Timing of initiation of reverse displacement on the Taranaki Fault, northern Taranaki Basin: Constraints from the on land record (Oligocene Te Kuiti Group)

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Abstract

Structures associated with the wedge of basement overthrust into Taranaki Basin along the Taranaki Fault, are regarded as hydrocarbon plays and have been tested by drilling through the tip of the overthrust. The timing of initiation of reverse displacement on Taranaki Fault is difficult to interpret from available seismic reflection data across it because the evidence has been masked by later movements. The record from the basin, as summarised in King & Thrasher (1996), suggests that the fault evolved from normal to reverse character during the mid-Oligocene. This was inferred from formation of a foredeep parallel to, and west of, Taranaki Fault and a marked increase in its paleo-water depth, as indicated by foraminiferal assemblages of Late Oligocene age.

A comprehensive re-assessment of the lithostratigraphy and sequence stratigraphy of the Late Eocene-Oligocene Te Kuiti Group exposed on land east of Taranaki Fault in central-western North Island, between Port Waikato and Awakino, provides new constraints on the early history of Taranaki Fault displacement. New age control has been achieved by a review of existing foraminiferal biostratigraphy combined with determination of Sr isotope ages from macrofossil samples. Six unconformity-bound sequences have been identified and mapped within the Te Kuiti Group. A major subaerial unconformity between sequences TK3 and TK4 combined with a basinward shift in the position of onlap for sequence TK4 indicate a dramatic change in stratigraphic development and basin dynamics during the mid-upper Whaingaroan at c. 29 Ma, corresponding to the change from mild extension (sag basin) to shortening across the Taranaki Fault Zone. We consider sequences TK4 – TK6 to each represent tectonic cycles of subsidence and basin inversion and we attribute the origin of these cycles to periodic locking of the Taranaki Fault décollement in underlying Murihiku basement, the accumulating strain causing uplift in the basin east of the fault zone, followed by free displacement, relaxation in the upper crust and subsidence. A 1st-order model is presented of the Late Oligocene to earliest Miocene vertical and horizontal displacement of basement on the Taranaki Fault Zone for a west –east transect through Awakino. It implies that the mid- to Late Oligocene displacement on the fault zone in the vicinity of Awakino was episodic, and that the thrust belt was narrow (c. 15 km). North of Kawhia Harbour there will have been a different displacement history with most of the total displacement occurring during the development of the c. 29 Ma unconformity at the base of Sequence TK4, whereas to the south between Awakino and Kawhia Harbour the majority of the total displacement occurred during the Otaian and at the end of it. The model also shows that the start of reverse/thrust displacement on Taranaki Fault must have involved the development of a completely new fault trace(s), rather than involving a change of sense of movement on the pre-existing normal fault. The Manganui Fault is part of the Taranaki Fault Zone and probably became active at c. 27 Ma during development of the unconformity between sequences TK4 & TK5. The model presented here has been validated against the subsurface Oligocene stratigraphy in Taranaki Basin.

Key Words:

Sequence stratigraphy, Te Kuiti Group, Eocene, Oligocene, Taranaki Fault Zone, Waikato region; Taranaki Basin.

Introduction

The Taranaki Fault Zone is a significant crustal scale structure within the eastern margin of Taranaki Basin (Fig. 1). This fault extends north – south for about 250 km mostly offshore central-western North Island, although it is part of a longer fault system extending for about 600 km from east Nelson to offshore southern Northland (Fig. 1). It forms an inter linkage of overlapping fault strands having variable strike and dip, variable amounts of throw, and different initial character and age. Much of the present character of the fault zone in the vicinity of Awakino can be attributed to early Miocene displacement on

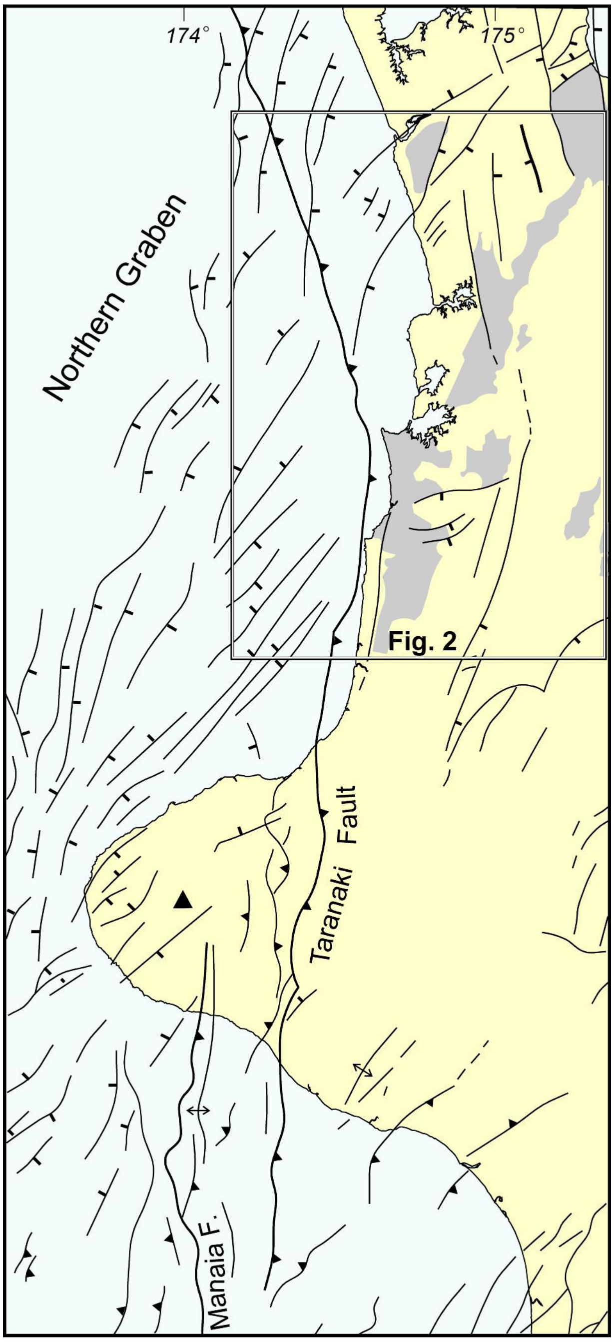


Fig. 1. Location map showing structural divisions and the principal tectonic features of Taranaki Basin. Note the extent of Fig. 2.

reverse and related thrust faults, which resulted in westward transport and emplacement of basement over parts of the Paleogene sedimentary succession along the eastern Margin of Taranaki Basin; thrusts that splay into the sedimentary succession west of the basement overthrust (e.g. Tarata Thrust Zone) converge eastward with the main thrust system beneath the basement wedge, forming a series of anticlines within the sedimentary succession, many of which have been tested by drilling and have proved to contain oil and gas (e.g. Ngaere-Waihapa Field) (King & Thrasher, 1996). Seismically imaged structures in the sedimentary succession beneath the main thrust have also been regarded as hydrocarbon plays and have been tested by the drilling of several holes through the tip of the basement wedge in different places (e.g. Te Rangi-1, Pukearuhe-1, Huinga-1, Rotokare-1, Rimu-1, Kauri-1).

Several features of the Taranaki Fault Zone have emerged from previous exploration and research activity: (i) the magnitude and importance of mid-Oligocene - Early Miocene displacement (e.g. King & Thrasher, 1996); (ii) evidence for at least part of the fault zone (Manganui Fault) having had mid-Cretaceous reverse displacement (Kamp et al., 2002), (iii) Late Cretaceous normal displacement (Thrasher, 1990; Kamp & Liddell, 2000); and (iv), clear southward progression along the fault zone of decreasing age within the Neogene when the last reverse displacement occurred (King & Thrasher, 1996; Vonk & Kamp, 2002; Kamp et al., 2004; Nicol et al., 2004).

Knowledge about the mid-Oligocene - Early Miocene development of the present character of this thrust zone is relatively limited, but it nevertheless had a significant impact on the development of Taranaki Basin and its hydrocarbon prospectivity. Overthrusting of the basement wedge along the Taranaki Fault Zone required the formation of a new fault trace, albeit very close to the pre-existing normal fault, which helped determined where the crustal shortening would be expressed. An important feature of the mid-Oligocene - early Miocene phase of structural inversion is the narrow band of topography developed above sea level on the hanging wall and within the fault zone. This is evident from the persistence of depocentres that accumulated Oligocene and Miocene marine strata (Te Kuiti and Mahoenui groups) immediately east of the basement involved in the hanging wall of Taranaki Fault.

