The Late Miocene Southern and Central Taranaki Inversion Phase (SCTIP) and related sequence stratigraphy and paleogeography

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Abstract

We present a new sequence stratigraphic scheme for Taranaki Basin that identifies four 3rd order duration (3 - 4 m.y.) sequences of Middle Miocene to Pleistocene age. These include: (i) the late-Middle Miocene (upper Lillburnian to uppermost Waiauan) Otunui Sequence; (ii) the Late Miocene (lower and lowermost-upper Tongaporutuan) Mt Messenger Sequence; (iii) the latest Miocene (uppermost-upper Tongaporutuan) to Early Pliocene (lower Opoitian) Matemateaonga Sequence, and (iv), the Late Pliocene (upper Opoitian) to Late Pleistocene (Castlecliffian) Rangitikei Sequence, which includes the Giant Foresets Formation offshore in northern Taranaki Basin. Full sequence development can be observed in the parts of these four sequences exposed on land in eastern Taranaki Basin and in Wanganui Basin, including the sequence boundaries and component systems tracts; the character of the various depositional systems and their linkage to correlatives in subsurface parts of Taranaki Basin can be reasonably inferred, although we do not develop the detail here.

Our sequence framework, with its independent age control, is integrated with established evidence for the timing of Late Miocene structure development in southern Taranaki (the Southern Inversion Zone of King & Thrasher (1996)) and new evidence presented here for the extent of Late Miocene unconformity development in central Taranaki. This shows that the Mt Messenger Sequence, particularly its regressive systems tract, results from a major phase of tectonism in the plate boundary zone, the crustal shortening then extending into the basin at c. 8.5 Ma and differentially exhuming parts of the sequence and underlying units in southern and central Taranaki Basin. This Southern and Central Taranaki Inversion Phase (SCTIP) peaked at around 7.5 Ma (mid-upper Tongaporutuan). At that time it extended across the whole of the area presently covered by Wanganui Basin, all of southern Taranaki Basin (Southern Inversion Zone), west to the Whitiki and Kahurangi Faults, and across southern parts of Taranaki Peninsula. We have also identified in outcrop sections, wireline logs for Peninsula exploration holes, and selected seismic reflection profiles, the occurrence of forced regressive deposits of the Mt Messenger Sequence. These deposits are mainly preserved beneath distal parts of the unconformity and basinward of it in central Taranaki Peninsula and west to the Tui Field, and need to be distinguished from the much younger Giant Forests Formation within the 3rd-order Rangitikei Sequence, which also shows clinoform development. The new sequence framework with its inferred stratal patterns also helps clarify understanding of the lithostratigraphic nomenclature for Late Miocene – Pliocene units beneath Taranaki Peninsula.

Key words:
Sequence Stratigraphy; Otunui Sequence; Mt Messenger Sequence; Matemateaonga Sequence; Rangitikei Sequence; Central and Southern Taranaki Inversion Phase (SCTIP); Southern Inversion Zone; Taranaki Fault Zone; Taranaki Basin; Taranaki Peninsula; southern King Country; Wanganui Basin.

Introduction

From the late-Early Oligocene (c. 29 Ma) and through much of the Miocene there is good evidence in seismic reflection profiles for continuing crustal shortening across the Taranaki Fault Zone and on related structures such as the Manaia Fault (Fig. 1). During the Late Miocene at c. 8.5 Ma the shortening became regionally more extensive, particularly in southern Taranaki Basin (e.g. Kamp & Green, 1990; King & Thrasher, 1996), where numerous anticlines formed at that time in association with reverse faults, whose traces reactivated in the opposite sense earlier normal fault displacement (e.g. Knox, 1982). Classical examples are the Cook, Wakamarama and Maui anticlines, which have mostly been tested by exploration drilling. King & Thrasher (1996) named the southern part of Taranaki Basin with these inversion structures the Southern Inversion Zone (Fig. 1).

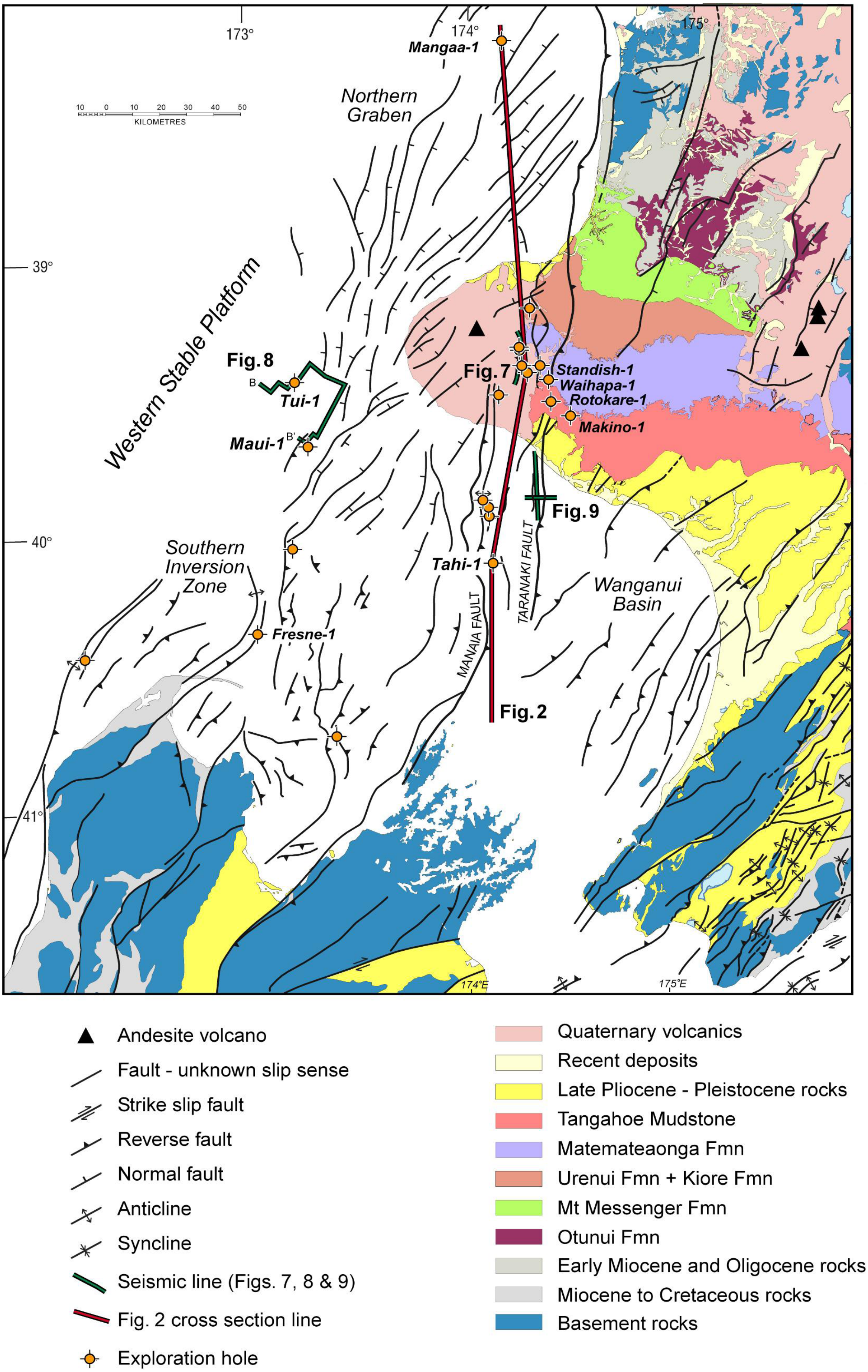


Fig. 1. *Structure map of Taranaki Basin showing the major stratigraphic units exposed in western North Island. The area with reverse faults and anticlines in southern Taranaki Basin is known as the Southern Inversion Zone. Note the location of the chronostratigraphic panel in Fig. 2 and seismic lines in Figs 7, 8 and 9.*

In this paper we focus on identification and mapping of the northern extent of the Late Miocene inversion zone, especially in Taranaki Peninsula, and on the influence the inversion had on late Neogene sedimentation in northern Taranaki Basin. Some petroleum reports (e.g. Buchan, 2001; Morris, 1993; Powis, 1997) have identified the occurrence of unconformity development northwest of the Maui Field and in the Peninsula area, with subsequent marine flooding, but integration of these types of observations into a unified understanding of the basin development during the Late Miocene has not to our knowledge been undertaken to date. The general difficulty of getting good (biostratigraphic) age control from cutting samples of the late Neogene section intersected by drilling, and the application of various lithostratigraphic schemes to the late Neogene succession beneath Taranaki Peninsula, has tended to mask clarity in understanding around the late Neogene development of central parts of the basin.

