Regional sediment recycling in the abyssal Southwest Pacific Ocean

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ABSTRACT

An active plate boundary with a high sediment output, three major submarine channels, and the world's largest deep western boundary current (DWBC) make up an extensive recycling system along the 4500 km continental margin, east of New Zealand. Seismic reflection, sedimentary, and oceanographic data demonstrate that detritus from the rising mountains of the New Zealand plate boundary is transferred to the Southwest Pacific abyssal floor by turbidity currents flowing along Solander (>450 km long), Bounty (950 km), and Hikurangi (1400 km) channels. These conduits discharge directly into the DWBC, which transports material north to form a series of sediment drifts. The northernmost drift, containing sediment from Hikurangi Channel and eroded drifts to the south, is now subducting into Kermadec Trench. Geochemical data suggest that sediment is recycled through the mantle to re-emerge in the arc volcanic rocks. Thus one cycle is completed and a new one begins.

INTRODUCTION

The boundary between the converging Pacific and Australian plates passes through the New Zealand region as a trench-transform-trench combination (Fig. 1). Part of the sediment from the terrestrial transform sector is trapped within the proximal trenches (Lewis and Pettinga, 1993). However, sand and mud also escape along submarine channels to the distant Southwest Pacific Basin, east of New Zealand.

Even though channels discharge material out to 1000 km from land, sediment fails to escape the plate boundary due to a major recycling system, which is documented here for the first time. Named the Eastern New Zealand Oceanic Sedimentary System (ENZOSS), its recognition has resulted from an evaluation of published research (e.g., Carter and Mitchell, 1987; Carter and Carter, 1988, 1993; Carter and McCave, 1994; Lewis, 1994), unpublished data from the New Zealand Oceanographic Institute, and records collected by the U.S.N.S. *Eltanin* (e.g., Hayes et al., 1972, 1976, 1977; Jacobs et al., 1972).

ENZOSS COMPONENTS

ENZOSS has three parts: (i) an active plate boundary that generates and eventually consumes sediment, (ii) three submarine channels to carry sediment to the abyssal floor, and (iii) the Pacific deep western boundary current (DWBC), which transports the channel discharges back toward the plate boundary.

Source

Sediment entering ENZOSS is derived mainly from rapidly rising mountains along the plate boundary (Adams, 1980). Since the late Miocene, when the rate of convergence increased at the boundary, the rapidly rising mountains have shed large volumes of detritus to the continental margin. This influx increased in the Pliocene-Pleistocene as shown at Deep Sea Drilling Project Site 594, where sedimentation rates rose from 2.7 to 13.8 cm/k.y. between the Pliocene and late Quaternary (Nelson, 1985). This change reflected greater mountain uplift (Kamp et al.,

