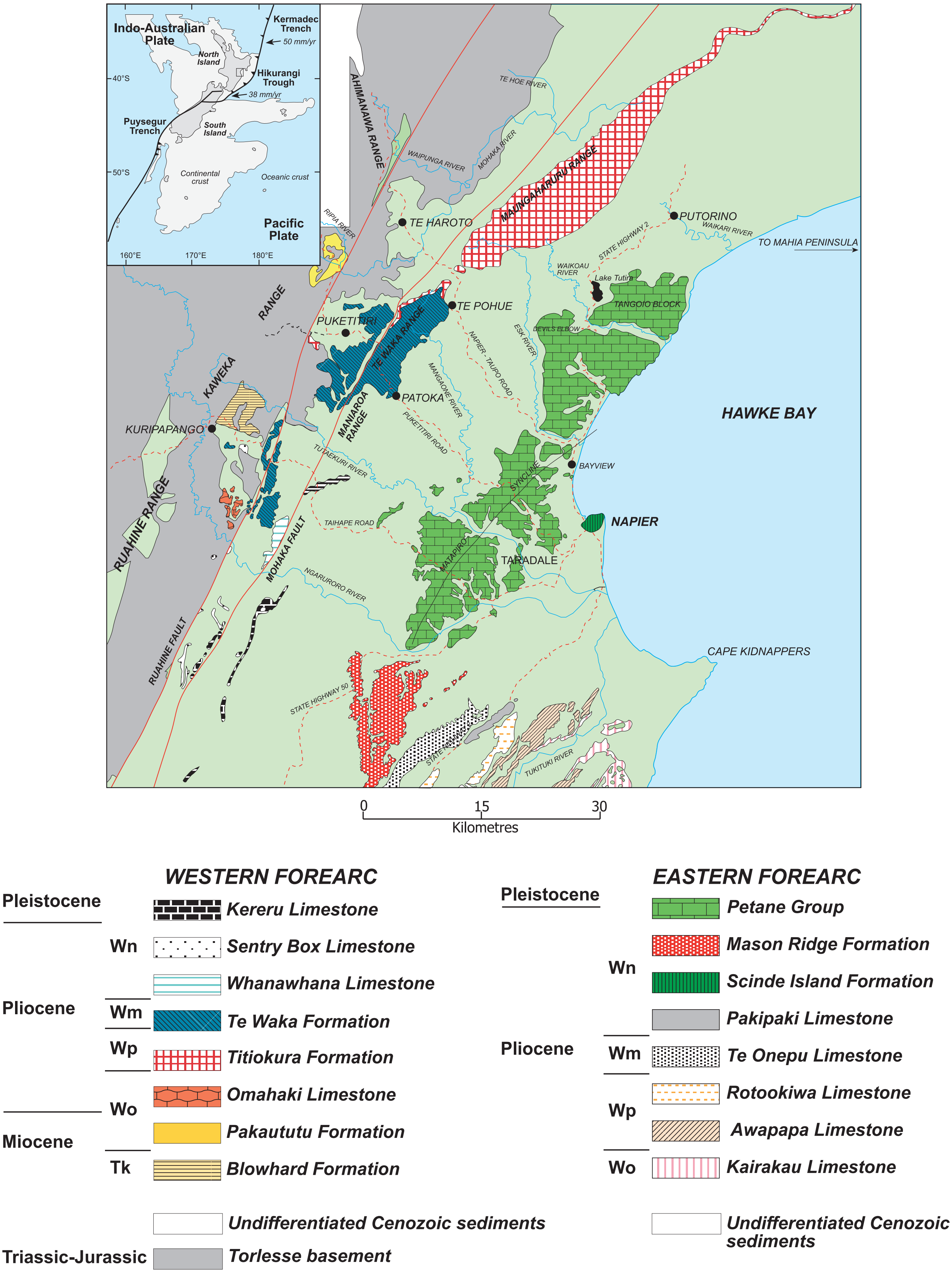

Figure 4. Distribution of limestone beds through western and central Hawke's Bay. Compiled from Beu (1995), Bland (2001), Graafhuis (2001), Caron (2002) and Bland (in prep). Although volumetrically sub-ordinate, these carbonate beds are widespread through the study area.

Limestone beds on the eastern side of the forearc basin are examples of cool-water "continent-detached" limestone units (e.g. Awapapa and Te Onepu Formations) (Fig. 4). These units lack the greywacke components of western limestone units and more commonly contain epifaunal bivalves such as pectens and oysters. Hydrocarbon exploration wells such as Taradale-1 show that limestone units on the margins of the basin are separated in a horizontal sense by thick mudstone beds and do not correlate across the study area. This well (Taradale-1) drilled 1200 m of Pliocene section containing beds having an outer-shelf to bathyal origin (Johnston and Francis 1996).

