ELSEVIER

Marine Geology 159 (1999) 35–62

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.nl/locate/margeo

Morphology and history of the Kermadec trench–arc–backarc basin–remnant arc system at 30 to 32°S: geophysical profile, microfossil and K–Ar data

Peter F. Ballance [a,*], Albert G. Ablaev [b], Igor K. Pushchin [b], Sergei P. Pletnev [b], Maria G. Birylina [b], Tetsumaru Itaya [c], Harry A. Follas [a,1], Graham W. Gibson [a,2]

[a] *University of Auckland, Private Bag 92019, Auckland, New Zealand*
[b] *Pacific Oceanological Institute, 43 Baltiyskaya Street, Vladivostok 690041, Russian Federation*
[c] *Research Institute of Natural Sciences, Okayama University of Science, 1-1 Ridai-cho, Okayama 700, Japan*

Received 8 January 1998; accepted 27 November 1998

Abstract

Knowledge of the time span of arc activity, essential for correct tectonic reconstructions, has been lacking for the Kermadec arc system, but is supplied in this paper through study of microfossils contained in dredge samples, and K–Ar ages on dredged basalt clasts. The Kermadec system at south latitudes 30 to 32° in the southwest Pacific comprises from west to east the Colville Ridge (remnant arc), Havre Trough (backarc basin), Kermadec Ridge (active arc) and Kermadec Trench (site of west-dipping subduction of Pacific plate lithosphere beneath the Australian plate). Data are presented from two traverses (dredge, magnetic, single-channel seismic) across the whole system. An important transverse tectonic boundary, the 32°S Boundary, lies between the two traverse lines and separates distinct northern (32–25°S) and southern (32–36°S) sectors. The northern sector is shallower and well sedimented with broad ridges and a diffuse backarc basin. The southern sector is deeper with narrow ridges and steep escarpments facing inwards to a little-sedimented, rifted backarc basin. The Kermadec Ridge slopes smoothly trenchward to a mid-slope terrace (forearc basin) with minor sediment fill at 5–6 km water depth. A steeper (10–24°) and more rugged lower trench slope is mantled with New Zealand-sourced rhyolitic vitric mud diamictons containing locally derived mafic volcanic clasts; one clast is of late Miocene age (K–Ar age 7.84 Ma). The arc (Kermadec Ridge) is capped by active volcanoes; very young K–Ar ages (< 150 ka) from basalts dredged from the 40-km wide transition zone between the Kermadec Ridge and the Havre Trough, north of the 32°S Boundary, support the concept of arc retreat to the southeast. South of the 32°S Boundary the Kermadec Ridge deepens and narrows, makes a left-step of 10 km, and presents a 2.8-km scarp face to the Havre Trough; K–Ar ages from dredged basalt clasts range from 1.25 to 2.04 Ma and indicate exposure of older arc rocks. The deepest and most sedimented portion of the backarc basin lies on the western side, both north and south of the 32°S Boundary, and the centre of basin opening is inferred to lie on the eastern side. There is foundered arc material and former hydrothermal activity in the centre of the rifted basin. The remnant

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[*] Corresponding author. Tel.: +64-9-373-7599; Fax: +64-9-373-7435; E-mail: pf.ballance@auckland.ac.nz
[1] Present address: 14 Merriefield Road, Auckland 10, New Zealand.
[2] Present address: 26 Hepburn Road, Henderson, New Zealand.

PII: S0025-3227(98)00206-0

arc (Colville Ridge) has subsided approximately 700 m. On the northern profile it is broad and has a perched sedimentary basin at 1 km water depth on the eastern flank. On the southern profile it is narrow and presents a 2.5-km scarp face to the Havre Trough. Arc substrate rocks are exposed on both ridges. Derived microfossils, sedimentary clasts with fossil-based depositional ages in the late Miocene and Pliocene, clasts of hypabyssal and plutonic rocks, and dated basalt clasts as old as 2 Ma, together indicate continuing collapse and surficial reworking on both ridges. Derived microfossils establish that the Colville and Kermadec Ridges have existed (initially as one ridge) since at least the earliest Miocene; by inference, ridge volcanism has been active since the same time, about 25 Ma. Rare older microfossils may indicate earlier existence of the ridge. A 25-Ma inception of arc volcanism is synchronous with contiguous arc sectors to the north (Tonga) and south (New Zealand). We have no new data on the age of the age of the Havre Trough, which is generally considered to be less than 5 Ma. A seamount entering the Kermadec Trench is early Eocene or older, and a ridge/seamount in the South Fiji Basin (west of the Colville Ridge) is middle Miocene or older.

Keywords: lower Miocene; subduction; Pacific plate; Tonga history; Colville Ridge; Havre Trough

1. Introduction

Volcanic/magmatic arcs are of critical importance in the reconstruction of past tectonic scenarios because they are linked unambiguously to a specific tectonic setting, and because their products are voluminous, petrologically distinctive, and have excellent preservation potential. In order to exploit their full potential in tectonic reconstructions it is necessary to obtain dates covering the full span of arc activity. This is commonly difficult to achieve because of erosion or burial of older rocks in the system, especially in continental arcs. However, in the case of oceanic arcs, where much of the accumulation is submarine, it has been found that the ridge environment encourages much reworking and recycling of older ridge material into younger sediments, and that microfossils can survive several such cycles (Ballance, 1991; Chaproniere, 1994b; Quinterno, 1994b; Tappin and Ballance, 1994). Thus, a hand sample of calcareous volcaniclastic sedimentary rock from a dredge haul has the potential to record several episodes of ridge building, while an assemblage of samples may contain a near-complete record of the biostratigraphic zones and stages spanned by ridge building. It is assumed that ridge building is synonymous with oceanic arc activity.

This paper describes such an investigation into the history of the Kermadec arc system at south latitudes 30 to 32°. It utilises a range of microfossil groups, and is supplemented by a number of whole-rock K–Ar ages on basalt clasts. The full history of the Kermadec arc was previously unknown, but our investigation shows that there are microfossils (principally foraminifera) representing all of the Neogene, from the earliest Miocene to the present. In contrast, there are very few indications of pre-Miocene sedimentation, from which we conclude that the inception of the Kermadec–Colville arc/ridge, and by implication the beginning of strongly convergent subduction at the Pacific–Australia plate boundary, took place around the Oligocene–Miocene boundary, ca. 25 Ma.

2. Regional setting

The Tonga–Kermadec–New Zealand arc system extends for 3000 km between latitudes 15 and 40°S, forming the southwestern-most portion of the circum-Pacific ‘Ring of Fire’ (Fig. 1). Old Pacific plate lithosphere (older than 80 Ma, Lonsdale, 1988) is being subducted westwards beneath the Australian plate at the Kermadec Trench, with a convergence rate at 31°S of 80–85 mm/year, comprising a Pacific plate vector of about 65 mm/year (DeMets et al., 1990), and a trenchward migration of the Kermadec Ridge of 15–20 mm/year (Wright, 1993a).

The Tonga–Kermadec arc was one of the first to be recognised as an arc–backarc basin–remnant arc triplet (Karig, 1970b). The three sectors of the Kermadec portion of the arc comprise the Kermadec Ridge, the Havre Trough and the Colville Ridge, respectively (Figs. 1–4).

The Kermadec Ridge (active arc) is exposed above sea level only on the active volcanic islands of Raoul, Macauley, Curtis and L’Esperance, which form the crest of the ridge between 29 and 32°S (Figs. 2–4) (Dupont, 1988). South of 32°S the Ker-