We approach the Neogene development of Taranaki Basin chiefly from description, mapping and dating of its stratigraphic units cropping out in the southern King Country region, eastern Taranaki Peninsula, and in Wanganui Basin (together referred to here as eastern Taranaki Basin margin), exposed as a result of long wavelength Late Pliocene and Pleistocene doming and exhumation of central North Island. Analysis of wireline records for well sections in Taranaki Peninsula has been the principal means by which we have correlated outcrop units into the subsurface of the Peninsula, with concepts tested by reference to selected seismic reflection profiles. In this paper we develop a 3rd-order sequence hierarchy for the late-Middle Miocene to Pleistocene succession in Taranaki Basin. It provides a chronostratigraphic framework for interpreting the basin's development, and together with paleogeographic maps, shows the influence of the Late Miocene inversion on basin sedimentation patterns in central and northern parts of Taranaki Basin.

Sequence stratigraphic and paleogeographic framework for the Middle Miocene to Pleistocene section in Taranaki Basin

Figure 2 is a south - north chronostratigraphic panel drawn for a section through Taranaki Basin between the Manaia Fault and the Tarata Thrust Zone (Fig. 1). This panel is tied to a series of paleogeographic maps, two of which are shown here as Figs 3 & 4. The panel has illustrated on it (as codes) the lithostratigraphic names used for the various units, and their inferred depositional environments (Fig. 5). On the right hand side we show our 3rd-order sequence nomenclature, and the stratigraphic nomenclature for part of the section as applied in the past by various authors. Using our sequence classification, we outline our integrated understanding of the basin development during the late-Middle Miocene to Pleistocene, referring to specific data and interpretations that justify the extent of the Late Miocene unconformity and associated sedimentation patterns. Elements of the Otunui Sequence are outlined here only to provide a context for the Mt Messenger Sequence, the deposition of which has been directly involved in the Late Miocene inversion phase.

Otunui Sequence

The Otunui Sequence includes depositional systems in Taranaki Basin of late-Middle Miocene age (uppermost Lillburnian to uppermost Waiauan), comprising hemipelagic mudstone facies of the upper part of the Manganui Formation (Fig.2). Beneath Taranaki Peninsula where the Otunui Sequence has been encountered in drilling, bathyal facies only have been identified, and they overlie basin floor fan/frontal splay deposits of the upper part of the Moki Formation. The absence of definitive shallow water (neritic or shelf depth) facies of late-Middle Miocene age in central and southern parts of Taranaki Basin, and indeed generally in northern South Island, reflects (i) the degree of subsidence attained by the basin at that time, (ii) its under-filled state, and (iii), the degree of subsequent (Late Miocene) inversion and erosion. Although deep water facies only are preserved, there must have been contemporary shelf and upper slope depositional systems to the south and southeast through which mainly muddy sediment was sourced to the basin. An indication of the degree of subsequent uplift and basin inversion on the Taranaki and Manaia faults is illustrated by the complete removal of these depositional systems along the south eastern and southern margins of the basin, indicated by the green line in Fig. 2.

Insights into the architecture of the Otunui Sequence in northern parts of the basin can be gained from outcrop in the King Country region (Kamp & Vonk, 2006). There, the shelf and upper slope deposits of the Otunui Sequence form linked depositional systems with bathyal components in northern Taranaki Basin. During the upper Lillburnian (c. 14 Ma) rapid, regional subsidence occurred over the King Country region and northern parts of the

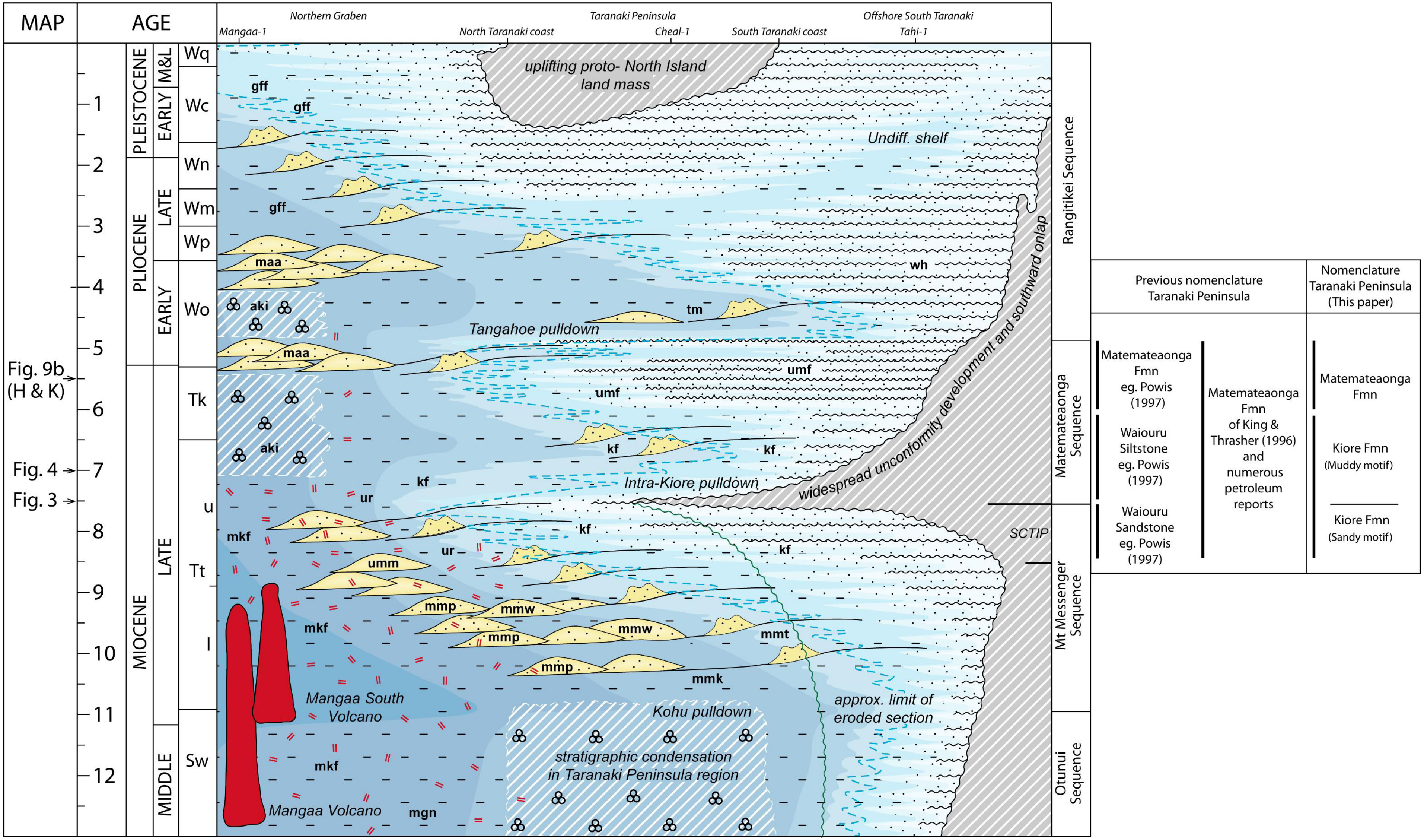


Fig. 2. *Chronostratigraphic panel (located on Fig. 1) with a 3rd-order sequence classification for Taranaki Basin and the distribution of formations, members, depositional paleo-environments and unconformities. The 6th-order unconformities are shown schematically, and are demonstrable only for beds of upper Tongaporutuan age and younger. The lithostratigraphy of Powis (1997) and King & Thrasher (1996) for part of the section is compared with the nomenclature of this paper. Map c refers to Fig. 9b in Hansen & Kamp (this volume). See Fig. 5 for the formation and member codes.*

Wanganui region. The resulting marine transgression is marked by an upper Lillburnian shell bed (Mangarara Formation) one to two metres thick unconformably overlying early-Early Miocene (Otaian) Mahoenui Group (Fig. 1). While sandy shelf facies above the transgressive shell bed can attain some tens of metres thickness, we have also logged thin channelised sandy debris flow facies only 20 m above the transgressive shell bed, suggesting that outer shelf to upper slope depositional environments developed very quickly. These deposits are followed by 100 to 200 m of mottled and highly burrowed, crudely bedded silty sandstone and sandy siltstone facies, forming poorly defined aggradational and slightly progradational higher order sequences. Hence, in outcrop north and east of the northern extent of the Late Miocene inversion zone (Fig 1) the Otunui Sequence has the key elements of a sequence, in this case probably of 3rd-order scale.

Exploration holes drilled through the Middle Miocene section (upper parts of Manganui Formation) in Taranaki Peninsula show it to comprise amongst the highest GR values in Manganui Formation (King & Thrasher, 1996), indicative of the accumulation of very fine-grained hemipelagic mudstone (e.g. Stratford-1). In Stratford-1, Morgans (2000) identified a thin (110 m-thick, 1710 -1820 mbKB) Waiauan section compared with thick Lillburnian and Tongaporutuan successions below and above, respectively. In Cardiff-1, Strong (2000) notes that basal Tongaporutuan beds sit unconformably on Lillburnian middle to lower bathyal beds, or on extremely condensed or unrecognised Waiauan beds. Morris (1993) viewed this unconformity as being erosional (his Sw marker). We interpret the thin Waiauan beds beneath much of Taranaki Peninsula as comprising variably condensed calcareous mudstone facies. The difficulties in identifying the Waiauan Stage arise from stratigraphic condensation rather than from erosion, given the mid-bathyal sea floor depths at that time. We view formation of these condensed lower slope facies as resulting from trapping of the contemporary terrigenous sediment being supplied from the evolving plate boundary, at that time located to the southeast, in a new depocentre (Otunui depocentre) along eastern Taranaki Basin margin. The development of this late-Middle Miocene flexural down warp east of Taranaki Fault Zone in the southern King Country region shut-off the accumulation of Moki Formation fans in central Taranaki Basin, trapping the fine sandstone and mudstone in shelf and upper slope depositional systems (Otunui Formation; Kamp et al., 2004). We term this pronounced subsidence in the southern King Country region the "Otunui Pulldown", because of its flexural character and there being no evidence for a crustal loading mechanism to drive the subsidence.

