Late Eocene – Early Miocene facies and stratigraphic development, Taranaki Basin, New Zealand: the transition to plate boundary tectonics during regional transgression

Author for correspondence:
Dominic P. Strogen,,
Email: d.strogen@gns.cri.nz

Dominic P. Strogen [ID], Karen E. Higgs, Angela G. Griffin and Hugh E. G. Morgans

GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand

Abstract

Eight latest Eocene to earliest Miocene stratigraphic surfaces have been identified in petroleum well data from the Taranaki Basin, New Zealand. These surfaces define seven regional sedimentary packages, of variable thickness and lithofacies, forming a mixed siliciclastic–carbonate system. The evolving tectonic setting, particularly the initial development of the Australian–Pacific convergent margin, controlled geographic, stratigraphic and facies variability. This tectonic signal overprinted a regional transgressive trend that culminated in latest Oligocene times. The earliest influence of active compressional tectonics is reflected in the preservation of latest Eocene – Early Oligocene deepwater sediments in the northern Taranaki Basin. Thickness patterns for all mid Oligocene units onwards show a shift in sedimentation to the eastern Taranaki Basin, controlled by reverse movement on the Taranaki Fault System. This resulted in the deposition of a thick sedimentary wedge, initially of coarse clastic sediments, later carbonate dominated, in the foredeep close to the fault. In contrast, Oligocene active normal faulting in a small sub-basin in the south may represent the most northerly evidence for rifting in southern Zealandia, related to Emerald Basin formation. The Early Miocene period saw a return to clastic-dominated deposition, the onset of regional regression and the southward propagation of compressional tectonics.

1. Introduction

The Oligocene of New Zealand broadly corresponds to an interval of slow regional subsidence and a period of maximum transgression of the Zealandia subcontinent. The deposits predominantly comprise variably calcareous siltstones and marls with locally thick development of limestones, and more rarely, sandstones. In the Taranaki Basin (Fig. 1) the deposits are highly condensed in the west, and thicken eastwards towards the contemporaneous landmass (Fig. 1; King & Thrasher, 1996; Hood *et al.* 2003*a*; Strogen *et al.* 2014).

The Late Eocene to Early Miocene interval is of interest for two reasons. Firstly, it marks the transition from transgressive to regressive sedimentation, as the basin morphed from a passive- to active-margin setting, associated with the inception of the Australian–Pacific convergent plate boundary along the eastern margin of Zealandia (Fig. 1; King *et al.* 1999; King, 2000). As such, understanding stratigraphic development during this interval can significantly advance our knowledge of the tectonic development of both the Taranaki Basin and wider Zealandia. Secondly, Oligocene strata form an important part of petroleum systems in the Taranaki Basin. Thickly developed fine-grained facies form regional top seals, while locally occurring limestones and sandstones form reservoirs in a number of commercial hydrocarbon discoveries.

Despite the economic and tectonic significance of Late Eocene – Early Miocene strata, and numerous well penetrations in the Taranaki Basin, this interval remains relatively poorly understood. Parts of the Oligocene succession have been the focus of previous studies (Hood *et al.* 2003*a*,*b*; B. Hopcroft, unpub. M.Sc. thesis, Univ. Waikato, 2009), and Strogen *et al.* (2014) presented a reappraisal of the regional Oligocene palaeogeographic evolution in the Taranaki Basin. However, these studies have been relatively broad in nature, and have not attempted to break the Oligocene succession down into stratigraphic sequences, correlated around the basin. Moreover, the majority of studies have focused on Oligocene units cropping out in adjacent areas, such as the Waikato–King Country Basin (Nelson, 1978; Tripathi & Kamp, 2008; Kamp *et al.* 2014) and the West Coast Basin (Riordan *et al.* 2014), often in isolation to facies development in the offshore portions of the basin.

In our study, we have attempted a regional correlation of Late Eocene – Early Miocene sediments in the Taranaki Basin using representative wells. This well data has been used to develop a better understanding of the distribution and development of facies through this interval, which will provide insights into both seal/reservoir potential and tectonic signals related to the development of the Australian–Pacific plate boundary zone.
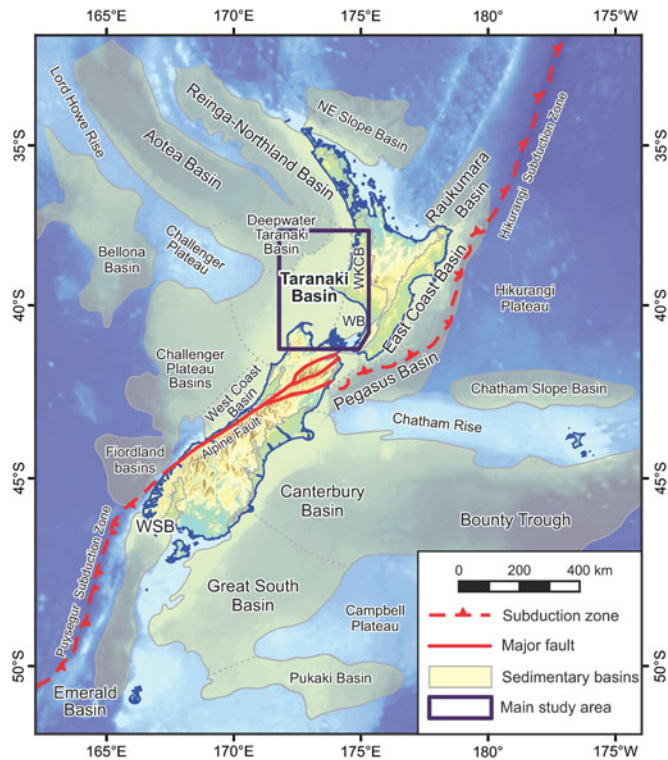
Fig. 1. (Colour online) Location map of the greater New Zealand region (Zealandia), showing bathymetry, distribution of major sedimentary basins and structural features, and localities named in the text. The main study area is indicated by the box. WB – Wanganui Basin; WKCB – Waikato–King Country Basin; WSB – Western Southland Basin.

2. Geological setting

The Taranaki Basin covers an area of *c.* 100,000 km², predominantly offshore beneath the present-day shelf, to the west of New Zealand's North Island (Figs 1, 2). It contains up to 11 km of mid-Cretaceous to Cenozoic strata, and is bounded along its eastern margin by the buried, >450 km long, crustal-scale Taranaki Fault System (TFS; King & Thrasher, 1996; Stagpoole & Nicol, 2008). It is one of a series of connected Cretaceous–Cenozoic basins that extend along the western margin of New Zealand (Fig. 1; King *et al.* 1999), including the Reinga-Northland and West Coast basins (Fig. 1). Immediately east of the TFS lie the Waikato–King Country and Wanganui basins, which typically contain thinner and younger infill than the Taranaki Basin.

The Taranaki Basin and wider Zealandia region have experienced a complex tectonic history. Long-lived Paleozoic and Mesozoic subduction, terrane accretion and magmatism was followed by separation from eastern Gondwana during Cretaceous rifting, and finally by tectonics associated with convergence across the Australian–Pacific plate boundary that now bisects New Zealand (e.g. Walcott, 1978; Kamp, 1986; Bradshaw, 1989; King & Thrasher, 1996; King, 2000; Wood & Stagpoole, 2007; Strogen *et al.* 2017). Across the study region, the pre-Neogene tectonic history has been variably overprinted by Australian–Pacific convergent plate boundary tectonics (King & Thrasher, 1996; King, 2000; Ghisetti & Sibson, 2006; Stagpoole & Nicol, 2008; Reilly *et al.* 2015). Eastern and southern parts of the Taranaki Basin are within the active plate boundary deformation zone, whereas western parts have remained relatively undeformed since latest Paleocene time.

2.a. Late Eocene – Early Miocene lithostratigraphy

The Late Eocene to Early Miocene stratigraphy of the Taranaki and surrounding basins is summarized in Figure 3. In the Taranaki Basin, the Late Eocene stratigraphy is well established, consisting of the proximal Kapuni Group (Mangahewa and McKee formations) and distal Moa Group (Turi and Tangaroa formations), and is not discussed further here (see King & Thrasher, 1996; Higgs *et al.* 2012a). Table 1 describes the Oligocene–Early Miocene Ngatoro Group, which is divided into the Otaraoa, Tikorangi and Taimana formations (King & Thrasher, 1996), as well as a number of informal units. Owing to lateral facies variations and changes in the use of terminology through time, the Oligocene lithostratigraphy in the Taranaki Basin is inconsistent and ambiguous. However, while we recognize that the lithostratigraphic scheme requires amendment, it is beyond the scope of the current paper to address this. We therefore primarily refer to biostratigraphically (Fig. 4) correlated units (U1–U6) through the remainder of this paper. The only outcrop exposures of Oligocene strata within the Taranaki Basin occur in NW Nelson (Figs 2, 5a, b). The range of petrographic facies encountered in Oligocene units is illustrated in Figures 5 and 6, showing the wide range of mixed siliciclastic–carbonate rocks present.

3. Data sources and methodology

This paper documents the geographic, stratigraphic and facies variability of Late Eocene to Early Miocene-aged strata in the Taranaki Basin. The work is based on borehole data, primarily from internal GNS Science studies (https://www.gns.cri.nz) and from data held by New Zealand Petroleum and Minerals (NZP&M; https://data.nzpam.govt.nz). A total of 44 petroleum wells (Fig. 2) with good-quality wireline log and biostratigraphic data have been used, demonstrating representative intervals from the latest Eocene (Runangan) to Early Miocene (Altonian). Data include stratal thickness, lithology, age and palaeobathymetry. See Table S1 in the online Supplementary Material for full well details. Much of the Oligocene section is either very thin (western areas) or heavily faulted (northeast), and so seismic data was not used as a primary input into this study. The entire Oligocene section (Fig. 7) is encompassed by only two regionally mapped seismic horizons (P50 and N05; Fig. 3), and so correlation of U1–U6 is below seismic resolution across much of the basin.

3.a. Biostratigraphy

In New Zealand, Paleogene stage boundaries are based primarily on the stratigraphic ranges of selected benthic and planktonic foraminifera (Hornibrook *et al.* 1989; Morgans *et al.* 2004) calibrated to the International Geologic Time Scale (Gradstein *et al.* 2012) following Raine *et al.* (2015a,b). Palynology is used as the primary dating tool for non- and marginal-marine strata (Raine, 1984; revised in Raine, 2004). Foraminifera have been the main dating tool used in this study, although palynology has been used in a few wells to date non-marine strata. Local New Zealand stages covering the Late Eocene – Early Miocene interval, the criteria for their recognition and a comparison with the international timescale, are provided in Figure 4. This summarizes results from Hornibrook *et al.* (1989), Berggren *et al.* (1995), Morgans *et al.* (1996, 2004), Cooper (2004) and Nelson *et al.* (2004).

Existing biostratigraphic data have been collated for all 44 study wells, and include quantitative and qualitative data,
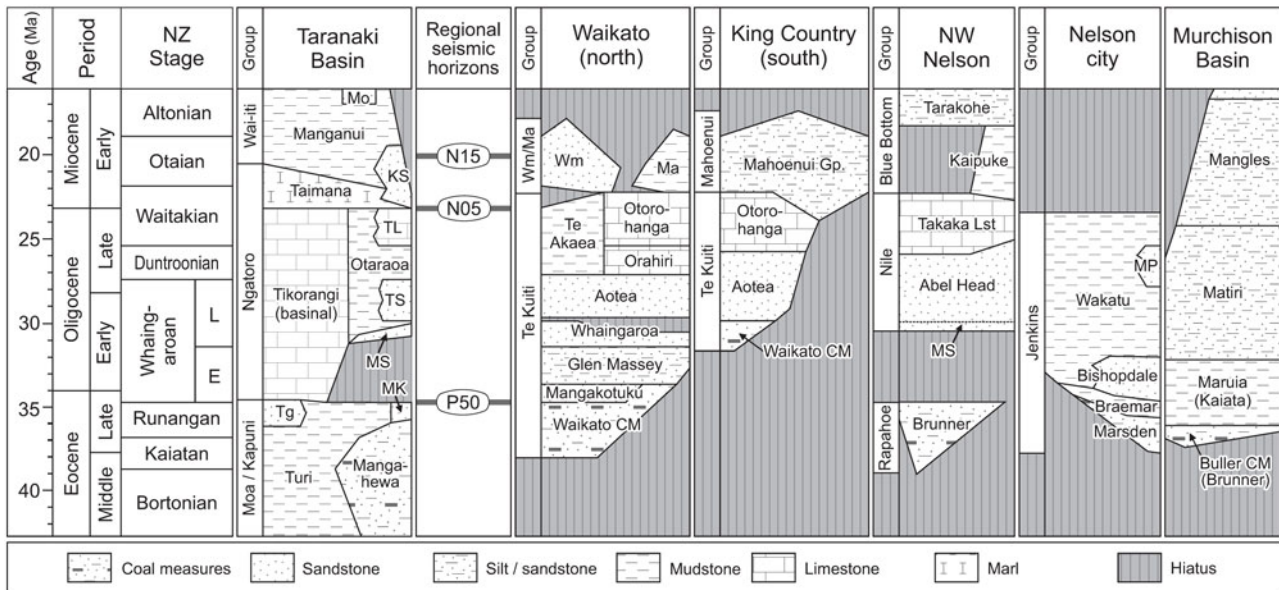
Fig. 2. (Colour online) Mid-Oligocene (latest Whaingaroan–Duntroonian) palaeogeography of the Taranaki Basin, after Strogen *et al.* (2014), showing location (highlighted by boxes) of the study wells used in transects (Figs 9–11) and other features/places named in the text.

primarily for foraminifera, that provide age control for correlating units, and palaeoenvironmental information (Table 2) to aid log facies interpretation. Re-examination of several samples helped better define the lower part of the Runangan to Early Whaingaroan interval; these new interpretations are provided on the full well correlation panels in the online Supplementary Material (Figs S1–S4).

3.b. Geophysical well logs, cores and facies analysis

Conventional wireline log data have been examined from all study wells, with raw data sourced from NZP&M (https://data.nzpam. govt.nz). Log suites include gamma ray (GR), calliper (cali), neutron-density (N-D), sonic (DT) and resistivity (R). Data quality is generally good, although there are some data gaps and log-offsets close to casing points, which are marked for reference on the log plots.

