Evolution of the Giant Foresets Formation, northern Taranaki Basin, New Zealand

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Abstract

Plio-Pleistocene aggradation and progradation has resulted in the rapid outbuilding of the continental shelf margin, northern Taranaki Basin. Seismic reflection profiles reveal that this outbuilding is characterised by bold clinoforms which offlap in a basinward direction. This stacked succession of clinoforms, collectively termed the Giant Foresets Formation, obtains thicknesses of over 2 km in places, and has had a significant effect on the thermal regime of the region. This integrated study was initiated to document the Late Neogene evolution of this formation, and thereby gain insights on sedimentary distribution patterns, timing of sedimentation, and controls on progradation and aggradation.

Latest Miocene extension in the northern Taranaki Basin, related to rotation of the Hikurangi subduction zone, greatly influenced sedimentation patterns in the Pliocene. Palinspastic reconstruction shows that initial extension of the Northern Graben occurred before Giant Foresets Formation sedimentation began. Sediment, sourced from erosion to the east, was preferentially funneled into the newly created Northern Graben during the late Miocene and early Pliocene, while areas to the north and west underwent a period of sediment starvation. During the late Pliocene, and into the Pleistocene, sediment accumulation outpaced graben extension, and by the end of the Mangapanian, the graben was overtopped. During this period, the progradational front associated with the outbuilding of the continental shelf-slope margin advanced northwards. Throughout the Nukumaruan, continuing to the present day, shelf migration was extremely rapid. While at least seven cyclical sea level changes, with an approximate periodicity of 400 ka (fourth-order) have been identified, overall, depths shallowed from dominantly bathyal, to dominantly shelfal.

Introduction

The depositional history of the northern part of Taranaki Basin (Fig.1) is characterised by rapid progradation and aggradation of a late-early Pliocene to Recent continental margin succession that underlies the modern shelf and slope. It is characterised by clinoform development, and the stratigraphic name ascribed to the whole succession is the Giant Foresets Formation (Shell BP Todd 1976). This formation reaches a thickness of 2200 m and comprising a substantial part of the total basin fill. It represents a major part of the regressional phase of Taranaki Basin and we associate it with the 2nd order Rangitikei megasequence (Kamp et.al., this volume), which is also represented in Wanganui Basin. The thickness and rapid accumulation of the Giant Foresets Formation will have had a significant impact on the petroleum systems of Taranaki Basin, particularly in terms of driving the maturation of hydrocarbons and their migration (Beggs 1990; McAlpine 2000). Surprisingly, few detailed studies have been undertaken on the Giant Foresets Formation.

The primary objective of this study has been to develop a better understanding of the evolution of the Giant Foresets Formation. This has involved integration of data derived by several techniques, including mapping and interpretation of seismic reflection profiles, analysis of geophysical (wireline) logs, acquisition and analysis of planktic and benthic foraminiferal data for key well sections, as well as decompaction and backstripping of reflection lines for palinspastic reconstructions. This paper provides a broad overview of these techniques as applied, and presents some preliminary results obtained to date. The investigation is ongoing.

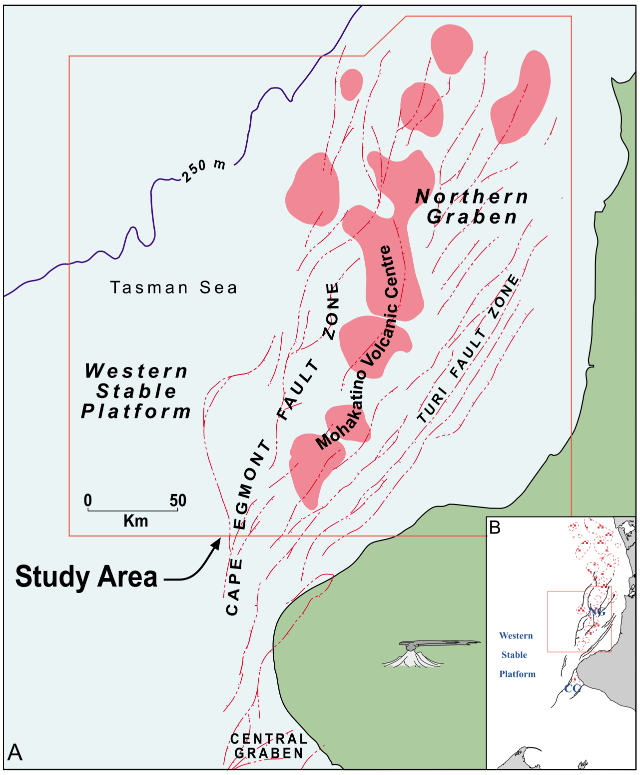


Fig.1: (A) Location of study area including structural features of the region. (B) inset shows location of detailed study area. Top Miocene features after Thrasher and Cahill (1990).

Geological setting

The parts of Taranaki Basin investigated in this study include the Northern Graben and the northwestern part of the Western Stable Platform (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. The Western Stable Platform has been influenced by crustal flexure (Holt and Stern 1994) but has not been internally disrupted by faulting (King and Thrasher 1996).

A synthesis of the geological character and development of Taranaki Basin has been written by King and Thrasher (1996). The basin formed during the late Cretaceous, and initially underwent extension associated with Tasman Sea spreading. During the latest Cretaceous to early Oligocene the basin accumulated sediments in a type of passive margin under a regional transgression where subsidence exceeded sedimentation. From the middle to late Oligocene the eastern margin of the basin started to subside more rapidly, and this has been attributed to lithospheric loading associated with the initial phase of development of the Australia-Pacific plate boundary zone through the New Zealand platform. During the Miocene the basin registered in its structures and sediment types the influence of the evolving plate boundary much more clearly. This involved earliest Miocene basement overthrusting on the Taranaki Fault, and late-early Miocene formation of the Tarata Thrust Zone. By the middle Miocene the direct effects of compression within the northern part of the basin and along its eastern margin had ceased. This coincided with the onset of submarine arc volcanism within northern part of the basin (Mohakatino Volcanic Centre; Fig. 1). The volcanic arc paralleled the trend of the contemporaneous subduction zone. Eruptions continued until about 7-8 Ma (King and Thrasher 1996). The volcanic massifs remained as topographic highs influencing sediment distribution patterns until the late Pliocene. During the Pliocene the volcanic arc migrated southeastward onshore into the Taupo Volcanic Zone, where it has been active since the latest Pliocene or early Pleistocene. Following the migration of volcanism onshore, the northern parts of Taranaki Basin became extensional, with formation of the Northern and Central Grabens. These depocentres were rapidly in filled by progradation of the Giant Foresets Formation.

The Giant Foresets Formation comprises a shelf to slope to basin floor succession of fine muds, through to silts and sands (ARCO Pet. Ltd. (NZ) Inc.1992; Shell BP Todd 1981; Hematite Petroleum 1970). The top-sets often contain shelly or pebbly intervals, and the succession is sporadically volcaniclastic. Correlative units of the Giant Foresets Formation onshore include the Tangahoe Mudstone and Whenuakura Subgroup and younger Nukumaruan and Castlecliffian strata in Wanganui Basin (Fig.2) (Kamp et.al., this volume). The Giant Foresets Formation is underlain by

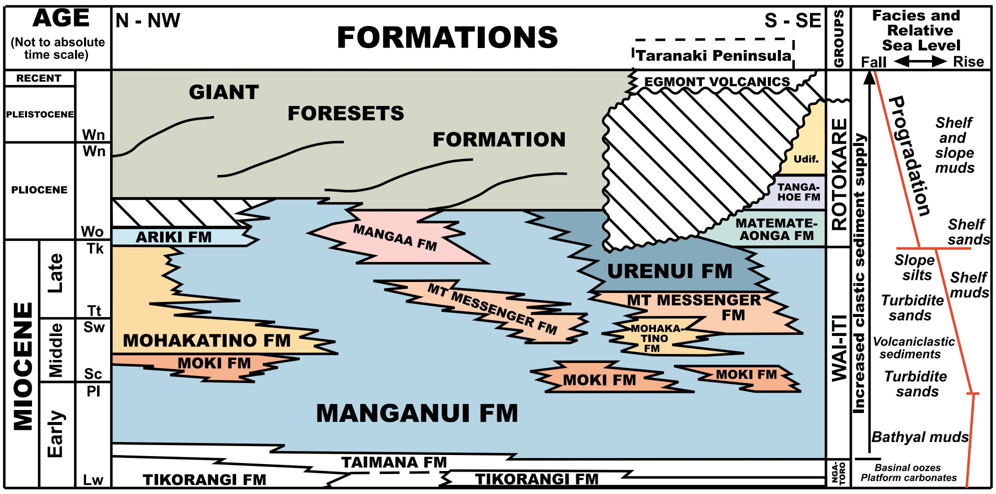


Fig.2: Miocene to Recent stratigraphic framework for Taranaki Basin. This figure illustrates the general age and progradational nature of the Giant Foresets Formation. Modified from King and Thrasher (1996).

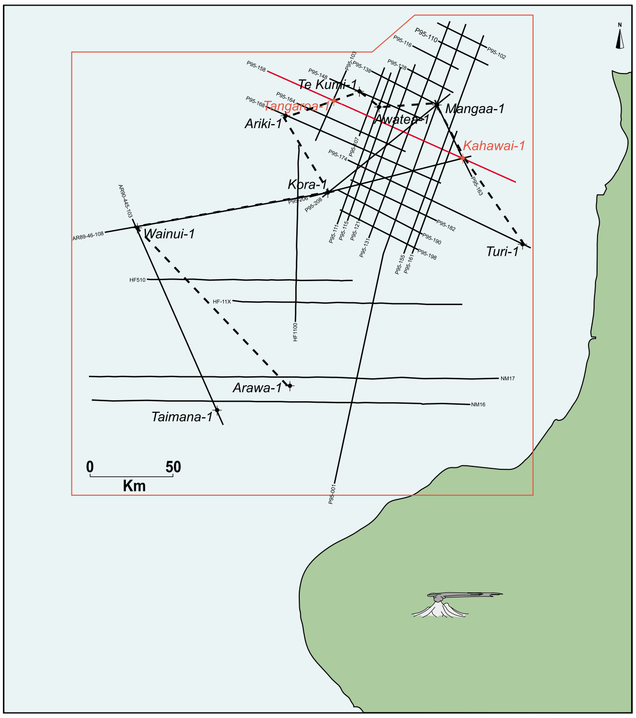


Fig.3: Seismic grid and well location map. Line P95-158 (highlighted) is used in the palinspastic reconstruction. Dashed line shows transect for Fig.4 (chronostratigraphic panel).

been identified and mapped. Many of these units have been able to be mapped over a wide area, and have provided the basis to construct structure contour and isopach maps. This has allowed the development of the shelf-slope margin to be tracked through time. General lithologic trends in the Giant Foresets Formation have been established from geophysical wireline logs for each of the wells in the study area (see Fig.3 for well locations), well completion reports and composite well logs.