The westernmost margins of the study area comprise a mixture of thick siltstone, sandstone, limestone and minor conglomerate facies that represent the oldest Neogene units exposed. The early to middle-Pliocene interval comprises limestone facies interbedded with sandstone and siltstone beds. The Late Pliocene-Early Pleistocene part of the basin fill is characterised by the presence of greywacke and limestone beds as part of cyclothems (Fig. 5D). Although volumetrically sub-ordinate to sandstone and siltstone units these beds are prominent due to the influence they have had on the geomorphology of the study area. Late Miocene beds are usually of outer-shelf and upper-bathyal depositional environments. This contrasts with the Pliocene-Pleistocene portion of the succession, which is dominated by shelf facies.

Greywacke conglomerate (Fig. 5B), prominent in the Petane Group, records the progradation of a large fluvial braid plain that developed in response to accelerated uplift along the North Island axial ranges (Bland 2001; Graafhuis 2001). These fluvial systems periodically swept over an exposed continental shelf due to eustatic sea-level fall and the subsequent increase in fluvial gradient (Bland 2001). Subsequent sea-level rise submerged these beds depositing marine siltstone and sandstone facies, until a following regression again exposed the shelf, and allowed further fluvial deposition. In a down-dip direction it is likely that these conglomerate beds pass into limestone facies, a transition which is visible in part across the Tangoio Block (Haywick *et al.* 1991).

Deeper water environments bounded much of the study area, with depocentres located around the Waikari, Hawke Bay and Taradale regions for much of the Miocene-Pliocene (Beu 1995; Graafhuis 2001). Sediments in these regions are dominated by mudstone facies, contrasting with the largely shallower-water sandstone/limestone/conglomerate facies deposited in adjacent areas to the west.

Lithofacies

Sedimentary facies representing all of inner- to outer-shelf, bathyal, estuarine, shoreface and fluvial environments have been identified, of which the former is dominant. The persistence of the shelf facies through the succession indicates that sedimentation rates nearly matched subsidence rates through time. Siltstone facies are largely products of deposition in middle- to outer-shelf depths. These facies are generally 10-80 m thick, although Late Miocene siltstone units (e.g. Waitere Formation) are up to 700 m thick. Sandstone deposits display characteristics of shoreface to middle-shelf water depths and are usually 10-50 m thick. Late Miocene-Early Pliocene sandstone formations, however, may be up to 400 m thick (e.g. Mokonui Formation). Conglomerate beds are dominated by deposits of fluvial to estuarine paleoenvironments, although some shoreface to innermost-shelf paleoenvironments are evident. Conglomerate beds are 1-15 m thick, averaging 5 m thick (Fig. 5B). Limestone beds appear to have developed in inner to middle-shelf water depths, whenever the flux of siliciclastic sediments into the basin was low enough for carbonate-secreting organisms to build up substantial deposits. Limestone facies range from 2-50 m thick, and are commonly interbedded with sandstone, siltstone and less commonly conglomerate facies. Older (Late Miocene-Early Pliocene) limestone beds are largely comprised of epifaunal calcite-dominated faunas (with subordinate infaunal organisms), whereas younger (Late Pliocene-Early Pleistocene) limestone beds are dominated by infaunal aragonitic bivalves with minor to common epifaunal bivalves. Of all of these facies, it is the widespread distribution of sandstone and limestone units that present the most potential for hydrocarbon reservoirs in the subsurface.

Cyclicity

The Late Pliocene-Early Pleistocene portion of the basin fill contains a characteristic cyclothemic succession (Fig. 5D) up to 700 m thick. Cyclothems typically comprise a thin shellbed or limestone, gradationally (though rapidly) overlain by siltstone facies. The limestone or shell bed is inferred have accumulated during Transgressive Systems Tracts (TSTs), whereas siltstone facies are inferred to be Highstand Systems Tract deposits (HST). Siltstone facies grade upward into a fine- to medium-grained sandstone through a series of alternating sandstone-siltstone beds 5-30 cm thick. The sandstone units represent the Regressive Systems Tract (RST). Sequences are then capped by a greywacke conglomerate or limestone bed, depending on the position on the paleoshelf. Greywacke conglomerate beds record deposits of late RST and Lowstand Systems Tracts (LST). Limestone facies are typically inferred to represent RST or TST deposits, the internal composition and character of the limestone determining which systems tract the individual bed is associated with.