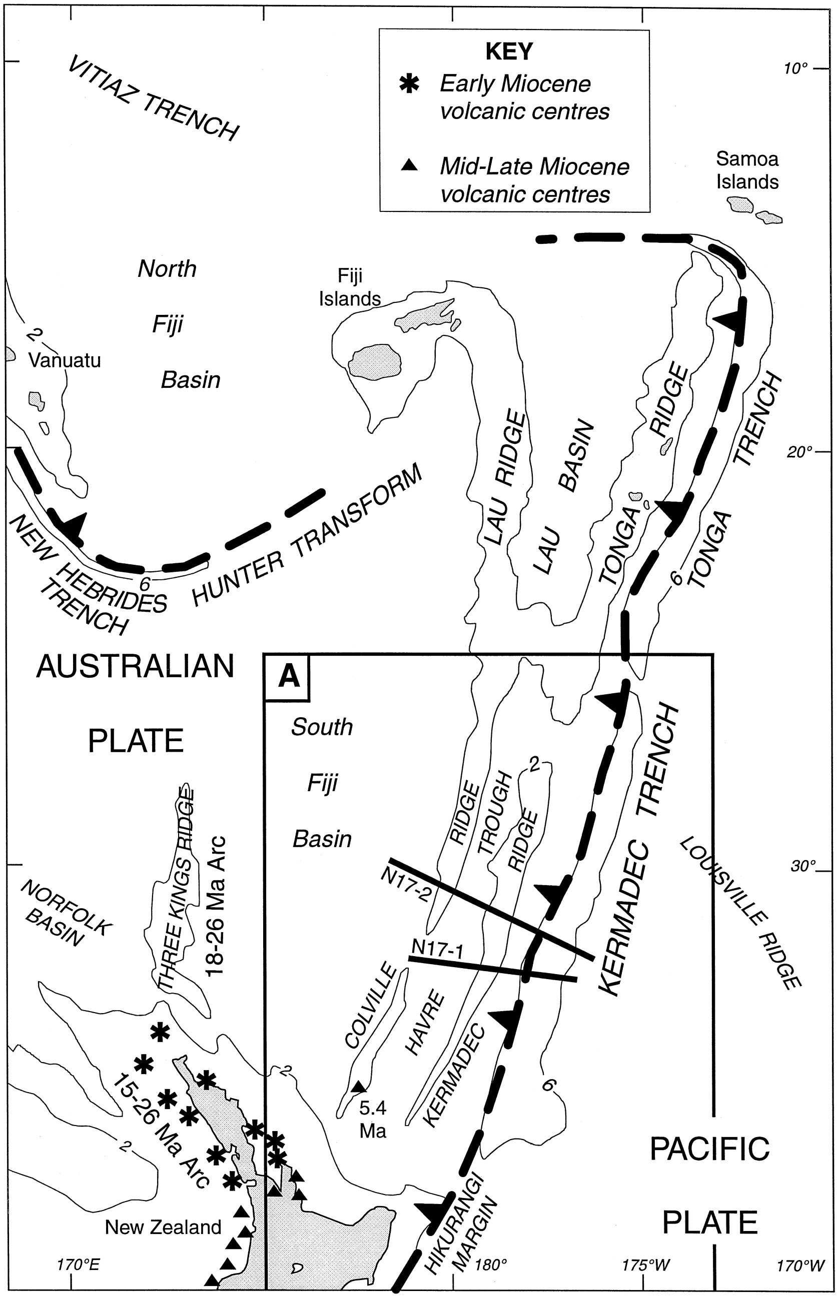


Fig. 1. Map of the Southwest Pacific Ocean showing the regional tectonic setting and location of the two dredged profiles. Depth contours in kilometres. The presently active arcs comprise New Zealand–Kermadec Ridge–Tonga Ridge, linked with Vanuatu by transforms associated with the North Fiji Basin. Colville Ridge–Lau Ridge is the remnant arc. Havre Trough–Lau Basin is the active backarc basin. Kermadec–Tonga Trench marks the site of subduction of Pacific lithosphere westward beneath Australian plate lithosphere. North and South Fiji Basins are marginal basins of late Neogene and probable Oligocene age, respectively. Box A = the area covered by Fig. 2. 5.4 = K–Ar date of dredged basalt sample (Adams et al., 1994). Miocene volcanic centres in New Zealand and the Three Kings Ridge are shown for reference in the later discussion.

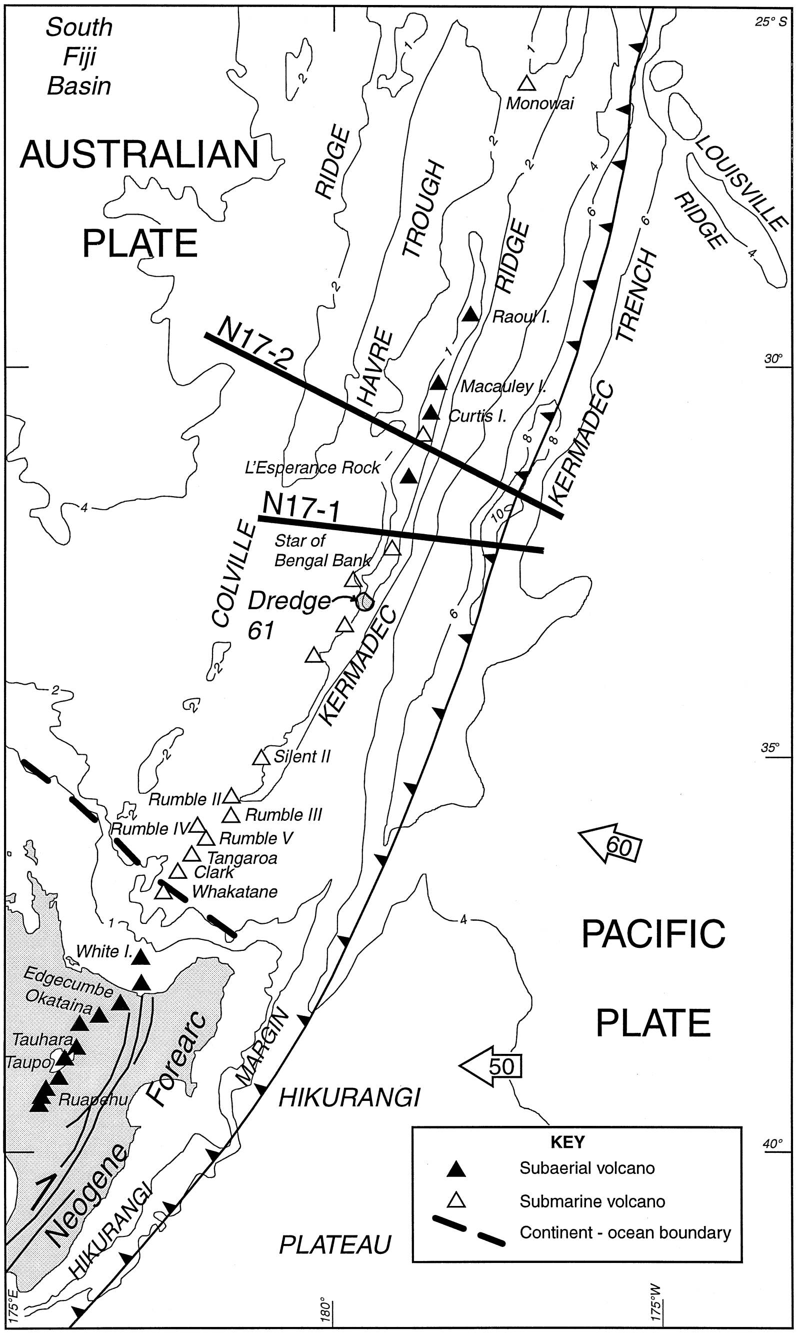


Fig. 2. Bathymetric map of the Kermadec and Colville Ridges showing the location of the two sampling profiles, and known active arc volcanoes of the Taupo Volcanic Zone (North Island New Zealand) and Kermadec Ridge. Open arrows = direction and rate (mm/year) of Australia–Pacific relative plate motion (DeMets et al., 1990; Sutherland, 1995). The change in morphology of the Kermadec Ridge, from crestal volcanoes, to volcanoes west of the ridge crest, occurs to the south of Star of Bengal Bank. The position of Dredge 61 is shown for reference in the later discussion of age of the arc system. Bathymetry and volcanoes from Wright (1994).

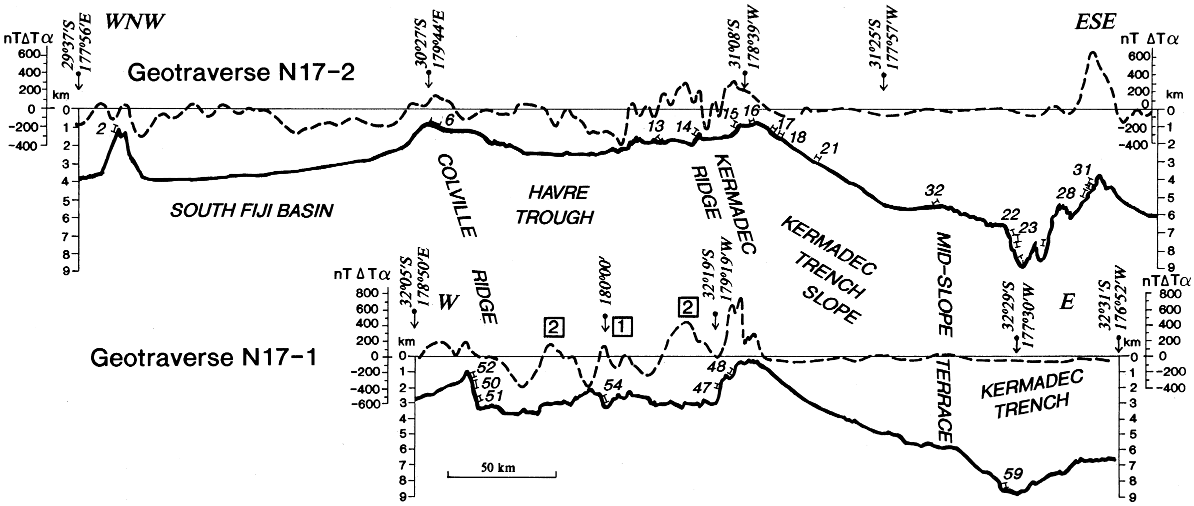


Fig. 3. Topographic profiles and shipboard magnetic profiles along the two lines shown on Figs. 1 and 2. Numbers indicate dredge sites.

madec Ridge makes a left-step of about 10 km, and becomes deeper, narrower and asymmetric, presenting a steep face to the backarc basin. South of about 32°30′S the ridge forms a morphological frontal arc ridge while active vents are located west of the ridge (CANZ, 1997). Many of the known active volcanoes between 29 and 37°S are located at the southeastern end of a northwest-trending chain of inactive cones (CANZ, 1997), from which it is inferred that the Kermadec Trench and subduction zone are retreating southeastwards as the backarc basin widens (Wright et al., 1996; Wright, 1997).