Mt Messenger Sequence

The Mt Messenger Sequence includes depositional systems of Late Miocene age (lower and lower-upper Tongaporutuan) in northern Taranaki Basin and the southern King Country region (Fig. 2). The sequence is markedly asymmetric, with a comparatively thin transgressive systems tract and a thick regressive systems tract, the later including the well known progradational continental margin wedge comprising the bulk of the Mt Messenger, Urenui and Kiore formations (e.g. King et al., 1993; Kamp et al., 2004). The case for making this a distinct sequence rests on the evidence for marked flooding at the base of the Mt Messenger Formation along the eastern basin margin, and a widespread unconformity at the top of the sequence. In the eastern Taranaki Peninsula and southern King Country region where the base of the Mt Messenger Formation is well exposed, we have mapped a massive fine-grained hemi-pelagic lower slope (mid-bathyal) mudstone facies named the Kohu Member, which conformably overlies Otunui Formation muddy sandstone. Benthic foraminifera from samples across this contact indicate about 400 m of increase in water depth from upper- to mid-bathyal environments associated with a marked landward shift in the position of onlap. In bathyal parts of the basin, particularly beneath Taranaki Peninsula, there was stratigraphic condensation due to terrigenous sediment being supplied to the basin having been trapped in the Kohu depocentre east of the Taranaki Fault Zone. High foraminiferal content in the uppermost part of the Manganui Formation in some Peninsula well logs is marked by a spike in sonic velocity due to cementation of planktic foraminifers. This sonic marker has been used by some exploration companies to map the base of the Mt Messenger Formation beneath the Peninsula where the sandstone facies are poorly developed, and in accordance with this practice, we place these condensed facies in the base of the Mt Messenger Formation, rather than at the top of the Manganui Formation. In the North Taranaki coastal section between Mokau and Awakino, the base of the Mt Messenger Formation is typically mapped at the base of the first thick-bedded sandy debris flows forming the Ferry Sandstone Member; bathyal mudstone (Kohu Member) as a distinctive unit is absent, and the underlying unit is Mohakatino

Formation lower slope sediments redeposited from the flanks of offshore volcanic centres, although intercalated siliciclastic mudstone beds do occur. The unconformity at the top of the Mt Messenger Sequence was formed in southern and central Taranaki Basin through widespread uplift and subaerial erosion, ravening, at its highest stratigraphic level the upper Tongaporutuan Kiore Formation.

The majority of the Mt Messenger Sequence comprises regressive systems tract (RST) deposits, forming an outer shelf-slope-basin depositional system probably characterised by clinoform development (Fig.2). In a basinward profile it includes rapidly-aggraded, wavy, channelised, upper slope (thin) heterolithic sediment gravity flow facies, and thick-bedded, channelised (upper slope), sandstone facies of the Kiore Formation. Shelfal facies with shell bed development (e.g. Kohuratahi Shell Bed) are only preserved at the top of the RST (Kiore Formation) below the unconformity (Fig. 2), and we have mapped these facies in eastern Taranaki Peninsula and in the Whanganui River section. In Fig. 2 we show schematically the shelf-slope break through time, with Urenui Formation having accumulated basinward in upper slope environments. It comprises massive to laminated mudstone facies with (i) steep-sided canyons in-filled with heterolithic facies, and (ii), wide, channelised, thick-bedded fine sandstone facies (King et al., 1993). Mt Messenger Formation accumulated as mid-slope facies (Whitecliffs Member, muddy turbidites; Kaieto Member, channelised fine sandstone) to lower slope facies (Ferry Sandstone Member & Tongaporutu Member, thick-bedded, fine sandstone). In northern parts of Taranaki Basin the lower slope facies overlie and interfinger with volcaniclastic facies of the Mohakatino Formation originating from contemporary volcanism and possibly cone collapse events.

The Mt Messenger Sequence is most complete as linked depositional systems east of the Taranaki Fault Zone in the Kohu depocentre of eastern Taranaki Peninsula and southern King Country. Beneath the Peninsula area the contemporary sea floor morphology was characterised by submarine swells (e.g. Manaia Anticline, Tarata Thrust Zone) and intervening troughs down which sandy debris flows were guided, which resulted in a different architecture to the more open and regular slope to the north and east. In southern parts of Taranaki Basin the upper slope and shelfal components of the depositional systems are not preserved, having been eroded during the Late Miocene inversion phase. Hence the next youngest 3rd-order sequence (Matemateaonga Sequence) progressively overlies to the south strata older than the Mt Messenger Sequence (Fig. 2). The Late Miocene erosion of much of the Mt Messenger Sequence together with the subtlety of the relationship between its regressive systems tract and the overlying unconformity, has confounded many previous investigations, and masked the northern extent of the Late Miocene inversion.

Matemateaonga Sequence

The Matemateaonga Sequence includes depositional systems of latest Miocene (upper Tongaporutuan) and earliest Pliocene (lower Opoitian) age in Taranaki Basin (Vonk & Kamp, 2004) (Fig. 2). As for the Mt Messenger Sequence, it is markedly asymmetric with a comparatively thin transgressive systems tract and a thick regressive systems tract. The lower sequence boundary is a regional unconformity having a tectonic origin involving Late Miocene inversion of southern and central parts of Taranaki Basin. Regional subsidence of the unconformity surface with south-directed onlap and marine transgression immediately followed the preceding inversion phase. This onlap onto successively older formations in the part of Taranaki Basin west of the Taranaki Fault, and over basement to the east of the fault, has given rise to what has been commonly referred to in well completion reports, and in King & Thrasher (1996), as the “Base-Pliocene unconformity”. The earliest strata overlying the unconformity surface are actually of upper Tongaporutuan age, although they become progressively younger (Kapitean and lower Opoitian) to the south as a result of the ongoing onlap in that direction. In eastern Taranaki hill country and in the Whanganui River section where we observe the uppermost part of the regressive succession in outcrop, the beds overlying the unconformity accumulated in outer shelf to upper slope (upper bathyal) environments as part of the Kiore Formation; contemporary shelf deposits will however occur in the subsurface to the south (Fig. 2). The sedimentologic evidence from outcropping strata for the rapid development of upper bathyal conditions above the unconformity leads us to name this subsidence event the “Intra-Kiore Pulldown”. It was characterised by rapid regional flexural subsidence and was followed by subsidence and sediment accumulation at rates exceeding 1 m per 1000 y. Despite southward onlap, the rates of sediment supply were such that the continental margin concurrently prograded northward, especially during the Early Pliocene (lower Opoitian) (Fig. 2). In deeper parts of the basin (northern Taranaki) the start of accumulation of Ariki Formation marl coincides with the Intra-Kiore Pulldown and regional onlap in the southeast. The Ariki Formation on the Western Platform and correlative marly units in and around the Northern Graben have been shown to comprise two phases of condensed sedimentation, a lower one associated with the Matemateaonga Sequence, and a younger one (upper Opoitian) associated with the Tangahoe Pulldown (Hansen & Kamp, this volume). The accumulation of thick marl (up to 109 m in Ariki-1) is surprising given the volume of terrigenous sediment delivered to Taranaki Basin generally, and it can be directly attributed to the temporary cessation of siliciclastic sediment delivery to northern Taranaki Basin as a result of the sediment being tied up within the retrogradational shelf and upper slope depositional systems of the Matemateaonga Sequence. Most of the thickness of the Matemateaonga Sequence however involves progradational or regressive systems tract strata (Fig. 2). The lower Opoitian age of the lower part of the Mangaa Formation ("Mangaa B Sands") (e.g. Hansen & Kamp, 2006) in the Northern Graben, which forms well defined submarine fan deposits, suggests that it forms the bathyal component of a depositional system contiguous with the shelfal strata now cropping out in eastern Taranaki Peninsula (Fig. 2). The Matemateaonga Formation comprises well developed shelfal cyclothems of 6th-order (41 k.y duration) cyclicity (Vonk & Kamp, 2004; Kamp et al., 2004) and 4th-order (c. 400 k.y. duration) cycles are known as well (Fig. 2). The upper boundary of the Matemateaonga Sequence lies near the top of the Matemateaonga Formation (Kamp et al. 2004).

