Late Miocene – Early Pleistocene paleogeography of the onshore central Hawke's Bay sector of the forearc basin, eastern North Island, New Zealand, and some implications for hydrocarbon prospectivity

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Abstract

The timing of trap formation in relation to the timing of source rock burial and maturation are important considerations in evaluating the hydrocarbon prospectivity of onshore parts of the forearc basin in central Hawke's Bay. We describe here aspects of the Late Miocene to Early Pleistocene paleogeography for the area based on detailed field mapping and lithofacies analysis, to help constrain petroleum systems evaluations. Key conclusions are:

- Most deformation of the forearc basin fill appears to be relatively young (i.e. post-2 Ma). This deformation has occurred after a major phase of Late Miocene to Pliocene sediment accumulation, and is particularly significant along the northwestern and southeastern margins of the basin.
- The axis of the forearc basin in central Hawke's Bay appears to have undergone little structural deformation. Gentle force and reverse faults in the subsurface may be suitable traps.
- The most widespread potential reservoir beds are Miocene sandstone beds.
- Potential hydrocarbon source rocks are mostly absent from western parts of the basin due to significant Neogene uplift and erosion. They are, however, probably still widely preserved beneath central parts of the basin where uplift and erosion have been much less pronounced.
- Miocene structures within the axis of the basin, buried by the Late Miocene to Pleistocene siliciclastic succession, are likely exploration targets.

The forearc basin has been substantially inverted along its western side since the latest Pliocene, resulting in erosion of older sediments, including potential source rocks, down to basement in ranges flanking its western side. The stratigraphy along the eastern margin of the forearc basin, and particularly the outcrop pattern of westward-younging Plio-Pleistocene limestones, records the development of faulting and folding associated with the elevation and growth of the inboard part of the accretionary wedge. Parts of the forearc basin succession have become involved in the accretionary wedge, which has migrated westward through time.

Uplift of the inboard margin of the accretionary wedge since the latest Miocene helped to cause an interior seaway to develop to the west during the Pliocene. Distinctive coarse-grained bioclastic carbonate sediments of the Te Aute lithofacies were deposited along both margins of the seaway, which was most extensive during the Late Pliocene (Mangapanian). Although significant volumes of siliciclastic sediment were supplied to the basin during the Pliocene, strong tidal currents periodically swept much of these sediments northeastward. Tidal connections existed during the Pliocene into Wanganui Basin in the vicinity of Kuripapango and Manawatu Gorge. By the latest Pliocene (lower Nukumaruan), the interior seaway became closed in the south with uplift of the Mount Bruce block in northern Wairarapa.

Potential reservoirs within the map area include both shelf and redeposited sandstone beds in the Miocene to Early Pliocene Tolaga Group. Thick, coarse-grained, variably cemented Plio-Pleistocene limestone lithofacies in the Mangaheia Group are widespread along the margins of the basin, and have been the targets for several past exploration programmes. However, drilling has shown that the attractiveness of the Pliocene limestone facies as reservoir beds is limited because they quickly pass laterally into siliciclastic mudstone away from the margins of the basin.

Keywords:
Paleogeography; Hawke's Bay; East Coast Basin; Hikurangi margin; Neogene; Tolaga Group; Mangaheia Group; Kidnappers Group; Te Aute lithofacies

Introduction

Paleogeographic reconstructions of a general nature covering all of eastern North Island were published in Beu (1995) and Field et al. (1997). Since then new and detailed geological mapping (1:50,000 scale) has been undertaken over most of the forearc basin in central parts of Hawke's Bay (Bland, 2006), underpinned by rationalisation of the prior lithostratigraphy, which was unnecessarily complex (Bland et al., 2007; Kamp et al., 2007). This has provided a sound basis for re-interpretation of the paleogeographic development of the basin, which has also been aided by new sedimentological analyses available for the extensive carbonate units that accumulated along the margins of the basin during the Pliocene (Bland et al., 2004; Caron, 2002; Caron et al., 2004, 2006). In this paper we present a series of new paleogeographic maps for central parts of the Hawke's Bay region and describe then in relation to sedimentological and structural information for corresponding formations and members. These maps have been depicted relative to the modern coastline without allowing for the magnitude of dextral displacement on faults, or the effects of crustal shortening or tectonic rotation, mainly because it is difficult to precisely quantify such displacements and partition them into particular intervals. The paleogeographic maps, by virtue of the summaries of facies and depositional systems they represent, may aid hydrocarbon exploration in the basin, with the caveat that they have been built up chiefly from examination of units that crop out in the region, together with reference to exploration hole data.

Geological setting

Hawke's Bay Province in eastern North Island lies within the forearc region of the Hikurangi ocean-continent convergent margin, the northern part of the obliquely convergent Australia-Pacific plate boundary zone through continental New Zealand (Fig. 1 & 2). This paper focuses on the area on land between Raupunga in the north and the Ohara Depression and Mason Ridge in the south (Fig. 1). The lowlands in central Hawke's Bay and much of the embayment offshore (Hawke Bay), lie within the principal forearc basin of the convergent margin, between the inboard part of the accretionary prism that involves the hill country south of Cape Kidnappers, and the high country of the axial ranges in the west (Ruahine, Kaweka and Ahimanawa ranges) (Pettinga, 1982; Kamp 1982). The part of the accretionary prism underlying the Maraetotara Plateau and the hills to the south contains a Late Miocene accretionary slope basin that accumulated turbidites and mass-emplaced sandstone beds in bathyal environments, and is structurally associated with bounding melange zones that formed as imbricate thrust faults (van der Lingen & Pettinga, 1980) The forearc basin differs in being much more structurally simple and in containing a longer-lived stratigraphic succession, possibly as much as 5 km thick (Cutten, 1994). Based on the most recent rotation data describing the relative movement of the Australia and Pacific plates (Cande & Stock, 2004), it is clear that the subducted oceanic Pacific slab was progressively emplaced in a southwest direction beneath North Island during the Neogene (Kamp & Furlong, 2006). This implies that the Hikurangi Trough, the structural trench offshore to the east where the oceanic plate starts subducting beneath the overriding Australia plate, progressively developed to the south from East Cape to Kaikoura during the Neogene, and a slab has been beneath central parts of Hawke's Bay only since 10 – 12 Ma. This places constraint on the age of the start of convergent margin processes and hence of the accretionary prism and forearc basin; Tongaporutuan and younger strata could have accumulated in a convergent margin setting, whereas older strata (Early and Middle Miocene) may be better associated with the prior, possibly strike-slip, tectonic setting.

The sedimentary fill exposed at the surface in the forearc basin in central parts of Hawke's Bay comprises a transgressive-regressive Late Miocene (Tongaporutuan) to Early Pleistocene (c. 10-1.6 Ma) succession about 2,500 m thick. Progressive onlap of late Neogene sediments onto basement is evident along the western margin of the basin. The oldest beds overlying basement are of Tongaporutuan (Late Miocene) age, and occur in the vicinity of the Napier-Taupo Highway (State Highway 5). Farther to the south and in the Ohara Depression, the youngest beds over basement are of lower Nukumaruan (Late Pliocene) age. In general, the basin contains a mixed carbonate-siliciclastic succession, with carbonates becoming more common, although volumetrically limited, in the Pliocene section. Conglomerates derived from erosion of the Triassic-Jurassic basement exposed in the axial ranges only become significant from the Late Pliocene.

Lithostratigraphy and outcrop patterns

The Neogene lithostratigraphy and its nomenclature for central parts of Hawke's Bay are summarised in Fig. 3, and the distribution of many of the formations are illustrated in Fig. 4. At the highest level, the stratigraphy comprises three groups: (i) the Tolaga Group, incorporating Early Miocene (Otaian) to Early Pliocene (lower Opoitian) formations; (ii) the Mangaheia Group, incorporating upper Opoitian to Nukumaruan (Late Pliocene-Early Pleistocene) formations, and (iii) the middle Pleistocene (Castlecliffian) Kidnappers Group, which mostly comprises alluvial fan deposits. Full description of each of the groups, formations and members are given

Fig. 1. Map of Hawke's Bay showing localities mentioned in this paper, and petroleum exploration wells used in the paleogeographic reconstructions.