Fig. 3. Summarized Mid Eocene – Early Miocene stratigraphy for the Taranaki and surrounding basins, illustrating lithostratigraphic units (generally formations, groups on left), highly simplified lithology and regionally mapped seismic horizons. Taranaki Basin modified after King & Thrasher (1996) and New Zealand Petroleum & Minerals (2013). Waikato Basin modified after Kamp et al. (2014). All other basins modified after King et al. (1999). Seismic horizons after Strogen & King (2014) and Bull et al. (2016). CM – coal measures; KS – 'Kauri Sandstone'; Ma – Mahoenui Gp; MK – McKee Fm; Mo – Moki Fm; MP – Magazine Point Fm; MS – Matapo Sandstone Mbr; Tg – Tangaroa Fm; TL – Tikorangi Limestone; TS – Tariki Sandstone Mbr; Wm – Waitemata Gp.

Few conventional cores have been cut through Oligocene strata in the Taranaki Basin because of the dominant fine-grained lithologies. However, cores are available through the Matapo and Tariki Sandstone members, and through parts of the Tikorangi Formation (see Table S1 in the online Supplementary Material for details). Detailed work has previously been undertaken on numerous cores from the Tariki Sandstone Member (Higgs et al. 2001, 2004a) and the Tikorangi Formation (Hood et al. 2003a,b), and results from these studies are incorporated here. Although representing only a fraction of the total Oligocene succession in the Taranaki Basin, the cored intervals nevertheless provide detailed facies and petrographic insight to some significant parts of the stratigraphy.

Facies have been assigned to Late Eocene – Early Miocene strata in all study wells. Given the paucity of core, the scheme is highly simplified and based on lithology interpreted from wireline log motifs and cuttings descriptions, with palaeobathymetry data derived largely from foraminifera (Hayward, 1986). A general guide to the criteria used to assign log facies is presented in Table 2. These log facies are grouped into three main proximal to distal facies associations as follows: (1) shallow marine, (2) shelfal and (3) bathyal; and four main lithologies, (1) siltstone–mudstone, (2) marl or calcareous siltstone, (3) limestone and (4) sandstone.

3.c. Stratigraphic correlation and mapping

Regional-scale stratigraphic correlation between study wells was undertaken, with correlation datums guided by wireline log response/profiles tied to biostratigraphy. Only a few key surfaces (Figs 8–11) have been picked because of poor resolution of biostratigraphic dating through the studied interval. Owing to the thin nature of the Oligocene in distal areas and complex post-Oligocene faulting in some thicker proximal areas, seismic correlation was not useful for subdivision of the study interval.

Results from this study have been synthesized into a series of maps (Fig. 12) showing the thickness variations for each of the

units correlated across the Taranaki Basin. Present-day along-hole depths (AHBKB) are used and have not been corrected for well deviation, structural dip or compaction, as most wells are vertical or near-vertical. The thickness maps are contoured, based only on well data, constrained where possible by additional data from measured sections onshore, in the Waikato–King Country (Kamp et al. 2008) and Nelson (Nathan et al. 1986) regions. The TFS has been used as a gridding boundary.

4. Correlation of latest Eocene to earliest Miocene strata

Eight significant regional correlation surfaces (CS) have been picked, based on facies boundaries, across the Taranaki Basin (Fig. 8). They are shown on a series of well correlations, both parallel and perpendicular to the eastern basin margin, and are summarized into three N–S and two E–W cross-sections (Figs 9–11), with the full log suite and biostratigraphic data illustrated in the online Supplementary Material (Figs S1–S4). Five surfaces (CS2, 5–8) have log signatures characterized by an upward change to higher GR and wider N-D separation, and/or by GR spikes. In most cases this reflects a change from relatively carbonate-rich to more terrigenous sedimentation. Three surfaces (CS1, 3 and 4) are recognized on the basis of a sharp lithological change marked by a decrease in GR and a kick in the N-D log. In most cases this reflects a change to more carbonate-rich deposition. In many cases these correlated surfaces are close to stage boundaries, but owing to the poor biostratigraphic resolution, we have picked horizons as facies boundaries based on wireline log response. As such, correlation picks are likely to represent significant surfaces, and may represent transgressive surfaces, flooding surfaces and candidate sequence boundaries or their correlative conformities (Emery & Myers, 1996; Catuneanu, 2006). These regional correlation surfaces (Fig. 8) break the succession into six major packages (U1–U6). CS3 is used to subdivide U2 into U2a and U2b, although these sub-units are not distinguishable biostratigraphically.

A description of the main correlation surfaces (CS1–8) and the intervening sediment packages (U1–6) are presented below,

Table 1. Summary of the Oligocene–Early Miocene stratigraphy of the Taranaki Basin

Formation	Member or 'informal unit'	Age	Dominant lithology	Environment of deposition	Thickness	Comments	References	Figure
Otaraoa	undifferentiated	Lwh–eLw	Siltstone, variably calcareous. Sandy intervals, see sub-units below	Outer shelf to upper bathyal	<100–1200 m	Grades laterally into Tikorangi Fm. Thickens rapidly towards TFS. Several coarser grained sub-units	King & Thrasher (1996)	
	Matapo Sandstone	lLwh	Glauconitic sandstone	Shelfal, transgressive	8–50 m	Basal Otaraoa unit, often unconformable over older strata	Palmer (1985); King & Thrasher (1996)	5a–d
	'Rimu Limestone'	lLwh	Glauconitic skeletal grainstones to glauconitic sandstones	Shelfal, transgressive	<25 m	Calcareous equivalent of Matapo. No real distinction between two. Also erroneously used to refer to calcareous Tariki Sst Mbr	Harris et al. (1999); Core Lab (2003)	5e, f
	Tariki Sandstone	lLwh	Clean, fi–co sandstones, locally calcareous. Sandstone packages separated by mudstone units	Submarine fan, upper bathyal	≤300 m	Forms much of the lower Otaraoa Fm beneath the eastern Taranaki Peninsula. Deposited in a rapidly deepening foredeep	King & Thrasher (1996); Higgs et al. (2001, 2004a)	6c
	'Ld-sandstones'	Ld	Sandstone within Ld Otaraoa	Submarine fan, upper bathyal	<150 m	Informal name, applied to Ld-sands in Tuihu-1. See also Magazine Point Fm below	Higgs & Morgans (2001)	
	'Kauri Sandstone'	Ld–Pl	vf–fi sandstone. Rare conglomerate and mudstone	Shelfal to upper bathyal	450 m	Local to Rimu-Kauri to Kupe areas. Main development is in Po–Pl, but sandstones occur from Ld onwards	Higgs et al. (2004b)	6f
Abel Head	–	Lwh–Ld	Calcareous sandstones and siltstones	Shallow-marine shelfal	<50 m	Basal Oligocene unit, onshore NW Nelson. Grades gradually upwards into Takaka Lst. May contain glauconitic Matapo Sst equivalent at base	Bishop (1971); King & Thrasher (1996)	5a, b
Magazine Point	–	Ld	Calcareous sandstones and conglomerates	Submarine fan; upper bathyal	>140 m	Coarse submarine-fan unit, isolated outcrop at Nelson City	Johnston (1979); Higgs et al. (2004a)	
Tikorangi	undifferentiated	Lwh–eLw	Various calcareous facies	Outer shelf to lower bathyal	<200 m	See below	King & Thrasher (1996)	
	'basinal megafacies'	Lwh–eLw	Foraminiferal micritic limestones, marls, calcareous mudstones	Outer shelf to lower bathyal	<200 m	Lateral equivalent of both Otaraoa Fm and 'foredeep megafacies'. Distal ooze deposits	King & Thrasher (1996); OMV (2004)	6d
	'foredeep megafacies'	eLw	Bioclastic grainstone, packstone, wackestone, marl and calcareous sandstone	Outer shelf to upper bathyal	<200 m	Tikorangi Fm sensu Palmer (1985), Taranaki Peninsula. Older 'foredeep megafacies' may occur in north, equivalent to Tariki Sst Mbr. Shelfal carbonate facies redeposited	Palmer (1985); King & Thrasher (1996); Hood et al. (2003a,b)	6a, e
Takaka Limestone	–	Ld–eLw	Bioclastic grainstone	Shelfal	<50m	Equivalent to Tikorangi in NW Nelson, transition from underlying Abel Head Fm	King & Thrasher (1996)	5a
Taimana	undifferentiated	lLw–Po	Marl, calcareous mudstone	Bathyal	<250 m	Intermediate facies between Tikorangi and Manganui fms. Where Tikorangi absent, very similar to Otaraoa	King (1988a,b); King & Thrasher (1996)	

Fig. 4. Middle Eocene – Early Miocene timescale, showing comparison of international and New Zealand stages and substages, and criteria for their identification. After Morgans *et al.* (2004) and Raine *et al.* (2015*b*). HO – highest occurrence; LO – lowest occurrence.

including thickness and facies variations across the Taranaki Basin within each package. Whilst these correlated packages are generally likely to be time-equivalent, the development of a detailed sequence stratigraphic model is beyond the scope of the study, owing to the generally poor temporal resolution of the biostratigraphic data. The thickness of the Oligocene section from regional seismic mapping in the southern Taranaki Basin (Fig. 7; Bull *et al.* 2016) compares well in general with the total thickness from well data (Fig. 12f) and mirrors the trends seen within individual units.

4.a. U1: latest Eocene (Ar)

Most deposits of latest Eocene (Runangan) age comprise terrigenous shelfal to bathyal siltstones and mudstones (Turi Formation; Fig. 3) with localized development of submarine-fan sandstones in the northern part of the basin (Tangaroa Formation; Gresko *et al.* 1992). Runangan-aged strata have been identified in most study wells, with notable exceptions being many southern wells where local uplift, tilting and erosion of Eocene deposits has occurred (Bierbrauer, 2010; Strogen *et al.* 2014). No thickness map has been produced for U1, as its base has not been mapped.

In the north, an intra-Runangan (CS1) surface is taken at the base of a low GR and high N-D response that represents a transient, highly calcareous interval within the latest Eocene submarine-fan facies. This 'Tangaroa Limestone' (OMV, 2004, 2007; Strong, 2008) is composed of hemipelagic marlstones that separate younger Tangaroa fan lobe deposits in the cored interval

at Kora-4 (Jordan, 1989) and in Moana-1 (OMV, 2007). CS2 (top-Runangan) is characterized by a GR spike and a positive N-D inflection, well defined in northern parts of the basin, and also fairly well constrained by foraminiferal dating (e.g. Moana-1; Fig. 9a). Given the dominantly clastic marine depositional setting at this time, we interpret CS2 as a flooding surface (FS).

4.b. U2: Early Oligocene (eLwh)

Early Whaingaroan (U2) strata are best preserved in the north (<90 m; Fig. 9a), where bathyal palaeoenvironments dominate, with significant thicknesses recorded as far south as Witiora-1. Revised biostratigraphy suggests that the Tangaroa Formation extends into the Early Whaingaroan, at least locally (Kora-1, -4, this study; Moana-1, Strong, 2008). Away from the main Tangaroa Formation depocentre, U2a comprises highly condensed bathyal mudstones, with bathyal carbonates (U2b) deposited above CS3.

U2 has not been identified in most wells south of Takapou-1 (Fig. 9a), or in any wells on the Taranaki Peninsula (Fig. 11). However, thin U2 (<20 m) does occur in Cook-1 (Fig. 10b) and a few other offshore southern wells. Facies are very different to the north, with shallow-marine (Abel Head Formation, Tasman-1) to coastal-plain facies (Surville-1). U2 is unusually thick at Surville-1 (>100 m; Figs 10a, 12a). Although there is some uncertainty with dating, the entire Oligocene interval is very thick at Surville-1, and all correlated units are interpreted to increase in thickness relative to other southern wells (Fig. 12b–d). Seismic data suggest that the Surville Fault, currently a major reverse fault, was acting in a

Table 2. Facies criteria used for latest Eocene to earliest Miocene strata

Facies	Lithology	Palaeo-water from forams	Additional comment
Coastal plain to marginal marine	Interbedded sand, silt, mud and coal	Non-marine	Coal signature on logs
Shoreface to shallow marine	Sandstone	Non-marine to inner shelf	Blocky to locally upward-cleaning log profile
Shelfal muds	Mudstone/siltstone	Inner to outer shelf	
Slope muds	Mudstone/siltstone	Uppermost to mid-bathyal	
Basinal muds	Mudstone/siltstone	Mid- to lower bathyal	
Shelfal sands	Variably argillaceous sandstone	Inner to outer shelf	Locally glauconitic (GR spike)
Sandy slope	Argillaceous sandstone/siltstone	Uppermost to mid-bathyal	May include some distal submarine-fan facies
Proximal submarine fan and channel	Sandstone with minor interbedded siltstone/ mudstone	Uppermost to lower bathyal	High net: gross
Distal submarine fan or interlobe	Interbedded sand, silt, mud	Upper to lower bathyal	Low net: gross
Shelfal limestone	Limestone	Inner to outer shelf	Shallow shelf and redeposited limestone
Slope-basinal limestone	Variably argillaceous limestone	Uppermost to mid-bathyal	Redeposited limestone
Slope-basinal marls	Marls and calcareous mudstone	Upper to mid-bathyal	Variably calcareous; gradational to slope-basinal limestones and slope/ basinal muds

Facies are displayed adjacent to logs and biostratigraphy data in the online Supplementary Material (Figs S1–S4)

Palaeo-water zone	Water depth	Planktonics
Inner shelf	0–50 m	0–30 %
Mid-shelf	50–100 m	0–30 %
Outer shelf	100–200 m	30–90 %
Upper bathyal	200–600 m	>90 %
Mid-bathyal	600–1000 m	>90 %
Lower bathyal	1000–2000 m	>90 %

normal sense through Oligocene time, controlling a local depocentre (Fig. 14). This depocentre is also clearly picked out on regional seismic mapping (Fig. 7).

In the northern Taranaki Basin, an intra-Early Whaingaroan surface (CS3) is recognized at a facies dislocation, well defined on logs (e.g. Moana-1, Ariki-1; Fig. 9a), between terrigenous mudstone/ siltstone and overlying calcareous deposits. The upper part of U2 (U2b) is markedly more calcareous, and is characterized by bathyal marl and limestone. However, there is no clear difference in palaeobathymetry above and below CS3, with deposits above and below recording middle to lower bathyal palaeo-water depths, although these depth divisions are very broad (Table 2).

4.c. U3: mid-Oligocene (lLwh)

Most Whaingaroan-aged strata in the Taranaki Basin belong to U3 and show great variability in both thickness (Fig. 12) and lithology across the basin (Fig. 5). CS4 (base-Late Whaingaroan) is considered a particularly significant surface in that it locally represents a large time gap, whereby mid-Oligocene strata overlie rocks of Paleocene to Late Eocene age. This surface is the Oligocene unconformity described by King & Thrasher (1996), Leask (1993) and Strogen *et al.* (2014).