Rangitikei Sequence

The Rangitikei Sequence includes depositional systems of Late Pliocene (upper-Opoitian) through to Late Pleistocene (Castlecliffian) age in Taranaki and Wanganui basins (Fig. 2). This is also a strongly asymmetric sequence characterised by a comparatively thin transgressive systems tract and a very thick regressive systems tract (Fig. 2). The lower sequence boundary in eastern Taranaki Peninsula and farther east is marked by an unconformity at the base of the Parangarehu Shell Bed near the top of the Matemateaonga Formation. This transgressive shell bed is 1-3 m thick and is overlain by 4-5 m of sandstone that grades upwards into the Tangahoe Mudstone. The lowermost 20-30 cm of the Tangahoe Mudstone is glauconitic in central and eastern parts of Wanganui Basin, with benthic foraminifera from samples below and within the glauconitic layer indicating about 400 m of increase in water depth from mid shelf to upper/mid bathyal environments (Kamp et al. 2004). The very rapid increase in bathymetry at the base of the Tangahoe Mudstone mainly reflects rapid subsidence forming the Wanganui Basin depocentre, which is the youngest of a series of flexural down warps formed successively to the south in central-western North Island during the Neogene, which we have named the Tangahoe Pulldown (Kamp et al., 2004). In Toru Trough and in eastern Taranaki Peninsula the Tangahoe Mudstone displays north eastward prograding clinoforms on seismic reflection lines (Ogilvie, 1993); outcrop of this stratigraphic level to the east comprises massive hemi-pelagic mudstone enclosing several discrete horizons of channelized submarine fans. The Tangahoe Mudstone grades upward into sandy shelf cyclothems (Whenuakura Group, Fleming, 1953; Naish et al., 2005) in eastern parts of Wanganui Basin. The Tangahoe Mudstone slope facies (slope sets) and the Whenuakura Group shelf facies (top sets) are early parts of a very substantial regressive systems tract that in its middle to upper parts built out as the Giant Foresets Formation into the Northern Graben and across the Western Platform, forming the modern continental shelf and slope morphology in central and northern Taranaki Basin (e.g. Hansen & Kamp, 2004). The submarine fans in the upper part of the Mangaa Formation ("Mangaa A Sands") are probably part of a linked depositional system including the slope fans in the Tangahoe Mudstone, although the deposition of the upper Mangaa Formation submarine fan was strongly influenced by the fault-controlled asymmetry of the Northern Graben, rather than having been deposited on a featureless basin floor. The upper part of the Ariki Formation on the Western Platform and equivalent marly beds under the upper part of the Mangaa Formation in the Northern Graben, accumulated in distal parts of the basin as a result of the shut-off in terrigenous sediment supply consequent upon the Tangahoe Pulldown (Hansen & Kamp, this volume). This marl forms condensed facies on the basin floor. The architecture of the upper part of the Rangitikei Sequence has been complicated during the Pleistocene by continuing subsidence and depositional onlap in southern parts of Wanganui and Taranaki basins, and concurrent regional doming of central North Island. The uplift of central North Island (southern King Country and Taranaki Peninsula) and accompanying erosion exhumed parts of the Rangitikei Sequence, thereby leading to offlap (progradation) in northern parts of Wanganui Basin and in north western parts of Taranaki Basin (Fig. 2).

Southern and Central Taranaki Inversion Phase (SCTIP)

The literature to date addressing the Late Miocene inversion in southern Taranaki Basin has tended to emphasise the style, character and timing of inversion on particular or related structures within the basin (e.g. Knox, 1982; Kamp & Green, 1990; Bishop & Buchanan, 1995; King & Thrasher, 1996; Crowhurst et al., 2002). How this structure development related to concurrent depositional patterns elsewhere in the basin has received little, if any, attention. Our Middle Miocene – Pleistocene sequence stratigraphic and paleogeographic framework for the basin shows (i) that the inversion is more extensive than previously considered, particularly in the Taranaki Peninsula area (Fig. 3), and (ii), that the inversion of the basin was immediately preceded by accumulation of the thick regressive systems tract of the Mt Messenger Sequence, the two probably having a common origin (Fig. 2). Our sequence stratigraphic framework therefore integrates evidence for the extent and timing of the Late Miocene inversion phase with the stratal patterns, linked depositional systems and paleoenvironments of the underlying sequence. We infer that the pulse of sediment comprising the RST of the Mt Messenger Sequence reflects erosion associated with a major phase of shortening and relief development within the developing Australia – Pacific plate boundary zone to the southeast of the basin, with late migration of the crustal shortening into the basin, thereby uplifting and exhuming part of the associated sediment wedge. In the Fresne-1 structure, low temperature thermochronology clearly dates the start of exhumation of the middle Cenozoic succession at 8.5 Ma (Kamp & Green, 1990), with the majority of the erosion over the structure ending around 4 Ma (Crowhurst et al., 2002), although marine onlap was delayed until c. 1 Ma, or later. Along the Taranaki and Manaia Faults there is evidence for more-or-less ongoing faulting and growth of anticlines through the Early and Middle Miocene, probably maintaining high-standing basement east of the Taranaki Fault. Hence there is a need to distinguish ongoing backthrusting along the basin bounding faults from what appears to have been relatively short-lived and extensive inversion of structures in southern and central parts of the basin. We call the widespread and short-lived inversion phase the "Southern and Central Taranaki Inversion Phase", abbreviated SCTIP. This phase started around 8.5 Ma and reached its peak at 7.5 Ma. The timing of the end of this inversion at the northern shoreline is dated from our magnetostratigraphy for the Whanganui River section, although, as noted above, uplift and erosion will have continued over much of southern Taranaki Basin into the Pliocene.

Relationship between Late Miocene regressive deposits and the SCTIP unconformity

The Late Miocene involvement of southern and central parts of Taranaki Basin in crustal shortening resulted in a change from normal to forced regression within the upper part of the Mt Messenger Sequence. The extent of the stratigraphic section preserving the evidence for forced regressive sedimentation will be limited by the extent of subsequent uplift and erosion associated with (i) the SCTIP unconformity, which became more pronounced south of about Hawera, removing the underlying regressive deposits (Fig. 2), and (ii), erosion associated with the modern erosion surface in Taranaki Peninsula, which has cut-out much of the stratigraphic section of interest, certainly along the northern part of the Peninsula. Hence the area containing a record of late regressive sedimentation will lie along a west-east oriented zone either side of the 7.5 Ma lowstand shoreline (Fig. 3), corresponding in Taranaki Peninsula to the area between Makino-1 in the south and the McKee Field in the north, which is about where the SCTIP will crop out. Figure 6 shows the upper parts of selected wireline logs for four exploration holes in central Taranaki Peninsula stepping southward across the zone preserving the late forced-regressive deposits. The red line marks in each wireline record the inferred position of the SCTIP unconformity. Note in the Urenui Formation the very uniform gamma, sonic and resistivity log signatures corresponding to its massive to laminated mudstone facies. There is textural coarsening upwards within the Urenui Formation, the conformable transition to Kiore Formation being placed where the gamma values decrease and the signal becomes more variable, which also marks the start of distinct sonic velocity spikes in the section, and increasing and more variable resistivity values (Fig. 6). This lower (sandy motif) part of the Kiore Formation in these holes is up to 270 m thick and we infer that the depositional environments rapidly shallowed from an upper slope/upper bathyal environment to shelf depths as a result of forced regression ahead of uplift and erosion of the sea floor. There are systematic patterns in the logs below the SCTIP unconformity indicative of shelf cyclothem development; that is, glacio-eustatic sea level oscillations (6^{th}-order sequences)

