The early Middle Miocene paleoenvironmental setting of New Zealand

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ABSTRACT

New Zealand has a middle Miocene (~16.4-11.2 Ma) sedimentary record that extends from terrestrial through to distal oceanic paleoenvironmental settings available for study in outcrop, petroleum exploration wells and deep sea drillholes. We use this data to establish a new model for the region at the beginning of middle Miocene times on a palinspastic base map, as a starting point for the study of later middle Miocene global cooling and its effects.

The New Zealand record provides useful clues to SW Pacific circulation patterns and the effects of global cooling during the middle Miocene. The New Zealand subcontinent extended over several degrees of paleolatitude and probably formed a north-south barrier to warm, South Pacific gyre circulation, forcing warm-temperate surface currents to pass up the western coast. To the south, cold circumpolar currents entered the Pacific and passed up the SE margin of paleo-New Zealand. Shelves were narrow in the north and west but broadened to several tens of kilometres wide in the east and south.

Age-recalibration of published stable isotope data from DSDP sites 608, 588 and 590 shows the main cooling period of the middle Miocene coincides with the New Zealand Lillburnian Stage. There also appears to have been a short period of cooling of bottom waters around 16.3 Ma (the base of the New Zealand Clifdenian Stage), perhaps recording climatic instability just prior to buildup of the East Antarctic Ice Sheet. Though we cannot yet determine if the ~16 Ma cooling was associated with glacioeustatic sea level fall, the proximal sedimentary record for New Zealand at this time is consistent with a fall, followed by a rise. There is good evidence for contemporaneous tectonism and this might account for much or all of the fall. However, because the fall in relative sea level occurred in several basins, on either side of the plate boundary, a purely tectonic origin would require it to be a New Zealand-wide event.

Key words: middle Miocene, New Zealand, paleogeography, paleoclimate, isotopes, DSDP site, 608, 588, 590, eustasy, tectonics

RESUMEN

Nueva Zelanda tiene un registro sedimentario correspondiente al Mioceno medio (~16.4-11.2 Ma) que se extiende desde condiciones paleoambientales terrestres hasta ambientes oceánicos distantes disponible para su estudio en afloramientos, exploración de pozos petroleros y perforaciones marinas profundas. Utilizamos estos datos para establecer un nuevo modelo para la región al inicio del Mioceno medio basados en un mapa palinspástico de base, como un punto de partida para el estudio del enfriamiento global y sus efectos durante el Mioceno medio tardío.

El registro de Nueva Zelanda proporciona indicios útiles sobre los patrones de circulación del Pacífico Suroccidental y sus efectos sobre el enfriamiento global durante el Mioceno medio. El subcontinente de Nueva Zelanda se extendió a lo largo de varios grados de paleolatitud y probablemente formó una barrera norte-sur a la circulación cálida de giro del Pacífico Sur, forzando a las corrientes tibias superficiales a subir por la costa occidental. Hacia el sur, las frías corrientes cir-

cumpolares entraron al Pacífico y subieron por la margen sureste de Nueva Zelanda. Las plataformas eran angostas en el norte y occidente pero se ampliaron a varias decenas de kilómetros en el este y sur.

La recalibración de edades de los datos de isotopía estable publicados de los sitios DSDP 608, 588 y 590 muestra que el periodo principal de enfriamiento del Mioceno medio coincide con la etapa Lillburniana de Nueva Zelanda. También parece haber habido un periodo corto de enfriamiento de las aguas profundas alrededor de 16.3 Ma (la base de la etapa Clifdeniana de Nueva Zelanda), quizás registrando una inestabilidad climática justo antes de la formación de la Capa de Hielo de la Antártica Este. Aunque todavía no podemos determinar si el enfriamiento de ~16 Ma estuvo asociado con una caída glacio-eustática del nivel del mar, el registro sedimentario proximal para Nueva Zelanda en ese tiempo es consistente con una caída, seguida de una elevación. Existe suficiente evidencia de un tectonismo contemporáneo y esto podría ser la causa de gran parte, o de toda, la caída. Sin embargo, debido a que la caída en el nivel relativo del mar ocurrió en varias cuencas, en ambos lados de los límites de la placa, un origen puramente tectónico hubiese producido un evento en toda Nueva Zelanda.

Palabras clave: Mioceno medio, Nueva Zelanda, paleogeografía, paleoclima, isótopos, Sitios DSDP 608, 588, 590, eustasia, tectónica.

