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Evolution of the sedimentary system beneath the deep Pacific inflow off eastern New Zealand

L. Carter[a,*], R.M. Carter[b], I.N. McCave[c]

[a] *National Institute of Water and Atmosphere, P.O.Box 14901, Wellington, New Zealand*
[b] *James Cook University, Townsville, Qld 4811, Australia*
[c] *Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK*

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Abstract

Results from Ocean Drilling Program sites 1121–1124 show the Eastern New Zealand Oceanic Sedimentary System (ENZOSS) evolved in response to: (1) the inception of the circum-Antarctic circulation, (2) orbital and non-orbital regulation of the global thermohaline flow, and (3) development of the New Zealand plate boundary. ENZOSS began in the early Oligocene following opening of the Tasmanian gateway and inception of the ancestral Antarctic Circumpolar Current (ACC) and SW Pacific Deep Western Boundary Current (DWBC). Widespread erosion, marked by the Marshall Paraconformity, was followed by extensive drift formation in the late Oligocene–early Miocene. Alternating nannofossil chalk and nannofossil-rich mud deposited in response to 41-kyr orbital regulation of the abyssal circulation, with the mudstones representing times of increased inflow of corrosive southern-source waters. Drift deposition at the deepest sites was interrupted by bouts of erosion coincident with Mi1–5 isotopic events signifying expansions of the East Antarctic Ice Sheet and enhanced bottom water formation. By late Miocene times, the basic ENZOSS was established. South of Bounty Trough, the energetic ACC instigated an erosional/low depositional regime. To the north, where the DWBC prevailed, orbitally regulated drift deposition continued. Increased convergence at the New Zealand plate boundary enhanced the terrigenous supply, but little of this sediment reached the deep ENZOSS as the three main sediment conduits – Solander, Bounty and Hikurangi channels – had not fully developed. The Plio–Pleistocene heralded a change from a carbonate- to terrigenous-dominant supply caused by interception of the DWBC by the three channels (~1.6 Ma for Bounty and Hikurangi, time of Solander interception unknown). The Solander and Bounty fans, and Hikurangi Fan-drift systems formed, and drifts downstream of those systems, received terrigenous detritus. Supply increased with accelerating uplift along the plate boundary, but delivery to the DWBC was regulated by eustatic fluctuations of sea level. Times of maximum supply to all three channels was during glacial lowstands whereas the supply either ceased (Bounty, Solander), or reduced (Hikurangi) in highstands. In glacial times, sediment was entrained by a DWBC invigorated by an increased input of Antarctic bottom water. The ACC also accelerated under strengthened glacial winds. Thus, glacials were times of optimum sediment supply to ENZOSS depocentres where depositional rates were 2–3 times more than interglacial rates.

Keywords: Deep Western Boundary Current; sediment recycling; Ocean Drilling Program; New Zealand

* Corresponding author. Tel.: +64-4-3860-300; Fax: +64-4-3862-153. *E-mail address:* l.carter@niwa.cri.nz (L. Carter).

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1. Introduction

The Eastern New Zealand Oceanic Sedimentary System (ENZOSS) is a model proposed by Carter et al. (1996a,b) to integrate the climatic, geologic and oceanographic factors controlling the sedimentary regime beneath the deep Pacific inflow. Briefly, ENZOSS is a large sediment recycling system that extends along the 4500-km-long margin of the New Zealand microcontinent – a fragment of Gondwana that is now sheared by the active, collisional Australian/Pacific plate boundary (Fig. 1). Uplift and erosion along the terrestrial reach of the plate boundary has delivered large volumes of sediment to the coast. Much of this sediment is eventually captured within the catchments of three submarine channel systems that guide turbidity currents to the Southwest Pacific Basin. There, a Deep Western Boundary Current (DWBC) redirects the material northwards as a series of sediment drifts. The northernmost drift, containing sediment from the local channel plus detritus carried from the distant south, is now subducting into Kermadec Trench to be recycled through the mantle and re-emerge at the plate boundary as arc volcanics. As a result, one cycle ends and another begins.

The original ENZOSS model was constructed using data from shallow (0–5 m sub-seabed) cores, 3.5-kHz seismic profiles and physical oceanographic observations. Consequently, the interpretation related mainly to late Quaternary sequences. Single channel seismic profiles were also analysed to provide an insight into pre-Quaternary successions. However, the absence of long cores limited the stratigraphic and palaeoenvironmental value of that seismic database. Fundamental questions relating to the development of the abyssal circulation and its affect on drift deposition, the inception of discharge from submarine channels into the DWBC, the impact of the Australian/Pacific plate boundary on the deep-ocean sediment supply, and other questions, remained largely unanswered.

Since the original study, several new initiatives have provided data to allow the ENZOSS concept to be tested, and to give an insight into the system's evolution. Foremost is Leg 181 of the Ocean Drilling Program (ODP) (this volume; Carter et al., 1999). Deep-ocean cores from ODP Sites 1121–1124 (Table 1), situated along the course of the DWBC as it passes through the Southwest Pacific gateway, provide new data on the responses of ENZOSS to the profound changes in palaeoceanography and plate tectonism affecting the Southern Ocean in Cenozoic times. The recently completed ODP Leg 189 (Exon et al., 2001) provides additional information on the palaeocirculation 'upstream' from New Zealand, off southern Tasmania. Locally, recent papers by Lewis et al. (1998), Lean and McCave (1998), Schuur et al. (1998), Hall et al. (2001, 2002, 2003), Hayward (2001), Stickley et al. (2001), Joseph et al. (2004, this issue) and others have all contributed pieces to the ENZOSS jigsaw puzzle.

2. Modern environmental setting

ENZOSS extends from the western mountain chain and volcanic arc marking the onshore New Zealand plate boundary, east to the abyssal Southwest Pacific Basin (Fig. 1). Oblique compression along the plate boundary is causing rapid uplift of the axial mountain ranges that are comprised mainly of easily eroded greywackes and other sedimentary rocks as well as schists. Add

Table 1
Circumstances of ODP Sites 1121–1124

ODP Site	Setting	Latitude	Longitude	Depth (m)	Penetration (m)	Oldest sediments
1121	Campbell 'Skin Drift'	50°53.88′S	176°59.86′E	4488	139.7	Palaeocene
1122	Bounty Fan	46°34.78′S	177°23.62′W	4432	627.4	E. Miocene
1123	N. Chatham Drift	41°47.15′S	171°29.94′W	3290	632.8	L. Eocene
1124	Rekohu Drift	39°29.90′S	176°31.89′W	3967	473.1	Cretaceous