The Lau–Havre backarc basin widens to the north and is propagating southwards, being a spreading basin in the north (Lau) and a rifting system in the south (Havre) (Bevis et al., 1995; Benes and Scott, 1996; Parson and Wright, 1996; Taylor et al., 1996). In the far north a basin opening rate of about 160 mm/year is added to a plate convergence rate of about 80 mm/year, to give a total convergence at the Tonga Trench of about 240 mm/year, the highest tectonic rate yet measured (Bevis et al., 1995). Southward towards New Zealand all rates decline as the pole of Pacific–Australian rotation is approached.

North of latitude 32°S, the Havre Trough is shallower than 3000 m, and has gently sloping, poorly defined margins (CANZ, 1997). In contrast, south of 32°S the trough is generally deeper than 3000 m and has steep, sharply defined margins that are considered to be fault-controlled (Wright, 1997; this study).

The junction between the Havre Trough and Lau Basin is generally placed at a shallower area that lies inboard of the confluence between the Louisville Ridge and the trench at 25°S (Fig. 1). There is little difference in bathymetric character between the northern Havre Trough and the southern Lau Basin (CANZ, 1997).

The Colville Ridge (remnant arc) is entirely submarine. It extends from a poorly defined transition from the Lau Ridge remnant arc, of which it is apparently a simple southward continuation, at about 25°S, to a termination near the New Zealand continental slope at 36°S. Existing bathymetry (CANZ, 1997) indicates a marked change in ridge morphology at 31°35′S. North of that point (Fig. 4), the ridge is 60 or more km wide, and generally symmetrical in profile; where asymmetry exists the steeper side can be either to east or west. South of 31°35′S the ridge is narrower, generally less than 40 km wide, and strongly asymmetrical, presenting a steep eastern flank to the Havre Trough. The ridge also changes trend, from 015 to 030°, south of 31°35′S.

Further south, beyond the oceanic portion of the Colville remnant arc, arc volcanism on the Colville trend, between mid-Miocene and late Pliocene, ex-

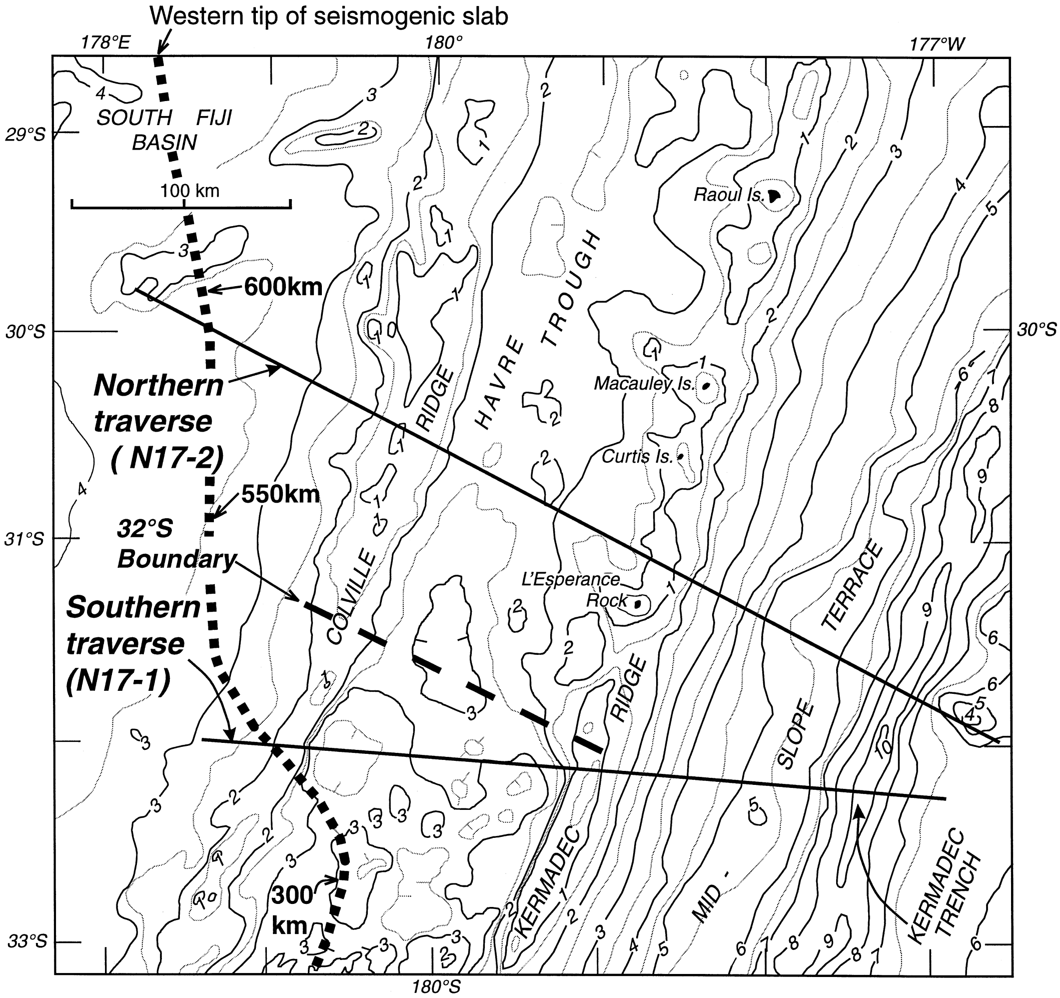


Fig. 4. Bathymetric map (from CANZ (1997)) showing the topographic contrasts between the areas north and south of the 32°S Boundary, and the approximate position and depth of the western tip of the seismogenic subducting slab from the work of Pelletier and Dupont (1990). The change on the Kermadec Ridge, from active volcanoes forming the crest of the ridge to being situated 20–30 km west of the ridge, takes place at around 32°30′S. Contours in kilometres, with 0.5 km contours down to 6.5 km but not deeper.

tended a further 500 km to the southwest across the continental crust of the North Island of New Zealand (Herzer, 1995; Stagpoole, 1997) (Fig. 1).

Thus, the arc, backarc basin and remnant arc all show marked changes in morphology and trend at a well marked line, here termed 32°S Boundary from its initial recognition and naming by Pelletier and Dupont (1990). The line trends WNW–ESE, at right angles to the ridges, between latitudes 32°12′ on the Kermadec Ridge and 31°35′S on the Colville Ridge (Fig. 4). The two long sections of the arc–backarc basin–remnant arc trio that are separated by the 32°S Boundary maintain their general form northward to the boundary of the northern Havre Trough at 25°S, and southward to the transition to continental rifting at 37°S. The Boundary also coincides with a marked southward shallowing of the tip of the seismogenic Benioff zone (Pelletier and Dupont, 1990). The possible significance of the 32°S Boundary is discussed later.

South of 37°S, Pacific plate lithosphere is subducted obliquely beneath the continental crust of

North Island, New Zealand. Here the Hikurangi Margin comprises, in the south, a sedimented trench and adjacent accretionary prism (Lewis and Pettinga, 1993), and in the north, a poorly sedimented trench adjacent to a steep and tectonically eroded continental slope (Collot et al., 1996; Collot and Davy, 1998). The arc in New Zealand comprises the Taupo Volcanic Zone (Fig. 2). Convergence becomes increasingly dextral–oblique to the south, with a transition to the Alpine Fault transform at 42°S.

To the north, the oceanic Kermadec arc joins the oceanic Tonga arc. The boundary between the two arc segments is placed where the Louisville hotspot chain of seamounts (Lonsdale, 1986; Lonsdale, 1988; Watts et al., 1988) is being consumed obliquely at the trench, causing a shallowing of the trench (Ballance et al., 1989) (Figs. 1 and 2).

This study describes the historical and morphological results from two detailed sampling (dredge) and profiling traverses (single-channel seismic with a 3-l (180 in.^{3}) airgun; and magnetic) across the entire system, between south latitudes 30 and 32° (Figs. 1–4). The traverses were conducted from the *RV Aleksandr Nesmeyanov* (Cruise N17, 1989).

3. Previous work

3.1. Kermadec trench and trench slope

The Kermadec Trench is known mainly from swath-based bathymetry in the south, and broad-scale bathymetry in the centre and north (CANZ, 1997). The trench is deeper than 9000 m in the north, reaches a maximum depth of 10,000 m at latitude 32°S, and shallows southward. It shallows markedly when it meets the northern edge of the subducting Hikurangi Plateau at 36°S (Collot and Davy, 1998) (Fig. 2). Pelletier and Dupont (1990) took single-channel seismic profiles across the outer trench slope, trench and lower inner trench slope at 31°30′S and 34°30′S, noting greater roughness on the descending plate, and greater steepness of the lower inner trench wall, on the northern traverse. They inferred a greater degree of tectonic erosion north of 32°S than south of it, and extended their 32°S Boundary eastward across the trench. Ruppel et al. (1994) measured heat flow (which ranged from >100 to <20 mW m^{-2}, in places negative), and took single-channel seismic profiles, on the northern Kermadec forearc at 28 and 30°S. They noted a continuous but patchy sediment cover up to 500 m thick, which thins downslope. In contrast to Pelletier and Dupont (1990) they inferred a lack of tectonic erosion north of 32°, but note evidence for erosional and slumping processes controlling sediment thickness and hence heat flow. Prior to our study, bottom samples were confined to two gravity cores from the southernmost trench (Gamble et al., 1996).