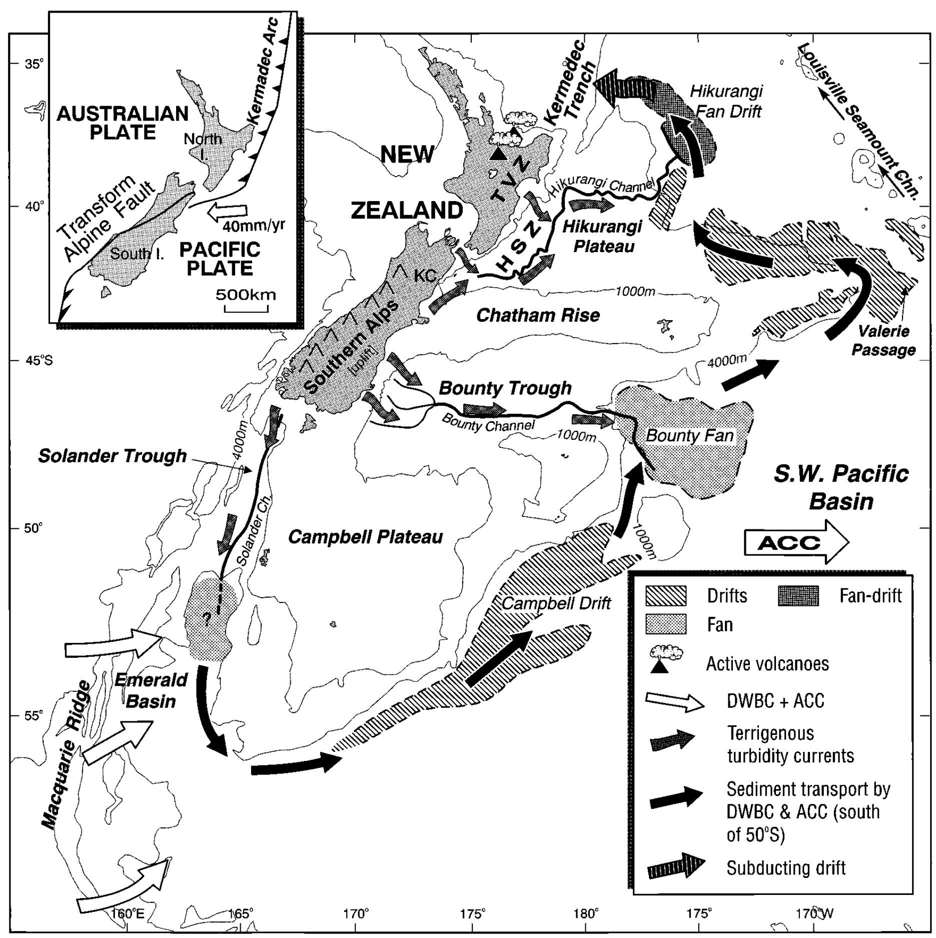

Figure 1. Main elements of ENZOSS including (i) sediment source at plate boundary (inset), (ii) three main supply channels, (iii) ocean sediment pathway controlled by Pacific deep western boundary current (DWBC) locally reinforced by Antarctic Circumpolar Current (ACC), and (iv) sediment sink at Kermadec Trench subduction zone. HSZ—Hikurangi subduction zone, TVZ—Taupo volcanic zone, KC—Kaikoura Canyon.

1989), progressive exposure of easily eroded schist (Cutten, 1979), and greater frequency and severity of glaciations (e.g., Prell, 1982). Modern rivers and coasts now supply ~147 million t/yr of suspended load to the eastern and southern New Zealand continental shelf; this mass being ~1% of the estimated global detrital input to the oceans (Milliman and Syvitski, 1992; Griffiths and Glasby, 1985).

Submarine Channels

Sediment is transferred from the shelf to the abyssal floor along three channels that cross wide submarine plateaus and discharge at the margins of the plateaus, which also form the boundary for the DWBC (Fig. 1; Carter and McCave, 1994).

The most southerly conduit, Solander Channel, begins at the continental slope off southernmost New Zealand and runs south for >450 km along the axis of Solander Trough (Figs. 1 and 2a; Hayes et al., 1976, 1977). For much of its course, Solander Channel is bordered by levees dominated by the east bank, which is consistent with Southern Hemisphere Coriolis deflection of overspilling turbidity currents (Carter and Carter, 1988). Underlying the channel is 560 m of layered Pliocene-Pleistocene sediment (Davey, 1977), which is probably alternating pelagites and turbidites/hemipelagites of interglacial and glacial origins, respectively (Florida State University, 1973; Osborn et al., 1983). Eventually, Solander Channel empties into the 4500-m-deep Emerald Basin, but survey coverage is insufficient to identify the resultant deposit, which contains >400 m of inferred Neogene sediment (Davey, 1977).

The second conduit, Bounty Channel, starts at a 500–1250-m-deep fan-canyon complex off the central South Island where canyons coalesce into a single channel running 950 km along the axis of Bounty Trough to the extensive Bounty Fan at 4500 m depth in the Southwest Pacific Basin (Figs. 1 and 2b; Carter and Carter, 1988). Throughout Bounty Trough, channel overspill has formed pronounced levees that are best developed near the trough mouth where up to 550 m of sediment has been deposited since the late Miocene (Carter et al., 1990). These overbank deposits consist of alternating calcareous pelagites and terrigenous turbidites/hemipelagites (Carter and Carter, 1988), the latter being deposited during glacial lowstands when South Island rivers meandered over the emergent continental shelf and emptied directly into Bounty Trough (Griggs et al., 1983; Nelson et al., 1993). Such conditions caused turbidity currents to sweep along Bounty Channel and feed the Bounty fan. In contrast, the interglacial Bounty Trough was starved of terrigenous material because the fluviatile input decreased due to the creation of onshore lacustrine sediment traps and reduced erosion of the South Island hinterland (Carter and Carter, 1990). Furthermore, sediment reaching the shelf was diverted from the trough by along-shelf currents that were established as sea-level rose. Consequently, interglacial periods feature calcareous pelagites as occurs in the modern Bounty Trough and Channel (Carter and Carter, 1988).

