Megasequence architecture of Taranaki, Wanganui, and King Country basins and Neogene progradation of two continental margin wedges across western New Zealand

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Abstract

Taranaki, Wanganui and King Country basins (formerly North Wanganui Basin) have been regarded as discrete basins, but they contain a very similar Neogene sedimentary succession and much of their geological history is held in common. Analysis of the stratigraphic architecture of the fill of each basin reveals the occurrence of four 2nd order megasequences of tectonic origin. The oldest is the early-early Miocene (Otaian Stage) Mahoenui Group/megasequence, followed by the late-early Miocene (Altonian Stage) Mokau Group/megasequence (King Country Basin), both of which correspond to the lower part of the Manganui Formation in Taranaki Basin. The third is the middle to late Miocene Whangamomona Group/megasequence, and the fourth is the latest Miocene-Pleistocene Rangitikei Supergroup/megasequence, both represented in the three basins. Higher order sequences (4th, 5th, 6th), having a eustatic origin, are evident in the Whangamomona and Rangitikei megasequences, particularly those of 5th order with 41 ka periodicity. The distribution of the megasequences are shown in a series of cross-section panels built-up from well -to-well correlations, complemented by time-stratigraphic cross-sections.

The base of each megasequence is marked by marine flooding and represents a discrete phase in basin development. For the first megasequence this corresponded to rapid subsidence of the King Country Basin in a compressional setting and basement overthrusting on the Taranaki Fault, with the rapid introduction of terrigenous sediment during transgression. The Mahoenui megasequence accumulated mostly at bathyal depths; no regressive deposits are evident, having been eroded during subsequent uplift. The second (Mokau) megasequence accumulated during reverse movement on the Ohura Fault, formation of the Tarata Thrust Zone, and onlap of the basement block between the Taranaki Fault and the Patea-Tongaporutu-Herangi High (PTH). The Whangamomona megasequence accumulated during extensive reflooding of King Country Basin, onlap of the PTH High and of basement in the Wanganui Basin. This is an assymetrical sequence with a thin transgressive part (Otunui Formation) and a thick regressive part (Mount Messenger to Matemateaonga Formations). It represents the northward progradation of a continental margin wedge with bottom-set, slope-set and top-set components through Wanganui and King Country basins, with minor progradation over the PTH High and into Taranaki Basin. The Rangitikei megasequence is marked by extensive flooding at its base (Tangahoe Mudstone) and reflects the pull-down of the main Wanganui Basin depocentre. This megasequence comprises a second progradational margin wedge, which migrated on two fronts, one northward through Wanganui Basin and into King Country Basin, and a second west of the PTH High, through the Toru Trough and into the Central and Northern Grabens of Taranaki Basin and on to the Western Platform as the Giant Foresets Formation, thereby building up the modern shelf and slope.

Fifth and 6th order sequences are well expressed in the shelf deposits (top-sets) of the upper parts of the Whangamomona and Rangitikei megasequences. They typically have a distinctive sequence architecture comprising shellbed (TST), siltstone (HST) and sandstone (RST) beds. Manutahi-1, which was continu-

ously cored, provides calibration of this sequence architecture to wireline log character, thereby enabling shelf deposits to be mapped widely in the subsurface via the wireline data for hydrocarbon exploration holes. Similar characterization of slope-sets and bottom-sets is work ongoing. The higher order (eustatic) sequences profoundly influenced the local reservoir architecture and seal properties of formations, whereas the megasequence progradation has been responsible for the regional hydrocarbon maturation and migration. Major late tilting, uplift and erosion affected all three basins and created a regional high along the eastern Margin of Taranaki Basin, thereby influencing the migration paths of hydrocarbons sourced deeper in the basin and allowing late charge of structural and possibly stratigraphic traps.

Introduction

Taranaki Basin is widely known as a hydrocarbon prospective and productive sedimentary basin. By contrast, the Wanganui and King Country basins, located immediately to the east of Taranaki Basin and onshore in North Island, are regarded as frontier basins without the same level of prospectivity. Why then is it of value to the petroleum exploration industry in New Zealand for the character and origin of these basins to be better understood?

The answer is clear. 1) The thick Neogene regressive wedge of sediment that drove maturation and migration in Taranaki Basin, also accumulated in the adjacent basins, where it is remarkably well exposed and accessible to investigation and its internal architecture can be more easily established. 2) The various timings of Neogene structural deformation in Taranaki Basin, responsible for the formation of most of its hydrocarbon traps, are difficult to establish from seismic reflection images, whereas they are easier to elucidate in the onshore basins where the tectonic signal is stronger. 3) The wider understanding of the geological evolution of western North Island that can be obtained from investigation of Wanganui and King Country basins allows for an improved concept of the paleogeographic development of the region and hence controls on source-to-sink sediment pathways and interactions with contemporary structures. 4) Late Miocene through Pleistocene sea-level changes of global extent and eustatic origin, influenced sedimentation with 100 k and 41 k periodicity in Taranaki Basin as much as in the adjacent basins where the stratigraphic and sedimentological response is quite evident. 5) Outcrop analogues can be developed in Wanganui and King Country basins to improve understanding of reservoir architecture and seal properties for application in Taranaki and other basins.

We are nearing completion of a comprehensive analysis of Wanganui Basin funded by The New Zealand Foundation for Research Science and Technology. While Wanganui Basin has been the focus of this work, later phases of it have involved extension into eastern parts of Tananaki Basin and reconnaissance work in the King Country Basin to the north. This work has identified the unity between these basins in terms of the common Neogene wedges of sediments they contain and the progressive and related basin development. This emerges chiefly from synthesis of the stratigraphic architecture of the basin fills.

The purpose of this paper is to present the high-level stratigraphic architecture of the fills of the Taranaki-Wanganui-King Country basins and to identify the orders of cyclicity within them. The Neogene wedge, which is the regressive part of the 1st order Late Cretaceous-Recent sequence in New Zealand (King et al. 1999), is shown to contain four 2nd order megasequences. The two younger megasequences are also shown to contain higher order sequences of tectonic and eustatic sea-level origin. It is hoped that this analysis will provide a different perspective and useful context for hydrocarbon exploration in the region.

Geological outline of central-western North Island

Figure 1 represents a geological map of central-western North Island, and Fig 2 represents the structure for the equivalent area. Figure 3 illustrates schematically the occurrence of major stratigraphic units in each of the three basins.

The extent of Taranaki Basin (Fig. 2) is generally well understood. Its eastern margin is usually taken as the Taranaki Fault with respect to the late Cretaceous and Paleogene section, or the Patea-Tongaporutu-Herangi High (PTH) for the Neogene section. The King Country Basin (formerly known as the North Wanganui Basin) lies to the east of the northern part of Taranaki Basin. Its southern and common boundary with Wanganui Basin is poorly defined with no obvious structure. It lies within a southward dipping monocline (Wanganui Monocline, Fig. 2) that reflects progressive southward onlap on to basement and concomitant uplift to the north. For the purposes of the Wanganui Basin analysis, the base of the section in the northern part of the basin has been taken as the base of the Matemateaonga Formation, which is a level at which substantial subsidence of basement occurred with marked southward migration of the shoreline.

Much of the Neogene tectonic development of the region and the evolution of the basins can be read from the geological and structure maps (Figs 1&2). Through time the northern part of Taranaki Basin has become differentiated from the King Country Basin, emphasised by the onshore versus submarine Earth surface environments at present and a significant unconformity across the shoreline. By contrast, the southern part of Taranaki Basin and Wanganui Basin have become depositionally unified; currently the Central Graben, Toru Trough and Wanganui Bight are different depocentres in effectively the same basin (Fig.2). These differences and similarities have originated late in the geological development of the region, chiefly since the late Pliocene. This has been largely a consequence of very

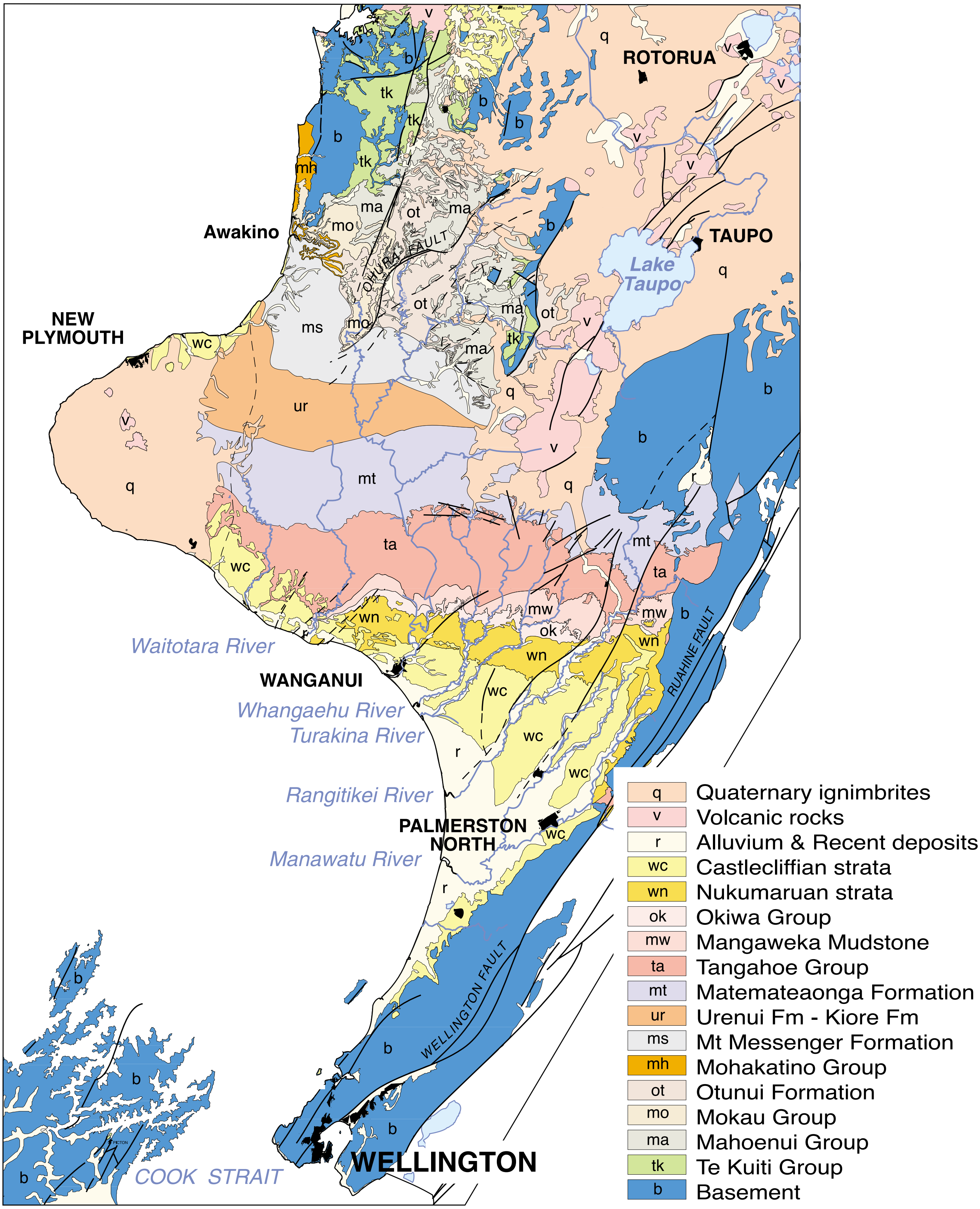


Fig.1. Geology map of western North Island, showing the main stratigraphic units in the Taranaki, King Country and Wanganui basins.

significant doming and concurrent erosion over the King Country Basin extending out to the Turi Fault Zone driven by an extensional tectonic environment, which also formed the Northern and Central Grabens and Taupo Volcanic Zone.