INTRODUCTION

The middle Miocene was a time of major global climatic cooling. Stable isotope data indicate the oceans cooled by several degrees and it is inferred that the East Antarctic Ice Sheet expanded during this time (Savin *et al.*, 1975; Shackleton and Kennett, 1975; Kennett, 1977). The δ^{18}O isotope record indicates that the cooling and ice sheet expansion occurred in steps, most probably with accompanying glacioeustatic falls in sea level (*e.g.*, Bartek *et al*., 1991; Miller *et al*., 1991; Flower and Kennett, 1993). Changes also occurred in the δ^{13}C signature that were consistent with cooling caused by a reverse-greenhouse mechanism (Monterey Hypothesis of Vincent and Berger, 1985). In this model, organic carbon was locked up in sediments of the Monterey Formation and of coeval circum-Pacific correlatives, thus removing carbon from the ocean-atmosphere system, reducing atmospheric CO_2 and causing cooling. Recently, however, Pagani (1999) reported that CO_2 levels were high during middle Miocene global cooling, contrary to expectations (see Flower, 1999). Further studies of the middle Miocene are needed for better understanding of climate change during this period and its causes.

New Zealand's SW Pacific record spans several degrees of paleolatitude and paleoenvironmental settings range from terrestrial to oceanic. Neogene uplift has exposed outcrops of terrestrial, shelf and slope deposits, petroleum exploration wells provide data on bathyal settings near to New Zealand and DSDP and ODP sites provide data on distal, fully oceanic settings. Our study focuses on determining what effects middle Miocene global climate changes had on the sediments and biota of this region. Preliminary results are presented, based on paleogeographic mapping of the New Zealand region for the beginning of the middle Miocene, as a starting point for comparisons with studies underway of younger parts of the middle Miocene.

Biostratigraphic, isotopic, magnetostratigraphic and cyclostratigraphic studies presently underway will assist correlation of the proximal record (*viz.* outcrop, petroleum well and seismic data) with the distal record of oceanic DSDP and ODP sites in the New Zealand region, and will lead to a higher resolution chronostratigraphy for the middle Miocene of New Zealand. The effects of contemporaneous tectonism associated with the Australian-Pacific plate boundary complicate the sedimentary record of climate and glacioeustasy in particular and it is difficult to assess reliably the relative effects of these factors.

Previous work

Most of the Cretaceous and Cenozoic sedimentary rocks of New Zealand have been studied as part of a series of basin analysis projects (Figure 1). These reviews incorporate extensive biostratigraphic and lithostratigraphic reviews of outcrop sections, and well and seismic data collected by petroleum exploration companies. Much of the data and conclusions from these studies form the framework for the present study of the middle Miocene and, in particular, the data under "Proximal Record" below. Though many paleogeographic maps of New Zealand for the middle Miocene have been published before (*e.g*., Stevens and Suggate, 1978; King *et al.*, 1999), none has been prepared on a palinspastic base and at the high temporal resolution for the early middle Miocene presented here.