An important question to be resolved is the exact timing of the initiation of significant reverse movement on Taranaki Fault. The established view is that this occurred near the middle of the Whaingaroan Stage at about 28-32 Ma (King & Thrasher, 1996), although a Middle Eocene age has recently been proposed (Stagpoole & Nicol, in press). The mid-Oligocene age is based on assessment of Taranaki Basin stratigraphy and in particular the middle Oligocene timing of a rapid increase in paleobathymetry (Hayward, 1993) in the Taranaki Peninsula area that led to the development of a foredeep west of the overthrust basement wedge, viewed as having

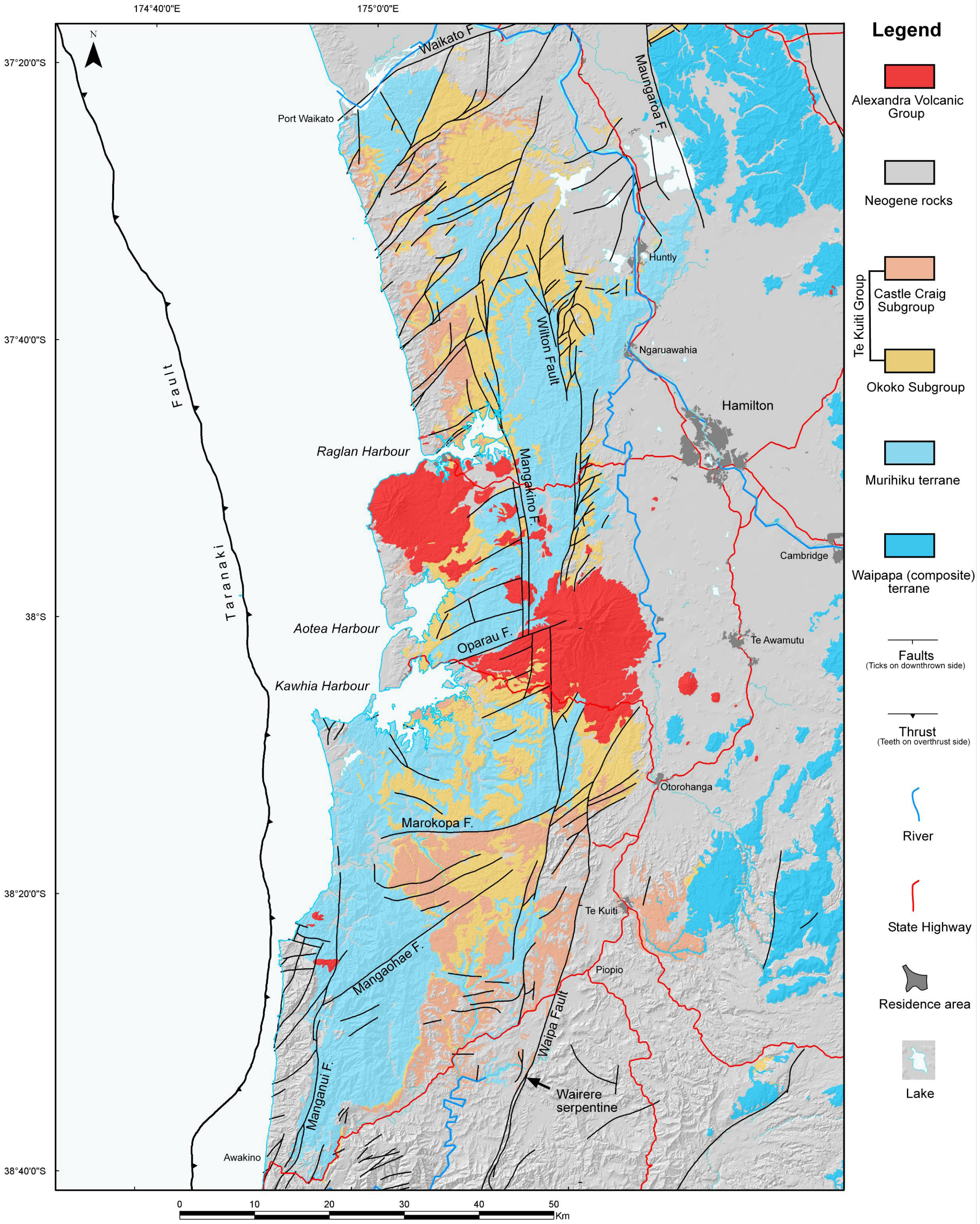


Fig. 2. Geological map of the Waikato and northern part of the King Country regions, showing the distribution of the Okoko and Castle Craig subgroups of the Te Kuiti Group in relation to other units and the Taranaki Fault.

loaded the basin (Holt & Stern, 1994). The record in the basin adjacent to Taranaki Fault from which the Oligocene timing of the start of reverse movement might be inferred is however complicated by the effects of subsequent basement overthrusting.

The approach we adopt here to determine the timing of initiation of significant reverse displacement within the Taranaki Fault Zone, involves analysis and interpretation of the Oligocene and Early Miocene marine stratigraphic successions in the depocentres east of the fault zone. These sequences record a transition from having accumulated on the footwall of the normal Taranaki Fault to having accumulated on the hanging wall of the fault as displacement changed from normal to reverse (actually, a new fault formed). Earlier examination of upper parts of this marine succession (Nelson et al., 1994) inferred a Late Oligocene (Whaingaroan - Duntroonian boundary, c. 27 Ma) initiation of reverse fault displacement from changes in bedding dip and especially sedimentologic evidence of reworked and mass-emplaced bored limestone intraclasts in the Orahiri Limestone, the intraclasts probably having been derived from an uplifted hanging wall block within the Taranaki Fault Zone. In this paper we apply new understanding about the Oligocene Te Kuiti Group stratigraphy in the Waikato-King Country region to show that the reverse fault displacement in the section of the Taranaki Fault Zone between Awakino River mouth and Raglan Harbour started earlier at c. 29 Ma (mid-upper Whaingaroan). This marked the start of a 6 m.y. phase (29-23 Ma) of episodic displacement on the Taranaki Fault Zone driven by stress arising within the crust east of the Taranaki Fault Zone mainly in eastern North Island, as the through-going continental transform (Alpine Fault) evolved ahead of the start of Hikurangi margin subduction (Kamp & Furlong, 2006).

Structure of the Taranaki Fault Zone

Taranaki Fault is a major east-dipping, thick-skinned fault with dips of 25-45 degrees to depths of at least 12 km, and possibly to the base of the crust (Stagpoole & Nicol, in press). Taranaki Fault extends for at least 250 km through offshore central-western North Island and is part of a longer (600 km) fault system including the Manaia and Waimea-Flaxmore faults (Fig.1) (King & Thrasher, 1996). The fault zone strikes north-south through the Taranaki Peninsula. North of Te Ranga-1 there is a 25 degree change in strike to the north-northwest. Stagpoole & Nicol (in press) have shown from seismic reflection data that in many places the fault zone comprises multiple slip surfaces that may splay from the main fault surface to occur entirely within the Cenozoic sedimentary succession (e.g. Tarata Thrust Zone), or occur as surfaces resulting in interdigitating basement and Cretaceous-Cenozoic strata, or occur as surfaces confined entirely to the basement wedge. The fault zone has accommodated at least 12-15 km of dip-slip displacement.

A north-trending basement ridge lies east of Taranaki Fault, being emergent as the Herangi High between Awakino and Kawhia Harbour, and buried in the subsurface to the south as the Patea-Tongaporutu High. Manganui Fault (Happy, 1971; Campbell & Raine, 1989) is a prominent fault parallel to Taranaki Fault lying within the Herangi Range, and is regarded as part of the Taranaki Fault Zone (King & Thrasher, 1996). The basement highs are overlain by progressively younger Cenozoic strata to the south. North of Tairua Point Oligocene calcareous beds overlie the Murihiku Terrane basement (Nodder et al., 1990), whereas late-Early Miocene strata overlie it at Awakino, Late Miocene in Uruti-1, latest Miocene (Kapitean) in Manutahi-1, and Pliocene in Wanganui Basin (Prost et al., 2004).

Lithostratigraphy, unconformities and sequences within the Te Kuiti Group

The Te Kuiti Group (Henderson & Ongley, 1923; Kear & Schofield, 1959, 1978; Kear, 1963; Nelson, 1978; White & Waterhouse, 1993) crops out extensively east of the Taranaki Fault Zone in central-western North Island (Edbrooke, 2001, 2005) (Fig. 2). It directly overlies basement, usually with a pronounced angular unconformity. The top basement structure in central-western North Island is strongly influenced by pre-Te Kuiti Group paleotopography (Nelson, 1973), synsedimentary basement uplift (Nelson et al., 1994; Kamp et al., 2002), and penecontemporaneous and especially post-depositional faulting (Hall et al., 2006).

North of Kawhia Harbour most surface exposures of the Te Kuiti Group lie in a belt east of the modern coastline, whereas south of Kawhia Harbour the group crops out in a belt east of the Herangi High (Fig. 2). In its lower parts, immediately above basement, the Te Kuiti Group comprises Waikato Coal Measures, whereas its upper part comprises a marine shelf to upper slope succession. The marine units are extensively eroded from areas farther to the east, however outliers do occur as far east as Coromandel Peninsula (Kear, 1955; Dix & Nelson, 2006). The Te Kuiti Group has been regionally mapped as two subgroups, a lower one named Okoko Subgroup, and an upper one named Castle Craig Subgroup (Tripathi et al., 2008). The Te Kuiti Group is overlain by scattered outcrops of Early Miocene Waitemata Group and Quaternary deposits north of Raglan Harbour, mainly exposed in coastal cliff sections, and by Early Miocene Mahoenui Group south of Raglan Harbour (e.g. Edbrooke, 2001, 2005). The structure of the group is mainly influenced by two sets of normal faults, one striking north-south and the other northeast-southwest (Nelson & Hume, 1987; Spörli et al., 1989) (Fig. 2). The normal faults are mainly of late Neogene age, postdating the Oligocene succession. Over most of the outcrop area the beds are horizontal or have dips of a few degrees. The steepest dips at 31^0 occur near Awakino Tunnel on the eastern flank of the Herangi High (Nelson et al., 1994; Kamp et al., 2002).