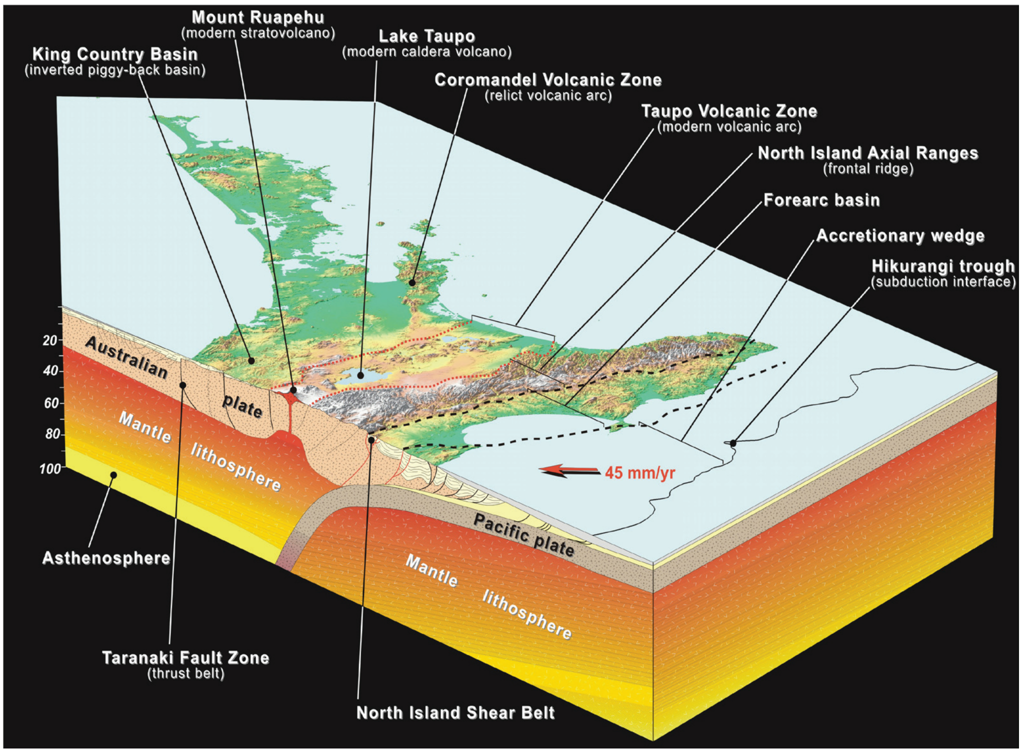


Fig. 2. Cut-away model of the modern subduction setting of North Island involving subduction of the Pacific plate beneath the Australia plate. Data used in this figure were derived from Beanland (1995), Field, Uruski et al. (1997), Barnes and Nicol (2002), and Barnes et al. (2002).

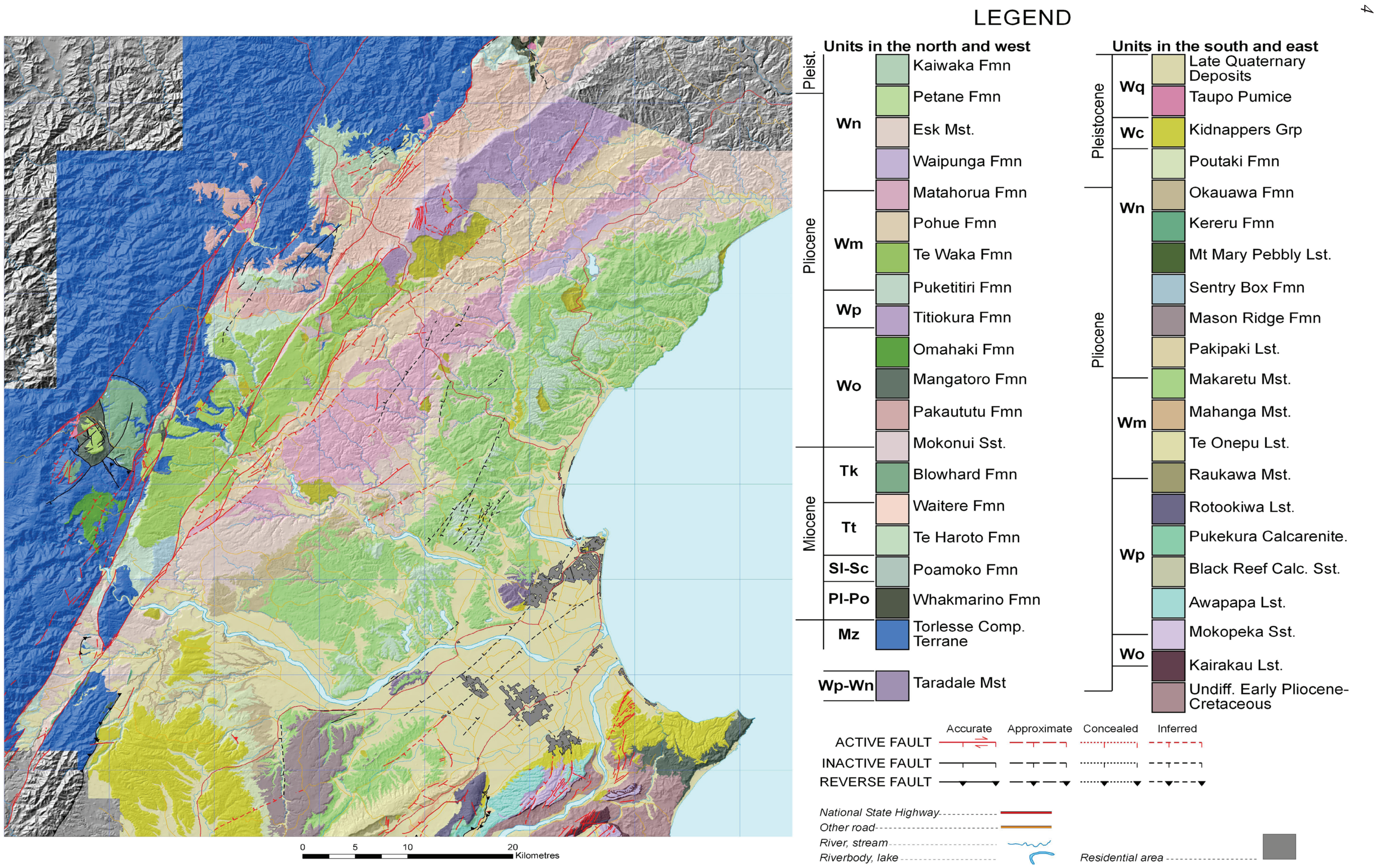


Fig. 3. Simplified geological map of the central Hawke's Bay area (after Bland, 2006).