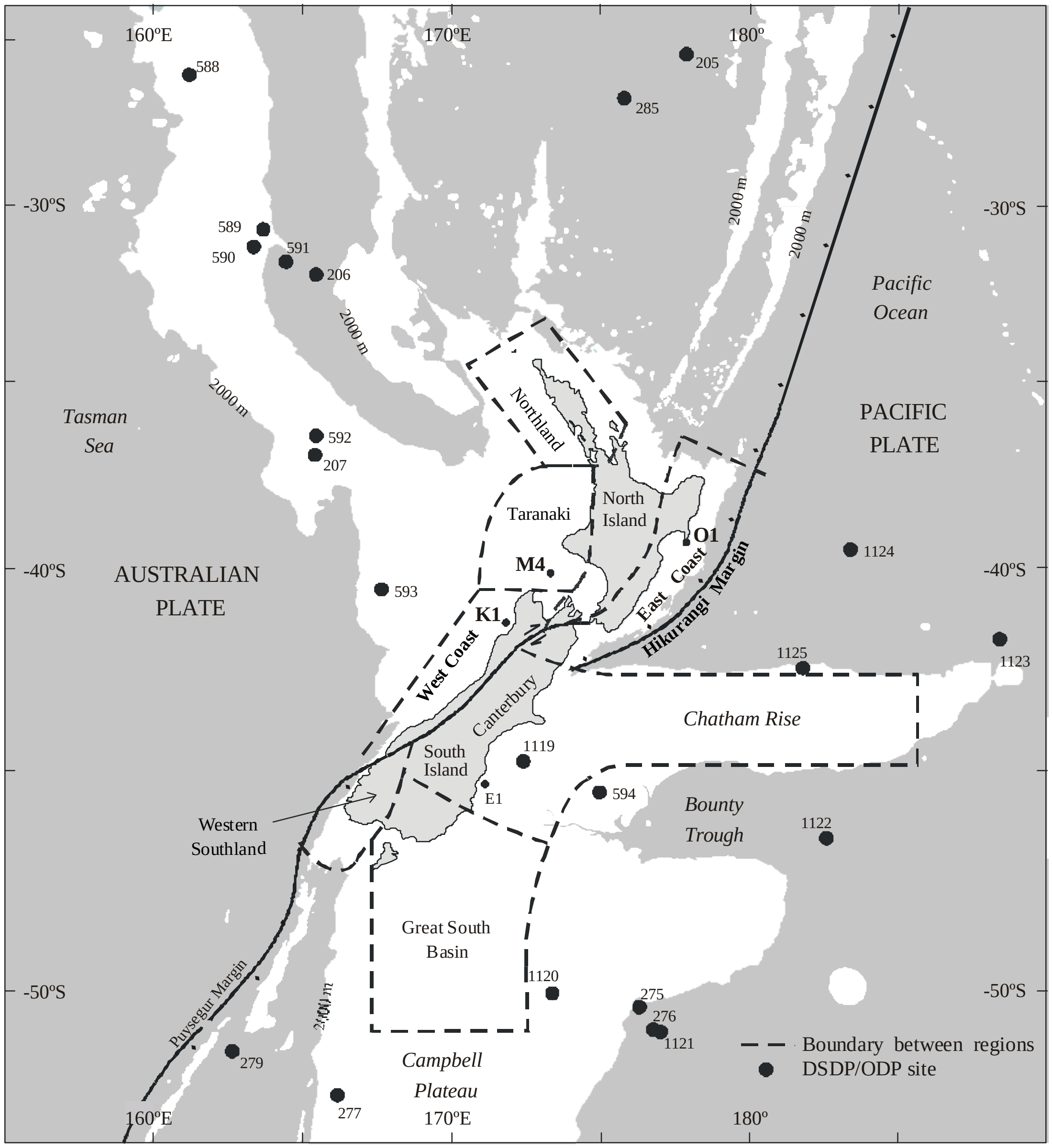

Figure 1. Present-day New Zealand, showing some of the main sedimentary basins. Data from each basin was used to develop the paleogeography map (Figure 4). The main references for each region are: Northland (Isaac *et al*., 1994), East Coast (Field *et al*., 1997), Canterbury (Field *et al*., 1989), Great South Basin (Cook *et al*., 1999), Western Southland (Turnbull *et al*., 1993), West Coast (Nathan *et al*., 1986) and Taranaki (King and Thrasher, 1996). Petroleum exploration wells: O1 = Opoutama-1, E1 = Endeavour-1, K1 = Kongahu-1, M4 = Maui-4.

Dating

In New Zealand, the middle Miocene is subdivided formally into the Clifdenian (oldest), Lillburnian and Waiauan Stages (Figure 2) that have their stratotypes in southern South Island. The stages are correlated generally and subdivided on the basis of foraminiferal biostratigraphy although, in shallow water facies, molluscan datums are commonly used in preference. The base of the Clifdenian is generally accepted as the base of the middle Miocene in New Zealand although there are few local geochronological or magnetostratigraphic data to confirm this correlation. Berggren *et al.* (1995) placed the base of the Langhian (base middle Miocene) at 16.4 Ma. The base of the Langhian is marked by the first occurrence (FO) of *Praeorbulina curva*, the earliest praeorbuline element of the *Orbulina* bioseries. This species shows a significant departure in chamber packing from its ancestral form, *Globigerinoides trilobus.* Berggren *et al.* (1995) place this FO