As part of our basin analysis of the eastern Taranaki, Waikato and King Country regions we have reviewed, remapped and rationalised Te Kuiti Group stratigraphy (Tripathi et al. 2008) (Figs. 3 & 4). The combination of marked lithofacies variations within and between formations, erosion of the record in critical areas, and burial by younger volcanic deposits has historically led to miscorrelation of units and the introduction of multiple names for particular units. Rationalisation of the lithostratigraphy of the Te Kuiti Group has been a necessary prerequisite to being able to identify the geological signals with it. In our revised scheme, seven formations and 24 members of Kaiatan to Waitakian (Late Eocene to Early Miocene) age are identified (Fig. 3).

As part of the present study, detailed section descriptions and correlations were made for the known extent of the Te Kuiti Group in central-western North Island. The facies details and inferred contact types and relationships between lithologic units are presented in a stratigraphic synthesis (Tripathi et al., in prep.). Special emphasis has been given to the significant stratigraphic discontinuities (erosional unconformities, depositional hiatuses) between units. Although several inter- and intra-formational unconformities and disconformities have been reported in past investigations (Kear & Schofield, 1959; Nelson, 1978; White & Waterhouse, 1993, 1994) their extents have not previously been mapped on a regional scale. These stratigraphic discontinuities, when combined with faunal and/or numerical dating, have enabled the correlation of lithologically diverse but time-equivalent stratigraphic units (i.e. depositional systems) across central-western North Island. The Te Kuiti Group has been classified into

Waikato (north)				King Country (south)			
White & Waterhouse (1993)		This study		White & Waterhouse (1993)		This study	
Waitemata Group				Mahoenui Group			
		Castle Craig Subgroup				Castle Craig Subgroup	
Otorohanga Lst		Regarded as Waitemata Group basal units		Otorohanga Lst	Piopio Lst Waitanguru Lst Pakeho Lst	Otorohanga Lst	Piopio Lst Waitanguru Lst Pakeho Lst
Waitomo Sst				Waitomo Sst			
Te Akatea Fm	Carter Zst Raglan Lst	Te Akatea Fm	Carter Zst Raglan Lst	Orahiri Lst	Te Anga Lst Mangaotaki Lst	Orahiri Fm	Waitomo Sst Te Anga Lst Mangaotaki Lst
		Okoko Subgroup				Okoko Subgroup	
Aotea Fm	Patikirau Zst Mangiti Sst Waimai Lst	Aotea Fm	Patikirau Zst Waimai Lst / Mangiti Sst	Aotea Fm	Kihi Sst Hauturu Sst Waimai Lst	Aotea Fm	Kihi Sst Hauturu Sst / Waimai Lst
Whaingaroa Fm	Kotuku Zst	Whaingaroa Fm	Waikorea Sst Kotuku Zst	Whaingaroa Fm	Orotangi Sst Kotuku Zst Awamarino Lst	Whaingaroa Fm	Ngapaenga Zst Awaroa Lst
Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst	Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst	Glen Massey Fm	Ahirau Sst Elgood Lst	Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst
Mangakotuku Fm	Rotowaro Zst Pukemiro Sst Glen Afton Cst	Mangakotuku Fm	Waikaretu Sst Rotowaro Zst Pukemiro Sst Glen Afton Cst	Mangakotuku Fm	Undifferentiated	Mangakotuku Fm	Waikaretu Sst Rotowaro Zst
Waikato Coal Measures		Waikato Coal Measures		Waikato Coal Measures		Waikato Coal Measures	

Fig. 3. *Te Kuiti Group stratigraphic nomenclature adopted here versus in White & Waterhouse (1993).*

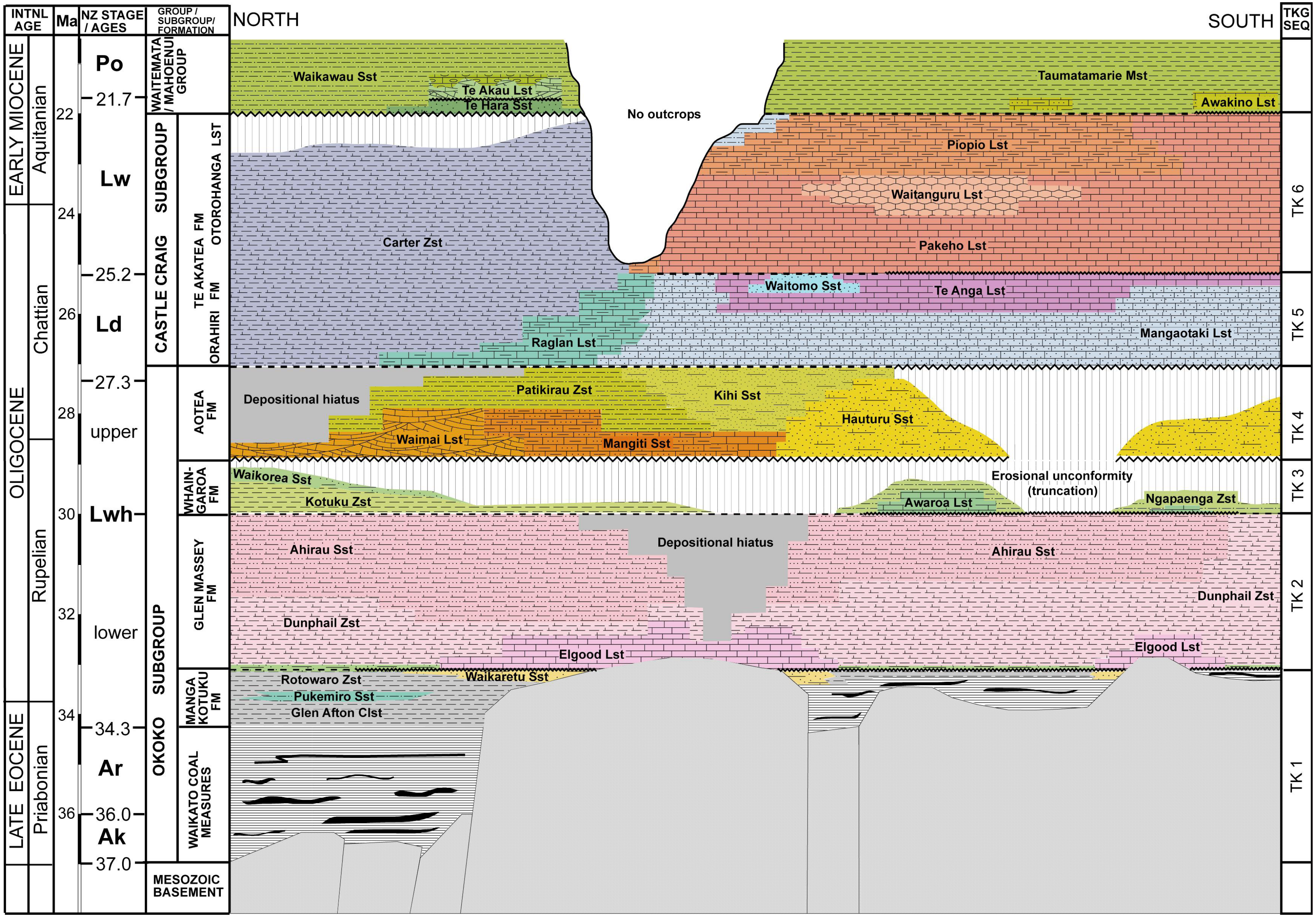


Fig. 4. *Chronostratigraphic panel of the Te Kuiti Group arranged north-south, showing the stratigraphic extent of unconformity-bound sequences TK1 to TK6.*

six unconformity-bound sequences, although correlative conformities do occur between some sequences, particularly in northern parts of the basin (Fig. 4).

At the broadest level, the Te Kuiti Group is subdivided into two subgroups: the Okoko Subgroup (new) named after Okoko valley in inland Kawhia; and the overlying Castle Craig Subgroup (Barrett, 1962, 1967; Hopkins, 1966, 1970). The Okoko Subgroup is dominated by calcareous siltstone and sandstone members, with limestone members commonly occurring at the base of formations. Four Vail-type sequences, named TK1 to TK4, have been mapped within the Okoko Group (Fig. 4). Sequence TK1 includes the Waikato Coal Measures and the Mangakotuku Formation and records non marine deposition in paleovalleys concurrent with some extensional faulting (Hall et al., 2006), and marine onlap in estuarine and shallow shelf paleoenvironments involving dominantly muddy lithology. Sequence TK2 corresponds to the Glen Massey Formation. Its lowermost member (Elgood Limestone Member) rests unconformably on basement or on the Mangakotuku Formation, the unconformity having been formed through wave planation (transgressive surface of erosion). An important feature of TK2 is that siltstone facies thicken towards the present Herangi Range implying that during the lower Whaingaroan there was minimal topography east of Taranaki Fault between Kawhia Harbour and Awakino. Sequence TK3 corresponds to the Whaingaroa Formation, which primarily comprises siltstone facies, and thin limestone facies where Awaroa Limestone unconformably overlies TK2, the unconformity having formed through wave planation in the south, with a correlative conformity occurring between TK2 and TK3 in the northern and central areas of the basin. The Whaingaroa Formation is very heavily eroded, chiefly as a result of the incision associated with the extensive unconformity at the base of the Aotea Formation, accentuated in the southern region by the erosion associated with the unconformity at the base of the Orahiri Formation (Figs. 4 & 5). Aotea Formation (Sequence TK4) comprises lithologically diverse facies dominated by limestone facies (Waimai Limestone Member) in the north and sandstone facies (Hauturu Sandstone Member) in the south. Hauturu Sandstone is closely associated with the eastern margin of the Herangi Range and the abundance of quartz in its composition indicates supply of an exotic siliciclastic source from the south during the accumulation of the Aotea Formation.