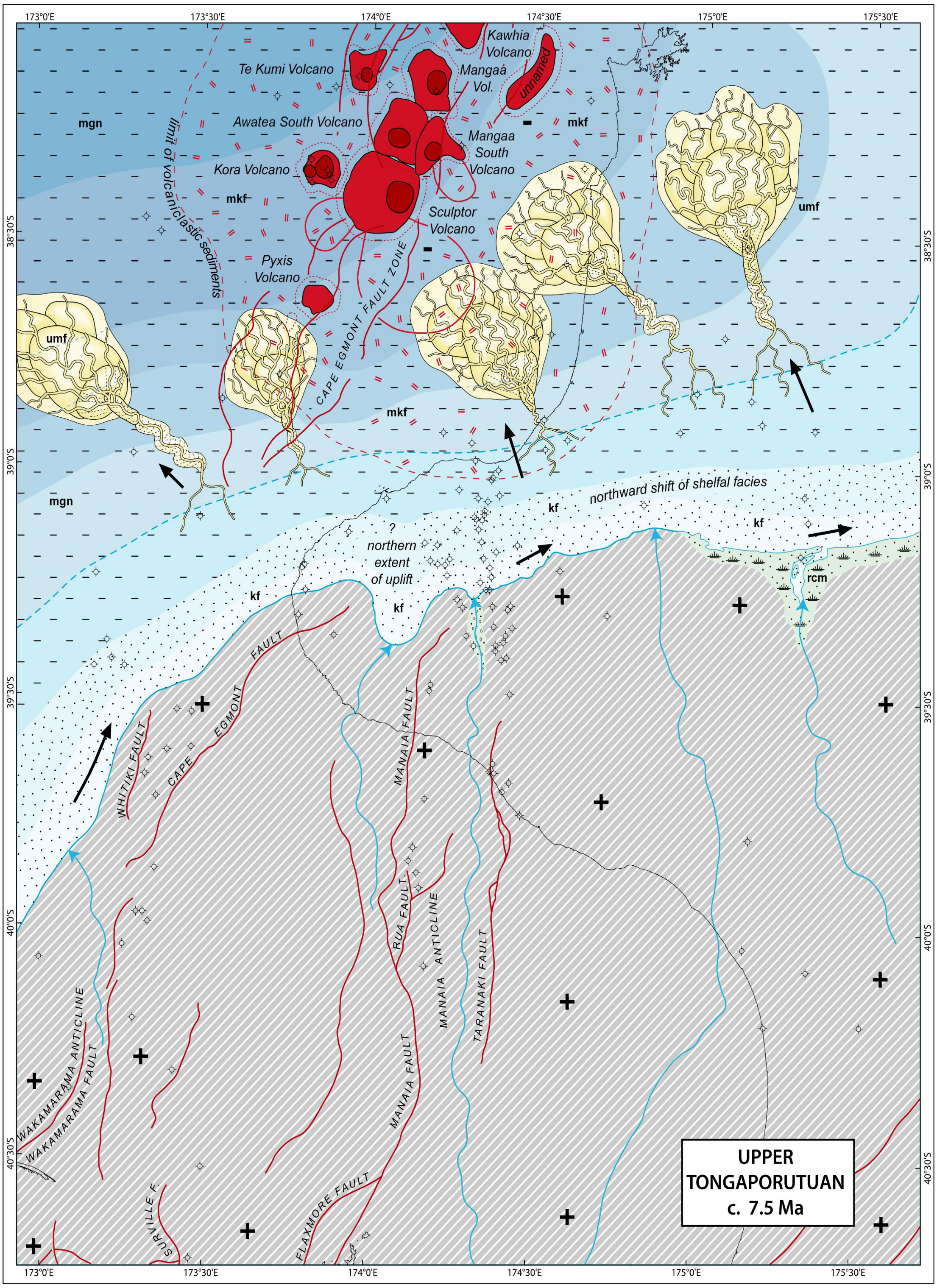


Fig. 3. *Paleogeographic map drawn for c. 7.5 Ma (upper Tongaporutuan) for Taranaki Basin including the region to the east (southern King Country region and Wanganui Basin). See Fig. 5 for legend.*

were superimposed upon, and possibly accentuated, the tectonically-driven forced regression. Above the SCTIP unconformity the logs indicate a sudden shift to massive sandy mudstone facies, which we informally refer to as the muddy motif of the upper part of the Kiore Formation (Fig. 6). Note how this facies in turn coarsens upwards, as for the Urenui Formation, from upper slope/bathyal mudstone facies into Matemateaonga Formation, which has highly variable log character corresponding to the development of shelf cyclothems with alternating shell beds, mudstone and sandstone facies. Figure 7 shows a composited broadly north-south oriented seismic reflection line through Stratford-1, Radnor-1 and Cheal-1 (projected), parallel to, and west of the holes included in Fig. 6. We have mapped the SCTIP unconformity in the southern half of the line where reflectors have been truncat-

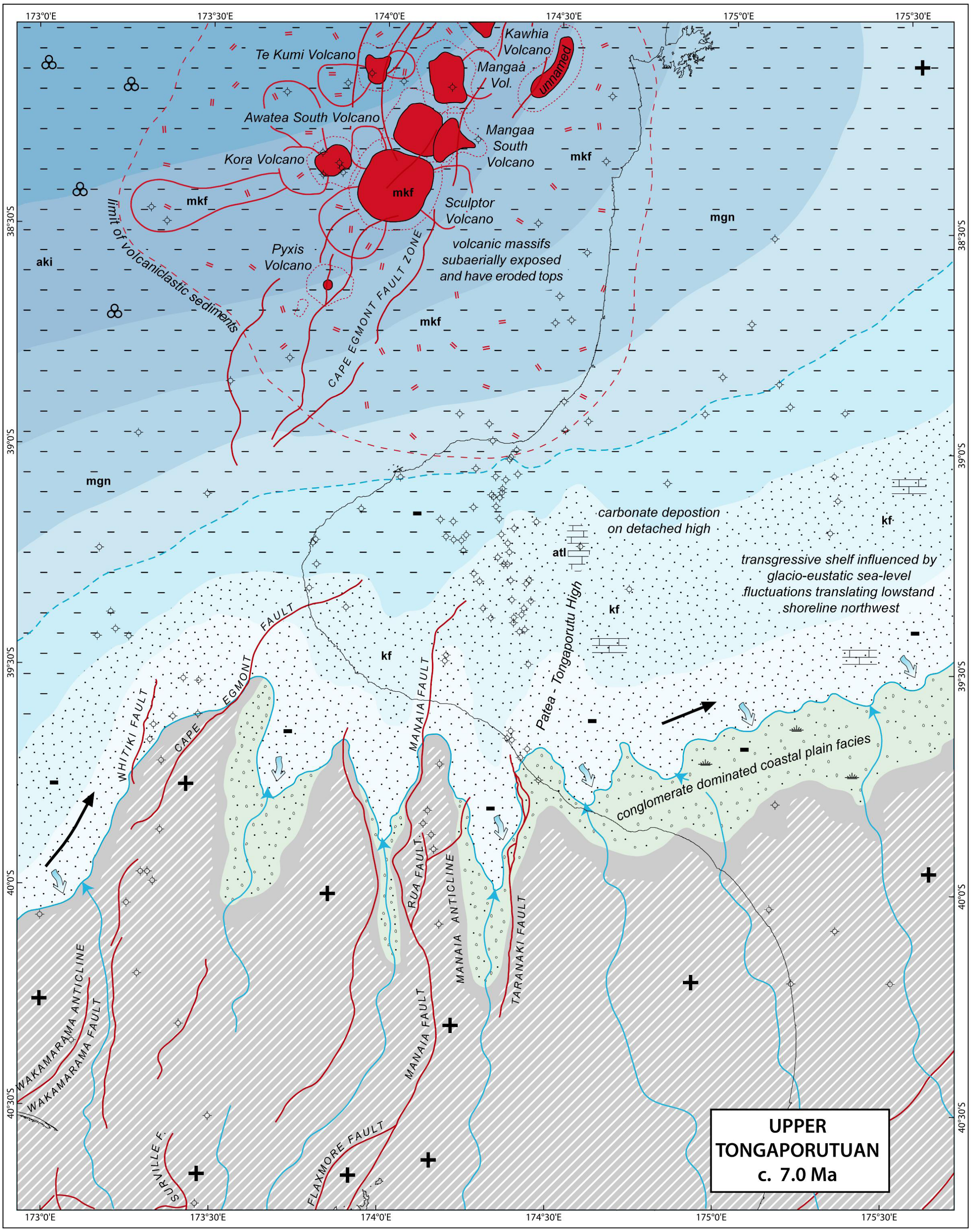


Fig. 4. *Paleogeographic map drawn for c. 7.0 Ma (upper Tongaporutuan) for Taranaki Basin including the region to the east (southern King Country region and Wanganui Basin). See Fig. 5 for legend.*

ed, and north to the point where reflectors appear to be conformable and we infer a correlative conformity. The dipping reflectors under the unconformity surface in the vicinity of Stratford-1 and Radnor-1 have stronger dips than can have arisen through tectonic tilting; consequently, we interpret these sloping reflectors as clinoforms formed in the Kiore Formation to Urenui Formation facies transition as a result of the forced regression of the shoreline and progradation of the linked depositional systems. Figure 8A is a composited seismic line from Matthews (2002) through Maui B, Maui A, and across to the Tui Field (Buchanan, 2001), showing the present day structure, and in Fig. 8B, the line flattened on the SCTIP unconformity. As for Fig. 7, the unconformity passes north westward into conformable section, and the beds underneath the unconformity surface, probably of upper Tongaporutuan age,