3.2. Kermadec Ridge (active arc)

The petrology, volcanology and history of the four volcanic Kermadec islands (29°20′ to 31°30′S, Fig. 4) have been studied to varying extents (Lloyd and Nathan, 1981; Smith and Brothers, 1987; Smith et al., 1988; Lloyd et al., 1996; Brook, in press). All ages obtained from the islands are Quaternary. The lavas range from basic to rhyolitic in composition. Northward from the islands to Monowai seamount (Fig. 2), the northernmost known active volcano on the Kermadec arc (Brothers et al., 1980; Davey, 1980), satellite gravity data (Sandwell and Smith, 1994) indicate the presence of many unexplored submarine volcanoes.

Dupont (1979, 1982), Dupont and Herzer (1985) and Dupont (1988) used three single-channel profiles through the central and northern arc and trench to note morphological differences between the Tonga and Kermadec forearcs, which they attributed to the subduction of the Louisville Ridge beneath the Tonga arc.

The arc south of 33°30′S has been studied by MR1 swath mapping methods, allowing a division of the frontal arc/ridge into five en echelon segments, and suggesting that the western margin with the Havre Trough is a west-dipping detachment fault (Wright, 1997). The submarine volcanoes of the arc south of 35°S, and the transition to the continental arc of New Zealand at 37°S, have been extensively studied (Gamble et al., 1990; Gamble et al., 1993a,b; Wright, 1993a,b; Wright, 1994; Blackmore and Wright, 1995; Gamble and Wright, 1995; Gamble et al., 1995; Wright, 1996; Wright et al., 1996; Wright, 1997).

3.3. Havre Trough (backarc basin)

Aeromagnetic anomalies in the north and south of the Havre Trough backarc basin were originally interpreted as indicating opening by symmetrical spreading since 2 Ma (Malahoff et al., 1982). However, later swath mapping in the central part of the basin, by swath GLORIA and reconnaissance Seabeam methods (Caress, 1991), and in the southern part of the basin by swath GLORIA and SYS09 methods (Wright, 1993b,a), revealed basement fabrics suggesting a widening axis consisting of a number of en echelon segments. The segments are offset clockwise from the trend of the basin and are off-centre, located within 50 km of the active arc, but are not the deepest parts of the basin. The basin is still largely at the rifting stage of opening (Parson and Wright, 1996; Wright, 1997). Wright (1993a) concluded that the southern sector of the basin, between 35 and 37°S, began opening at about 5 Ma and is opening at a rate of 15–20 mm/year by intrusion of parallel dike segments between fault blocks.

Pelletier and Dupont (1990) noted the strong bathymetric contrast between the sectors of the trough north and south of the 32°S Boundary, and suggested a possible connection with the marked shallowing of the tip of the seismic Benioff zone that also occurs at the Boundary, from a depth of 550 km north of 32° to <300 km south of 32° (Fig. 4).

3.4. Colville Ridge (remnant arc)

MR1 swath mapping and imagery south of 33°30′S allowed Wright (1997) to divide the ridge into four en echelon segments, and to interpret the steep eastern flank in terms of zigzag antithetic faults forming the western side of the Havre rift structure, and bounding a back-tilted ridge flank terrace.

Prior to our cruise, no systematic dredging program had been undertaken on the Colville Ridge. North of 33°30′S the ridge was known from a few single-channel seismic profiles (Karig, 1970a,b; Caress, 1991), and bathymetric mapping (CANZ, 1997). Pelletier and Dupont (1990) noted the marked bathymetric change at about 31°S and included it in their 32°S Boundary.

3.5. Regional analysis

Collot and Davy (1998) analysed the active Tonga–Kermadec arc and forearc in terms of the influence of two oceanic eminences on the Pacific plate that are subducting obliquely, such that their area of influence is migrating progressively southwards along the plate boundary. In the north, the Louisville seamount chain and broad swell, and in the south the Hikurangi Plateau (Fig. 1), are each interpreted as having caused tectonic erosion of the lower forearc, between about 21 and 27°S, and between 30°S and about 39°S, respectively. The area between 27 and 30°S has not been subject to significant tectonic erosion, but will be as the Louisville Ridge sweeps southward. Collot and Davy (1998) suggest a causal connection, between the influence of tectonic erosion south of 30°S, and the westward stepping of the active volcanoes of the Kermadec arc from the ridge crest north of about 32°30′S, to a position 15 to 20 km west of the ridge crest south of 32°30′S. While Pelletier and Dupont (1990) suggest tectonic erosion in the trench north of 32°, both Ruppel et al. (1994) and Collot and Davy (1998) suggest accretion.

4. Previous age information

All previous age data from the island volcanoes has indicated Quaternary, mostly late Quaternary, ages (Lloyd and Nathan, 1981; Lloyd et al., 1996; Brook, 1998). A single K–Ar dated dredge sample from the southern Kermadec arc gave 0.77 Ma (Wright, 1994). The interpretation of Malahoff et al. (1982) regarding aeromagnetic anomaly mapping suggested 2 Ma for the inception of the Havre Trough backarc basin, but the recent recognition of more complex, asymmetrical rifting and dike-intrusion fabrics (Wright, 1993a) means that there is no direct constraint on the age of the Trough; as noted above, Wright (1993a) inferred an age of about 5 Ma for the trough. A basalt dredged from the Colville Ridge at 35°05′S yielded a K–Ar age of 5.4 ± 0.1 Ma (Adams et al., 1994).

Because both the arc and remnant arc ridges are continuous with their counterparts in the Tonga and

New Zealand arcs to the north and south, all three sectors would be expected to have a similar history, since they were presumably responding to the same changes in Australia–Pacific plate motions. The history of both the Tonga and New Zealand sectors is quite complex, and, in order to lay a proper foundation for the interpretation of our new data on the Kermadec and Colville Ridges, it is outlined in the following section.

5. Brief eruptive history of the Tonga and New Zealand arcs

5.1. Tonga

Fig. 5 shows all the available pre-Pliocene age data, both biostratigraphic and radiometric, for the Tonga–Lau arc–remnant arc pair. All references are given in the figure caption. The Pliocene–Quaternary history of arc-rifting and spreading (Clift et al., 1994; Parson and Wright, 1996) is not shown since the emphasis in this paper is on the Miocene and earlier history.

The data indicate a middle Eocene period (50–40 Ma) of tholeiitic island arc activity (Hawkins and Falvey, 1985), the volcanic rocks being overlain unconformably at ’Eua Island and in ODP 841 by limestones with epiclastic volcanic material, of latest middle Eocene to earliest Oligocene age. Material from the oil wells on Tongatapu indicates volcanic rocks of late Eocene to earliest Oligocene age, though as noted below there is now doubt concerning early Oligocene fossils in the Tongatapu wells.

Chaproniere (1994a) has noted an almost total lack of early Oligocene rocks on the Tonga arc. The only material of that age known to date is a few derived nannoplankton (Quinterno, 1994b). Duncan et al. (1985) reported Ar–Ar ages from ’Eua Island of 40–46 Ma (mid-Eocene), 31–33 Ma (early Oligocene) and 17–19 Ma (mid-Miocene). The earlier ages fit well with other age information indicating middle Eocene island arc activity in the Tonga

