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Late Miocene to early Pliocene stratigraphic record in northern Taranaki Basin: condensed sedimentation ahead of Northern Graben extension and progradation of the modern continental margin

ROCHELLE J. HANSEN
PETER J. J. KAMP
Department of Earth Sciences
The University of Waikato
Private Bag 3105
Hamilton 2001, New Zealand

Abstract The middle Pliocene–Pleistocene progradation of the Giant Foresets Formation in Taranaki Basin built up the modern continental margin offshore from western North Island. The late Miocene to early Pliocene interval preceding this progradation was characterised in northern Taranaki Basin by the accumulation of hemipelagic mudstone (Manganui Formation), volcaniclastic sediments (Mohakatino Formation), and marl (Ariki Formation), all at bathyal depths. The Manganui Formation has generally featureless wireline log signatures and moderate to low amplitude seismic reflection characteristics. Mohakatino Formation is characterised by a sharp decrease in the GR log value at its base, a blocky GR log motif reflecting sandstone packets, and erratic resistivity logs. Seismic profiles show bold laterally continuous reflectors. The Ariki Formation has a distinctive barrel-shaped to blocky GR log motif. This signature is mirrored by the SP log and often by an increase in resistivity values through this interval. The Ariki Formation comprises (calcareous) marl made up of abundant planktic foraminifera, is 109 m thick in Ariki-1, and accumulated over parts of the Western Stable Platform and beneath the fill of the Northern Graben. It indicates condensed sedimentation reflecting the distance of the northern region from the contemporary continental margin to the south.

The latest Miocene (Kapitean) age of Ariki Formation beneath the Northern Graben gives a maximum age for the start of crustal extension in the basin; a minimum early Pliocene (Opoitian) age is provided by the age of the base of the Mangaa Formation, which infills part of the graben. Uplift on the margins of the graben allowed condensed Ariki Formation to continue to accumulate into the Waipipian. The Mangaa Formation has blocky to tabular profiles on SP and resistivity logs, particularly in Mangaa-1. The formation comprises several sandstone-dominated submarine fan deposits that thicken into the master graben fault. Accumulation of the Mangaa Formation within the graben continued into the Waipipian when it was supplanted by the bottom-sets of the Giant Foresets Formation. It was not until the latest Pliocene (Nukumaruan) that sedimentation rates exceeded subsidence rates in the graben, leading to progradation of the Giant Foresets Formation over the Western Stable Platform in northern Taranaki Basin.

Keywords Taranaki Basin; Northern Graben; Manganui Formation; Mohakatino Formation; Ariki Formation; Mangaa Formation; Giant Foresets Formation; Whangamomona Group; Rangitikei Supergroup; condensed sedimentation

INTRODUCTION

The Pliocene–Pleistocene succession in Taranaki Basin comprises largely the Giant Foresets Formation, which has built up the modern shelf and slope. Underlying the Giant Foresets Formation in northern Taranaki Basin are diversified sediments of contrasting lithologies reflecting local as well as distant sediment sources (Fig. 1, 2). The Mohakatino Formation contains primary volcanic deposits as well as volcaniclastic sediments derived from erosion of an andesitic volcanic arc now down-faulted and buried in the Northern Graben and along its western margin. Manganui Formation comprises hemipelagic mudstone that interfingers with Mohakatino Formation and Mount Messenger Formation.

Northern Taranaki Basin also contains distinctive marl known as the Ariki Formation (Fig. 2) (King & Thrasher 1996). This unit reaches 109 m thickness in Ariki-1 and is mainly distributed over the Western Stable Platform, but also occurs beneath the Northern Graben fill. It represents a late Miocene to early Pliocene interval of condensed sedimentation, the occurrence of which is remarkable in the context of the voluminous siliciclastic and volcaniclastic sediments typically supplied to Taranaki Basin during the Neogene.

This paper deals with the occurrence, distribution, and age of the late Miocene to early Pliocene stratigraphic units that accumulated in northern Taranaki Basin during the transition from the end of andesitic arc volcanism to the start of graben formation and progradation of the Giant Foresets Formation. We also relate the depositional history of these units to the wider development of continental margin depositional wedges that accumulated concurrently in Wanganui, King Country, and eastern Taranaki Basins.

GEOLOGICAL SETTING

Taranaki Basin is located offshore along the west coast of the North Island and comes onshore in Taranaki Peninsula and northernmost South Island (Fig. 1). It is broadly subdivided into the Eastern Mobile Belt and the Western Stable Platform (King & Thrasher 1996) (Fig. 1). The Western Stable Platform is a relatively stable and structurally simple province. Conversely, the Eastern Mobile Belt has a composite architecture and evolution, and has been variably overthrust, folded, extended, uplifted, and eroded (King & Thrasher 1996; Armstrong et al. 1998; Kamp et al. 2004, this

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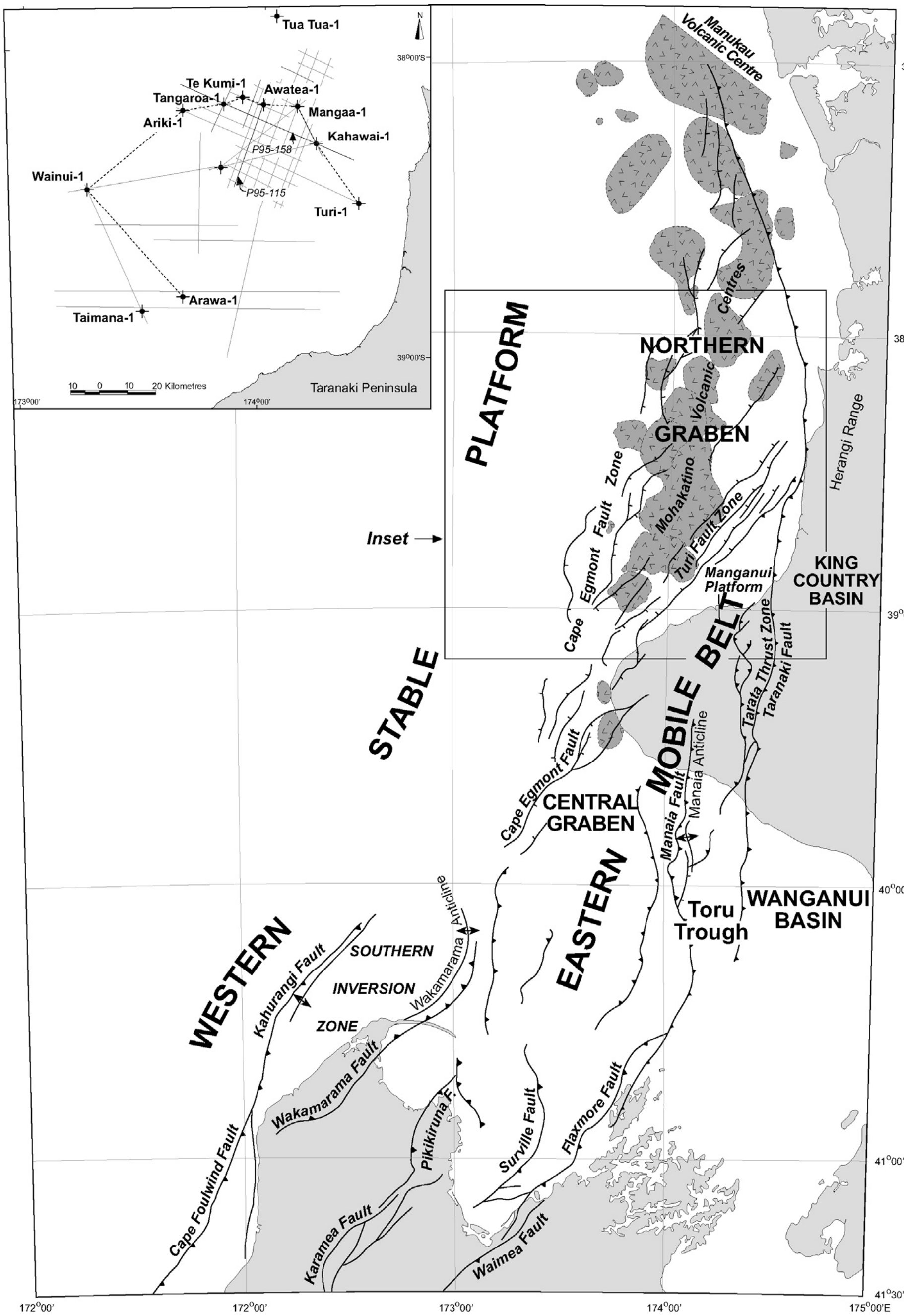

Fig. 1 Structural domains and principal tectonic features, Taranaki Basin, after King et al. (1993), King & Thrasher (1996), and Thrasher et al. (2002). *Inset*: Location of hydrocarbon exploration holes and seismic lines examined in this study. Note particularly the location of reflection lines P95–158 (Fig. 8) and P95–115 (Fig. 13). Dashed line linking certain holes marks the extent of the chronostratigraphic panel in Fig. 15A.

issue). The Eastern Mobile Belt is subdivided into a northern region, which includes the Northern and Central Grabens, and a southern region, which includes the Tarata Thrust Zone and Southern Inversion Zone (Fig. 1).

The Northern Graben is delineated to the west by the Cape Egmont Fault Zone and to the east by the Turi Fault Zone (Fig. 1). The Eastern Mobile Belt also includes a buried Miocene andesitic volcanic arc (Mohakatino Volcanic Centre) trending north–south along the centre of the Northern Graben. This arc was most active during the middle–late Miocene, continuing to c. 8–6 Ma (Thrasher et al. 2002).

The Northern Graben started to form during the latest Miocene to early Pliocene. Its tectonic origin lies in backarc extension on the western margin of the Australia-Pacific plate boundary zone. While the graben experienced subsidence, its eastern flank (east of the Turi Fault Zone) was uplifted and eroded, forming the Manganui Platform (Fig. 1). West of the Northern Graben, the Western Stable Platform has been characterised by persistent subsidence (e.g., Hayward 1987; Hayward & Wood 1989). The lowermost formation deposited during graben development is the Mangaa Formation (Fig. 2), which accumulated as a series of basin-floor fan deposits. This unit is overlain by the Giant Foresets Formation, which represents the progradation across the basin of the continental margin wedge underlying the modern shelf and slope. The Giant Foresets Formation is overthickened in the Northern Graben as a result of syn-sedimentary faulting and differential subsidence. By the late Pliocene (Nukumaruan), the continental margin wedge had infilled the graben and was prograding on to the Western Stable Platform.