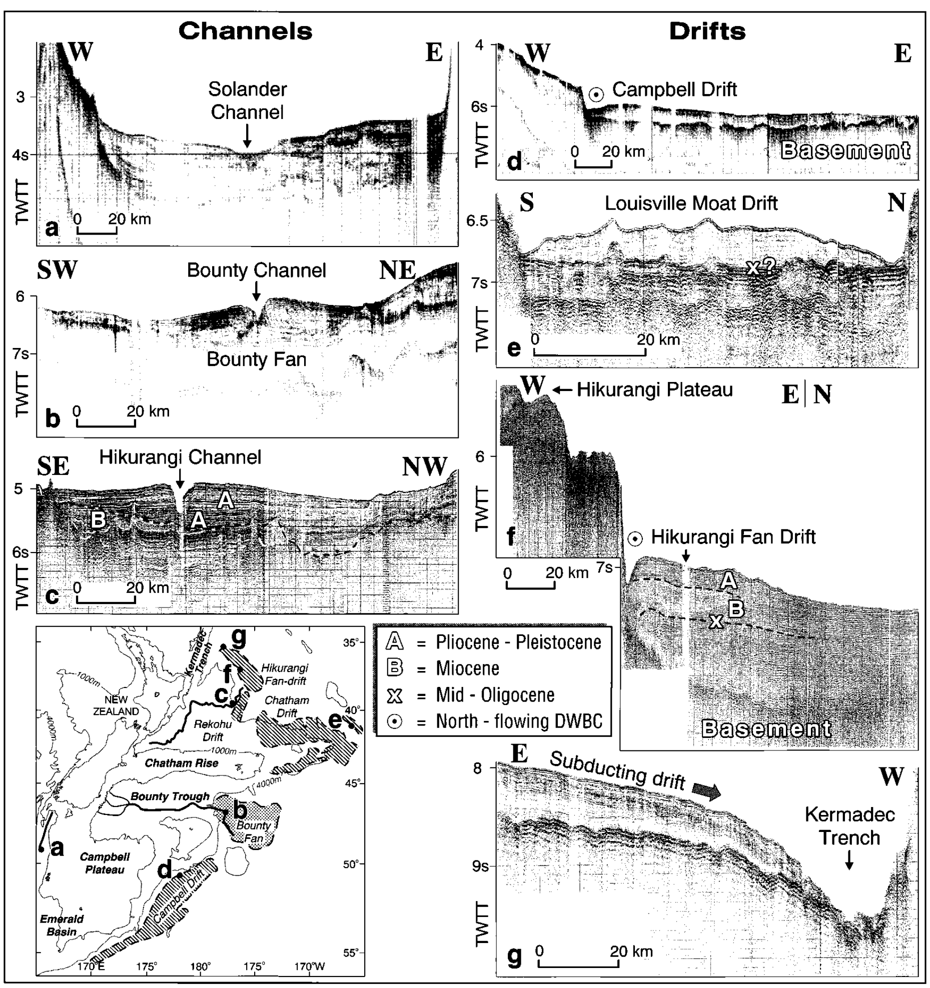

Figure 2. Selection of single-channel airgun profiles outlining morphology and structure of channels and some drifts along abyssal sector of ENZOSS. TWTT—two-way travel time.

The third and longest pathway is Hikurangi Channel (Fig. 2c). Arising at prominent canyons off central New Zealand, the channel meanders 800 km north along the axis of the Hikurangi subduction zone before swinging east and northeast across Hikurangi Plateau for a further 600 km (Lewis, 1994). The channel splits at the plateau margin; one arm turns south to feed a large fan, the other arm merges with a 300-km-long boundary channel eroded by the DWBC along the foot of Hikurangi Plateau (Fig. 2f; Carter and McCave, 1994). In contrast to the other conduits, Hikurangi Channel has carried turbidity currents in interglacial as well as glacial periods (Fenner et al., 1992; Lewis, 1994). This situation arises because the canyons feeding the channel intercept highstand sediment transport systems; e.g., Kaikoura Canyon heads to within 1 km of shore (Lewis, 1994).

Deep Western Boundary Current

The DWBC inflow to the Southwest Pacific Ocean is at Macquarie Ridge where the deep circulation is reinforced by the Antarctic Circumpolar Current (ACC). This combined flow passes around the Macquarie Ridge and through prominent ridge gaps, thus forming strong jets and eddies that pass across Emerald Basin to the flank of Campbell Plateau where currents are steered northeastward (Fig. 1; Gordon, 1972, 1975). Short-term flow records note maximum speeds of 30–40 cm/s in the inflow region (Gordon, 1975).