Outcrop patterns

A striking feature of the outcrop pattern in the northern part of Wanganui Basin and the southern part of King Country Basin is the west-east strike of the formations (Fig. 1). This involves the Mount Messenger Formation (late Miocene, Fig.3) through to Nukumaruan strata (late Pliocene- early Pleistocene, Fig.3). These units are structurally conformable and dip 2-4° S. Significantly, the distribution of Castlecliffian strata (middle to late Pleistocene, Figs.1&3) only are influenced by the occurrence of the axial ranges (Ruahine-Tararua Range), which are known to have been uplifted at this time. In the central and northern parts of the King Country Basin the stratigraphic units are older (Oligocene Te Kuiti Group, Early Miocene Mahoenui and Mokau Groups) and have shallow to negligible dip, being influenced more locally by tilting about faults (e.g. Ohura Fault) having northeast-southwest strikes sympathetic to those defining the Northern Graben and Taupo Volcanic Zone

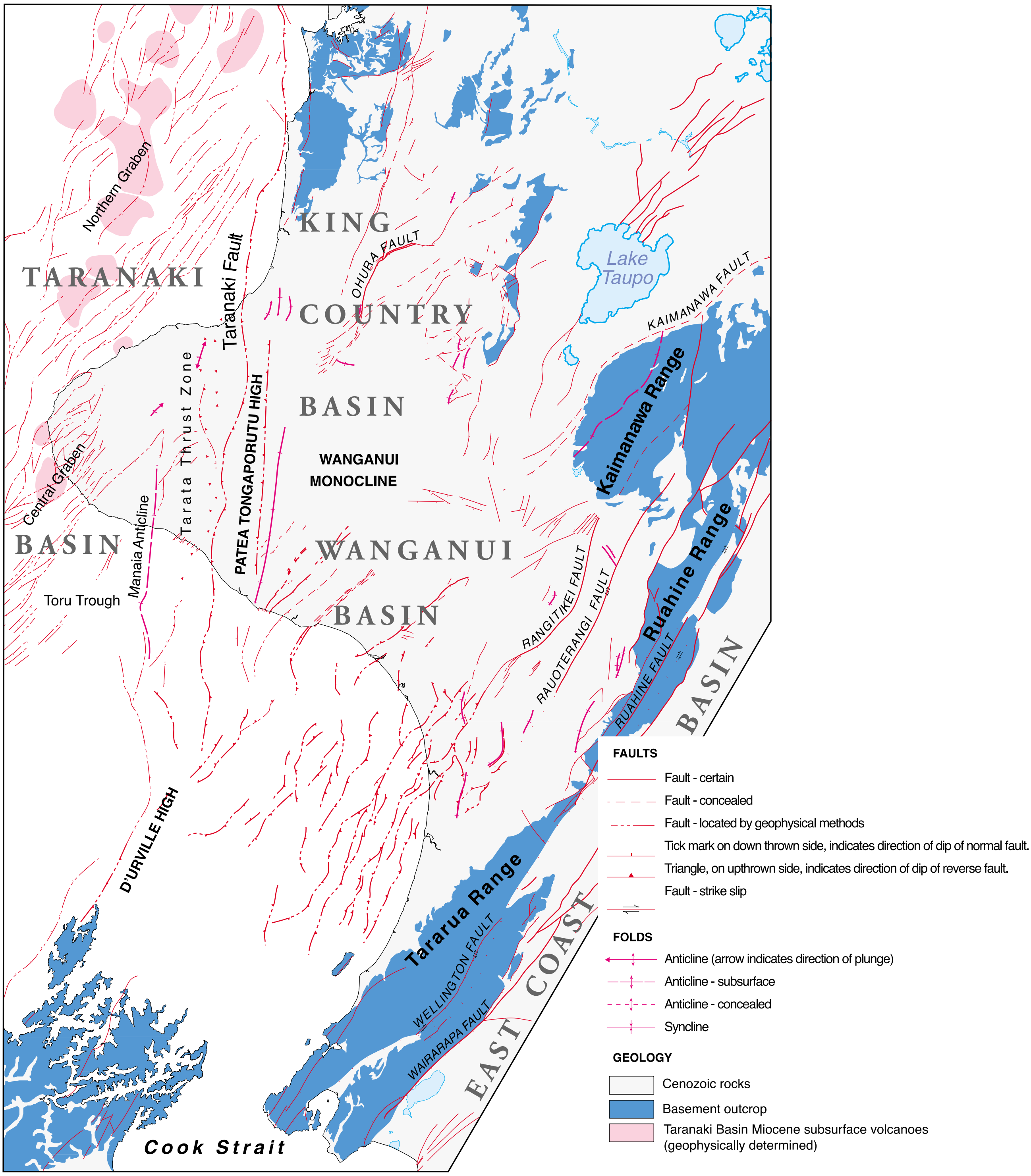


Fig.2. Map of western North Island showing the major geological structures, and the distribution of basement.

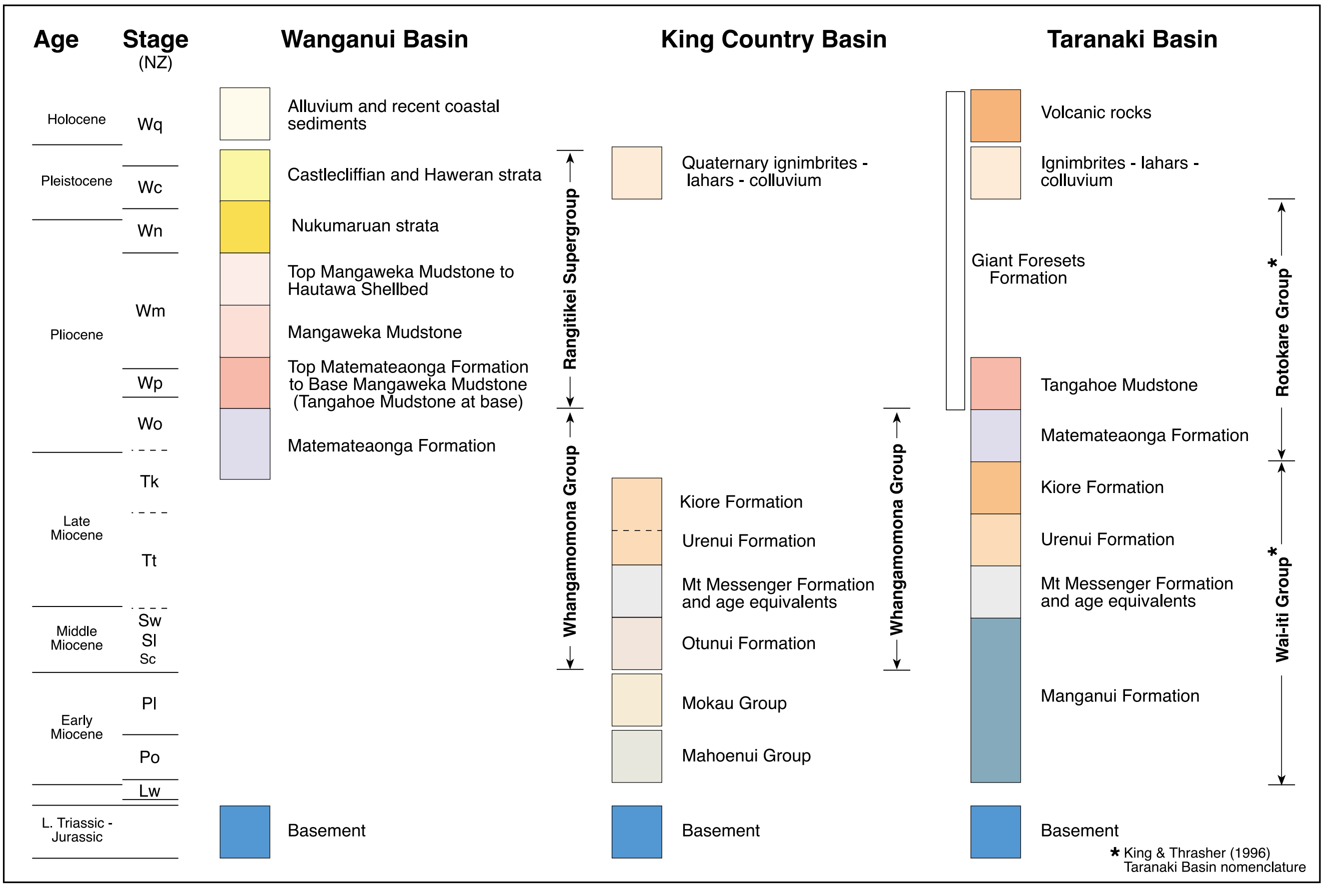


Fig.3. Figure showing the major stratigraphic units in each of Taranaki, King Country and Wanganui basins and the age of these units.

(Fig 2). Preliminary analysis of the magnitude and extent of erosion from King Country Basin and northern parts of Wanganui Basin suggest that up to 2.5 km of section has been eroded.

What stratigraphic units were removed? We consider, based on the information in the following figures, that this involved the middle Miocene through Pliocene marine units exposed in the Wanganui Monocline that were formerly much more extensive to the north. Their subsequent removal requires a mechanism, but also implies that the King Country Basin was a much more long-lived marine sedimentary depocentre than previously thought. This has implications for the late Miocene-Pliocene paleogeographic development of North Island. We also suggest that the marked discordance been the west-east strike of the Wanganui Monocline and the trend of the convergent plate margin, including the axial ranges, suggests that the uplift leading to the exhumation of the Oligocene and early Miocene successions in the King Country was not driven by crustal thickening related to accretionary plate margin processes or interaction across the subduction thrust, but rather, by mantle-driven processes consequent upon steepening of the dip of the subducted slab, as reflected in the Pliocene - Pleistocene migration of the volcanic arc from the Northern Graben into the Taupo Volcanic Zone.

The late Miocene Urenui Formation through to early Pliocene Tangahoe Mudstone clearly crosses the surface projection of the Taranaki Fault without offset. Further to the west these formations are overlain by volcaniclastic sediments of the Mt Taranaki ring-plain. An issue is whether or not these formations maintain their character and west-east strike beneath the subsurface of Taranaki Peninsula. This question is addressed in the following section, which impinges upon outcrop-subcrop correlations in the eastern parts of the peninsula (Vonk et al., this volume).

Stratigraphic architecture of the basin fills

To illustrate the stratigraphic architecture of the fills of the three basins a series of cross-sections and related time-stratigraphic panels have been constructed. Figure 4 shows the line of the cross-sections in relation to the geology of the western part of Wanganui Basin, the Taranaki Peninsula and the southern part of the King Country Basin. The cross-sections (Figs 5-9) are essentially well-to-well correlations, but they are keyed into outcrop. As many of the panels intersect basement, they indicate the form of the structure contour on basement and hence the basin morphology. The interpretation of the stratigraphy in the wells has followed close inspection of the wireline log character of the units in each of the wells and for some of them the placement of formation boundaries has been based on outcrop information.