Late Miocene and Early to middle Pliocene units in the study area accumulated during periods of oscillating sea-level (Vonk *et al.* 2002), but cyclothemic character is not obvious within them. It was not until the Late Pliocene that the basin reached a point where subsidence rates and sediment fluxes were such that well-developed cyclothems were formed and preserved.

Structural elements

The North Island shear belt (Fig. 1) occurs in the western parts of the study area and includes two major transcurrent fault systems, the Ruahine and Mohaka Faults. Other significant faults cropping out in the study area include the


A
Te Waka Formation
Titiokura Formation
Mokonui Formation
B
C
D
Waipatiki Formation
Te Ngaru Formation
Tangoio Formation
E

Figure 5. Photographs of selected stratigraphic units in the study area. A: Sandy limestone beds of the Titiokura and Te Waka Formations exposed on the northwestern face of the Te Waka Range. The sharp unconformable contact between the Titiokura and underlying Mokonui Formation is arrowed. B: Non-fossiliferous greywacke conglomerate bed of the Matahorua Formation exposed near Lake Tutira in the north of the study area. Note the prominent sandstone lenses within the conglomerate. C: Densely fossiliferous concretionary sandstone beds of the Te Haroto Formation, Napier-Taupo Road. This outcrop occurs approximately 50 m stratigraphically above the unconformable contact between Torlesse basement and the Te Haroto Formation. D: Cyclothemic strata of the Petane Group exposed in coastal cliffs south of Waipatiki Beach, Tangoio Block. The Tangoio Formation marks the upper RST portion of one cycle. The overlying Te Ngaru Formation comprises coarsening-upwards siltstone to sandy siltstone of an HST that passes conformably into sandstone and limestone of the overlying Waipatiki Formation (RST). Note the people (circled) for scale. E: Torlesse basement unconformably overlain by slightly concretionary sandstone of the Blowhard Formation, Kuripapango area. Prominent are greywacke "sea-stacks" protruding into the overlying sandstone. Some of Formation at this locality have yielded specimens of *Sectipecten wollastoni* (Late Miocene, Kapitean-restricted).

Wakarara, Kaweka, Glenross, Miriroa, Patoka, Rukumoana and Rangiora Faults (Fig. 3). Neogene sedimentary beds crop out in the region of the North Island shear belt, and in places "straddle" structures in this region. This situation has afforded an opportunity to place some constraints on the timing and scale of movements on these features.

The Ruahine and Mohaka Faults are relatively straight, steeply-dipping structures, even over steep topography, with significant vertical and horizontal offsets. It appears probable that the Ruahine Fault has been active since at least the Early Pliocene (and possibly Late Miocene), based on the presence of thick greywacke conglomerate beds adjacent to the fault trace that thin rapidly away from the structure. Browne (2003) reports similar facies of a similar age in the Kuripapango area on the crest of the Kaweka Range. Horizontal displacement on the Ruahine Fault since the Early Pliocene is likely to be <10 km.

Major strike-slip displacement is restricted to the Mohaka, Ruahine, and to a lesser extent, the Rangiora Faults. The Patoka Fault, likely to be a splinter fault off the Mohaka Fault, has had at least three displacement events during the past 5,300 years, although has only shown dip-slip displacement (Halliday *et al.* 2003). The Kaweka Fault, a major structure at the foot of the Kaweka Range, displays only sub-ordinate strike-slip displacement (Beanland 1995). Vertical displacement on the Kaweka Fault diminishes rapidly from Kuripapango on the Napier-Taihape Road north to the Pakaututu region (Bland *et al.* 2003). Browne (2003) estimates approximately 2000 m of vertical throw on the fault in the Kuripapango area, a figure that drops rapidly to 120 m at the northern end of the Kaweka Range.

Reversals in the sense of displacement are evident on both the Ruahine and Mohaka Faults. These changes have had a profound influence on the deposition, distribution and preservation of sedimentary beds in the basin (Fig. 7). A dramatic change in sedimentary facies in the Early Pliocene succession appears to occur across the Mohaka Fault suggesting this structure provided some form of depositional control during the Late Miocene-Early Pliocene. While the modern sense of uplift on the Ruahine Fault is on its western side, cross-sections through the Puketitiri region demonstrate that a period of uplift resulting in at least 350 m of vertical displacement on the eastern side of the fault has occurred since the middle Pliocene (Fig. 7). These changes may have resulted from a general basinwide change from reverse displacement to strike-slip displacement on these faults during the Late Pliocene.