The unconformity passes into a correlative conformity in the northwestern part of the Taranaki Basin, where bathyal limestones accumulated throughout U2b and U3 (Fig. 8). In this region, Whaingaroan strata display a characteristic curving log profile that cleans upwards to CS4 (e.g. Te Kumi-1; Fig. 9). CS4 is taken near the curve inflection, with deposition above this surface representing predominantly calcareous deposition. In the west, U3 is interpreted as bathyal limestone deposits (Fig. 6d) belonging to the 'basinal megafacies' of Hood *et al.* (2003a,b) or the 'Lower Tikorangi Member' of OMV (2004). They thicken eastwards (Figs 7a, 12b) towards the TFS, where 'foredeep megafacies' dominate (Fig. 6a, b). These strata locally contain a high clastic component (Fig. 6a) and may be considered a calcareous Tariki Sandstone Member equivalent. CS5 in this northern region is marked by a clear increase in GR and N-D separation, indicative of the re-introduction of argillaceous clastic material in the Duntroonian times (Fig. 9a). Thickening of U3 in the northern basin (from 20 to 90 m) is not as dramatic as that seen further south.
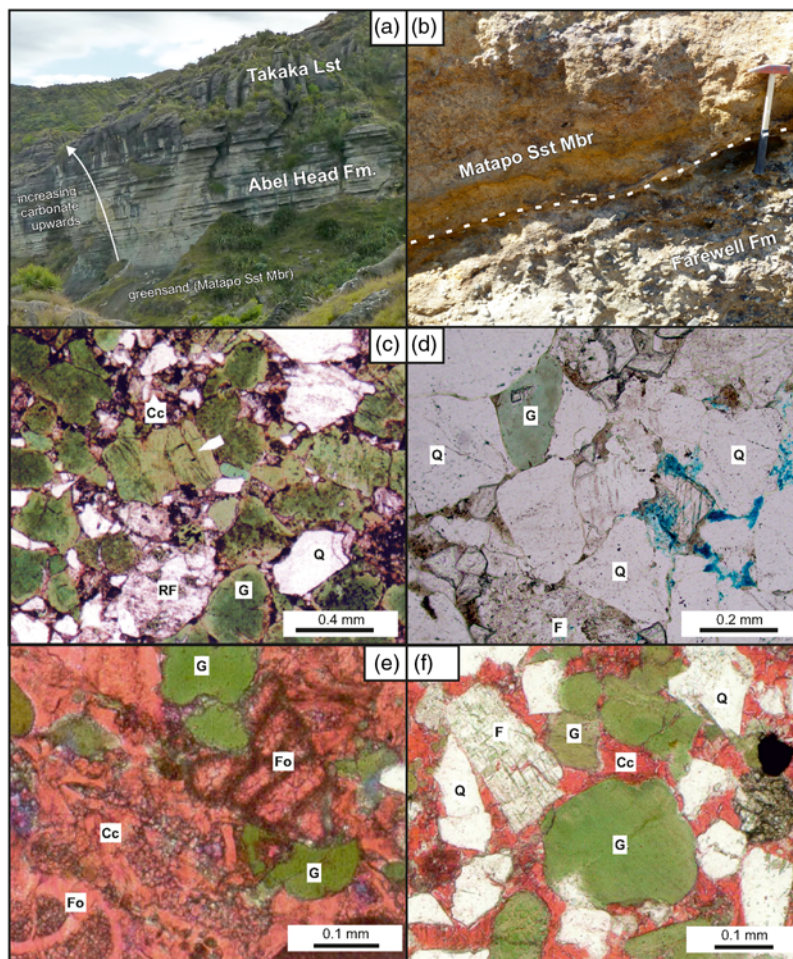
Fig. 5. (Colour online) Plates illustrating the basal Oligocene unconformity (CS4) and glauconitic beds. (a) Oligocene outcrop from NW Nelson, between South Head and Sharks Head. Thick basal greensand unit; its unconformable contact with the underlying Paleocene is obscured by vegetation. Above is a gradual transition from the sandstone-dominated Abel Head Formation to the carbonates of the Takaka Limestone, with calcareous beds becoming more common and thicker upwards. Total outcrop thickness ~100 m. (b) Unconformity between the Paleocene Farewell Formation and the weathered glauconitic Oligocene Matapo Sandstone Member, Pillar Point, NW Nelson. Hammer for scale is 40 cm long. (c) Toru-1, 3765.4 m, Matapo Sandstone Member: thin-section view of a highly glauconitic sandstone with subordinate quartz, feldspar and lithic fragments. (d) Onaero-1, 3478 m, Matapo Sandstone Member: thin-section showing minor glauconite within a quartzo-feldspathic sandstone. (e) Kauri-A1, 3443 m, 'Rimu Limestone': thin-section showing glauconitic limestone with common skeletal grains. (f) Kauri-A1, 3442 m, 'Rimu Limestone': thin-section of a highly glauconitic sandstone with other grains including common quartz and feldspar. Q – quartz; RF – rock fragment; G – glauconite; Cc – calcite; Fo – foraminifera. Sources: (c) Martin & Baker (1991); (d) Higgs *et al.* (2012*b*); (e, f) Core Lab (2003).

U3 is thickest in the eastern parts of the basin, beneath the Taranaki Peninsula (Fig. 11), where strata of the mostly terrigenous Otaraoa Formation thicken to ~400 m towards the Taranaki Fault (Fig. 12b). U3 commonly overlies Eocene (U1) deposits, suggesting that U2 is highly condensed, was eroded at the CS4 unconformity or was never deposited. This thickening can be seen on seismic in the southern Kupe area, where the P50–N05 interval, representing the whole Oligocene section, thickens towards both the Manaia and Taranaki faults (Fig. 13).

The Matapo Sandstone Member (Fig. 5a–d) is a highly glauconitic unit that occurs at or near the base of U3 in this area. It thins rapidly, to be replaced in the southern Taranaki Peninsula by the highly calcareous 'Rimu Limestone' (Fig. 11). Given the lithological similarities between these units (Fig. 5c–f), and the variation within them, this distinction seems somewhat arbitrary. Although the age of these units is poorly constrained, their deposition appears to be restricted to the Late Whaingaroan times. The Matapo Sandstone Member is associated with a sharp glauconite-related GR spike. Similar glauconitic units occur at several levels within the Abel Head Formation (Bishop, 1971)

that crops out onshore NW Nelson (Fig. 5a, b; King & Thrasher, 1996, their fig. 4.5), where stacked transgressive surfaces developed locally.

Identification of CS4 in the eastern Taranaki Basin is heavily reliant on biostratigraphic data, given the significant variations in lithology and log response. In Wharehuia-1, a conventional core of Late Whaingaroan age underlies the characteristic 'Matapo' GR spike, and CS4 is taken at the clear facies dislocation between strata likely belonging to U1 and U3 (Fig. 11). The cored section comprises a range of clean to slightly argillaceous bioturbated, glauconitic sandstones, indicative of the *Skolithos* and locally *Cruziana* ichnofacies (Higgs *et al.* 2001), and are interpreted to represent transgressive lower-shoreface to shelfal sandstones. A similar, though undated, sandstone interval is observed below the characteristic 'Matapo' GR spike at Waihapa-1 (Fig. 11).

The majority of U3 beneath the Taranaki Peninsula is composed of bathyal siltstone/mudstone (Otaraoa Formation) and/or sandstone (Tariki Sandstone Member). The main depocentre was adjacent to the Taranaki Fault, in the central eastern peninsula (Fig. 12b), where interbedded sandstone and mudstone turbidites
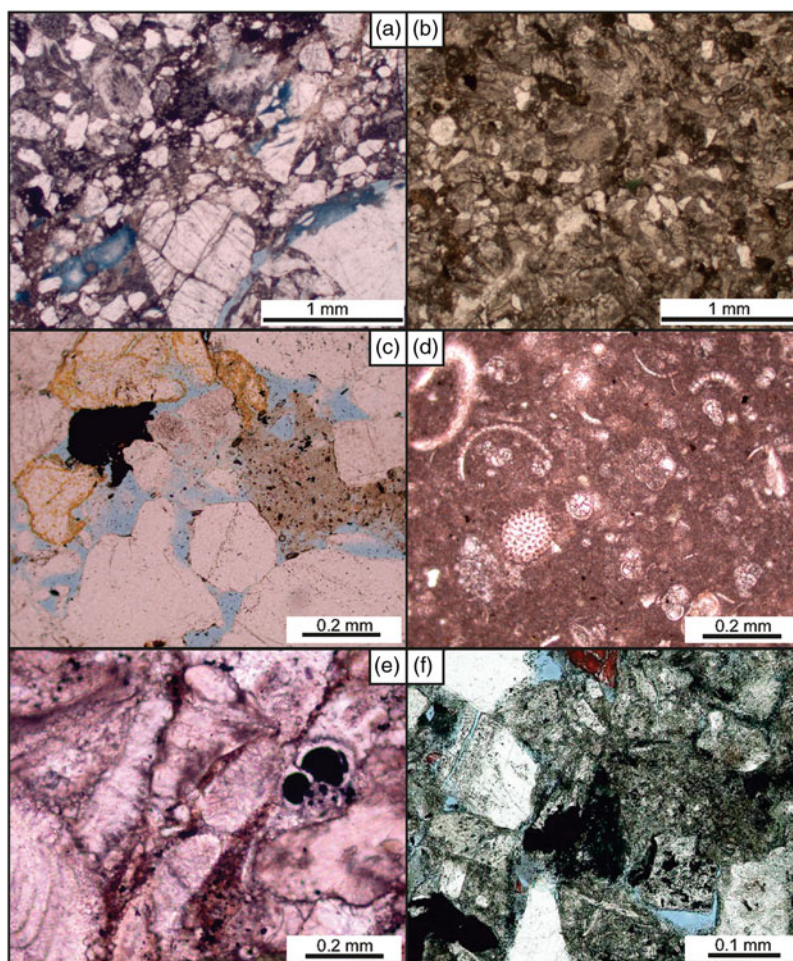
Fig. 6. (Colour online) Thin-section microphotographs illustrating the Oligocene mixed siliciclastic–carbonate system. (a, b) Awakino-1, 2169.5 and 2181.5 m, 'Tikorangi Limestone' (lLwh) showing variably sandy nature of foredeep megafacies; time-equivalent to the Tariki Sandstone Member. (c) Tariki-4A, 2717 m, Tariki Sandstone Member (lLwh) showing the quartzo-feldspathic and locally carbonate-poor composition of these submarine-fan facies. (d) Witiora-1, 3050 m, 'Tikorangi Limestone' (?Lwh) showing the micrite-dominated, condensed nature of these basinal megafacies with common foraminifera and echinoid spines. (e) Hu Road-1A, 3040 m, Tikorangi Limestone (Lw) illustrating common bryozoan, foraminifera and larger bioclasts within this shallow-marine grainstone. (f) Kauri-E4, 2565.85 m, 'Kauri Sandstone' showing a highly lithic composition compared with the older Tariki Sandstone Member (c). Sources: (a, b) GNS Science data; (c, d) Higgs *et al.* (2012*b*); (e, f) Harris & Frankiewicz (2004).

were deposited as submarine fans (de Bock *et al.* 1990; Higgs *et al.* 2001). Several cycles of submarine-fan development are interpreted, each capped by a clay-dominated unit (Fig. 11; Higgs *et al.* 2001, 2004*a*). Although clastic sedimentation dominated U3 in this part of the basin (e.g. Fig. 5c), sandstones are locally calcareous, with strata equivalent to the Tariki Member assigned to the 'Rimu Limestone' in Tawa-B1 (Fig. 11; Swift Energy New Zealand Ltd, 2005).

In some wells on the Taranaki Peninsula, CS5 is biostratigraphically well constrained, and generally corresponds to an increase in argillaceous content marked by higher GR and wider N-D separations (e.g. Totara-1, Wharehuia-1; Fig. 11). It likely represents a flooding surface, although no clear and consistent increase has been recorded in the palaeo-water depth of overlying strata. However, CS5 is difficult to pick in wells without good age constraint away from the main area of Tariki Sandstone deposition, where it occurs within a thick interval of bathyal Otaraoa Formation siltstones.

In southwestern parts of the basin, U3 is very thin and represents a highly condensed, variably calcareous unit (Figs 9b, 10). In some cases, CS4 is picked at the same depth as CS3, but we suggest this is due to non-deposition rather than erosion of U3. CS5 in

this part of the basin is marked by a GR peak and an increase in N-D separation that is locally well constrained by foraminifera (e.g. Maui-4; Fig. 10a). This again is suggestive of a return to more argillaceous clastic sedimentation above CS5.

4.d. U4: early Late Oligocene (Ld)

Duntroonian (Ld) deposits are bracketed by CS5 and CS6. Age dating is not precise enough to confidently identify the top Duntroonian, and U4 likely consists of only early–mid Duntroonian strata (Fig. 8). Overall, U4 is relatively argillaceous, compared to the more calcareous or arenaceous U3, in northwestern and eastern areas, respectively. This is the 'Middle Tikorangi Member' of OMV (2004). CS6 is picked on a GR spike associated with an increase in the N-D separation. In some wells (e.g. Okoki-1, Tirua-1, Witiora-1, Taranga-1), palaeoenvironmental data also suggest an increase in palaeo-water depth above CS6, which we suggest forms a regional flooding surface.