Wanganui Basin-eastern Taranaki Basin: Santoft-1A to Tuhua-1

The cross-section form Santoft –1A to Tuhua-1 starts near the modern depocentre of Wanganui Basin, passes north to Parakino-1 in the Wanganui River valley, east across the

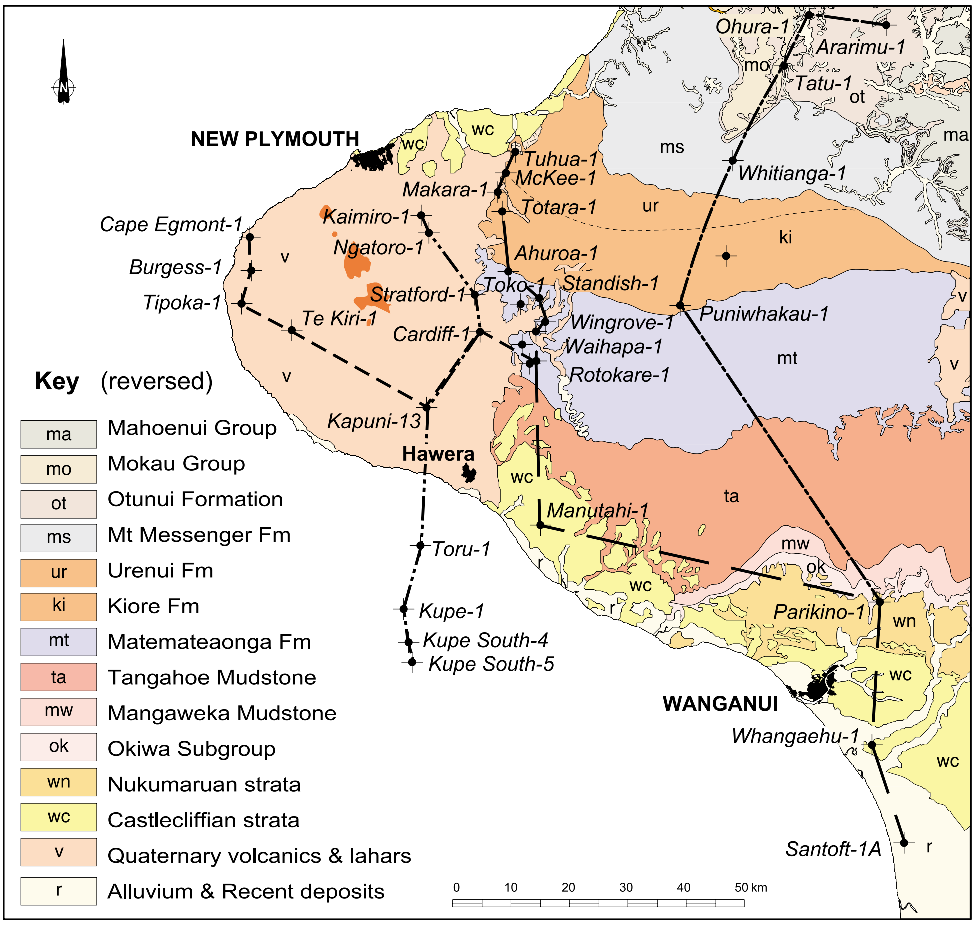


Fig.4. Geological map of central-western North Island including Taranaki Peninsula, showing the location of key hydrocarbon exploration holes and the line of four cross-sections.

Patea-Tongaporutu High to Manutahi-1, north along the eastern margin of Taranaki Basin, and crosses the Taranaki Fault between Rotokare-1 and Wingrove-1 (Fig. 5). It shows the consistent and shallow south to southwesterly dip of the beds irrespective of the basin containing them. The steeper dip of the beds between Parakino-1 and Whangaehu-1 reflects the marked and young subsidence in Wanganui Basin. Importantly, the Matemateaonga Formation and Tangahoe Mudstone were clearly deposited in both basins. Another interesting feature is the elevation of the top of the Tikorangi Formation in the vicinity of McKee-1, occurring at deeper levels to the south in the Waihapa-1 area. The tilting that affected the eastern margin of Taranaki Basin, uplifting amongst other units the reservoirs and traps in the Tikorangi Formation, was clearly a phenomenon that extended across northern parts of Wanganui Basin as well, and was probably related to the continued subsidence of southern parts of Wanganui Basin. This tilting is a geologically late event, probably of Late Pliocene –Pleistocene age, which elevated the eastern margin of Taranaki Basin in the Peninsula area and must have been a factor in controlling hydrocarbon migration and charge.

Figure 5 also shows the distribution in time of the units along the cross-section line. The striking feature is the southward onlap on to basement of the middle Miocene to Pleistocene sedimentary succession. The onlap followed the cessation of differential displacement on the Taranaki Fault in the Peninsula area. The rate of onlap increased markedly during the latest Miocene and earliest Pliocene, reflecting subsidence and deposition over northern parts of Wanganui Basin. The southward onlap implies a northerly paleoslope and differential subsidence down-to-the-north. This pattern was clearly reversed after deposition of the Tangahoe Mudstone, with southward tilting involving both the basement and cover succession and occurring without differential movement on the Taranaki Fault. This tilting uplifted the Paleogene section west of the Taranaki Fault some thousands of metres to create a regional structural high, thereby attracting the migration of hydrocarbons.

In the Santoft-1A to Tuhua-1 cross-section we identify two 2nd order megasequences, the Whangamomona and Rangitikei megasequences. The base of the middle to late Miocene Whangamomona Group/megasequence is placed at the base of a limestone succession lying unconformably on basement near the base of Rotokare-1. This limestone has a Clifdenian to Lillburnian age and probably corresponds to the Mangarara Limestone, which is distributed widely as a basal onlap facies of Clifdenian-Lillburnian age overlying Mokau Group or Mahoenui Group or basement in the King Country, including sites on the Tongaporutu-Herangi High (Uruti-1; Awakino River mouth; King et al. 1993). The Mount Messenger, Urenui and Kiore Formations accumulated within a progradational slope to basinal continental margin (King & Thrasher, 1996). At that time there must have been a very narrow shelf along the cross-section line between Rotokare-1 and Manutahi-1. During accumulation of the Matemateaonga Formation, the shelf widened significantly, but northward progradation and offlap continued and possibly even accelerated, reflecting an increase in the rate of sediment supply to the margin from accelerated erosion of the Southern Alps. The top of the Whangamomona megasequence is placed at the top of the Matemateaonga Formation rather than at its base, because the top/base of the Tangahoe Mudstone marks the more significant flooding surface, which terminated the preceding margin progradation. While there was substantial onlap at the base of the Matemateaonga Formation, off-lap dominated and the landward shift in the position of onlap is more marked at the base of the Tangahoe Mudstone.

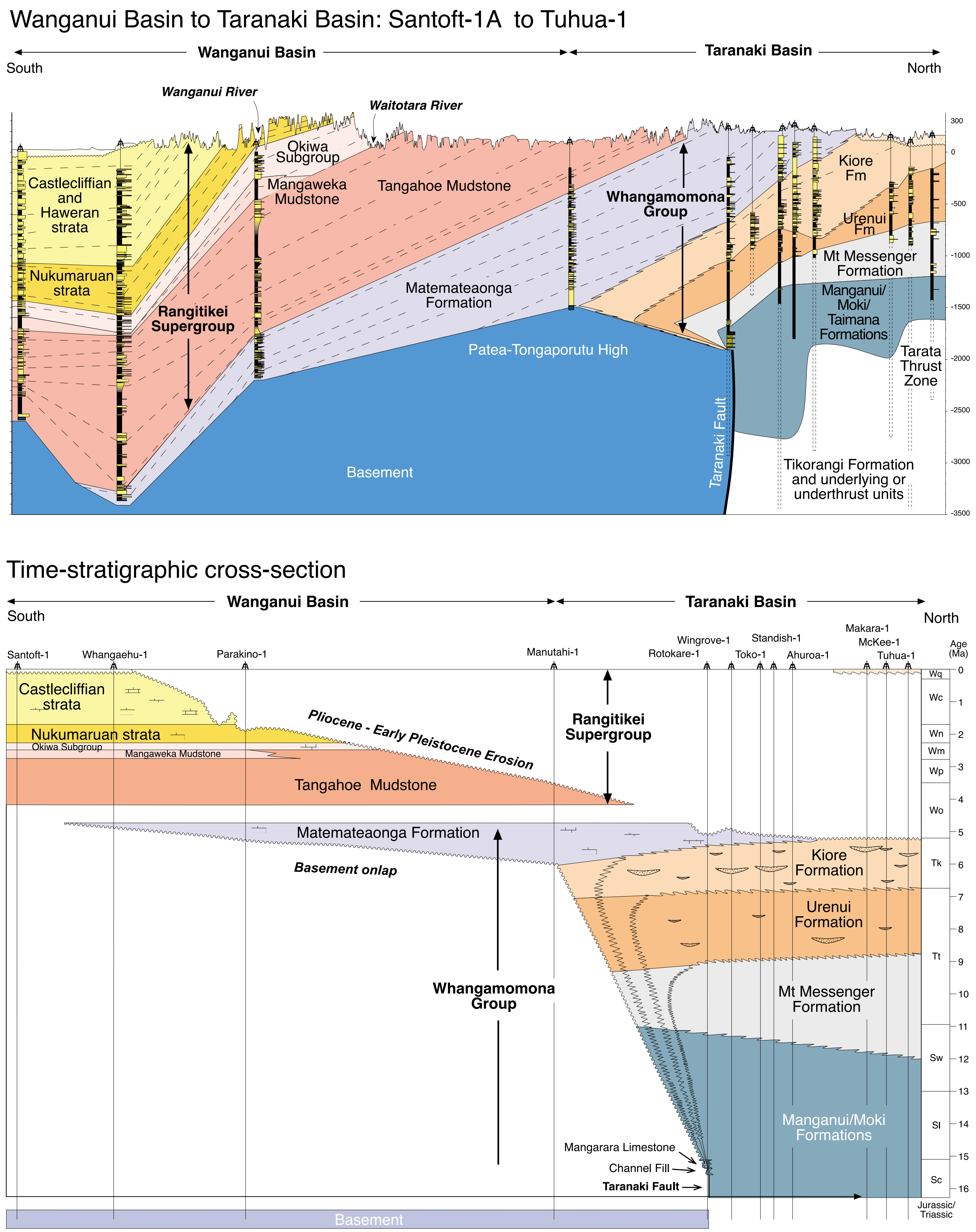


Fig.5. Wanganui Basin to Taranaki Basin (Santoft-1A to Tuhua-1) stratigraphic panel built up from well-to-well correlations, and related time-stratigraphic cross-section.

We have not tested the extent to which the occurrence of the Whangamomona Group can be mapped in the offshore parts of Taranaki Basin, where the stratigraphy comprises undifferentiated Manganui Formation (King and Thrasher 1996). During the middle Miocene the water depths were already bathyal and these parts of the basin may not have experienced a discrete phase of subsidence, such as that observed in the eastern margin of the basin and in the King Country Basin.

In their basin synthesis, King and Thrasher (1996) placed a group boundary (Wai-iti to Rotokare) at the base of the Matemateaonga Formation, considering this to be widely unconformable in the vicinity of the Taranaki Peninsula.