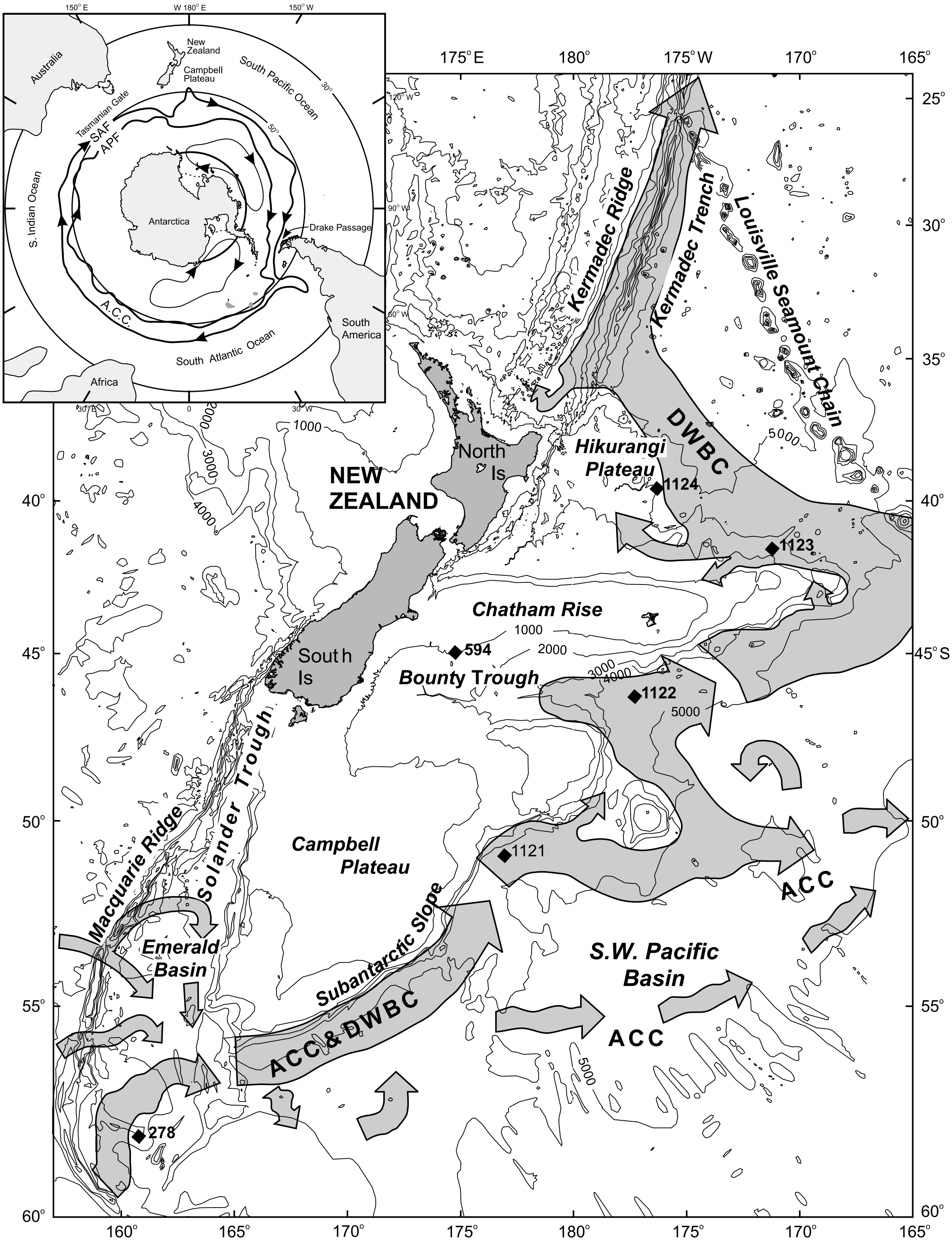


Fig. 1. Location of DSDP sites 278 and 594 and ODP sites 1121–1124, together with the deep Pacific inflow comprising the Deep Western Boundary Current (DWBC) and to the south of Bounty Trough, its combination with the Antarctic Circumpolar Current (ACC). Depth contours are in metres. Inset shows the generalised flow of the ACC including the Subantarctic Front (SAF) and the Antarctic Polar Front (APF) (modified from Whitworth, 1988).

to this a vigorous, mid-latitude climate, and the scene is set for the production of large volumes of sediment (e.g. Milliman and Syvitski, 1992). Presently, the ENZOSS east coast, between East Cape and Stewart Island, receives about 109 Mt/yr of fluvial sediment comprised of ~97% suspended load (Hicks and Shankar, 2003). While newly revised total mass is less than the 146 Mt/yr estimated previously by Griffiths and Glasby (1985), it is still significant, corresponding to ~0.5% of the sediment input to the world ocean!

Offshore, modern sediment is restricted largely to the continental shelf by the present sea level highstand and the along-shelf transport regime, as well as locally subsiding shelf basins (Carter and Herzer, 1979; Foster and Carter, 1997). As a result, two of the three conduits to the deep ocean – Solander and Bounty channel systems – are bypassed and hence, are largely inactive (McCave and Carter, 1997). In contrast, the submarine canyons feeding into Hikurangi Channel intercept the along-shelf sediment stream and divert it 1400 km into the path of the DWBC (Lewis, 1994). The present highstand model changed markedly during lowstands when rivers traversed an emergent shelf and discharged directly into the catchments of all three submarine channels (Carter and Carter, 1993; Carter et al., 1996b).

The channels, extending 700 km in the case of Solander Channel, 950 km for Bounty Channel and 1400–2000 km for Hikurangi Channel, guide turbidity currents into the path of the Pacific DWBC. This major flow is part of the global thermohaline circulation (e.g. Schmitz, 1995), and passes northwards along the entire length of the New Zealand margin en route for the central Pacific Ocean (Warren, 1981; Whitworth et al., 1999). South of Bounty Trough, the DWBC is accompanied by the Antarctic Circumpolar Current (ACC). This largely wind-driven circulation interacts with the pronounced submarine topography off southernmost New Zealand to form a series of jets, meanders and mesoscale eddies (Gordon, 1972; Morrow et al., 1992). These perturbations dominate the DWBC along the steep flanks of Campbell Plateau (Stanton and Morris, in press), and accelerate bottom currents to speeds above the threshold of fine sand movement (Carter and Wilkin, 1999). As a consequence, drift deposition is minimal along the southern part of the deep ENZOSS margin, and it is not until the ACC departs from the DWBC at Bounty Trough that major sediment drifts and fans accumulate (Fig. 2; Carter and McCave, 1994, 1997; McCave and Carter, 1997). From Chatham Rise northwards, a suite of ridge-, terrace-, moat- and fan-drifts, with thicknesses often exceeding 300 m, have deposited in water depths of 2500–5000 m (Carter and McCave, 1997, 2002). The northernmost deposit, the Hikurangi Fan-drift, has grown over 300 km down-current from its main source, the Hikurangi Channel, and is now descending into the Kermadec subduction zone at the northern limit of ENZOSS (Fig. 1).

3. Evolution of ENZOSS

ENZOSS began with the onset of the abyssal flow through the Tasmanian gateway around 33.5 Ma in the early Oligocene (Exon et al., 2001). Since that time, the system has evolved in response to the opening of major seaways, the growth of Antarctic ice sheets, the development of the Pacific/Australian plate boundary, and global palaeoclimatic oscillations. Thus, changes have taken place at varying time scales ranging from 10^6 years for tectonic related events, 10^4–10^5 years for orbitally-related palaeoclimatic fluctuations, 10^3–10^1 years for Dansgaard–Oeschger cycles and climatic shifts such as the Pacific Decadal Oscillation, and $<10^1$ years for seasonal, annual to El Niño–Southern Oscillation events.

In Section 3.1 we discuss the effects of the various forcing mechanisms on ENZOSS commencing with the long-term tectonic related events, and culminating in the short-term perturbations that presently shape the system.

3.1. Onset of the abyssal circulation

One manifestation of the arrival of abyssal currents in the New Zealand region is the presence of widespread unconformities that were caused by erosion, non-deposition, dissolution of carbonate