U4 shows a similar thickness distribution to U3 (Fig. 12c), highly condensed in southwestern parts of the basin and thickening eastwards towards the TFS, to ~300 m onshore Taranaki Peninsula
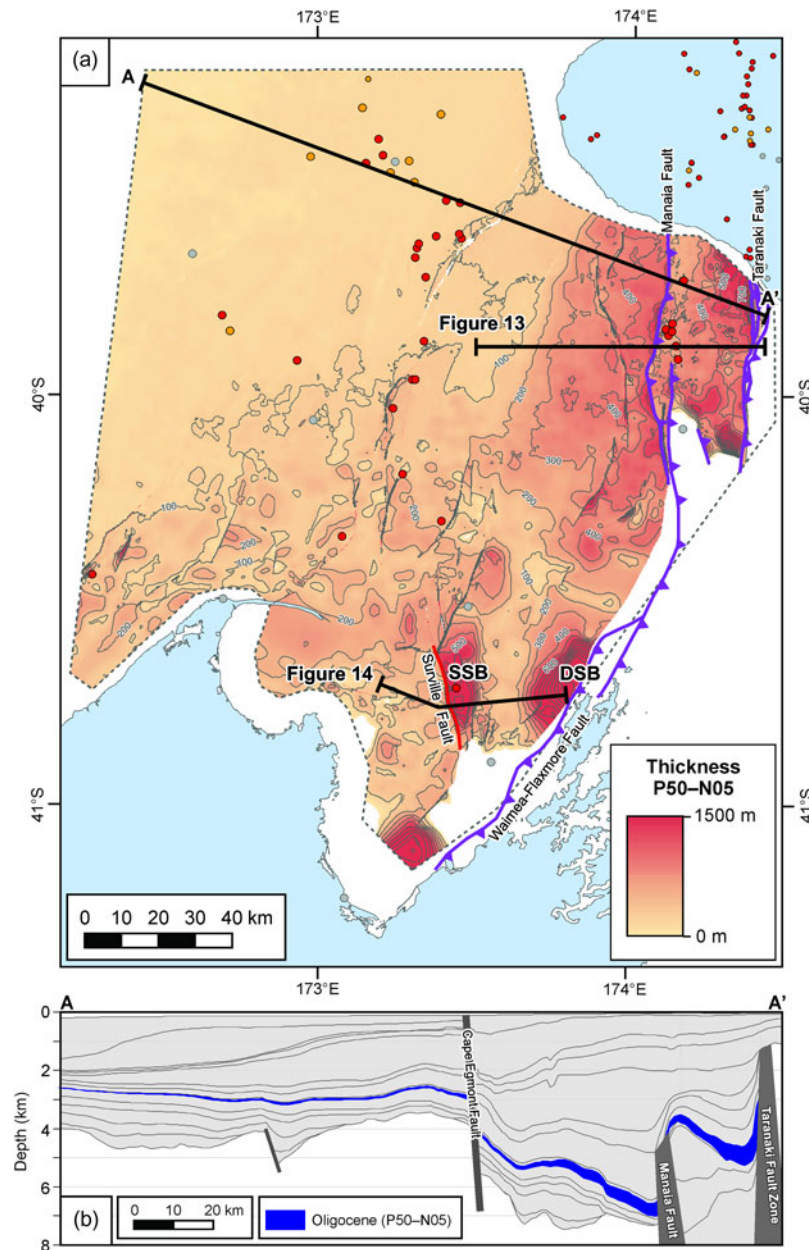
Fig. 7. (Colour online) (a) Thickness of the Oligocene, encompassed by regional horizons P50 and N05, from regional seismic mapping (after Bull *et al.* 2016). Major faults active during the study interval also shown; southern Manaia and Waimea–Flaxmore faults after King & Thrasher (1996). The location of the seismic sections shown in Figures 13 and 14 are also indicated. Well and fault symbology as in Figure 2. DSB – D'Urville Sub-basin; SSB – Surville Sub-basin. (b) Cross-section through the depth model of Bull *et al.* (2016), drawn along line A–A', with the Oligocene interval highlighted.

(Fig. 11) and ~130 m thick in northern areas (Fig. 9). Localised Duntroonian-aged sandstones occur, with ~150 m thick sandstones penetrated in Tuihu-1 ('Ld-sandstones' of Higgs & Morgans, 2001), and cropping out as the Magazine Point Formation at Nelson city (Fig. 2; Higgs *et al.* 2004a). These were deposited from a range of gravity-driven mass-flows, in outermost shelf to upper bathyal (Tuihu-1) or deeper, mid-bathyal palaeo-water depths (Nelson city). Overall, submarine-fan development in U4 appears to have been even more areally restricted, more carbonate-rich and possibly deposited in deeper water than in U3.

Most of U4 is composed of monotonous, bathyal siltstone–mudstone. However, small-scale cyclicity is locally observed in the northern part of the Taranaki Basin, demonstrated by cyclical wire-line log profiles, some of which show distinctive upward-cleaning packages (e.g. Tirua-1; Fig. 9a). A shelfal palaeo-water depth and overall upwards increase in resistivity logs at Tirua-1 may represent local carbonate bank or shoal development, with a cyclical upwards shallowing, or simply a reduction in terrigenous sediment input prior to rapid deepening above CS6.

4.e. U5: Late Oligocene (Ld–eLw)

U5 comprises a lower package of argillaceous siltstones that grade upwards into variably calcareous siltstone and limestone. CS7 is picked at the top limestone, and approximates the Early/Late Waitakian (Oligocene/Miocene) boundary. U5 also shows significant thickening, from <20 m in the far west to >500 m in the east, beneath the Taranaki Peninsula (Fig. 12d). This thickening is again less
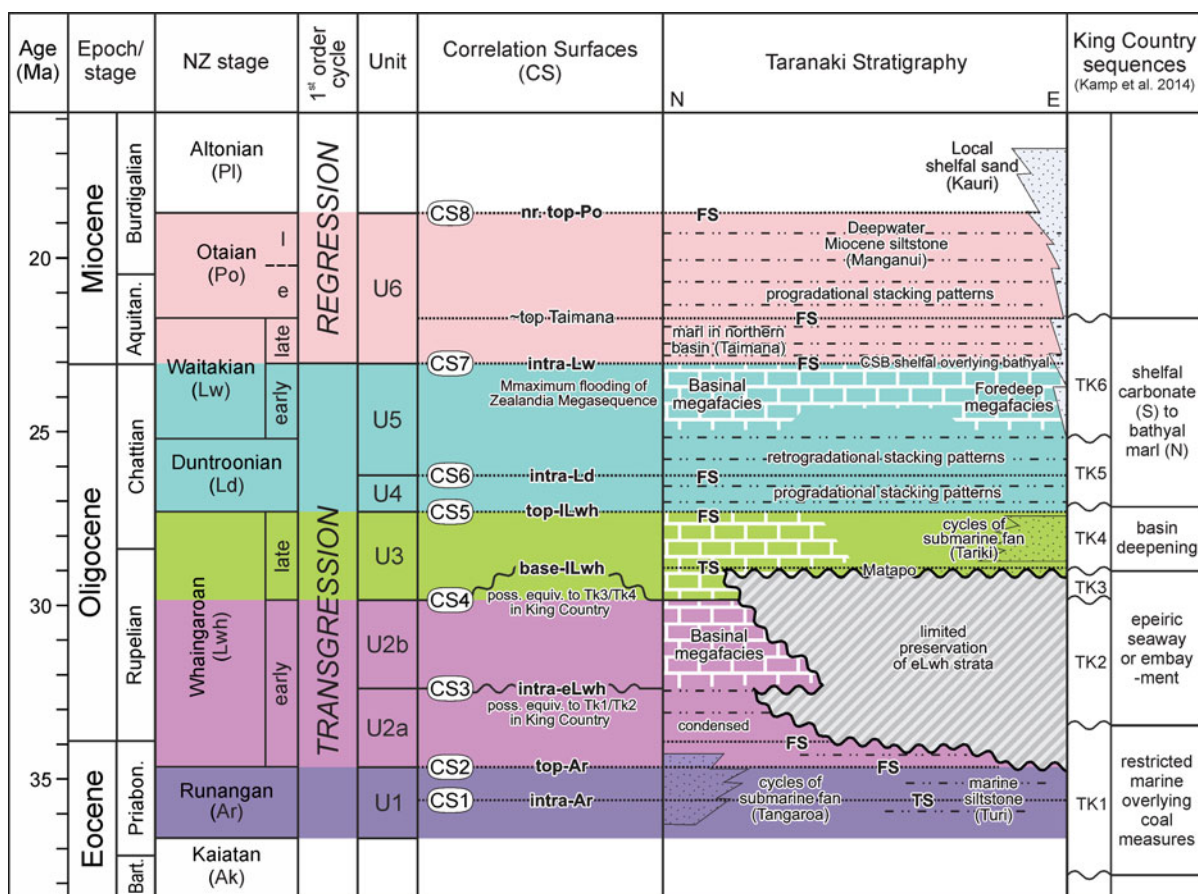
Fig. 8. (Colour online) Summary chronostratigraphic scheme for the latest Eocene – Early Miocene in the Taranaki Basin, showing the main units (U1–U6) and the correlation surfaces that divide them (CS1–CS8) identified in this study. The colours are used to discriminate the sequences in the transects shown in Figures 9–11.

pronounced in the northern offshore region, with U5 relatively thick (~100 m) compared to older units in the Kora-Ariki area, well to the west of the TFS (Figs 9a, 12d). This unit is very thin in distal western wells in the south (<10 m), showing slight thickening to the east (>60 m). However there are no well data constraining this in the east, close to the TFS (Manaia and Waimea–Flaxmore faults; Fig. 12d).

In eastern areas, particularly beneath the onshore Taranaki Basin (Fig. 11), U5 displays an overall upward-cleaning above CS6, from argillaceous bathyal siltstone into limestone facies (the Tikorangi Formation, *sensu* Palmer, 1985; or 'foredeep megafacies' of Hood *et al.* 2003a,b). These thick bathyal limestones are supportive of considerable mass-emplacement of shelf-derived carbonate sediment through the Late Oligocene times.

Further north, at least two sedimentary cycles are evident from the logs. The topmost, cleanest limestone unit (labelled 'eLw lst' on Fig. 9a) has a locally blocky log response and is likely the 'Upper Tikorangi Member' of OMV (2004). However, most of the interval is relatively argillaceous and has been included within the basinal megafacies of Hood *et al.* (2003a). It is possible that the block-shaped GR log signature at the top, together with bathyal palaeo-water depths, may indicate some mass-emplacement of limestone towards the end of the interval.

An upward-cleaning through U5 is also observed in parts of the southern basin, where the gamma log locally displays a characteristic barrel-shape (e.g. Tasman-1; Fig. 10). This is the Takaka Limestone equivalent, generally considered to represent inner shelf carbonates

(Hood *et al.* 2003a). However, palaeo-water depths based on foraminifera suggest outer shelf to uppermost bathyal conditions, and further work is needed to investigate whether these deposits represent limestones redeposited from the Takaka Limestone high.

4.f. U6: Early Miocene (lLw–Po)

Unit U6 marks a return to more terrigenous deposition, with CS7 marking a boundary between the limestones of U5 and the overlying marls of the Taimana Formation (King & Thrasher, 1996). These marls represent a transitional facies, characterized by an intermediate wireline log response, between the underlying limestone and overlying siltstones (e.g. Wainui-1 to Tirua-1; Fig. 9a). These comprise several stacked progradational packages in the northern Taranaki Basin adjacent to the TFS (Fig. 9a). This lithological change is accompanied by an increase in palaeobathymetry, observed in several wells, from upper to mid-bathyal, consistent with CS7 representing a flooding surface. In some cases, marls overlying CS7 are dated as Early Waitakian, perhaps suggesting this correlation surface may be somewhat diachronous. As with older units, U6 shows thickening from the west (<10 m) to east (>300 m) towards the TFS (Fig. 12e), this being less pronounced in the north. This thickening is observed on seismic in the south (Kupe area), where the N05–N15 (Early Miocene) interval thickens towards both the Manaia and Taranaki faults (Fig. 13).

Most of U6 is composed of bathyal siltstones and mudstones of the Manganui Formation, with high GR and wide N-D separation, commonly showing a slight upward-cleaning log profile. CS8 is
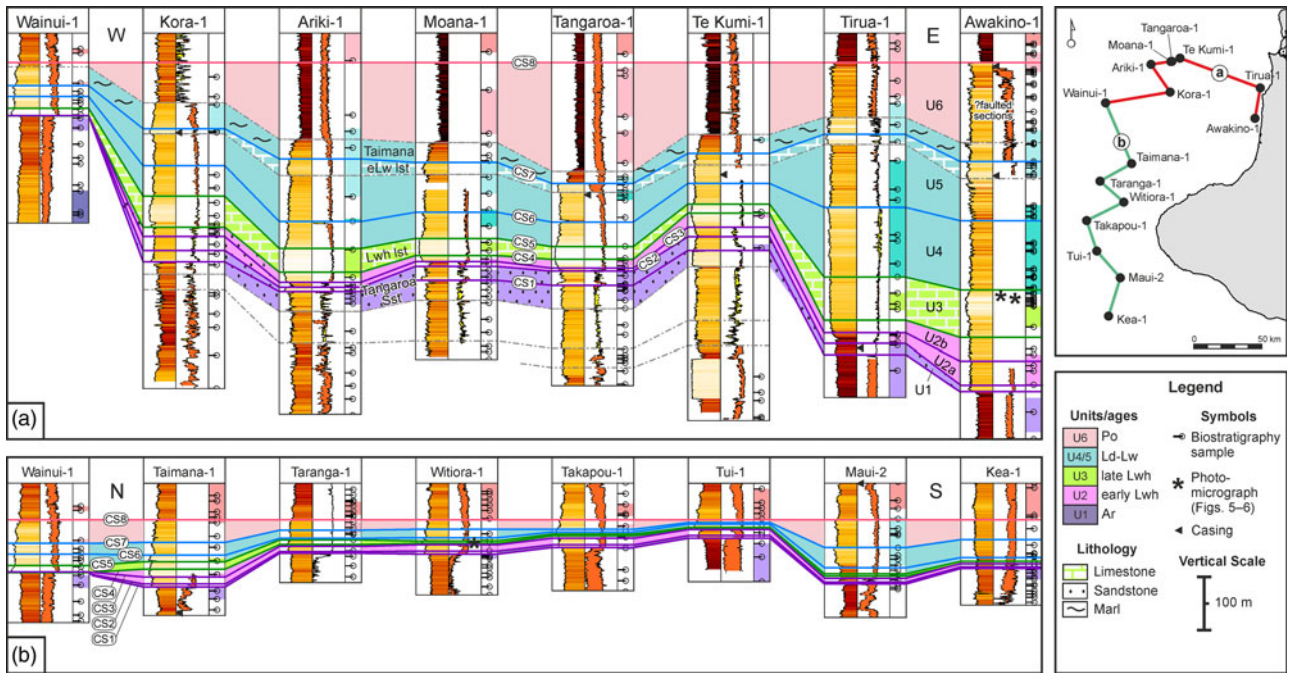
Fig. 9. (Colour online) Offshore (a) W–E and (b) N–S transects through Late Eocene to earliest Miocene, Taranaki Basin. Inset map shows well locations. The cross-section is hung on CS8 (approximate top Otaian). Illustrated for each well from left to right: GR log, neutron-density logs, biostratigraphy data, with age control shaded. See online Supplementary Material for correlations with full log suites and comments. Vertical scale same for all correlation panels.
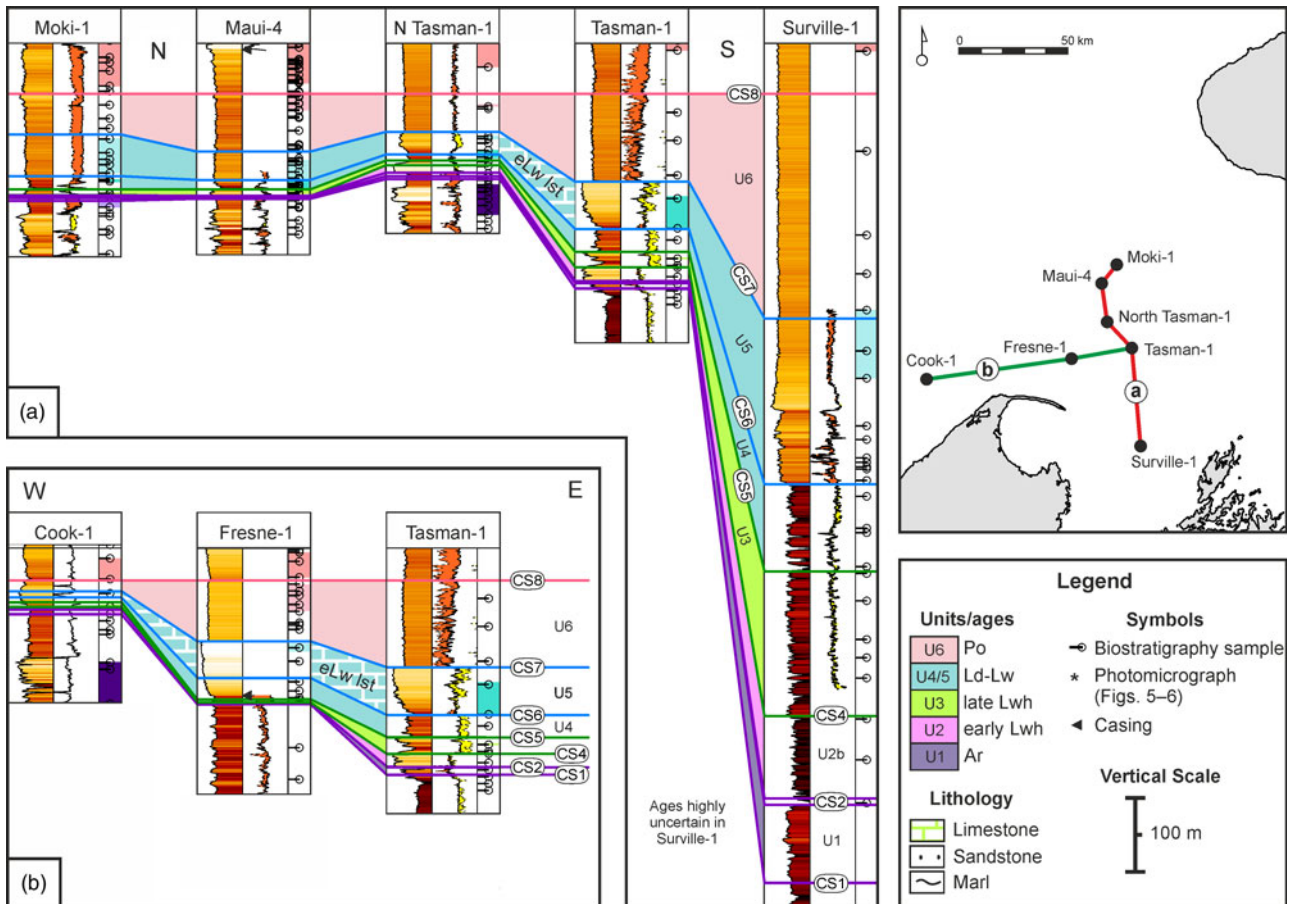