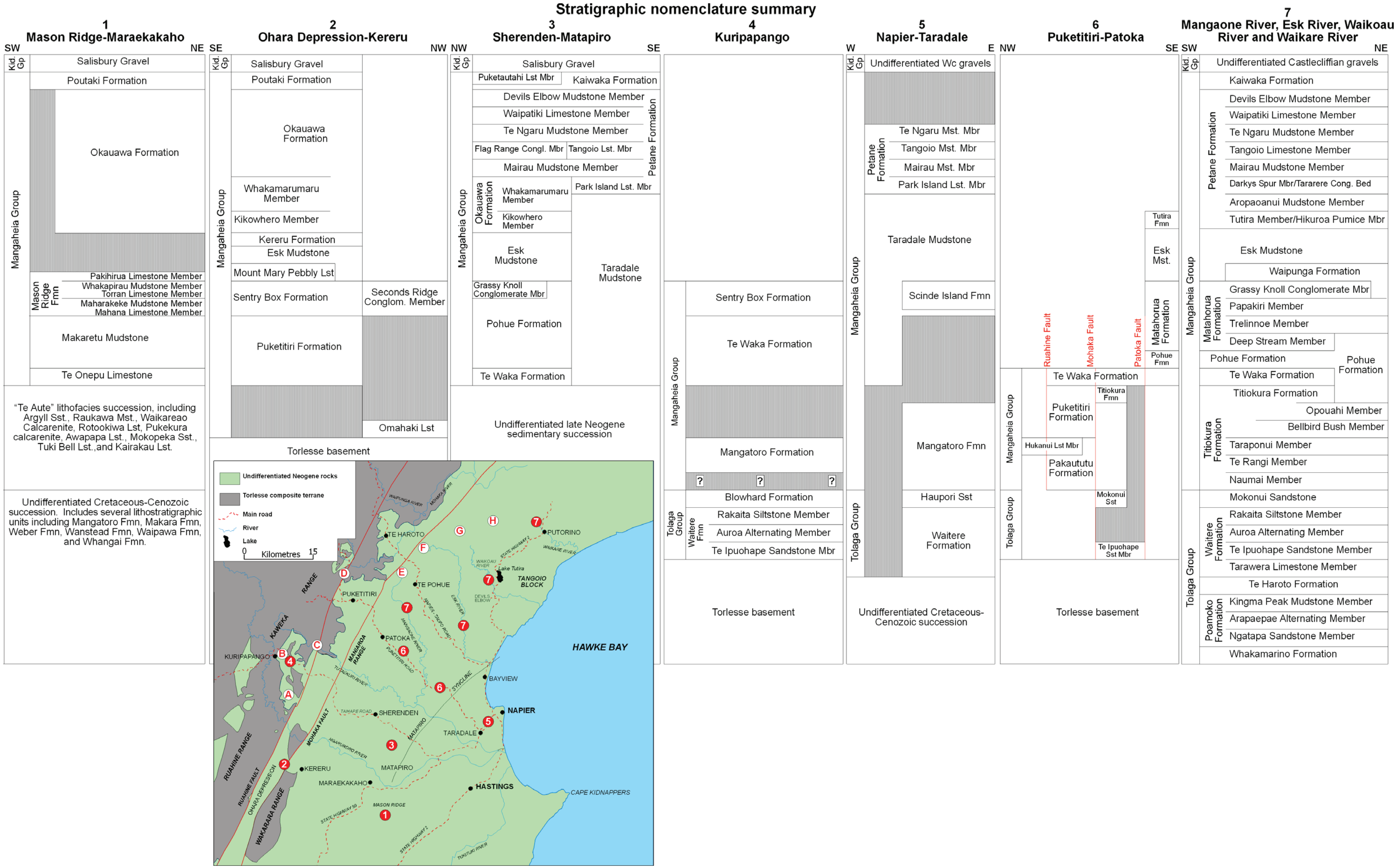


Fig. 4. Summary of the Neogene lithostratigraphic nomenclature for central parts of Hawke's Bay from Bland et al. (2007).

in Bland et al. (2007), supported by stratigraphic data in Kamp et al. (2007). The outcrop distribution of these stratigraphic units is largely controlled by the northeast – southwest strike of the predominant structures, which are oriented parallel to the plate boundary zone. The older Neogene units (Miocene) are faulted against basement, or onlap basement along the margin of the axial ranges in the west, with successively younger units cropping out in belts lying closer to the axis of the forearc basin. The dips of the beds decrease from around 10 degrees to a few degrees as the age of the units decrease and with increasing distance from the basement contact into the axis of the basin. Note in Fig. 4 how the strike of the Neogene formations is slightly more easterly than the strike of the eastern edge of the basement outcrop, which is strongly influenced by strike-slip faults (Ruahine and Mohaka Faults). This phenomenon partly refects the southward onlap onto basement of successively younger formations (see also Fig 3) and partly reflects truncation through uplift of basement and erosion of cover sediments since the latest Pliocene (lower Nukumaruan). The southeast limb of the forearc basin has been structurally involved in the uplift of the inboard margin of the accretionary prism, which is reflected in the progressive displacement to the northwest and into the axis of the forearc basin of successively younger Pliocene limestone and associated units (Kamp et al., 1988; Caron, 2002; Caron et al., 2004). Indeed, during the upper Nukumaruan (Late Pliocene – Early Pliocene) the whole of the forearc basin shallowed and emerged, with differential uplift of both the northwestern and southeastern margins, the former associated with uplift of basement and displacement on a series of oblique-slip faults, and the latter associated with subduction accretion. These late phases of deformation are expressed in interesting interactions with sedimentation, as shown in the paleogeography.

Paleogeography

Early and Middle Miocene (Otaian-Waiauan, 21.7 - 10.92 Ma)

The oldest Neogene rocks cropping out in central Hawke's Bay are the Early Miocene (upper Otaian - Altonian) upper bathyal Whakamarino Formation (Cutten, 1994), the basal formation of the Tolaga Group in this area. The Whakamarino Formation was deposited soon after the inception of the modern plate boundary through the New Zealand subcontinent, an event that marked the cessation of passive-margin sedimentation in the East Coast Basin. The Whakamarino Formation is a mudstone facies containing turbidites and it probably accumulated in a bathyal environment. Units of the same age and environment in eastern North Island include the Cocos Flysch and Rere Sandstone in the Gisborne area (Francis, 1994). During accumulation of the Whakamarino Formation there may have been a seaway across the whole of central North Island (Kamp et al., 2004).

The Whakamarino Formation is unconformably overlain by shelf early Middle Miocene (Clifdenian) beds of the Poamoko Formation. This infers an interval of emergence, uplift and erosion in parts of the Hawke's Bay region during the upper Altonian, and subsequent subsidence and transgression in the Clifdenian. There was a progressive increase in water depth from shelf to bathyal conditions through the Poamoko Formation, Ngatapa Sandstone Member, Arapaepae Alternating Member and into the Kingma Peak Mudstone Member (upper Lillburnian age). Water depths during deposition of the Arapaepae Alternating and Kingma Peak Mudstone Members were probably as great as middle bathyal (> 400-600 m; Cutten, 1994). During the Middle Miocene the rest of the Hawke's Bay area probably remained at outer shelf to bathyal water depths.

No rocks of Waiauan age are known from outcrop in the central and western Hawke's Bay area, suggesting emergence of the basin. In the Wairoa-Mahia area to the northeast, Waiauan sandstone (Tunanui Formation; Mazengarb & Speden, 2000) are recorded in Tuhara-1 (IRBA, 1998c), and Waiauan Tangihau Mudstone and Makaretu-D Sandstone is reported in Opoho-1 (IRBA, 1999b). Waiauan turbidites and other types of mass-emplaced sandstone crop out around Lake Waikaremoana (Grindley, 1960). In the Elsthorpe area, lower Waiauan muddy sandstone and flysch are unconformably overlain by upper Waiauan (shelf?) Waipuna Limestone. In places, this limestone contains abundant greywacke pebbles, which imply an emergent basement source (Kingma, 1971), which was probably present in the vicinity of the present-day Ruahine Range area (Lillie, 1953). In central Hawke's Bay, mid-Pliocene (Waipipian) Taradale Mudstone overlies steeply-dipping Waiauan flysch in Mason Ridge-1 (Leslie, 1971b), and Waiauan Waipuna Limestone was intercepted in Whakatu-1, where it unconformably overlies Early Miocene mudstone (Ozolins & Francis, 2000). However, no rocks of Early Oligocene to Late Miocene (lower Tongaporutuan) age were intercepted in the Hukarere-

1 well (WENZ, 2001), and beds of Early Eocene (Mangaorapan) to Late Pliocene (lower Waipipian) age are absent in Taradale-1 (Darley & Kirby, 1969; Beu, 1995). Shelf sandstone of Waiauan age was reported in Hawke Bay-1 (BP Shell Aquitane Todd Petroleum Development Ltd, 1976).

It is therefore likely that western parts of basin were subaerial for much of the late-Middle Miocene (Waiauan) and remained so until the early-Late Miocene (lower Tongaporutuan). Central and eastern parts of the basin were mostly at outer shelf to bathyal depths, indicated by the presence of flysch and other redeposited lithofacies (Kingma, 1958; van der Lingen & Pettinga, 1980; Pettinga, 1982), although some shelf deposition, or redeposition of shelf-sourced carbonate is indicated by the Waipuna Limestone (Kingma, 1971; Ozolins & Francis, 2000) and areas of missing section. It is inferred that the absence of Early – Middle Miocene rocks in Hukarere-1 (WENZ, 2001) and Oligocene – Miocene rocks in Taradale-1 (Darley & Kirby, 1969) reflects later phases of uplift and erosion.

Late Miocene

Tongaporutuan (10.92 - 6.5 Ma)

The Tongaporutuan (Fig. 5) was characterised by submergence of the western basin margin leading to sedimentation in bathyal environments during the Kapitean. Tongaporutuan rocks crop out widely in northwestern and southeastern parts of the basin, and are also widespread in the subsurface beneath the Hawke's Bay area (Cutten, 1994; Mazengarb & Speden, 2000).

Lowermost Tongaporutuan sediments crop out in the Tarawera and Te Haroto areas where the Te Haroto Formation was deposited over basement (Francis, 1994; Bland et al., 2007). In the "middle" Tongaporutuan, the entire western margin subsided, reflected in deposition of the shelf Tarawera Limestone Member, and coarse-grained, highly fossiliferous lower beds of the Te Ipuohape Sandstone Member (both in the Waitere Formation; Bland et al., 2007). Continued subsidence resulted in deposition of the bathyal Auroa Alternating and Rakaita Siltstone Members (Waitere Formation). In eastern parts of the basin deep marine sedimentation recorded in the Makara Formation continued through the Tongaporutuan (Kingma, 1958, 1971; van der Lingen & Pettinga, 1980).