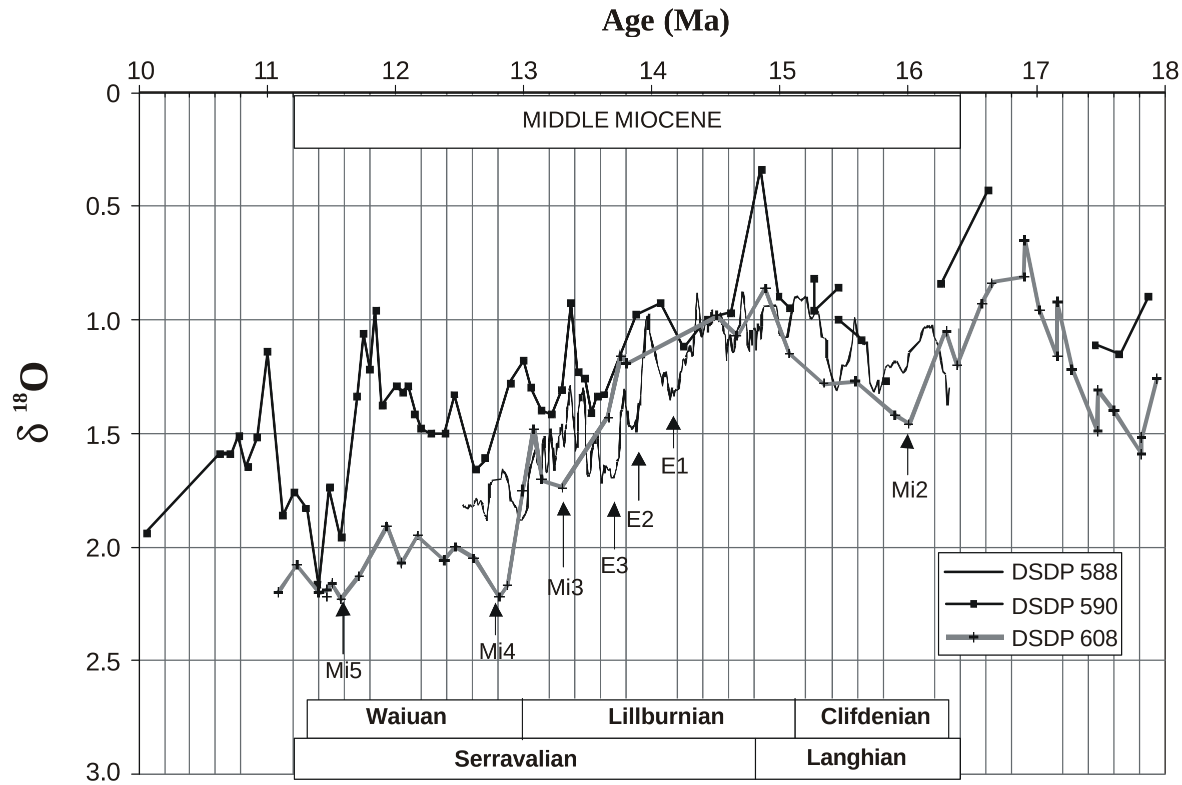

Figure 2. Recalibrated ä^{18}O curves for DSDP Sites 588, 590 and 608. The three New Zealand middle Miocene stages are correlated with the two international stages and absolute ages after Morgans *et al*. (1996) following Berggren *et al*. (1995). Site 588 data are from benthic *Cibicidoides* (Flower and Kennett, 1993) with data smoothed using a 5-point moving average and with ages adjusted to Berggren *et al*. (1995). Site 590 data are for the benthic *Cibicidoides kullenbergi*, from (Kennett, 1986), with age data adjusted: the Berggren *et al*. (1985) ages for the nannofossil datums of Richter *et al.* (1988) have been recalibrated to the geomagnetic polarity time scale of Cande and Kent (1995) using Wei (1997). The gap in data at ~16 Ma reflects the base middle Miocene unconformity at 590. Data for Site 608 are for benthic *Cibicidoides* spp. from Wright *et al*. (1992) after Miller *et al*. (1990) and Clement *et al*. (1987) with ages adjusted to Berggren *et al*. (1995). For locations of sites 588 and 590 see figures 1 and 3. Site 608 is in the North Atlantic. Events Mi2 to Mi5 are from Miller *et al*. (1991); E1-E3 are from Flower and Kennett (1993). The correlation of the Lillburnian-Waiauan boundary with the International Time Scale is particularly poorly-constrained (Morgans *et al*., 1996).

near the middle of chron C5Cn.

The base of the New Zealand Clifdenian Stage is also marked by the FO of *Praeorbulina curva*. The local FO of *P. curva* is not constrained by magnetostratigraphy or radiometric dating but was placed, pending further work, at 16.3 Ma by Morgans *et al.* (1996) by comparison with the ages in Berggren *et al.* (1995). In our study, the base of the Clifdenian is placed at the level at which there are at least 10% of *Praeorbulina curva* morphotypes relative to advanced *Globigerinoides bisphericus* morphotypes. This datum is slightly younger than the first occurrence of very rare *P. curva* in well-preserved oceanic sequences, such as at DSDP Site 593. However, the datum is considered to be more representative of proximal sequences, where very rare early morphotypes of *P. curva* are unlikely to be recorded due to lower relative abundance of planktics. Berggren *et al.* (1995) have noted that in advanced populations of *G. bisphericus* the morphological transition to *P. curva* occurs over a period of less than 0.1 Ma.

The base of the Lillburnian Stage is marked by the FO of *Orbulina suturalis* and the stage is informally divided into upper and lower parts by the FO of *Orbulina universa*. The top of the Lillburnian Stage is marked by the last occurrence (LO) of *Fohsella peripheronda* (Scott, 1991). The Waiauan stage occurs from immediately above the LO of *F. peripheronda* to immediately below the base of the Kaiti Coiling Zone (a distinctive zone of dextrally-coiled *Globorotalia miotumida* that marks a temporary excursion in the species' preferred sinistral coiling direction, Scott, 1995).

We have re-plotted the isotope results from DSDP Sites 588 and 590 from the Tasman Sea (Kennett, 1986; Flower and Kennett, 1993), and Site 608 from the North Atlantic (Wright *et al.*, 1992) against a revised time scale based on Berggren *et al.* (1995). This allows comparison with the New Zealand time scale (Figure 2), though it does not allow for any diachroneity between the bio-events used by Berggren *et al.* and the same events in the New Zealand region.