A series of normal and reverse faults occur east of the Mohaka Fault throughout the study area, and act to partition strain associated with the obliquely convergent Hikurangi margin

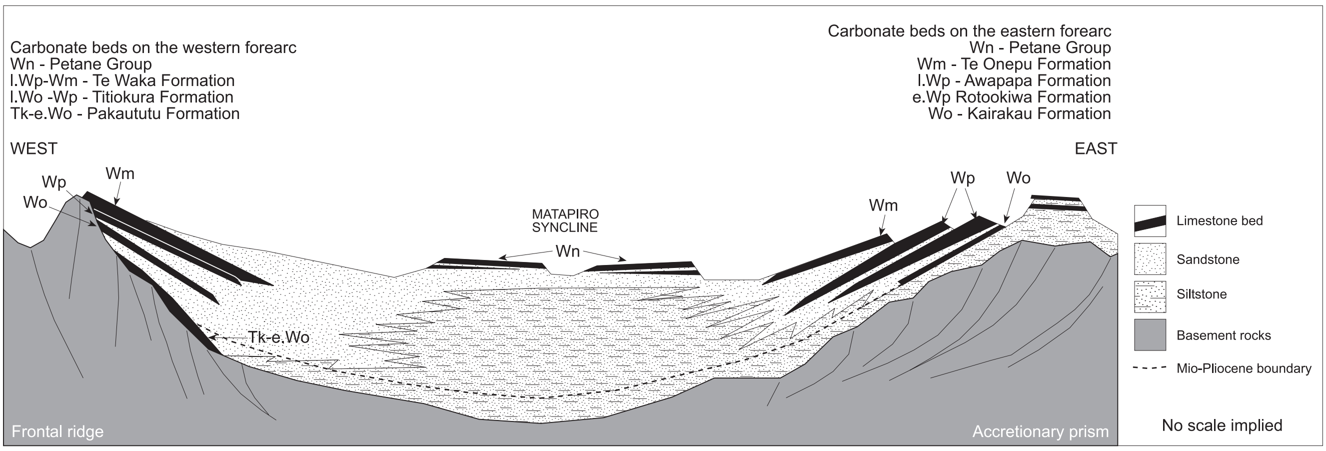

Figure 6. Schematic cross-section through the central part of the forearc basin. Note the manner in which limestone beds on the western and eastern sides of the basin do not extend far into the sub-surface. The presence of Nukumaruan (Wn) limestone beds in central parts of the section illustrates how the margins of the basin have been progressively uplifted through time, and how the basin has been infilled from both margins towards the centre.

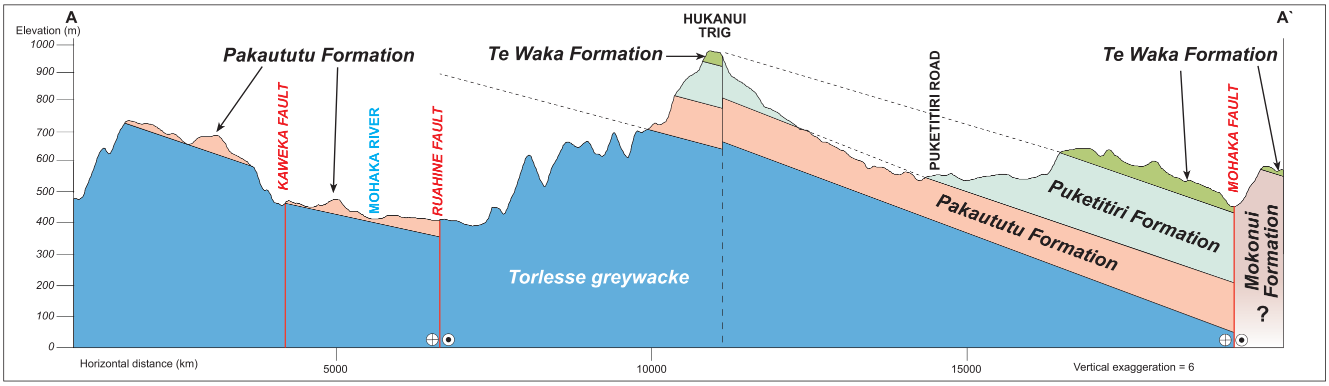

Figure 7. Geological cross-section for the Pakaututu area in the western part of the study area. While the western (left) side of the Ruahine Fault displays the modern uplift, displacement of the Pakaututu Formation demonstrates older uplift on the eastern (right) side of the fault of at least 350 m. A prominent change in the Early Pliocene stratigraphy occurs across the Mohaka Fault. The Te Waka Formation (middle Pliocene) occurs on both sides of the fault.