South of Bounty Trough, the ACC uncouples from the DWBC and flows east (Fig. 1). The DWBC continues northeast, presumably at a reduced speed because of the loss of momentum supplied by the ACC and the change from steep plateau margin to near-flat trough floor. Once across Bounty Trough, the DWBC intensifies against the steep sides of Chatham Rise (Warren, 1981). This acceleration is confirmed by eroded drifts in Valerie Passage, and by pronounced nepheloid layers. North of Valerie Passage, the main DWBC extends to Hikurangi Plateau, with a filament also bathing the flanks of Louisville Seamount Chain. As Hikurangi Plateau is 3500–4000 m deep, the upper DWBC spreads west over the plateau. The deeper flow, however, is constrained by the plateau margin and travels northwest to Kermadec Trench, where it is redirected north by the topography (Warren, 1981; Carter and McCave, 1994).

ABYSSAL TRANSPORT WITHIN ENZOSS

ENZOSS begins off southernmost New Zealand where sediment from the terrestrial plate boundary is transported to Emerald Basin via Solander Channel, but only during glacial lowstands. South of 52°S, jets and eddies within DWBC-ACC create a strongly erosional regime. As a result, basinal sediments are reduced to a few remnants mantled by manganese nodules and patches of rippled sand (Gordon, 1975). At the mouth of Emerald Basin, the prevailing northward flow and associated marked benthic nepheloid layer (Carter and McCave, 1996) indicate that suspended load from the eroded basinal sediments moves northeast along Campbell Plateau. Very little of this load settles out south of 55°S because of intense currents associated with energetic eddies shed from Macquarie Ridge (Gordon, 1975; Morrow et al., 1992). By comparison, north of 55°S, up to 800 m of sediment has accumulated to form Campbell Drift, which extends 850 km along the base of Campbell Plateau at ~5000 m depth (Fig. 2d; Hayes et al., 1976). A moat, scoured by the locally intensified DWBC, separates the drift from the plateau (Ovenshine et al., 1975).

North of Campbell Drift, the abyssal transport system receives its second terrigenous injection, this time from Bounty Channel. It discharges into a sluggish DWBC with the result that Bounty fan has built 150–200 km *directly across* the current path (Fig. 1; Carter and Carter, 1993). Nevertheless, the flow is sufficiently strong to winnow the fan surface and scour channel levees (Carter et al., 1990). Mica within the fan-channel sediments has been geochemically "fingerprinted" and used as a tracer for the material entrained by the DWBC (Carter and Mitchell, 1987). In this manner, Bounty mica has been traced to drifts 1000 km downstream of Bounty fan.

The sediment path from Bounty Trough is northeast to Valerie Passage and then northwest once through the passage. En route, a series of small drifts, in part derived from reworked Bounty fan material, has formed on the flanks of Chatham Rise and in Valerie Passage.

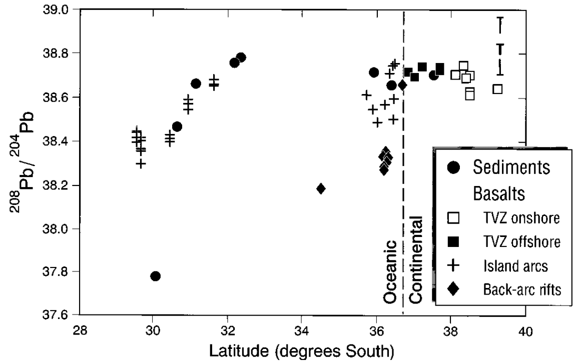

Figure 3. $^{208}Pb/^{204}Pb$ **showing southward increase within basalts toward locus of sediment subduction; this change reflects basalt contamination by subducted, isotope-enriched sediment including Hikurangi fan drift. T—lead isotope range for Torlesse metasediments (after Gamble et al., 1996); TVZ—Taupo volcanic zone.**

Once north of Chatham Rise, the DWBC receives detritus directly from eruptions in the Taupo volcanic zone of the North Island (Fig. 1). Although the largest of these mainly rhyolitic eruptions can disperse ash south of the rise, the main zone of tephra deposition is east of the North Island (Carter et al., 1995). Since the last glaciation, four major and several minor eruptions have delivered an estimated 400 km^3 of airfall to the Southwest Pacific (Carter et al., 1995). This airfall averages ~45 Mt/yr, compared to 147 Mt/yr fluvial input, and is therefore a significant part of the abyssal sediment supply.