We concur that this boundary is unconformable in the Toru Trough north from Tahi-1 to the Kapuni Field. However this is not the case north and east of Kapuni. An additional complication was miscorrelation of Matemateaonga

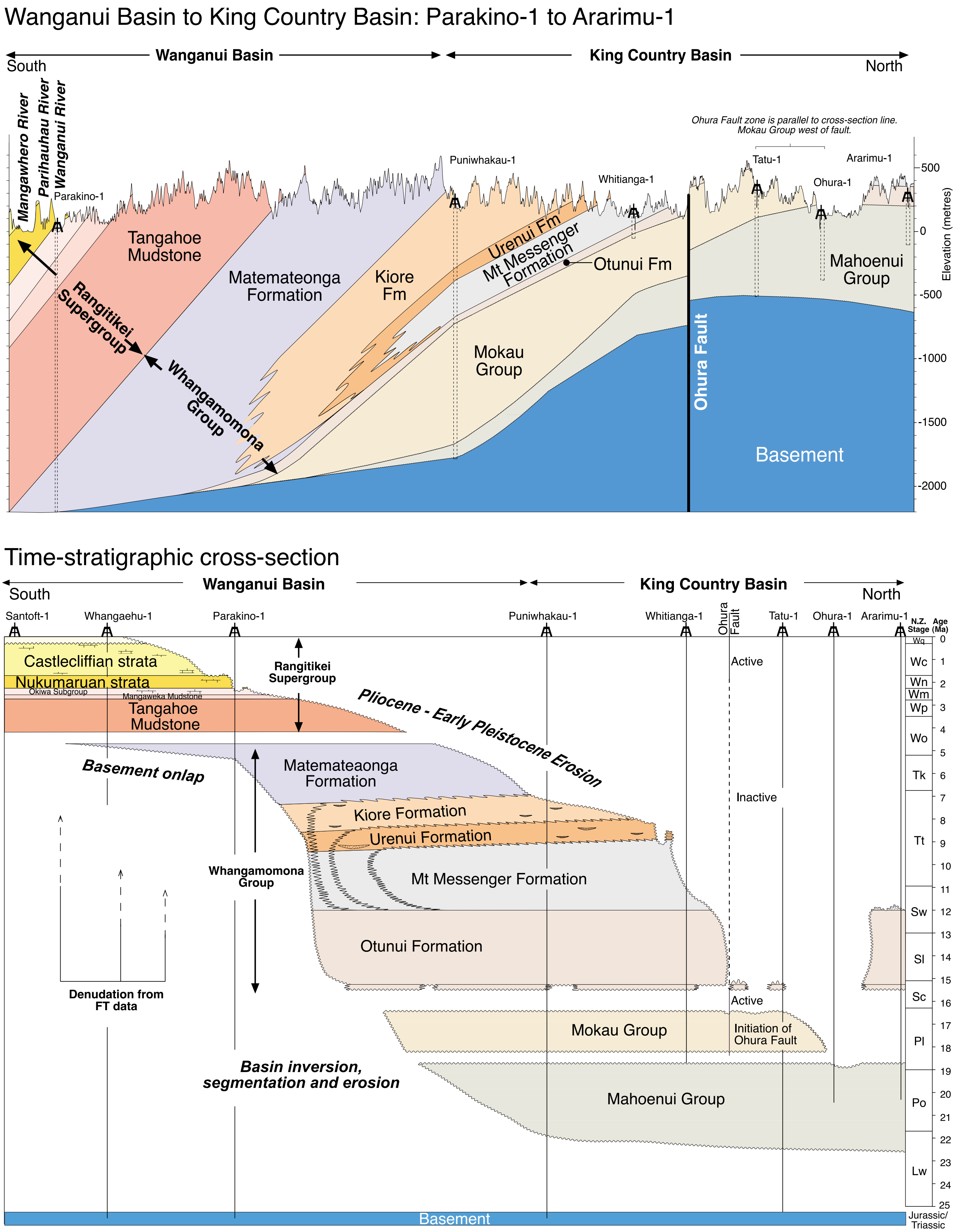


Fig.6. Wanganui Basin to King Country Basin (Parakino-1 to Ararimu-1) stratigraphic panel built up from well-to-well correlations, and related time-stratigraphic cross-section.

Formation with Whenuakura Subgroup deposits beneath the western parts of the Peninsula.

The base of the Tangahoe Mudstone is the most extensive flooding surface in the whole of the middle Miocene to Pleistocene succession of the three basins. This flooding surface marks the base of the Rangitikei Supergroup/megasequence. The supergroup rank is applied to this unit because of the numerous lithostratigraphic groups established by Fleming (1953) for the late Pliocene and Pleistocene succession of Wanganui Basin. The extensive flooding is associated with a marked landward (to south) shift in the position of onlap. Across a few metres of section, the paleoenvironment changes from shoreface/inner shelf to bathyal water depths, a deepening of about 400 m, which generated a paraconformity marked by glauconitic mudstone (Hayton 1998). We have mapped this boundary from the Cape Egmont Fault Zone in Taranaki Basin to the eastern (Ruahine) margin of Wanganui Basin. We indicate below that the Rangitikei megasequence correlates with the Giant Foresets Formation, which underlies the modern shelf and slope offshore to the west in Taranaki Basin.

Wanganui Basin - King Country Basin: Parakio-1 to Ararimu-1

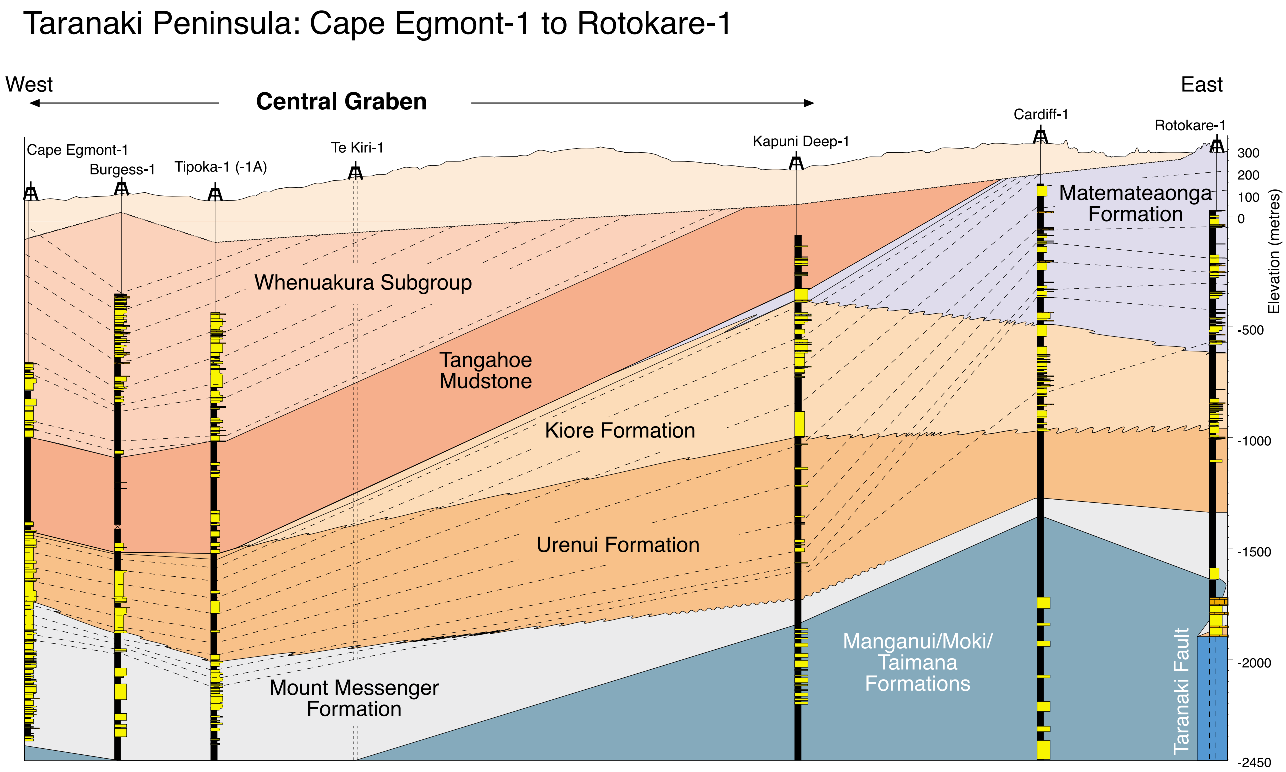
Figure 6 illustrates a cross-section through the axis of the Wanganui and King Country basins. It emphasises the structural conformity of the formations and how the slope on the basement surface is sympathetic to the dip on the formation contacts; that is, the Wanganui Monocline, defined from the dip of bedding of Miocene sediments (Fig.2), is also evident in the structure on basement. The mechanism responsible for the tilting of the formations also differentially uplifted the basement. The cross-section also shows the persistent southward onlap of successive formations on to basement, suggestive of a northerly paleo-slope prior to late uplift and tilting to the south.

The time-stratigraphic section (Fig 6) highlights the occurrence of four unconformity-bounded megasequences. The first two are of early Miocene age. The Mahoenui Group comprises massive mudstone (Taumatamaire Formation) and flysch (Taumarunui Formation) facies (Nelson and Hume 1977). The initial subsidence of the basin containing this succession was very rapid, and is marked by thin, coaly incised valley fill deposits, a thin tabular transgressive (onlap) shellbed (part of Mahoenui Group, but mapped by Hay (1967) as Te Kuiti Group), about 100 m of massive shelf to slope mudstone, and then 500 m or more of basin floor redeposited sediments. The Mahoenui Group extended into the early part of the Altonian Stage (Topping 1978). Surprisingly, no regressive slope or shelf facies have been identified at the top of the Mahoenui Group. Presumably, these were eroded during a short-lived and marked phase of uplift and erosion that affected the whole of the basin. This inversion was associated with reverse movement on the Ohura Fault. The block to the east of the fault maintained elevation above sea level throughout the rest of the early Miocene, and sourced sediments to the block to the west of the Ohura Fault, where a coal measure to inner shelf succession several hundred metres thick (Mokau Group, second megasequence, Fig. 6) accumulated unconformably over Mahoenui Group and onlapped basement to the south (Fig.6).

The third Neogene megasequence is represented by the Whangamomona Group (Fig. 6). During the middle Miocene the whole of the King Country region subsided, resulting in the accumulation of a transgressive shelf succession represented by the middle Miocene Otunui Formation over the Mahoenui Group in the east and the Mokau Group in the west. The basal facies of the Otunui Formation are heterolithic, commonly characterised by an onlap shellbed known as the Mangarara Limestone (Henderson and Ongley 1923). At the Awakino River mouth this unit is a gritty glauconitic calcareous sandstone (King et.al. 1993). The Otunui Formation is 100 to 200 m thick and comprises crudely bedded silty fine sandstone and sandy siltstone, with occasional conglomeratic channels. The Otunui Formation passes conformably upwards into the Mount Messenger Formation, initially as a massive mudstone, with redeposited sandstone beds (sandy debris flow deposits) occurring within a few 10s of m of this contact, reflecting rapid late middle Miocene subsidence to bathyal conditions.