The foraminiferal content of numerous unwashed well cutting samples from each of four wells (Arawa-1, Ariki-1, Kora-1 and Wainui-1) have been analysed, revealing paleoenvironmental information, including water depth and changes in benthic species and abundance levels. These data are useful in better understanding the depositional history of the Giant Foresets Formation. They are also being explored to establish whether or not they can identify cyclicity in environmental parameters at the level observed in the seismic reflection lines. Backstripping and decompaction modelling, using age, paleobathymetric, and lithologic data obtained from the methods outlined above, have enabled palinspastic reconstruction of several seismic lines. These reconstructions, coupled with paleogeographic maps, effectively summarise the geological history and evolution of the Giant Foresets Formation.

the Manganui, Mangaa, or Ariki formations and in places by Miocene volcanic massifs (e.g. Kora-1 well site) (Fig.2).

Data sets

Thirty two seismic lines, including 25 from the P95-series (Petrocorp Exploration, PR 2261, 1995) and seven from various earlier data sets, have been interpreted as part of this investigation (Fig.3). The reflection lines have been interpreted using methods outlined in Mitchum et.al. (1977) and Vail (1987). More than 60 discrete seismic units have

Chronology

The Giant Foresets Formation is the uppermost stratigraphic unit in the northern part of Taranaki Basin. The youngest parts of the formation are therefore of Recent age and include the surficial sea-floor sediments. The base of the unit is however strongly progradational in a north to northwest direction (Fig.2) and therefore will be diachronous. The age of the base of the formation is also complicated by the widespread occurrence of a condensed section and paraconformity, and the practical difficulty of identifying

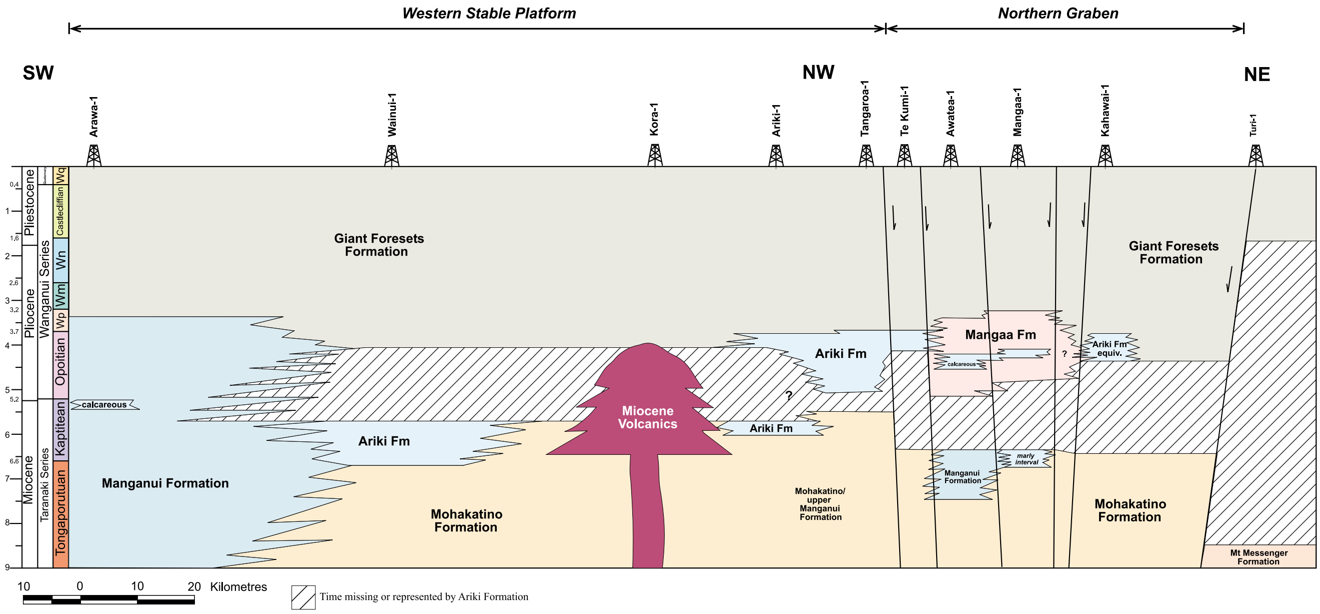
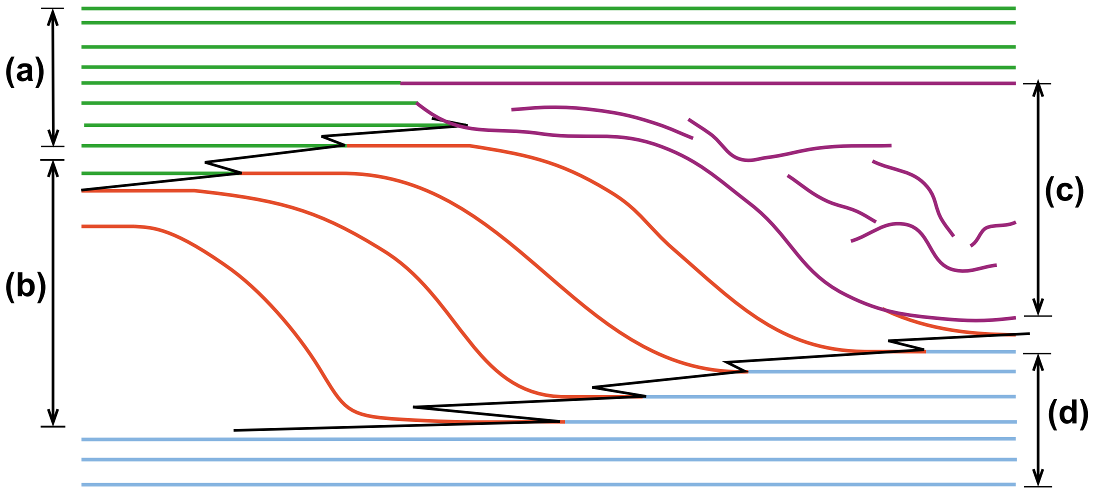


Fig.4: Chronostratigraphic panel, northern Taranaki Basin. Timescale and stage boundaries after Morgans et.al. (1997). Stage abbreviations; Wq – Haweran, Wn – Nukumaruan, Wm – Mangapanian, Wp – Waipipian. Note that the greatest thickness obtained by the Ariki Formation at any site is about.110 m (Ariki-1). Much of the time represented by the apparent unconformity may actually be represented by, but not identified in, the Ariki Formation.



(a) Topsets - sub-parallel, sub-horizontal, moderately continuous reflectors;
(b) Progradational foresets - offlapping and dipping basinward, moderately continuous reflectors;
(c) Degradational foresets - lower amplitude, more steeply dipping and chaotic reflectors;
(d) Bottomsets - sub-horizontal, slightly inclined reflectors, with variable continuity.

Fig.5: Schematic illustration of foreset divisions (after Beggs 1990), showing relative position in a shelf- slope- basin setting.

the New Zealand Pliocene Stages within the condensed section given the spacing of cutting samples.

The Ariki Formation was named for a marl encountered in Ariki-1, which has a Kapitean (latest Miocene) age (Fig.4) and 110 m thickness. The Ariki Formation underlies the Giant Foresets Formation. The Ariki Formation has also been identified in this study in several other well sections. It occurs in Wainui-1, Tangaroa-1, and Te Kumi-1. A thin (c.21 m-thick), marl is noted at Kahawai-1, and may be an equivalent of the Ariki Formation based on age and stratigraphic position. At all sites where it is present, this marl is associated with a sharp increase in planktic foraminiferal percentage compared with the overlying Giant Foresets Formation. This increase in planktic foraminiferal content is a feature that can be used to help locate the base of the Giant Foresets Formation, or time equivalent horizons, even in more terrigenous rich sediments (Manganui Formation), for example in Arawa-1 and Taimana-1, and at the base of the Mangaa Formation in Awatea-1 and Mangaa-1. At many of these sites, with the exception of the more southerly wells (Taimana-1, Arawa-1) late Tongaporutuan to late Kapitean and sometimes Opoitian sediments are very condensed (Fig.4). In Fig.4 the extent of the Ariki Formation in space and time and the extent of the associated paraconformity, as we have established it to date, are mapped in a southwest to northeast transect that takes in many of the hydrocarbon wells.

The origin of this condensed section is related to a period of terrigenous sediment starvation across much of the northern part of Taranaki Basin. It corresponds to the accumulation of the thick Kiore and Matemateaonga Formations in the King Country and Wanganui basins as a prograding continental margin, and the limited extent of this progradation in Taranaki basin (Kamp et.al., this volume). Later parts of the paraconformity development are related to a marked early Opoitian (earliest Pliocene) tectonic pulldown of Wanganui Basin and Toru Trough (earliest Pliocene), which caused a dramatic flooding and southward onlap across Wanganui Basin and southeastern parts of Taranaki Basin. This caused the accumulation of the Matemateaonga Formation to cease, and the water depths to increase from shoreface to bathyal, allowing the Tangahoe Formation to accumulate at slope depths; contemporary shelf sedimentation was focused to the south in Wanganui Basin. The deposition of the Giant Foresets Formation represents the progradation of a second continental margin (Rangitikei megasequence) northward into Wanganui and Taranaki basins (Kamp et.al., this volume). The Giant Foresets Formation in northern parts of Taranaki Basin are younger than 4 Ma (Fig.4). Note in Fig.4 the occurrence of the Mangaa Formation in the Northern Graben, and that its accumulation reflects deposition during the early Pliocene (Opoitian Stage).