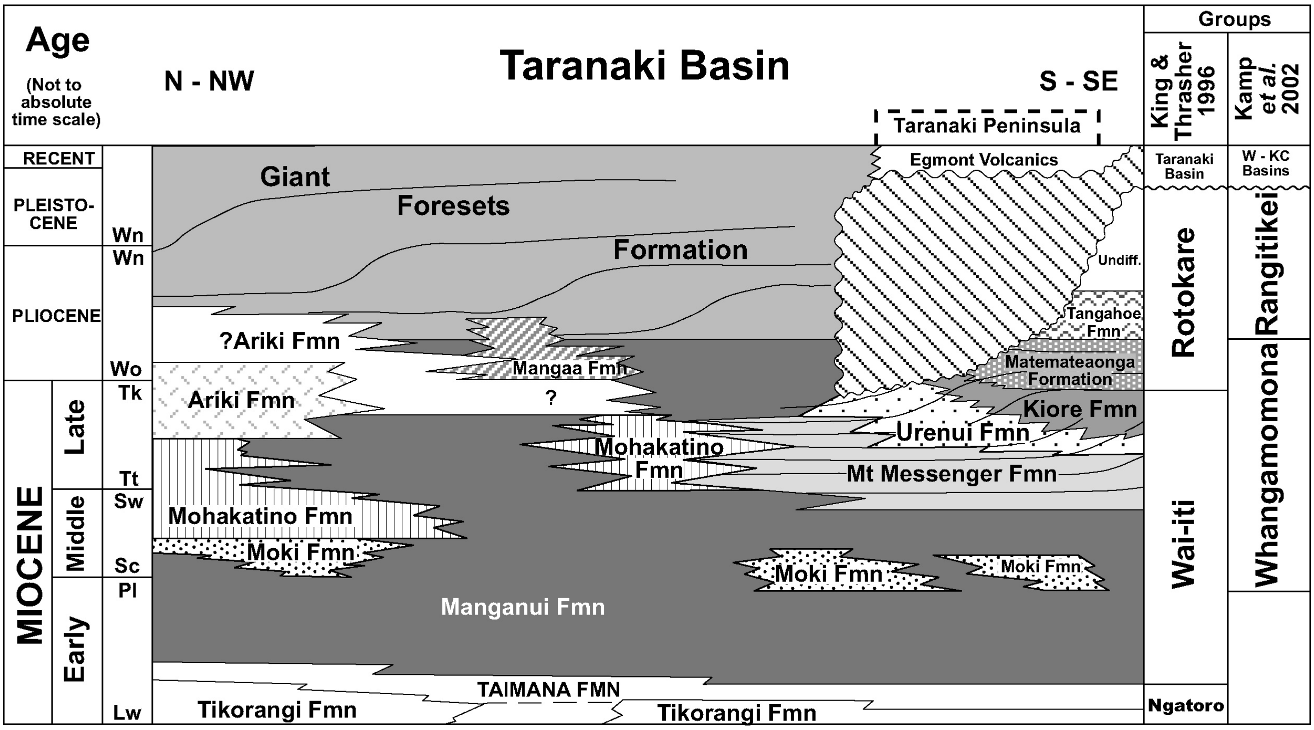

Fig. 2 Simplified Neogene stratigraphic nomenclature for Taranaki Basin modified from King & Thrasher (1996). Whangamomona Group and Rangitikei Supergroup nomenclature after Kamp et al. (2004). W-KC represents Wanganui and King Country Basins. Kiore Formation after Vonk et al. (2002).

GEOPHYSICAL AND LITHOLOGICAL CHARACTERISTICS OF THE MANGANUI, MOHAKATINO, ARIKI, MANGAA, AND GIANT FORESETS FORMATIONS, NORTHERN TARANAKI BASIN

Manganui Formation

The Manganui Formation includes most fine-grained basinal Neogene clastic rocks in Taranaki Basin and encloses sandy submarine fan deposits (Moki, Mount Messenger Formations; Fig. 2). Subdivision of the Manganui Formation is sometimes convenient, and the term "lower" Manganui Formation was adopted for the interval between the Taimana and Moki Formations (King & Thrasher 1996). In the northern parts of Taranaki Basin, the Manganui Formation interfingers particularly with volcaniclastic sediments of the Mohakatino Formation, and where the host formations cannot be differentiated, the composite name (upper) Manganui-Mohakatino Formation is used.

The Manganui Formation is mud dominated, occupying an exclusively bathyal depositional environment, as reflected in its relatively featureless wireline log signatures. Typically, the Manganui Formation displays a similar wireline signature basin-wide, showing an arcuate profile on gamma-ray (GR) logs, with higher GR counts at the top and bottom of the succession (King & Thrasher 1996). However, in some northern Taranaki Basin wells (e.g., Arawa-1, Fig. 3), the GR log has only a broadly arcuate profile.

Internal reflector characteristics on seismic reflection profiles reflect the fine-grained and lithological homogeneity of the Manganui Formation. Most internal reflectors are of moderate to low amplitude, and many display lateral continuity, with reflectors being subparallel to wavy. Occasional brighter internal reflectors correlate with sonic, GR, and resistivity spikes on wireline logs, suggesting partial lithification and/or cementation, possibly concretions.

Mohakatino Formation

The middle–late Miocene Mohakatino Formation (Fig. 2) has a significant tuffaceous or volcaniclastic content, which diminishes steadily away from source (Mohakatino Volcanic Centre). The formation is represented onshore in northern Taranaki coastal sections as the Purupuru Tuff (Hay 1967; King et al. 1993; Hansen 1996). Offshore, volcaniclastic sediments of the Mohakatino Formation are distributed widely throughout the northern and northeastern parts of the basin proximal to the various volcanic centres (Fig. 1).

The volcaniclastic sediments of the Mohakatino Formation are clearly evident on wireline log responses. The base of the formation is delineated by a sharp up-hole decrease in the GR log value, and the top of the formation is marked by a progressive increase in the GR log value (Fig. 4). The basal deflection can be widely correlated between offshore well records (King & Thrasher 1996), making this horizon an important middle Miocene marker in Taranaki Basin. Between the upper and lower boundaries, the formation is often characterised by a linear (smooth) to blocky GR log motif, indicative of massive sandstone beds. Resistivity logs are comparatively erratic, with higher values than enclosing formations. Spontaneous potential (SP) logs do not display a characteristic signature (Fig. 4), while sonic (velocity) logs show variable trends, exhibiting either slightly higher or slightly lower velocities than the underlying or overlying formations.

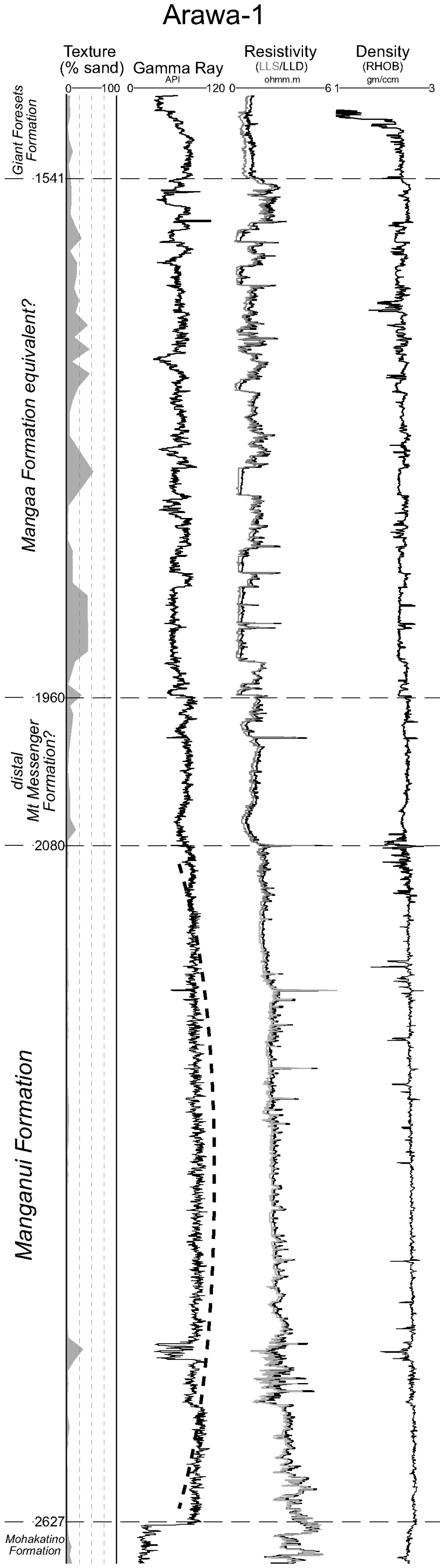

Fig. 3 Typical wireline characteristics of the Manganui Formation (northern Taranaki Basin) from Arawa-1. The broadly arcuate profile noted by King & Thrasher (1996) is barely evident in the lower part of the formation (dashed line).

On seismic reflection profiles, the Mohakatino Formation is characterised by bold, laterally continuous reflectors that often onlap volcanic edifices. The boundaries of the formation are commonly delineated by bright, high amplitude horizons that display extensive lateral continuity. Internally, reflectors are subparallel, smooth to slightly hummocky, and of variable amplitude, indicating both the interbedded nature of the formation and the depositional mechanisms by which the sandstone beds accumulated (turbidity current or debris flow). Away from the main volcanic centres, the internal seismic character of the Mohakatino Formation becomes more homogeneous, although the lower bounding reflector of the formation is usually bright.

In all well sections in which Mohakatino Formation sediments are encountered (e.g., Fig. 4), the volcaniclastic content diminishes up-section. This reflects in part a waning of volcanic activity into the late Miocene (Shell BP Todd Oil Services Ltd. 1984), and partly the effects of masking due to the increasing rates of accumulation of siliciclastic beds from the late Miocene onwards.

Ariki Formation

The Ariki Formation (Fig. 2) was named by King (1988) to describe a late Miocene–Pliocene condensed interval of marl encountered in several well sections (Ariki-1, Tangaroa-1, Te Kumi-1, Wainui-1, Tane-1) on the Western Stable Platform. It attains a thickness of 109 m at Ariki-1 and has been identified as far north as Tua Tua-1 (Rankin & Barbaresig 1988). The Ariki Formation represents a significant period of terrigenous sediment starvation during the late Miocene and early Pliocene in northern Taranaki Basin.

The Ariki Formation comprises (calcareous) marl with abundant planktic foraminifera. It is delineated by a distinctive set of wireline log motifs (e.g., Tangaroa-1, Fig. 4, 5), particularly by low GR values, reflecting high carbonate content. Tangaroa-1 displays a unique barrel-shaped GR motif, which is mirrored by the SP log, and an increase in sonic, resisitivity, and bulk density values through this interval. Though somewhat muted in Ariki-1 and Wainui-1 (Fig. 5), similar wireline log trends are also displayed in these wells.

At Tangaroa-1, the marked deflections observed on GR and SP wireline logs correspond to the high-amplitude reflectors that delineate the upper and lower boundaries of the Ariki Formation at this site, a result of the velocity contrasts between the marl and the underlying and overlying formations. These characteristics, together with a reflection-free zone between the seismic boundaries, are taken to indicate the occurrence of a condensed pelagic unit. Seismic evidence suggests that the difference between wireline responses at different well sites may be attributed to a combination of depositional mechanisms; while still displaying a bright basal reflector in seismic profiles in the vicinity of Ariki-1 and Wainui-1, internally the formation appears to be seismically chaotic, characterised by wavy or hummocky, discontinuous and moderate amplitude reflectors, with an indistinct upper boundary. Both Ariki-1 and Wainui-1 occur on the flanks of a paleohigh on to which the Ariki Formation onlaps, suggesting that debris flows sourced off this high contributed to the accumulation of the formation in places.

Well sections show a marked Opoitian–Waipipian decrease in planktic foraminiferal content between the Ariki and Giant Foresets Formations. This is particularly evident in Ariki-1 and Wainui-1 (Fig. 5, 6), but it is also present at the base of the Giant Foresets Formation in Arawa-1 and Kora-1 where the Ariki Formation is not present (Fig. 6). The high planktic foraminiferal content indicates that the Ariki Formation accumulated beneath fully oceanic watermasses. The decrease in foraminiferal content did not, however, correspond to an associated decrease in paleobathymetry at these sites, as shown by the paleoecology of the foraminifera (Hansen 2003). Instead, reduction in planktic foraminiferal content indicates a reduction in the availability of nutrients. We attribute this abrupt change in watermass conditions to a local change in the ocean circulation pattern. This probably involved a deflection away (oceanward) from these sites of nutrient-rich coastal upwelling cells ahead of the advancing continental margin.