The Whangamomona Group comprises an asymmetric (in thickness but not time) transgressive-regressive cyclothem of identical timing and character to that described above for the eastern margin of Taranaki Basin. Soon after bathyal conditions were achieved in the King Country Basin (late Waiauan-early Tongaporutuan Stages) the depositional sequence became regressive with the progradation of slope (Urenui and Kiore Formations) and shelf (Matemateaonga Formation) deposits over the lowermost slope to basin floor deposits of the Mount Messenger Formation. Concurrently, these units, especially the Matemateaonga Formation, onlapped the basement to the south. This geometry required there to be a persistent increase in sediment flux delivered to the continental margin, particularly from 7-8 m.y. ago, after which most of the thickness of the megasequence accumulated. There is a coincidence between the middle Miocene subsidence and start of accumulation of the Otunui Formation, and fission track thermochronological data recording the initiation of the erosion, probably driven by uplift of basement underlying the Ruahine Range. The modern Ruahine Range is much younger, having formed since about 1.2 Ma, but clearly there was more than 4 km of denudation of the basement starting about 15 m.y. ago. This erosion probably sourced the Otunui Formation and younger beds, but a Southern Alps source probably became dominant form about 10-12 m.y. ago.

The fourth megasequence comprises the Rangitikei Supergroup. In the northern parts of Wanganui Basin the base of the Tangahoe Mudstone is also the major flooding surface and is marked by a condensed horizon of glauconitic mudstone, with some 600 k.y. represented by 20-30 cm of sediment (Hayton 1998). This is followed within a few 10s of metres by thick redeposited sandstone beds that accumulated in broad channels as slope-sets to bottom-sets. A progradational shelf succession (top-sets) of late Pliocene (Mangapanian Stage) aged sediments belonging to the Paparangi and Okiwa Subgroups (McIntyre and Kamp, 1998,



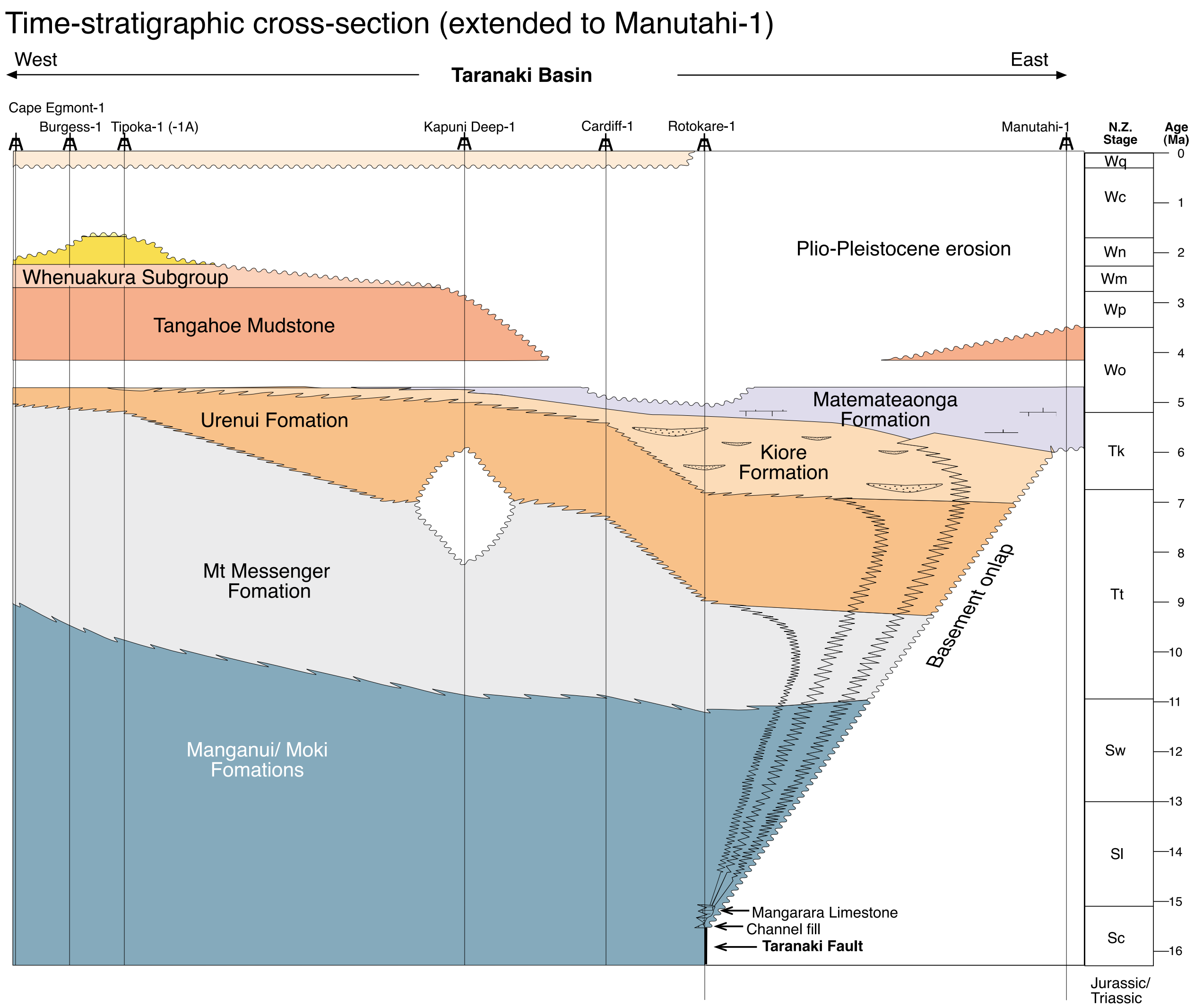


Fig.7. Taranaki Peninsula (Cape Egmont-1 to Rotokare-1) stratigraphic panel built up from well-to-well correlations, and related time-stratigraphic cross-section (extended to Manutahi-1).

Kamp and McIntyre, 1998, McIntyre 2001) overlies the slope deposits. The Nukumaruan and Castlecliffian (latest Pliocene and Pleistocene) successions accumulated in Wanganui Basin exclusively as shelf sequences (top-sets) (Fleming 1953, Beu and Edwards 1984, Kamp and Turner 1990, Abbott and Carter 1994, Naish and Kamp, 1995, 1997).

Taranaki Peninsula: Cape Egmont –1 to Rotokare-1

Figure 7 is a cross-section across Taranaki Peninsula. The distribution of the Mount Messenger Formation in it includes fine-grained sediments of Tongaporutuan (late Miocene) age, which have been erosionally truncated over the Manaia Anticline in the vicinity of Kapuni-Deep-1.

The key feature in this cross-section is identification of a paleo shelf-slope break, represented by the transition between the top-sets of the Matemateaonga Formation and the upper slope-sets of the Kiore Formation. See Vonk et.al. (this volume) for description of the Kiore Formation and interpretation of its paleo-environmental setting. Mapping of the subsurface distribution of these formations depends critically upon interpretation of the wireline log character of these respective units. In the section below on the character of the Manutahi-1 record, we outline the distinctive wireline log signals associated with the shelf top-sets; Vonk et.al.(this volume) outline for Rotokare-1 the log signal for Kiore Formation, inferred to have accumulated in an uppermost slope setting. The shelf-slope break was strongly aggradational and weakly progradational to the west between Rotokare-1 (23 shelf sequences present, including outcrop above the well site) and Kapuni Deep-1 (2 shelf sequences) compared with the degree of northward progradation between Wanganui and King Country basins. The position of the shelf edge was evidently influenced by the Patea-Tongaporutu High, possibly because the main sediment pathway was governed by differential subsidence in the axis of the Wanganui-King Country basins, which lay to the east. Through most of the latest Miocene (Kapitean Stage) and early part of the early Pliocene (early Opoitian Stage) there was a marked west-facing slope west of Rotokare-1/Cardiff-1 (Fig. 7). In Cape Egmont-1, Burgess-1 and Tipoka-1 the Urenui Formation contains lower slope/basin floor redeposited sandstone beds akin to the fan deposits in the lower part of the Mount Messenger Formation exposed in the North Taranaki coastal section (King et.al. 1993).

Figure 7 shows that a very strong distinction occurs between the Tangahoe Mudstone and the Matemateaonga-Kiore Formations beneath the peninsula, separating the Whangamomona and Rangitikei megasequences. This boundary corresponds to a fining of texture and the occurrence in the base of the Tangahoe Mudstone of distinctive redeposited sandstone beds. Despite the fact that a slope to basin floor environment existed beneath the peninsula in the early Pliocene, this area was still influenced by the tectonic pull-down that was marked across Wanganui Basin at this time. A major effect of the pull-down was an interval of terrigenous sediment starvation because of the accommodation rapidly generated in the southern part of Wanganui Basin, which lay between the Southern Alps sediment source and the Taranaki Basin. The bottom-sets and slope-sets of the Tangahoe Mudstone pass upwards into shelf deposits of the Whenuakura Subgroup, which are well exposed in the coastal section south of Hawera, immediately west and east of the Patea-Tongaporutu High (Whitten 1973; Fleming 1953). These shelf deposits are of middle to late Pliocene (Waipipian to Nukumaruan Stages) age, are erosionally truncated, dip southwestward and were clearly affected by the late tilting phase that affected northern Wanganui Basin and the King Country Basin.

The Giant Foresets Formation correlates with the Rangitikei megasequence and represents the younger progradation to the west and north of the Peninsula through the Central and Northern Grabens and on to the Western Platform (Hansen and Kamp, this volume). The Urenui to Matemateaonga Formations are not part of the Giant Foresets Formation, but rather, are part of the older (Whangamomona) progradational megasequence.

Toru Trough -Taranaki Peninsula: Kupe South-5 to Kaimiro-1

Figure 8 illustrates a south-to-north well correlation through Toru Trough and into central Taranaki Peninsula (Kupe South-5 to Kaimiro-1). It shows the late Miocene unconformity at the base of the Matemateaonga and Urenui Formations beneath the Toru Trough, reaching as far north as the Manaia Anticline in the Kapuni Field. Facies transitions between the shelfal Matemateaonga Formation and the Kiore and Urenui Formations reflect the line of the cross-section in relation to the former shelf-slope break, with Kapuni Deep-1 lying mostly west of this break, except for accumulation of the younger two shelf sequences of the Matemateaonga Formation.

The other major feature evident in the cross-section is the dip on the Tangahoe Mudstone-Whenuakura Subgroup deposits and how this dip decreases between Kupe-1 and Kupe South-4. This illustrates the extent of the late tilting that affected the three basins as described above. It also maps out the extent of the influence of the tectonic pull-down that occurred at the base of the Tangahoe Mudstone and formed the main Wanganui depocentre.