Geophysical characteristics

Seismic reflection characteristics of the Giant Foresets Formation

The Giant Foresets Formation is well known for, and indeed was named, for its spectacular stacked succession of bold off-lapping clinoforms that prograde towards the modern continental slope (Shell BP Todd 1976). The formation typically has four parts based on its seismic character (Beggs 1990)(Fig.5).

1. Top-sets. These comprise sub-parallel, sub-horizontal, moderately continuous reflectors. Lithologies include sandstone, muddy siltstone, and shellbeds or disseminated shell hash, consistent with accumulation on a continental shelf.
2. Progradational foresets. These display moderately continuous reflectors, off-lapping in a basinward direction. The depositional setting is a continental

slope with accumulation of fine-grained mudstone and muddy siltstone.

3. Degradational foresets. These reflectors represent structure on a continental slope, but the reflectors dip at steeper angles than the depositional surface, and are more chaotic reflecting mass movement downslope. The units are lithologically variable. Units can incise deeply into underlying strata.
4. Bottom-sets. These sub-horizontal to slightly inclined reflectors represent deposition on a basin floor. They may have variable continuity. Lithologies making up these units can be sandstone or mudstone.

Figure 6 illustrates an uninterpreted and an interpreted version of line P95-158 (Fig.3). The grid of seismic has been used to map multiple seismic units throughout the study area. This has involved 60 seismically distinct units, or packages. Most of these seismic units have (or have had) top-set, foreset (either progradational or degradational) and bottom-set components. However, along the eastern margin of the basin there has been substantial post-depositional uplift and parts of the seismic units have been truncated by erosion.

Interpretation of the seismic grid enables construction of structure contour and isopach maps (in TWT and depth/thickness). These can then be used to interpret several features, including depositional style (e.g. whether or not the shelf margin advanced as a series of depositional lobes, or a more linear foreset front), changing location of depocentres, migration direction of the shelf margin, and overall geometry of the formation. Of particular importance is the base Giant Foresets Formation structure contour map, shown in Fig.7 in TWT. This map shows that most accommodation was generated within the Northern Graben, and to the north and west of the study area, with a smaller fault-bound depocentre immediately to the northeast of Arawa-1. A series of isopach maps (Fig.8) show how the Northern Graben was infilled during the middle to late Pliocene (Waipipian-Mangapanian Stages; Figs 8a&b). The Opoitian isopach map includes Mangaa and Manganui Formations. By the Nukumaruan Stage, the foreset front was clearly made up of a linear sedimentary body. Individual seismic units occur as a series of migrating lobes within these fronts. Sediments were thickest during the Opoitian-Mangapanian Stages over the Western Stable Platform, while in the Northern Graben, the majority of sediment was deposited during the Opoitian (in the central part of the graben) and from the Nukumaruan onwards.

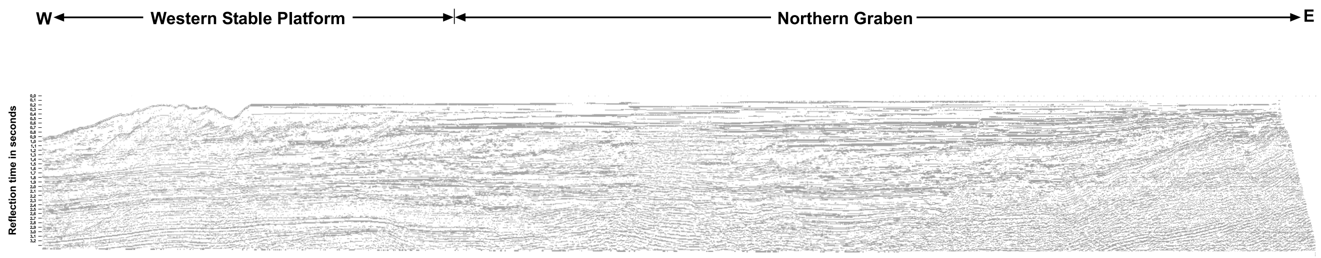
Wireline log motifs

The characteristics of wireline logs were examined for each of the 11 wells used in the study area (e.g. Fig.9). Log types include gamma ray (GR), spontaneous potential (SP), sonic, resistivity, and density logs. Lithology was interpreted from a combination of available wireline logs, composite well logs, and well completion reports. This in turn enabled lithologies to be attributed to specific log motifs or combinations of log motifs. These reveal that, in comparison with underlying formations, the Giant Foresets Formation has few distinctive characteristics. The overall muddy/silty nature of this formation is reflected in the quiet log signatures, although an overall coarsening upwards nature is noted in some wells. The base of the formation is nearly always delineated by a sharp kick to the left on GR, independent of the lithology of the underlying formation.

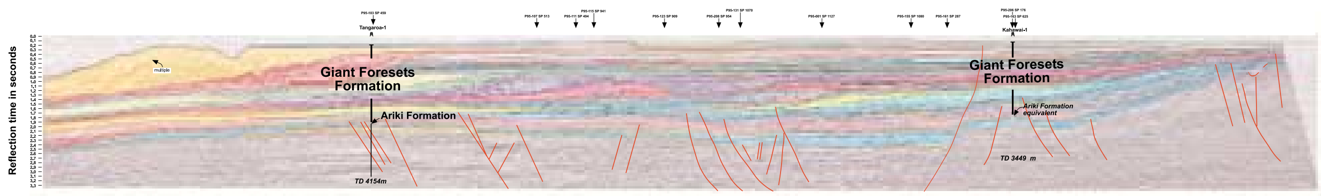
Given the clarity of clinoform development in many of the seismic reflection lines it is surprising that the wireline logs are apparently so bland. However, when enlarged, and compared against the seismic section for each well (Fig.10), a distinct relationship between prominent reflectors (clinoforms) and the base of upward-fining or upward-coarsening units or packages of units is evident, even though these units may only display variation within fine-grained lithologies.

Paleoenvironmental interpretation

Detailed analysis of foraminifera from suites of cutting samples from each of four wells (Ariki-1, Arawa-1, Kora-1 and Wainui-1) has enabled paleobathymetry and depositional environments to be established for sections



(a) Seismic reflection profile P95-158, uninterpreted.



(b) Seismic reflection profile P95-158, interpreted.

Fig.6: Example of one of the seismic reflection profiles used in this study (P95-158; refer to Fig.3 for location). Note the highly incised nature of the degradational foresets compared with the smoother profile of the progradational foresets. See also Fig.14 for palinspastic reconstruction of line. Depth is in two-way-travel time (seconds).

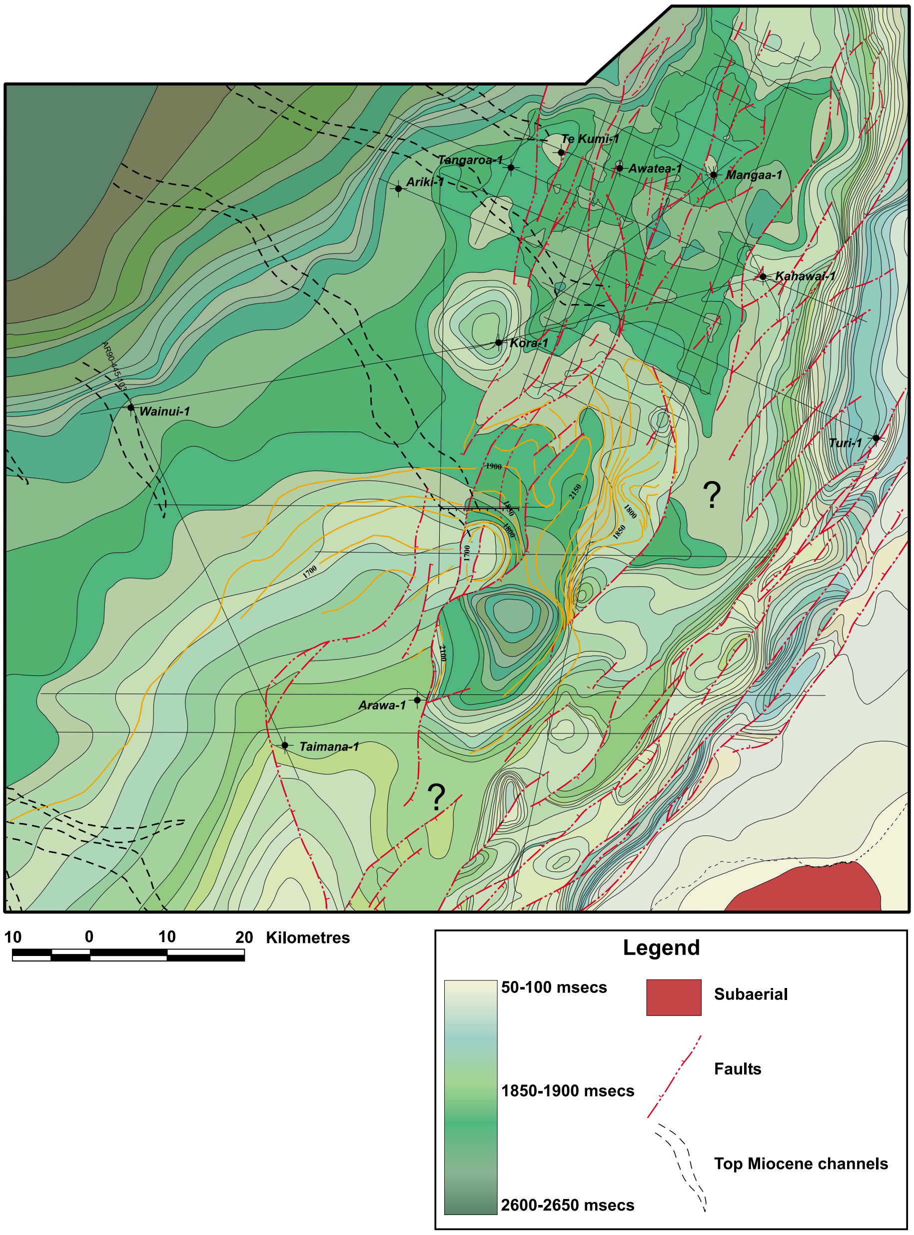


Fig.7: Base Giant Foresets Formation structure contour map, in two-way-travel time (msecs). Compiled from Hansen (in prep.) and Thrasher and Cahill (1990).

through the Giant Foresets Formation. The analyses included the calculation of foraminiferal planktic:benthic ratios to show changing surface water mass with time, and statistical analysis of benthic species and diversity, as well as cluster analysis, to highlight depth trends. Figure 11 illustrates the results of cluster analysis for Ariki-1, using the Multivariate Statistical Package developed by Kovach (1999). Species associations were clustered using modified Morista Similarity, and faunal sample associations clustered using Bray-Curtis Distance Matrix. Depth ranges were estimated using the resultant dendrograms, and a paleobathymetric curve generated for each well (Fig.12). These show several features.