Fig. 10. (Colour online) Southern offshore (a) N–S and (b) W–E transects through Late Eocene to earliest Miocene, Taranaki Basin. Details as in Figure 9.
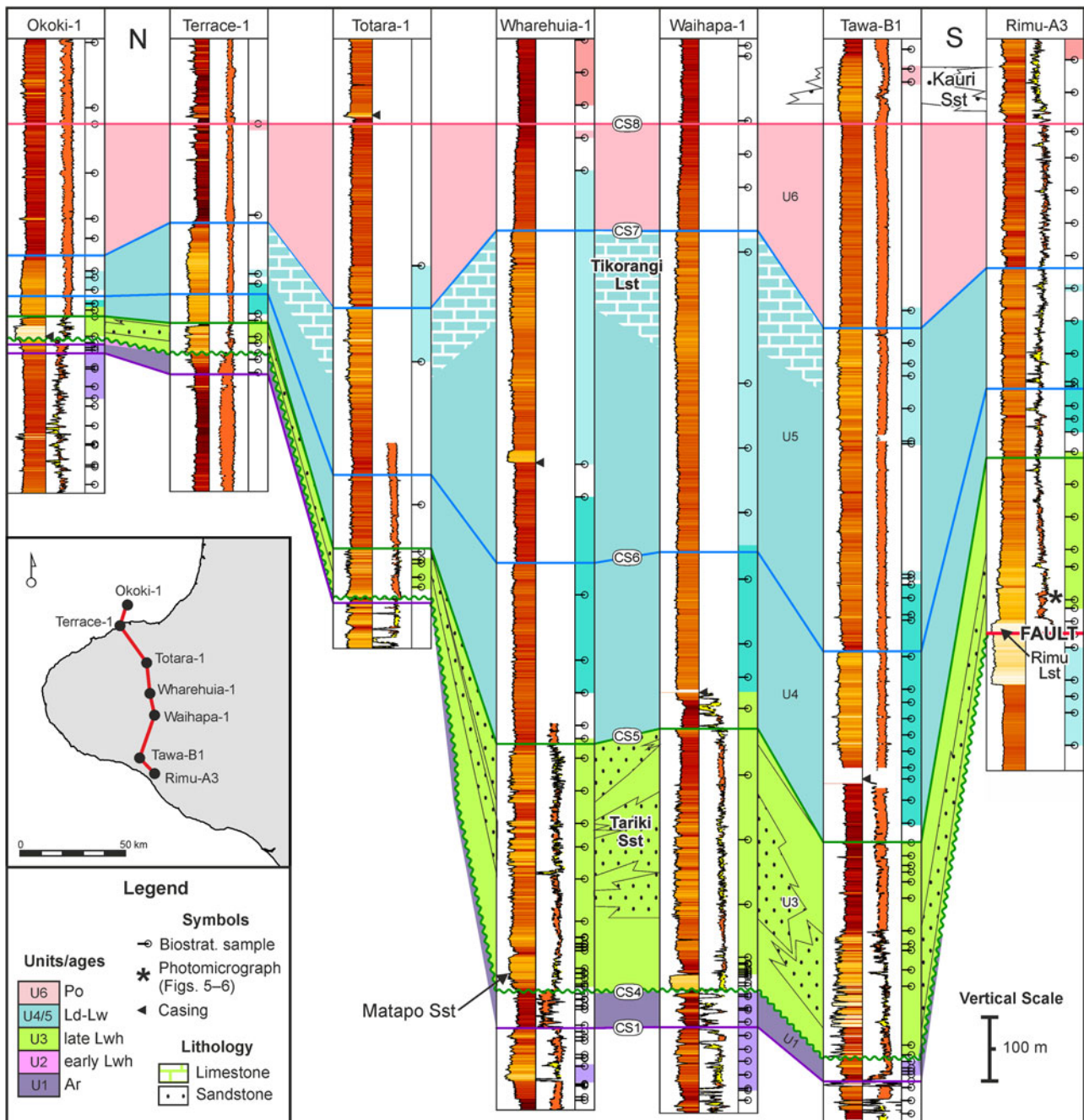
Fig. 11. (Colour online) Onshore (eastern Taranaki Basin) N–S transect through Late Eocene to earliest Miocene, Taranaki Basin. Details as in Figure 9.

tentatively picked on a possible flooding surface at the approximate Otaian/Altonian boundary. However, precise age dating is problematic, and generally, CS8 is picked on the log response. Sandstone stringers are rarely developed within the Otaian siltstones, but are locally well developed in the overlying Altonian siltstones (above CS8), and include the majority of the 'Kauri Sandstone' (Figs 6f, 11). Although this unit is as old as Duntroonian, it was most extensively developed in the Waitakian–Altonian times (U6 and younger), spreading as far west as Kupe (Higgs *et al.* 2004b). Biostratigraphic data suggest an intra-Waitakian shallowing in the Rimu-Kauri area, followed by a subsequent deepening in the U6 'Kauri Sandstone' (Higgs *et al.* 2004b).

5. Discussion: sedimentary evolution through the Late Eocene–Early Miocene times

The Cretaceous–Cenozoic sedimentary record of New Zealand has been described in terms of a first-order depositional cycle (King & Thrasher, 1996). Within this cycle, the Oligocene represents a time of major change in sedimentation patterns coincident with maximum marine flooding, represented by the Waka Supergroup (Mortimer *et al.* 2014). This unit is linked to a culmination of passive margin sedimentation and inception of a new subduction margin. In the Taranaki Basin, Oligocene sedimentation is marked by a shift from the previous and prolonged (>40 Ma) coastal-paralic clastic
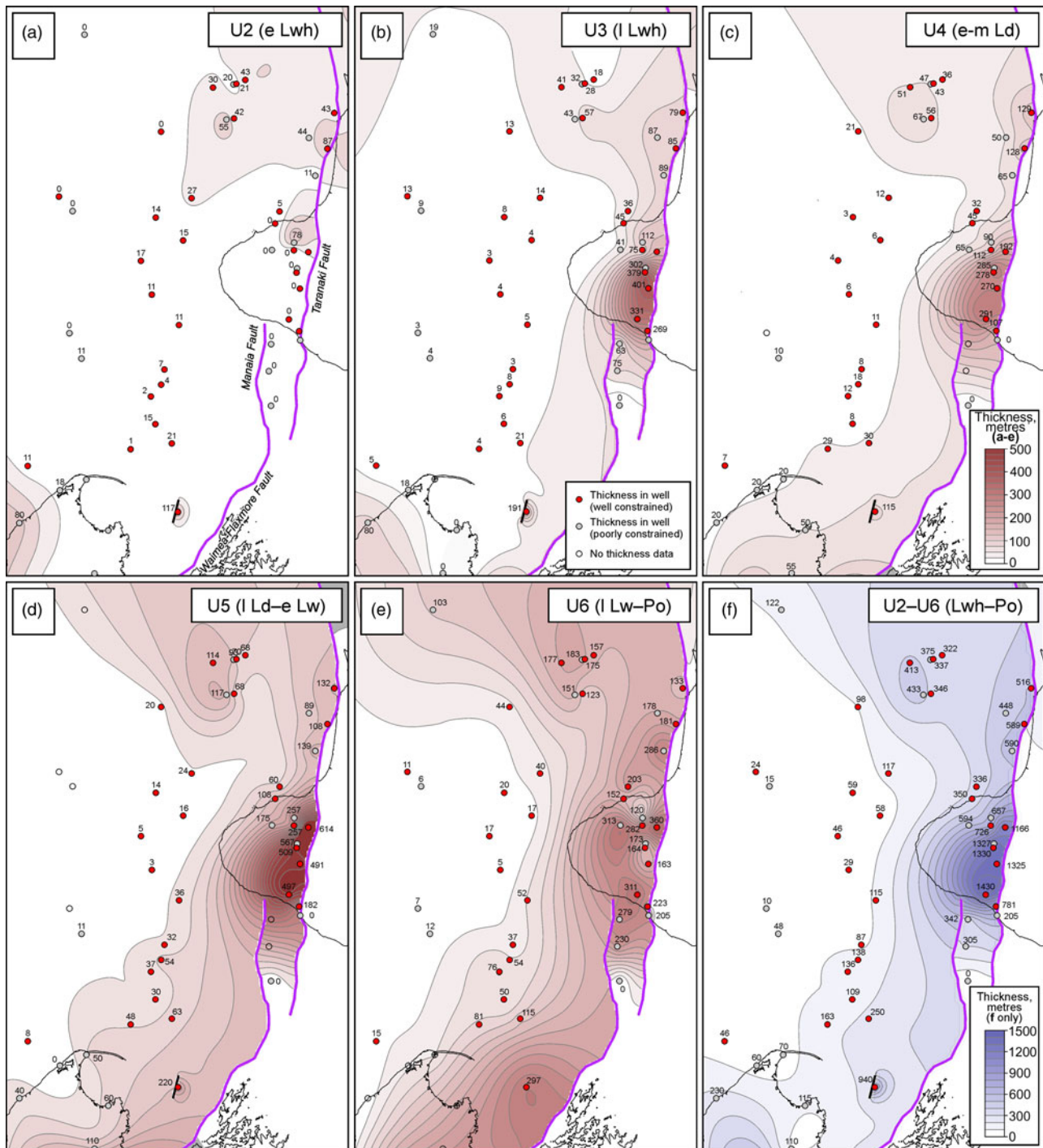
Fig. 12. (Colour online) (a–e) Thickness maps for the Oligocene to Early Miocene packages U2–U6 and (f) for their combined total thickness. Same colour scale for (a) to (e), but different for (f). No map was produced for U1 (latest Eocene), as its basal surface was not mapped. The Taranaki Fault System, used in the gridding process, is also shown. Based only on well and measured section data; thicknesses in metres. See text for discussion.

deposition through Late Cretaceous–Eocene time, into a deepwater carbonate-dominated system, with maximum transgression marked by the top of the Early Waitakian (U5) Tikorangi Limestone (King & Thrasher, 1996). This shift in regional sedimentation patterns is attributed to the onset of reverse movement on the TFS and the associated development of a foredeep along the eastern margin of the basin (e.g. Tripathi & Kamp, 2008; Strogen *et al.* 2014) in response to the initial development of a new boundary between the Australian

and Pacific plates (Stagpoole & Nicol, 2008; Bache *et al.* 2012; Reilly *et al.* 2015).