Second order megasequences and two phases of continental margin progradation

Figure 9 is a block diagram that shows schematically the depositional and stratigraphic architecture of the two, second order, megasequences comprising the middle Miocene to Pleistocene succession in the Wanganui, King Country and Taranaki basins. Both the Whangamomona and Rangitikei megasequences formed as northward prograding continental margin wedges, and had similar top-set, slope-set and bottom-set stratal architecture. This architecture is preserved for the Whangamomona megasequence because of the tectonic pull-down at the base of the Tangahoe Mudstone, the subsequent burial, and the late tilting. Very unusually, the onlap margin of the Whangamomona megasequence has been preserved, but the deeper-water more oceanward part

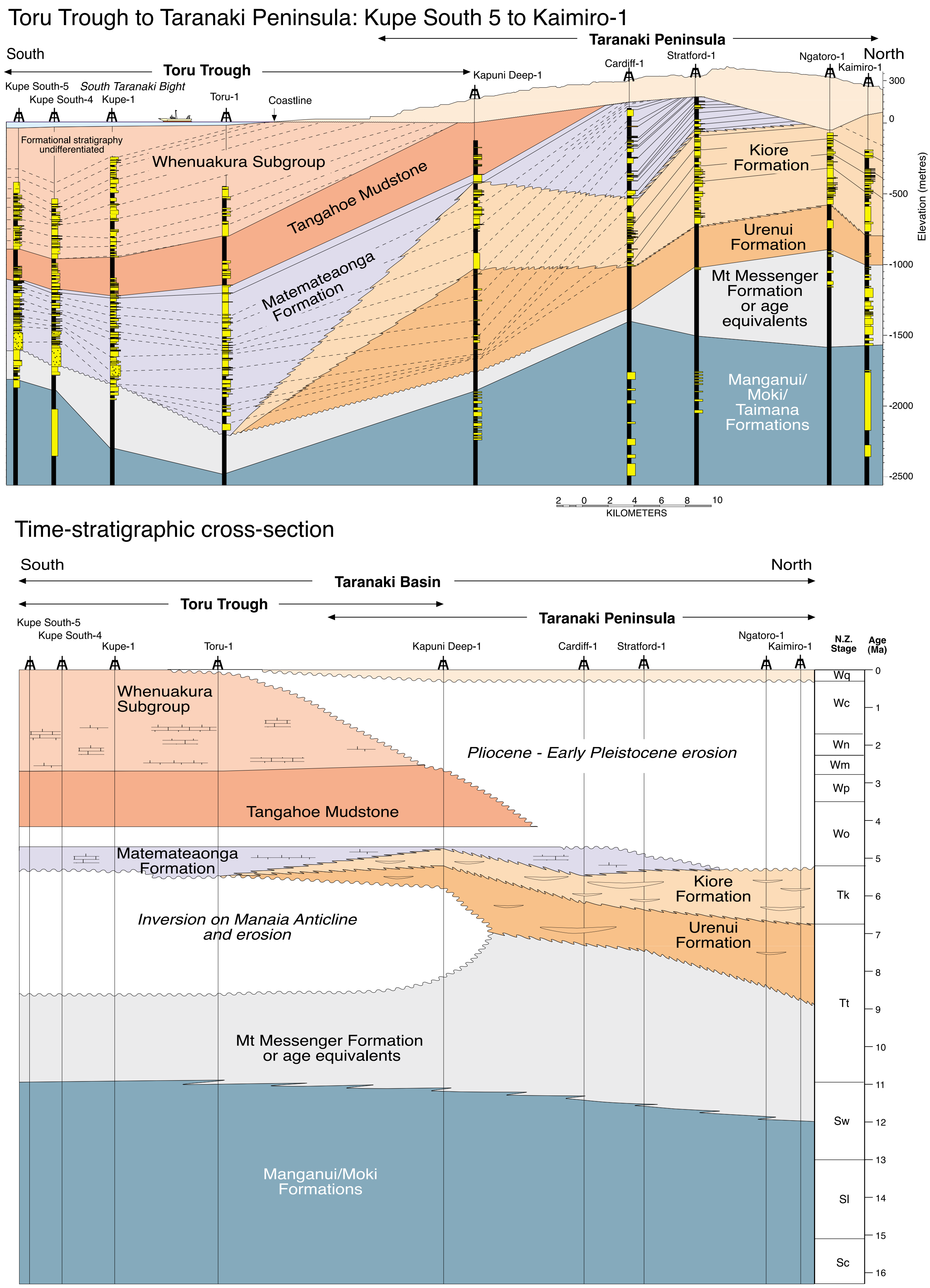


Fig.8. Toru Trough to Taranaki Peninsula (Kupe South-5 to Kaimiro-1) stratigraphic panel built up from well-to-well correlations, and related time-stratigraphic cross-section.

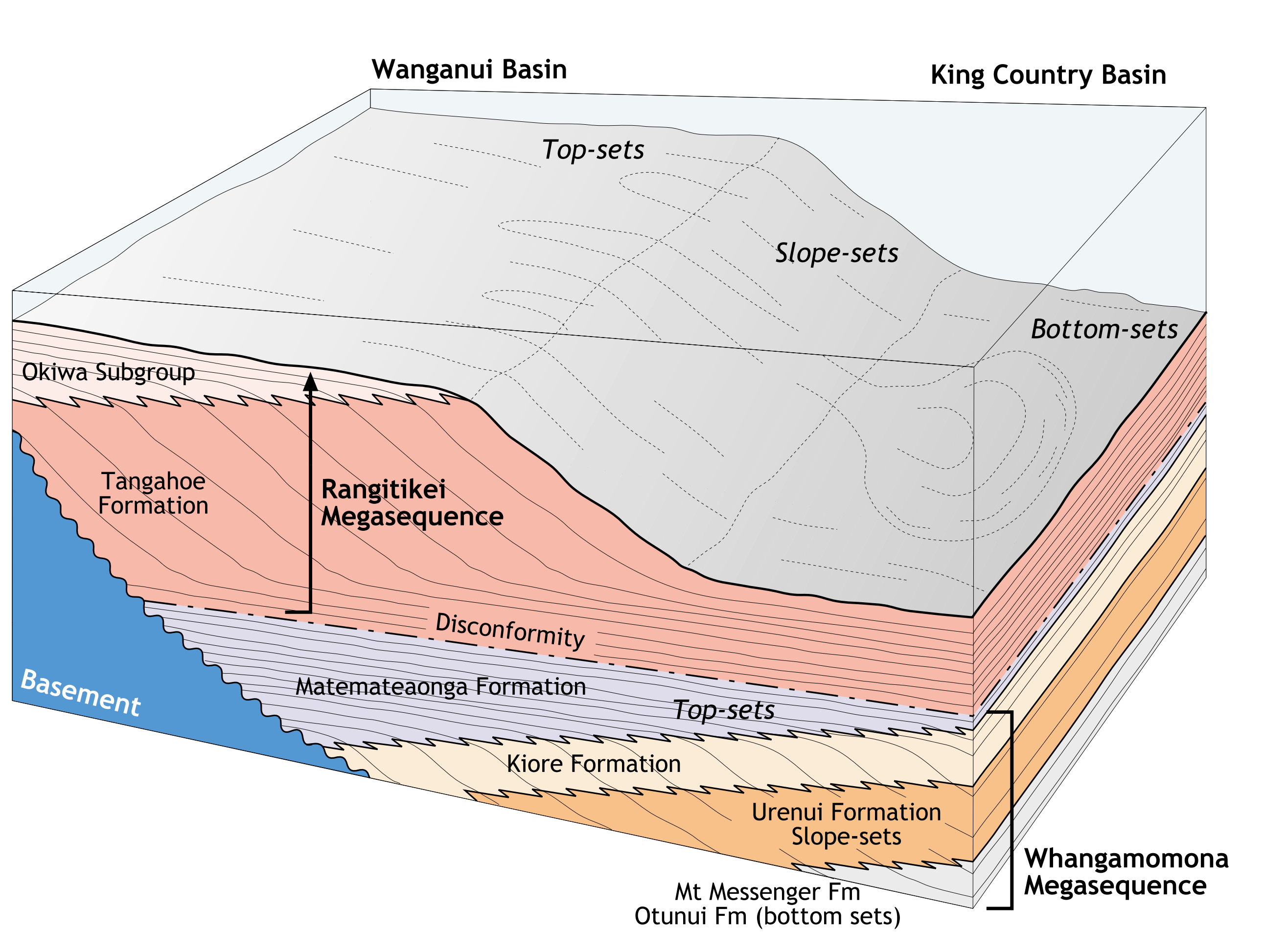


Fig.9. Block diagram showing schematically the occurrence of two continental margin wedges representing the Whangamomona and Rangitikei megasequences, each having prograded northward through central-western North Island during the late Neogene.

has been uplifted and truncated by erosion within the King Country Basin. This megasequence is mappable along the eastern margin of Taranaki Basin, upon, and to the west of the Patea-Tongaporutu-Herangi High, part of it being exposed in the northern Taranaki coastal section (Mount Messenger and Urenui Formations). The Kiore and Matemateaonga Formations crop out to the south in the hill country of eastern Taranaki Peninsula (Vonk et.al, this volume).

The Whangamomona Megasequence was confined mainly to the Wanganui and King Country Basins, which reflected the main sediment supply route and depositional axis, but the megasequence also extended into Taranaki Basin, as outlined above. The continental margin comprising the Rangitikei megasequence advanced northward in two fronts, one directly northward from the Southern Alps source through Wanganui Basin and into the King Country Basin, while the other was directed west of the Patea-Tongaporutu High through the Toru Trough and into the Central and Northern Grabens of Taranaki Basin and ultimately on to the Western Platform (Hansen and Kamp, this volume). This megasequence has been uplifted and removed totally from the King Country Basin and erosionally truncated in the northern parts of Wanganui Basin and over the Taranaki Peninsula, but it forms the thick deposits underlying the extensive modern shelf and slope in the offshore parts of Taranaki Basin, where it is known as the Giant Foresets Formation. The erosion of the Whangamomona, Mokau and Mahoenui Groups in the King Country Basin contributed significantly to the source of the sediments making up the lower parts of the Giant Foresets Formation.

Fourth, fifth and sixth order sequences

Fourth, fifth and sixth order sequences are considered to be of 400 ka, 100 ka and 41 ka duration, the later two being related to Milankovitch orbital parameters, widely considered to have modulated Earth's climatic and sea level history during the late Cenozoic. The 100 ka cyclicity characterises the last 800 thousand years of Earth history, whereas 41 ka cyclicity appears to have been the dominant climatic mode prior to 0.8 Ma.

Fourth, fifth and sixth order sequences are evident to various degrees within the Whangamomona and Rangitikei megasequences. These lower orders of cyclicity are reflected in the lithofacies character and stratal geometry of the formations and units occurring within the megasequences. The 4th, 5th and 6th order sequences are the level at which reservoir geometry and character and seal properties are determined. The order of sequence most evident within the megasequences are the 6th order sequences. These dominate the sequence development in top-sets of the Matemateaonga Formation, Okiwa and Paparangi Subgroups and in Nukumaruan and lower Castlecliffian strata. This arises because of a very characteristic succession of shellbed-siltstone-sandstone lithofacies, typically of 25-70 m thickness (Naish and Kamp 1997; Kamp and McIntyre 1998; Vonk et al. this volume). In middle to upper parts of Castlecliffian strata in Wanganui Basin, the shelf top-sets have the same sequence architecture, but the cyclothems are of 100,000 ka duration (Kamp and Turner 1990; Abbott and Carter 1994). Sequences with durations of several hundred thousand years, possibly 4th order, are evident in the Matemateaonga Formation in axial parts of Wanganui Basin, and in parts of the Rangitikei Supergroup (e.g. Mangaweka Mudstone). Their origin is considered to relate to tectonic pulses rather than to climatic or sea level oscillations.

The identification of 4th, 5th and 6th order sequences in the slope-sets and bottom-sets of each of the younger two megasequences are more difficult to achieve and date than for the top-sets. King et al (1994) have described sequences in the Urenui Formation and Mount Messenger Formation in the northern Taranaki coastal section, which are probably of 5th order cyclicity. The combination of the inclined depositional surface in slope environments, the more random depositional and mass movement processes that occur off the shelf, and the accidental position of outcrop sections and drill hole locations with respect to the depositional lobes, conspire to make it difficult to reconstruct a comprehensive record of 4th, 5th and 6th order sequences in off-shelf settings, and hence establish their periodicity. The approach we are taking to make progress in the better definition of these sequences is one of applying detailed field mapping, facies analysis, integrated stratigraphy and chronology in eastern Taranaki Peninsula, the King Country area and northern Wanganui Basin. Where possible, we are correlating outcrop sequences with subcrop sequences through the analysis of wireline log records available for exploration holes (Kamp et al. in prep; Vonk et al. this volume). The correlations of sequences shown in Figs 5-8 have been built up by this approach.