We have identified two sequences within the Castle Craig Subgroup, which contains the bulk of the limestone facies in the Te Kuiti Group (Fig. 4). Sequence TK5 (Orahiri Formation, lower part of Carter Siltstone Member) in the south unconformably overlies either Aotea Formation, Whaingaroa Formation or Glen Massey Formation. The sandy Mangaotaki Limestone Member contains reworked Hauturu Sandstone material, becoming more carbonate rich in the overlying Te Anga Limestone Member. These two shelf limestone members south of Kawhia Harbour link paleogeographically to upper slope facies (Carter Siltstone Member) in the north, initially via the micritic Raglan Limestone Member (Fig. 4). Sequence TK6 (Otorohanga Limestone) unconformably overlies Sequence TK5 southwest of Kawhia Harbour proximal to the Herangi Range, and transitions into Carter Siltstone to the north, although the intervening facies are mostly buried by volcanics. Importantly, both sequences TK5 and TK6 show south-directed retrogradational stacking patterns (Fig. 4).

North of Raglan Harbour a sharp planar surface separates the Te Kuiti Group from the Waitemata Group. The amount of section eroded at this contact increases to the east across South Auckland, as progressively older Te Kuiti Group strata lie beneath the Waitemata Group in that direction (Kear, 1963). In some areas, Te Kuiti Group has been completely removed as a result of this uplift and erosion that preceded Waitemata Group deposition (Kear & Schofield, 1978). In the sections along the west coast (Waikawau, Kaawa, and Carters beaches) a bored, wave-planed unconformity surface is developed at the top of Carter Siltstone, indicating that uplift was sufficient to elevate Carter Siltstone from upper bathyal depths into the wave zone where erosion occurred. All the units unconformably overlying the Carter Siltstone (e.g. Te Hara Sandstone Member and Te Akau Limestone Member) are included here within the Waitemata Group, and these units have diversified lithologies reflecting onlap and neritic facies development at the base of the Waitemata Group, as might be anticipated in basal onlap facies.

In most of the southern region, the transition from the Te Kuiti Group into the Mahoenui Group has been reported as conformable (Nelson, 1978). However, in the Awakino Gorge area there is an erosional contact between the Te Kuiti Group and the Mahoenui Group (type G; Nelson, 1973), the basal Awakino Limestone Member (Mahoenui Group) resting upon

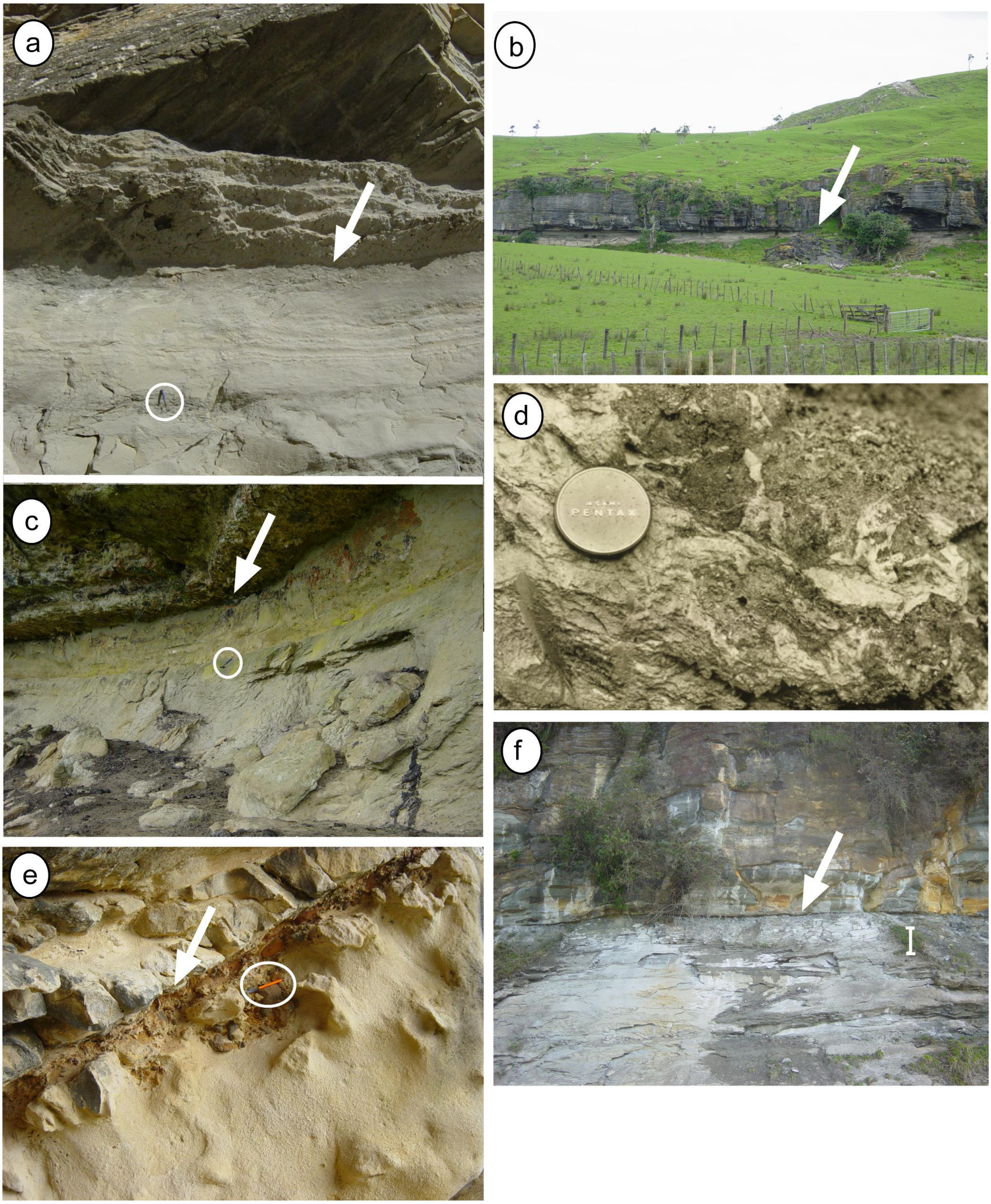


Fig 5. Examples of unconformities separating Te Kuiti Group sequences. ***(a)*** *Planar contact between Kotuku Siltstone Member (TK3) and Waimai Limestone Member (TK4) at Waikawau Beach. Hammer circled for scale.* ***(b)*** *Sharp planar contact between Waikorea Sandstone Member (Tk3) and Waimai Limestone Member (TK4), Waimai Stream Bridge, Te Akau Coast Road.* ***(c)*** *Planar contact between Ahirau Sandstone Member (TK2) and Hauturu Sandstone Member (TK4) at the Mahoe Road section. Hammer circled for scale.* ***(d)*** *Close-up view of the highly burrowed and glauconitic contact between Dunphail Siltstone Member (TK2) and overlying Hauturu Sandstone Member (TK4) at Awakino Tunnel. Photo: C.S. Nelson.* ***(e)*** *Scoured pebble-filled contact (arrowed) between Hauturu Sandstone Member (TK4) and Orahiri Formation (TK5) at Awakino Tunnel. Pen circled for scale.* ***(f)*** *Planar (arrowed) contact between Kihi Siltstone Member (TK4) and Mangaotaki Limestone Member (TK5) at the Mangaotaki Bridge section, SH3. Bar for scale is 30 cm high.*

Orahiri and Aotea formations with increasing proximity to the Herangi Range (Kamp & Vonk, 2006). At Bexley Station tunnel, the contact is inferred to lie between Otorohanga Limestone and algal-rich Awakino Limestone Member (Nelson, 1973). The nature of these contacts reflect local tilting and erosion due to mobility of the Herangi High prior to deposition of Mahoenui Group siltstone and limestone facies, although there is also marked fanning of dip with the Mahoenui Group siltstone on the southwestern flanks of the Herangi Range, indicating ongoing tilting during the Otaian (Kamp & Vonk, 2006).

Mid to Late Oligocene basin inversion - subsidence cycles

We distinguish two types of unconformities between the various Te Kuiti sequences. We infer the unconformities at the base of each of sequences TK2 and TK3 to have originated mainly through wave planation; for those at the base of each of sequences TK4, TK5 and TK 6, we infer marked subaerial erosion with subsequent wave planation as well (Fig. 5). Between sequences TK 1 & 2 the stratal pattern is one of successive onlap with minimal intervening subaerial erosion; the Waikaretu Sandstone Member is a very thin (0.5 to several metres) regressive sandstone marginal to residual basement topography, and the transition to Sequence TK2 is associated with a marked landward shift in onlap, as shown by the open shelf paleoenvironments of the Elgood Limestone Member (Fig. 4). Between sequences TK2 & TK3 there is also a marked landward shift in stratal onlap (Fig. 4). Over the northern and central regions of the basin the contact between these sequences is a correlative conformity, with marked deepening from inner shelf accumulation of Ahirau Sandstone Member into mid- to outer-shelf Kotuku Siltstone Member, and only south of Kawhia Harbour where Awaroa Limestone Member accumulated, is a wave-planned unconformity developed. Hence, we interpret the accumulation of sequences TK1 -TK3 as arising from progressive, albeit punctuated, marine onlap and inundation of a prior landscape, driven chiefly by regional subsidence marginal to Taranaki Basin associated with minor extensional faulting and sag basin formation.