1. During the Pliocene, cyclical changes in sea level at 41 ka periodicity, as evident form the oxygen isotope records of deep sea cores, were not readily observable in terms of changing water depth. While changes in sea level of the order of 100 m would be significant at shelf depths, such changes would not cause the same sedimentary response at bathyal depths, at which all sites resided during this period. Changes in relative sea level do become more obvious in the top-sets.

2. Two bathymetric deepening events occurred during the interval studied. The first occurred during the mid Pliocene (Waipipian), and in all cases shows a deepening from upper bathyal to mid bathyal. This event appears to have been longest at one of the deeper sites (Wainui-1). The second occurred during the late Nukumaruan to Castlecliffian, with a deepening from mid/outer shelf to outer shelf/upper bathyal depths (depending on site) recorded.

Cyclicity

Unlike Wanganui Basin, where shelf cyclothems can be clearly observed and correlated on the basis of the regular occurrence of shellbeds (both in outcrop and well-log; e.g., Kamp et al. in prep., this volume; McIntyre, 2001), sediments of the Giant Foresets Formation display few characteristics that lend themselves to delineation of cyclothems. This is in part due to the dominantly muddy nature of the sediment, and in part to the generally deep-water depositional setting, but may also be due to the fact that the majority of sediment is inferred to have been deposited during periods of low relative sea level. While the Giant Foresets Formation contains successive clinoforms, it is not immediately apparent that the sediments between successive clinoforms represent individual eustatic sea level cycles. It is therefore necessary to have another means of assessing sea level change.

To help define cyclicity, both in terms of which seismic units represent actual relative sea level change, and which ones represent 'event' deposition, wireline interpretation and foraminiferal information from Ariki-1, Arawa-1, Kora-1 and Wainui-1 were integrated with seismic reflection profiles (e.g. Fig.13). Textural trends (obtained from sieve and/or laser-sizer analyses) were also incorporated in the data integration. This work is still on going, however, some trends have been identified.

1. Peaks in the abundance of benthic foraminifers are often coincident with spikes in sediment texture (indicated either by textural logs and/or wireline characteristics). These also

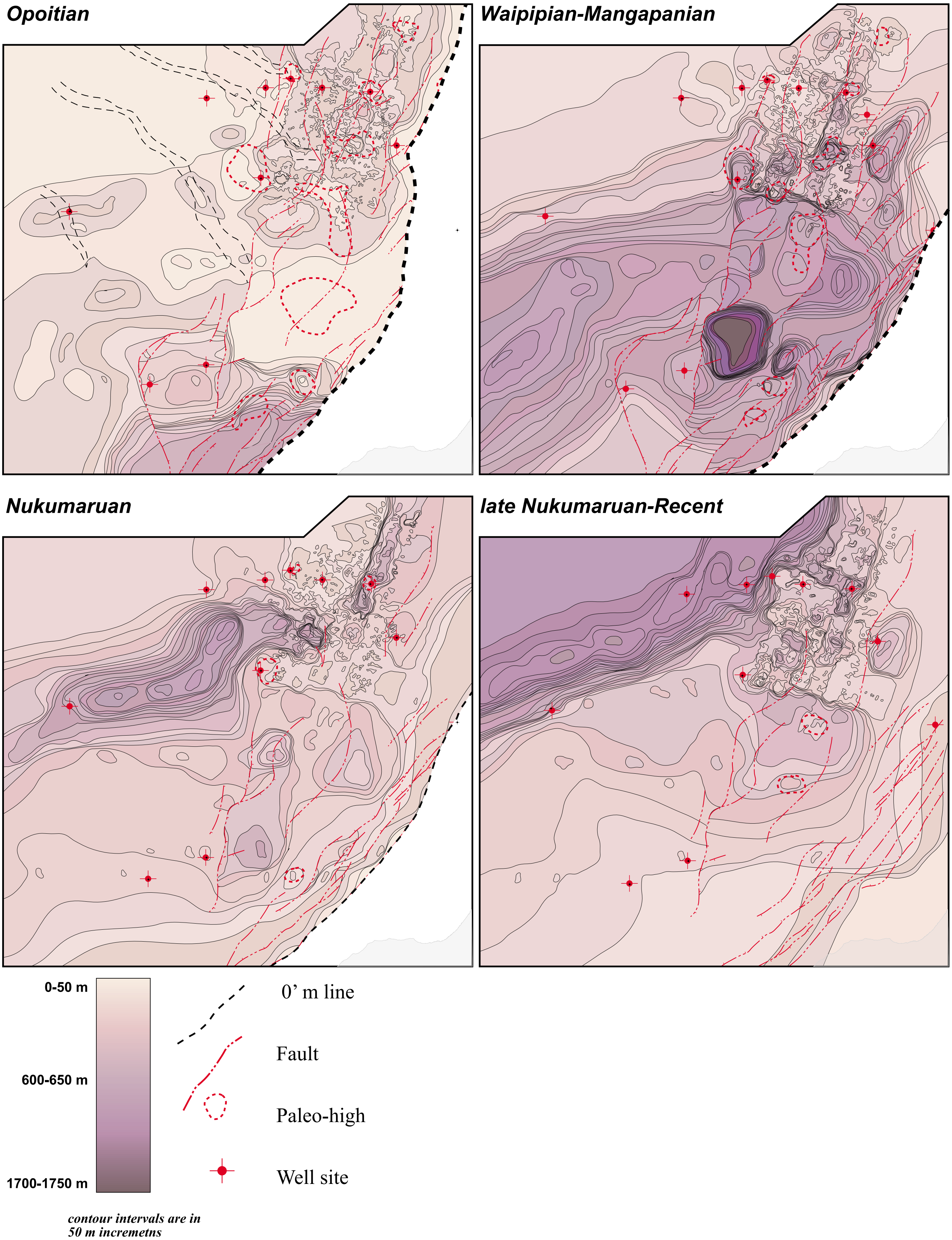


Fig.8: Isopachs showing depositional pattern for the Giant Foresets Formation through time. Thickness is in metres. '0' m line is point at which sediment is no longer represented as a result of erosion and/or non-deposition.

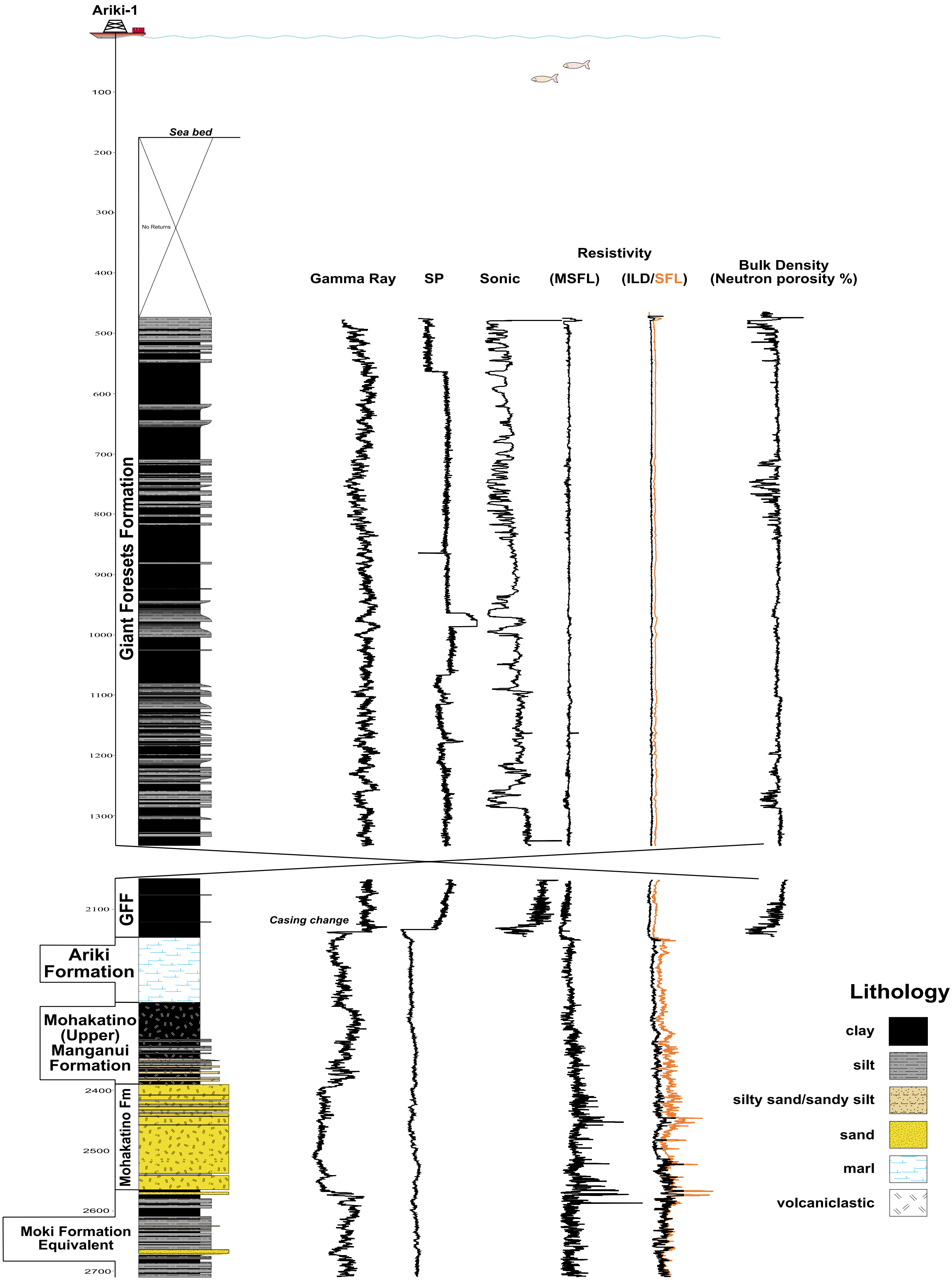


Fig.9: Wireline log signals for the Giant Foresets Formation. Note that all logs display a characteristically quieter signature than underlying formations. Base of the formation is often delineated by a kick to the left on GR and SP, and to the right on resistivity and bulk density.