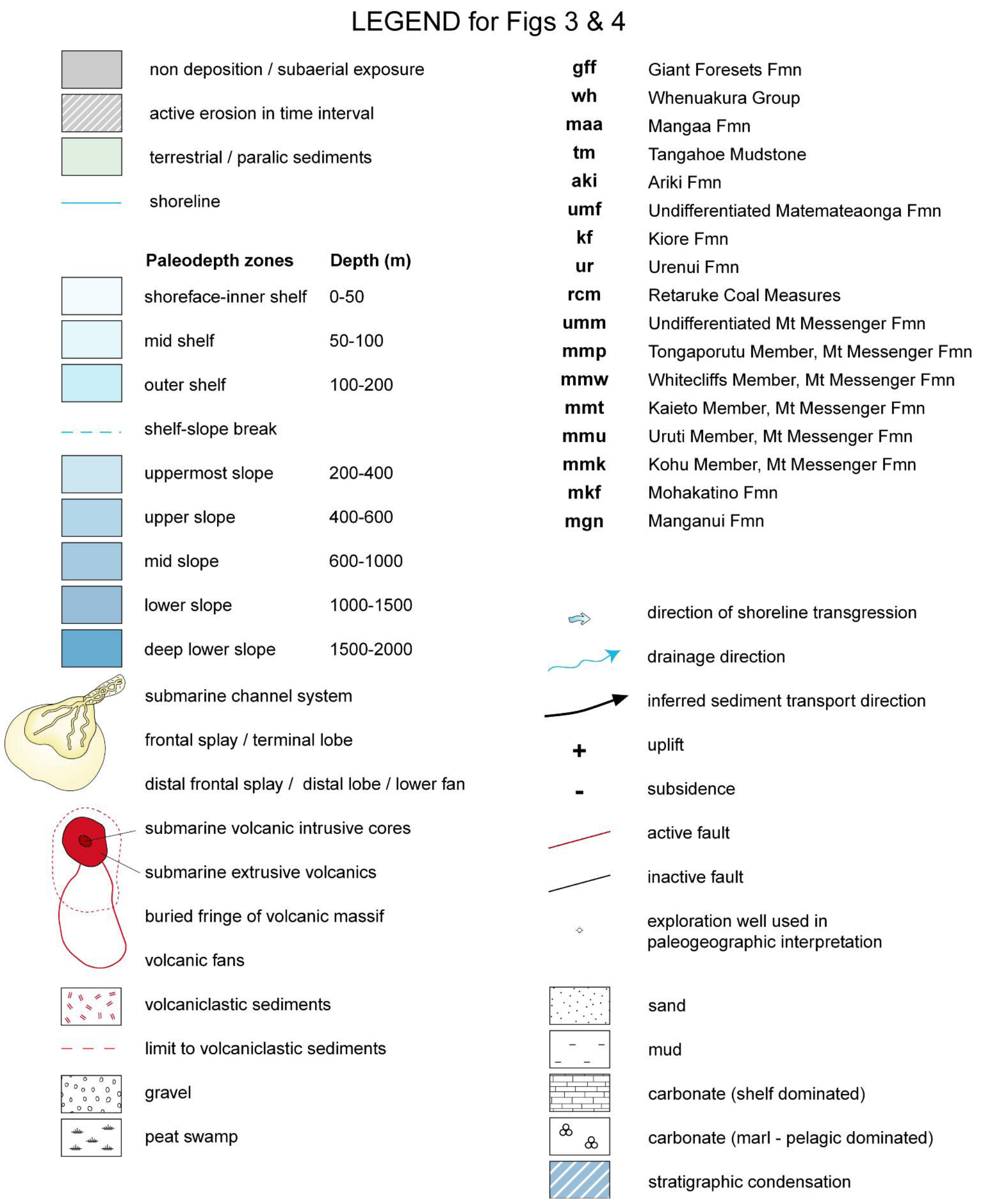


Fig 5. Legend for paleogeographic maps in Figs 3 & 4.

have depositional dips arising as clinoforms from rapid progradation of the contemporary continental slope forced by the Late Miocene tectonically-driven uplift of southern and central Taranaki Basin. The north-south oriented seismic line illustrated in Fig. 9A from STOS (2004), lies parallel to Taranaki Fault and well south of the SCTIP lowstand shoreline (Fig. 3). In contrast to Figs 7 & 8, there has been significant tilting and erosional truncation of beds beneath the SCTIP unconformity surface as a result of the Late Miocene tectonically-driven uplift. The west-east oriented seismic line in Fig. 9B shows that the SCTIP unconformity crosses the Taranaki Fault to lie upon the basement surface east of the fault. The fault has about 150 m of Late Pliocene (post Tangahoe Mudstone) offset on it and is associated with broad folding and uplift of the Patea High. Note the rugose relief on the basement surface, which developed during the Late Miocene uplift phase, reflecting the development of river valleys, the floors of which, and ultimately the sides, were onlapped and overtopped by accumulation of the Matemateaonga Formation.

Implications for stratigraphic nomenclature

We have presented above the basis of a new Middle Miocene to Pleistocene sequence stratigraphic subdivision for Taranaki Basin, which together with the evidence for the SCTIP unconformity and its timing, simplifies understanding of the geological development of the basin. It also helps clarify some confusion in PR reports around stratigraphic nomenclature for the Late Miocene and Early

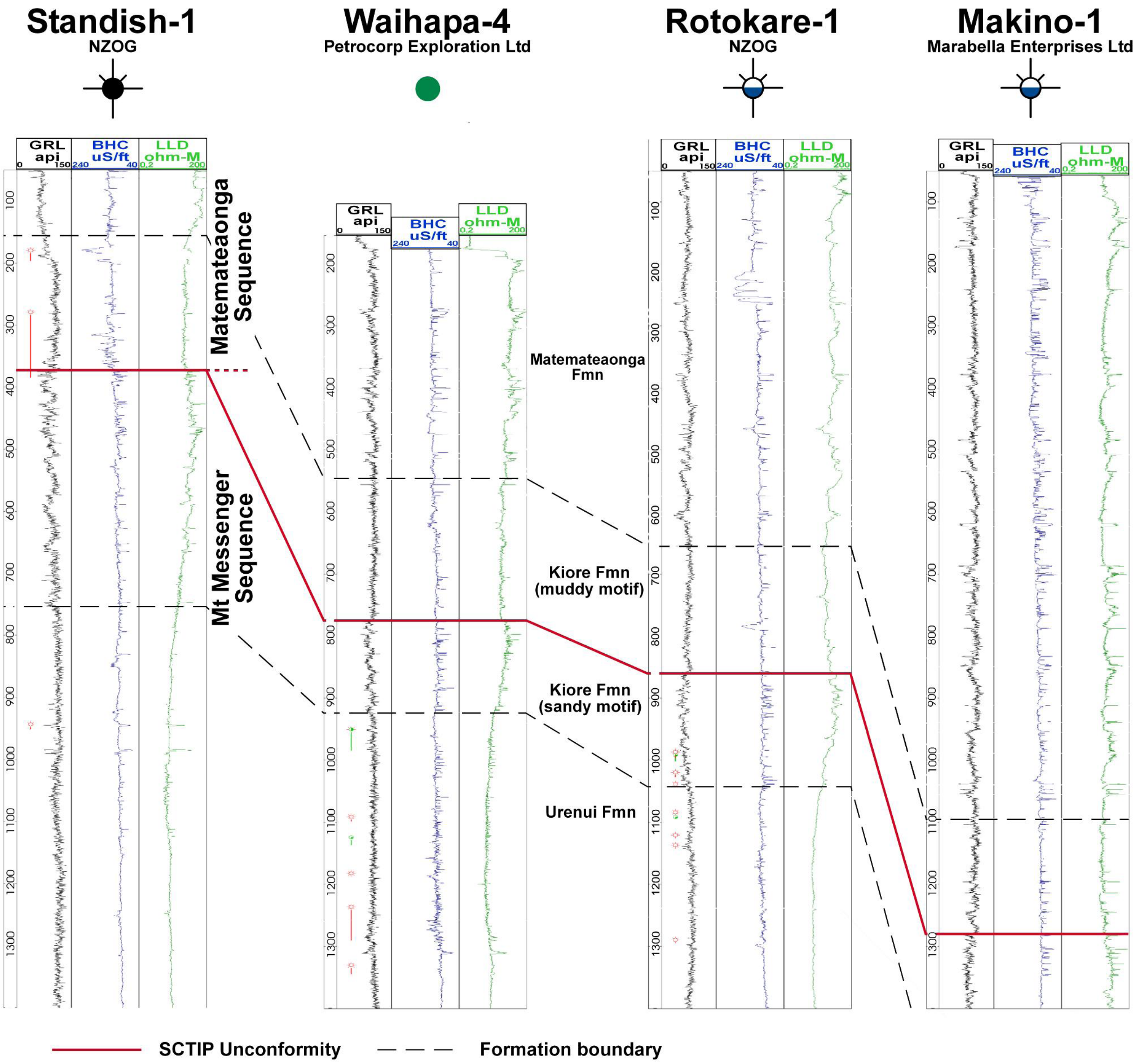


Fig. 6. *North – south correlation of wireline logs for four exploration holes in central parts of Taranaki Peninsula (Standish-1 is the most northern hole) showing in red the Late Miocene SCTIP unconformity. See text for interpretations.*

Pliocene units, which we now briefly address:

1. In eastern Taranaki Peninsula and northern Wanganui Basin there is a very clear distinction between the latest Miocene and Early Pliocene paleoshelf strata containing thin tabular shell beds and overlying siltstone and sandstone beds. We name this succession the Matemateaonga Formation (Vonk & Kamp, 2004; Kamp et al., 2004), following Powis (1997), taking a more restricted view of the stratigraphic extent of the formation than the usage in King & Thrasher (1996), for example.
2. In the same area and extending into southern King Country, we map a thick underlying succession as Kiore Formation, named after Kiore-1. The Urenui Formation, as observed in sea cliffs along the North Taranaki coast, is demonstrably a correlative of the lower part of the Kiore Formation inland to the east, where it differs in having abundant channelised and redeposited sandstone beds and bedded sandy siltstone facies. In many PR reports for holes intersecting this unit in the subsurface of central Taranaki Peninsula, the Kiore Formation has been named Lower Matemateaonga Formation.
3. Powis (1997) and authors of some other PR well completion reports have used the name “Waiouru Sandstone” for the late regressive facies within our Mt Messenger Sequence (i.e. our sandy motif unit within the Kiore Formation, Fig. 6). Waiouru Sandstone was first used by Fleming (1978) for what we now know is Early Pliocene Matemateaonga Formation in eastern parts of Wanganui Basin, and we strongly suggest that the use of this name for beds in Taranaki Basin is unnecessarily confusing.
4. For the same reasons as in 3 above, Waiouru Siltstone is a poor name for the silty motif unit within the upper part of our Kiore Formation (Fig. 6).