The transition from sequences TK3 to TK 4 marks a substantial change in unconformity and basin development. Sequence TK3 is deeply incised across the whole of its outcrop extent and completely eroded in parts of central and southern regions of the basin (Figs.4 & 6a), which is remarkable given the preceding mid- to outer-shelf depositional paleoenvironment of the Kotuku Siltstone and Ngapaenga Siltstone members of the Whaingaroa Formation. The unconformity between these sequences was also subsequently wave-planned (Fig. 5), and Sequence TK4 marks a substantial basinward shift in the position of onlap, as inferred from the shoreface to inner shelf paleoenvironments of Waimai Limestone Member and Hauturu Sandstone Member (Fig. 4). The unconformity between sequences TK4 & TK5 west of the Herangi Range is superimposed on the unconformity between TK3 & TK4 removing Hauturu Sandstone as well as most of the Whaingaroa Formation, whereas it is a correlative conformity in the northern parts of the basin (Figs 4 & 6b). The more limited erosional extent of the unconformity at the base of TK5 compared with the one at the base of TK4 (Fig. 6a versus 6b) reflects the persistent subsidence at this time north of Kawhia Harbour compared with a repeated phase of emergence of the basin south of Kawhia Harbour. We also note that the transition from Sequence TK4 to TK5 marked the start of extensive limestone accumulation (Mangaotaki Limestone Member), albeit sandy (from reworked Hauturu Sandstone) to start with, with development of the carbonate factory along rocky shorelines around an uplifted Herangi High south of Kawhia Harbour; the limestone facies, everywhere where they are exposed today, are fragmental and have been transported from where the primary fauna and flora grew, except for the oyster banks (Nelson, 1978). We think that the Manganui Fault moved as a reverse fault at c. 27 Ma when the lower sequence boundary to TK5 formed (Fig. 6b). The unconformity between sequences TK5 and TK6 is erosional east of the Herangi High and separates limestone facies (Fig. 4). The same pattern of persistent subsidence in the north and emergence at sequence boundaries in the south is evident for both sequences TK5 and TK6, although the occurrence of mild retrogradation points to southward migration of the tectonic hinge along the western basin margin (Fig. 4).

The unconformity between the Te Kuiti and Waitemata groups is strongly erosional and involved uplift of Carter Siltstone Member form an upper bathyal environment, where it was accumulating, to one where it was wave planed. The northern part of this Late Eocene - Oligocene basin was completely inverted, with uplift and erosion increasing to the northeast (Hunua Range) and tapering to the west, and south towards Kawhia Harbour; tectonic uplift

MAP (a) EARLY OLIGOCENE (mid-Whaingaroan) Extent of sub-Aotea unconformity

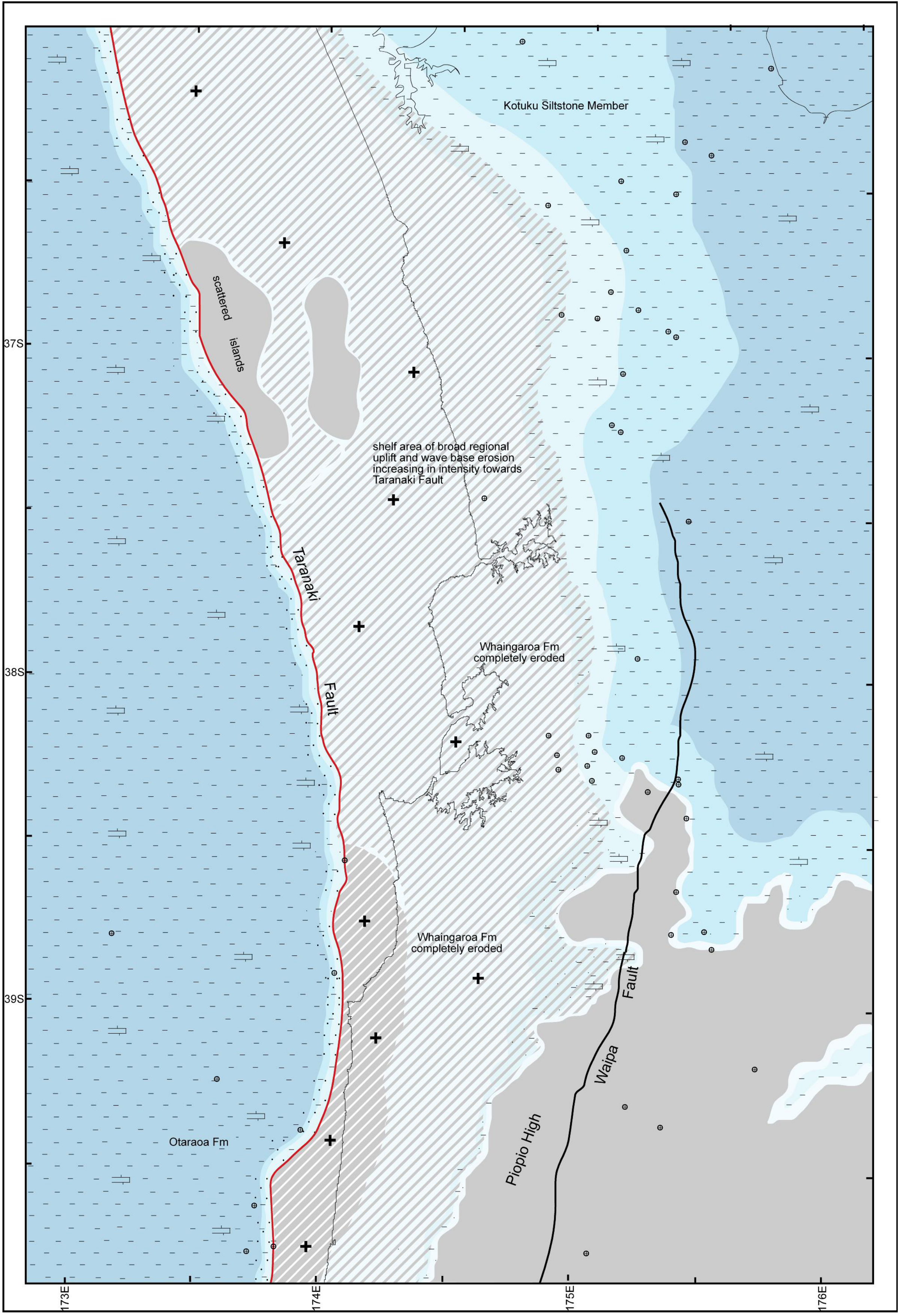
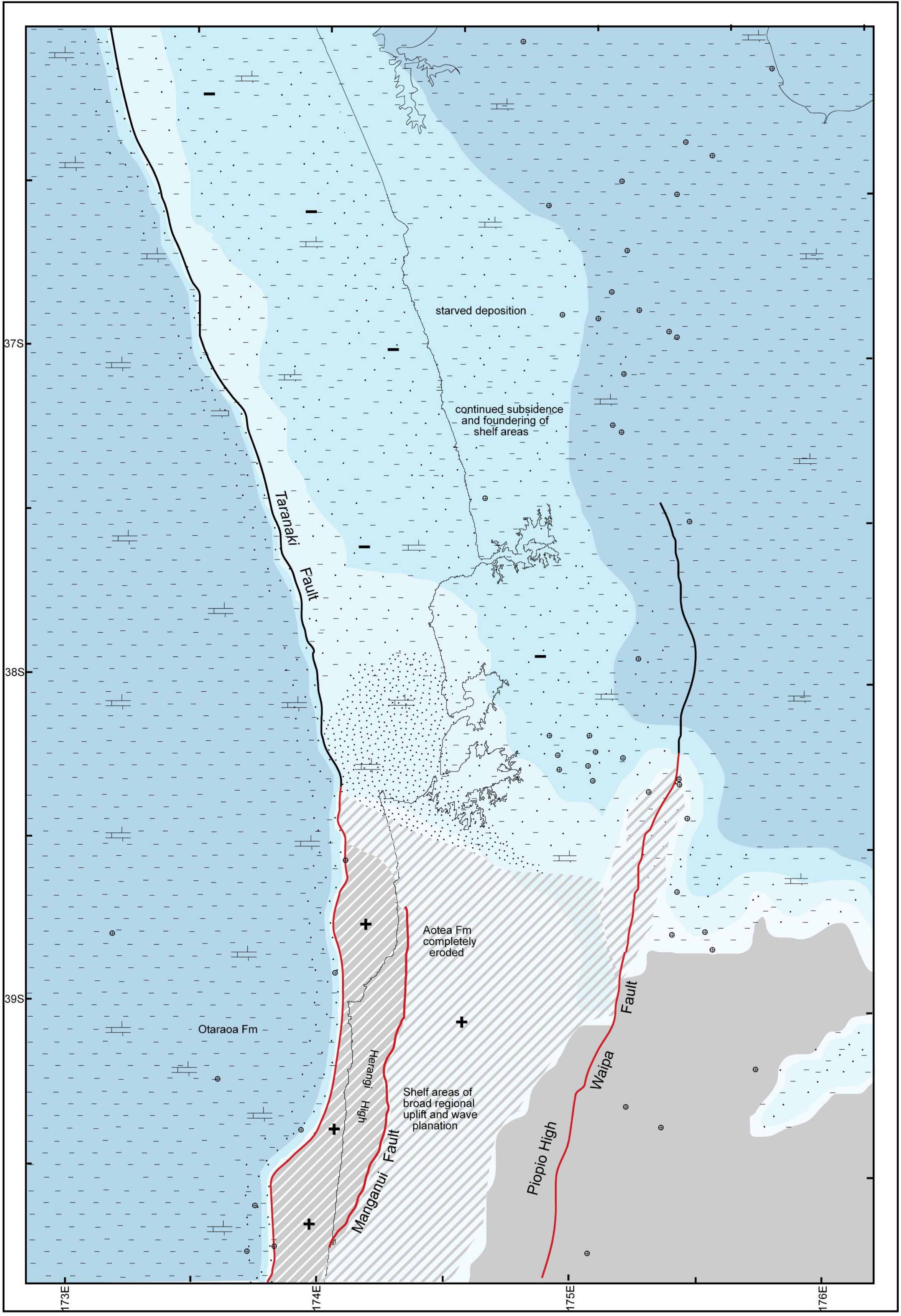