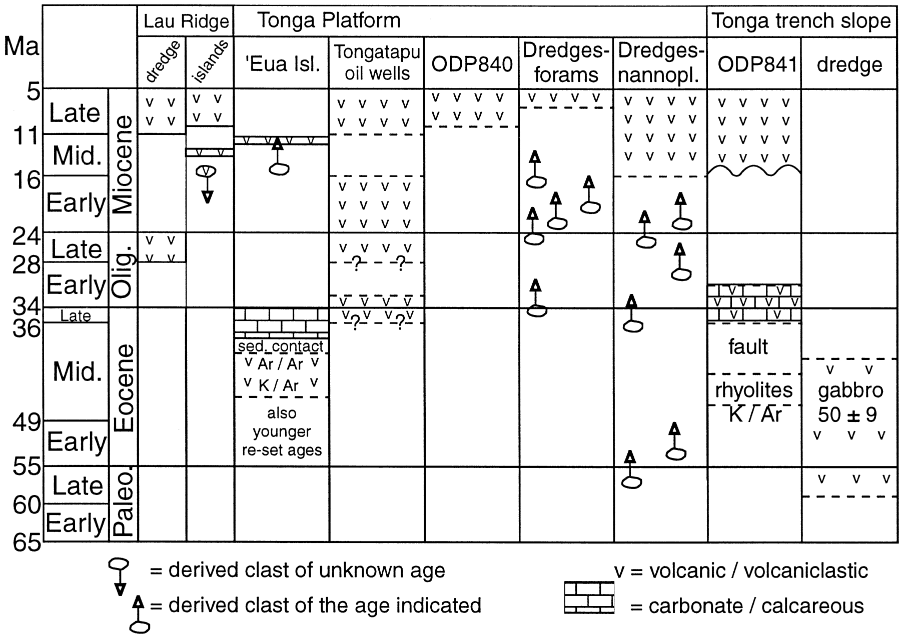


Fig. 5. The known pre-Pliocene history of the Tonga arc from all current sources, as recorded on the Lau Ridge (remnant arc), Tonga Platform (frontal arc), and Tonga trench slope. Note the break between Eocene arc activity and late Oligocene–early Miocene arc activity; the early Oligocene hiatus in volcanism and sedimentation is almost complete. It is argued in the text that the Eocene volcanic rocks are an allochthonous tectonostratigraphic terrane. Based on the following sources: Cole et al., 1985; Cunningham and Anscombe, 1985; Duncan et al., 1985; Lowe and Gunn, 1986; Acland et al., 1992; Tappin, 1993; Chaproniere, 1994a,b,c,d,e; Clift et al., 1994; McDougall, 1994; Nishi and Chaproniere, 1994; Quinterno, 1994a,b,c; Tappin and Ballance, 1994; Tappin et al., 1994; Clift et al., 1998.

region (Fig. 5), but there are difficulties in reconciling the younger ages with field evidence. The lava flows dated at 31–33 Ma (early Oligocene) are located stratigraphically beneath Eocene limestones, and recent mapping on 'Eua Island has shown no evidence for possible lava flows younger than the limestones (Tappin and Ballance, 1994; D.R. Tappin, personal communication). The dikes dated at 17–19 Ma intrude the Eocene volcanics, but are not known to intrude younger rocks. Furthermore, although the ages correlate well with Miocene activity elsewhere (Fig. 5) the Miocene rocks on 'Eua are younger than the dike ages, and are relatively distal volcaniclastic sediments (Tappin and Ballance, 1994); there is no evidence of Miocene lavas on 'Eua Island or on nearby Tongatapu Island (Cunningham and Anscombe, 1985). Eruptive rocks of this age are found on the Lau remnant arc (Fig. 5).

Thus, there is a strong likelihood that the 31–33-Ma dates on lavas have been reset (all basement igneous rocks on 'Eua exhibit moderate to severe secondary alteration, Duncan et al., 1985), and a distinct possibility that the 17–19-Ma ages have also been reset. Similarly, gabbro intrusions encountered at the bottom of two oil wells on Tongatapu, and K–Ar dated at 13.9 ± 1 and 21.3 ± 0.4 Ma (Cunningham and Anscombe, 1985), are intruded into Eocene volcanic rocks, raising the possibility that they too may be reset Eocene ages.

A resumption of arc volcanism in the Neogene is widely recorded. There is abundant evidence of activity of mid- to late-Miocene age and younger, and rather more fragmentary evidence of activity beginning in the late Oligocene and continuing through the early Miocene.

It has been assumed by most previous authors that the Eocene arc activity at Tonga and Fiji was caused by west-dipping subduction of the Pacific plate, i.e., was a direct precursor of the Neogene regime. However, the rocks themselves contain no evidence of subduction polarity, and when reconstructions are made for the Eocene, by closing the North and South Fiji Basins (Fig. 1), Tonga and Fiji are brought close to New Caledonia, where there is evidence of a northeast-dipping subduction zone in the Eocene that is lacking associated arc rocks (Aitchison et al., 1995; Meffre, 1995). Thus, there is a good prima facie case for regarding the Eocene arc rocks of Tonga as the missing half of the subduction couplet of New Caledonia; that is, they may be an allochthonous tectonostratigraphic terrane that was translated eastwards during the opening of the South Fiji Basin and its northern continuation the Solomon Sea (Hall, 1997), and therefore they tell us nothing directly about west-dipping subduction of the Pacific plate.

The position adopted in this paper is that the present cycle of west-dipping, magma-producing subduction of the Pacific plate began in Tonga in the late Oligocene, approximately 28 Ma.

5.2. New Zealand

In northern New Zealand, and its contiguous northern submarine ridges (southern Norfolk and Three Kings), there is abundant evidence, both from extensive obduction and from the commencement of arc volcanism after a long period of tectonic and volcanic quiescence, of the establishment of west-dipping, strongly convergent subduction around 26 Ma, latest Oligocene (Hayward, 1993; Takagi et al., 1993; Isaac et al., 1994; Herzer, 1995; Herzer and Mascle, 1996; Herzer et al., 1997; Mortimer et al., 1998). Some reset K–Ar dates from hornblende diorite cobbles derived from the obducted ophiolite, of 27–29 Ma (Sprott, 1997; determinations by T. Itaya) suggest that precursor tectonic activity in the subduction zone may date back to 28–29 Ma.

The initial configuration of the New Zealand arc was complex. Separate arc segments were located on Northland (northwest-trending), Three Kings Ridge and Norfolk Ridge (north-trending) (Fig. 1). The configuration simplified at the end of the early Miocene, about 15 Ma, when the New Zealand sector was 'captured' by the Colville sector (Ballance, in press). All the early Miocene arc segments became extinct, and the Colville arc then extended southwestwards 500 km across the North Island (Herzer, 1995) (Fig. 1).

Thus, the present cycle of subduction and arc volcanism in both Tonga and New Zealand began in the latest Oligocene, around 28–26 Ma.

6. Materials

Dredged materials comprise igneous and volcaniclastic/bioclastic rocks (Ablaev et al., 1989; Tararin et al., 1996; Ballance et al., in press), ranging from shallow marine to deep marine in origin. Microfossils (foraminifera, nannoplankton) were identified by scientists of the Pacific Oceanological Institute, Vladivostok, and by H.A. Follas and G.W. Gibson of Auckland University (Ablaev et al., 1989; Pletnev et al., 1991; Follas, 1993). K–Ar whole-rock ages of fresh basalt clasts were determined by T. Itaya (Pushchin et al., 1996).

In samples containing abundant reworked fossils it is commonly difficult to determine the actual depositional age of the most recent host sediment (Tappin and Ballance, 1994). That has not been a problem in this study since the focus has been largely on determining the ages of all the earlier volcanic or organic materials contained in each sample.

More-or-less duplicate sets of samples are held at the Pacific Institute of Oceanology, Vladivostok; Department of Geology, The University of Auckland, New Zealand; and the New Zealand Oceanographic Institute, Wellington, New Zealand.

7. Results

7.1. Kermadec Trench—outer slope

The northern traverse intersected an ocean plate seamount entering the trench at latitude 31°50′S (Figs. 3 and 6). Dredges from 7700–7100 m (N17–27), 5120–4680 m (28) and 4550–4390 m (29) water depth recovered microvesicular basalts and foram-bearing volcanic sandstones, all variously altered and palagonitised and leached of calcite. There were also samples of micrite, and two hard, white phosphatic rocks (20–25% P_2O_5) (Ablaev et al., 1989).

A basalt clast from near the summit gave a K–Ar age of 54.8 ± 1.9. Ma (Table 1) (early Eocene). Basalts have typical oceanic seamount compositions (Tararin et al., 1996). Calcareous oozes from near the summit yielded the foraminifera *Globorotaloides suteri* and *Globoquadrina altispira*, and the calcareous nannoplankton *Chiasmolithus*, indicating original depositional ages of Paleogene to Miocene. Ad-

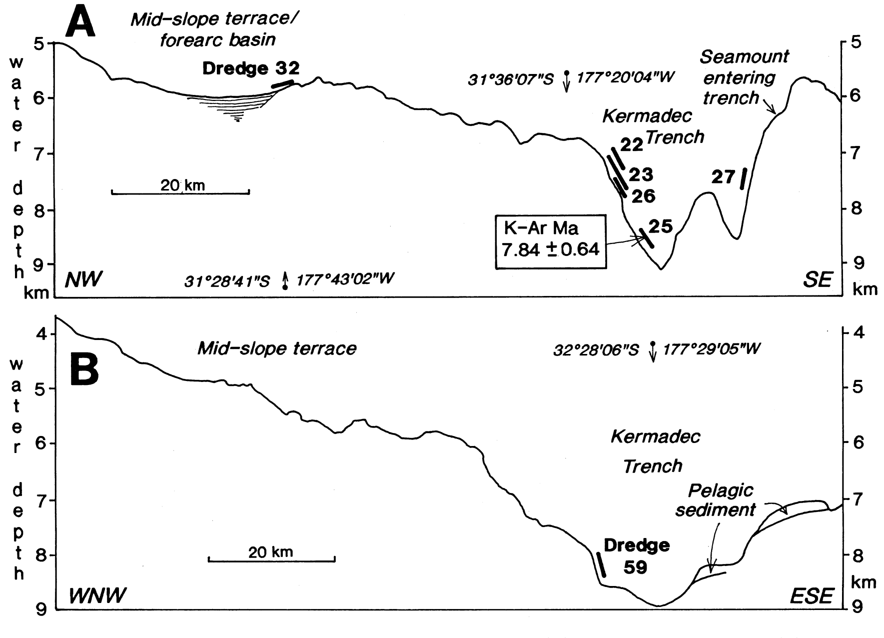


Fig. 6. Topographic profiles of the forearc basin, lower trench slope and trench. (A) Northern traverse and (B) southern traverse. Showing dredge sites, and a K–Ar age from a basalt lava clast on the lower inner trench wall.