The occurrence of the SCTIP unconformity within

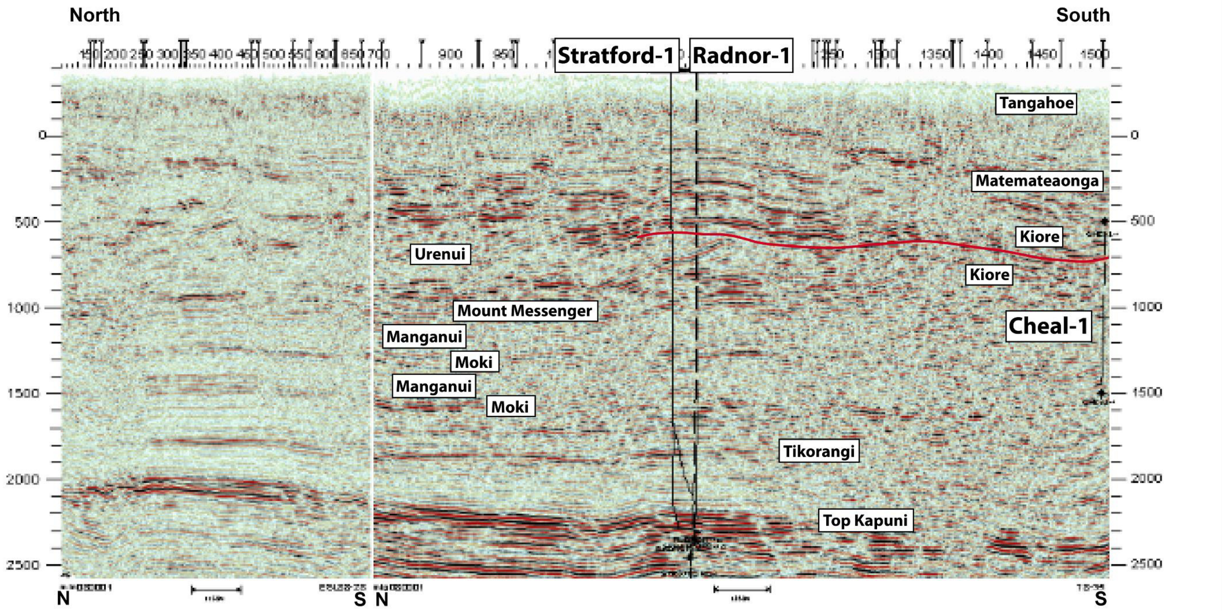


Fig. 7. Composited north – south seismic line in central Taranaki Peninsula showing in red the extent of the Late Miocene SCTIP unconformity, which north of Stratford becomes a correlative conformity. Note the occurrence of clinoforms beneath the unconformity in the vicinity of Radnor-1 and Stratford-1, which reflect forced regression in response to relative sea level fall driven by the basin uplift.

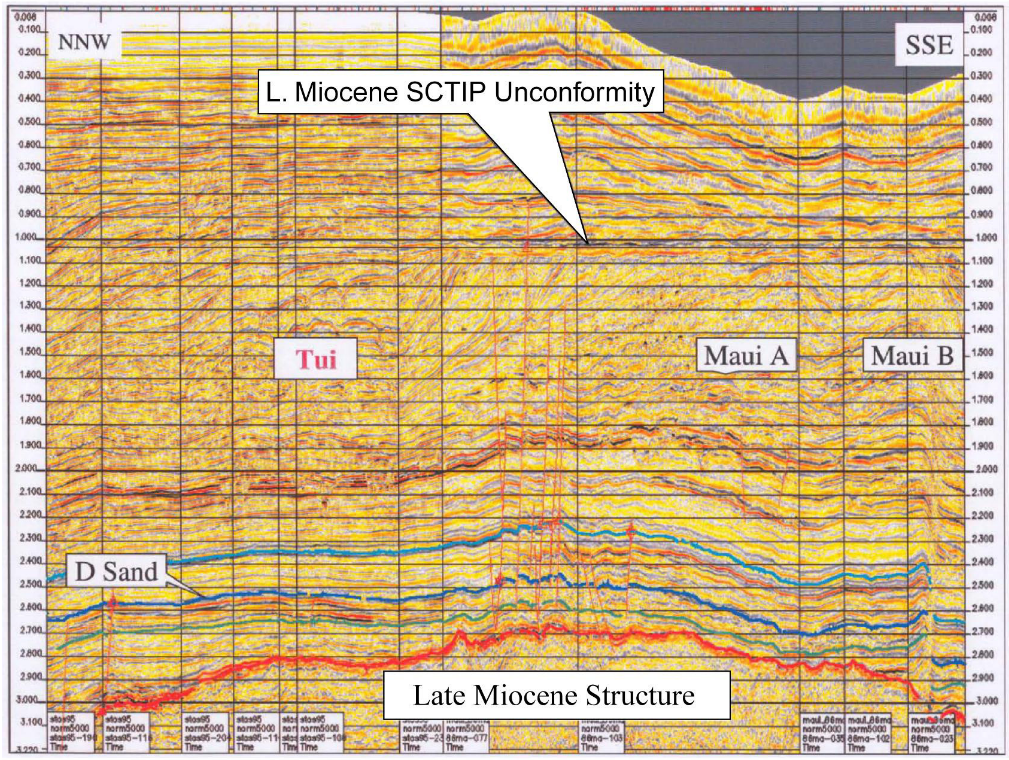
the Kiore Formation, with distinctive facies above and below, would suggest either that different formation names be established for the beds either side of the unconformity, or that the one (Kiore) formation be retained, with different members being applied to the different facies above and below the unconformity. We prefer the later option, and will move to formalise definitions elsewhere. Having a robust lithostratigraphy for the basin is important to enable communication, but we think that a robust sequence stratigraphic scheme is potentially more powerful in communication of understanding of the basin's dynamics and sedimentation.

Paleogeographic development

We have developed a new series of detailed paleogeographic maps for the Neogene of Taranaki Basin, two of which are illustrated here in Figs 3 & 4. Fig. 3 is drawn for the peak of the Southern and Central Taranaki Inversion Phase, as described above. There is clearly some uncertainty associated with this map. The amount of rock uplift will have been greatest east and south of Taranaki Fault, where basement was broadly elevated; in the Southern Inversion Zone of King & Thrasher (1996), the topography will have been more variable, with thrust-cored anticlines rising above a general surface, with intervening valleys controlling the location of north-flowing river channels. The northern and western fringes of the land area will have had low relief and the precise location of the shoreline and its coastal geomorphology are estimated from seismic reflection data. It is possible that shallow embayments occurred in the area between the Cape Egmont Fault and the Manaia Fault, rather than land, as shown. Alongshore drift of sand to the east is likely to have been well developed. The accumulation of fluvial facies in the east reflects the development of the Retaruke Coal Measures.

Figure 4 is drawn for the upper Tongaporutuan interval following the Intra-Kiore Pulldown and establishment of south-directed onlap. The coastal geomorphology of the shoreline would have been strongly indented due either to steep-sided valleys that had developed in the basement east of the Taranaki Fault, or due to broader valleys controlled by reverse faulted anticlines. As a consequence of the sediment being supplied to the margin being tied up in retrogradational shelf systems, active deposition on slope fans and hemi-pelagic sedimentation on the basin floor had ceased, allowing Ariki Formation to accumulate as marl on the Western Platform and over the area that became the Northern Graben, which was probably starting to be outlined by normal faults at this time.