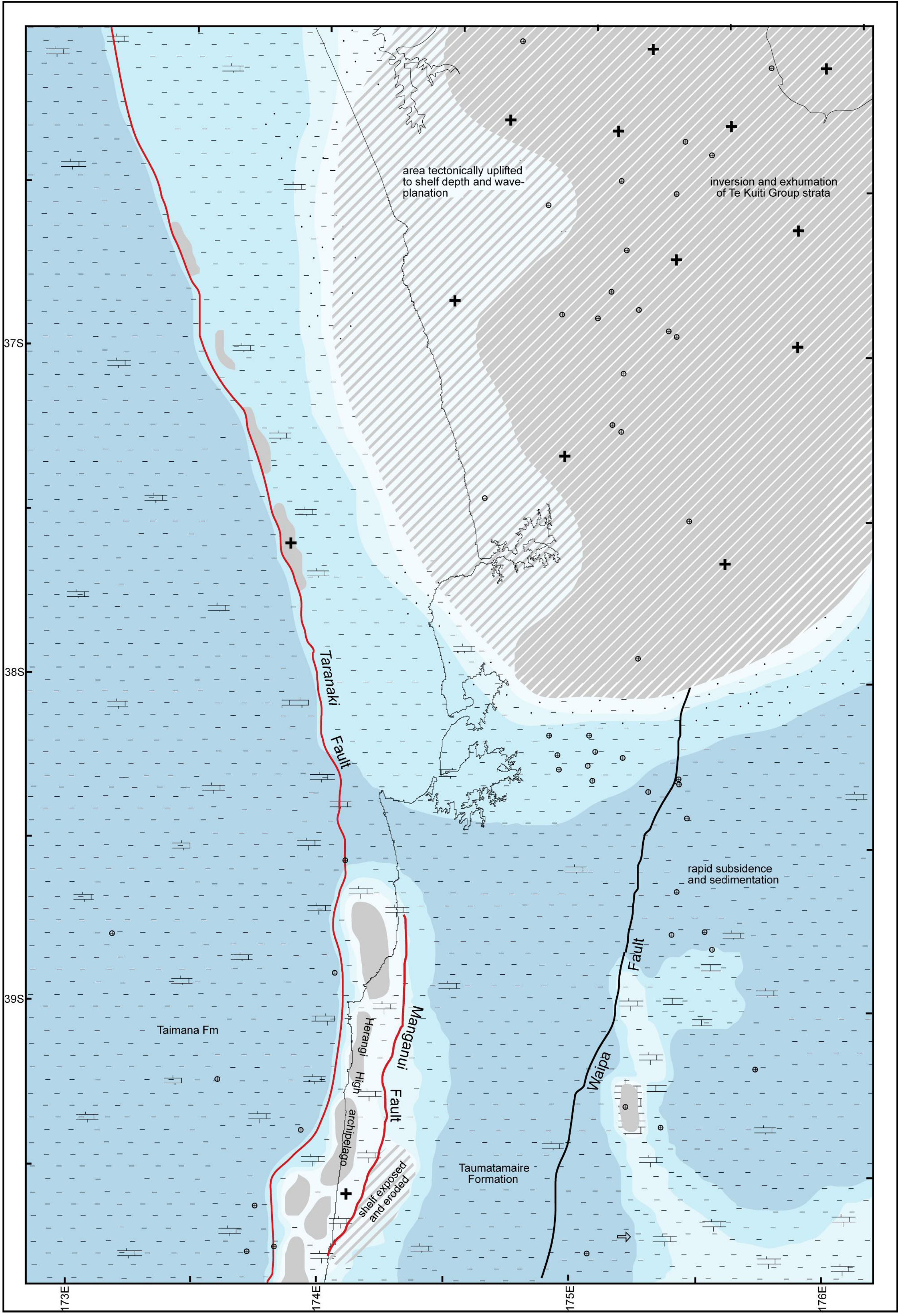
Fig. 6. Selected paleogeographic maps from a set of 13 developed in this investigation for the sequences within the Te Kuiti Group and the transition to overlying Waitemata and Mahoenui groups. Map (a) shows the extent of the unconformity at the base of Sequence TK4 (Whaingaroa - Aotea Formation contact) when significant reverse displacement on the Taranaki Fault is

MAP (b) MID-OLIGOCENE (upper Whaingaroan to lower Duntroonian) Extent of sub - Castle Craig Subgroup unconformity



inferred to have started (c. 29 Ma). ***Map (b)*** *shows the extent of the unconformity at the base of Sequence TK5 (Aotea Formation – Castle Craig Subgroup contact) when displacement on the section of Taranaki Fault north of Kawhia Harbour had died, and when Cenozoic displacement on the Manganui Fault started.* ***Map (c)*** *(next page) shows the extent of the unconformity at the top of Sequence TK6 in the north (Te Kuiti Group - Waitemata Group contact) and the contact with the Mahoenui Group.*

MAP (c) EARLY MIOCENE (uppermost Waitakian to lowermost Otaian) Extent of sub-Waitemata - Mahoenui Group unconformity



at this unconformity was focussed along the eastern coast of Auckland compared with the prior focus along the Taranaki Fault Zone (Fig. 6c). The contact between the Te Kuiti and Mahoenui groups is mostly conformable, involving substantial subsidence, increased paleobathymetry by 400-600 m, and a marked landward shift in the position of marine onlap, especially to the south and east. Along the western margin with the Herangi Range however, there is evidence for initial uplift and erosion of the Te Kuiti Group, with onlap onto basement and continuous tilting of a narrow shelf (Kamp & Vonk, 2006) (Fig. 6c).

In summary, the character and extent of inter-formational unconformities together with the stratal patterns within the Te Kuiti sequences (such as they can be inferred from their depositional systems), indicate a major change in the basin's development at c. 29 Ma (mid-upper Whaingaroan) during the termination of Sequence TK3. The three unconformities between sequences TK3 & TK6 each involved phases of subaerial erosion and subsequent wave planation, with the extent of successive unconformity development decreasing and becoming more focussed with time on the margin with the Herangi High. We consider sequences TK4 – TK6 to each represent tectonic cycles of subsidence and basin inversion. Although we cannot explore the details here, there is paleogeographic unity between a tectonic origin for these sequences, the characteristics of the respective depositional systems within them, and the major facies differences between them (e.g. appearance of the exotic composition of the Hauturu Sandstone Member; conditions for development of the TK5 & 6 carbonate factories; and southward retrogradation of sequences TK5 & 6). The unconformities between the Te Kuiti and overlying Waitemata and Mahoenui groups also have tectonic origins, reflecting for the Waitemata Group, uplift and erosion associated with the start of subduction to the northeast (east Northland, east Auckland, Bay of Plenty), and for the Mahoenui Group, an Otaian phase of thrusting on the Taranaki Fault Zone near Awakino.