By using these correlations (Figure 2) we can expect to find sedimentary and faunal events associated with the main, baseline shift in $\delta^{18}O$ of 0.5-1.0 per mil, attributed to the build-up of the East Antarctic Ice Sheet and major global cooling, during the Lillburnian Stage. Sedimentary and faunal events associated with lesser isotope excursions might also be recognisable, such as Mi2 (of Miller *et al.*, 1991) in the lower Clifdenian, a "composite" event (E1-E3 of Flower and Kennett, 1993) in the upper Lillburnian, and further events near the base and top of the Waiauan. The high-resolution dataset from DSDP 588 (Flower and Kennett, 1993) suggests the possibility of additional events in the mid-upper Clifdenian. Results from ODP Leg 181, and high-resolution isotope studies underway at DSDP 593 and from outcrops in New Zealand, should test these correlations.

Foraminiferal ocean temperature proxies

Surface-water temperature proxies in this study are based on planktic foraminifera. A preliminary review of Clifdenian sequences indicates at least two biogeographic assemblages at or near the base of the Clifdenian: a warm temperate assemblage dominated by *Zeaglobigerina* and *Globigerina* and with >5% *Globigerinoides* (a warm-water subtropical/tropical taxon); and a cool temperate assemblage dominated by *Zeaglobigerina* and *Globigerina* and with <5% *Globigerinoides*. Although warm-water taxa are noted, no truly subtropical assemblages occur. Most assemblages have relatively low abundances of warm-water taxa (rarely exceeding 15%), moderately low diversities, moderately small specimens with compactly-coiled tests, and small supplementary apertures in globigerinoidine taxa.

Tectonic setting

At present, New Zealand straddles the boundary between the Pacific and Australian plates (Figure 1). To the northeast, at the Hikurangi margin, the Pacific plate is subducting thickened oceanic crust beneath continental crust of the Australian plate. To the southwest of New Zealand, at the Puysegur margin, the oceanic crust of the Australian plate is subducting beneath continental crust of the Pacific plate. A northeast-trending transform, the Alpine Fault, crosses New Zealand and links the two subduction margins. This system developed during the late Paleogene and tectonics associated with its changing geometry affected middle Miocene sedimentation.

In the early middle Miocene (Figure 4), the Puysegur subduction margin had not yet developed and the early Alpine Fault transform was the main tectonic feature in southern New Zealand (Davey and Smith, 1983). The effects of plate tectonism in the proto-North Island included volcanism in the north and reverse faulting and shortening associated with Hikurangi margin subduction (reviewed in King, 2000).

Arc volcanism in Northland that had begun ~22 Ma (Isaac *et al.*, 1994) was waning by the early middle Miocene, though new centers were establishing at Coromandel Peninsula and in northern Taranaki Basin. The East Coast (North Island) region was adjacent to the Hikurangi subduction margin and shows evidence of thrust development, probable strike slip faulting and anticline growth during the middle Miocene (Field *et al.*, 1997). King and Thrasher (1996) also identified middle Miocene thrusting in Taranaki, to the west, and Nathan (1986) noted significant middle Miocene subsidence and uplift events in the West Coast region of the South Island.

PALEOGEOGRAPHY

Distal record

The clay mineral assemblages at Site 593 were inferred by Robert (1986) to have been derived from the South Island, suggesting northeastward current flow in the eastern part of the Tasman Sea. The warm surface currents indicated by planktic foraminiferal assemblages at 593 are therefore inferred to have flowed northeastward along the west coast of New Zealand (Figure 4). Such currents may well have intensified between Northland and the West Norfolk Ridge (Eade, 1988; Isaac *et al.*, 1994), on the north side of the New Caledonia Basin.

The Clifdenian interval at Site 593 is condensed (sedimentation rate 0.9 m/Ma), perhaps indicating a change in bottom current regimes during this Stage. Faunas east and south of Western Southland (Sites 279 and 594 and petroleum exploration wells Kawau-1 and Endeavour-1) suggest cooler surface waters than at Site 593. These cooler currents probably swept the top of the Chatham Rise, causing the winnowing of early Miocene sediments and contributing to development of extensive hardground and glauconite and phosphorite deposits on the Rise (Zobel, 1984). The Deep Western Boundary Current would have passed to the east of Campbell Plateau (Carter and McCave, 1994).

Proximal record

Data for the following descriptions were derived mainly from the review volume for each respective basin study region (see citations in Figure 1). The central parts of the New Zealand subcontinental platform are inferred to have been eroding in the early middle Miocene due to uplift associated with convergent motion on the Australia-Pacific plate boundary. There is no direct evidence for seaways across New Zealand at this time and New Zealand appears to have formed a solid, north-south barrier to ocean circulation systems over a wide latitude (Figure 3). However, late Neogene erosion of central New Zealand has removed most of the middle Miocene record for axial New Zealand and the possibility of trans-New Zealand seaways cannot be ruled out. Heavy mineral studies in Canterbury (Smale in Field *et al.*, 1989) and regional studies of the East Coast North Island (Field and Delteil, 1998) indicate that basement rocks had shed much of their cover of Cretaceous to early Miocene sediments by the early middle Miocene. Conglomerate is rare in early middle Miocene formations, in contrast to the late Miocene, suggesting that the rising axial belt had generally subdued relief.