The third injection of sediment is from Hikurangi Channel at 39°S (Carter and McCave, 1994). The channel has operated throughout glacial and interglacial cycles and is presently guiding turbidity currents to the abyssal floor at a rate of 2–3/1000 yr (Lewis, 1994). As a result, a large fan has formed, but because the DWBC is intensified against the Hikurangi Plateau margin, the fan is drawn out into a 300-km-long ridge (Fig. 2f). Termed the *Hikurangi fan drift*, it contains 400 m of Pliocene-Pleistocene fan-drift sediments overlying a Miocene paleodrift (Carter and McCave, 1994). In addition to micas from Bounty Trough, cores from the fan drift and environs contain the subantarctic diatom *Nitzschia kerguelensis*, which further attests to contributions from distal southern sources (Carter and Mitchell, 1987; Fenner et al., 1992).

The northwest growth of Hikurangi fan drift and the westward motion of the Pacific plate cause the drift to descend into the Kermadec Trench subduction zone where the deposit is progressively disrupted by mass wasting as it approaches the 7200-m-deep trench axis (Fig. 2g; Carter and McCave, 1994). The axis has only a scant sediment cover, and the western trench wall is mainly exposed rock with patches of pelagic and volcanic detritus. This setting contrasts strongly with the Hikurangi subduction zone to the south where >3 km of Pliocene-Pleistocene fill underlies the trough floor and the western trough wall is an accretionary prism (Lewis and Pettinga, 1993). The dearth of sediment in Kermadec Trench reflects a low supply due to the trench's isolation from Hikurangi Channel. Thus, the small amount of material reaching Kermadec Trench on the descending plate and as pelagic rain is liable to be subducted rather than off-scraped to form an accretionary prism (Lallemand et al., 1994).

RECYCLING THROUGH THE SUBDUCTION ZONE

The trail does not stop in the trench. Basalts that erupted from the Kermadec arc and adjacent back-arc have trace and minor element characteristics of subduction-related magmas (Gamble et al., 1996). These lavas also have enriched isotopic compositions that infer a sediment component in their petrogenesis. Lead isotopes are particularly sensitive indicators (Fig. 3). $^{208}Pb/^{204}Pb$ ratios in arc basalts, back-arc basalts, and trench sediments show a strong north-south polarity that reflects a diminishing northward input of sediment, including Hikurangi fan drift, into the source region of the supra-subduction zone magmas by the subducting Pacific plate.

EVOLUTION OF ENZOSS

ENZOSS began c. 30 Ma with the opening of the circum-Antarctic seaway and instigation of the ancestral ACC-DWBC (Kennett and von der Borch, 1985). The Miocene witnessed formation of several drifts that became the cores of modern drifts. Until 10 Ma, the channels probably delivered little sediment to the drifts, Bounty fan had not reached the DWBC (Carter and Carter, 1993), and Hikurangi Channel had not diverted east to form Hikurangi fan drift (Lewis, 1994). The status of Solander Channel at that time is unknown. The situation changed c. 10 Ma when a new phase of compressional deformation along the New Zealand plate boundary enhanced the terrigenous input to the ocean (Nelson, 1985; Kamp et al., 1989). By the early Pliocene, Bounty fan reached the DWBC (Carter et al., 1990). Formation of Hikurangi fan drift may have been later with the suggested late Pliocene–early Pleistocene easterly diversion of Hikurangi Channel (Lewis, 1994).

The terrigenous input increased further with Pliocene-Pleistocene climatic changes. In glacial periods, all channels were active and emptied directly into the DWBC. These were probably periods of maximum sediment transport through ENZOSS. However, in interglacial times, Solander and Bounty channels became dormant, although Hikurangi Channel continued to function. Despite the reduced terrigenous supply overall, transport continued in interglacials through direct injection from Hikurangi Channel and erosion of existing abyssal deposits, e.g., Emerald Basin, along Campbell and Hikurangi plateaus, Valerie Passage.

To conclude, ENZOSS may be regarded as a dynamic, evolving system that differs markedly from more conventional recycling models for convergent margins. In the case of the latter, sediment is trapped within proximal trenches and recycled back directly (e.g., Lewis and Pettinga, 1993). With ENZOSS, sediment initially escapes entrapment and disperses out to 1000 km beyond the subduction zone. This material would be irretrievably lost if not for the DWBC, which entrains the sediment along its 4500 km course and eventually returns it to the margin subduction zone to complete one cycle and begin another.

ACKNOWLEDGMENTS

Funded by the New Zealand Foundation for Science, Research and Technology (CO1422; Obj. OVD 502) with help from the British Council Link Scheme. We thank staff of the research ships *Rapuhia* and *Lavrentyev*, colleagues at the New Zealand Oceanographic Institute for their assistance, and J. Woodhead of the University of Melbourne. S. Nodder and K. Lewis graciously reviewed the manuscript.

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Manuscript received April 15, 1996
Manuscript accepted May 8, 1996