Results from our study are consistent with regional stratigraphic patterns, and indicate intermittent but overall transgression from Late Eocene (U1) to Late Oligocene (U5) times, followed by overall regression in the Early Miocene (U6) time. Within this overall transgressive–regressive system there is also evidence for smaller-scale cyclicity, shown by stacking patterns observed on wireline
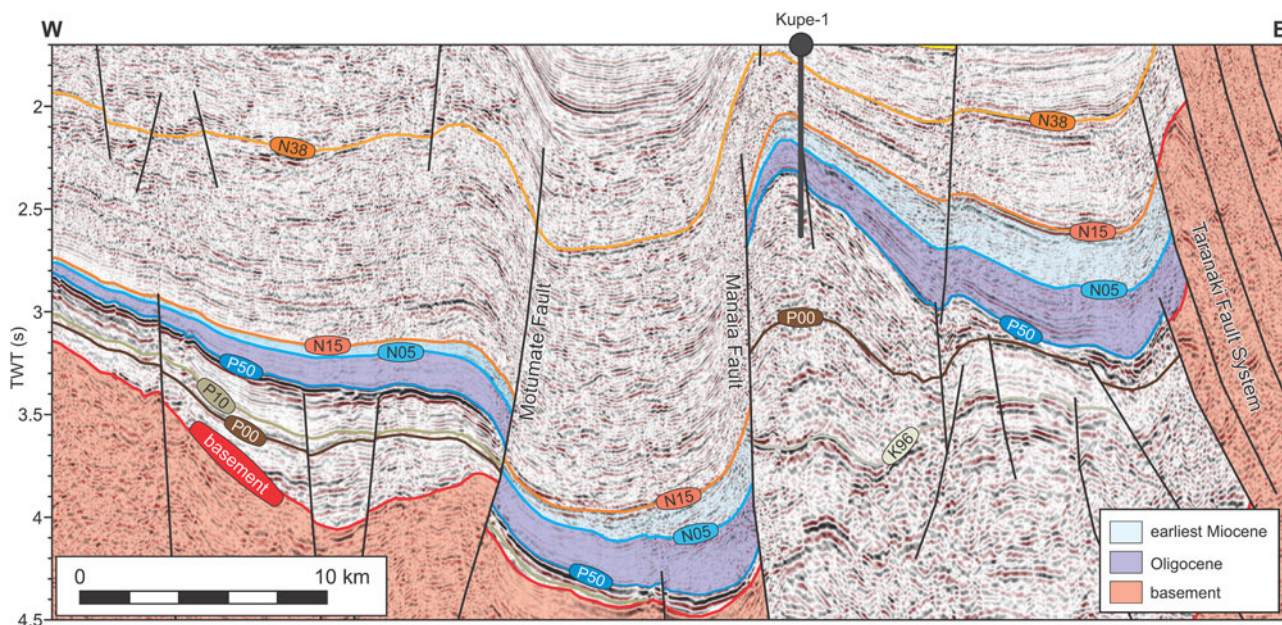
Fig. 13. (Colour online) Interpreted seismic transect (lines hzt82a-118 and sk-10) through well Kupe-1. Mapping after Bull *et al.* (2016), with the Oligocene (P50–N05; purple) and earliest Miocene (N05–N15; light blue) highlighted. Both units can be seen to thicken from west to east towards both the Manaia and Taranaki faults, which were active as reverse faults during deposition. Basement highlighted in pink. See Figure 7a for location.
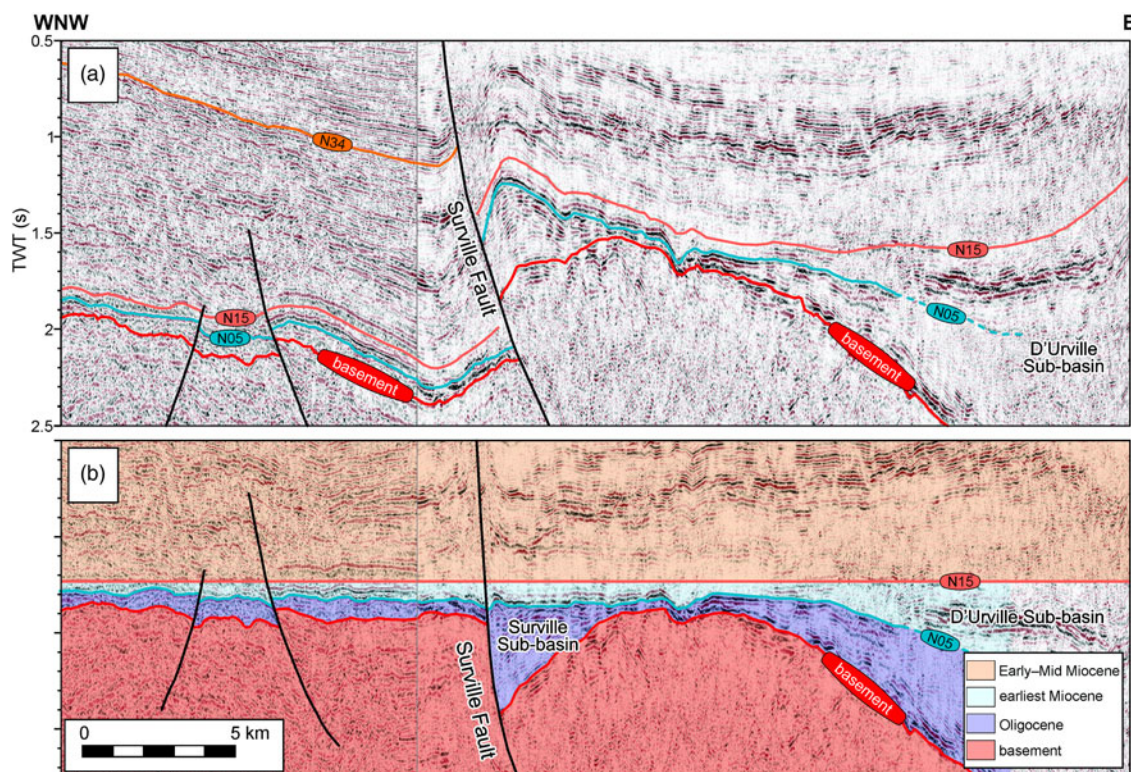

Fig. 14. (Colour online) Interpreted seismic transect (lines w83-6c and cs-3) across the Surville Sub-basin, ~4 km south of well Surville-1. Mapping after Bull *et al.* (2016). (a) Unflattened seismic transect. (b) Seismic transect flattened on N15 (Early Miocene, likely late Otaian). See Figure 7a for location. Although the Surville Fault has been active as a major reverse structure through most of the Neogene period (post N15), the flattened panel shows it was active as a normal structure through the Oligocene period (basement–N05). There is no obvious thickness variation across the fault in the earliest Miocene (N05–N15), suggesting likely inactivity. Both the Oligocene and earliest Miocene thicken to the east in the D'Urville Sub-basin, towards the Waimea–Flaxmore Fault (just beyond the righthand end of the section), which was likely active in a reverse sense throughout, although this is not certain.

log profiles, and by the regional development of carbonates and interpreted transgressive or flooding surfaces (Fig. 8). These superimpose a possible second-order cyclicity, which is interpreted to have spanned much of the Oligocene period (*c.* 6 Ma). Important elements of the development of the Taranaki Basin through Late Eocene to Early Miocene times, based on the results from this study, are discussed below.

5.a. Late Eocene – Early Oligocene: transition from passive- to early active-margin

Latest Eocene strata in the Taranaki Basin are interpreted as the transgressive systems tract (TST) of the Middle–Late Eocene second-order sedimentary cycle (Higgs *et al.* 2012*a*). Sedimentation (U1), during ongoing regional transgression, was dominated by calcareous shelfal siltstones (Turi Formation) with deepening palaeobathymetry through time. Deposition of the Tangaroa Formation deepwater submarine fans in latest Eocene – earliest Oligocene times in the northern Taranaki Basin represent a striking facies change compared to the transgressive shoreline to shelfal facies, typical of the Eocene period (King & Thrasher, 1996; Higgs *et al.* 2012*a*, 2017). The presence of these fans, the deepening and steepening of palaeobathymetry (Strogen *et al.* 2014) and the slight thickening of U2 towards the Taranaki Fault (Fig. 12a) likely represent the first mild influence on sedimentation of reverse faulting on the TFS, at least in the northern Taranaki Basin. This is also supported by changes to provenance at this time. Recycled Mesozoic pollen within the Tangaroa Formation sandstones is indicative of a Murihiku Supergroup basement source east of the Taranaki Fault (King & Thrasher, 1996), whereas detrital mineral composition and zircon data of the sandstones are consistent with sediment derivation primarily from recycled older Cretaceous–Eocene deposits (Higgs & King, 2018).

Sediment cyclicity is evident within the Tangaroa Formation, some of which may simply represent lobe-switching. However, the presence of the correlatable 'Tangaroa Limestone' within the sands could be evidence of superimposed, higher-order sedimentary cyclicity, possibly related to periodic movement on the Taranaki Fault. It likely represents a pelagic ooze deposit during a time of low siliciclastic sediment supply, and is consistent with a stratigraphically important break in clastic sedimentation.

Where Early Whaingaroan strata are preserved in the northern Taranaki Basin, CS3 marks a significant facies change from predominantly siliciclastic (U2a) to carbonate (U2b) deposition. Although the age of CS3 is poorly constrained, it may correlate to the Early Whaingaroan TK1/TK2 sequence boundary interpreted by Tripathi & Kamp (2008) in the Waikato–King Country Basin (Fig. 8). This marked an expansion of marine and carbonate deposition in the area to the east of the TFS, which may explain the change to more carbonate facies in U2b in the northern Taranaki Basin.

5.b. Mid-Oligocene uplift, erosion and condensed sedimentation

The base-Late Whaingaroan unconformity (CS4) reflects a period of locally significant erosion and tilting of underlying strata in the southern Taranaki Basin. U3 overlies strata as old as Paleocene, with U2 absent across much of the southern Taranaki Basin. The age of CS4 (*c.* 30 Ma) approximately corresponds to a substantial eustatic fall on global sea-level curves (e.g. 28.5 Ma; Hardenbol *et al.* 1998), and therefore eustasy could have played some part in its development. In addition, unconformities of Oligocene age, such as the Marshall Paraconformity of Carter (1985) or Marshall Unconformity of Field *et al.* (1989), are widespread in sedimentary

rocks throughout New Zealand, particularly in South Island. These surfaces have been the subject of considerable debate, including the number of unconformity surfaces, their ages and the reasons for their development (Carter & Landis, 1972; Lewis & Belliss, 1984; Carter, 1985; Fulthorpe *et al.* 1996; King *et al.* 1999; Lever, 2007). They are usually associated with phosphatisation, glauconite concentrations in overlying sediments and the development of hardgrounds (Carter & Landis, 1972) and are widely thought to be related to significant Oligocene oceanographic changes in Southern Ocean circulation.

However, there is clear evidence for major changes in the tectonic regime in the Taranaki Basin, starting as early as the Late Eocene times (e.g. Stagpoole & Nicol, 2008; Strogen *et al.* 2014; Higgs & King, 2018). It is likely, therefore, that erosion and tilting, such as that seen in the Kupe area (Strogen *et al.* 2014, their fig. 5), represents a phase of regional Late Eocene to Early Oligocene tectonic uplift and inversion. This may be linked to inversion observed throughout the greater Tasman Frontier region, which has been related to subduction initiation processes (Sutherland *et al.* 2010, 2017; Bache *et al.* 2012), although the precise age of this uplift is as yet poorly constrained as possibly Late Eocene (Etienne *et al.* 2018). The CS4 unconformity in the Taranaki Basin is, therefore, interpreted to have developed in response to the ongoing transition from passive- to active-margin tectonics, and is unlikely, therefore, to be a purely eustatic feature or related to the Marshall Paraconformity/Unconformity.

The condensed Matapo Sandstone and 'Rimu Limestone' sit above CS4, their glauconitic nature representing localized sediment bypass or starvation (Bishop, 1971; King & Thrasher, 1996). These deposits are most likely diachronous, representing a phase of gradual transgression, prior to the onset, still within Late Whaingaroan time, of rapid localized subsidence and deepening (see Section 5.c below).

5.c. Foredeep creation and mixed siliciclastic–carbonate deposition

Soon after the gradual transgression of CS4, rapid Late Whaingaroan subsidence resulted in the creation of an elongated foredeep close to the TFS (Figs 2, 12b). Throughout the remainder of the Oligocene period, this foredeep was filled with a thick sequence of strata of varying lithology. Oligocene units all thin westwards (Fig. 12) to more distal areas, where limestones were deposited in bathyal water depths and generally represent background pelagic ooze deposits ('basinal megafacies'). This deepening marks the onset of significant reverse activity on the TFS, at least in central and southern parts of the Taranaki Basin. It likely correlates with deepening seen above the mid-Oligocene TK3/TK4 sequence boundary in the Waikato–King Country Basin (Tripathi & Kamp, 2008), which formed a piggyback basin to the east of the TFS. This is the most extensive intra-Oligocene unconformity in the Waikato–King Country Basin, with uplift and erosion over a 30 km wide zone east of the TFS, and marks the onset of severe deformation in the hangingwall of the TFS (Kamp *et al.* 2014). Development of the foredeep fill in the Taranaki Basin was punctuated by several changes in depositional facies, which reflect local and more regional tectonic and provenance signals.

Initial, Late Whaingaroan (U3), deposition in the foredeep beneath the Taranaki Peninsula was clastic dominated, including thick variably calcareous submarine-fan sandstones (Tariki Sandstone Member; de Bock *et al.* 1990) and thick bathyal mudstones (Otaraoa Formation). Several discrete cycles of submarine-fan sedimentation occurred (Higgs *et al.* 2001, 2004*a*), likely

controlled by episodic fault activity on the TFS. The fans were sourced primarily from east of the Taranaki Fault, where older Paleogene sediments and basement were uplifted and eroded (Higgs & King, 2018). Further north, redeposited limestones ('foredeep megafacies'; Hood *et al.* 2003a,b) were deposited close to the TFS during the Whaingaroan times (U2b–U3). These likely represent redeposition of contemporaneous platform limestone facies that occur in the Waikato–King Country Basin (Nelson, 1978; Tripathi & Kamp, 2008; Kamp *et al.* 2014). While lithologically different, they formed by similar processes to the Tariki Sandstone Member, namely hangingwall uplift and erosion on the TFS. Less pronounced relative thickening is seen throughout Oligocene times (U3–U5) in the northern Taranaki Basin, compared to beneath the Taranaki Peninsula (Fig. 12b–d). This may reflect less intense uplift along the northern portion of the TFS, and explain the reworking of contemporary platform carbonate facies, rather than deeper erosion of older cover rocks and basement further to the south during Late Whaingaroan time.

The end-Whaingaroan (CS5) marks an end to both carbonate deposition in northern Taranaki and to extensive coarse clastic deposition in the eastern Taranaki Peninsula. Although sandstone facies are present within U4 ('Ld-sands', 'Kauri Sandstone' and Magazine Point Formation), they are far less extensive than in U3. Possible reasons for this Duntroonian reduction in coarse clastic material could include regional transgression leading to a reduced area of uplifted hangingwall available for erosion, or a relative waning in activity on the TFS. However, these are not supported by the continued high sedimentation rates in Duntroonian time (Fig. 12b–c). A change in provenance could be one reason for this switch to more argillaceous facies. Continuing hangingwall uplift and erosion, resulting in the complete removal of older cover rocks to the east of the TFS by the end-Whaingaroan, may have led to a change from reworking of coarse quartzose Cretaceous–Paleogene cover rocks to direct erosion of highly argillaceous Eastern Province basement (Higgs & King, 2018). The change from calcareous to more argillaceous facies in U4 in the northern Taranaki Basin may also reflect this provenance change to a more argillaceous Eastern Province source, tied to an increase in clastic sediment input. Progradational siltstone/mudstone packages within U4 may reflect episodic activity on the TFS.