The extent of the Western Stable Platform over which the Ariki Formation can be mapped is shown in Fig. 7. It cannot be confidently traced east of Te Kumi-1 due to fault complications (Te Kumi Fault). The limited distribution of the Ariki Formation is also illustrated on Fig. 8, which is an interpreted seismic reflection profile oriented northwest–southeast across the Northern Graben (see Fig. 1 for location). The paleohigh on to which the Ariki Formation laps can be observed towards the northwestern end of the seismic reflection profile, in the vicinity of Tangaroa-1 (which is located at the apex of the high).

Other marly horizons

Through lithological and geophysical characterisation of the Ariki Formation, it has been possible to identify the occurrence of other possibly correlative marly horizons in well sections in northern Taranaki Basin (Arawa-1, Taimana-1, Kahawai-1, Mangaa-1, and Awatea-1) (Fig. 9). This provides an opportunity to correlate stratigraphic units on the Western Stable Platform with those in the Northern Graben.

A thin (10–15 m) interval of calcareous siltstone to silty limestone occurs at the base of the Giant Foresets Formation (Fig. 9) in Arawa-1 (c. 1541 m below Kelly Bushing (bKB)) and in Taimana-1 (c. 1500 m bKB) to the south of the main part of the Northern Graben. This unit shows moderate GR values, high resistivity, and high sonic velocity. Kahawai-1 intersects (1921 m bKB; Fig. 9) a very thin (c. 9 m) marly unit unconformably overlying Mohakatino Formation.

Within the main part of the Northern Graben, two marly to silty units are identified in Mangaa-1 (c. 2504–2610 and 2786–2822 m bKB; Fig. 9, 10, 11) and Awatea-1 (2433–2540.5 and 2669–2690 m bKB; Fig. 9, 11) in association with the Mangaa Formation. The upper interval is better developed and separates a lower Opoitian packet of interbedded sandstone and mudstone of the Mangaa Formation from an upper packet. The lower unit is of latest Miocene age. Both intervals can be correlated between wells through seismic reflection profiles (Fig. 11, 12A,B), but cannot be directly correlated to the Ariki

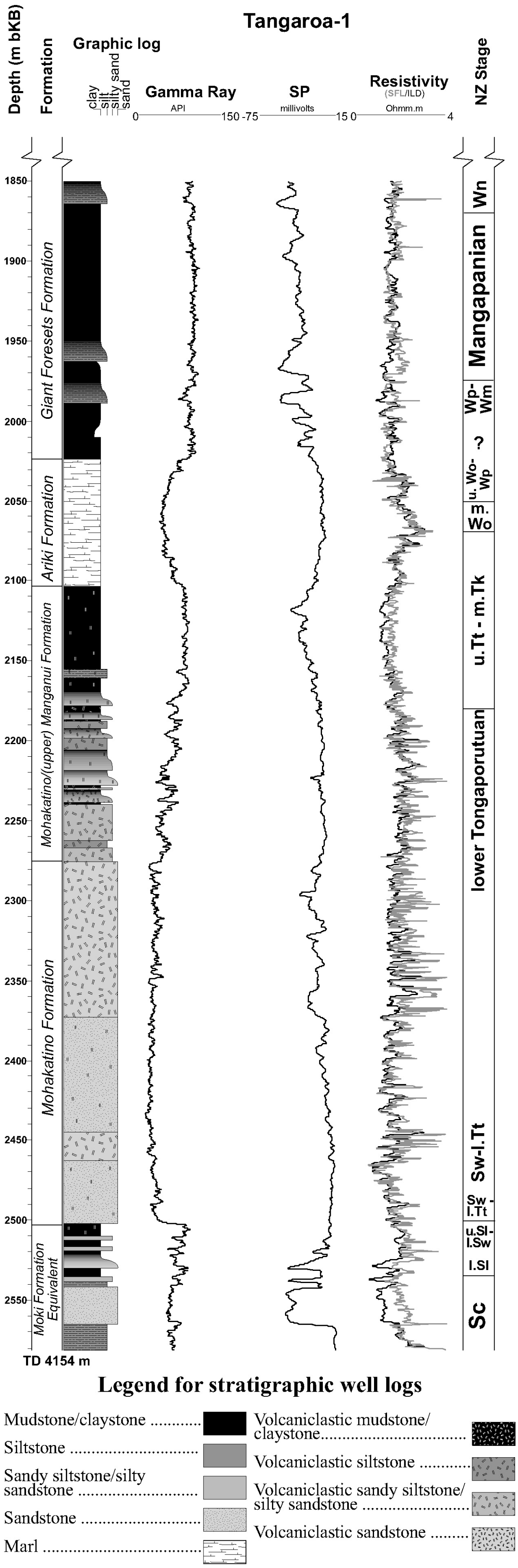

Fig. 4 Wireline characteristics of the Mohakatino, (upper) Manganui, and Ariki Formations in Tangaroa-1. Condensed units (marl) are often delineated by low gamma ray, moderately high SP, and moderately high resistivity values. Note also the highly erratic resistivity log through the Mohakatino Formation, and the upward-fining gamma-ray log motif, related to the waning of volcanism. Biostratigraphy from King & Thrasher (1996, appendix 3). Biostratigraphic stage abbreviations are defined in Fig. 5. ➤

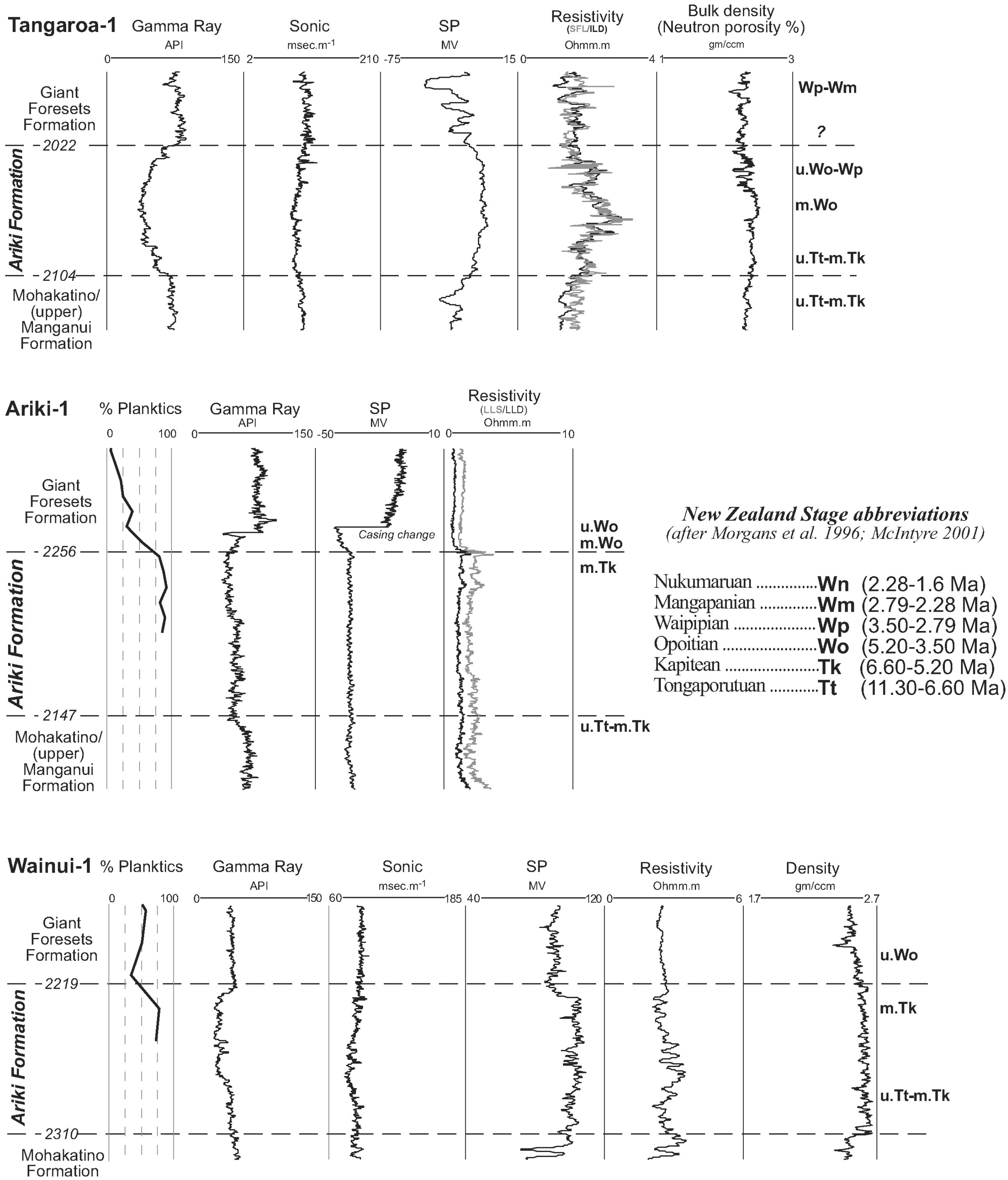

Fig. 5 Wireline characteristics of the Ariki Formation in Tangaroa-1, Ariki-1, and Wainui-1. Biostratigraphy for Tangaroa-1 from King & Thrasher (1996) with re-evaluation of some Pliocene datums by Scott (2001 pers. comm.); in Ariki-1 from Hansen (2003) and Hayward (1986); and in Wainui-1 from Hansen (2003).

Formation on the Western Stable Platform (Tangaroa-1), or to the marly unit in Kahawai-1.