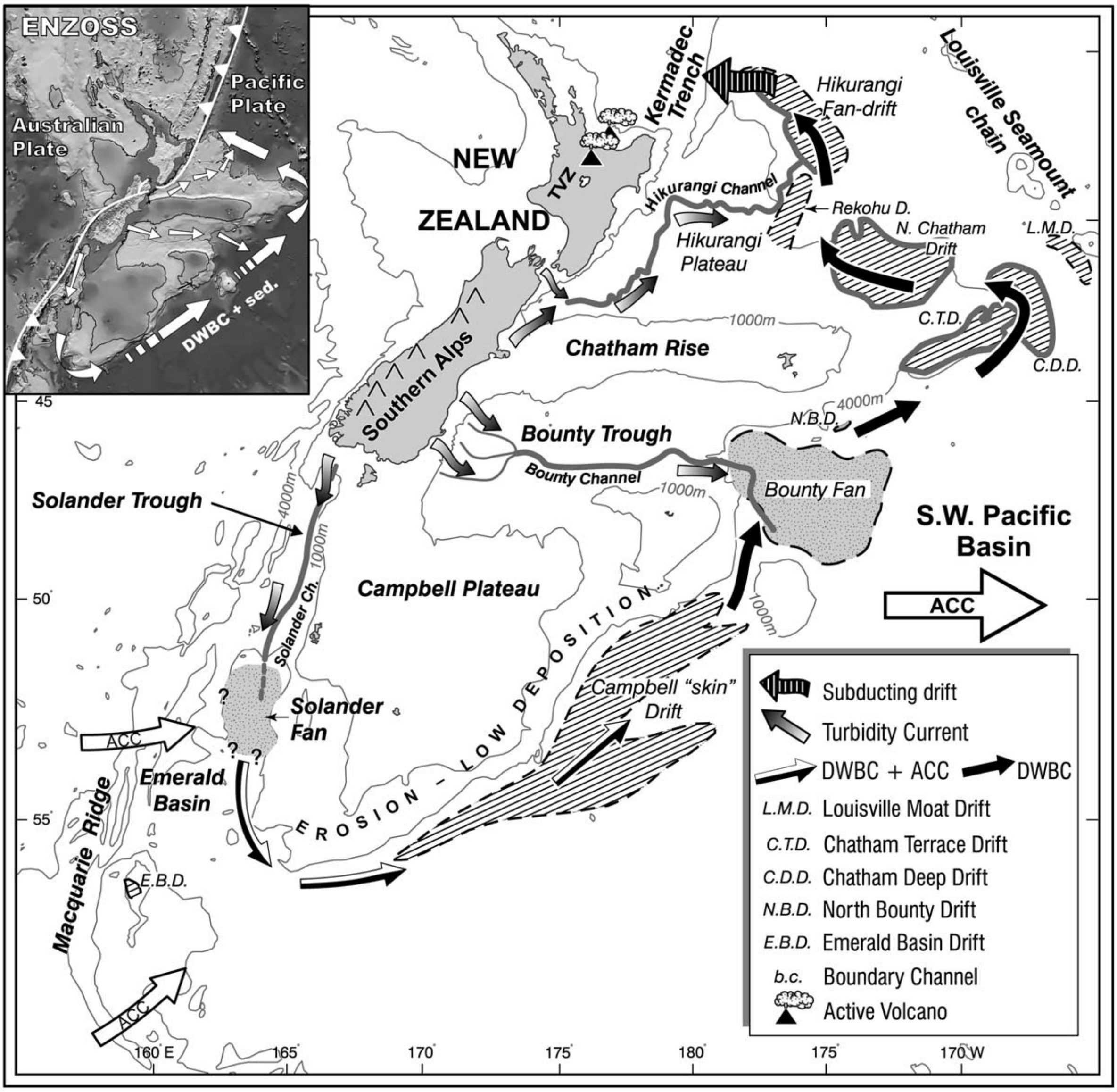


Fig. 2. The ENZOSS system (inset) with the New Zealand source, the main sediment delivery channels (small arrows) and the abyssal transport system (large arrows). Larger map outlines the Solander, Bounty and Hikurangi channels and the main depocentres beneath the DWBC. The northern limit of ENZOSS is the Hikurangi Fan-drift where it subducts into Kermadec Trench (modified from Carter and McCave, 2002).

or some combination of these processes (e.g. Kennett et al., 1975; Kennett and von der Borch, 1985). The temporal and spatial distribution of the hiatuses, including those recorded by previous DSDP legs to the New Zealand region, are recorded in fig. 8 of Carter et al. (1999).

3.1.1. Late Palaeocene–Eocene erosion

The oldest unconformities of between 58–39 Ma and 37–34 Ma were recorded at the most northern Site 1124. Contemporaneous erosion also may have occurred at the southernmost Site 1121 where Palaeocene (55 Ma) sediments underlay a major unconformity, but synchroneity with the northern hiatuses could not be confirmed as post-unconformity Site 1121 sediments are dated at 17 Ma (Graham et al., 2004, this issue). Hiatuses of similar age to Site 1124 have been noted at DSDP sites in the Tasman Sea (Kennett and von der Borch, 1985), where erosion is related to a time of marked cooling in the deep ocean concomitant with the inception of Antarctic ice sheets (e.g. Kennett, 1995). However, a cold southern source seems unlikely for Site 1124 which has: (1) temperate to subtropical diatoms with no displaced Subantarctic/Antarctic forms, and (2) foraminifera that are distinctly less corroded than late Oligocene and younger assemblages (Carter et al., 1999). Alternatively, the region may have received currents from the north, perhaps similar to those modelled for the Pacific Ocean by Mikolajewicz et al. (1993). Their boundary conditions – a closed Drake Passage and Tasmanian gateway, and an open Panama Isthmus – are similar to those existing in the late Eocene (e.g. Lawver and Gahagan, 1998). The model exhibits a westward equatorial flow across the Pacific Ocean with the shallow current passing north of New Zealand and possibly through the Tasman Sea as a proto-East Australian Current (Kennett and von der Borch, 1985; Exon et al., 2001). Any deep current (>3000 m depth) may have deflected down the eastern side of New Zealand to erode the Palaeocene–middle Eocene section at Site 1124. Assuming a northern source, these incipient abyssal erosion events are not considered to mark the onset of the ENZOSS circulation.

3.1.2. *Early Oligocene regional erosion – inception of the deep inflow*

The early Oligocene was a time of widespread erosion in the Southwest Pacific Ocean (Kennett, 1977; Kennett and von der Borch, 1985; Carter et al., 1999). The resultant regional hiatus or Marshall Paraconformity (Carter and Landis, 1972; Carter, 1985) has been recorded in the Tasman Sea (Kennett, 1977; Exon et al., 2001); on Lord Howe Rise (Kennett and von der Borch, 1985); on eastern South Island and adjacent continental margin (Carter and Landis, 1972; Fulthorpe et al., 1996), and in North Chatham and Rekohu drifts by Leg 181. At the last sites the paraconformity extends between 33.6 and 20.5 Ma (1123) and 33–27 Ma (1124), whereas the Campbell 'skin' drift (1121) rests on a Palaeocene to early Miocene hiatus (Graham et al., 2004, this issue), that may also encompass early Oligocene erosion. Onshore, the Marshall Paraconformity is better constrained at ~32–29 Ma (Fulthorpe et al., 1996).

The onset of erosive, deep currents was driven by the tectonic opening of key gateways, accompanied by associated palaeoclimatic and palaeoceanographic responses (Fig. 3). These events, and their relevance to the abyssal flow, are as follows.

(1) Continued separation of Australia from Antarctica was accompanied by development of a circum-Antarctic circulation – the direct forerunner of the modern ACC (Kennett et al., 1975; Kennett and von der Borch, 1985). The flow was not fully operational until the tectonic separation at South Tasman Rise and the opening of Drake Passage. Opening of the former has been reliably placed at 33.5 Ma (Exon et al., 2001, 2002), but there is uncertainty about the inception of Drake Passage. Lawver et al. (1992) suggest a connection via Powell Basin may have formed as early as 38 Ma, whereas Barker (2001) indicates that the opening of the passage may be as late as 22–17 Ma. Between these extremes is a 30–28 Ma opening estimated by Livermore (pers. commun., 2002).

(2) Inception of a circum-Antarctic flow enhanced the cooling of Antarctica and the development of ice sheets (Miller et al., 1991; Zachos et al., 1992). Surface waters cooled by up to 3°C (Wei, 1991), and a thermohaline flow formed (Exon et al., 2002).

(3) Cooling of the Antarctic region accentuated atmospheric thermal gradients thereby increasing wind strength (e.g. Kennett and von der Borch, 1985). An increase in the surface wind stress is critical for the initiation and strengthening of the ancestral ACC.