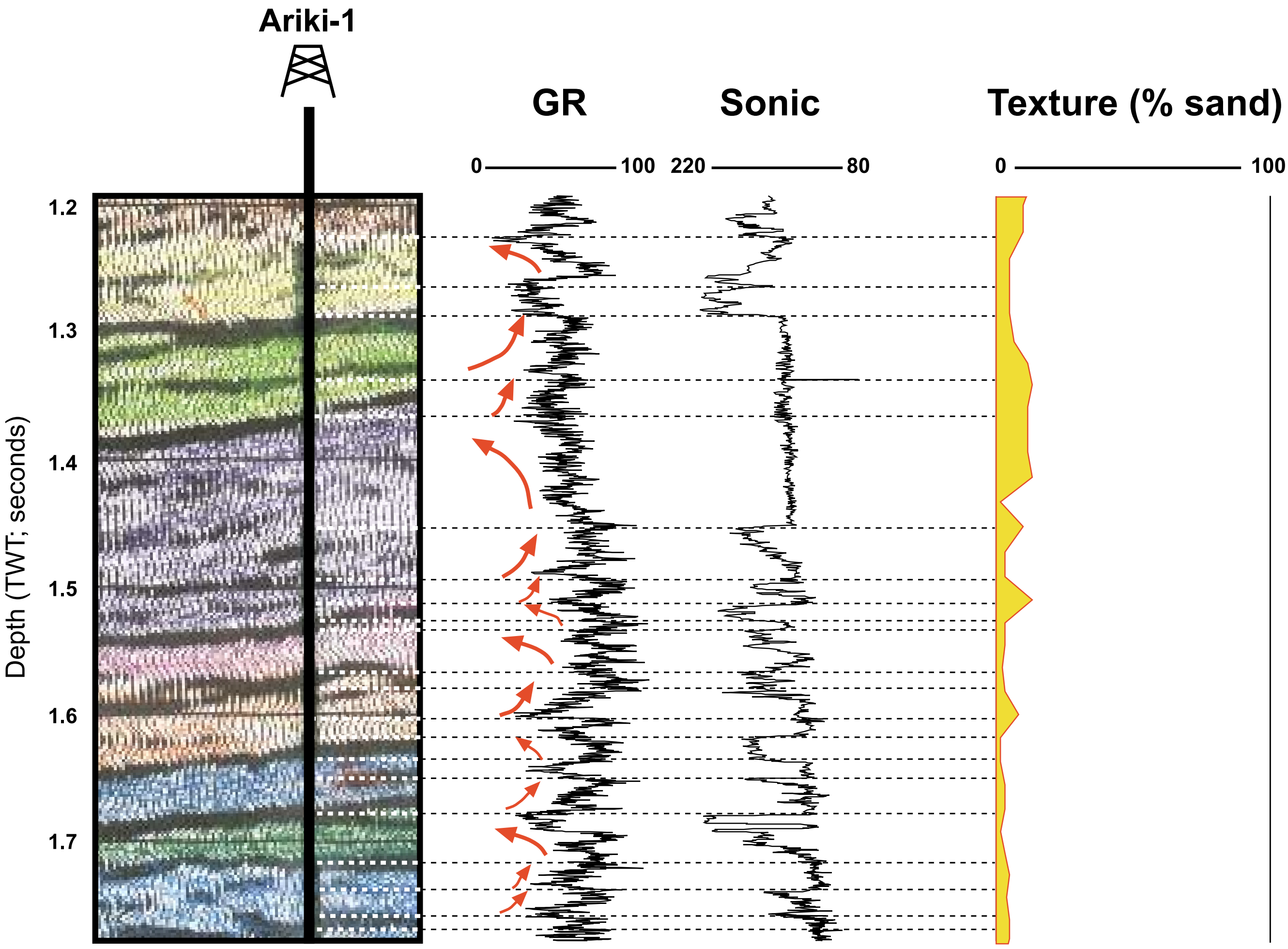


Fig.10: Correlation of wireline log and seismic reflection profile for Ariki-1. Bold reflector horizons correlate well with bases of upward-fining or upward-coarsening units, or packages of units. Textural trends have been added for comparison.

coincide with increases in the abundance of shallow water benthic faunas in deep water sediments. This may indicate the influx of shelf sediments to deeper water conditions possibly associated with periods of falling sea level (e.g. Pickering et al. 1989).

2. Opportunistic benthic species, such as Uvigerina perigrina, Bulimina marginata, f. aculeata, and Evolvocassidulina orientalis, are able to colonise and multiply rapidly in environments that are stressful to other species (e.g., an environment of high organic carbon influx (van der Zwann et al. 1999; sen Gupta and Machain-Castillo 1993)). High numbers of these species, coupled with low overall species diversity, suggests periods during which the sea floor environment has undergone a dramatic change, and has been subsequently re-colonised by species that are able to proliferate under the stressful conditions. Such a dramatic change may occur as a result of a catastrophic sedimentary event (e.g., debris flow, slump). Some of these events may be related to sea level changes.

3. There is a positive correlation between lower planktic foraminiferal abundance (indicating less oceanic conditions), and peaks in benthic abundance (Fig.13). In deeper water situations, eustatic sea level change is not of sufficient magnitude to change bathyal-restricted habitats, whereas on the shelf, a fall or rise in sea level of c.60-100 m will severely alter the dynamics of shallow water environments. However, lowering sea level may change surface water mass conditions, changing (decreasing) surface productivity, and theoretically resulting in fewer planktic faunas.

The integration of these various types of data are still in the early stages. We are attempting to test the hypothesis that mixed shallow and deep-water faunal assemblages, when correlated to peaks in the textural curve, and dips in planktic ratios, can be used as proxies for sea level change. As sea level lowers and shorelines move seaward, coarser-grained lithologies, sourced from more energetic shallower water environments, are more likely to be transported to deeper, less turbid environments. At such times, postmortem transportation of shallow water faunas escalates, and the associated influx of organic carbon allows the proliferation of opportunistic species. Falling sea level conditions may be indicated by the inclusion of shallow water taxa in deeper water faunas, and a corresponding decrease in planktic abundance. Sedimentation related to event deposition, on the other hand, may instead be registered by either an isolated textural peak, or a sudden increase in numbers of opportunistic species.

Bold reflectors on seismic reflection profiles, such as those that bound clinoform sets, are inferred to arise from partial lithification during sea level highstands (Beggs, 1990). By

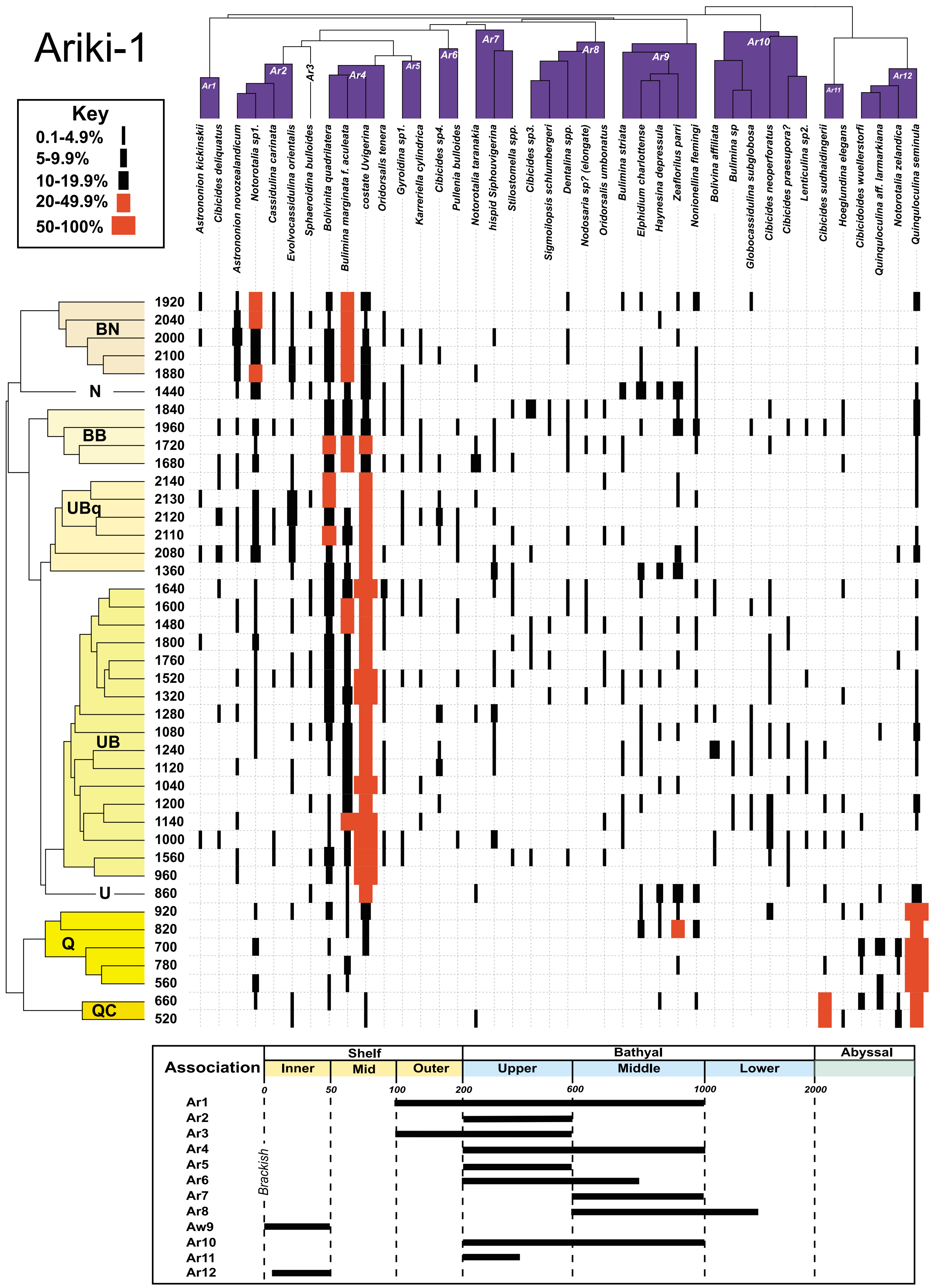


Fig.11: Example of cluster analysis undertaken for Ariki-1. Species associations (top) are clustered using modified Morista Similarity. Faunal sample associations (left) are clustered using Bray-Curtis Distance Matrix. Depth ranges of species associations are illustrated below cluster diagram.