At Mangaa-1, the upper marly unit is described as a highly calcareous mudstone (Hematite Petroleum (NZ) Ltd 1970). In Mangaa-1 (Fig. 10), GR values decrease up-hole sharply at the base of this unit and gradually increase upwards through it; the GR log is featureless at Awatea-1. Both SP and resistivity logs show strong responses indicative of fine-grained or soft lithologies, although in both of these wells, the resistivity log is variable throughout these calcareous intervals, rather than being consistently high. At Awatea-1, this upper unit was called the Urenui Formation by Murray

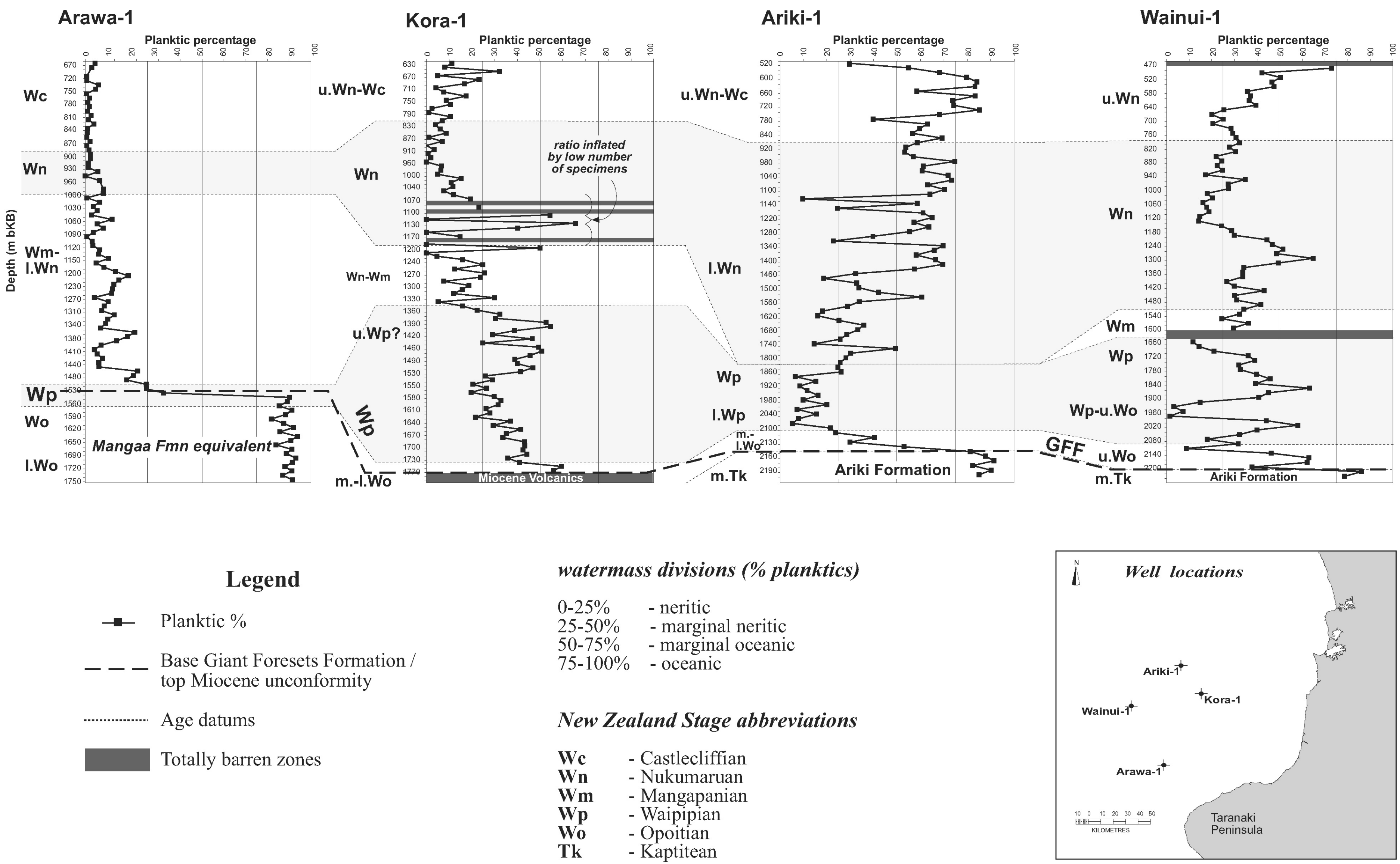

Fig. 6 Planktic content (percentage) in selected wells, northern Taranaki Basin. A dramatic reduction in planktic percentage, and change from oceanic to neritic watermass conditions, occurs between the Ariki Formation and the Giant Foresets Formation at Ariki-1 and Wainui-1, and between the Mangaa Formation equivalent and Giant Foresets Formation at Arawa-1. These data imply a sudden change in circulation patterns in northern Taranaki Basin. Watermass zones after Hayward et al. (1999).

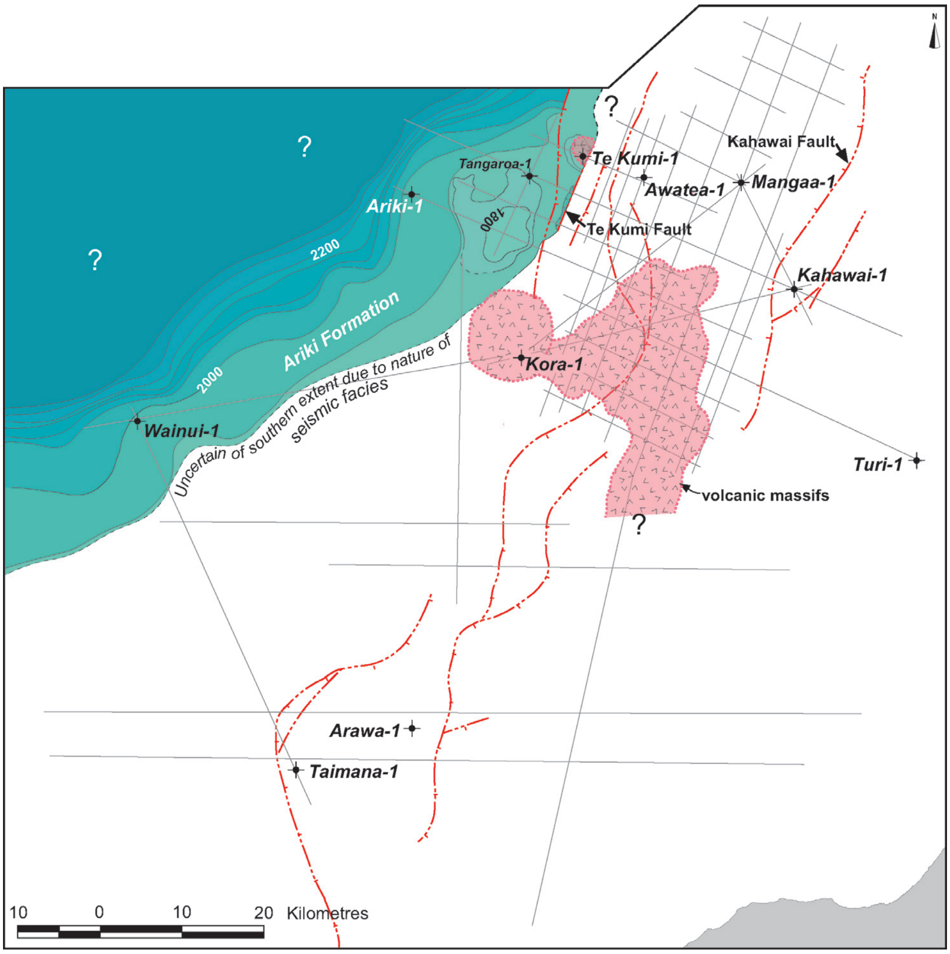

Fig. 7 Maximum extent of the Ariki Formation (structure-contour map in two-way travel time) in northern Taranaki Basin. To the northeast, the Ariki Formation is abruptly truncated against Te Kumi Fault (downthrown to the east). The southern limits of Ariki Formation are hard to define due to its chaotic and disrupted seismic reflection character. Pale pink areas represent parts of volcanic massifs inferred to have been exposed above the paleo-seafloor during the early Opoitian.

& de Bock (1996), who described it as being distinctly marly at the base, grading upward into siltstone. The lower part of the upper unit corresponds to a seismic interval bound by particularly distinctive bold and continuous reflectors, with a quiet, reflection-free internal character, much like the Ariki Formation at Tangaroa-1 and Te Kumi-1. The upper unit has been mapped over a considerable portion of the northern part of the Northern Graben (Fig. 12A). In seismic profiles, this upper unit drapes across the basin-floor fan lobes of the Mangaa Formation.

The lower marly unit in both Mangaa-1 and Awatea-1 is not as well recorded on wireline logs. However, lithological reports suggest that these units do indeed occur, and seismic analysis suggests that, as with the upper marly unit, the lower unit can also be correlated between wells. The distribution of the lower unit within the Northern Graben is illustrated in Fig. 12B. The southern boundary of this unit appears to be truncated by the upper unit.

Mangaa Formation

Mangaa Formation derives its name from latest Miocene–Pliocene-aged sandstone beds encountered at Mangaa-1 in the Northern Graben. These sandstone beds are younger and geographically separated from sandstone beds of the Mount Messenger and Moki Formations (Fig. 2). They constitute the initial (mainly early Pliocene) fill of the Northern Graben and accumulated as submarine fan deposits. Awatea-1 is the only other well in which Mangaa Formation is encountered. In both of these wells the Mangaa Formation unconformably overlies the Mohakatino and (upper) Manganui Formations and underlies the Giant Foresets Formation.

Mangaa Formation is physically divided into two sandstone and mudstone packages, separated by the upper silty to marly unit, as described above (Fig. 10, 11). Forder & Sissons (1992) divided the Mangaa Formation at Mangaa-1 into the Moki C1 Sands (youngest) and Moki C2 Sands (oldest). This nomenclature has subsequently been abandoned (e.g., King & Thrasher 1996) as the Moki Formation applies to Miocene sediment, whereas the Mangaa Formation is probably mainly Pliocene in age. At Awatea-1, Murray & de Bock (1996) similarly divided the Mangaa Formation into younger (Mangaa A) and older (Mangaa B) sandstone packages separated by an upper marly unit. These divisions are retained in this study, and also applied to Mangaa-1. Sandstone beds within the Mangaa Formation are exceptionally well expressed on wireline logs, with blocky to tabular profiles bounded by abrupt upper and lower contacts clearly displayed on SP and resistivity logs, particularly at Mangaa-1 (Fig. 10). Subordinate serrate motifs of the GR, SP, and resistivity logs reveal the presence of interbedded mudstone, and are indicative of thick-bedded and amalgamated deposits, probably the result of high-density turbidity current or sandy debris flow deposition on submarine fans. Individual sandstone beds may be up to 10 m thick and amalgamated packages are up to 40 m thick, separated by muddier lithologies c. 10–20 m thick.