Table 1
Radiometric whole-rock K–Ar dates on basalt clasts

Ship number (N17-)	Lab number	K (wt.%)	Radiogenic Ar 40 (10^{-8} cm^3 STP/g)	K–Ar age (Ma)	Non-radiogenic Ar (%)	Location
13-1	S25-152	0.405 ± 0.020	0.06 ± 0.17	0.04 ± 0.11	99.4	Havre Trough E.-north
13-2	S25-154	0.359 ± 0.018	0.21 ± 0.17	0.15 ± 0.12	97.9	Havre Trough E.-north
14-1	S25-153	1.082 ± 0.022	0.34 ± 0.13	0.08 ± 0.03	95.3	W. slope Kermadec R.-north
25-2	S25-116	0.290 ± 0.015	8.84 ± 0.58	7.84 ± 0.64	78.7	Kermadec Trench, 8.5 km
31-1	S25-111	2.055 ± 0.041	444 ± 13	54.8 ± 1.9	58	Seamount on Pacific plate
47-1	S25-118	0.265 ± 0.013	1.60 ± 0.49	1.56 ± 0.48	94.9	W. slope Kermadec R.-south
47-9	S25-115	0.222 ± 0.011	1.47 ± 0.18	1.71 ± 0.23	87.2	W. slope Kermadec R.-south
48-1	S25-114	0.167 ± 0.008	0.81 ± 0.20	1.25 ± 0.31	93.4	W. slope Kermadec R.-south
48-2	S25-110	0.216 ± 0.011	1.40 ± 0.18	1.67 ± 0.23	87	W. slope Kermadec R.-south
48-3	S25-155	0.218 ± 0.011	1.69 ± 0.15	2.00 ± 0.20	82	W. slope Kermadec R.-south
48-4	S25-117	0.214 ± 0.011	1.26 ± 0.18	1.52 ± 0.22	88.1	W. slope Kermadec R.-south
48-6	S25-112	0.176 ± 0.009	1.39 ± 0.20	2.04 ± 0.31	88.6	W. slope Kermadec R.-south
48-9	S25-113	0.242 ± 0.012	1.41 ± 0.19	1.50 ± 0.21	88.7	W. slope Kermadec R.-south
54-1	S25-119	0.282 ± 0.014	1.50 ± 1.70	1.37 ± 1.55	98.6	Havre Trough, middle valley, W. side

mixture with younger taxa indicates reworking on the seamount slopes. The age of the seamount is therefore early Eocene or older. The underlying ocean crust is older than 80 Ma (Lonsdale, 1988).

No dredges were taken on the southern traverse. The single-channel seismic profile shows about 0.3 STWT of layered sediment, which is broken into extensional horst and graben as it bends into the trench (Fig. 6).

7.2. Kermadec Trench— lower inner trench slope

On both profiles the lower inner trench slope, topographically below the forearc basin, is seismically opaque and has an irregular surface (Fig. 6). On the northern traverse it is divided into two distinct parts. The upper part maintains a lumpy but gentle slope to a depth of 6.5 km, where it steepens significantly to about 24°. Maximum trench depth is about 9 km. Several dredges on the steep slope below 6.5 km (sites 22, 23, 25, 26) recovered grey rhyolitic vitric muds, forming diamictons with basaltic debris. There is much evidence of deposition and redeposition by gravity flow processes, in the form of diamict textures, graded beds, mudstone clasts in mud matrix, diamicton clast in a younger diamicton. The vitric mud is sourced mainly from voluminous calc–alkaline rhyolitic eruptions in northern New Zealand (Taupo Volcanic Zone) (Wilson et al., 1984), about 1000 km to the southwest. This unusual oceanic trench sediment is discussed fully by Ballance et al. (in press).

The basaltic clasts in the diamictons include one dated at 7.84 ± 0.64 Ma (Table 1) (late Miocene). Their petrochemistry is in some respects intermediate between ocean floor and arc compositions, and may imply volcanic sources near the trench slope break (Tararin et al., 1996). However, no indication of active vents has yet been found, and at least one clast is old (7.8 Ma) and thus, could have travelled down the slope from the arc. Forearc volcanism has not been reported elsewhere, but there are intrusions into forearc sediments both in Tonga and the Mariana arc (Marlow et al., 1992; Clift et al., 1994; Clift et al., 1998)

On the southern traverse the lower inner slope is irregular and slopes overall at about 10°. One dredge attempt (59) recovered 3 small mudstone clasts, one of which has been investigated and is a rhyolitic vitric mud identical to that from the northern traverse (Ballance et al., in press).

7.3. Forearc basin

A mid-slope terrace at 5–6 km water depth is well developed on both traverses. In the north (Fig. 6) it forms a forearc basin 20 km wide, underlain by up to 0.5 s two-way travel time (STWT) of landward-tilted sediment. On the southern traverse it forms a hummocky bench with negligible underlying sediment visible on the profile. An attempt to dredge the northern terrace (Dredge 32) was unsuccessful, and there is no further information on the forearc basin. In the analogous Tonga forearc basin to the north, ODP Site 841 penetrated 1 km of sediment, and documented subsidence of about 6 km since the Eocene (Parson and Hawkins, 1991).

7.4. Kermadec Ridge and upper trench slope

Our two traverses (Figs. 3 and 4) crossed the ridge to the north and south of the 32°S Boundary, but both traverses intersected the northern morphological sector where the active volcanoes form the crest of the ridge. In other words, there is a mismatch on the Kermadec Ridge, between the narrowing, deepening and ridge-offset which defines the 32°S Boundary, and the step-over of active vents from the ridge crest to a position 20–30 km west of the ridge crest, which appears to take place 50–100 km further south (Fig. 4).

The northern traverse passed between the volcanic islands of Curtis and L’Esperance Rock. Here the Ridge at 31°08′S, 178°39′W is seismically opaque, presenting a broad crest 10 km wide at 800 m water depth. There is a long, smooth, slightly hummocky upper trench slope, down to the mid-slope terrace (forearc basin) at 5–6 km water depth (Fig. 7A). Dredges from both sides of the Ridge (Figs. 3 and 7; dredge stations 15 to 17) yielded blocks of basalt, andesite–dacite, quartz diorite, plagiogranite, and tuffs. Volcanic rudites are common; they include some matrix-free forms that may represent subaerial Strombolian eruption products. The rocks have typical island arc tholeiitic compositions (Tararin et al., 1996).

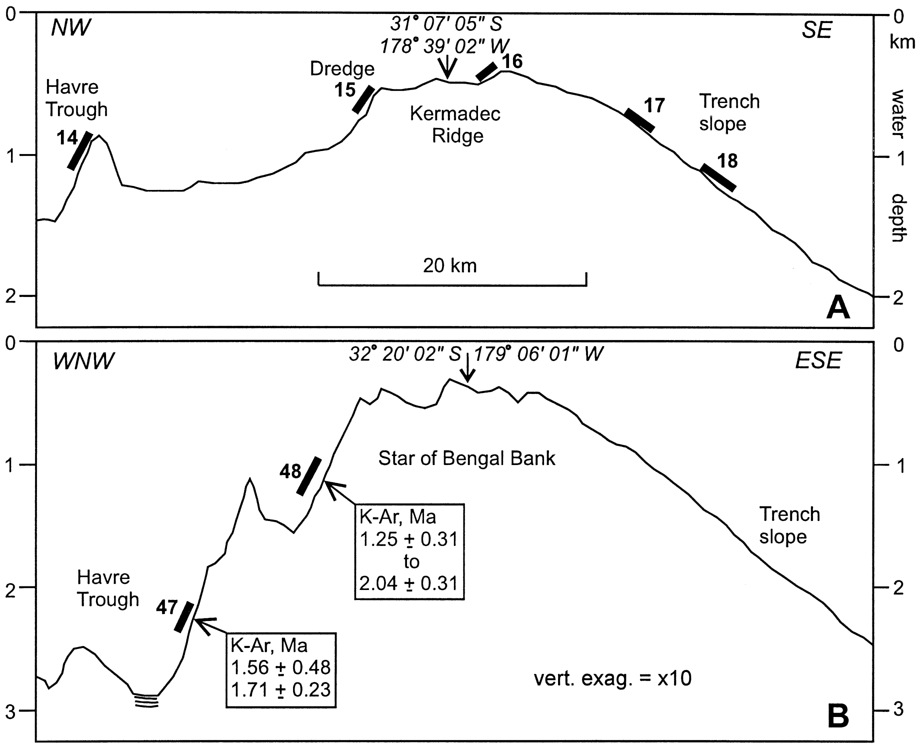


Fig. 7. Topographic profiles of the Kermadec Ridge on the northern (A) and southern (B) traverses, with dredge sites and K–Ar dates from selected basalt lava clasts.