By Early Waitakian time (upper U5), thick resedimented limestones ('foredeep megafacies' of Hood *et al.* 2003a,b; Tikorangi Formation, *sensu* Palmer, 1985) dominated deposition in the peninsula foredeep. These were likely sourced from platform facies on the adjacent Patea-Tongaporutu High (Fig. 2; Hood *et al.* 2003a,b), indicating this was now transgressed. Similar platform carbonates are known to have been resedimented from the Herangi High in the north (Nelson *et al.* 1994). Input of coarse clastic sediment was restricted to the Rimu-Kauri area in the south ('Kauri Sandstone'; Higgs *et al.* 2004b). As in U3, these distinctions are somewhat arbitrary, with highly calcareous Kauri Sands and sandy Tikorangi Limestone facies occurring, indicating a continuum between coarse clastic and carbonate facies.

5.d. Controls on regional subsidence and transgression

Regional subsidence and transgression occurred throughout the Late Eocene–Oligocene times in the Taranaki Basin and surrounding areas. Transgression was punctuated by several flooding surfaces, some of which may correlate to those in the Waikato–King Country Basin (Fig. 8; Kamp *et al.* 2014). While compressional processes controlling foredeep creation dominated subsidence

close to the TFS, gradual transgression was manifested by the spread of increasingly carbonate-dominated facies across adjacent platform areas, such as in the Waikato–King Country Basin (Nelson, 1978; Tripathi & Kamp, 2008; Kamp *et al.* 2014) and NW Nelson (Nathan *et al.* 1986). Transgression culminated in Early Waitakian times, marked by a return to calcareous facies in the Taranaki Basin (Fig. 8). This time represents maximum regional transgression throughout Zealandia, with widespread carbonate deposition (King *et al.* 1999; Mortimer *et al.* 2014).

This ongoing slow regional Eocene–Oligocene transgression may reflect continuing post-rift thermal subsidence, although considerable time had passed since the end of rifting (>20 Ma in the proximal Taranaki Basin, as much as 50 Ma in distal areas; Strogen *et al.* 2017). This may have been enhanced by an episode of more rapid regional deepening, following on from earlier regional uplift discussed previously (Etienne *et al.* 2018). This deepening has been ascribed to lithospheric processes related to subduction initiation (e.g. Sutherland *et al.* 2010; Bache *et al.* 2012; Baur *et al.* 2014). Deepening is observed in subsidence curves in western wells such as Tane-1 (Strogen *et al.* 2014), well away from the effects of the TFS, although its timing is poorly constrained.

5.e. earliest Miocene onset of regression in the Taranaki Basin

A major change occurred within the Waitakian, marking the onset of a long-lived regression that has continued to the present day, and was related to an intensification of plate boundary deformation throughout Zealandia (King *et al.* 1999; King, 2000; Bull *et al.* 2018). The Taimana Formation (lower U6) represents the first minor influx of clastic sediments (Fig. 8) and the transition from the carbonate- to clastic-dominated depositional system. Deposition of thin (Fig. 12e), highly condensed deep bathyal marls continued in the western Taranaki Basin throughout U6, prior to the slope-shelf progradation that would not reach distal areas until later in the Miocene, post CS8 (King & Thrasher, 1996; Strogen, 2011; Bull *et al.* 2018).

The earliest Miocene saw changes to the foredeep adjacent to the TFS, which spread further south, along much of the eastern margin of the Taranaki Basin, compared to the Oligocene period (compare Fig. 12b–d and e). This reflects Early Miocene southward translation of the locus of reverse faulting onto the Manaia and Waimea–Flaxmore faults. This is illustrated by significant thickening of Early–Mid Miocene strata in the footwall of the Manaia Fault, compared to Oligocene–earliest Miocene units (Fig. 13; Bull *et al.* 2016). This southward translation of faulting is also consistent with the onset of significant reverse faulting in the Murchison Basin and elsewhere on the West Coast in the Early Miocene times (Otaian–Altonian; Ghisetti *et al.* 2016). It also fits with observations that the northern segment of the Taranaki Fault, north of the Taranaki Peninsula, was inactive by late Early Miocene times (late Altonian; Stagpoole & Nicol, 2008).

5.f. Evidence for extension in the southern Taranaki Basin

Through Late Eocene–Oligocene times, the southern Taranaki Basin sat close to a transition between compression related to the developing plate boundary in the north and extension related to sea-floor spreading in the Emerald Basin in the south (e.g. King, 2000). This extension resulted in widespread, but poorly constrained, Late Eocene–Oligocene extension in the West Coast (Nathan *et al.* 1986; Riordan *et al.* 2014) and western Southland (Fig. 1) basins (Turnbull *et al.* 1993, 2008). The northward

termination of this rifting has always been unclear. It has been suggested to extend into the southern Taranaki Basin (King & Thrasher, 1996), but poor seismic reflection data quality and intense structural inversion have made this hard to demonstrate.

We suggest that the Surville Sub-basin (Figs 7, 14) is the first well-documented example of Oligocene extension in the Taranaki Basin, and explains the anomalous thickness of Oligocene strata in Surville-1 (Figs 7, 10a) compared to other southern Taranaki Basin wells. The Surville Fault (Fig. 14) appears to have been active as a normal fault throughout the Oligocene times (horizons P50–N05), experienced a brief period of quiescence in the earliest Miocene times (N05–N15) and then experienced a significant structural inversion as a reverse fault from the late Otaian (post-N15) onwards. This faulting history is similar to that suggested for many normal faults in the West Coast region from the Murchison Basin southwards (Ghisetti et al. 2016).

The major D'Urville Sub-basin (Fig. 7a) depocentre just to the east of the Surville Sub-basin appears to be a southwards continuation of the foredeep associated with the TFS, although its Oligocene history is far from clear, owing to extremely poor seismic data and coverage. This suggests there may be a complex interaction between normal and reverse faulting in this area.

6. Conclusions

This paper documents the geographic, stratigraphic and facies variability of Late Eocene to Early Miocene strata in the Taranaki Basin, using high-quality wireline log data from 44 petroleum wells together with biostratigraphic data to constrain the age and depositional setting. This succession comprises widely variable clastic and carbonate facies that transition from sandstone through calcareous sandstone to limestone, and from micritic limestone through marl to siltstone/mudstone. This has resulted in an inconsistent and often ambiguous lithostratigraphic scheme for Oligocene strata, which requires revision.

We have subdivided the latest Eocene to Early Miocene succession in the Taranaki Basin using eight regional surfaces (CS1–CS8) based primarily on wireline log response augmented with foraminiferal control. The surfaces record facies dislocations relating to changes in lithology (e.g. carbonate/clastic) and/or palaeo-water depth, and divide the succession into units U1 to U6, summarized in Figure 8.

Significant thickness variations are observed across the Taranaki Basin in all mapped units (Fig. 12) and show similar patterns of eastward thickening towards the TFS from mid-Oligocene to Early Miocene times (U3–U6). The thickness of the Oligocene section from regional seismic mapping in the southern Taranaki Basin compares well in general with the total thickness from well data and mirrors the trends seen within individual units. Early Whaingaroan (U2) strata are limited to parts of the northern and southern Taranaki Basin. Elsewhere U2 is highly condensed, absent owing to erosion at CS4 or, in most cases, likely never deposited. This mid-Oligocene unconformity (CS4) remains somewhat enigmatic, although its clearly angular nature in parts of the southern Taranaki Basin implies it was tectonically driven. The creation of this unconformity and subsequent regional subsidence during U3 are most likely related to plate boundary initiation processes preceding more intense localized tectonic activity on the TFS itself. In the northern Taranaki Basin, U2 reflects sedimentation patterns associated with early mild compression on northern parts of the TFS.

Mid-Oligocene to Early Miocene (Late Whaingaroan–Otaian) thickness maps all illustrate the presence of thick sediments deposited in a foredeep adjacent to the TFS, with the thickest strata beneath the eastern part of the Taranaki Peninsula. These patterns suggest that sedimentation in the eastern Taranaki Basin was controlled by reverse movement on the TFS. Strata thin away from this foredeep into the western basin, where very thin and condensed sedimentation persisted throughout latest Eocene to earliest Miocene times. The shape of this foredeep changed in Early Miocene time, broadening and extending further to the south. This reflects a southward movement in the locus of faulting along the TFS, and coincides with the onset of significant reverse faulting to the south in onshore South Island.

Notably, the small Surville Sub-basin in the southernmost Taranaki Basin is shown to have acted as an extensional feature through the Oligocene period, prior to its Miocene inversion. This marks the northernmost confirmed extension related to Emerald Basin formation, and confirms the southern Taranaki Basin as a transitional zone between compressional deformation in the north and extension to the south during Oligocene time.

Author ORCIDs. (iD) Dominic P. Strogen 0000-0002-1744-1289

References

Bache F, Sutherland R, Stagpoole V, Herzer R, Collot J and Rouillard P (2012) Stratigraphy of the southern Norfolk Ridge and the Reinga Basin: a record of initiation of Tonga–Kermadec–Northland subduction in the southwest Pacific. *Earth and Planetary Science Letters* **321–322**, 41–53.

Baur J, Sutherland R and Stern T (2014) Anomalous passive subsidence of deep-water sedimentary basins: a prearc basin example, southern New Caledonia Trough and Taranaki Basin, New Zealand. *Basin Research* **26**, 242–68.

Berggren WA, Kent DV, Swisher CC and Aubry MP (1995) A revised Cenozoic geochronology and chronostratigraphy. In *Geochronology, Time Scales and Global Stratigraphic Correlation* (eds WA Berggren, DV Kent, MP Aubry and J Hardenbol), pp. 129–212. Tulsa, OK, USA: SEPM Special Publication no. 54.

Bierbrauer K (2010) Eocene deformation and erosion in the southern Taranaki Basin – implications for a tectonic subdivision of the Kapuni Group. In *New Zealand Petroleum Conference Proceedings 2010*, p. 25. Wellington: Ministry of Economic Development.

Bishop DG (1971) *Geological Map of New Zealand 1:63, 360 Sheet S1, S3 and pt. S4 Farewell–Collingwood*. Wellington: Department of Scientific and Industrial Research, 19 pp + 11 map.

Bradshaw JD (1989) Cretaceous geotectonic patterns in the New Zealand region. *Tectonics* **8**, 803–20.

Bull S, Hill M, Strogen DP, Arnot MJ, Seebeck H, Kroeger KF and Zhu H (2016) *Seismic Reflection Interpretation, Static Modelling and Velocity Modelling of the Southern Taranaki Basin (4D Taranaki Project)*. GNS Science Report 2016/02. Lower Hutt: GNS Science, 73 pp.

Bull S, Nicol A, Strogen DP, Kroeger KF and Seebeck HS (2018) Tectonic controls on Miocene sedimentation in the Southern Taranaki Basin and implications for New Zealand plate boundary deformation. *Basin Research*, published online 17 October 2018. doi: 10.1111/bre.12319.

Carter RM (1985) The mid-Oligocene Marshall Paraconformity, New Zealand: coincidence with global eustatic sea-level fall or rise? *The Journal of Geology* **93**, 359–71.

Carter RM and Landis CA (1972) Correlative Oligocene unconformities in southern Australasia. *Nature Physical Science* 237, 12.

Catuneanu O (2006) *Principles of Sequence Stratigraphy*. Amsterdam: Elsevier Science, 386 pp.

Cooper RA (ed.) (2004) *The New Zealand Geological Timescale*. Institute of Geological and Nuclear Sciences Monograph 22. Lower Hutt: Institute of Geological and Nuclear Sciences, 284 pp.

Core Lab (2003) *Reservoir Performance Assessment of the Tariki, Kauri, and Manutahi Sandstones Rimu-Kauri Field, New Zealand*. New Zealand Unpublished Open-file Petroleum Report, PR2787, 879 pp, 813 enclosures.

de Bock JF, Palmer JA and Lock RG (1990) Tariki Sandstone early Oligocene hydrocarbon reservoir, eastern Taranaki, New Zealand. In *New Zealand Petroleum Conference Proceedings 1989*, pp. 214–24. Wellington: Ministry of Economic Development.

Emery D and Myers KJ (1996) *Sequence Stratigraphy*. Oxford: Blackwell Science, 297 pp.

Etienne S, Collot J, Sutherland R, Patriat M, Bache F, Rouillard P, Henrys S, Barker D and Juan C (2018) Deepwater sedimentation and Cenozoic deformation in the Southern New Caledonia Trough (Northern Zealandia, SW Pacific). *Marine and Petroleum Geology* 92, 764–79.

Field BD, Browne GH, Davy BW, Herzer RH, Hoskins RH, Raine JI, Wilson GJ, Sewell RJ, Smale D and Watters WA (1989) *Cretaceous and Cenozoic Sedimentary Basins and Geological Evolution of the Canterbury Region, South Island, New Zealand*. New Zealand Geological Survey Basin Studies 2. Lower Hutt: New Zealand Geological Survey, 94 pp.

Fulthorpe CS, Carter RM, Miller KG and Wilson J (1996) Marshall Paraconformity: a mid-Oligocene record of inception of the Antarctic circumpolar current and coeval glacio-eustatic lowstand? *Marine and Petroleum Geology* 13, 61–77.

Ghisetti FC and Sibson RH (2006) Accommodation of compressional inversion in north-western South Island (New Zealand): old faults versus new? *Journal of Structural Geology* 28, 1994–2010.

Ghisetti F, Sibson RH and Hamling I (2016) Deformed Neogene basins, active faulting and topography in Westland: distributed crustal mobility west of the Alpine fault transpressive plate boundary (South Island, New Zealand). *Tectonophysics* 693, 340–62.

Gradstein FM, Ogg JG, Schmitz M and Ogg G (2012) *The Geologic Time Scale 2012*. Amsterdam: Elsevier Science, 1176 pp.

Gresko MJ, Jordan DW and Thompson PR (1992) Sequence stratigraphic analysis of Tangaroa sandstone, northern Taranaki Basin. In *New Zealand Petroleum Conference Proceedings 1991*, pp. 234–44. Wellington: Crown Minerals.

Hardenbol J, Thierry J, Farley MB, Jacquin T, De Graciansky PC and Vail PR (1998) Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins* (eds PC de Graciansky, J Hardenbol, T Jacquin and PR Vail), pp. 3–13. Tulsa, OK, USA: SEPM Special Publication no. 60.