Units occurring at the boundary between the early and middle Miocene are shown schematically in Figure 3. In basins where there is sufficient age-control there is an up-section coarsening, in places with an unconformity at the base, in Clifdenian successions. These changes in lithofacies and paleobathymetry estimates based on foraminifera are consistent with a relative fall in sea level at about the base of the Clifdenian.

Paleogeographic mapping of the middle Miocene for Northland is based largely on inference as the middle Miocene is poorly preserved. Volcanism associated with waning subduction to the northeast continued from the early Miocene and coal measures of inferred middle Miocene age occur locally in northern New Zealand. Seismic profiles indicate that continental margins were steep and areas at shelf depths were narrow.

East Coast North Island outcrop evidence suggests a fall in relative sea level (tectonic and/or eustatic) at about the early to middle Miocene boundary. Bathyal channels filled with coarse, shelf-derived debris occur locally (Field and Scott, 1993) and shelfal sandstones transgress over early Miocene bathyal mudstones (Cutten, 1994; Crundwell, 1997). A shelf perhaps 10-20 km wide is inferred over much of the East Coast, with turbidite fans of probably middle Miocene age developed further east. Foraminifera in the Tattons Sandstone (Crundwell, 1987), and just west of Titihaoa-1 (Figure 4) and at Opoutama-1, suggest influence of a warm temperate current. This current might have been derived from the north or perhaps through a seaway across New Zealand west of Opoutama-1 (though, as discussed above, this latter option is speculative).

The eastern South Island was adjacent to the Alpine Fault transform and was probably more quiet tectonically than the East Coast region of the North Island. The South Island lacks the turbidite fans typical of the East Coast region and was marked by lower sedimentation and subsidence rates (Field and Browne, 1993). In present-day onshore and offshore Canterbury, shelfal to bathyal silty mudstones of the Waima, Tokama and Rifle Butts formations are the most common early middle Miocene lithology. Landward, shelf sands of the Mount Brown Formation are preserved in the north and fine-grained paralic White Rock Coal Measures occur in the south. At Endeavour-1, the base of the Clifdenian stage is not well defined but probably occurs at about 2,750 m. This depth coincides with an onlap surface evident on a seismic reflection profile (line CB82-19, Shell *et al.*, 1984) and is inferred to be a sequence boundary. The base of the Lillburnian stage coincides with a sequence boundary recognised on this seismic line and the Clifdenian record is truncated. The Clifdenian record is missing or at least incomplete

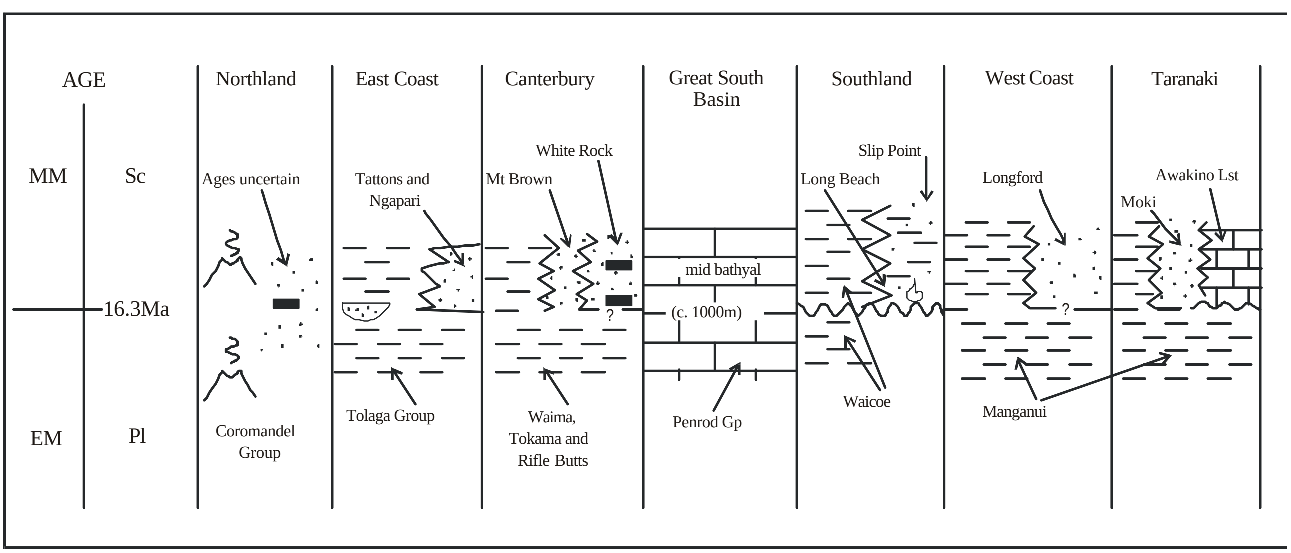

Figure 3. Schematic stratigraphy at base Clifdenian time within New Zealand's main sedimentary basins. EM = Early Miocene; MM = Middle Miocene; Pl = Altonian stage; Sc = Clifdenian stage. For each column, distal settings are depicted on the left and proximal settings are on the right.