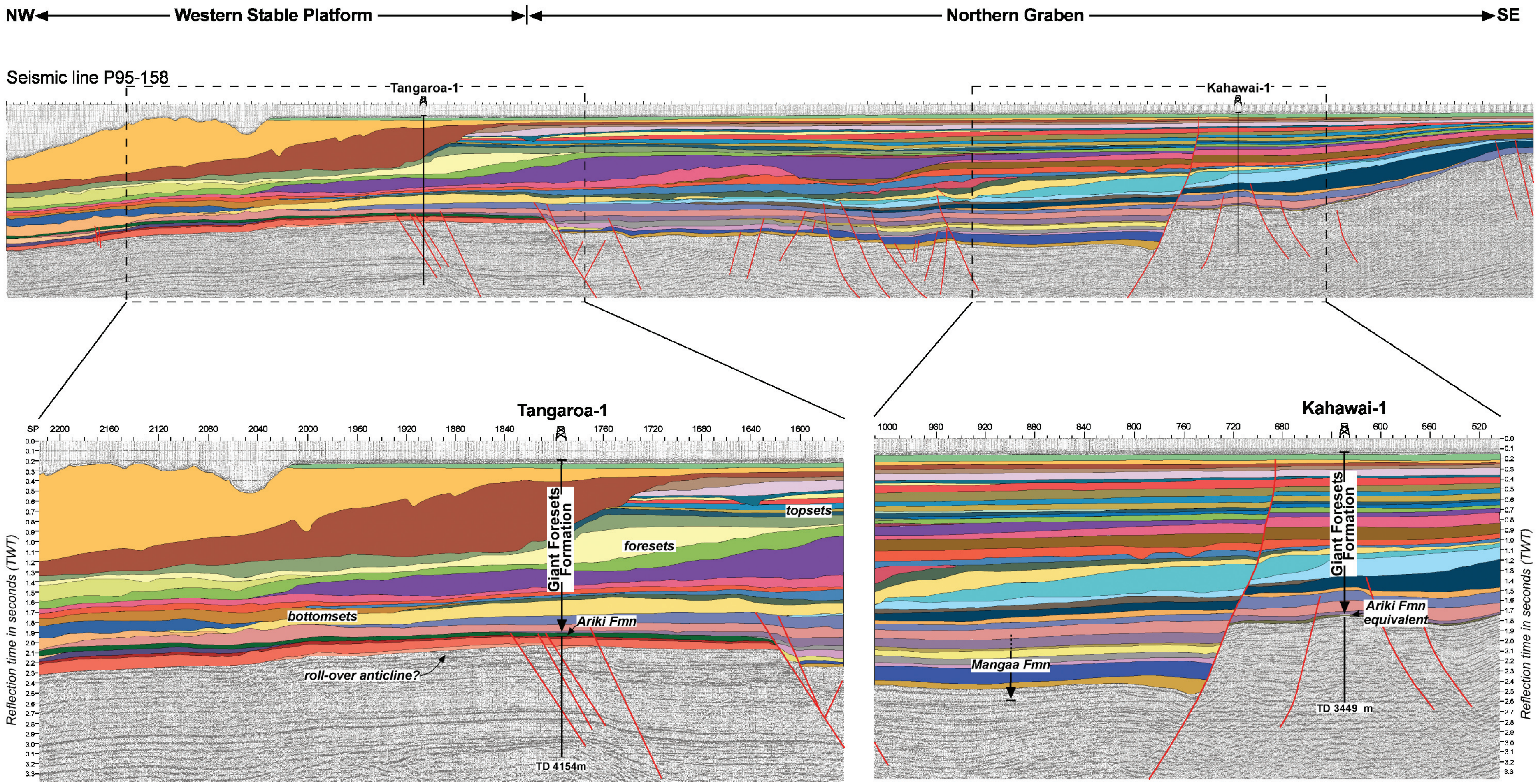

Fig. 8 Interpretation of the upper part of seismic reflection profile P95-158 (see Fig. 1 for location). This profile illustrates the asymmetric nature of the Northern Graben, the limited extent of the Mangaa Formation (indicated by arrow), and the seismic divisions of the Giant Foresets Formation. It also shows a possible roll-over anticline in the vicinity of Tangaroa-1 (*left*), which influenced the distribution and nature of the Ariki Formation, and uplift on Kahawai Fault (*right*), which contributed to condensed sedimentation in the vicinity of Kahawai-1. Seismic units from Hansen (2003).

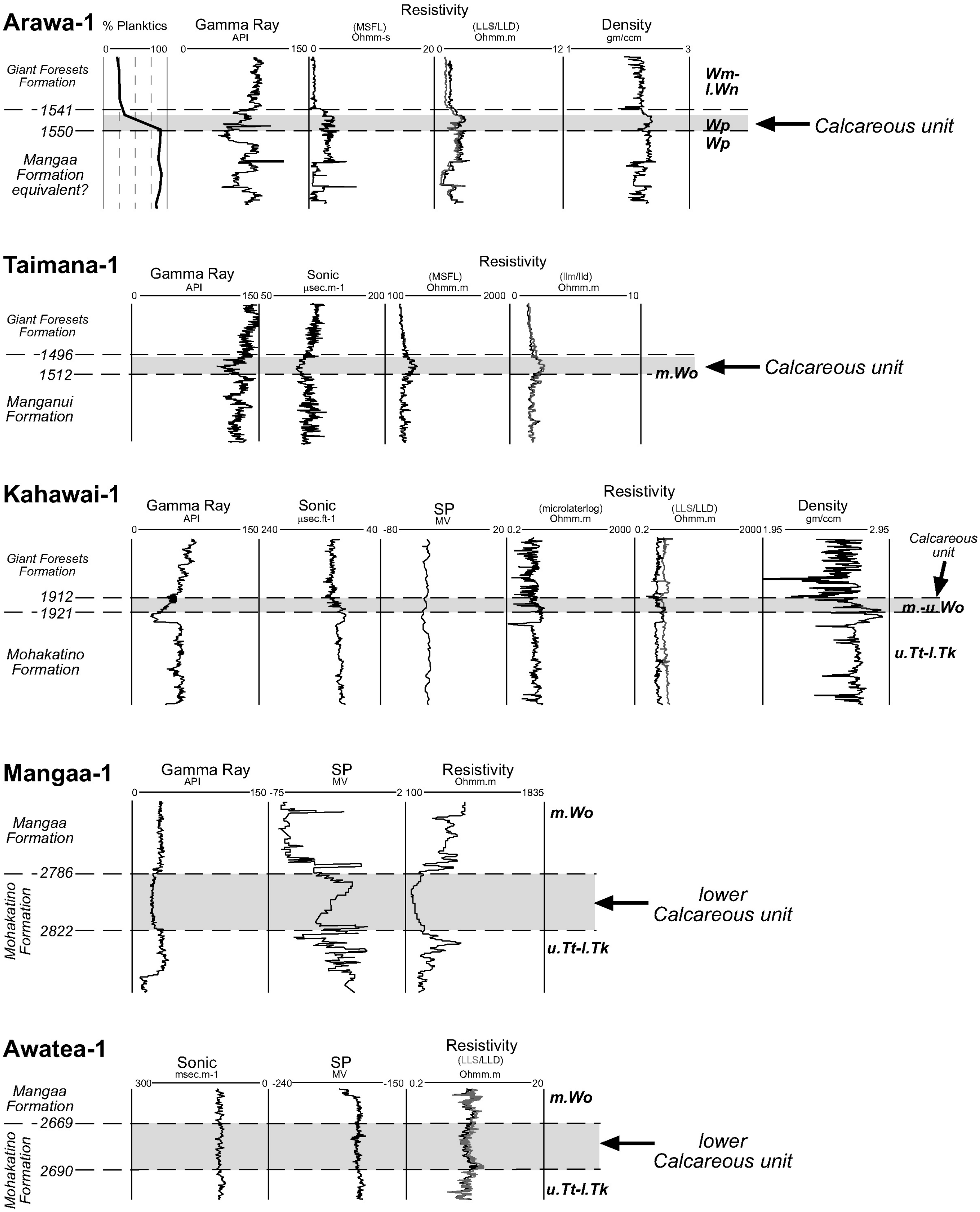

Fig. 9 Wireline characteristics of Ariki Formation equivalents. A thin interval at the base of the Giant Foresets Formation often displays similar characteristics to the Ariki Formation (e.g., Arawa-1, Taimana-1). A thin (c. 9 m) marly unit is also noted at Kahawai-1 overlying the Miocene–Pliocene unconformity. The lower marly unit present in the Northern Graben is shown for Mangaa-1 and Awatea-1. Biostratigraphy of Arawa-1 from Hansen (2003); Taimana-1 from Diamond Shamrock Oil Co. (NZ) Ltd. (1984); Kahawai-1 and Mangaa-1 from Waghorn et al. (1996); and Awatea-1 from Murray & de Bock (1996).

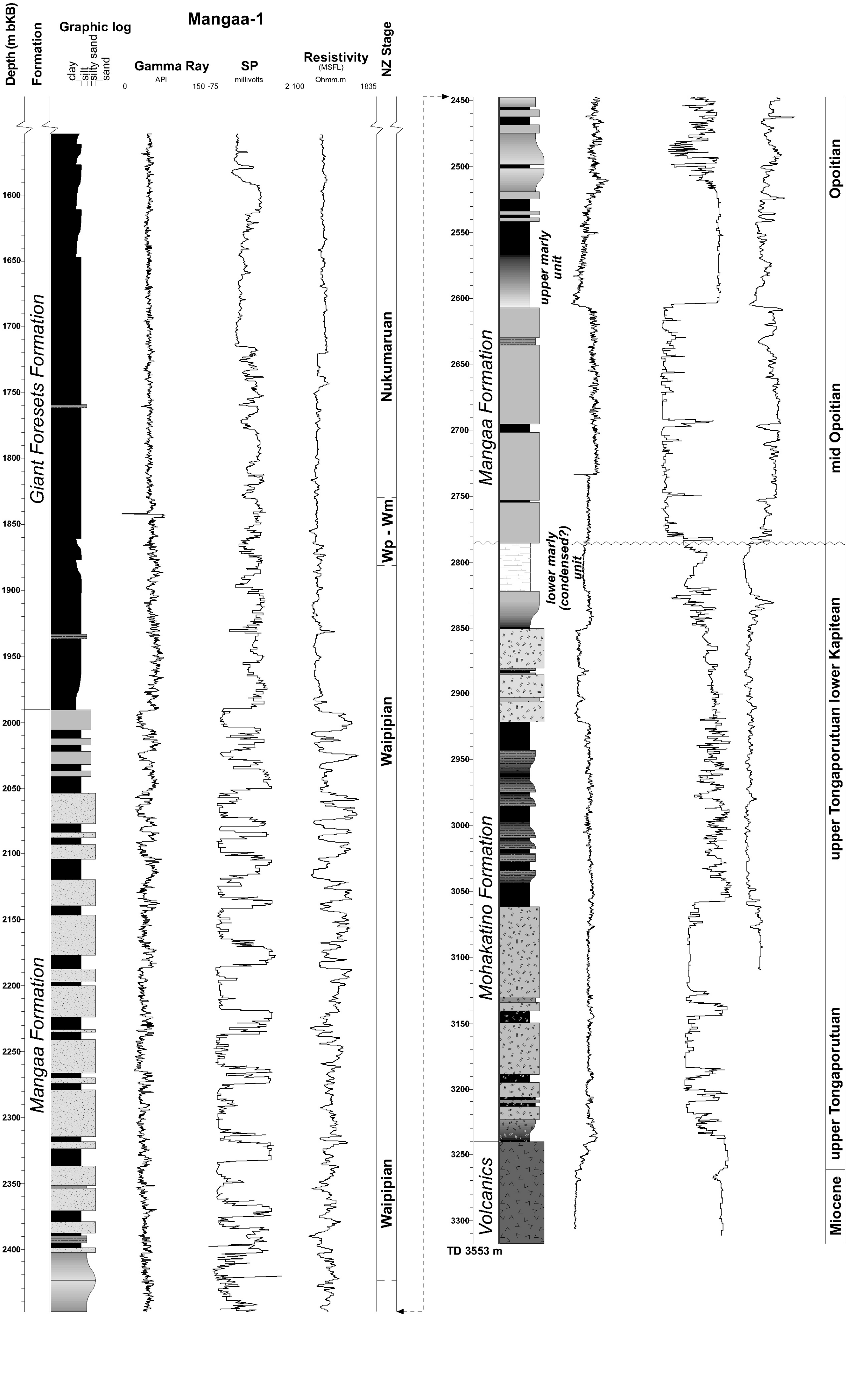

Fig. 10 Wireline characteristics (in stratigraphic order) of the Mohakatino, Mangaa, and lower Giant Foresets Formations in Mangaa-1 (Northern Graben). The upper and lower marly units, inferred to be stratigraphic equivalents of the Ariki Formation on the Western Stable Platform, are highlighted.