(4) Any Palaeocene–Eocene warm inflow from the north via the Panamanian Isthmus – locally termed the ancestral East Australian Current by Exon et al. (2002) – may have moderated or ter-

minated in response to the opening of Drake Passage and the initiation of a full circum-Antarctic flow (see Mikolajewicz et al., 1993).

The early Oligocene onset of a deep inflow into the Pacific was critical to the start of ENZOSS. In this early stage, the DWBC component of the inflow was potentially weaker than its Quaternary successor because Oligocene ice sheets were less extensive than now (e.g. Barrett, 1996). Whether or not the influx of Northern Component Water (Wright and Miller, 1996) or its Pliocene successor, North Atlantic Deep Water (NADW; Warren, 1983; Lawver and Gahagan, 1998) affected the DWBC, has yet to be reconciled. In reality, the prime force behind the inflow was the ancestral ACC, which was well underway by the middle Oligocene (Kennett and von der Borch, 1985). At that time, the orientation of New Zealand and its location in more southerly latitudes than now (e.g. Nelson and Cooke, 2001), meant that a larger part of the submarine microcontinent was exposed to the ACC. As New Zealand drifted north, the northern part of the microcontinent passed beyond the influence of the ACC, which may explain why the Neogene sections at sites 1123 and 1124 are well preserved compared to southern sections bathed by the ACC, e.g. DSDP 275, 276 and ODP 1121.

3.1.3. Late Oligocene–early Miocene drift accumulation

Following the widespread erosion accompanying the onset of the abyssal circulation, proto-ENZOSS went into a phase of deposition. At the time, the terrigenous input was low because Oligocene New Zealand was undergoing maximum flooding in the highstand phase of a long term (80 My), tectonically-controlled sea level cycle (Carter and Norris, 1976; Fulthorpe et al., 1996; King, 2000). Furthermore, the deep-ocean sediment channels had not yet reached the abyssal currents, even though conduits like Bounty Channel may have been in existence since the Palaeocene (Carter and Carter, 1987). As a result, sediments deposited immediately above the Marshall Paraconformity are dominantly limestones along the shallow ENZOSS margin off Canterbury, and nannofossil chalk at deep ocean sites 1123 and 1124 (Carter, 1988; Carter et al., 1999).

A clue that proto-ENZOSS was undergoing drift-like sedimentation is provided by seismic profiles through Hikurangi Fan-Drift, immediately north of Site 1124. This elongate deposit has formed over older constructional ridges that appear to be aligned sub-parallel to the ocean's western boundary and are separated from it by a shallow moat or zone of non-deposition, i.e. they have the morphological hallmarks of being formed by a boundary current (Carter and McCave, 1997). These interpreted 'palaeodrifts' rest on a regional reflector, confirmed to be the Marshall Paraconformity at nearby Site 1124 (Carter et al., 1999). Furthermore, post-unconformity sediments at Site 1124 have magnetic fabrics akin to drift deposits (Joseph et al., 2004, this issue).

Regionally, cyclic sedimentation commenced in the late Oligocene–early Miocene with the deposition of light, clayey nannofossil chalk beds alternating with dark, nannofossil mudstone (Carter et al., 1999; Weedon and Hall, 2004, this issue). The darker beds represent periods of increased inflow of cold, corrosive bottom waters from the south as revealed by an increased biosiliceous component that included Subantarctic/Antarctic diatoms plus a reduced and corroded planktonic foraminiferal assemblage. The presence of reworked Eocene/Oligocene diatoms confirms that at least part of the southern supply was from older oceanic sediment such as the highly eroded, deep-water apron cored at upcurrent Site 1121.

By analogy to light pelagite/dark hemipelagite alternations at Site 1123 (Hall et al., 2001, 2003), the Site 1124 alternations probably represent periods of increased deep inflow, which occurred during cool phases of orbital climatic cycles, in particular those with a frequency of 41 kyr. Palaeoenvironmental evidence, based on the distribution of trace fossil assemblages, suggest that the orbital changes are superimposed on a longer-term variability in the deep inflow (Weedon and Hall, 2004, this issue). Quiescent deep water conditions and low accumulation rates, represented by the *Zoophycos* ichnofacies, alternate with more energetic, better ventilated conditions recorded by trace assemblages tentatively correlated with *Cruziana* ichnofacies (e.g. Pemberton and MacEachern, 1995). We use the term 'tentative' because the *Cruziana* ichnofacies is believed to represent shallow marine zones, but our data suggest it may extend to greater depths. Each ichnofacies dominates over 22–34 m of core, which is equivalent to ∼0.8–1.3 Myr based on sedimentation rates (Carter et al., 1999). Towards the Oligocene/Miocene boundary, more energetic conditions prevailed judging by the dominance of the *Cruziana* ichnofacies. This phase was accompanied by low terrigenous mass accumulation rates (Joseph et al., 2004, this issue), which are consistent with the maintenance of strong flows.

3.1.4. Early–middle Miocene erosion and Antarctic ice sheets

The invigorated inflow in the Miocene culminated in a series of prominent hiatuses at Site 1124 (Fig. 3;Table 2). As Site 1123 sits well above the fast flowing core of the DWBC (assuming the structure of the Miocene inflow was similar to its modern counterpart), it has less pronounced erosional phases with brief hiatuses at ∼17 Ma (200 kyr long) and 14.5 Ma (300 kyr) (Carter et al., 1999; Hall et al., 2003).

The hiatuses formed at a time when the warm, early Miocene climate was punctuated by cold periods accompanying expansions of the East Antarctic ice sheet (e.g. Barrett et al., 1987; Miller et al., 1991; Flower and Kennett, 1995). Benthic oxygen isotope records imply orbitally paced expansions and contractions of ice volume, typically at a fundamental frequency of 41 kyr (Paul et al., 2000; Naish et al., 2001), which are punctuated by less frequent and larger eccentricity-driven excursions in oxygen isotopes – the Mi isotope zones of Miller et al. (1991). Zone Mi1, for example, is variously timed at 23.2–22.8 Ma (Shackleton et al., 2000) or 24.1–23.7 Ma (Cande and Kent, 1995) and was accompanied by expansion of the East Antarctic ice sheet, a deep-water cooling of 3°C, and erosion under grounding ice on the Antarctic continental shelf (Naish et al., 2001). Within the uncertainties in the age models presented here and in the published literature (e.g. see Naish et al., 2001), we find that single or clusters of Mi events correspond closely to the hiatuses at Site 1124 (Table 2). These correlations suggest that even though growth of the East Antarctic Ice Sheet produced a quickening of the DWBC, it is Mi1 and subsequent major glacial excursions that pushed the inflow above the threshold of erosion.

In between erosional phases, ENZOSS sedimentation underwent a series of broad changes. Site 1123 on Chatham Rise records an increase in carbonate accumulation commencing around 14 Ma (Winkler and Dullo, 2003). This change is consistent with increased oceanic productivity following the arrival and stabilisation of the STF on the Rise in the middle Miocene (Nelson and Cooke, 2001). About the same time, the clay mineralogy at Site 1123 began to alter from smec-

Table 2
Correlation of Mi isotopic zones with hiatuses at Leg 181 Site 1124

Mi Zone	Age[1] [Ma]	Site1124 Hiatuses Age[3] [Ma]
Mi 5	11.3	
Mi 4	12.6	11-14
Mi 3	13.6	
Mi 2	16.1	16.5-15
Mi 1b	18.1	
Mi 1a	21.2	22.4-17.5
Mi 1	23.8/22.9[2]	

Ages from Miller et al. (1991)[1]; from Oligocene–Miocene boundary ages summarised in Naish et al. (2001)[2]; from Carter et al. (1999)[3].

tite- to illite- and chlorite-dominant assemblages (Winkler and Dullo, 2003). This change may relate to the inception of the East Cape Current, which forms the northern 'dynamic' boundary of the STF. The current would have introduced clays from the tectonically active and chlorite/illite-rich provenance of the North Island – a contention given some credence by the presence of lower North Island pollen in the Plio–Pleistocene section at Site 1123 (Mildenhall et al., 2004, this issue). Deep-water Site 1124 records higher terrigenous fluxes in the middle Miocene (Joseph et al., 2004, this issue), which may be related to erosion of abyssal sediments up-current as suggested by the presence of reworked Subantarctic diatoms (Carter et al., 1999). At Site 1122, for example, middle Miocene deposits exhibit frequent bouts of winnowing as revealed by well developed, laminated and cross laminated sands interspersed with hemipelagic muds. Significantly, the sands have a distinctive chlorite component similar to that of eroded, chlorite-rich Palaeocene (and younger?) apron sediments at Site 1121. That the flux increased because of input from Hikurangi or Bounty Channel is unlikely as these conduits had not yet reached the DWBC path (Lewis et al., 1998; Carter et al., 1999). Even at the head of Bounty Trough, Site 594 records a dominance of calcareous biopelagites throughout the early–middle Miocene (Nelson, 1985).