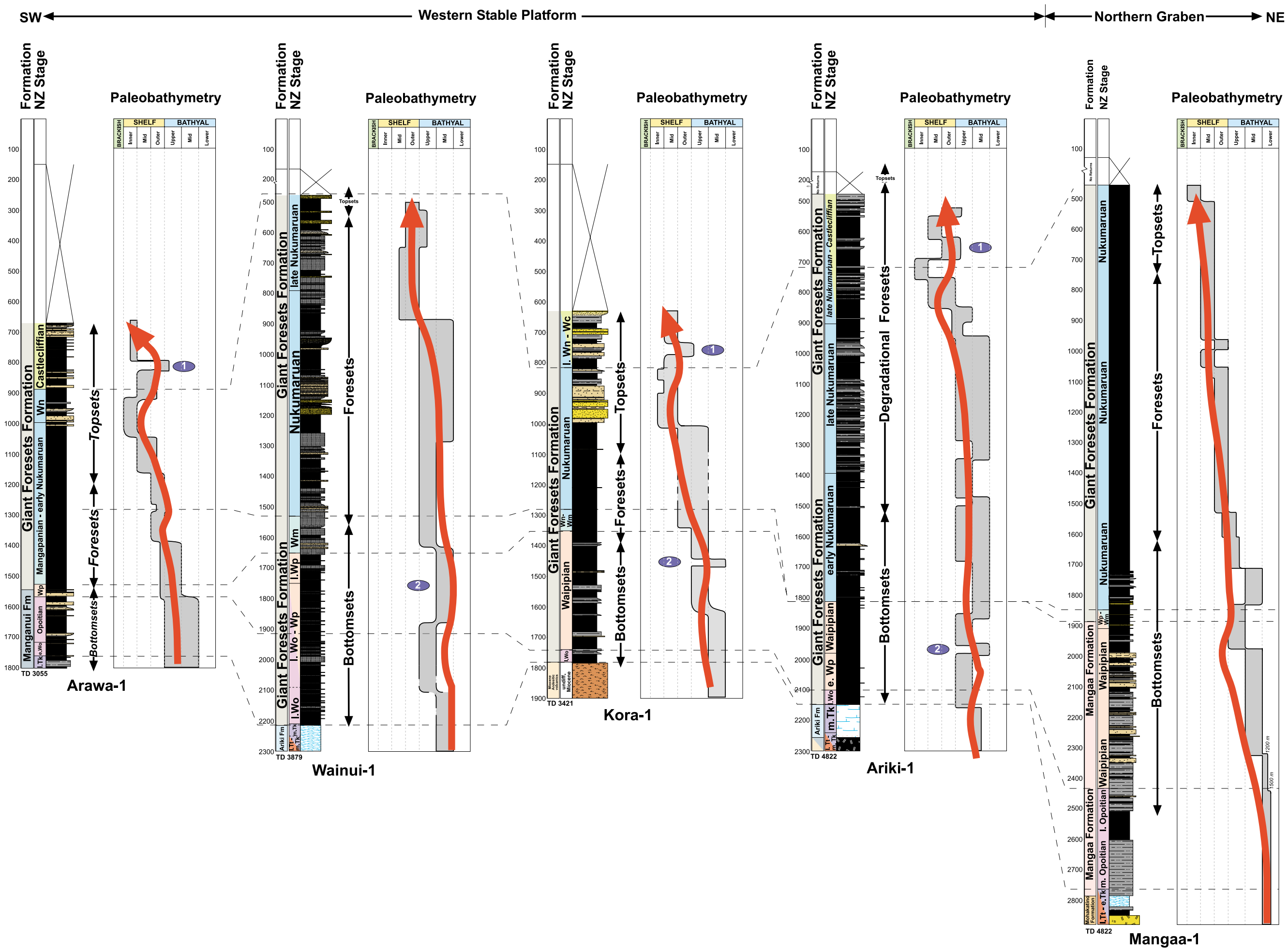


Fig.12: Paleobathymetric curves estimated for Arawa-1, Ariki-1, Kora-1, and Wainui-1. Mangaa-1 is also included as the biostratigraphy for this well has recently been re-evaluated. (Waghorn et al., 1996). Thick arrows highlight general bathymetry trends. Circled numbers indicate possible correlatable events. See Fig.9 for lithologic key.

integrating environmental and textural data with seismic reflection profiles, it is possible to identify an order of cyclicity previously not identified. For example, in Fig. 13 (Ariki-1), seven cycles with an approximate periodicity of 400 ka (fourth-order eustatic), have tentatively been identified. Each of these correlate to one or more discrete seismic packages.

Palinspastic reconstruction

Backstripping and decompaction of sedimentary units is an effective way of summarising the geological evolution and burial history of an exploration well or section. This is achieved by sequentially removing layers of sediment, thereby allowing underlying units to rebound back to their original surface position. Normally, this is performed on a single well or on a series of wells. For this study, a backstripping program written by K. Sircombe was run on a seismic reflection profile (line P95-158). All depths in TWT were converted to depths in metres using a binomial supplied by Geosphere Exploration Services Ltd. Porosity and paleobathymetry were established from wireline and lithological data and foraminiferal paleobathymetry. Compaction coefficients were determined by estimating the relative proportions of sand, silt, mud, and limestone/marl of each individual seismic unit through which a borehole was drilled. Using initial (surface) porosity values (after Funnell et al., 1998), porosity with depth was calculated using Equation 1.

porosity = po exp(-z/d) Equation 1

where po = initial porosity at the surface, z = depth, and d = compaction co-efficient

The values obtained for each seismic unit were then combined using a mixing law (Equation 2) to provide porosity variation with depth.

combined porosity (1/p) = summation (vi/pi) Equation 2

where p = porosity, vi = proportion of a particular lithology, and pi = porosity determined from Equation 1.

Similarly, decompaction co-efficients (after Funnell et al., 1998) were mixed according to the proportion of each lithology, to obtain a value representative of the mixed porosity.

Line P95-158 (Fig.14; refer also to Fig.6 for un-interpreted and interpreted line) was chosen for decompaction as it