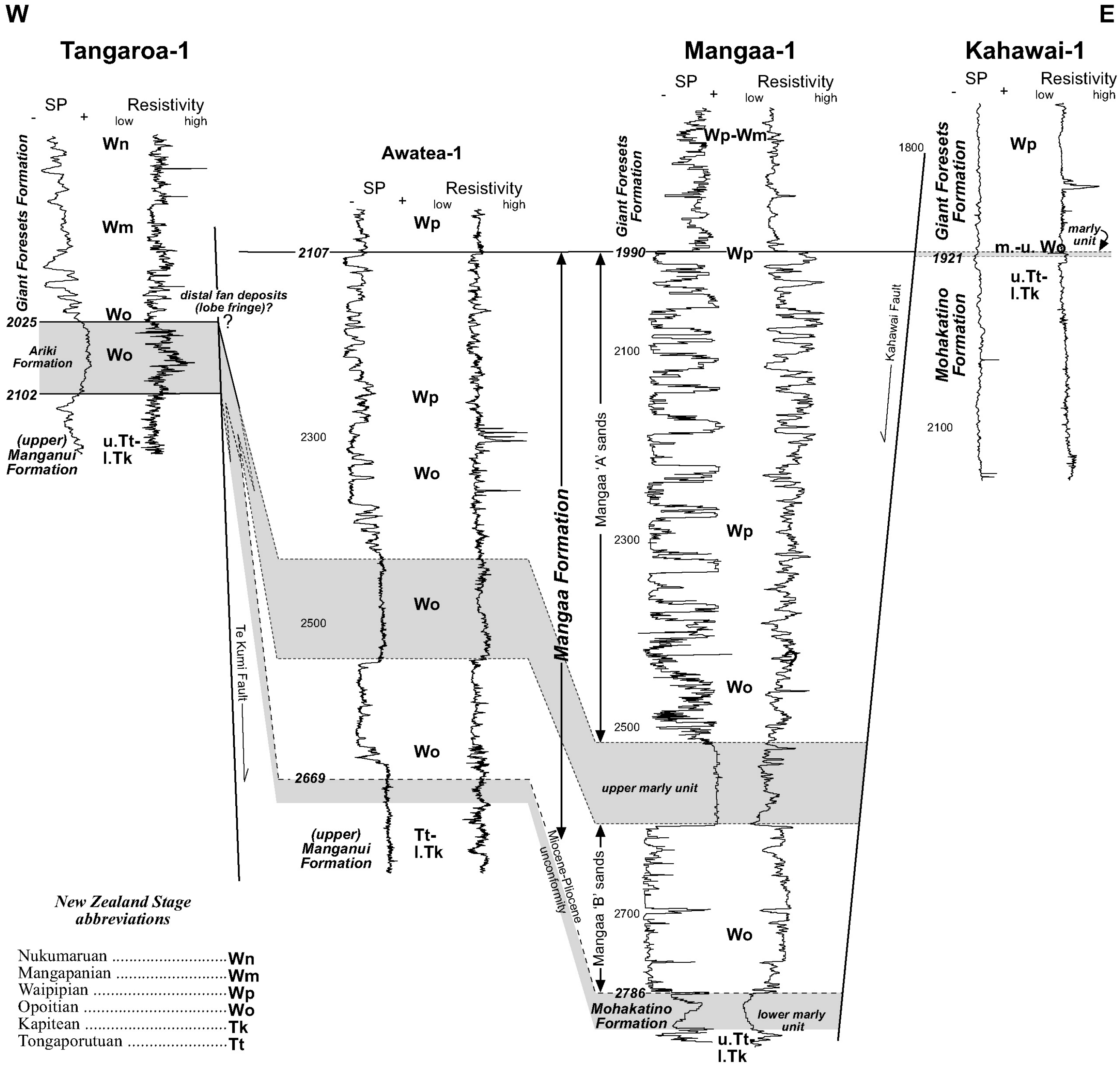

Fig. 11 Well correlations for northern Taranaki Basin based on wireline logs. The Mangaa Formation thins dramatically west of the axis of the Northern Graben reflected in the lateral pinching of sandstone units, which are best developed at Mangaa-1. Two silty to marly units, a lower one underlying the Mangaa Formation, and an upper one separating Mangaa A and B sands, are inferred to be stratigraphic correlatives of the Ariki Formation. Depth is in metres below Kelly Bushing.

Accumulation of the Mangaa Formation was localised and probably fault controlled, reflecting the early development of the Northern Graben. Te Kumi-1 and Tangaroa-1 are the closest wells to Awatea-1 and Mangaa-1 (Fig. 1, inset). They display an interval of several coarsening-upward cycles immediately above the Ariki Formation (e.g., Tangaroa-1, Fig. 11). These may be related to Mangaa deposition on the basis of age, and are possibly distal fan-edge deposits. At Arawa-1, a late Kapitean–Waipipian interval of distinctly coarser lithology (as suggested by wireline and textural data; Fig. 3) may correspond to the Mangaa Formation, but of younger age than the deposits in Mangaa-1. Consequently, we refer to this stratigraphic interval as "Mangaa Formation equivalent".

Seismic reflection profiles illustrate the low mounded fan morphology of the Mangaa Formation (Fig. 13). Overall, the blocky nature of the Mangaa Formation on wireline logs is mirrored by the reflection character of the seismic units that comprise the formation. Each seismic unit incorporates relatively transparent intervals representative of mass flow units deposited along the main depositional axis of a basin-floor fan complex, while the internal bright, parallel, and continuous reflectors correspond to intercalated mudstone beds. Towards the top and more distal margins of the formation, reflectors become less parallel and more hummocky and discontinuous, emulating the less blocky nature observed on equivalent depth wireline logs, and hinting at a waning of the basin-floor fan depositional system.

Giant Foresets Formation

The Giant Foresets Formation was first given formation status by Shell, BP and Todd (Pilaar & Wakefield 1978) for a series of striking clinoform-shaped (e.g., Fig. 8), basinward-dipping seismic packages. Beggs (1990) later divided the formation into foreset (slope facies), topset (shelf), and bottomset (basin-floor) facies (Fig. 8). Each successive clinoform represents the transient position of the shelf-slope, basin-floor profile as the continental margin wedge prograded basinward during the Pliocene and Pleistocene. The name "Giant Foresets Formation" has been widely used, but no formal definition has been published. King (1988) suggested retention of an informal formation status and this is followed here.

The Giant Foresets Formation displays the least distinctive or characteristic wireline signature of the late Neogene formations considered here. Lithologically, it is predominantly muddy, which has resulted in moderate to high GR values, low resistivity values, and relatively featureless sonic logs (Fig. 14). However, some gross trends are observed, including an overall coarsening-upward profile, illustrated principally by a gradual up-hole transition to lower API values on GR logs, a distinct coarsening in sediment texture, and numerous smaller scale fining- and coarsening-upward packages (lithologically, from claystone to siltstone to fine-grained sandstone and *vice versa*) (Fig. 14). The coarser upper part of the Giant Foresets Formation invariably corresponds to upper slope or shelf deposits.

While the Giant Foresets Formation represents ongoing aggradation and progradation of the Pliocene–Pleistocene continental margin wedge, a simple model of progressive northwestward outbuilding and widening of the continental shelf is complicated by the late Neogene extension and graben formation that affected northern Taranaki Basin. In particular, the depocentres of the Northern and Central Grabens initially funnelled and trapped sediment. Differential fault movement along the Turi and Cape Egmont Fault Zones also produced widely varying stratigraphic thicknesses of the Pliocene–Pleistocene sequences. For example, post-Miocene sediments reach nearly 3000 m thickness in the Northern Graben to the east of Arawa-1, but may be <100 m thick over the Manganui Platform.

CHRONOSTRATIGRAPHY

A review of the late Miocene–Pleistocene biostratigraphy of four key well sections in northern Taranaki Basin (Arawa-1, Ariki-1, Kora-1, and Wainui-1) and integration of the results with other well sections, has enabled the construction of a chronostratigraphic panel across the region (Fig. 15A; see Fig. 16 for panel transect). The biostratigraphic data underpinning the panel are based on Hayward (1987), Hansen (2003), and various petroleum well completion reports. This panel summarises the timing of the cessation of arc volcanism, reworking of the eruptive products, graben formation, and progradation of the modern continental margin.

Hemipelagic sediment of the Manganui Formation accumulated chiefly in the western parts of northern Taranaki Basin and persisted through to the late Miocene (Fig. 15A). Thin calcareous mudstone units accumulated during the upper Kapitean and upper Opoitian in the vicinity of Arawa-1. Ariki Formation extends from the upper Tongaporutuan to the lower Kapitean between Wainui-1 and Ariki-1 (Fig. 15A). It is probable that this

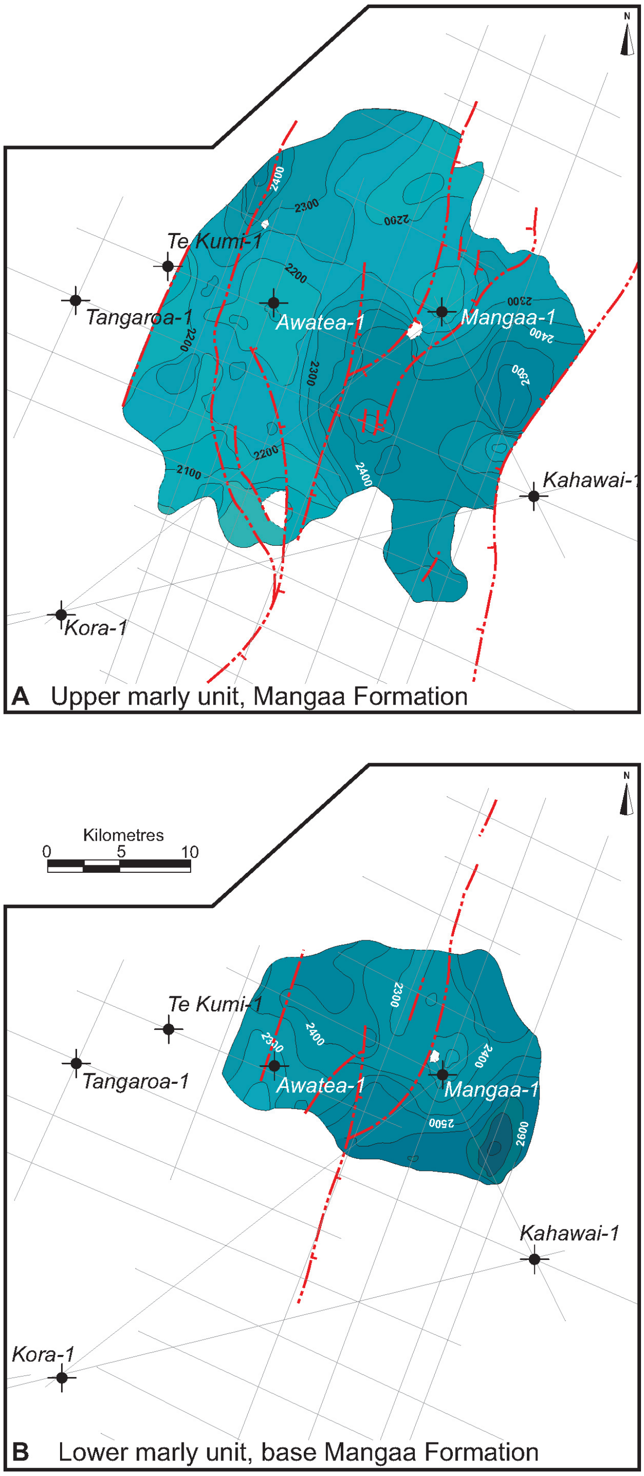

Fig. 12 Structure-contour map (TWT, 50 ms intervals) showing the extent of Ariki Formation correlatives in the Northern Graben. **A**, Upper marly to silty unit between Mangaa B and Mangaa A sands. **B**, Lower marly (condensed?) unit underlying the Mangaa Formation. Both units are correlatable between Mangaa-1 and Awatea-1, but cannot be geophysically correlated to the Ariki Formation on the Western Stable Platform through seismic reflection profiles, despite being age equivalents.