Sixth order sequences in Manutahi-1

Manutahi-1 (Fig.4) was continuously cored to basement by NZ Oil & Gas Ltd in 1985. The availability of a continuously-cored hole (Robinson et.al. 1987) through the Matemateaonga Formation and Tangahoe Mudstone has turned out to be a critical success factor, because it enabled us to examine the core in the context of our outcrop experience, from which we have developed a model of sequence architecture for mixed carbonate-siliciclastic shelf deposits (Naish and Kamp 1997). Moreover, for Manutahi-1, this sequence architecture has been able to be calibrated against a suite of wireline logs. The usefulness of this calibration is that it has given us confidence to map shelf sequences of high resolution (10-50 m thickness) in the wireline signals of other exploration holes for which core was not taken, and to distinguish shelf from slope sequences in them.

Figure 10 illustrates the stratigraphy and wireline response for the cored part of Manutahi-1. It also shows the stratigraphic extent of 6th order sequences within the Matemateaonga Formation. The formation in this hole shows basement onlap, followed by 300 m (1100 to 1385 m KB) of accumulation of sandstone and conglomerate beds in shoreface to inner shelf paleoenvironments, followed by 600 m (407 to 1100 m KB) of sediment that accumulated in shelf deposits ranging from shoreface to mid/outer shelf paleoenvironments. A condensed surface occurs at 407 m KB and marks a sharp transition to the Tangahoe Mudstone. Prominent, internally massive sandstone beds within the lower part of the Tangahoe Mudstone accumulated at bathyal depths through mass-emplacement processes, probably as sandy debris flows. They represent the deposition of bottom-sets of the Rangitikei megasequence over top-sets of the Whangamomona megasequence, which required an intervening episode of marked bathymetric deepening without associated sedimentation.

Twenty-nine sequences have been identified in the Matemateaonga Formation (Fig. 10). They are numbered from the top down because the flooding at the base of the Tangahoe Formation was isochronous across the Wanganui and Taranaki Basins, whereas the development of the first shelf sequence is strongly diachronous across the basins, reflecting the progradation of the shelf top-sets. The definition of the stratigraphic extent of the 6th order sequences, and systems tracts within them, identified in Manutahi-1 are based on inspection and description of the core, with particular attention given to the location of key surfaces such as the sequence boundary/ravinement surface and downlap surface/maximum flooding surface.

Figure 11 shows a portion of the core at an expanded scale and the typical sequence architecture (Naish and Kamp 1997). Sequence M18 starts with an erosional base, marking a transgressive surface of erosion (TSE) formed by ravinement, probably wave erosion of the underlying sandstone during transgression. This sequence boundary is overlain by a 70 cm-thick (compound) shellbed comprising the Transgressive systems tract (TST, Fig.11). The downlap surface is sharp, the overlying slightly fossiliferous siltstone marking the outer, feathered edge of downlapping clinoforms of a mud wedge comprising the High Stand systems tract (HST). The siltstone grades upward into sandstone, which marks the seaward progradation of well sorted regressive shoreline facies, formed under falling eustatic sea level conditions. We place the sandstone units, where they occur over siltstone, in a Regressive systems tract (RST), acknowledging that the lower boundary is probably diachronous across the paleoshelf. Sequence M17 (Fig.11) is an example of a more siltstone rich sequence. It contains two shellbeds in the TST, one being an onlap shellbed and the other a backlap shellbed (Naish and Kamp 1997). The RST is particularly thin, possibly indicating a less marked eustatic sea level fall associated with this cycle.

There is a distinctive and repetitive wireline response to the sequence architecture of the shelf top-sets in the Matemateaonga Formation in Manutahi-1 (Figs 10 & 11).

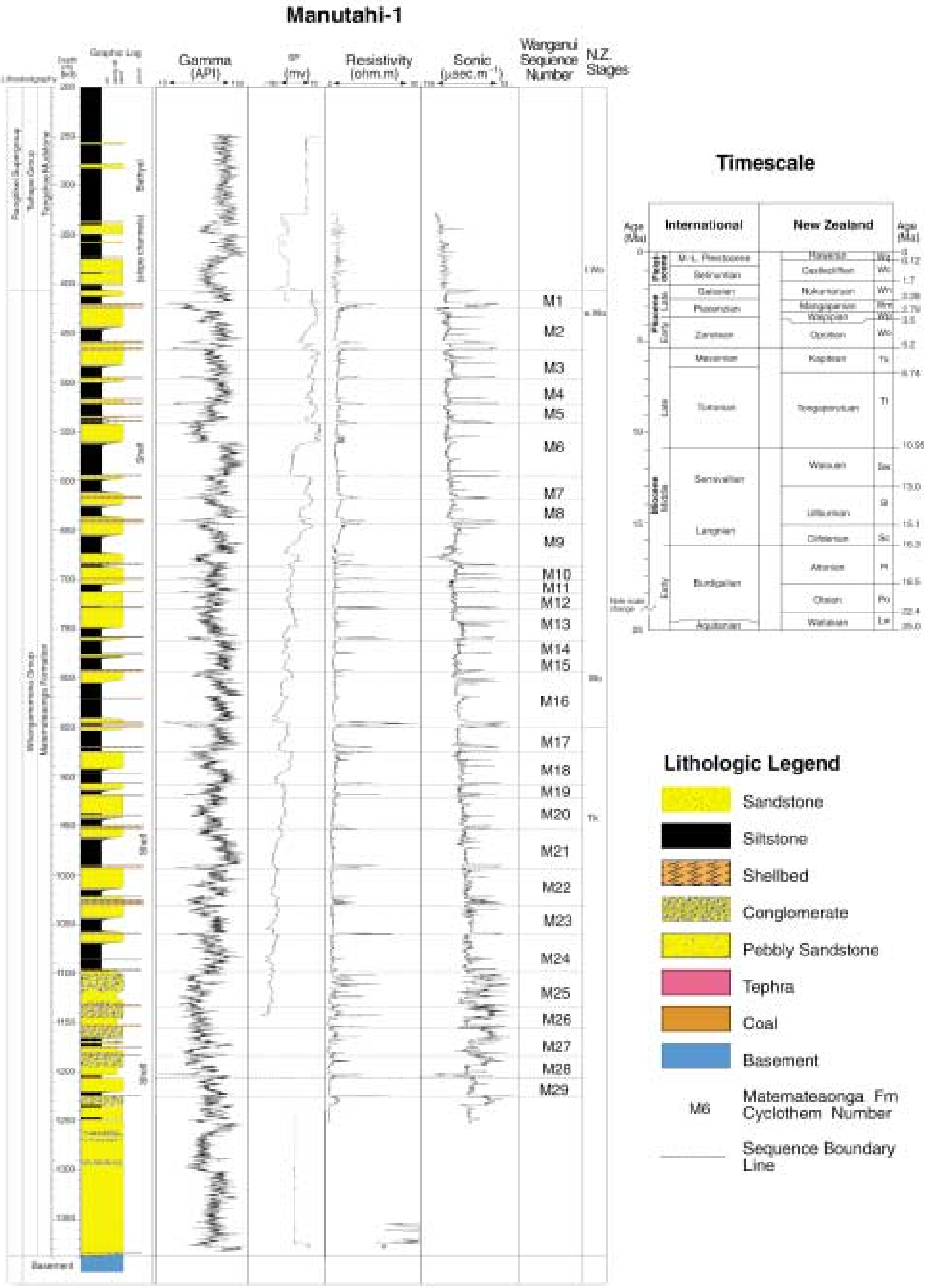


Figure 10: Stratigraphic log of Manutahi-1, related wireline logs and 6th order sequence numbers for the Matemateaonga Formation.

The gamma ray signal shows low values in TST shellbeds, distinct increases across downlap surfaces, high values in HST siltstone and lower values in RST sandstone. The SP (self potential) log response shows the opposite pattern: lowest values in HST siltstone and highest values in RST sandstone. Self Potential does not respond to the occurrence of shellbeds. Resistivity shows a very simple pattern of prominent low value peaks corresponding to shellbeds, virtually no variation in HST siltstone and minor variation in RST sandstone. Sonic velocity shows a very sharp response to shellbeds probably due to their degree of cementation, with low variation in HST siltstone and RST sandstone. Thin lensoidal shell accumulations formed through minor flooding or storm reworking can occur randomly in HST and RST units (Fig.11). These can be clearly distinguished from the TST shellbeds by the combination of a minor sonic response and very minor variations in resistivity.

The calibration established for Manutahi-1 between shelf sequence architecture and wireline log response has been tested against the record for Matemateaonga Formation in the lowermost 450 m of Parakino-1, as well as in the shelf deposits of Santoft-1A and Whangehu-1 and holds very well (Kamp et.al. in prep.). This has shown that regardless of whether the sequences are 5th (100 ka) or 6th (41 ka) order, the sequence architecture and wireline log character are identical. Vonk et.al. (this volume) outline the distinctive wireline log character of the uppermost slope deposits of the Kiore Formation in Rotokare-1, based on outcrop-subcrop correlation of this unit in eastern Taranaki Peninsula. The Urenui Formation, which accumulated in mid-slope environments, has a very bland set of log characteristics, except for occasional sandstone beds corresponding to slope channel fills. In this regard it is similar to the record of the Tangahoe Mudstone. This understanding of wireline log character and how it relates to the lithofacies types and stratal architecture for slope-sets and top-sets has underpinned the correlations shown in the cross-section panels of Figs 5-8.

Concluding remarks and paleogeographic implications

King et al. (1999) have synthesised the Cretaceous to Recent sedimentation patterns in New Zealand basins and interpreted them in terms 1st and 2nd order megasequences of tectonic origin. A nation-wide synthesis requires a degree of generalisation and compromise to be made to identify the unifying features, but these are inevitably made at the expense of regional differences. This work has re-examined the Neogene stratigraphic architecture of the Wanganui Basin, King Country Basin and parts of the Taranaki Basin, and established that since the early Miocene four 2nd order megasequences have formed rather than three, including the Mahoenui Group, Mokau Group, Whangamomona Group (new) and Rangitikei Supergroup (new). Their origin relates to the wider evolution of the Australia-Pacific plate boundary zone, and more particularly to the emplacement of the subducted slab of Pacific plate beneath the central-western North Island region (e.g. Kamp 1999). The number, age and character of these megasequences are therefore unlikely to correlate precisely with megasequence development elsewhere in New Zealand, particularly in South Island basins, whose tectonic history was dominated by different plate boundary processes.

The megasequence development is evident in Taranaki Basin, particularly along the eastern margin, but is more subtle than in King Country Basin, which lay closer to the plate boundary zone. The shortening that lead to the subsidence of King Country Basin during the earliest Miocene (Otaian Stage) and accumulation of Mahoenui Group (the first megasequence), was expressed as basement overthrusting along the Taranaki Fault and by a marked transition to terrigenous sedimentation at the base of the Wai-iti Group. The late early Miocene inversion, segmentation and faulting (Ohura Fault) in King Country Basin associated with accumulation of Mokau Group (the second megasequence), was expressed in eastern Taranaki Basin as movement on the Tarata Thrust Zone, followed by subsidence and onlap (Manganui Formation) of the basement block north of the Taranaki Peninsula between the Taranaki Fault and the Tongaporutu-Herangi High. A latest early Miocene short-lived uplift and erosion phase at the end of the accumulation of the Mokau Group lead to unconformity development across the King Country Basin, and over the PTH High along the eastern margin of Taranaki Basin. The regional middle Miocene subsidence in King Country Basin that lead to the accumulation of the Otunui Formation and the rest of the Whangamomona Group (the third megasequence), is expressed along the eastern margin of Taranaki Basin by further onlap of basement (Patea-Tongaporutu-Herangi High), which became more marked during the latest Miocene (Kapitean Stage) when the Matemateaonga Formation accumulated in Wanganui Basin. Rapid subsidence during the early Pliocene (mid-Opoitian) resulted in extensive flooding across all three basins and the accumulation of the Tangahoe Mudstone and the rest of the Rangitikei Supergroup (the fourth megasequence).