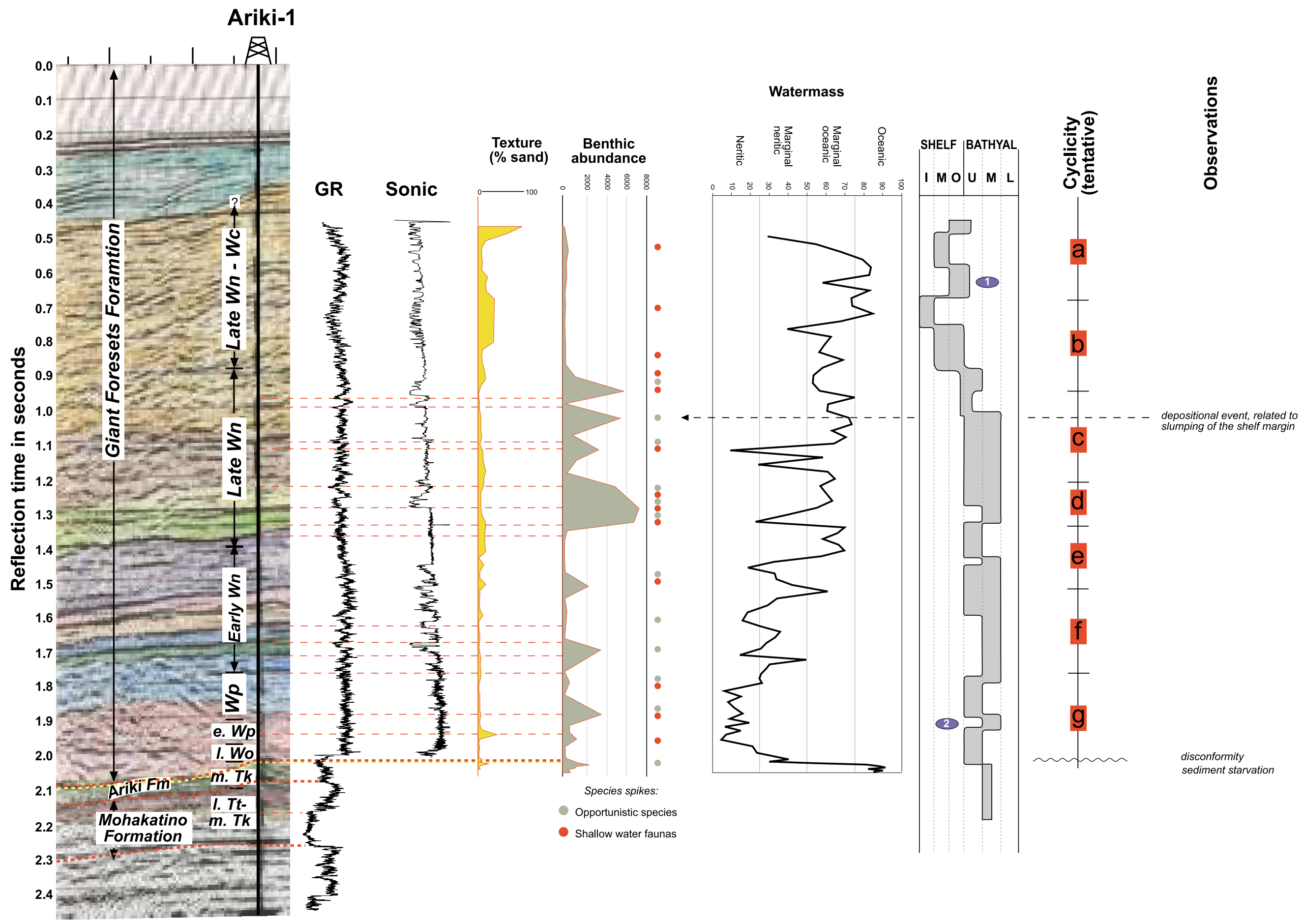


Fig.13: Integrated seismic reflection, wireline logs, textural, and foraminiferal data, to highlight cyclical trend in the Giant Foresets Formation. Fourth-order eustatic(400 ka) cycles are tentatively identified. Note the dramatic decrease in planktic percentage between the Ariki and Giant Foresets Formations.

intersects two wells (Tangaroa-1 and Kahawai-1), which could be used to obtain lithologic data. It also contains many of the seismic units mapped across the study area, and extends from the Turi Fault Zone in the east to the modern shelf margin and slope. Because of the large fault at the eastern end of the line, and the rapidly increasing water depth at the western end of the line, P95-158 was broken into 6 parts, depths to seismic units adjusted using relative shelf-slope-basin position as indicated on the reflection profile (where the shelf break is estimated to be ~250 m), and porosity and decompaction values extrapolated from the nearest well. Inherently, errors will arise due to changes in lithology along the length of the line that cannot be accounted for.

The resulting palinspastic reconstruction clearly illustrates the development of the asymmetrical Northern Graben. Initially, basin floor and basin floor fan sediments (variously sandy to muddy bottom-sets) began to infill a graben that had already begun developing by 4 Ma (Fig. 14d; Mangaa Formation). Bottom-sets sedimentation, followed by the appearance of foresets marking the progradation of the continental margin, continued to infill the graben concurrently with graben development, as illustrated by Figs. 14b and 14c. This series of figures also illustrates that the Western Stable Platform (west of Tangaroa-1) has, in sharp contrast, remained relatively quiescent during the Plio-Pleistocene. This has previously been described in King and Thrasher (1996). Major uplift on the large fault to the west of Kahawai-1 (part of the Turi Fault Zone) occurred during the Mangapanian-Waipipian Stages, with continual uplift noted through to the Nukumaruan (note tectonic curve). Conversely, the western margin of the graben was affected to a much lesser degree, as indicated by a much smoother profile to the tectonic curve.

Late Miocene to Late Pleistocene paleogeography

One of the main objectives of this study is to better constrain the paleogeographic development of the northern part of Taranaki Basin. This is being achieved by the integration of seismic reflection data (for geometry, sediment distribution, location of channels and other sediment pathways and barriers, and migration of the shelf-slope break), wireline log data (primarily for lithologic information), and foraminiferal paleoecologic data (paleobathymetry, influx of shallow water taxa). Figure 15 displays a series of paleogeographic maps that illustrate and document the evolutionary development of the Giant Foresets Formation within the northern part of Taranaki Basin.

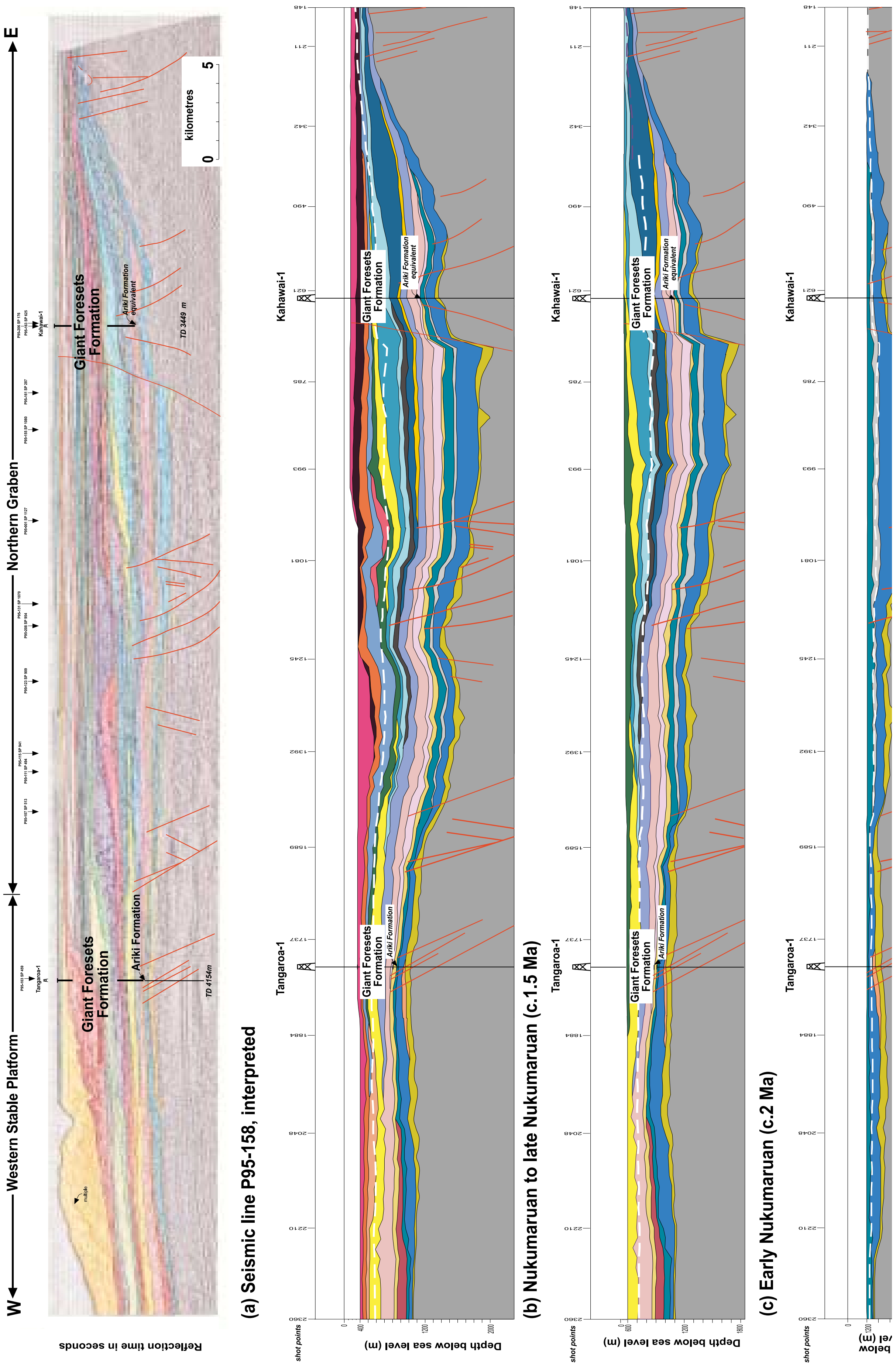
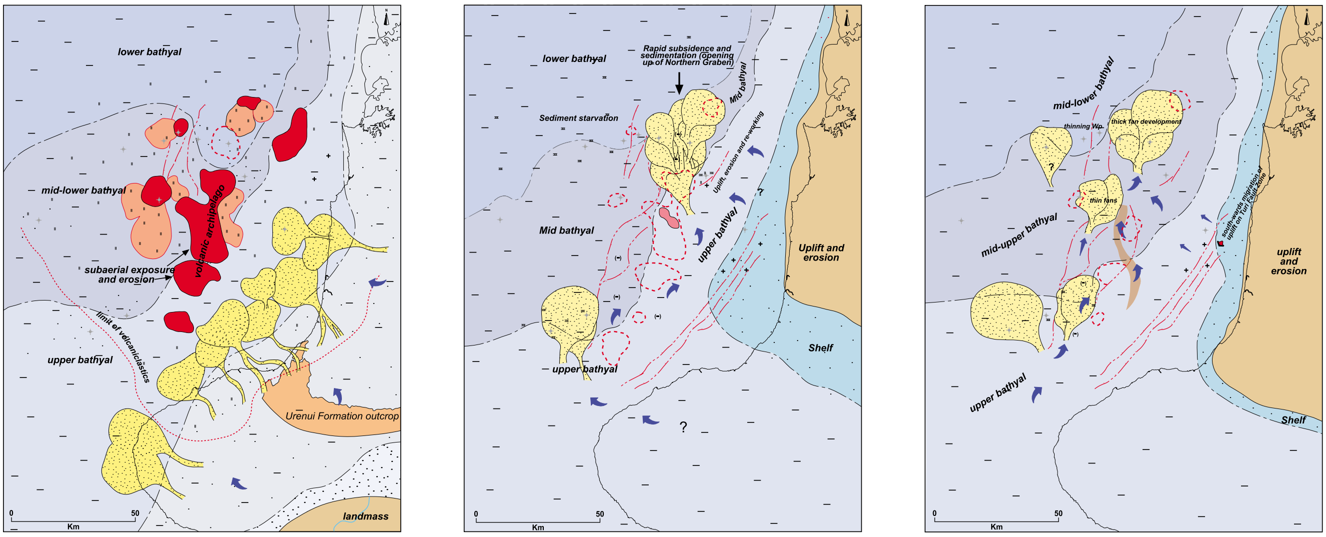


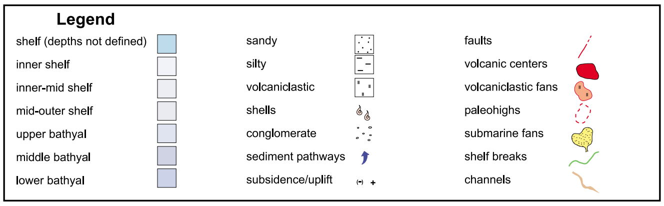
Fig.14: Palinspastic reconstruction of seismic reflection profile P95-158. Seismic units have been progressively decompacted and backstripped. Dashed line is tectonic curve. Late Opoitian (late-early Pliocene) marks the age at the base of the Giant Foresets Formation along this profile.