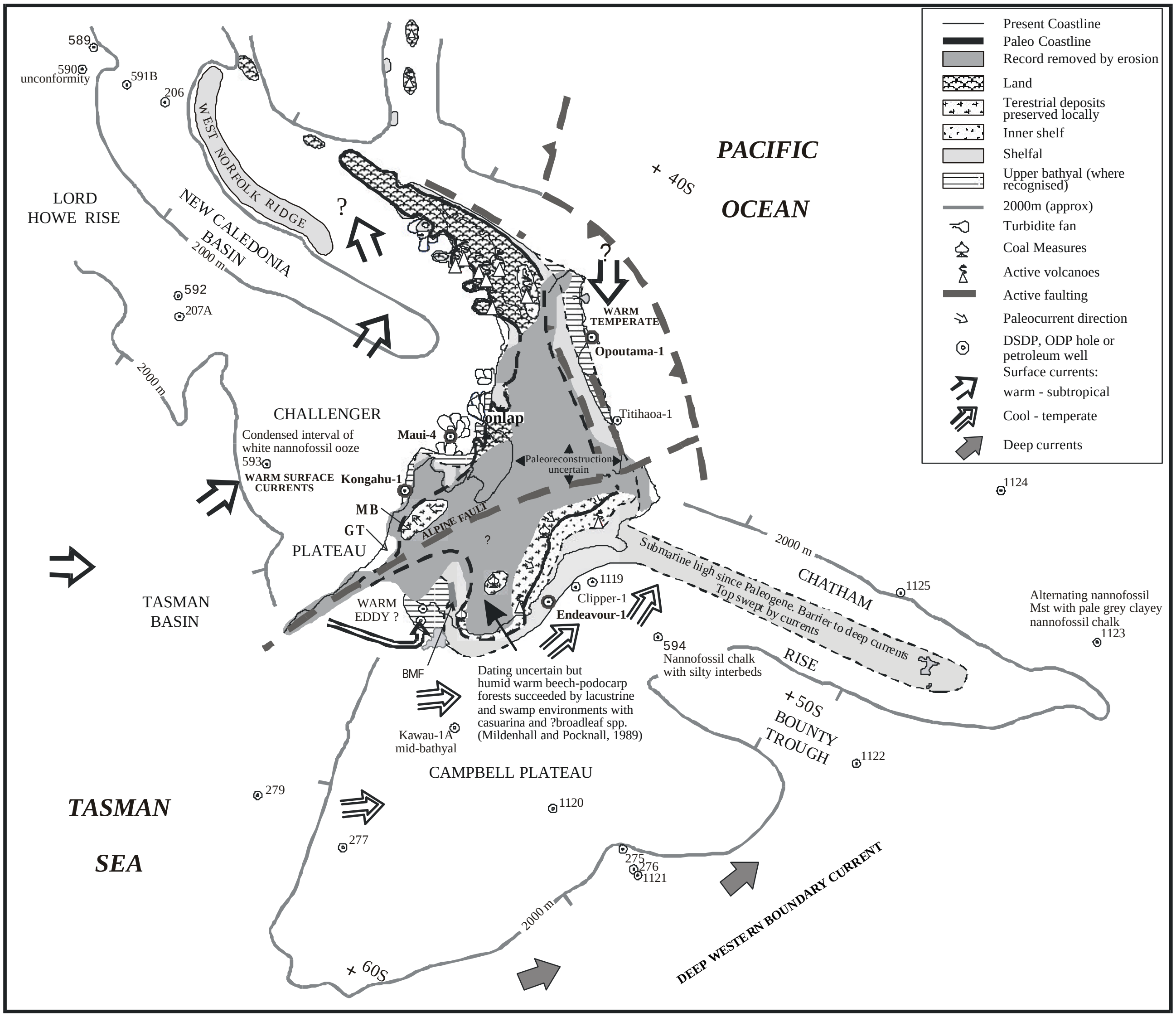

Figure 4. Paleogeographic map at base Clifdenian times. The palinspastic map used in this study is derived from both plate motions and New Zealand geological data (after King, 2000, #16). BMF = Bell Mount Fault, MB = Murchison Basin, GT = Grey Trough. Terrestrial palynology after Mildenhall AND Pocknall (1989).

at the Clipper-1 well (Figure 4).

In Western Southland there is a widespread, commonly angular unconformity seen in seismic profiles between the early Miocene and early middle Miocene. The Bell Mount Fault was active, and lay along the shelf break between terrestrial to generally shallow marine sediments in the east of the basin and bathyal mudstone of the Waicoe Formation in the west. In the shelfal part, the base of the middle Miocene lies within or on the Long Beach Shellbed that is overlain by deeper water Slip Point Siltstone (Wood, 1969). The mudstones of the Waicoe Formation contain low numbers of planktics, suggesting a sheltered neritic environment. Oceanic circulation appears to have been restricted and this would be consistent with a submarine high extending to the southwest from the Alpine Fault (Figure 4). A warm temperate planktic foraminiferal assemblage suggests warm Tasman Sea currents reached this part of Western Southland. Further to the east and south of Western Southland, planktic faunas indicate the surface currents were cool temperate. The Great South Basin on the Campbell Plateau was blanketed by Penrod Group, middle Miocene bathyal mudstones.