Cutten (1994) has interpreted significant growth and associated erosion of a Pohokura Anticline before deposition of the Waitere Formation, although his hypothesis has not been tested by us. He also inferred continued growth of this structure after accumulation of the Waitere Formation.

Kapitean (6.5 - 5.28 Ma)

Marine sedimentation continued uninterruptedly across the Tongaporutuan-Kapitean boundary in western Hawke's Bay, with ongoing deposition of the Rakaita Siltstone Member (Waitere Formation) (Cutten, 1994; Bland et al., 2007). A marine connection between Wanganui and East Coast Basins, informally named the "Kuripapango Strait" by Kingma (1971), remained open into the lower Kapitean. Water depths during this time were greater along the area now occupied by the northeast parts of the Maungaharuru Range, compared with the area to the south of State Highway 5 (SH5). South of SH5 the transition from Rakaita Siltstone Member to Mokonui Sandstone is unconformable, whereas it is gradational to the north. Well to the south of SH5, around Kuripapango, the Blowhard Formation onlaps basement (local conglomeratic facies are known; Browne 2004a), and is a correlative of the Mokonui Sandstone, albeit older than some of the facies north of SH5 where it accumulated through depositional offlap.

Outer shelf to upper bathyal deposition probably continued over much of the accretionary wedge during the Kapitean (van der Lingen & Pettinga, 1980; Francis 1993), although uplift and erosion occurred over parts of it during the upper Kapitean and lower Opoitian (Kingma 1971; van der Lingen & Pettinga 1980; Beu, 1995) judged from unconformities beneath the Haupori Sandstone and Kairakau Limestone. Outer shelf to upper bathyal deposition was inferred in Hawke Bay-1 (BP Shell Aquitane Todd Petroleum Development Ltd, 1976). Shelf deposition probably also occurred over the locations of Te Hoe-1, Kereru-1, Whakatu-1, Mason Ridge-1, Ongaonga-1, Takapau-1, and Speedy-1.

Early Pliocene

Opoitian (5.28 - 3.6 Ma)

In the Wairoa-Gisborne area, the Opoiti Limestone Member and Ormond Limestone were deposited during the lower Opoitian (Beu, 1995; Mazengarb & Speden, 2000). In the western part of Hawke's Bay south-directed marine onlap continued during the Opoitian with accumulation of Mangatoro Formation in deeper water (upper bathyal) than the onlap that started in the vicinity with accumulation of the Blowhard Formation. Concurrently, uplift in the north along the western margin resulted in erosion, as observed at Hells Hole (V20/235127; Bland et al., 2004).

Substantial subsidence occurred to the north in the Wairoa Sub-basin, where bathyal mudstone of the Opoiti Formation was deposited over shelf Opoiti Limestone Member (Beu, 1995). In eastern parts of the basin Haupori Sandstone of lower Opoitian age was deposited in the vicinity of the present-day Maraetotara Plateau and around Napier (Francis, 1993; WENZ, 2001). This sandstone was deposited at mid shelf depths in the Maraetotara area (Francis, 1993) and near the shelf break in Hukarere-1 (WENZ, 2001). Subsidence during the upper Opoitian led to accumulation of Mangatoro Formation in upper bathyal depths over much of central Hawke's Bay.

Rocks of upper Opoitian age (e.g. Beu, 1995; Graafhuis, 2001; Nelson et al., 2003; Bland et al., 2007) record the deposition of the first "Te Aute" limestone facies along the margins of a developing interior seaway named the "Ruataniwha Strait" by Beu (1995). The eastern margin of this seaway probably comprised a series of shoaling, shelf platforms, perhaps with a small number of islets during periods of low sea level. The western shelf of the basin was narrow, probably no more than several kilometres wide. It was bounded by a Torlesse basement with a rocky coastline. The presence of land in the west and shoals in the east resulted in the earliest constriction of tidal currents through the seaway.

By the end of the Opoitian, mixed bioclastic-siliciclastic sediments were accumulating along northwestern margins of the basin (Titiokura Formation; Bland et al., 2004), from the Putere Lakes in the northeast to the central parts of the Maungaharuru Range in the southeast. Deposition of the Pakaututu Formation occurred adjacent to a rocky coastline and probably in a large embayment or harbour. The Pakaututu Formation probably represents the nearshore equivalent of the Titiokura Formation. Concurrently, the Kairakau Limestone accumulated along eastern margins of the Ruataniwha Strait from the vicinity of Te Mata Peak in the north to at least as far south as Patangata (Pettinga, 1980; Beu, 1995; Caron, 2002). Whakapunake Limestone was deposited atop sea-floor highs in the Wairoa and Mahia areas (Beu, 1995). Microfauna and lithological indicators from Hawke Bay-1 (BP Shell Aquitane Todd Petroleum Development Ltd, 1993), Hukarere-1 (Morgans & Wilson, 2002), and Whakatu-1 (Ozolins & Francis, 2000) indicate outer shelf to upper bathyal deposition throughout the Opoitian. Opoitian beds are absent from Mason Ridge-1 (Leslie, 1971b) and Taradale-1 (Darley & Kirby, 1969), and Kereru-1 failed to intercept beds older than Waipipian (Johnston & Francis, 1996).

Late Pliocene

Waipipian (3.6 - 3.0 Ma)

The Waipipian record in central Hawke's Bay is characterised by the development of extensive carbonate banks and depositional offlap around the margins of the forearc basin, as well as accumulation of siliciclastic siltstone (Puketitiri Formation). The absence of Waipipian rocks within the axial ranges make it difficult to assess the occurrence of a seaway between Wanganui Basin and central Hawke's Bay at this time. The shoreline along the western margin was irregular and often rocky with an emerging basement hinterland. During the lower Waipipian the Puketitiri Formation was deposited as siltstone over the (Opoitian) Pakaututu Formation in the Puketitiri area and to the east in the forearc basin (Johnston & Francis, 1996). Titiokura Formation calcareous sandstone continued to accumulate in the vicinity of the Te Waka Range (Beu, 1995; Bland et al., 2004). In the Napier and Taradale areas the Taradale Mudstone accumulated. Local tilting and erosion at Opau Stream east of Puketitiri probably formed from shortening between the Mohaka Fault and Patoka Fault.

The eastern margin of the basin progressively emerged as a consequence of subduction accretion in the Hikurangi margin. The Awapapa Limestone (lower Waipipian) and Rotookiwa Limestone (upper Waipipian) accumulated on the flanks of the Elsthorpe Anticline (Beu, 1995; Caron et al., 2004). Black Reef Calcareous Sandstone was deposited at Black Reef, possibly due to growth of the Kidnappers Anticline. In northern Hawke's Bay the continued growth of fold structures in the Wairoa Sub-basin resulted in deposition of the Tahaenui Limestone (Beu, 1995) atop sea-floor highs, which graded on their flanks into outer shelf to upper bathyal siliciclastic Wairoa Formation. By the upper Waipipian Wairoa Formation accumulated over much of the Wairoa Sub-basin.

Mangapanian (3.0 - 2.4 Ma)

The Ruataniwha Strait as a seaway during the Mangapanian had very diversified facies within it, with significant areas of carbonate banks accumulating along both margins (Kamp et al., 1988; Beu, 1995). The inboard margin of the accretionary wedge was at shallow water depth, probably exposed as an archipelago of islands. The seaway was open at its northern and southern ends, and connections between the East Coast and Wanganui Basins were probably present via the Kuripapango and Manawatu Straits (Kamp et al., 1988; Browne, 2004a; Bland, 2006), with low-lying basement exposed in the vicinity of the present-day Ruahine Range. A rocky greywacke coastline extended from the Ohara Depression in the south to Patoka, beyond which the coastline was probably more regular with uplifted Cretaceous, Paleogene and Neogene sediments exposed at the surface. The seaway was swept by strong tidal currents, as inferred from giant cross-bedded limestone facies in the Te Waka Formation near Puketitiri (Bland, 2006). The strong tidal currents aided transport of siliciclastic sediment northward into the vicinity of the present-day Waikare and Raupunga areas (Graafhuis, 2001), which remained outer shelf to uppermost bathyal depocentres throughout the Mangapanian.