The sediment sources for the Mahoenui and Mokau megasequences appear to have had local origins as their petrography reflects the local basement composition. The middle Miocene accumulation of the Otunui Formation coincides with the initiation of substantial erosion of basement to the south, as indicated by fission track thermochronological data. From the start of deposition of the Mount Messenger Formation, the general southern source, ultimately involving erosion of the Southern Alps, became dominant and accounts for the marked northward progradation of the Whangamomona megasequence. This prograding margin was chiefly deposited in the King Country Basin, and at later stages in Wanganui Basin. During the late Miocene this margin over topped the PTH High and formed a narrow shelf and slope along the eastern margin of Taranaki Basin. The terrigenous sediment supply to King Country Basin, northern parts of Wanganui Basin and Taranaki Basin was dramatically shutoff during the middle early Pliocene when the region was rapidly tectonically pulled down. A second prograding margin then developed from the southern part of Wanganui Basin forming the Rangitikei megasequence. This margin had two fronts, one that moved north along the axis of the Wanganui-King

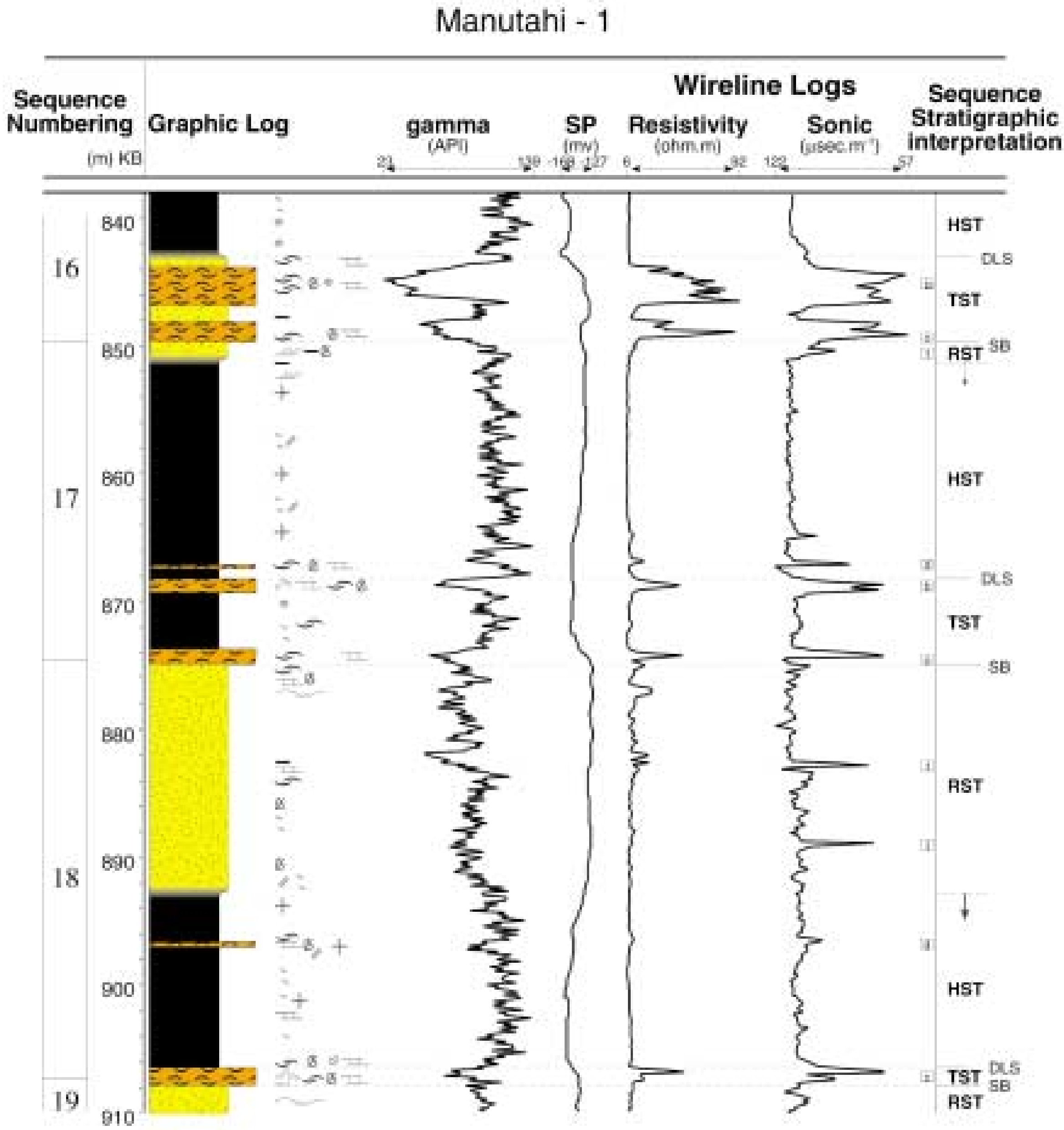


Figure 11: Stratigraphic and wireline log detail for sequences 16 to 19 in Manutahi-1, also showing the extent of systems tracts.

Country Basin, and another to the west of the PTH High, which prograded north through the Toru Trough and Central Graben into the Northern Graben and westward on to the Western Platform. This prograding wedge makes up the Giant Foresets Formation and underlies the modern shelf and slope west of central-western North Island. The Whangamomona and Rangitikei megasequences have driven most of the hydrocarbon maturation and migration in Taranaki Basin, and contain potential stratigraphic reservoirs as well.

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References

Abbott, S.T., Carter, R.M. 1994: The sequence architecture of mid-Pleistocene (c. 1.1-0.4 Ma) cyclothems from New Zealand: facies development during a period of orbital control on sea level cyclicity. In: de Boer, P.L., Smith, D.G. (Eds.), Orbital Forcing and Cyclic Sequences. Special Publication of the International Association of Sedimentologists 19, 367-394.

Beu A.G., Edwards, A.R. 1984: New Zealand Pleistocene and late-Pliocene glacio-eustatic cycles. Palaeogeography, Palaeoclimatology, Palaeoecology 46: 119-142.

Fleming, C.A. 1953: The geology of Wanganui Subdivision. New Zealand Geological Survey Bulletin 52.

Hansen, R.J., Kamp, P.J.J. 2002: Evolution of the Giant Foresets Formation, northern Taranaki Basin, New Zealand. Proceedings 2002 New Zealand Petroleum Conference, Auckland 24-27 February, 2002.

Hay, R.F. 1967: Geological map of New Zealand, Sheet 7, Taranaki. 1:250,000. D.S.I.R., Wellington.

Hayton, S.H. 1998: Sequence stratigraphic, paleoenvironmental, and chronological analysis of the late Neogene Wanganui River section, Wanganui Basin. PhD thesis, The University of Waikato, Hamilton.

Henderson, J., Ongley, M. 1923: The Geology of the Mokau Subdivision. New Zealand Geological Survey Bull. 24.

Kamp, P.J.J. 1999: Tracking crustal processes by FT thermochronology in a forearc high (Hikurangi margin, New Zealand) involving Cretaceous subduction termination and mid-Cenozoic subduction initiation. Tectonophysics 307, 313-343.

Kamp, P.J.J., McIntyre, A.P. 1998: The stratigraphic architecture of Late Pliocene (2.8-2.4 Ma) asymmetrical shelf sequences, western Wanganui Basin, New Zealand. Sedimentary Geology 122, 53-67.

Kamp, P.J.J., Turner, G. 1990: Pleistocene unconformity bounded sequences (Wanganui Basin, New Zealand) correlated with global isotope record. Sedimentary Geology 68, 155-161.

Kamp, P.J.J. and others, Geology of Wanganui Basin and its petroleum systems, in prep.

King, P.R., Browne, G.H., Slatt, R.M. 1994: Sequence architecture of exposed late Miocene basinfloor fan and channel-levee complexes (Mount Messenger Formation), Taranaki Basin, New Zealand. In: P. Weimer, A.H. Bouma, and B.F. Perkins (editors), Submarine Fans and Turbidite Systems, Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation, 15th Annual Research Conference.

King, P.R, Thrasher, G.P. 1996: Cretaceous –Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. Institute of Geological and Nuclear Sciences Monograph 13.

King, P.R., Naish, T.R., Browne, G.H., Field, B.D., Edbrooke, S.W. (compilers), 1999: Cretaceous to Recent sedimentary patterns in New Zealand. Institute of Geological and Nuclear Sciences folio series 1, version 1999.1. Folder with 35p, 1 enclosure. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited.

King, P.R., Scott, G.H., Robinson, P.H. 1993: Description, correlation and depositional history of Miocene Sediments outcropping along the North Taranaki coast. Institute of Geological and Nuclear Sciences Monograph 5, IGNS, New Zealand.

McIntyre, A.P., 2001: Geology of Mangapanian (Late Pliocene) strata, Wanganui Basin: Lithostratigraphy, paleontology and sequence stratigraphy. Unpublished PhD thesis, The University of Waikato.

McIntyre, A.P., Kamp, P.J.J. 1998: Late Pliocene (2.8-2.4 Ma) cyclothemic shelf deposits, Parikino, Wanganui Basin, New Zealand: lithostratigraphy and correlation of cycles. New Zealand Journal of Geology and Geophysics 41, 69-84.

Naish, T.R., Kamp, P.J.J. 1995: Late Pliocene marine cyclothems, Wanganui Basin, New Zealand. New Zealand Journal of Geology and Geophysics 38 (2), 223-243.

Naish, T.R., Kamp, P.J.J. 1997: Sequence stratigraphy of 6th order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui Basin, New Zealand: a case for the regressive systems tract. Geological Society of America Bulletin 109, 978-999.

Nelson, C.S., Hume, T.M. 1977: Relative intensity of tectonic events revealed by the Tertiary sedimentary record in the North Wanganui Basin and adjacent areas, New Zealand. New Zealand Journal of Geology and Geophysics 20: 369-392.

Robinson, P.H., Morris, B.D., Scott, G.H. 1987: Lithologic log and micropaleontology of Manutahi-1 core, onshore south Taranaki, New Zealand. New Zealand Geological Survey Report PAL 12.

Topping, R.M. 1978: Foraminifera from the Mahoenui Group, North Wanganui Basin. Unpubl. PhD Thesis, University of Auckland.

Vonk, A., Kamp, P.J.J., Hendy, A.W., 2002: Outcrop to subcrop correlations of late Miocene-Pliocene strata, Taranaki Peninsula. Proceedings 2002 New Zealand Petroleum Conference, Auckland 24-27 February, 2002.

Whitten, R.F. 1973: The Waipipian Stratigraphy and Paleoecology of the South Taranaki Coast. Unpubl. MSc. Thesis, University of Auckland.