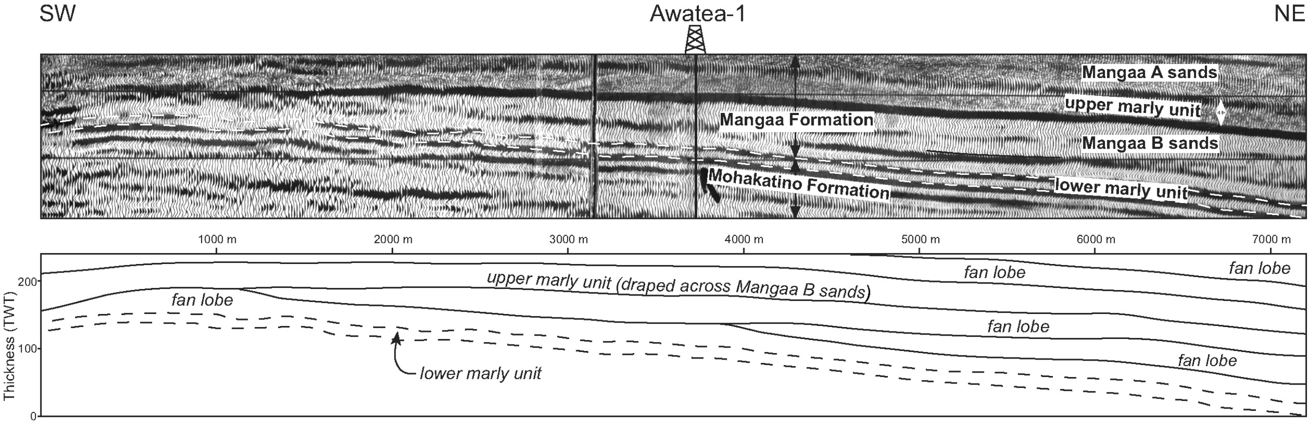

Fig. 13 Seismic reflection profile P95-115 showing the characteristics of the Mangaa Formation in the vicinity of Awatea-1 (see Fig. 2 for location). Note the mounded character of individual fan lobes and the draping nature of the upper marly unit.

formation extends to the end of the early Opoitian, but this cannot be proved with the available widely spaced well cuttings because of the condensed nature of the latest Miocene to early Pliocene section. Tangaroa-1 and Te Kumi-1 lie along the eastern margin of the Western Stable Platform, where Ariki Formation of Opoitian and early Waipipian age definitely occurs. The presence of volcaniclastic Mohakatino Formation sediments progressively decreases during the upper Tongaporutuan–Kapitean, reflecting the final stages of erosion of the andesitic volcanoes in the northern region.

The Northern Graben between Te Kumi Fault and the fault immediately to the west of Turi-1 contains all of the stratigraphic units considered in this paper. Manganui Formation is intercalated with Mohakatino Formation, generally no younger than early Kapitean in age. A lower marly unit has the same age (early Kapitean) as the Ariki Formation on the Western Stable Platform and provides a maximum age on graben formation. The lowest part of the Mangaa Formation is early Pliocene (Opoitian) in age and gives a minimum age on graben formation. In Kahawai-1, a marly unit of Opoitian age accumulated on the footwall of a fault block, probably topographically above the graben floor where Mangaa Formation accumulated. The Giant Foresets Formation is no older than late Opoitian and did not overwhelm the depositional setting until late Waipipian. The majority of the progradation of slope-sets and topsets occurred during the Nukumaruan (King & Thrasher 1996; Hansen 2003).

DISCUSSION

Timing of cessation of andesitic arc volcanism

Arc volcanism contributed most of the middle and late Miocene coarse sediment in northern Taranaki Basin. Volcanism first occurred in northern Taranaki Basin at c. 15 Ma (Lillburnian) (King & Thrasher 1996) and mainly from c. 12 Ma (latest Waiauan; Thrasher et al. 2002) in wells located in the Northern Graben. Volcanism along the axis of the Northern Graben continued into the late Miocene.

In the absence of continuously cored holes that allow distinctions to be made between volcanically versus sedimentologically emplaced beds, it is difficult to define the timing of the end of volcanism. Most of the youngest Mohakatino Formation beds encountered in wells comprise reworked volcaniclastic sediment sourced from erosion of possibly extinct volcanoes. Reworking continued into the Kapitean at some sites (e.g., Tangaroa-1), but no volcaniclastic sediment is recorded later than this. Active volcanism in the northern Taranaki Basin probably ended during the late Tongaporutuan to early Kapitean.

Condensed latest Miocene to early Pliocene marl sedimentation in Taranaki Basin

The Ariki Formation represents a period of accumulation of pelagic sediment and hence terrigenous sediment starvation in northern Taranaki Basin. This is remarkable as throughout most of the Neogene, voluminous terrigenous sediment was being generated within the plate boundary zone and sourced to Taranaki Basin and other basins. The accumulation of pelagic sediment therefore required special conditions to form. Part of this is related to the watermass conditions and a favourable latest Miocene to early Pliocene paleoceanography supplying sufficient nutrients to the region through current circulation patterns to support the biological productivity. Part of the explanation also lies in the cessation of active andesitic volcanism in northern Taranaki Basin, which minimised the local supply of clastic sediments to the basin floor. A third factor was the limited progradational extent in northern Taranaki Basin of the contemporary middle Miocene to early Pliocene continental margin wedge (Whangamomona Sequence, Kamp et al. 2004). This depositional wedge was mainly focused in King Country Basin, although part of it lay along the eastern margin of Taranaki Peninsula with the most northerly extent of the basin-floor fans (Mount Messenger Formation) being at Turi-1. A fourth factor for one of the marl units was topographic elevation above the graben of a fault block on the eastern side of the graben and a rollover anticline on the western side of the graben, which were sites where pelagic sediments could accumulate above basin-floor deposits. The age of the Ariki Formation at Tangaroa-1 constrains the timing of the development of this anticline from latest Kapitean to early Opoitian.

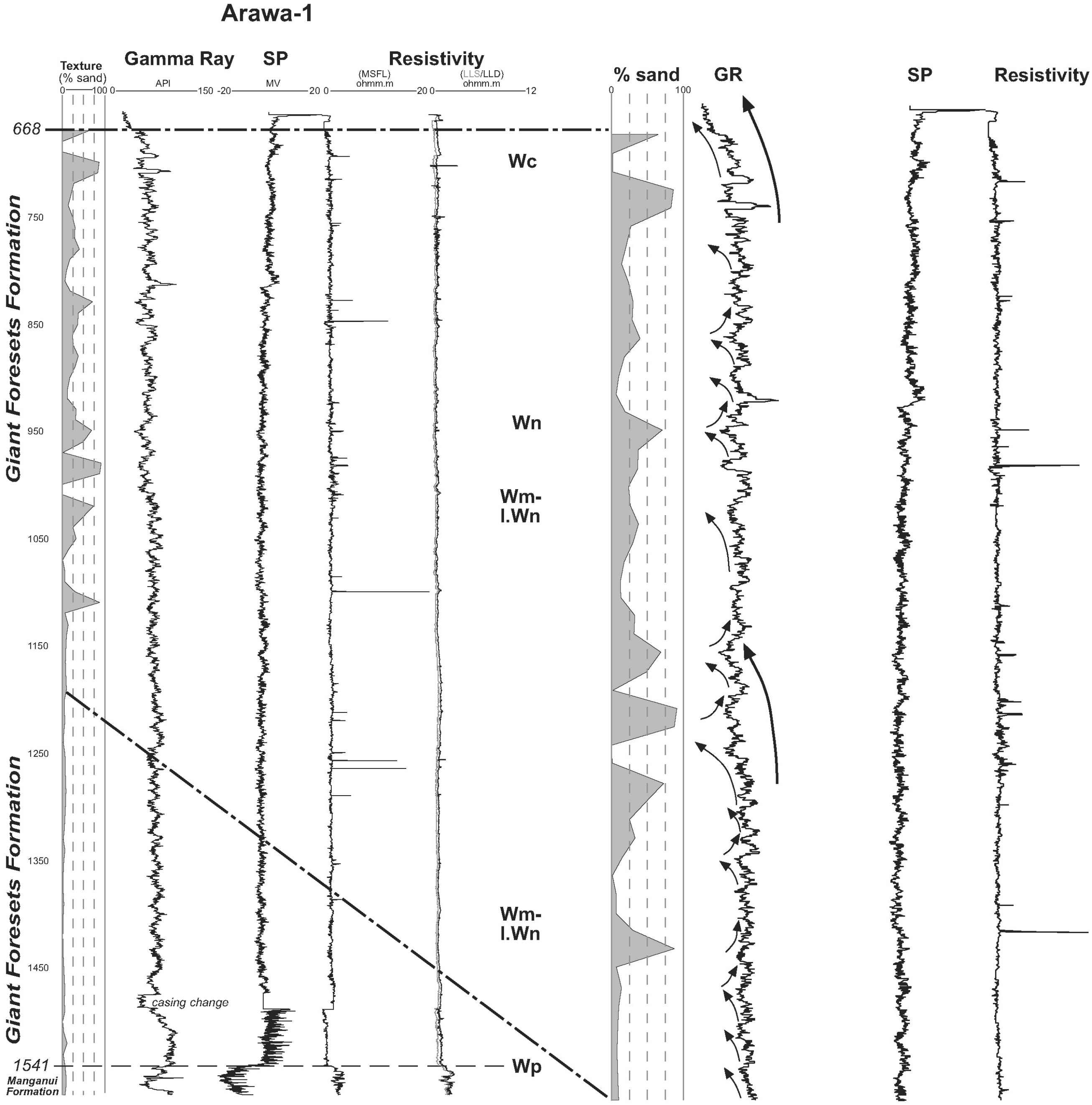

Fig. 14 Wireline characteristics of the Giant Foresets Formation in northern Taranaki Basin (Arawa-1). The wireline motif in this unit is often nondescript, although high resolution, serrate and overall upward-fining and coarsening cycles are discernible on the GR log. The upper few hundred metres is characterised by a distinct coarsening in sediment texture. Arrows depict high frequency coarsening- and fining-upward cycles.

Timing of Northern Graben formation and impact on sediment distribution patterns

The initial formation of the Northern Graben during the latest Miocene and early Pliocene controlled to some extent the sediment distribution patterns by trapping mass-emplaced sediments. Most of the faulting linked to graben development occurred during the early Pliocene (e.g., the marly unit at Kahawai-1 constrains initiation of uplift on Kahawai Fault to the late Kapitean to early Opoitian), postdating volcanism and offsetting many of the volcanic massifs (Thrasher et al. 2002). Since the early Pliocene, most normal fault activity has centred on the Turi Fault Zone (Stagpoole 1997). While displacement on some faults (e.g., Kahawai Fault) continues almost to the modern seabed, most of the movement on faults had ceased by the mid Pleistocene.