B



A

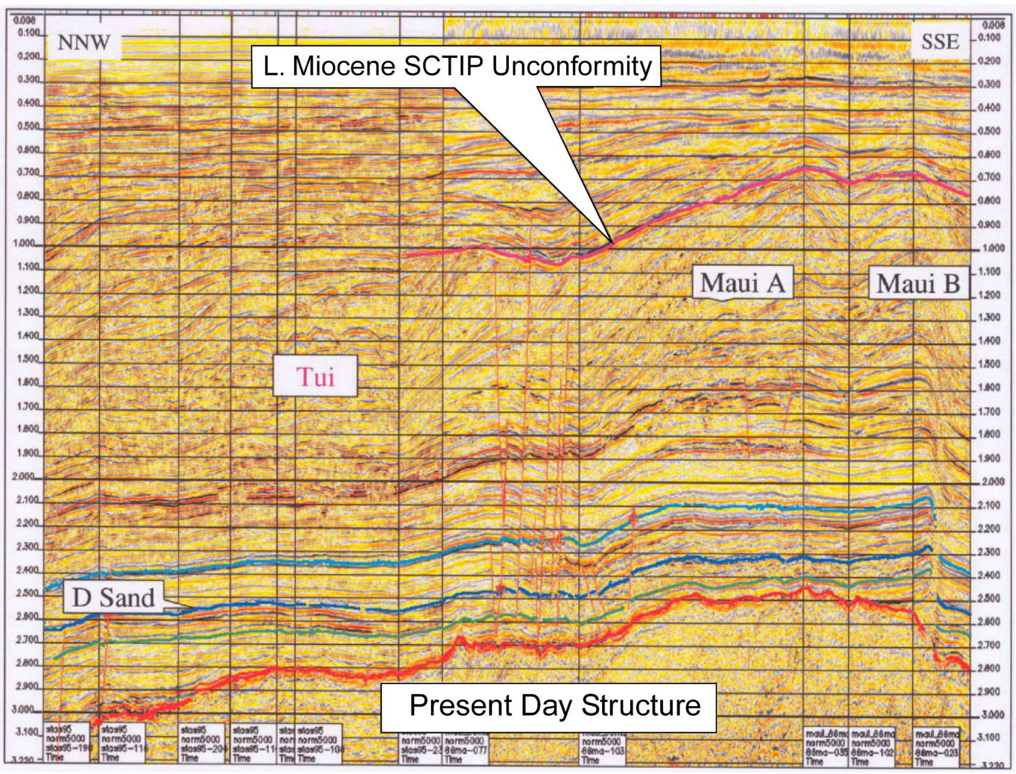


Fig. 8. *In A (lower panel) a composite seismic reflection profile through the two Maui Field and west to the Tui Field showing present day structure and in particular the extent of the Late Miocene SCTIP unconformity. In B (upper panel) the seismic line has been flattened on the SCTIP unconformity. Note the occurrence of slope dips (clinoforms) beneath the left hand (western) end of the SCTIP unconformity, reflecting forced regression and offlap. The seismic line is located on Fig. 1. From Matthews (2002) with age of the unconformity re-interpreted as being of Late Miocene age.*

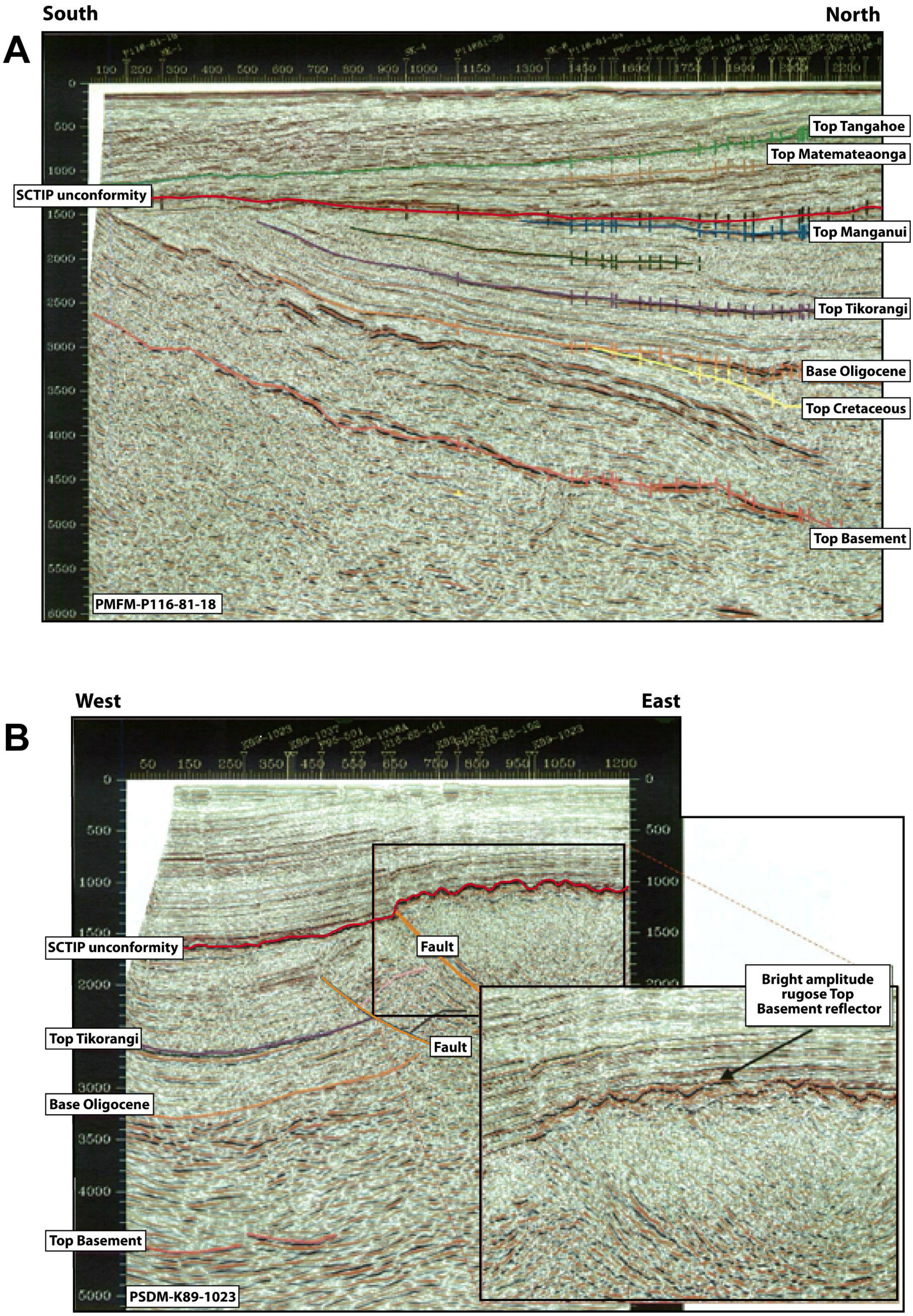


Fig. 9. *In A (upper panel) a north-south seismic reflection line immediately west of the Taranaki Fault south of Taranaki Peninsula showing tilted basement and Late Cetaceous to Early Miocene section, with reflectors truncated by the Late Miocene SCTIP unconformity. Overlying units (Matemateaonga Formation and Tangahoe Mudstone) have been tilted to the southwest as part of the doming of central North Island. In B (lower panel) a west – east cross line crosses the Taranaki Fault. Note the broad folding with 150 m of Late Pliocene offset on the Taranaki Fault, and the rugose relief on the top basement surface formed during the latest Miocene.*

Discussion

Neogene sedimentation in Taranaki Basin and phases of structure development have been critical to the development of its active hydrocarbon system(s). In this paper we have integrated the basin's sedimentation history with its late Neogene structure development via a new sequence stratigraphic framework illustrated in Fig 2. This highlights how the Mt Messenger Sequence, particularly its RST, results from a major phase of tectonism in the plate boundary zone, the crustal shortening then extending into the basin at c. 8.5 Ma and differentially exhuming the parts of the sequence and underlying units in southern and central Taranaki. The development of subsequent 3rd-order sequences was controlled by the formation of depocentres in eastern Taranaki Basin, each more southerly located, and the affect these depocentres had as terrigenous sediment traps. Prior understanding has possibly underestimated the degree of Late Miocene uplift and erosion and its extent in Taranaki Peninsula and across to the Tui Field. This uplift and erosion completely removed the shelf and upper slope components of depositional systems in southern and eastern parts of the basin that formerly linked to the deeper-water Mt Messenger facies beneath Taranaki Peninsula.

The development of our sequence stratigraphic framework (Fig. 2) has been strongly influenced by our mapping, facies and sequence analysis of Neogene marine successions exposed on land in eastern Taranaki Basin (i.e. southern King Country region and Eastern Taranaki Peninsula hill country) (Kamp & Vonk, 2006). Observations of outcrop sections has highlighted the character of sequence boundaries, enabled us to obtain good age control, and to infer stratal patterns from inferred depositional environments. We have also identified in outcrop the late regressive deposits of the Mt Messenger Sequence, which forced us to consider possible explanations, leading to their relationship to the Southern and Central Taranaki Inversion Phase (SCTIP).

In Fig. 2 we have shown schematically the stratigraphic and geographic extent of cyclothems we consider being of 6th-order duration (41 k.y) based on our paleomagnetic and biostratigraphic age control. We have no evidence for 5th-order duration (100 k.y.) cyclicity in the Late Miocene and Pliocene successions, but these do occur in the Middle Pleistocene Castlecliffian succession in Wanganui Basin (e.g. Kamp & Turner, 1990). There are however cycles of 4th-order duration (200-400 k.y) within the Mateaonga Formation. This suggests that the four main sequences described in this paper are of 3rd-order scale, corresponding to durations of 3-4 m.y.

Acknowledgements

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