Displacement model for Taranaki Fault Zone

We view the Oligocene and Early Miocene successions in the Waikato and King Country regions as providing useful constraints on the history of vertical motion of the Herangi High and wider basement topography east of the Taranaki Fault Zone. In Fig. 7 we present a 1st-order model of the Oligocene to earliest Miocene vertical and horizontal displacement of basement on the Taranaki Fault Zone for a west–east transect through Awakino (Fig. 2). This model is drawn to true scale for different time horizons keyed into the Te Kuiti sequences, and honours the structure of the fault zone and known constraints on the total amount of horizontal displacement on it, as well as the magnitude and extent of subsidence and uplift/inversion for successive inter-formational unconformities within the Te Kuiti Group. The qualitative elements of the model are the partitioning of the total amount of horizontal (thrust) displacement into the successive inversion phases during the Oligocene; that is, the intervals of unconformity development at the base of each of sequences TK4, TK5, TK6 and within Sequence TK6. The interpretations in the model are as follows. (i) Reverse displacement on the Taranaki Fault started at c. 29 Ma, corresponding to the development of the unconformity at the base of Sequence TK4, which we infer involved (the first phase of) widespread inversion of the Te Kuiti Group depocentre along the whole of the margin east of the northern section of Taranaki Fault (Awakino to Port Waikato, Fig. 6a). (ii) The mid- to Late Oligocene displacement on the thrust fault at Awakino and to the north was episodic, which we infer from the repeated tectonic cycles of uplift-erosion-subsidence-shelf sedimentation, represented by sequences TK4 – TK6 and their bounding unconformities. The model demonstrates that the Oligocene – earliest Miocene thrust belt involving basement was very narrow at about 15 km wide. North of Kawhia Harbour there will have been a different displacement history with most of the total displacement occurring during the development of the c. 29 Ma unconformity at the base of Sequence TK4 (Whaingaroa – Aotea formation contact, Fig. 6a). The model also shows that, unlike Late Miocene structural inversion of prior normal faults in southern Taranaki Basin (e.g. Knox 1982), the start of reverse/thrust displacement on Taranaki Fault must have involved the development of a completely new fault trace(s); this new fault dips east, whereas the prior normal "Taranaki Fault" must have dipped to the west, judging from the relative elevation of the top of basement either side of the fault between the Late Cretaceous and Early Oligocene. This 3-5 km mid-Oligocene offset in basement elevation, its co-location with the Murihiku – Brook Street basement terrane boundary, and the 10-45 degree easterly dips within the western limb of the Kawhia Syncline probably determined the eastern Taranaki location of where some of the mid-Oligocene – ear-

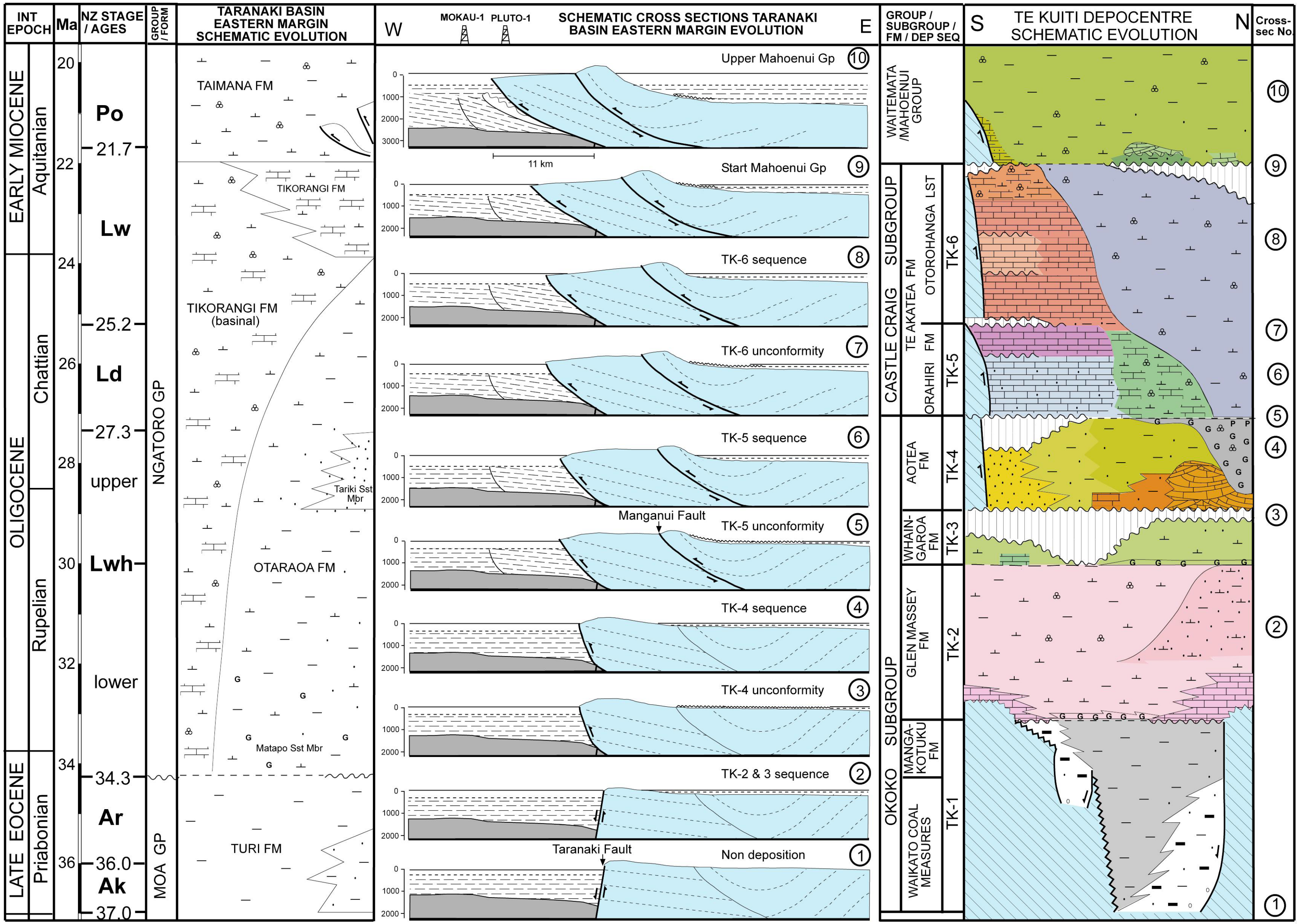


Fig. 7. *Schematic model to true scale of development of the Taranaki Fault Zone, constrained by its structure and the stratigraphy and basin dynamics of the Te Kuiti Group in Waikato and northern King Country depocentres. Note how a new Taranaki Fault Zone develops at c. 29 Ma, the Manganui Fault develops at c. 27 Ma, most of the displacement occurs during the Otaian, and the thrust belt is narrow (c. 15 km wide).*

liest Miocene (30-23 Ma) stress originating in the proto plate boundary zone in eastern North Island would be taken up. The structurally truncated upper end of the pre-existing normal "Taranaki Fault" (Fig. 7) has not been identified in deep parts of industry seismic reflection profiles across the eastern margin of Taranaki Fault, possibly because of a lack of coherent acoustic signal some 12 -15 km east of the tip of the fault. In terms of a mechanism linking mid- to Late Oligocene thrust displacement on a shallow east-dipping fault zone to sequence TK4 – TK6 basin inversion events, we envisage periodic locking of the décollement, the accumulating strain causing uplift in the basin east of the fault zone, followed by free displacement, relaxation in the upper crust and its subsidence. We appreciate, and the model shows, that there was minimal horizontal displacement at the start (c. 29 Ma) and during subsequent Late Oligocene phases of deformation, possibly being only 1 to a few km. The majority of the total displacement in the Awakino transect occurred during the Otaian when the Mahoenui Group was accumulating east of the Herangi High, and at the end of the Otaian when this basin was inverted (Kamp & Vonk, 2006).

Taranaki Basin stratigraphic test of the timing of the start of crustal shortening

The Oligocene subsurface succession in Taranaki Basin might be expected to contain stratigraphic signals of the mid-upper Whaingaroan (c. 29 Ma) transition from extension to shortening across Taranaki Fault, and provide a test of the interpretation and timing established here from the Te Kuiti Group. In Fig. 8 we show in comparative chronostratigraphic panels, one for Taranaki Basin and the other for the Te Kuiti Group succession, how the respective lithostratigraphies may relate. Key points arising from stratigraphic comparisons include the following:

(i) The Late Eocene start of Te Kuiti Group sedimentation (Waikato Coal Measures) corresponds to accumulation of Turi Formation (shelf siltstone), both indicative of regional subsidence and depositional onlap. Middle-Late Eocene strata in Taranaki Basin are thickest along the eastern margin of the basin thickening into Taranaki Fault, and given evidence of synsedimentary normal faulting in the Waikato Coal Measures to the east (Hall et al., 2006) and on the Manaia Fault to the west (Cardiff-1 area; Hoolihan and Yang, 1992), it is probable that the Taranaki Fault was a master normal fault during the Late Eocene (Kamp, 1986). Late Eocene coal measure sedimentation in fault-controlled grabens in southern Taranaki Basin (King & Thrasher, 1996) may also have an extensional origin. Overall the Middle – Late Eocene depositional setting is one of east-stepping and younging extensional or sag basins (Waikato/Te Kuiti Group depocentre developed east of Taranaki Basin in the L. Eocene-Oligocene), with south-directed depositional onlap, and the non marine - marine facies transition occurring further south in Taranaki Basin than in the Waikato region, possibly due to lesser amounts of extension in the north (Waikato) compared with farther south (southern Taranaki Basin).

(ii) Latest Eocene and earliest Oligocene strata in Taranaki Basin are generally highly condensed, reflecting very low terrigenous sediment supply (King & Thrasher, 1996); the signal is one of minimal tectonism consistent with a weakly extensional setting and inconsistent with concurrent shortening across Taranaki Fault and the generation of associated topography, which would produce copious sediment supply. The Matapo Sandstone Member in eastern Taranaki Basin is lower Whaingaroan in age, thin (8-15 m), shelf, glauconitic calcareous sandstone indicating stratigraphic condensation during marked south-directed depositional onlap (King & Thrasher, 1996).