Harris D and Frankiewicz K (2004) *Kauri-E4, Kauri-4A, Kauri-4A ST1 and Kauri-4A ST2 Well Completion Report*. New Zealand Unpublished Open-file Petroleum Report, PR2968, 756 pp.

Harris D, Frankiewicz K, Swift S, Aucoin A and Scott B (1999) *Rimu-A1 Well Completion Report*. New Zealand Unpublished Open-file Petroleum Report, PR2447, 1310 pp., 1313 enclosures.

Hayward BW (1986) *A Guide to Paleoenvironmental Assessment Using New Zealand Cenozoic Foraminiferal Faunas*. New Zealand Geological Survey Report PAL 109. Lower Hutt: New Zealand Geological Survey, 73 pp.

Higgs KE, Crouch EM and Raine JI (2017) An interdisciplinary approach to reservoir characterisation; an example from the early to middle Eocene Kaimiro Formation, Taranaki Basin, New Zealand. *Marine and Petroleum Geology* 86, 111–39.

Higgs KE and King PR (2018) Reservoir sandstone provenance and sediment dispersal in a complex tectonic setting: Taranaki Basin, New Zealand. *Sedimentary Geology* 372, 112–39.

Higgs KE, King PR, Browne GH and Morgans HEG (2004a) Oligocene submarine fan systems in Taranaki: a proven reservoir and an outcrop comparison. In *New Zealand Petroleum Conference Proceedings 2004*, 10 pp. Wellington: Ministry of Economic Development.

Higgs KE, King PR, Raine JI, Sykes R, Browne GH, Crouch EM and Baur JR (2012a) Sequence stratigraphy and controls on reservoir sandstone distribution in an Eocene marginal marine-coastal plain fairway, Taranaki Basin, New Zealand. *Marine and Petroleum Geology* 32, 110–37.

Higgs KE and Morgans HEG (2001) *Tuihu-1 Well Study*. New Zealand Unpublished Open-file Petroleum Report, PR4541, 49 pp.

Higgs KE, Morgans HEG, King PR and Browne GH (2001) *A Reservoir Study of the Tariki Sandstone, Onshore Taranaki*. New Zealand Unpublished Open-file Petroleum Report, PR2616, 350 pp., 319 enclosures.

Higgs KE, Pollock RM, Field BD and Strong CP (2004b) *Kauri Sandstone Reservoir Study, Taranaki Basin, New Zealand*. Institute of Geological and Nuclear Sciences, Client Report 2004/72, 344 pp.

Higgs KE, Strogen DP, Griffin AG, Ilg B and Arnot MJ (2012b) *Reservoirs of the Taranaki Basin, New Zealand*. GNS Science Data Series, 2012/13a. 1 CD.

Hood SD, Nelson CS and Kamp PJJ (2003a) Lithostratigraphy and depositional episodes of the Oligocene carbonate-rich Tikorangi Formation, Taranaki Basin, New Zealand. *New Zealand Journal of Geology and Geophysics* 46, 363–86.

Hood SD, Nelson CS and Kamp PJJ (2003b) Petrogenesis of diachronous mixed siliciclastic-carbonate megafacies in the cool-water Oligocene Tikorangi Formation, Taranaki Basin, New Zealand. *New Zealand Journal of Geology and Geophysics* 46, 387–405.

Hornibrook ND, Brazier RC and Strong CP (1989) *Manual of New Zealand Permian to Pleistocene Foraminiferal Biostratigraphy*. New Zealand Geological Survey, Paleontological Bulletin 56. Lower Hutt: New Zealand Geological Survey, 175 pp.

Johnston MR (1979) *Geology of the Nelson Urban Area*. New Zealand Geological Survey Urban Series 1. Wellington: Department of Scientific and Industrial Research, 52 pp. + 51 fold map.

Jordan DW (1989) *Sedimentologic Analysis of Conventional Core Samples from the Kora-4 Well, New Zealand*. New Zealand Unpublished Open-file Petroleum Report, PR1444, 38 pp.

Kamp PJJ (1986) The mid-Cenozoic Challenger Rift system of western New Zealand and its implications for the age of Alpine fault inception. *Geological Society of America Bulletin* 97, 255–81.

Kamp PJJ, Tripathi ARP and Nelson CS (2008) *Stratigraphic Columns and Correlations for the Late Eocene – Oligocene Te Kuiti Group, Central-Western North Island, New Zealand*. New Zealand Unpublished Open-file Petroleum Report, PR3901, 257 pp.

Kamp PJJ, Tripathi ARP and Nelson CS (2014) Paleogeography of Late Eocene to earliest Miocene Te Kuiti Group, central-western North Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 57, 128–48.

King PR (1988a) *Well Summary Sheets, Onshore Taranaki*. New Zealand Geological Survey Report G125. Wellington: Department of Scientific and Industrial Research, 14 pp.

King PR (1988b) *Well Summary Sheets, Offshore Taranaki*. New Zealand Geological Survey Report G127. Wellington: Department of Scientific and Industrial Research, 18 pp.

King PR (2000) Tectonic reconstructions of New Zealand 40 Ma to the present. *New Zealand Journal of Geology and Geophysics* 43, 611–38.

King PR, Naish TR, Browne GH, Field BD and Edbrooke SW (1999) *Cretaceous to Recent Sedimentary Patterns in New Zealand*. Institute of Geological and Nuclear Sciences Folio Series 1. Lower Hutt: Institute of Geological and Nuclear Sciences, 35 pp, 39 transects, 31 enclosures.

King PR and Thrasher GP (1996) *Cretaceous–Cenozoic Geology and Petroleum Systems of the Taranaki Basin, New Zealand*. Institute of Geological and Nuclear Sciences Monograph 13. Lower Hutt: Institute of Geological and Nuclear Sciences, 243 pp, 246 enclosures.

Leask WL (1993) Brunner Coal Measures at Golden Bay, Nelson: an Eocene fluvial-estuarine deposit. *New Zealand Journal of Geology and Geophysics* 36, 37–50.

Lever H (2007) Review of unconformities in the late Eocene to early Miocene successions of the South Island, New Zealand: ages, correlations, and causes. *New Zealand Journal of Geology and Geophysics* 50, 245–61.

Lewis DW and Belliss SE (1984) Mid-Tertiary unconformities in the Waitaki Subdivision, North Otago. *Journal of the Royal Society of New Zealand* **14**, 251–76.

Martin KR and Baker JC (1991) Petrology, diagenesis and reservoir quality of sandstones from the Kapuni Group in Toru No. 1, Taranaki Basin. In *Toru-1 Well Completion Report PPL 38116* (ed. SJ Crocker), pp. 586–647. New Zealand Unpublished Open-file Petroleum Report, PR1668.

Morgans HEG, Beu AG, Cooper RA, Crouch EM, Hollis CJ, Jones CM, Raine JI, Strong CP, Wilson GJ and Wilson GS (2004) Paleogene. In *The New Zealand Geological Timescale* (ed. RA Cooper), pp. 125–61. Lower Hutt: Institute of Geological and Nuclear Sciences Monograph 22.

Morgans HEG, Scott GH, Beu AG, Graham IJ, Mumme T, St George W and Strong CP (1996) *New Zealand Cenozoic Timescale (version 11/96)*. Institute of Geological and Nuclear Sciences Science Report 96/38. Lower Hutt: Institute of Geological and Nuclear Sciences, 12 pp.

Mortimer N, Rattenbury MS, King PR, Bland KJ, Barrell DJA, Bache F, Begg JG, Campbell HJ, Cox SC, Crampton JS, Edbrooke SW, Forsyth PJ, Johnston MR, Jongens R, Lee JM, Leonard GS, Raine JI, Skinner DNB, Timm C, Townsend DB, Tulloch AJ, Turnbull IM and Turnbull RE (2014) High-level stratigraphic scheme for New Zealand rocks. *New Zealand Journal of Geology and Geophysics* **57**, 402–19.

Nathan S, Anderson HJ, Cook RA, Herzer RH, Hoskins RH, Raine JI and Smale D (1986) *Cretaceous and Cenozoic Sedimentary Basins of the West Coast Region, South Island, New Zealand*. New Zealand Geological Survey Basin Studies 1. Wellington: Department of Scientific and Industrial Research, 89 pp.

Nelson CS (1978) Stratigraphy and paleontology of Oligocene Te Kuiti Group, Waitomo County, South Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics* **21**, 553–94.

Nelson CS, Kamp PJJ and Young HR (1994) Sedimentology and petrography of mass-emplaced limestone (Orahiri Limestone) on a late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of Taranaki Basin. *New Zealand Journal of Geology and Geophysics* **37**, 269–85.

Nelson CS, Lee D, Maxwell PA, Maas R, Kamp PJJ and Cooke S (2004) Strontium isotope dating of the New Zealand Oligocene. *New Zealand Journal of Geology and Geophysics* **47**, 719–30.

New Zealand Petroleum & Minerals (2013) *New Zealand Petroleum Basins*. Wellington: Ministry of Business, Innovation and Employment, 104 pp.

OMV New Zealand Limited (2004) *Seal Potential of Deepwater Oligocene Carbonates. Project Outline and Phase 1 Results. PEP38485 Northern Taranaki Basin*. New Zealand Unpublished Open-file Petroleum Report, PR3341, 21 pp.

OMV New Zealand Limited (2007) *Moana-1 Well Completion Report*. New Zealand Unpublished Open-file Petroleum Report, PR3830, 835 pp.

Palmer J (1985) Pre-Miocene lithostratigraphy of Taranaki Basin, New Zealand. *New Zealand Journal of Geology and Geophysics* **28**, 197–216.

Raine JI (1984) *Outline of a Palynological Zonation of Cretaceous to Paleogene Terrestrial Sediments in West Coast Region, South Island, New Zealand*. New Zealand Geological Survey, Report 109. Lower Hutt: New Zealand Geological Survey, 82 pp.

Raine JI (2004) New Eocene and Oligocene miospore zones and subzones. Appendix to Chapter 11. In *The New Zealand Geological Timescale* (ed. RA Cooper), pp. 162–3. Lower Hutt: Institute of Geological and Nuclear Sciences Monograph 22.

Raine JI, Beu AG, Boyes AF, Campbell HJ, Cooper RA, Crampton JS, Crundwell MP, Hollis CJ and Morgans HEG (2015a) *Revised Calibration of the New Zealand Geological Timescale: NZGT2015/1*. GNS Science Report 2012/39. Lower Hutt: GNS Science, 53 pp.

Raine JI, Beu AG, Boyes AF, Campbell HJ, Cooper RA, Crampton JS, Crundwell MP, Hollis CJ, Morgans HEG and Mortimer N (2015b) New Zealand geological timescale NZGT 2015/1. *New Zealand Journal of Geology and Geophysics* **58**, 398–403.

Reilly C, Nicol A, Walsh JJ and Seebeck H (2015) Evolution of faulting and plate boundary deformation in the Southern Taranaki Basin, New Zealand. *Tectonophysics* **651–652**, 1–18.

Riordan NK, Reid CM, Bassett KN and Bradshaw JD (2014) Reconsidering basin geometries of the West Coast: the influence of the Paparoa Core Complex on Oligocene rift systems. *New Zealand Journal of Geology and Geophysics* **57**, 170–84.

Stagpoole VM and Nicol A (2008) Regional structure and kinematic history of a large subduction back thrust: Taranaki Fault, New Zealand. *Journal of Geophysical Research* **113**, B01403. doi: 10.1029/2007JB005170.

Strogen DP (comp.) (2011) *Updated Paleogeographic Maps for the Taranaki Basin and Surrounds*. GNS Science Report 2010/53. Lower Hutt: GNS Science, 83 pp.

Strogen DP, Bland KJ, Nicol A and King PR (2014) Paleogeography of the Taranaki Basin region during the latest Eocene–Early Miocene and implications for the 'total drowning' of Zealandia. *New Zealand Journal of Geology and Geophysics* **57**, 110–27.

Strogen DP and King PR (2014) *A New Zealandia-Wide Seismic Horizon Naming Scheme*. GNS Science Report 2014/34. Lower Hutt: GNS Science, 20 pp.

Strogen DP, Seebeck H, Nicol A and King PR (2017) Two-phase Cretaceous–Paleocene rifting in the Taranaki Basin region, New Zealand; implications for Gondwana break-up. *Journal of the Geological Society, London* **174**, 929–46.

Strong CP (2008) *Foraminiferal Biostratigraphy of Moana-1 Offshore Well, Northern Taranaki*. New Zealand Unpublished Open-file Petroleum Report, PR3788, 14 pp.

Sutherland R, Collot J, Bache F, Henrys S, Barker D, Browne GH, Lawrence MJF, Morgans HEG, Hollis CJ, Clowes C, Mortimer N, Rouillard P, Gurnis M, Etienne S and Stratford W (2017) Widespread compression associated with Eocene Tonga-Kermadec subduction initiation. *Geology* **45**, 355–8.

Sutherland R, Spasojevic S and Gurnis M (2010) Mantle upwelling after Gondwana subduction death explains anomalous topography and subsidence histories of eastern New Zealand and West Antarctica. *Geology* **38**, 155–8.

Swift Energy New Zealand Ltd (2005) *Tawa B-1; Tawa B-1 ST1 & Tawa B-1 ST2*. New Zealand Unpublished Open-file Petroleum Report, PR3207, 1163 pp, 1166 enclosures.

Tripathi ARP and Kamp PJJ (2008) Timing of initiation of reverse displacement on the Taranaki Fault, northern Taranaki Basin: constraints from the on land record (Oligocene Te Kuiti Group). In *New Zealand Petroleum Conference Proceedings 2008*, 17 pp. Wellington: Ministry of Economic Development.

Turnbull IM, Browne GH, Mortimer N and Raine JI (2008) *Eocene Paleogeography of Western Southland and its Implications for Hydrocarbon Exploration*. New Zealand Unpublished Open-file Petroleum Report, PR3837, 68 pp.

Turnbull IM, Uruski CI, Anderson HJ, Lindqvist JK, Scott GH, Morgans HEG, Hoskins RH, Raine JI, Mildenhall DC, Pocknall DT, Beu AG, Maxwell PA, Smale D, Watters WA and Field BD (1993) *Cretaceous and Cenozoic Sedimentary Basins of Western Southland, South Island, New Zealand*. Institute of Geological and Nuclear Sciences Monograph 1. Lower Hutt: Institute of Geological and Nuclear Sciences, 86 pp.

Walcott RI (1978) Present tectonics and Late Cenozoic evolution of New Zealand. *Geophysical Journal of the Royal Astronomical Society* **52**, 137–64.

Wood RA and Stagpoole VM (2007) Validation of tectonic reconstructions by crustal volume balance: New Zealand through the Cenozoic. *Geological Society of America Bulletin* **119**, 933–43.