The western slope to the Havre Trough is concave and smooth, with little indication of seamounts. It merges with a 50-km wide, shallow (1–2 km water depth) hummocky, largely sediment-free terrain marked by high-amplitude magnetic anomalies (Figs. 7 and 9). Dredge 13 contains very young basalts (Table 1; K–Ar dates of 0.04 ± 0.11 and 0.15 ± 0.12 Ma, latest Quaternary), and one small piece each of limestone and white vitric tuff. Dredge 14, from a large hummock, recovered basalts (one dated 0.08 ± 0.03 Ma) plus granodiorite, dolerite, diorite, and basalt enclosing plagiogranite (shipboard identifications, Ablaev et al., 1989). This assemblage of arc substrate rocks, and very young basalts whose composition is arc tholeiitic (Tararin et al., 1996), suggests that the eastern half of the trough is a product of dissection of the arc by the backarc basin-forming processes, with an overlay of young arc volcanics. The bathymetric map (Fig. 4) suggests that the sediment-free, hummocky terrain is part of a southeast-trending ridge of young arc rocks leading up to the arc–crest volcanic centre of L'Esperance Rock (located south of our traverse), while the deeper, lightly sedimented terrain lying between the sites of dredges 13 and 15 (Fig. 9a) is possibly part of the Havre Trough, with a hummock (seamount) of young arc lavas that was sampled by Dredge 14.

This interpretation would imply that Quaternary arc volcanism has been extending southeastwards along specific volcanic-centre-related lines as the backarc basin has opened, as noted further south (Wright et al., 1996; Wright, 1997). The same scenario is suggested by the southeast-trending ridges leading up to the three island volcanoes north of our traverse (Fig. 4).

The ridge crest on the southern traverse, at 32°20S, 179°06W, comprises Star of Bengal Bank (Fig. 7B), which rises in places to near the sea surface. The jagged summit profile suggests uneroded volcanic edifices, though there is no historical record of eruptive activity. The upper trench slope east of the Bank, like the northern traverse, comprises a long and generally smooth, seismically opaque slope extending down to the mid-slope terrace (forearc basin) at 5 to 6 km water depth.

The western flank drops precipitously 2.8 km to the Havre Trough, with a step halfway down surmounted by a pinnacle (Fig. 7B). Dredge hauls 47 and 48 from 1 and 2 km water depth, respectively, recovered what appeared to be angular talus gravels of basalts and volcanic/carbonate sediments. K–Ar ages between 1.25 and 2.04 Ma from basalt clasts suggest that older arc substrate is exposed on the western ridge flank. Shallow dredge hauls made from *RV Vulcanolog* around Star of Bengal Bank (Follas, 1993) recovered basalts (some pillow-form) and shallow marine carbonate/volcanic sediments. Gravity core N17–41 on the crest of the ridge at about 450 m water depth recovered pebbles of limestone containing fragments of coral.

7.4.1. Age of Kermadec Ridge

K–Ar age determinations on basalt clasts from the ridge and its western flank (Table 1 and Figs. 7 and 9) range from latest Pliocene to late Quaternary. Fossil-bearing samples from both traverses (dredge sites 14 through 17, 47, 48, Figs. 7–9) yielded mostly Quaternary to Recent depositional ages, as judged by the youngest taxa present (foraminiferal, calcareous nannoplankton and palynomorph). However, most of these samples also contained older taxa (Fig. 8) indicating ages back to earliest Miocene/latest Oligocene, ca. 25 Ma. Sample 16-11 contained only long-ranging Neogene forms indicating a probable sample age of Pliocene. Older forms present in Dredge 16 include the calcareous nannoplankton *Cyclococcolithus leptoporus* (Murray, Blackman and Kamptner) (Miocene to Pliocene) and *Chiasmolithus* sp. (Paleocene through Oligocene).

R.V. Vulkanolog samples from the vicinity of Star of Bengal Bank (< 500 m) (M.R. Gregory, personal communication; Follas, 1993) similarly contain derived foraminifera with a wide range of Neogene ages (some are included on Fig. 8). Again, most samples also contain Quaternary-restricted taxa.

Further south at 33°17′S, 179°32′W, on the eastern slope of the Kermadec Ridge at 700 m water depth (Fig. 2), our Dredge 61, which was not part of the two traverses, recovered several clasts of calcareous volcanic sediment, two of which (N17-61/3, N17-61/4) contained only Miocene taxa (see 61/4, Fig. 8).

On the assumption that older taxa have been reworked and redeposited in younger sediments, the oldest taxa give a minimum age estimate for the Kermadec Ridge, since there is no other known source for the material than the ridge itself. Fig. 8 gives both New Zealand and mid-southern-latitude time ranges for individual taxa (Jenkins, 1985; Hornibrook et al., 1989). On this basis the Kermadec Ridge at latitude 31 to 33°S has been in existence since at least earliest Miocene time (New Zealand Waitakian Stage) with abundant evidence of volcanic sedimentation in the middle and late Miocene. K–Ar dates from the ridge crest indicate only a latest Pliocene maximum age, but one basalt clast from the lower trench slope yielded a late Miocene age (above). The presence of *Chiasmolithus* sp. and some foraminifera whose time ranges extend back beyond the earliest Miocene suggest that there may be some sediments on the ridge that are older than Miocene.

The presence of apparent Miocene clasts and derived Miocene and Pliocene fossils in the dredge hauls, along with basalts dated to late Pliocene–early Quaternary, and plutonic and dike rocks, indicates that on the upper portions of the Kermadec Ridge older material is commonly reexposed and reworked. Derived fossils can be recognised in some thin sections by having an infilling that is different from the enclosing sediment. Many rocks are bored and Mn-encrusted, indicating prolonged exposure on the sea floor following their most recent erosion and deposition.

Our samples were all taken from water depths greater than 750 m, and the carbonate was micritic ooze in all cases, thus, giving no direct evidence of subsidence or down-slope transport. In contrast, *RV Vulcanolog* dredge samples, from water depths of 120–330 m on Star of Bengal Bank, contained rhodoliths of coralline algae and clasts of skeletal shell hash containing bryozoans, echinoderm fragments, molluscs, brachiopods and barnacles (Follas, 1993). These are shallow water deposits, and the rhodoliths would have grown within the photic zone at less than 120 m. Thus, minor subsidence or downslope transport is indicated at Star of Bengal