Major, intra-middle Miocene unconformities removed the basal middle Miocene record over much of the present West Coast of the South Island (Nathan *et al.*, 1986). The western part of the region began to subside and the Murchison Basin and Grey Valley Trough continued to subside. In bathyal settings in the west, mudstones of the Manganui and Stillwater formations dominated, but further landward there is a general change up-section to sandy units (*e.g.* Longford Formation) at about the base of the middle Miocene succession.

Manganui Mudstone extends to the north, into the Taranaki Basin, though turbidite sands of the Moki Formation occur locally near the base of the middle Miocene. Further east, there are unconformites and evidence of flushing of shelfal sands and faunas into bathyal settings. These events were ascribed by King and Thrasher (1996) to pulses of tectonic activity on the Taranaki Fault.

New Zealand appears to have a good middle Miocene record of spores and pollen but the terrestrial climate for the early middle Miocene is not well understood as nowhere in New Zealand are pollen data sufficiently well dated. Current work is examining the palynomorph record of shelfal sections, where age control is from marine fossils, to develop a better pollen biostratigraphy and to relate it to foraminiferal biostratigraphic zones. In general, moist humid conditions prevailed in parts of Western Southland while further inland, in Central Otago, conditions were drier (Mildenhall, 2000).

DISCUSSION

A relative fall in sea level near the base of the Clifdenian Stage is apparent around most of New Zealand. Interim correlation of isotope data (Figure 2) suggests that the early part of the Clifdenian probably coincided with ocean cooling and hence the glacioeustatic fall of 50-75 m estimated for Mi2 by Miller *et al*. (1991). Transgressive, shallow marine sands of the East Coast region were probably deposited under a rising sea level on a broad shelf during a subsequent sea level rise slightly later in the Clifdenian. If so, this has significance for hydrocarbon reservoir assessment because other Clifdenian shelf sand deposits might be found in the subsurface. There should also be bathyal fan systems that built up through shelf flushing during the preceding sea level fall associated with Mi2; the Moki Formation turbidites of Taranaki seem to fit this model. Nevertheless, there is widespread evidence of tectonism: folding on the subduction margin of the East Coast (Cutten, 1994); an angular unconformity and active faulting under a compressional to transpressional regime in Western Southland (Turnbull *et al.*, 1993), and movement inferred on the Taranaki Fault in the Taranaki foreland basin (King and Thrasher, 1996). A wholly tectonic (rather than eustatic) origin for the inferred relative fall in sea level cannot be ruled out, though such a model would require contemporaneous, New Zealand-wide uplift in basins of differing tectonic origin.

It is difficult to distinguish any eustatic signals contemporaneous with active tectonism without reliable stable isotope data. So far we have been unable to obtain a reliable stable isotope signature from middle Miocene outcrops in New Zealand because of burial diagenesis. Our approach will be, of necessity, to accurately date isotope events using DSDP and ODP data and correlate these events with outcrops, petroleum wells and seismic reflection profiles.

Work in progress is extending our study through the rest of the middle Miocene. A New Zealand-wide review of middle Miocene proximal stratigraphic events is currently being linked to DSDP and ODP data to provide a coherent chronostratigraphic framework for New Zealand middle Miocene sedimentary and ecological events.

CONCLUSIONS

The middle Miocene record for the New Zealand region occurs in a diverse suite of paleoenvironmental settings, from terrestrial to distal oceanic across several degrees of paleolatitude.

Sedimentological and faunal data plotted on a new palinspastic map and constrained by recently revised local biostratigraphic datums depict the New Zealand subcontinent at 16.3 Ma. A terrestrial backbone, rising in response to development of the present plate boundary system, shed sediment into mainly deep marine settings in the north and west and onto broad shelves in the east and south.

The proximal record, combined with distal, DSDP data, suggests warm surface currents flowed northward along the west coast of New Zealand but did not pass further east than present-day Western Southland. Warm currents influenced at least northern East Coast. Cooler surface-water currents flowed northeast along the southeastern coast and would have enhanced development of phosphatic hardgrounds on the Chatham Rise.

Correlation of SW Pacific isotope records from sites 588 and 590 show the main period of global cooling during the middle Miocene occurred during the Lillburnian Stage. A precursor excursion consistent with cooling occurred in early Clifdenian times and this suggests that the sedimentary record of New Zealand for this time might show evidence for a glacioeustatic fall. Though evidence from proximal New Zealand is consistent with this, the record was at least locally overprinted by tectonism.

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