Subsidence of the Ohara Depression during the lower Mangapanian indicates displacement on the Ruahine, Glenross, Mohaka, and possibly Wakarara Faults. To the northeast, the Te Waka Formation was deposited as a succession of carbonate banks that migrated to the southwest, with the oldest beds at the type section (Te Waka Trig; Bland, 2001) and the youngest beds in the southwest (Awapai Station, Glenross Range; Bland, 2006). In many places Te Waka Formation accumulated directly over basement, as well as overstepping various late Neogene formations that had been uplifted and eroded during the Waipipian (Katz, 1973; Browne, 2004a; Bland et al., 2007). No Te Waka Formation is known south of the Ngaruroro River, indicating that the extensive Mangapanian carbonate banks did not develop in these areas, although they were deposited in southern Hawke's Bay around Ongaonga-1 and Takapau-1 (Leslie, 1971a, c). The Te Onepu Limestone, the classic "Te Aute" lithofacies limestone, was widely deposited along inboard parts of the rising accretionary wedge during the Mangapanian (Beu, 1995).

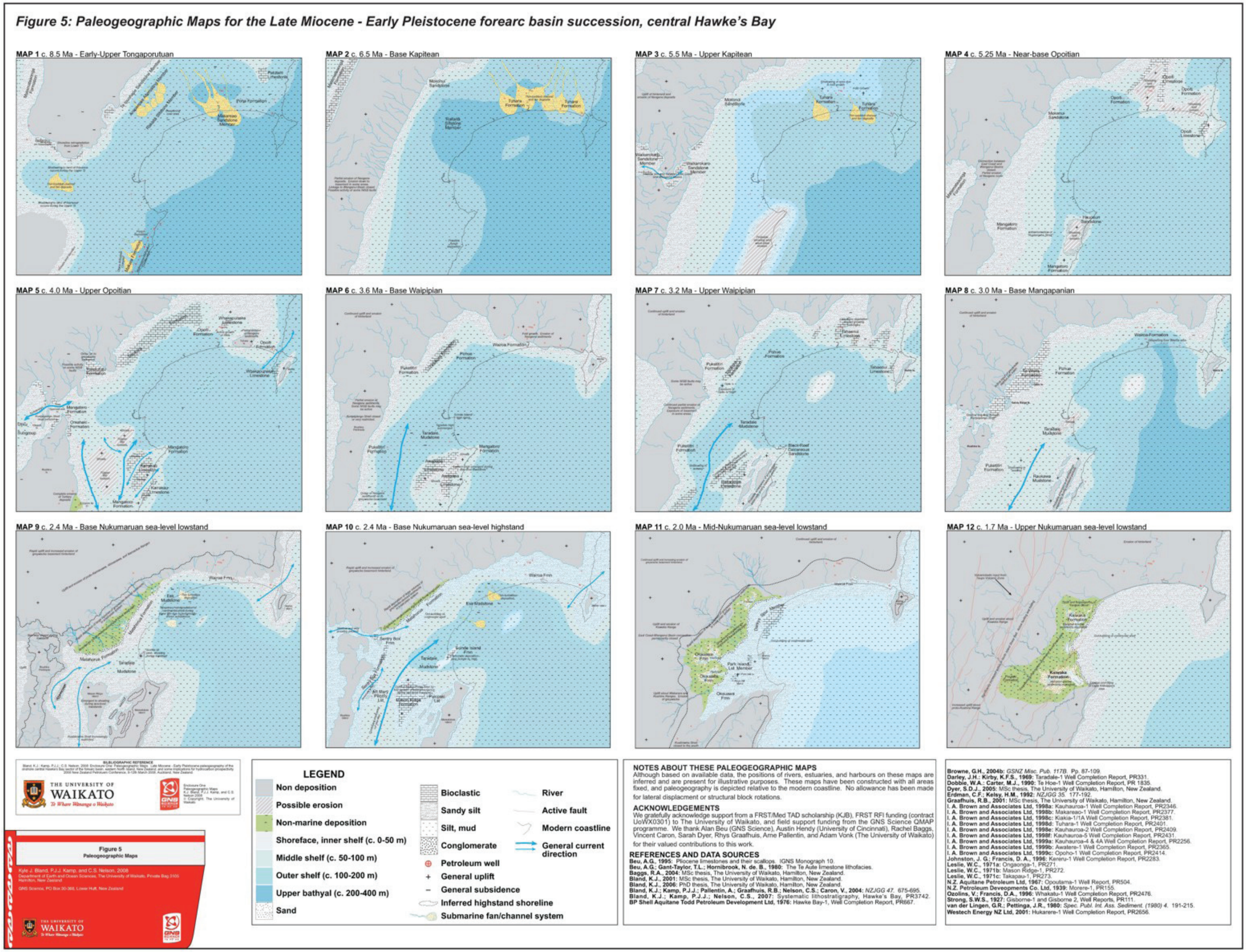
The siliciclastic Pohue Formation started to accumulate during the lower Waipipian in the Maungaharuru area (Graafhuis, 2001), when Titiokura Formation was accumulating to the south in the vicinity of the present-day Te Waka Range (Bland et al., 2004). By the end of the lower Mangapanian Pohue Formation was accumulating over the Te Waka Formation (Brash, 1982; Bland et al., 2007). The Te Waka Formation has not been identified in the Maungaharuru Range, but Pohue Formation is extensively mapped on its lower eastern slopes. By the upper Mangapanian the sandstone facies of the Pohue Formation had accumulating over Te Waka Formation from the Te Waka Range in the north to the Glenross Range in the south, and it is clear that this facies interfingers with Te Waka limestone facies south of SH5. The sandstone facies gave way to the accumulation of greywacke conglomerate (Matahorua Formation) in the uppermost Mangapanian (Bland et al., 2007), indicating uplift and exposure of basement northwest of SH5 in the Ahimanawa and Ikawhenua Ranges. The deposition of four prominent conglomerate units was associated with basinward progradation of a fluvial braidplain system during periods of eustatic sea-level fall and lowstand (Bland et al., this volume).

In Hawke Bay-1 the well record indicates mostly sandy siltstone deposition, although a 12 m-thick interval of coquina limestone was reported, possibly suggesting the development of a carbonate source on the structure (BP Shell Aquitane Todd Petroleum Development Ltd, 1976). Middle- to outer-shelf mudstone accumulated in the vicinity of Taradale-1 (Darley & Kirby, 1969; Beu, 1995) and Mason Ridge-1 (Leslie, 1971b), upper bathyal mudstone at Whakatu-1 (Ozolins & Francis, 2000), and upper bathyal to middle shelf mudstone accumulated over Kereru-1 (Johnston & Francis, 1996). No Mangapanian rocks were intercepted in Hukarere-1 (WENZ, 2001; Morgans & Wilson, 2002), with the Scinde Island high inferred to have been near sea level at this time. Outer shelf to upper bathyal siliciclastic lithofacies of the Wairoa Formation continued to accumulate in the Wairoa Sub-basin during the Mangapanian.

Latest Pliocene to Pleistocene

Nukumaruan (2.43 - 1.63 Ma)

The Nukumaruan record in central Hawke's Bay (Fig. 5 or see Enclosure 1) is characterised by the development of prominent cyclothems (e.g. Haywick et al., 1992; Bland et al., this volume), and by the intensification of deformation in both the North Island Shear Belt and the accretionary wedge (e.g. Erdman & Kelsey, 1992; Beanland et al., 1998; Nicol et al.,



NOTES ABOUT THESE PALEOGEOGRAPHIC MAPS

Although based on available data, the positions of rivers, estuaries, and harbours on these maps are inferred and are present for illustrative purposes. These maps have been constructed with all areas fixed, and paleogeography is depicted relative to the modern coastline. No allowance has been made for lateral displacment or structural block rotations.

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Fig. 5. Late Miocene - Pleistocene paleogeographic map enclosure.

2002; Bland, 2006). Regular sea-level oscillations of about 60-70 m occurred throughout the stage (Beu, 1995), at times strongly controlling the distribution of lithofacies belts. Limestone deposition is recorded from both the lowermost and upper parts of the Nukumaruan, although is absent from middle parts. Sediment flux was high, and ranged from about 0.3-2.6 m/k.y. (Haywick et al., 1991; Bland, 2006).

The eastern margin probably comprised a relatively elevated, continuous landmass by this time. The Ruataniwha Strait was open at its northern and southern ends in the lower Nukumaruan, although the southern end was closed by the upper Nukumaruan (Beu, 1995).