The aforedescribed long-term changes are overprinted with a prominent 41-kyr orbital beat as revealed by the middle Miocene benthic isotope record for Site 1123 (Hall et al., 2003). Cool phases were accompanied by a more rapid inflow as manifested by increased sortable silt and silt/clay ratios. Concomitant reductions in carbonate contents are attributed to dissolution by the cold inflow.

3.1.5. Late Miocene erosion and increased sediment input

The late Miocene witnessed a further bout of intensified bottom flow as attested by the hiatus from 10 to 5 Ma in sediments underlying the Bounty Fan at Site 1122 (Fig. 3). Restriction of this and other possible contemporaneous hiatuses (e.g. DSDP 279, 280) to the Southern Ocean, south of Chatham Rise, suggest that the bottom flow was responding to an intensified ACC. This change was possibly affected by climatic cooling that is presumed to have accompanied expansion of the West Antarctic Ice Sheet (e.g. Kennett and von der Borch, 1985), although direct evidence for the timing of the expansion is equivocal. In contrast, sites 1123 and 1124 to the north of the ACC have complete middle Miocene to Recent sections, although Site 1124 exhibits reduced sedimentation rates between 8–2 Ma. Lower sedimentation could reflect an overall increase in the strength of the DWBC caused by greater bottom water production proximal to the expanded Antarctic ice sheet, and the introduction of North Atlantic Deep Water (NADW). According to Warren (1983), NADW began forming around 5 Ma following restriction of the Panamanian Isthmus, and subsequent forcing of warm saline water into the North Atlantic where evaporation then produced the requisite density conditions for NADW formation.

The period of enhanced abyssal erosion in the late Miocene was also a time of increased terrigenous supply from New Zealand. Off the North Island, subduction and accretion that began in the middle–late Oligocene, caused thick sedimentary sequences to form in Hikurangi Trough (Walcott, 1987; Lewis and Pettinga, 1993). Following a period of quiescence in the middle Miocene (Rait et al., 1991), renewed and more intense convergence further increased the terrigenous flux to the trough (Walcott, 1987). However, little of this input reached the DWBC because the main supply conduit, the proto-Hikurangi Channel, terminated in Hikurangi Trough; a situation that remained until the end of the Pliocene according to the reconstructions of Lewis et al. (1998). In contrast, Miocene–Pliocene plate boundary motion along the South Island Alpine Fault was mainly strike slip with little compression. Thus, Miocene sediments in the adjacent Bounty Trough are overwhelmingly calcareous biopelagites (Nelson, 1985). Around 6.4 Ma, plate motion changed to produce oblique compression across New Zealand. The result was rapid uplift and erosion of the Southern Alps (Walcott, 1998). Even so, terrigenous sediment did not reach the head of

Bounty Trough until the early Pliocene (Nelson, 1985; Dersch and Stein, 1991). Likewise, we envisage a similar timing for the arrival of terrigenous sediment to the third ENZOSS conduit, Solander Trough, for it too received sediment from rivers draining the Southern Alps and adjacent ranges.

3.1.6. Plio–Pleistocene terrigenous supply via submarine channels

Up to the early Pliocene, DWBC drifts mainly received calcareous biopelagic detritus and sediment reworked from older deposits such as the continental apron at the base of Campbell Plateau (Site 1121). Increased uplift along the axial ranges of New Zealand in the latest Miocene enhanced sediment input to the ENZOSS margin, but little reached the deep-ocean sector of the system because submarine channels and fans had not yet intercepted the DWBC. Such interceptions occurred under different circumstances for each of the three main ENZOSS conduits.

The Solander Channel/Fan complex is assumed to have grown at least 700 km south of the New Zealand continental margin during the late Miocene–Pleistocene (Schuur et al., 1998). Initially, fan growth was unaffected by bottom currents, but later the southern Solander Fan became deeply eroded. Such a dramatic change possibly resulted from a redirection of the powerful ACC (and DWBC?) through a newly formed passage in the Macquarie Ridge Complex at 53.5°S (Schuur et al., 1998). The timing of this breach is suggested at ∼4.0–2.4 Ma on the basis of an unconformity at Site 278 (Kennett et al., 1975). The eroded sediment was reworked into drifts within Emerald Basin with suspended load moving east and north along the Campbell Plateau margin (Carter and McCave, 1997).

In contrast, the Pliocene Bounty Fan/Channel complex simply migrated east along the floor of Bounty Trough into the DWBC, its progress presumably accelerated by an increasing supply of sediment from New Zealand. At the head of Bounty Trough, Site 594 records the first traces of terrigenous input ∼4 Ma (Nelson, 1985) with marked increases from 2.5 Ma onwards (Dersch and Stein, 1991). At the trough mouth, presumed channel-guided turbidity currents reached the DWBC in the middle Pliocene (∼3.5 Ma) as recorded at Site 1122 by Carter et al. (1999). Scattered, fine sand turbidites are interspersed with tractive current-affected laminated sands suggesting interaction between the developing Bounty Fan and DWBC passing across the mouth of Bounty Trough. The incidence of turbidites increased between 1.54 and 1.02 Ma, after which the fan was fully established across the DWBC path (Carter and Carter, 1996). The increased terrigenous flux to the DWBC is not recorded at Site 1123, which presently sits over 1100 m above the apex of Bounty Fan, apparently beyond its sphere of influence (Hall et al., 2002).

The Bounty Channel/Fan complex is the best known of the three ENZOSS sediment injection points, and its study provides an insight into the interaction between sediment supply and abyssal circulation (Carter and Carter, 1987, 1993, 1996; Carter et al., 1990, 1996a). In essence, the fan has built directly across the DWBC where it decelerates crossing the subdued topography of the Bounty Trough mouth. As Bounty Channel developed eastwards, beyond the protective confines of Bounty Trough, the channel turned south into the DWBC. Such a change resulted from strong, preferential growth of the left bank levee (facing down-channel) under the combined influence of the DWBC and Southern Hemisphere Coriolis deflection of channel-spilling turbidity currents (Carter et al., 1990; Carter and Carter, 1996). Later in the fan evolution, the left bank levee at the main channel bend was breached, presumably by avulsing turbidity currents. Thus, the DWBC received sediment: (1) directly from turbidity currents discharging at the channel mouth and overspilling/avulsing channel banks, and (2) indirectly by DWBC winnowing of the fan surface as shown by acoustic facies mapping of Carter and Carter (1996). Entrained sediment shifted northwards to feed small ridge drifts near Bounty Fan or more distal drifts off eastern Chatham Rise and further north (e.g. Carter and McCave, 1997, 2002).