(iii) We make a significant distinction between the Matapo Sandstone Member and the rest of the Otaraoa Formation, which comprises up to 1200 m of upper Whaingaroan fine-grained calcareous clastic sediment. We stratigraphically place the start of significant shortening across the Taranaki Fault at the top of the Matapo Sandstone Member. The Tariki Sandstone Member, which lies a few metres stratigraphically above Matapo Sandstone, was deposited west of Taranaki Fault as a 250-320 m-thick submarine fan system in a rapidly deepening north-south oriented trough (de Bock et al., 1990). The rapid increase in paleobathymetry and the dramatic increase in terrigenous sediment supply associated with the Tariki Sandstone are consistent with a significant change in tectonic setting and the start of shortening across Taranaki Fault. Moreover, the petrography of the Tariki Sandstone suggests that it is a correlative (Fig. 8) of the Hauturu Sandstone Member (Aotea Formation, Sequence TK4), which immediately postdates the first basin inversion event east of the Taranaki Fault Zone (Fig. 4). The delivery of the Hauturu Sandstone facies into the Waikato-King Country region required, paleo-

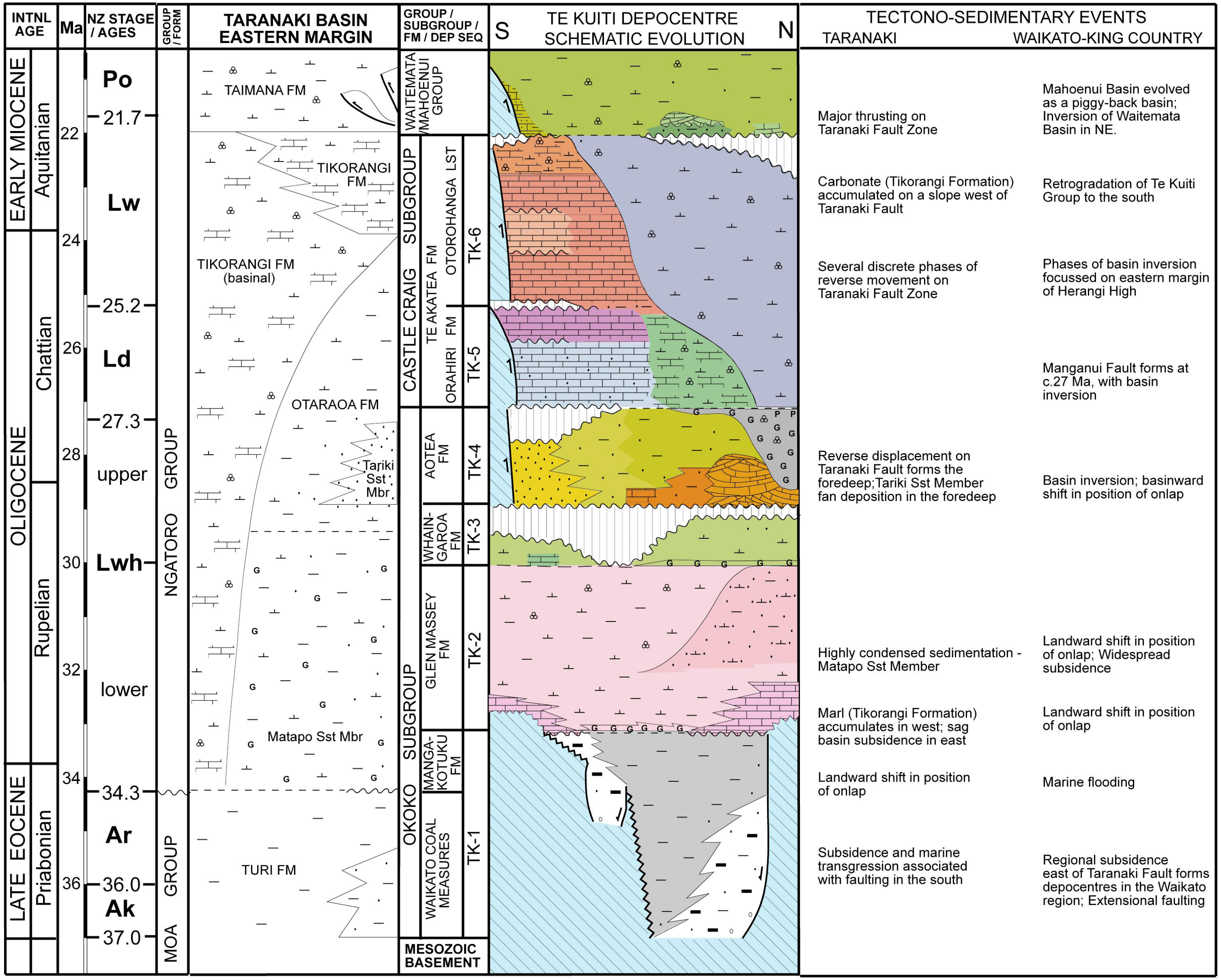


Fig. 8. *Chronostratigraphic panels showing comparative stratigraphy for the Taranaki Basin (from King & Thrasher, 1996) and the Te Kuiti Group, and interpretations of key tectonic events. Note that Tariki Sandstone and Hauturu Sandstone members are correlatives and their accumulation immediately postdates the transition from extension to shortening across the Taranaki Fault.*

geographically, the development of a north-south trending shoreline east of the Herangi High, and by implication first required uplift of the high, achieved by shortening across the Taranaki Fault Zone after c. 29 Ma. The Herangi High east of the fault could also have supported the shoreline that sourced the Tariki Sandstone facies to eastern Taranaki Basin in the Taranaki Peninsula area.

(iv) The Otaraoa Formation becomes increasing calcareous upwards in eastern Taranaki Basin, culminating with Waitakian Tikorangi Formation limestone facies (King & Thrasher, 1996; Hood et al., 2003) in the vicinity of, and north of, Taranaki Peninsula. It accumulated on a west-facing continental slope, the shelf-slope break being pinned to the tip of the basement wedge on the hangingwall of the Taranaki Fault, with the carbonate factory being located around rocky shorelines atop the high (Hood et al., 2004). The Tikorangi Formation limestone is a correlative of the Otorohanga Limestone (Sequence TK6) (Fig. 8), and the development of limestone facies was intimately associated with the development of clean, current-swept, stable rocky shorelines that typically develop around islands and ridges formed in basement rocks.

Conclusions and implications for hydrocarbon prospectivity

Fold structures in the Tarata Thrust Zone and strata beneath the wedge of over thrust basement in the Taranaki Fault have been tested as hydrocarbon plays in eastern Taranaki Basin with some success. The timing of the transition from extension to shortening across the Taranaki Fault, which provides a maximum age for the development of potential traps, formed during the shortening phase, remains controversial, with the most recent papers inferring a Middle Eocene age (Stagpoole & Nicol, in press; Nicol et al., 2007). Our approach has been to determine the timing of initiation of significant reverse displacement within the Taranaki Fault Zone by analysis and interpretation of the Oligocene and Early Miocene marine stratigraphic successions in the Waikato and King Country (Te Kuiti Group) depocentres east of the fault zone. The Te Kuiti Group contains six unconformity-bound sequences, and differences in the character of these unconformities together with the stratal patterns inferred from underlying and overlying depositional systems, point to a dramatic change in stratigraphic development and basin dynamics between sequences TK3 and TK4 during the mid-upper Whaingaroan at c. 29 Ma (Fig. 6a). The three unconformities that developed between sequences TK3 - TK6 each involved phases of subaerial erosion and subsequent wave planation, with the extent of successive unconformity development decreasing and becoming more focussed with time on the margin of the Herangi High (Fig. 6). We consider sequences TK4 – TK6 to each represent tectonic cycles of subsidence and variable basin inversion and we attribute the origin of these cycles to periodic locking of the Taranaki Fault décollement in underlying Murihiku basement, the accumulating strain causing uplift in the basin east of the fault zone, followed by free displacement, relaxation in the upper crust and subsidence. A 1st-order model (Fig. 7) of the Late Oligocene to earliest Miocene vertical and horizontal displacement of basement on the Taranaki Fault Zone for a west–east transect through Awakino infers that significant reverse displacement on the Taranaki Fault started at c. 29 Ma, that the mid- to Late Oligocene displacement on this fault in the vicinity of Awakino – Kawhia Harbour was episodic, and that the thrust belt was narrow (c. 15 km). North of Kawhia Harbour there will have been a different displacement history with most of the total displacement occurring during the development of the c. 29 Ma unconformity at the base of Sequence TK4 (Whaingaroa – Aotea formation contact) (Fig. 6a), whereas between Awakino and Kawhia Harbour the majority of the total displacement occurred during the Otaian and at the end of it (Fig. 7). The model also shows that the start of reverse/thrust displacement on Taranaki Fault must have involved the development of a completely new fault trace(s).

The model has been validated against the subsurface Oligocene stratigraphy in Taranaki Basin (Fig. 8). Key points are as follows: (i) The change from extension to shortening across the Taranaki Fault coincides with the top of the Matapo Sandstone Member, the point at which condensed sedimentation changed to the rapid accumulation of thick calcareous siltstone and a submarine fan system (Tariki Sandstone Member). (ii) The Tariki Sandstone Member is a deep water correlative of the Hauturu Sandstone Member that accumulated in neritic environments east of the Herangi High, both units having been sourced from the south, and both accumulating immediately after the start of significant reverse displacement on the Taranaki Fault. The Waitakian Tikorangi Limestone is a continental slope correlative of the shelf Otorohanga Limestone, both units having been sourced from carbonate factories around the Herangi High.

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