The base of the Nukumaruan is defined by the occurrence of Zygochlamys delicatula, and a short-lived northward migration of this subantarctic pectinid into southern North Island (Beu et al., 1977, 1981; Beu, 1995; Orpin et al., 1998) has been mapped. This scallop occurs in the Sentry Box Formation along the western margin of the basin from the Ohara Depression to Kuripapango (Erdman & Kelsey, 1992; Beu, 1995; Browne, 2004a; Bland, 2006). The presence of shallow-marine Sentry Box Formation on the Ruahine and Kaweka Ranges (Beu et al., 1981; Beu, 1995; Browne, 2004a) demonstrates that these ranges were mostly at shelf depths during the lowermost Nukumaruan. Farther to the northeast, cyclothemic conglomerate beds of the Matahorua Formation were deposited. The braidplain associated with the Matahorua Formation was at its greatest extent in the lowermost Nukumaruan, extending from Waiwhare in the southwest to at least Willowflat Road in the northeast (Fig. 5; Bland, 2006), with its basinward edge no closer than about 10 km northeast of the modern Hawke's Bay coast. Coevally, along the eastern side of the basin, Scinde Island Formation (Boyle, 1987), Mason Ridge Formation (Dyer, 2005), and Pakipaki Limestone (Beu, 1995) were deposited on and around structural highs, probably associated with the growing accretionary wedge. In all other parts of central Hawke's Bay the Taradale Mudstone continued to accumulate at shelf water depths, and in the Wairoa Sub-basin deposition of the Wairoa Formation probably continued at shelf to uppermost bathyal depths.

The Wakarara Range comprised a shoaling to semi-emergent basement island during lowermost Nukumaruan time, and deposition of Mount Mary Pebbly Limestone occurred around its flanks (Erdman & Kelsey, 1992; Bland et al., 2007). At about 2.36 - 2.3 Ma, marked subsidence occurred across central Hawke's Bay leading to accumulation of Esk Mudstone (Bland et al., 2007). This facies accumulated over both the Mount Mary Pebbly Limestone and Torlesse basement on the Wakarara Range. Farther to the northeast, non- to marginal-marine beds of the Grassy Knoll Conglomerate Member were overlain by outer shelf to upper bathyal Esk Mudstone and, further north again, Esk Mudstone overlay shelf Waipunga Formation. Shallow-marine (inner shelf) sandstone beds of upper Mangapanian age in the lower reaches of the Mohaka River (Beu & Maxwell, 1990) were overlain by lower Nukumaruan mudstone containing thin turbidites (Beu, 1995). It is uncertain what effect this rapid subsidence had on the eastern margin of the basin where shelf Scinde Island Formation (Boyle, 1987), Mason Ridge Formation (Dyer, 2005), and Pakipaki Limestone (Beu, 1995) had accumulated, as no Mangaheia Group sediments of this age are preserved. Certainly, Taradale Mudstone continued to accumulate around the Napier and Maraekakaho areas. It is possible that the structural highs at Scinde Island, Mason Ridge, and Pakipaki remained reasonably elevated during this period.

The Wakarara block of basement began to rise again at about 2.2 Ma and by about 2.15 Ma it was an island again, although the main phase of uplift of this range probably didn't occur until after deposition of the marginal-marine upper Nukumaruan Poutaki Formation (Erdman & Kelsey, 1992) at about 1.7-1.6 Ma (Bland, 2006). Uplift of the Wakarara Island was centred on the Big Hill-Ohara Depression section of the Mohaka Fault and the Wakarara Fault, and its emergence resulted in deposition of shallow-marine Kereru Formation around its margins (Erdman & Kelsey, 1992; Bland et al., 2007). It is likely that the Ruahine and Kaweka Ranges also began to rise at this time, finally closing off the connection between Wanganui and East Coast basins, and uplift of the Mount Bruce basement block along the Wairarapa Fault closed off the interior seaway at its southern end (Beu, 1995). The Esk Mudstone and Taradale Mudstone continued to accumulate in deeper (shelf) parts of the basin, and at c. 2.15 Ma cyclothemic deposits of the shelf Petane Formation and Okauawa Formation were first deposited. Braidplain progradation was renewed at this time from two areas, rather than the single system of the earlier Matahorua Formation. During sea level lowstand, a braidplain extended northeast from the Ohara Depression to Flag Range and Mount Cameron, depositing conglomerate beds of the Okauawa Formation (Fig. 5). Coevally, another braidplain prograded southeast over the Tangoio Block and Rissington areas, depositing conglomerate beds in the Tutira and Darkys Spur Members. It is inferred that the two systems then merged into one braidplain system with two main areas of sediment supply, with widespread deposition of the Flag Range Conglomerate Member (Petane Formation) at about 1.84 Ma. Although not preserved in outcrop, it is inferred that fluvial systems also existed during deposition of upper parts of the Mangaheia Group, based on the presence of common to abundant basement clasts in the Tangoio and Waipatiki Limestone Members (Petane Formation), and the Kaiwaka Formation (Haywick et al.,1992; Baggs, 2004; Bland, 2006).

Castlecliffian to Haweran (1.63 Ma - Recent)

Most of the Hawke's Bay area was above sea level by the end of the Nukumaruan (Early Pleistocene, c. 1.6 Ma). The Big Hill Fault developed, probably as a reverse fault, and contraction across it elevated the Big Hill basement block (Erdman & Kelsey, 1992). By about 1 Ma, the rate of uplift of the North Island axial ranges, especially the parts south of Kuripapango, had dramatically increased. This resulted in a substantial volume of greywacke detritus entering central Hawke's Bay with the widespread accumulation of thick greywacke conglomerate and marginal-marine beds of the Kidnappers Group. At this time a small basin developed west of Cape Kidnappers allowing accumulation of the Kidnappers Group (Kingma, 1971; Kamp, 1978). Prior to this basin forming, the area had been emergent due to uplift of the inboard part of the accretionary wedge, resulting in the development of an angular unconformity between Waipipian Black Reef Calcareous Sandstone (Mangaheia Group) and Castlecliffian Maraetotara Sandstone (Kidnappers Group) at Black Reef. The non-marine Salisbury Gravel, preserved along the axial range front and high hills to the east (Erdman & Kelsey, 1992; Dyer, 2005; Bland et al., 2007), represents the deposits of significant river systems that transported sediments to estuaries at Cape Kidnappers and Hawke Bay generally.

The increase in rate of uplift of the Ruahine Range at about 1 Ma coincides with the time when the Big Hill Fault began to accommodate strike-slip displacement (Erdman & Kelsey, 1992). Many contractional structures formed in the Ohara Depression during this period, including the Herricks Syncline and Anticline, and the Matapuna Fault. The Balcony Syncline, essentially a drag-fold abutting the downthrown side of the Big Hill-Ohara Depression section of the Mohaka Fault, formed as a result of uplift of the Wakarara Range (Erdman & Kelsey 1992; Bland & Kamp, 2006). The Wakarara Fault continued to displace basement, with the Wakarara Range rising on its western side; rocks along the eastern margin of the Wakarara Range continued to become involved in the Wakarara Monocline (Erdman & Kelsey, 1992; Bland, 2006). To the north in the Kuripapango area, the Miroroa Thrust (Browne, 1986) was probably active as a relay structure between the Comet and Ruahine Faults (Beanland, 1995).

Although various segments of the Mohaka Fault appear to have been active during the Neogene, inception of strike-slip displacement on the Mohaka Fault has probably only occurred since c. 0.5 Ma (Beanland, 1995; Beanland et al., 1998). Dextral-slip in the North Island Shear Belt has apparently continued to migrate outboard in association with on-going rotation of eastern North Island (e.g. Wallace et al., 2004; Nicol & Wallace, 2007). The Ruahine Fault may have started accommodating significant dextral-slip by 2.0 - 1.8 Ma (Erdman & Kelsey, 1992; Bland & Kamp, 2006), the Mohaka Fault was almost certainly accommodating dextral-slip by the Haweran (0.34 Ma; Beanland et al., 1998), and the more outboard Patoka and Rangiora faults began accommodating dextral-slip during the Holocene (0.01 Ma; Cutten et al., 1988; Halliday et al., 2003). In the Ohara Depression, the Ruahine Fault is presently moving on average 1.0 - 2.0 mm/yr and the Mohaka Fault is moving at 3.0 -4.0 mm/yr (Raub et al., 1987; Erdman & Kelsey, 1992).