Inception of the Hikurangi Channel point source resulted from a major change in the channel course that is linked ultimately to the development of the continental margin off the eastern

North Island. As noted earlier, Hikurangi Channel was restricted to the northeast-aligned floor of Hikurangi Trough up to the late Pliocene (Lewis, 1994; Lewis et al., 1998). Turbidity currents discharged as sheet flows that moved north and east across Hikurangi Plateau for ~300 km. Later Hikurangi Channel was diverted to the east by a giant mass failure deposit instigated by the impact of a subducting seamount with the thick accretionary prism of the continental slope. In adjusting its grade to a new base level, the diverted Hikurangi Channel eroded 400 km eastward, through the earlier sheet flow deposits, to reach Rekohu Drift (Site 1124). This Neogene drift deflected the channel a further 200 km to the northeast where it finally delivered sediment into the main DWBC flow along Rapuhia Scarp (McCave and Carter, 1997). Sediment mass accumulation rates for Site 1124 reveal a distinct pulse in the terrigenous flux at 1.65 Ma, followed by an irregular increase up to the present (Hall et al., 2002). Thus, the channel probably approached the drift about 1.65 Ma, an age that is supported by seismic data. Single channel profiles show the drift is draped by ~60 m of sediment which appears to be fine muddy overspill from Hikurangi Channel. According to the Site 1124 age model, the base of the overspill drape is estimated at ~1.6 Ma (Carter et al., 1999).

Obviously Hikurangi Channel did not discharge fully into the DWBC until sometime after 1.65 Ma to allow migration from Rekohu Drift to Rapuhia Scarp. Once at the scarp, the channel split. One branch merged into the northwest-trending boundary channel scoured along Rapuhia Scarp by the intensified DWBC. The second branch, initially turned southeast to face directly into the DWBC's path, but later moved east and meandered a further 600 km to dissipate on a small fan in the Southwest Pacific Basin (Lewis, 1994; Lewis et al., 1998). Nevertheless, most of the Hikurangi Channel discharge at Rapuhia Scarp was entrained by the fast flowing DWBC to feed the 300-km-long Hikurangi Fan-drift formed along the base of the scarp (e.g. McCave and Carter, 1997). Although the fan-drift was not drilled, the seismic stratigraphy reveals a 200–400-m-thick, terrigenous Pleistocene–Recent sequence, resting on 200–360 m of mainly Neogene palaeodrift, which in turn rests on the Marshall Paraconformity (Carter and McCave, 1994). Elongation of the fan-drift, coupled with motion of the Pacific plate, are jointly responsible for the transfer of the fan-drift into the Kermadec subduction zone to complete of the ENZOSS cycle (Fig. 1).

3.1.7. Plio–Pleistocene non-orbital effects

Additional to the inception of the channel supply, the Plio–Pleistocene ENZOSS was also subject to other non-orbital effects associated mainly with palaeoclimatic change and development of the Australian/Pacific plate boundary.

Deposition in southernmost ENZOSS, south of Bounty Trough, was interrupted by several bouts of erosion. The weakly constrained stratigraphy of Site 1121 on Campbell 'skin' drift suggests hiatuses about 2.2–1.8 Ma and at <0.42 Ma. Also, the pre-fan sequence at Site 1122 has a possible hiatus ~3.5 Ma (Carter et al., 1999). Osborn et al. (1983) reported on similarly timed hiatuses in piston cores from Macquarie Ridge–Emerald Basin region. Their stratigraphy, based on palaeomagnetic and microfloral data, suggests major erosional periods approximately at 4–3.4 Ma, 2.9–2.4 Ma, 0.8–2 Ma and <0.78 Ma. Identification of the deep thermohaline component (AABW or NADW) responsible for erosion is precluded by an absence of stable isotope data for southernmost ENZOSS. Uncertainty is compounded by the presence of the ACC, which is known to dominate the abyssal circulation in the region (Hollister and McCave, 1984; Carter and Wilkin, 1999). Accordingly, our comments are speculative. The earliest erosional event lies within the early Pliocene warm period when increased production of NADW possibly dominated the deep thermohaline circulation (e.g. Raymo et al., 1992; Kim and Crowley, 2000). Given the warmth of the times and hence a likelihood of reduced pole–equator thermal gradients, it is possible that the affect of the ACC on deep sedimentation was reduced. The cooling after the early Pliocene warm period witnessed a reduction in NADW although levels remained higher than the Pleistocene. Once the Northern Hemisphere ice sheets were established around 3–2.4 Ma, the deep ocean acquired its present structure with the thermohaline component taking on its pronounced glacial–interglacial cyclicity (e.g. Turnau and Ledbetter, 1989; Raymo et al., 1992). Such cyclicity affected speeds of the thermohaline flow as evinced by sortable silt profiles at Site 1123 (see Section 3.1.8). Glacial currents were shown to quicken although speeds were generally still too low to induce widespread erosion as manifested by the complete Pleistocene sections of sites 1123 and 1124. We therefore infer that the prominent Pleistocene hiatuses south of Bounty Trough result largely from the ACC.

Downstream of the energetic southern ENZOSS, the Plio–Pleistocene phases of erosion may be reflected in sediment burial fluxes at Site 1123 on North Chatham Drift (Hall et al., 2002). Pulses in the combined terrigenous and carbonate fluxes over the past 3 Ma may be related to upstream remobilisation of sediment by the ACC. That these pulses result from Bounty Channel discharge is discounted because: (1) Site 1123 sits well above the channel, and (2) the pulses occurred well before the channel emptied into the DWBC. Most of these pulses, which involve flux rates 2–4 times above the 'background' rate of 1–2 g/cm^2/kyr, are at best only weakly preserved on Rekohu Drift (1124), 550 km down-current of Site 1123. The implication is that the hydraulic regime on North Chatham Rise encouraged settling of DWBC suspended load. Nevertheless, the 'background' flux is maintained between sites 1123 and 1124 as also confirmed by the presence of mineral and microfossil tracers from Subantarctic and Antarctic settings (Carter and Mitchell, 1987; Fenner et al., 1992; Carter et al., 1999; Stickley et al., 2001).

Over the past 1 Myr, North Chatham and Rekohu drifts recorded distinct pulses in the biogenic carbonate flux when the accumulation of nannoplankton and foraminifers increased 2–3 fold (Hall et al., 2002; Joseph et al., 2004, this issue). These pulses, often lasting 0.1 Myr or more, are better seen at Site 1123, which is near the productive Subtropical Front (Bradford-Grieve et al., 1999). The cause of the productivity changes is open to speculation but it is interesting to note that the changes coincide with the middle Pleistocene transition from a climate dominated by 41-kyr orbital cycles to one over-shadowed by 100-kyr cycles (e.g. Schmieder et al., 2000).

Sediment supply to ENZOSS has also been influenced by explosive and voluminous rhyolitic eruptions associated with the Coromandel (CVZ) and Taupo (TVZ) volcanic zones of the North Island (Carter et al., 1995, 2003). Sites affected most are those closest to the volcanic sources, namely 1123–1125, although tephra layers also occur on Bounty Fan, 1000 km from source. Site 1124 is closest at 640 km from the TVZ. Since ~12 Ma, it received 134 tephra layers with mean and maximum thicknesses of 9.6 cm and 92 cm, respectively. On thickness alone, tephra accounts for nearly 6% of the Site 1124 sequence with an unknown amount of volcanic airfall bioturbated into the sediments (e.g. Carter et al., 1995). Indirectly, volcanism enhanced the ENZOSS supply through increased fluvial input as rivers eroded volcanically denuded landscapes typically mantled with unconsolidated volcanic ejecta (Pillans et al., 1993; Wilmshurst and McGlone, 1996). These expected changes in fluvial input relate mainly to North Island rivers. Thus, effects were mainly felt by the Hikurangi Channel component of ENZOSS. The Plio–Pleistocene witnessed a marked increase in the frequency and size of the eruptive deposits, e.g. at Site 1124 the frequency and mean thickness of macrotephra layers increased from 1 per 142 kyr and 7 cm in the Miocene to 1 per 35 kyr and 13.6 cm in the Pleistocene.