The Northern Graben acted as a local sink for sediment accumulation during the Pliocene, as evidenced by the Opoitian–Waipipian Mangaa Formation, although the presence of the two condensed intervals within the graben suggest periods of temporary hiatii across the graben. The limited distribution of the Mangaa Formation to the east and west of the main depositional axis is shown in Fig. 8 and 10,

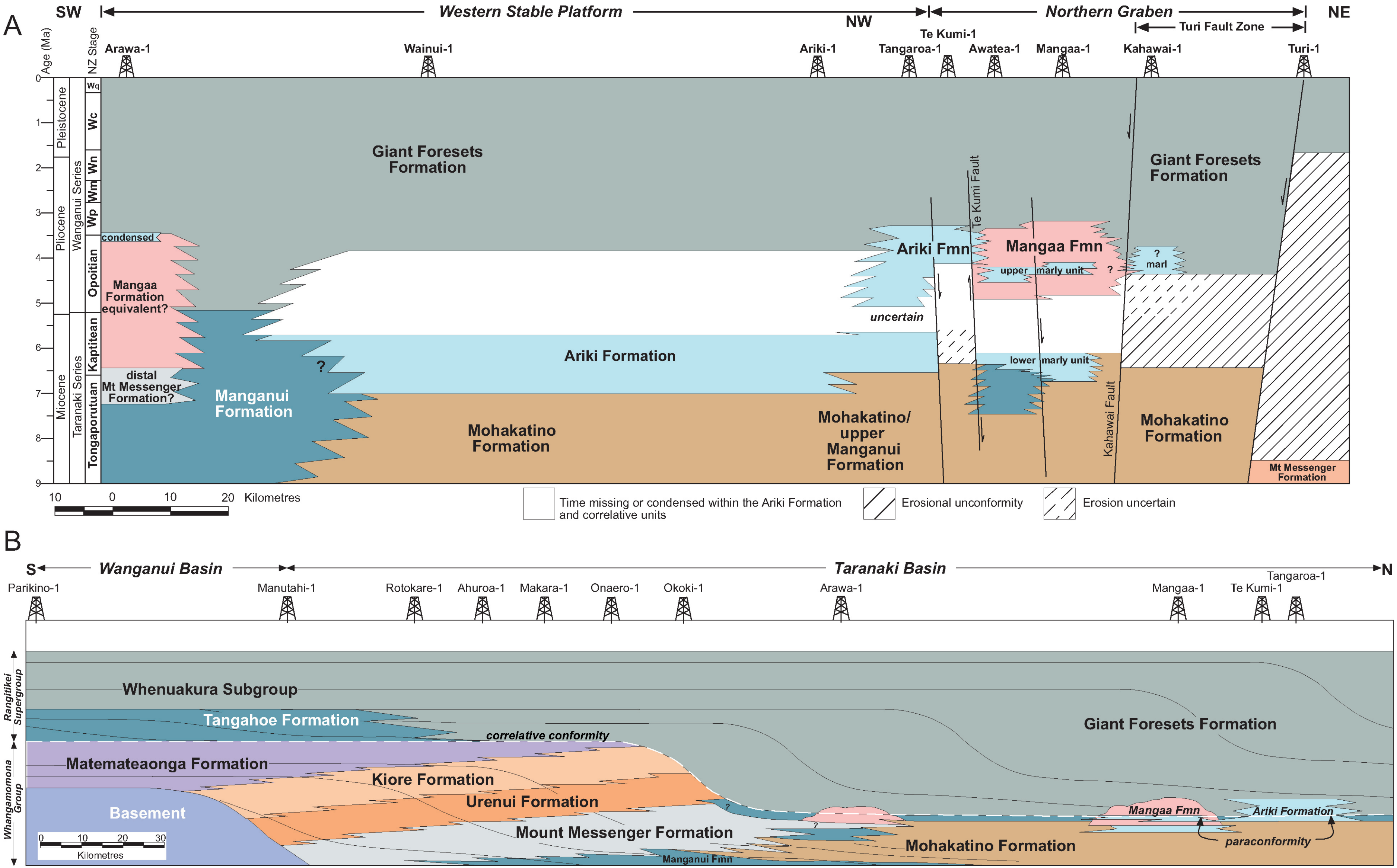

Fig. 15 West–east chronostratigraphic panel (**A**) and lithostratigraphic stacking patterns (**B**) in Wanganui and Taranaki Basins, illustrating the stratigraphic relationships between the Mohakatino, Manganui, Ariki, Mangaa, and Giant Foresets Formations. Note in (A) and (B) the complex distribution of the Ariki Formation and its association with other marly equivalents in the Northern Graben. The Ariki Formation is up to c. 109 m thick in Ariki-1 and encompasses the upper Tongaporutuan and Opoitian. Over parts of the Western Stable Platform the Opoitian Stage cannot be identified because of sampling resolution and the degree of condensation. The unconformity east of the Turi Fault Zone results from Pliocene–Pleistocene uplift and erosion. New Zealand Stage abbreviations: Wq, Haweran; Wn, Nukumaruan; Wm, Mangapanian; Wp, Waipipian. See Fig. 16 for location of panel.

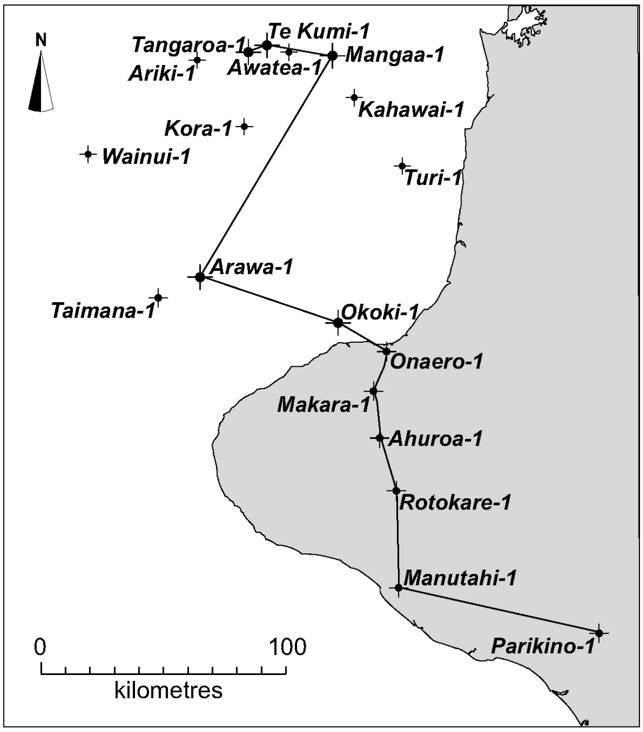

Fig. 16 Map showing the line of the panel illustrated in Fig. 15B.

which also highlight the asymmetrical nature of the graben. This asymmetry probably controlled in part the distribution of fan lobes associated with the Mangaa Formation; the less blocky nature of sandstone units at Awatea-1 compared with those at Mangaa-1 (Fig. 11) indicates that the main locus of deposition was in the vicinity of Mangaa-1. The age of the Mangaa Formation suggests that initially it may have been fed from the Matemateaonga shelf edge, which was at its greatest extent during the early Opoitian (Kamp et al. 2004). Later uplift and erosion of Whangamomona Group/Sequence strata in King Country Basin probably sourced the Mangaa Formation and the Giant Foresets Formation.

The Northern Graben depocentre influenced sediment distribution and accumulation patterns into the Nukumaruan, evidenced by the orientation of channels along the axis of the graben, and overthickening of the Giant Foresets Formation within the graben itself (Hansen 2003). It was not until the Nukumaruan that sedimentation rates began to exceed subsidence rates in the graben, causing sediment to spill over on to the Western Stable Platform.

Regional context for continental margin progradation

Outbuilding of the modern continental shelf-slope margin began in southern Taranaki Basin during the early Miocene as the regressive phase of a 1st-order megacycle (King & Thrasher 1992; King et al. 1999). Most of the progradation has been achieved, however, since the middle Miocene (Kamp et al. 2004). The Whangamomona (2nd order) Sequence of middle Miocene to earliest Pliocene age represents the first significant northward progradation of a continental margin wedge and was mainly confined to Wanganui and King Country Basins, with limited extent as a shelf-slope system along the eastern margin of Taranaki Basin (Kamp et al. 2004). The Rangitikei Sequence includes the Giant Foresets Formation and represents a second mid-Pliocene–Pleistocene progradational margin wedge, much of which underlies the modern shelf and slope in Taranaki Basin.

Figure 15B is a schematic reconstruction of the two megasequences (2nd order) representing progradation of the continental margin in Taranaki and Wanganui Basins. It is broadly drawn to (horizontal) scale and schematically palinspastically restored; that is, sediment layers have been back-stripped and decompacted. At the base of the figure is the progradational part of the Whangamomona Sequence, which includes the Mount Messenger Formation as lowermost slope to basin-floor deposits. Mount Messenger Formation interfingers with Mohakatino Formation, which also accumulated in bathyal water depths in northern Taranaki Basin. The Urenui, Kiore, and Matemateaonga Formations comprise the slope-set (foreset) and topset components of the Whangamomona Sequence. Late Pliocene–Pleistocene uplift and erosion centred in the King Country region (Kamp et al. 2004) has given rise to the outcrop exposure of these stratigraphic units, particularly along the northern Taranaki coastline.

During the early Opoitian, Wanganui Basin together with Toru Trough and the Central Graben (Fig. 1) subsided rapidly, thereby isolating the Whangamomona Sequence from its South Island sediment source and stopping its progradation. From the late Opoitian, Tangahoe Mudstone accumulated in Wanganui Basin and southern Taranaki Basin as progradational slope-sets (clinoforms) in upper–mid-bathyal environments over tectonically downwarped shelf deposits of the Matemateaonga Formation. The slope-sets of the Tangahoe Mudstone pass upward into topsets (shelf deposits), and the whole system subsequently prograded northward into northern Taranaki Basin as the Giant Foresets Formation building up the modern shelf and slope.

The Ariki Formation started accumulating when the Whangamomona Sequence was reaching its maximum progradational extent in King Country Basin and eastern Taranaki Basin (late Kapitean to early Opoitian). The condensed sedimentation represented by the Ariki Formation was enhanced during the late Opoitian by the tectonic subsidence in Wanganui and southern Taranaki Basins that formed the main Wanganui depocentre and Toru Trough (Kamp et al. 2004), thereby trapping the voluminous siliciclastic sediment (Tangahoe Mudstone and Whenuakura Subgroup) being supplied at that time from the Southern Alps, and enhancing terrigenous sediment starvation in northern Taranaki Basin.

Extensional faulting leading to the formation of the Northern Graben started during the latest Miocene (Kapitean) or earliest Pliocene (Opoitian). Uplift of the margins of the graben allowed Ariki Formation to continue to accumulate into the Waipipian (Fig. 15A). The distribution of the Mangaa Formation was controlled by asymmetrical graben subsidence. The difficulty in resolving the age of the base of this unit means that we are unsure whether the Mangaa Formation basin-floor fan deposits were sourced during the final phase (lower Opoitian) of progradation of the Whangamomona Sequence, or during subsequent cannibalisation of this sequence once uplift started in the King Country region. The progradation of the Giant Foresets Formation into the northern Taranaki Basin from the middle Pliocene (uppermost Opoitian–Waipipian Stages) onwards overwhelmed accu–mulation of the condensed Ariki Formation.

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