By the Late Pleistocene (Haweran) the Hawke's Bay area was almost entirely non-marine, and by c. 300 ka virtually the entire forearc basin had been uplifted. Beanland (1995) suggested that since the Late Quaternary regional uplift of the Hawke's Bay has been driven by a deep-seated crustal process, probably related to crustal thickening by sediment underplating. Reyners et al. (2006) have suggested that subduction of the buoyant Hikurangi Plateau is driving uplift of the forearc basin.

Implications for hydrocarbon prospectivity

The paleogeography presented here (Fig. 5) for the Hawke's Bay area is inferred from the distribution of lithofacies and the nature of related depositional systems, and so provides a basis to comment upon the hydrocarbon prospectivity of the basin. The presence of several gas seeps in the central Hawke's

Bay area attests to an active hydrocarbon system, and that generation and expulsion thresholds have been reached in places (e.g. Francis, 1995). Near-commercial gas deposits have been discovered in the Wairoa area (Kauhauroa-1; IRBA, 1998a), and Te Hoe-1 flowed sub-commercial gas on reservoir test from Middle Cretaceous Te Kooti Sandstone. The lack of source rocks in Te Hoe-1 indicates that moveable hydrocarbons exist in the area (Dobbie & Carter, 1990). In Taradale-1, Pliocene-aged Taradale Mudstone unconformably overlies Wanstead Formation (Darley & Kirby, 1969). Relatively high gas levels were recorded from Mangapanian mudstone in the well, and gas leaked at 12 MSCFD from behind the 20” casing once the well was abandoned.

Source

Potential source rocks are present beneath many parts of the basin, especially central areas that were not significantly uplifted during the Neogene. The Upper Calcareous Member of the Late Cretaceous – Paleocene Whangai Formation and the Paleocene Waipawa Formation are the source rocks with most potential in the basin. Both are likely to be present beneath much of the Hawke’s Bay area. Mudstone beds within the Cretaceous Glenburn Formation have exhibited some excellent gas-generation potential (Field et al., 1997). The Glenburn and Whangai Formations were intercepted in Hukarere-1 (WENZ, 2001), although the Waipawa Formation was absent. All pre-Pliocene Cenozoic rocks, including potential source rocks, were found to be absent in Ongaonga-1 and Takapau-1, where Late Pliocene limestone unconformably overlies basement (Leslie, 1971a, c). This is consistent with much of the western margin of the basin, where late Neogene uplift and erosion has removed large parts of the Paleogene-Neogene succession.

Reservoir

Intervals of Miocene sandstone, deposited in shelf and bathyal settings, are the most promising Neogene reservoir intervals in the Hawke’s Bay area. They tend to be thicker, more continuous, and more widely distributed than younger Plio-Pleistocene sandstone beds, whose distribution has been strongly controlled by glacio-eustatic sea-level fluctuations. The Early Miocene Whakamarino Formation contains redeposited sandstone beds interbedded with mudstone, and is probably widespread in western parts of the basin, although their reservoir quality and thickness in the subsurface remains uncertain. The Middle Miocene Ngatapa Sandstone Member (Poamoko Formation), Late Miocene Te Ipuohape Sandstone Member (Waitere Formation), and Late Miocene – Early Pliocene Mokonui Sandstone represent significant intervals of shelf sandstone that are likely to have been deposited across large parts of the western basin margin. Both the Ngatapa Sandstone and Te Ipuohape Sandstone Members are overlain by thick intervals of mudstone. The distribution of Late Miocene mass-emplaced sandstone beds in the Wairoa Sub-basin, such as the Tunanui, Makaretu, Makareao, and Tuhara sandstone beds, may have been controlled by growing folds, with the sand bodies directed into the synclines between growing anticlines and pinching out on the flanks of the highs. Similarly, the distribution of mass-emplaced sandstone beds in eastern parts of the basin was strongly controlled by structural highs associated with the accretionary wedge (e.g. van der Lingen & Pettinga, 1980).

Although the Pliocene Te Aute lithofacies limestones have been reservoir targets for exploration drilling in the past, they appear not to be extensively distributed in the subsurface, and probably only occur at shallow depths. The thick Kairakau Limestone and Awapapa Limestone were not present in Whakatu-1 (Ozolins & Francis, 2000), even though the well-site lies only about 6 km from the prominent dipslope of Te Mata Peak. Similarly, Te Aute lithofacies limestones were also absent in Taradale-1, Mason Ridge-1, and Kereru-1, even though these rocks crop out in nearby locations. This indicates that Te Aute limestone facies along eastern margins of the basin only occur in close proximity to the structural highs upon which the related carbonate factories developed. The Late Pliocene (Waipipian) Tahaenui Limestone was penetrated at relatively shallow depths (c. 20-690 m AHBKB) by several wells in the Wairoa area, including Awatere-1, Kauhauroa-2 and -5, Kiakia-1, Tuhara-1, and Opoho-1 (IRBA, 1998b-e, 1999a, b). These wells were drilled above structural highs upon which the limestone was deposited. Only in Kauhauroa-2 were any older Pliocene limestone lithofacies intercepted, such as the Whakapunake Limestone or Opoiti Limestone Member (IRBA, 1998d), illustrating the restricted distribution of these formations in subcrop. Early to Middle Miocene limestone beds intercepted in several exploration holes (e.g. Awatere-1, Kauhauroa-1, 2, and -5, Kiakia-1, Makareao-1, and Whakatu-1) and present in outcrop outside the central/northern Hawke’s Bay area, such as the Kauhauroa (Early Miocene, Altonian), Waipuna (Middle Miocene, Waiauan), and Kiakia Limestones (Late Miocene, lower Tongaporutuan), offer potential as reservoir beds.

Seal

Potential seal rocks, mostly represented by siliciclastic mudstone lithofacies, are laterally and vertically widespread in the forearc basin fill of Hawke's Bay. The deep-water environments present during the Miocene mean that upper bathyal mudstone beds in the Miocene Tolaga Group are the most obvious sealing intervals due to their monotonous composition, thickness and wide distribution. These potential Miocene seals include the Pindari Mudstone and Poha Formation (Wairoa Sub-basin), and Kingma Peak Mudstone Member and Rakaita Siltstone Member (central and western Hawke's Bay). The thickest and most widespread Pliocene (Mangaheia Group) seal rocks include the Taradale Mudstone, Puketitiri Formation, and Mangatoro Formation. All of these seal intervals accumulated in near-axial parts of the basin, away from emerging landmasses and structural highs.

The smectitic Eocene-aged Wanstead Formation, widespread beneath Hawke's Bay, is likely to have sealed hydrocarbons migrating from Cretaceous and Paleocene sources, including the Upper Calcareous Member of the Whangai Formation and the Waipawa Formation (Field et al., 1997). The Wanstead Formation was intercepted in Whakatu-1 (Ozolins & Francis, 2000). The Oligocene Weber Formation, a basin-wide calcareous mudstone, has been intercepted by several exploration wells including Makareao-1, Opoho-1, and Hukarere-1. These rocks may provide adequate seal for older Paleogene reservoirs.

Structure

Miocene phases of deformation, especially during the Altonian, Waiauan, and Tongaporutuan/Kapitean Stages, may have produced structures suitable as traps. These structures have since been buried by significant thicknesses (> 2 km) of late Neogene rocks. It is possible that some may have become reactivated during late Neogene time.