3.1.8. Plio–Pleistocene orbital effects

Superimposed on the non-orbital effects is the regular beat of Milankovitch cycles, which have also left their mark on sediment supply, transport and deposition in the form of distinct glacial and interglacial motifs.

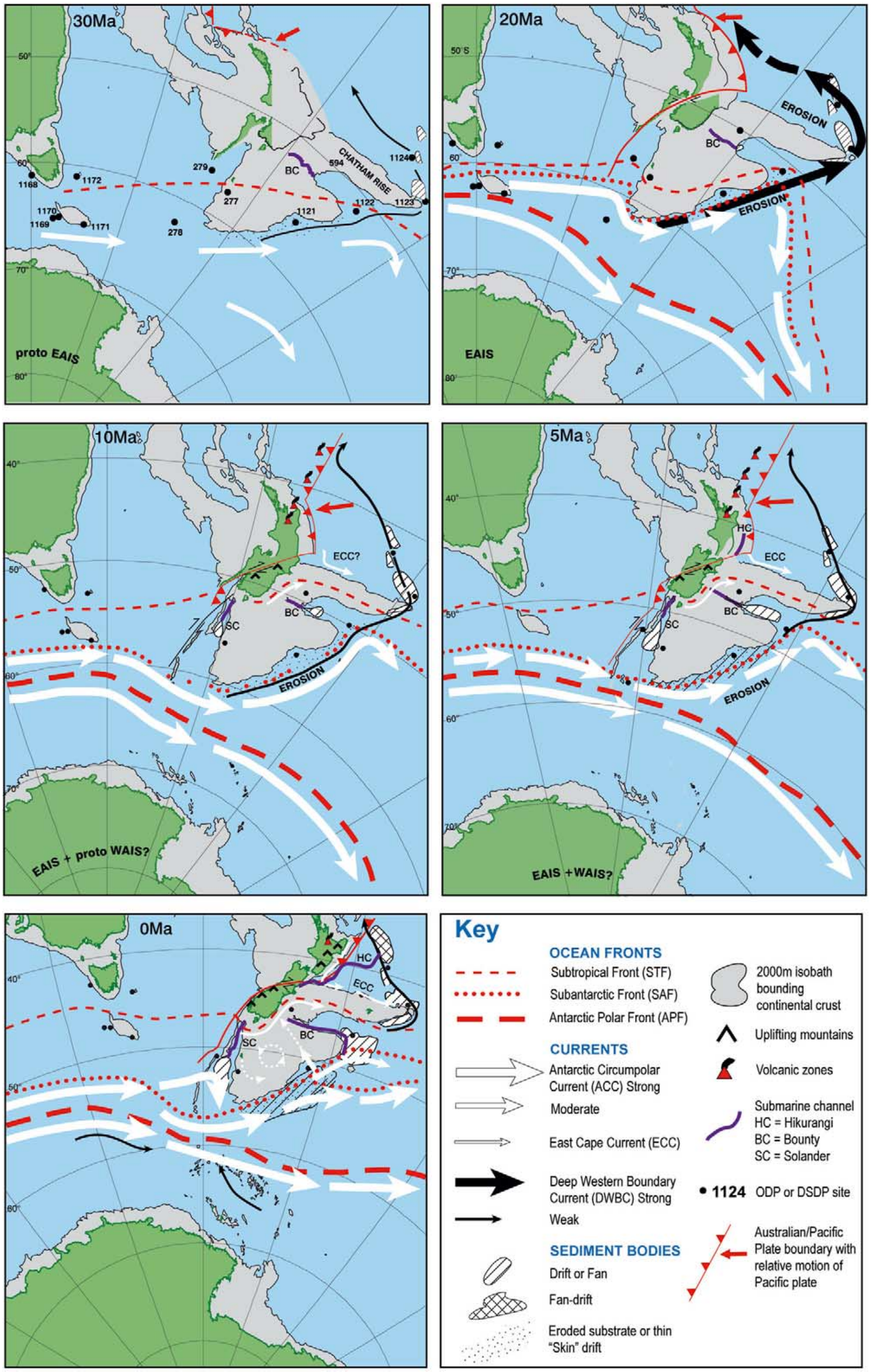
Glacial stages were accompanied by lowerings of sea level when sediment supply to the DWBC was at its optimum. Rivers draining a denuded and erosion-prone landscape discharged near or at the shelf edge (e.g. Herzer, 1981; Carter and Carter, 1993; McGlone et al., 1994). Sediment captured directly by canyons was funnelled into the main channels and hence into the abyssal flow. Up until the Pleistocene, the collisional margin of the eastern North Island was the exception.

There the combination of rapidly subsiding basins on the continental shelf, plus numerous slope basins, sequestered much of the sediment supply (Foster and Carter, 1997; Carter et al., 2002; Browne and Naish, 2003). In addition to the turbidity current flux, the deep ocean received more hemipelagic detritus via an invigorated surface circulation, and an increased aeolian flux reflecting the vigorous wind regime of glacial times (Stewart and Neall, 1984; Hesse, 1994). Using the palynological data of Mildenhall et al. (2004, this issue), it appears that Site 1123 also received suspended sediment from the lower North Island via the East Cape Current as well as southern sourced detritus carried by the DWBC. The overall higher terrigenous input of glacial times is shown by mass accumulation rates that commonly exceed interglacial rates by 2–3 times (e.g. Lean and McCave, 1998; Carter et al., 2000; Hall et al., 2002).

The increased terrigenous flux was captured by an invigorated DWBC as evinced by the grain size record for the last 1.2 Ma at Site 1123 (Hall et al., 2001). Using 'sortable silt' as a proxy for current speed (McCave et al., 1995), Hall et al. (2001) revealed an acceleration of the DWBC during glacials, accompanied by the dissolution of foraminifera at sites 1123 and 1124 (Weaver et al., 1998; Hall et al., 2002). We interpret such changes as responses to an increased production of cold, corrosive bottom water around Antarctica under the increased windiness or greater sea ice production of the times (see e.g. Hall et al., 2001). Certainly, deep drifts cored off eastern Chatham Rise record flushes of diatoms from Antarctica during MIS 2, 4, and 6 (Stickley et al., 2001). Furthermore, variations in diatom taxa from different environments suggest that the generation of open-ocean bottom water was more important in cold periods compared to the ice edge/shelf generation of warm periods. South of Chatham Rise, the glacial DWBC was possibly strengthened further by an invigorated ACC. Grain size profiles from beneath the ACC path along eastern Campbell Plateau reveal a marked coarsening of sediments during glacial and stadial periods (Neil et al., in press).

The ENZOSS interglacial sediment motif is markedly different. An ameliorated climate and expanded vegetation cover reduced the fluvial and aeolian input to the ocean (e.g. Stewart and Neall, 1984; Carter et al., 2002). In the South Island, retreating glaciers created large lakes that captured detritus and further reduced the terrigenous input judging by the last deglacial record (Carter and Carter, 1990). Sediment reaching the continental margin was largely confined there by the highstand hydraulic regime (e.g. Carter and Herzer, 1979; Carter et al., 1985). Along-shelf sediment transport became the norm, thus reducing the turbidity current and hemipelagic input to the deep ocean (e.g. Nelson, 1985; Nelson et al., 1993; Carter et al., 2000). Judging by the modern highstand, Solander and Bounty channels were largely bypassed (Carter and Carter, 1993). However, for the eastern side of the South Island, sediment accommodation space increased through the Neogene as the shelf widened by coast-normal progradation accompanied by along-slope accretion of contourites deposited from Subantarctic Mode water and Antarctic Intermediate Water in depths of 200–1200 m (e.g. Carter, 1988; Fulthorpe and Carter, 1991; Carter et al., 2004, this issue). The eastern North Island margin also captured sediment, but in this case it was through the tectonic development of subsiding shelf and slope basins (e.g. Carter et al., 2002).