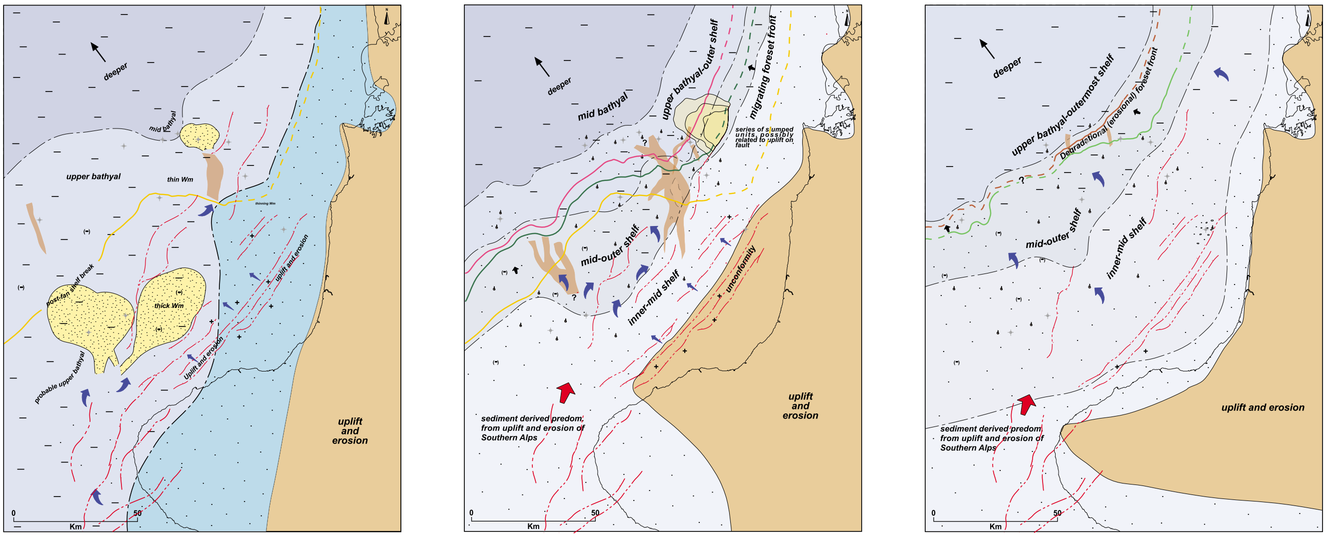
(a) Late Tongaporutuan to early Kapitean (c.8 Ma)

(b) Late Opoitian (c.4 Ma)

(c) Waipipian (c.3 Ma)



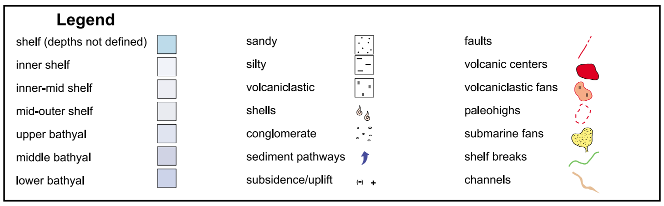
Hansen and Kamp, Fig.15



(d) Manganian (c.2.6 Ma)

(e) Early Nukumaruan (c.2 Ma)

(f) Late Nukumaruan to Castlecliffian (c.1 Ma)



Hansen and Kamp, Fig.15

Fig.15: Paleogeographic reconstructions. Maps compiled using data from Hansen (in prep.), Kamp et al., (in prep), Stagpoole (1997), and King and Thrasher (1996). Figures 15(d) to 15(f) continued over page.

During the late Tongaporutuan to early Kapitean (c.8 Ma; Fig.15a), before the shelf-slope break migrated northward from the southern part of the Taranaki Basin, the study area experienced under bathyal conditions. Volcanism, which had begun in the region at c.14 Ma, was beginning to wane, though surrounding sediments (Mohakatino and Manganui Formations) were still variously volcaniclastic as a result of sporadic eruptions and/or the emplacement of volcaniclastic turbidites. Large fans were forming to the south and east (Mount Messenger Formation). Initial opening of the Northern Graben in the latest Miocene is possibly indicated by slightly deeper water depths recorded at Awatea-1 and Mangaa-1.

Many wells centered on the Northern Graben record only a very thin Kapitean to Opoitian succession (Fig.15b). In more westerly located wells (Wainui-1, Ariki-1, Te Kumi-1, and Tangaroa-1), much of this missing time is represented by the Ariki Formation, a condensed marly unit. To the south, in the vicinity of Arawa-1 and Taimana-1, sediment was accumulating as a series of large lobate fans evident on seismic reflection profiles. These fans are interesting because, although analysis of benthic foraminifera suggests shallow-water (mid shelf) depths, their position on seismic reflection profiles indicate that deposition occurred seaward of the shelf-slope break. This suggests that an efficient mechanism was in place to transfer sediment containing high concentrations of shallow-water faunas from the shelf to slope. Indeed, a little further to the southeast, channelised conglomerates have been identified within the Kapitean stratigraphy of New Plymouth-2 (Shell BP Todd, 1965). Deeply incised channel complexes are also common in the Urenui Formation, a late Miocene succession that crops out in cliffs on the northern Taranaki coastline.

During the late Kapitean to Opoitian, sandy sediments were also being deposited in the Northern Graben. These sediments form the Mangaa Formation. The sediment was most likely sourced from uplift and erosion of the landmass to the east in the King Country. Sediments could not reach areas west of the graben because of the differential subsidence in the graben and because volcanic massifs, which were for the most part extinct, formed a series of paleohighs that directed sediments to the north.

Sedimentation during the Waipipian (c.3 Ma; Fig.15c) began to outpace accommodation created by the graben extension. The central part of the graben was still a focus of deposition, but by now thicker, silty and/or muddy sequences were being deposited over much of the Western Stable Platform, and particularly within a fault-bound depositional low to the east of Arawa-1. Water depths had begun to shallow during this period, although bathyal conditions persisted. Few distinct channels have been mapped, however, channelisation is indicated by the hummocky profiles of some horizons (along strike) on seismic reflection profiles. While volcanic massifs had been buried by accumulating sediment by the end of this period, they still formed positive relief on the sea floor, and probably influenced the direction of sediment flow. This pattern continued during the Mangapanian Stage (Fig.15d) with dominantly muddy sedimentation, and progressive shallowing. Mangapanian aged sediments appear to be thin, though this may be a manifestation of the difficulty of constraining this stage from microfaunal data. The Waipipian-Mangapanian isopach map (Fig.8) illustrates that by the end of the Mangapanian Stage, the prograding front of the Giant Foresets Formation was encroaching into the study area.

It was not until the Nukumaruan Stage that the foreset front began to rapidly advance across the study region. Figures 15e and 15f illustrate how progressive shelf margins, mapped from seismic reflection profiles migrate northwards and westwards. Sediment was now being dominantly sourced from the south, in part because uplift on the Turi Fault Zone provided a barrier for sediment from the east, but mainly because of substantial uplift and erosion of the Southern Alps. Throughout the Nukumaruan Stage the study region shallowed from bathyal depths (end of Mangapanian) to shelf depths, with marginal neritic watermass conditions prevailing. Much of the sediment represented by the Nukumaruan is variously sandy, silty, shelly, and occasionally pebbly, even at the deepest water sites, indicating a near-shore component. Several mapped channels and channel complexes are inferred to have been involved in the remobilisation and transport of this sediment to deeper water.

Isopachs maps of the Nukumaruan/late Nukumaruan to Castlecliffian starta (Fig.8) show migration of the foreset front. Foresets are particularly thick in the late Nukumaruan (to Recent), associated with the development of degradational foresets. These are inferred to have resulted from slumping of the continental margin during periods of low sea level (Beggs 1990), although the large thickness, and seismically distinct character of these upper units, suggests that there was a significant contribution from sediment sourced across the contemporary shelf.

Discussion

Interpretation of geophysical datasets, including seismic reflection profiles and wireline logs, integrated with foraminiferal paleoecology and palinspastic reconstruction, has enabled documentation of the Plio-Pleistocene evolution of the Giant Foresets Formation in the northern part of Taranaki Basin. While overall migration of the foreset front (continental margin) has progressed in an uncomplicated southeast to northwest direction, depositional patterns have been influenced by several factors. These include barriers such as topographic relief provided by extinct Miocene volcanoes, accommodation space provided by contemporaneous extension of the Northern Graben and other depositional sinks (e.g., the depression near Arawa-1), and interruptions to the supply of sediment flux as well as accelerations in this flux.

The Giant Foresets Formation is clearly cyclothemic in nature, and has long been recognised as representing a second-order tectonic cycle (King and Thrasher 1996). This study suggests that at least fourth order (400 ka) eustatic cycles can be identified in the formation through integration of geophysical and paleoenvironmental data. Deposition of the formation has also been influenced by accommodation space formed by contemporary extension of the Northern Graben. Progradation occurred in a southeast to northwest direction, but was initially directed into the depositional sink created by the Northern Graben, and then by the depositional low to the east of Arawa-1. Topographic relief provided by extinct Miocene volcanic massifs, and the asymmetrical development of the Northern Graben, provided barriers to effective sediment transport to western areas during the early to mid Pliocene. By the Waipipian to Mangapanian, these factors were no longer quite so influential, and sediment deposition across the study area was expressed as a migrating series of sedimentary (fan?) lobes. Compounded, these lobes are displayed as a linear body that illustrates the relative position of the prograding continental wedge through time.

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