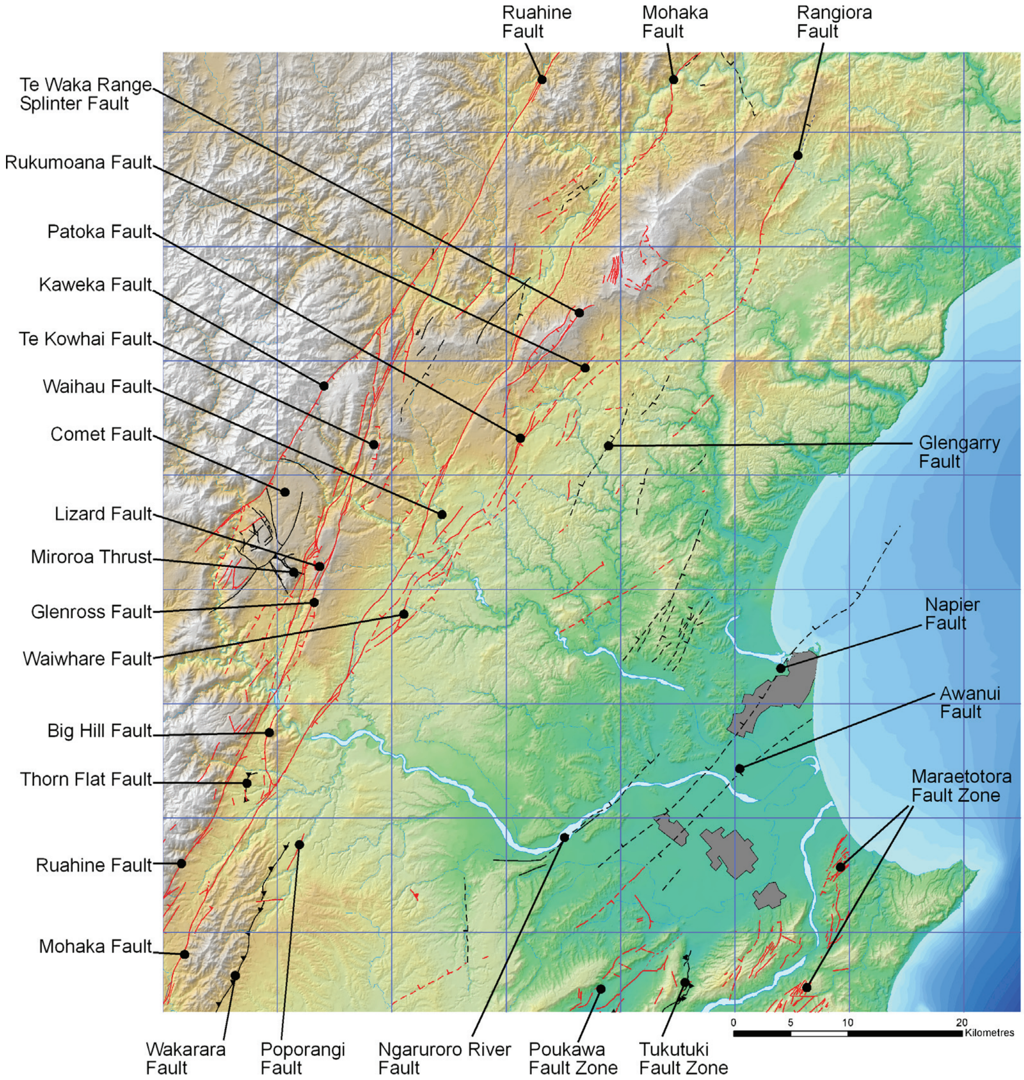

Fig 6. Map of Hawke's Bay showing faults active during the late Neogene.

Late-phase (upper Nukumaruan to Recent) deformation has affected many parts of the late Neogene succession (Fig. 6 & 7). Many fold structures associated with the North Island Shear Belt have formed during this current phase of deformation which commenced c. 2.0-1.8 Ma. However, it is uncertain whether these structures were in place when any potential hydrocarbon migration occurred. The present phase of deformation in the basin also poses obvious risks to the structural integrity of traps. Structures formed during the Early to Middle phase of deformation may still remain the best exploration targets. They will probably be buried by substantial thicknesses of mudstone, are potentially at depth where underlying source rocks are actively expelling hydrocarbons, and should contain several intervals of potential reservoir beds.

Charge and migration

The rapid burial of the forearc basin in the late Neogene, where over 2.5 km of sediment was deposited in about 5 m.y., may have driven late-phase generation and migration of hydrocarbons in this part of central Hawke's Bay. Potential source rocks form some of the oldest rocks in the basin, so they should be located beneath potential Neogene traps. The presence of many oil and gas seeps in Hawke's Bay attests to the presence of an active petroleum system (e.g. Francis, 1995), and that burial depths sufficient for hydrocarbon generation have been reached in many parts of the basin.

Summary

The revised paleogeographic interpretations presented here have been developed from the recent compilation of a variety of datasets, including detailed field mapping and petroleum exploration holes. Tectonic movement has been the most important factor controlling the stratigraphic and paleogeographic architecture of the Hawke's Bay region. Early Neogene sedimentation was characterised by the deposition of thick successions of bathyal mudstone, punctu-

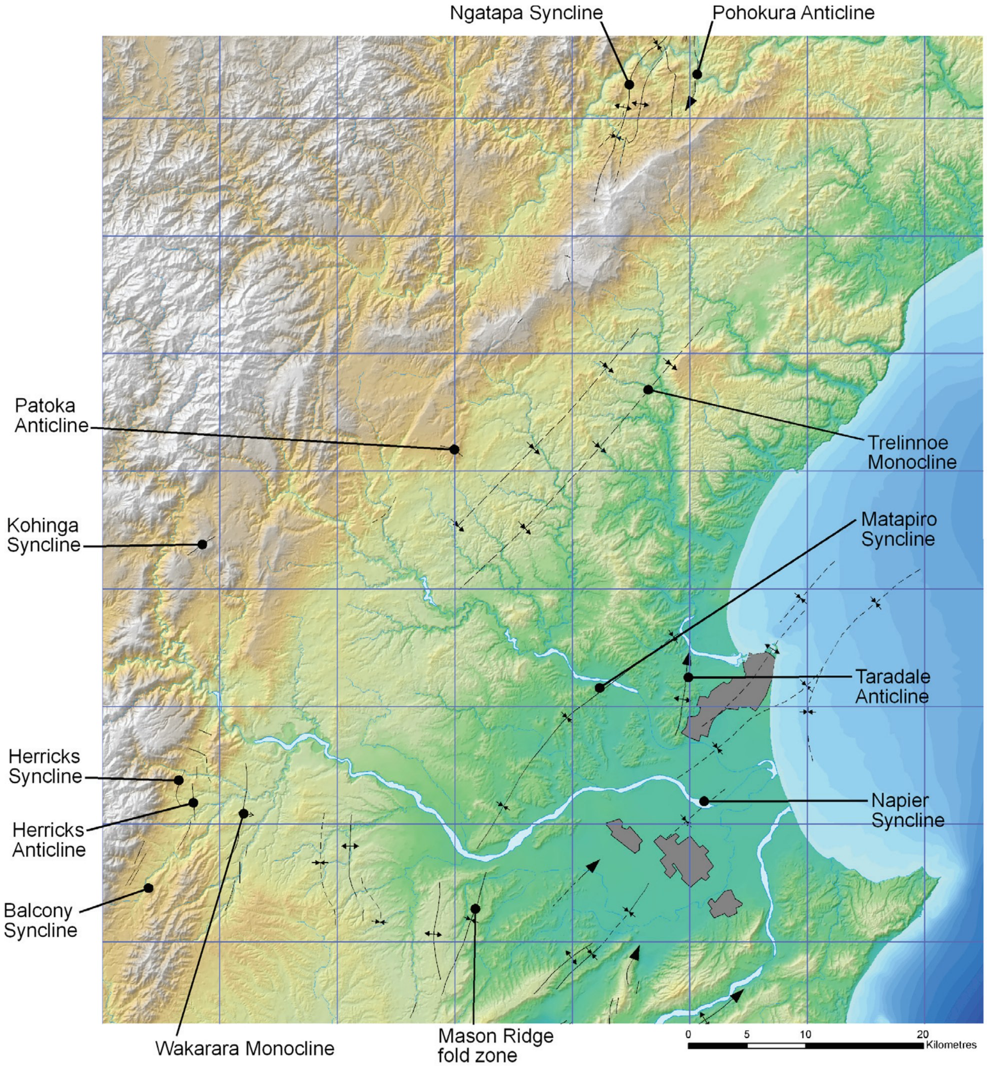

Fig 7. Map of Hawke's Bay showing folds active during the late Neogene.

ated by mass-emplaced sandstone lithofacies. Periods of accelerated uplift and deformation resulted in the formation of many structural features and unconformities in many parts of the basin. The distribution of lithofacies belts during the Late Neogene was often strongly controlled by glacio-eustatic oscillations in sea level, although tectonically-driven uplift and subsidence was still an important factor.

Hydrocarbon source rocks are probably widespread beneath central parts of the basin, but are absent along much of the western side of the basin due to extensive Neogene uplift and erosion. Significantly, widespread intervals of reservoir rocks were deposited across much of the Hawke's Bay area, as were thick successions of fine-grained mudstone. The quality of potential reservoir intervals in subcrop remains uncertain, however, due to a lack of subsurface information from sources such as cuttings and drill core. Early Neogene traps formed during Miocene compressional events in the forearc remain the most likely structural traps to be targeted. However, their structural integrity needs to be carefully considered in light of the current phase of deformation affecting the basin.

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