Compared to Solander and Bounty channels, Hikurangi Channel remained active in interglacial periods. One of the main feeders to Hikurangi Channel, namely Kaikoura Canyon, today comes within 500 m of shore and therefore intercepts the inner shelf transport zone – the dominant sediment pathway during highstands (e.g. Carter et al., 1985; Lewis and Barnes, 1999). Rapid sediment accumulation in the canyon head, seismic ground shaking, and the generation of self-perpetuating autosuspension flows are the likely mechanisms by which sediment is transferred from the canyon head, 1400 km to Hikurangi Fan-drift (Lewis and Barnes, 1999). The last major seismically triggered event recorded in the canyon head occurred ∼170 years ago, with another ∼300 years ago. Another feeder, Cook Strait Canyon, also supplies Hikurangi Channel in interglacial times. Local rivers and a powerful tidal regime



30Ma
CHATHAM RISE
BC
279
594
1124
1168
1172
277
1170
1169
1171
278
1121
1122
1123
proto EAIS
20Ma
50°S
EROSION
BC
EROSION
EAIS
10Ma
ECC?
SC
BC
EROSION
EAIS + proto WAIS?
5Ma
HC
ECC
SC
BC
EROSION
EAIS +WAIS?
0Ma
HC
ECC
BC
SC
Key
OCEAN FRONTS
Subtropical Front (STF)
Subantarctic Front (SAF)
Antarctic Polar Front (APF)
CURRENTS
Antarctic Circumpolar Current (ACC) Strong
Moderate
East Cape Current (ECC)
Deep Western Boundary Current (DWBC) Strong
Weak
SEDIMENT BODIES
Drift or Fan
Fan-drift
Eroded substrate or thin "Skin" drift
2000m isobath bounding continental crust
Uplifting mountains
Volcanic zones
Submarine channel HC = Hikurangi BC = Bounty SC = Solander
1124 ODP or DSDP site
Australian/Pacific Plate boundary with relative motion of Pacific plate

feed sediment to the canyon system, probably on a daily basis (Proctor and Carter, 1989). Again, the pronounced seismicity of this plate boundary sector is the likely trigger for the generation of turbidity currents. Despite the interglacial activity, transport through Hikurangi Channel was 2–3 times higher in glacial periods as evinced by mass accumulation rates on channel overbank deposits (Fenner et al., 1992).

Not surprisingly, the lower terrigenous input of interglacial periods was accompanied by a reduction in mass accumulation rates on drifts and submarine fans beneath the DWBC (Lean and McCave, 1998; Carter et al., 2000; Hall et al., 2002). Part of this reduction may also mark a generally weaker DWBC (Hall et al., 2001; Joseph et al., 2004, this issue) and ACC (Neil et al., in press). A weakened abyssal flow would depress the supply of reworked sediment to drifts, as supported by fewer reworked diatoms in interglacial drifts (Stickley et al., 2001).

4. Synopsis

The source to sink sedimentary system off eastern New Zealand evolved in response to: (1) the opening of the circum Antarctic seaway, (2) changes in the planet's thermohaline system with the development of polar ice sheets, and (3) the tectonic evolution of the New Zealand plate boundary, which controlled sediment supply to the system. These changes are overprinted with the rhythm of orbital forcing on sediment supply, abyssal sedimentation and current flow. Chronologically, ENZOSS developed as follows (Fig. 3).

(1) The Oligocene initiation of the circum-Antarctic flow, following the opening of the Tasmanian gateway and Drake Passage, caused widespread erosion and the formation of the Marshall Paraconformity, which is the foundation of ENZOSS.

(2) A period of drift accumulation followed in the late Oligocene–early Miocene. Maximum flooding of a low relief New Zealand, and the absence of submarine channel delivery systems, meant that drifts were composed mainly of biogenic carbonate and reworked sediment identified by the presence of Eocene/Oligocene diatoms. Alternating light pelagite and dark hemipelagite beds with a frequency of 41 kyr, confirm orbital control of sedimentation; the dark layers heralding increased inflow of corrosive Subantarctic/Antarctic bottom waters.

(3) Drift deposition was interrupted by several erosional phases that mainly affected the deepest sites. Our present age model suggests the hiatuses coincided with the Miocene Mi1–5 isotopic zones that relate to expansions of the East Antarctic ice sheet. Between erosional phases, ENZOSS carbonate sedimentation at Site 1123 increased as the STF reached and remained over Chatham Rise. Terrigenous deposition also increased at Site 1124 possibly in response to up-current erosion of abyssal sediments. Effects of the overriding 41-kyr orbital forcing were also felt with cold

Fig. 3. Generalised plate reconstructions showing key stages in the development of ENZOSS including (30 Ma) the opening of the Tasmanian gateway and inception of regional erosion under the developing ACC and DWBC, followed by first drift deposition north of Chatham Rise: (20 Ma) expansion of Antarctic ice resulted in stronger ACC and DWBC and widespread erosion/low deposition even north of Chatham Rise; New Zealand plate boundary continued to develop, but with little terrigenous input to deep ENZOSS: (10 Ma) plate boundary established but still no terrigenous input to deep ocean as main supply channels still forming; continued deposition of mainly biogenic-rich drifts north of Rise and ACC-controlled erosion/low deposition to the south; initial offshore deposition of tephra: (5 Ma) continued northward migration of New Zealand reinforced the separation of mainly ACC-erosional and DWBC-drift depositional regimes to the south and north of Chatham Rise respectively; strongly convergent plate boundary supplied terrigenous sediment that accumulated near the continental margin, except for localised escape to feed to proto-channel/fan systems; increasing amounts of volcanic ash: (0 Ma) modern ENZOSS fully formed by the Pleistocene with terrigenous sediment injected directly into abyssal flow as: (1) Solander Fan/Channel intercepted by a new branch of the ACC, (2) Bounty Fan/Channel grew directly across currents' path, and (3) Hikurangi Channel diverted from New Zealand into the DWBC; strong orbital control on sediment supply and ACC/DWBC; increased volcanic airfall. Reconstructions modified from Sutherland (pers. commun., 1999) and King (2000) while positions of oceanic fronts are from Nelson and Cooke (2001).

periods of strengthened bottom flow carrying increased reworked detritus from southern sources.

(4) By the late Miocene, ENZOSS was starting to take on its modern form. South of Bounty Trough, in the path of the powerful ACC, erosion prevailed between 5–10 Ma. To the north, deposition under the DWBC was the norm, albeit under an intensified current that was possibly forced by Pliocene expansion of the WAIS and establishment of NADW component of the thermohaline system.

(5) The late Miocene also heralded greater terrigenous input that resulted from increased convergence and uplift along New Zealand plate boundary. However, little of this sediment reached the DWBC as the three main supply channels were not fully developed.

(6) It was in the Plio–Pleistocene that the drifts changed to terrigenous-dominant sedimentation caused by the arrival of the three channels. The Solander Channel/Fan complex was intercepted by a new branch of the ACC (and DWBC?) that exploited a breach in Macquarie Ridge. The Bounty Channel/Fan complex simply migrated eastward to reach the path of the DWBC about 1.65 Ma. In contrast, it took a major collapse of the North Island margin to divert the originally northbound Hikurangi Channel eastwards into the DWBC, sometime after 1.6 Ma. The result was the formation of the extensive Hikurangi Fan-drift.

(7) With the channels came an influx of sediment regulated by Quaternary oscillations of climate and sea level. Highstands reduced or even cut off the terrigenous supply to a sluggish DWBC. Lowstands were periods of high sediment input into a DWBC that was invigorated by more AABW, and in the case of southern ENZOSS, by an ACC strengthened by glacial winds.

(8) Underlying the orbital signals are less regular and longer term responses to: (1) reorganisation of the ACC under evolving gateways and climate, (2) changes in the thermohaline flow caused by, for example, the onset of Northern Hemisphere glaciations, (3) variations in ocean productivity, and (4) volcanic eruptions which have locally contributed almost 6% to the northern ENZOSS budget.

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