(Fig. 3). While some of these faults have surface expression with traces, others are only identifiable in seismic sections. Broad-scale warping of sedimentary beds in the Esk Valley has been identified in both this study and by Leith *et al.* (2003). This deformation appears to be a consequence of blind reverse faulting at depth, and is evident on seismic lines shot through this area. At depth these features may be splays off the Mohaka Fault. It is likely that many subsurface folds exist in proximity to the North Island axial fault belt in the basin as evidenced from petroleum exploration reports (e.g. Francis 1991; Johnston and Francis 1996).

The dominant structure affecting the youngest (Nukumaruan) beds in the study area is the Matapiro Syncline (Fig. 4), a broad, gently dipping structure that extend from the Ngaruroro River along a roughly northeast-southwest trend towards the mouth of the Esk River at Bayview. North of Bayview only the western limb of the syncline is preserved (as the Hawke's Bay Monocline), with the upper part of the eastern limb eroded by wave action. Units in the syncline have dips of 4-2°.

A major structural feature occurs along the Ngaruroro River in the vicinity of Roy's Hill and SH50, separating Late Nukumaruan limestone beds north of the river from Early Nukumaruan limestone beds south of the river (Fig 4). The presence of this feature has been highlighted by recent mapping by Baggs (in prep) and Dyer (in prep), although both Kingma (1971) and Beu (1995) have suggested its existence in earlier work. In the vicinity of this structure the Ngaruroro River takes a major deviation towards the northeast, whereas for much of its course it follows a southeast trend (Fig. 2).

Potential reservoir and seal beds

The widespread distribution of sandstone and limestone facies in outcrop presents potential for the presence of many reservoir beds in the subsurface. Harmsen (1990) suggested that the Te Aute limestone lithofacies is an attractive prospecting target due to its coarse grain size, well-sorted nature, shallow burial history (meaning limited diagenesis) and relatively high porosity.

The occurrence of cyclothemic deposits through large parts of the basin has resulted in the occurrence of numerous potential reservoir and seal facies. The fine-grained, massive nature of many HST siltstone beds provides numerous seal rocks at high stratigraphic levels. Sandstone and limestone facies, with their coarser grain sizes and more porous character have potential as reservoir beds. Johnston and Francis (1996) report porosities of 35%-40% for limestone beds in parts of the study area and suggest they have excellent reservoir characteristics. Beu (1995) records a marked decrease in porosity in limestone beds from youngest to oldest units. The highest porosities of 41%-50% were recorded only in Petane Group and Scinde Island limestone units. Opoitian and Waipipian limestone beds were recorded as having a maximum porosity of 11%-20%. Beu (1995) suggests that 11%-20% porosity is still high enough to provide reasonably good reservoir pore space for hydrocarbons.

Field and Uruski *et al.* (1997) suggest that the Mokonui Formation, a Late Miocene to Early Pliocene sandstone unit of shallow-marine origin in the north of the study area has excellent reservoir potential.

The occurrence of numerous oil seeps through eastern North Island, and the discovery of near-commercial gas deposits in the Wairoa area demonstrate that hydrocarbon sources and generation have been widespread, and that migration has occurred and continues (Beu 1995).

Summary

The study area contains a Late Miocene-Early Pleistocene sedimentary succession that accumulated in a variety of paleoenvironments from bathyal to fluvial settings. The succession is dominated by thick siliciclastic beds, although it is punctuated by prominent cool-water skeletal limestone beds, particularly along the western margin and in central parts of the study area. The axis of the basin continued to be an area of deep-water into the Nukumaruan with turbidites and mudstone beds accumulating. This contrasts with areas nearby to the west where shelf sandstone and siltstone facies, and non-marine greywacke conglomerate facies were deposited. Likewise, deeper-water sediments accumulated in the Waikari and Hawke Bay regions into the Late Pliocene. Geological mapping has demonstrated that numerous potential reservoir and seal beds are likely to be present in the subsurface. Of the potential reservoir beds, the Te Aute limestone lithofacies, with their coarse-grained, porous character, hold good potential as targets. It is uncertain, however, how far these beds extend into the subsurface, but it is known from drilling that they do not extend through the axis of the basin.

The North Island shear belt has acted to truncate parts of the succession through a combination of strike-slip and dip-slip faulting. Associated with these fault movements has been the development of numerous sub-surface folds (antiforms, synforms and monoclines), some of which have been targeted by hydrocarbon exploration holes (e.g. Kereru-1, Taradale-1).

The thick Pliocene-Quaternary succession in the study area, deposited late in the history of the basin, is highly favourable for the generation and expulsion of hydrocarbons from known oil-prone Paleocene source rocks, for the generation of biogenic methane and for charging late-formed structures (Johnston and Francis 1996).

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