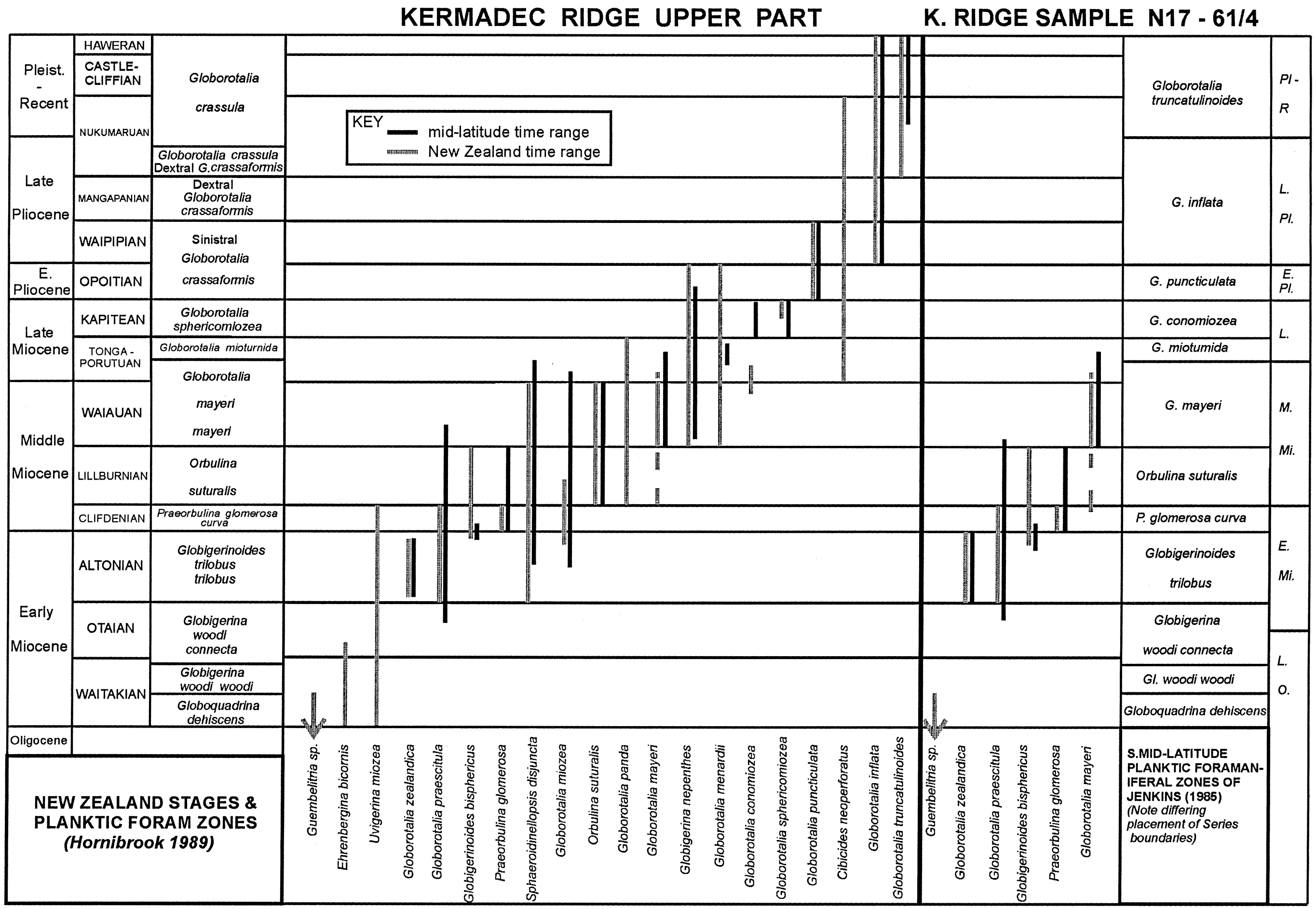


Fig. 8. Age ranges of selected microfossil taxa obtained from dredged rock clasts from the upper parts of the Kermadec Ridge. The age ranges are taken from either or both of the New Zealand faunas (Hornibrook et al., 1989) and the mid-latitude faunas (Jenkins, 1985). The left-hand part of the diagram includes taxa selected from all samples, and shows that the age of the Ridge extends back to at least the earliest Miocene. The right-hand part of the diagram shows taxa from one rock sample, from dredge sample N17/61, from the western slope of the Kermadec Ridge at approximately 33°S (Fig. 2). It indicates a mid-Miocene age, with derived early Miocene fossils, for that sample.

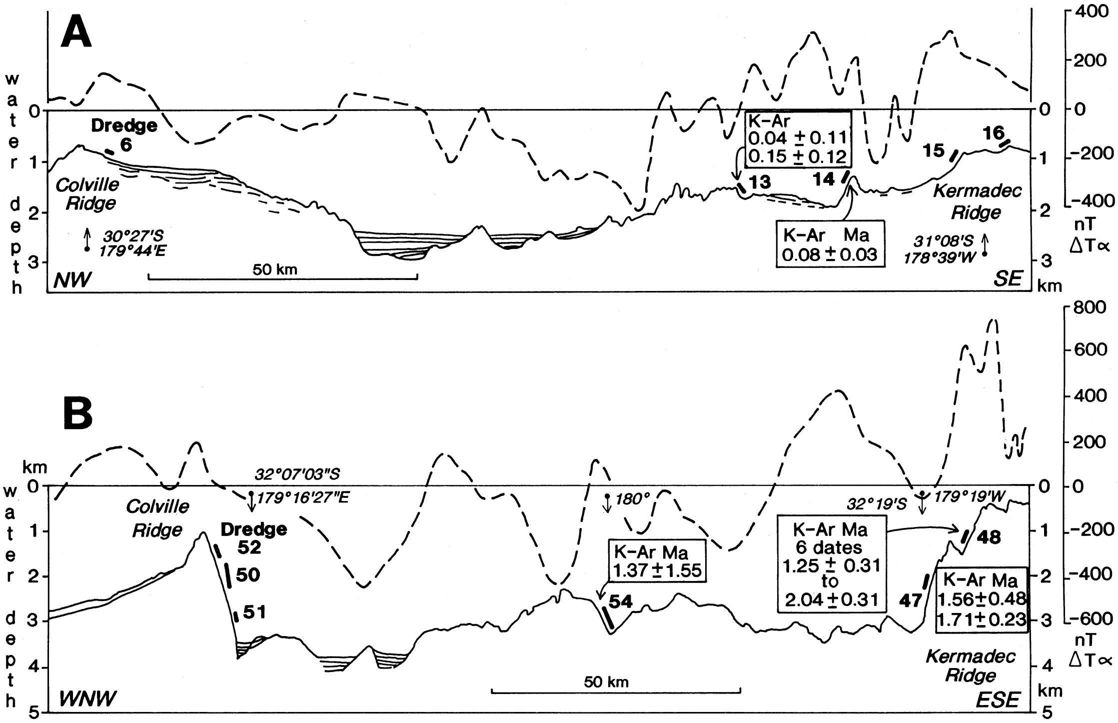


Fig. 9. Profiles of the Havre Trough on the northern (A) and southern (B) profiles, showing dredge sites, K–Ar dates on selected basalt lava clasts, and the magnetic anomaly. Note the contrast in form of the Trough on the two crossings (north and south of the 32°S Boundary), and the asymmetry on both profiles, with deeper and more sedimented portions lying on the west side. From single-channel seismic reflection data.

Bank, or alternatively rhodolith formation occurred during glacial low sea levels.

7.5. The Havre Trough backarc basin

There are notable differences in the form of the Havre Trough on our two traverses (Figs. 4 and 9). On the northern profile, north of the 32° Boundary, it is shallow, asymmetrical, well sedimented, and does not have an obvious rift morphology. On the southern profile, south of the Boundary, it is deep, less strongly asymmetric, little sedimented, and has a very clear rift morphology.

7.5.1. Northern traverse

The western half of the trough has a smooth, flat floor at about 2.5 km depth, about 40 km wide, underlain by 0.5 to 0.7 STWT of layered sediment. Several buried and partially emergent seamounts are evident. They were not dredged. The western flank of the trough comprises a band of hummocky terrain about 20 km wide, leading up to a perched sedimentary basin at just over 1 km water depth which is clearly part of the Colville Ridge. This terrain was not sampled.

The eastern half of the trough is shallower, less than 2 km water depth, and merges with the Kermadec Ridge through a hummocky zone about 50 km wide. As discussed above, the western, sediment-free portion of this terrain is interpreted to be part of a southeast-trending chain of arc centres leading to the arc–crest volcanic centre of L'Esperance Rock (Fig. 4), overlain on a shallow portion of the Havre Trough where arc substrate rocks are exposed.

Seismic profile D–D′ of Caress (1991) passed northeastward through the area between our two traverse lines, mostly to the north of the 32°S Boundary. Thus, the morphology shown is similar to our northern traverse.

7.5.2. Southern traverse

Just 150 km south of our northern traverse, and south of the 32°S Boundary, the form of the Havre Trough is completely different (Fig. 9B). Steep, inward-facing fault scarps, 2.5 km high on the west side, 2.8 km high on the east side, are separated by 120 km of rugged sea floor with little sediment, and water depths of 2.5 to 4 km. As on the northern profile, the deepest part of the basin, and the only part with appreciable sediment (up to 0.5 STWT), lies adjacent to the western fault margin. This may be the oldest part of the rift.

The central area of rugged and raised sea floor contains a deep valley at longitude 180°00, which is more or less in the centre of the Trough on our crossing. Dredging here (site 54, 3280–2760 m depth) recovered 40–50 basalt clasts, all heavily Fe–Mn encrusted, along with a number of cavernous, bored, multi-layered ferro-sulphide and manganese crusts up to 7 cm thick. The basalt clasts are petrochemically identical with island arc tholeites of the Kermadec arc (Tararin et al., 1996), which suggests that the floor of the basin is composed of foundered arc rocks, while the ferro-sulphide crusts indicate the operation of hydrothermal vents at some time. One K–Ar date (Table 1) gives an age of 1.37 ± 1.55 Ma, but has a very large error factor and is therefore not reliable.

The patch of low-backscatter sea floor recorded on a GLORIA swath traverse at 31°30′S and longitude 180°, about 70 km north of our traverse, and interpreted to represent sedimented sea floor by Parson and Wright (1996), is not evident on our profile. Sea floor lineations on that swath, and also on a single Sea Beam swath which crossed our line (Caress, 1991), trend about 070°, nearly 50° clockwise from the overall trend of the Trough.

7.5.3. Age of the Havre Trough

Of the four K–Ar dates available from basalts, three are very young (< 0.15 Ma) and as discussed above probably relate to the evolution of the Kermadec Ridge, while the older one (1.37 ± 1.55 Ma) is unreliable.

Other than short sediment cores containing Quaternary taxa, the only fossil data we have from the trough are from a limestone clast in Dredge 13, which contains *Globigerinoides trilobus* (Reuss) (Miocene), and *Globorotalia inflata* (d'Orbigny) (early Pliocene to Recent). The simplest explanation of the old microfossils, given that the two species do not overlap in age, is that the limestone was deposited on the Colville/Kermadec Ridge, incorporating derived older materials in the normal way (above), immediately prior to opening of the Havre Trough. It was then incorporated in the trough during opening. If the limestone originated within the trough, the implication of Miocene-aged materials within the trough would be contrary to all other indicators.

The floor of the Havre Trough north of the 32°S Boundary is generally about 2.5 km deep, while south of the Boundary it is 3 to 3.5 km deep. There is a transition zone about 100 km wide, located north of the Boundary. The difference in depth could be caused by greater sediment thickness if the northern part of the trough is older, as postulated by Parson and Wright (1996). However, the available evidence north of the Boundary (Caress, 1991, profile D–D′; this study, Fig. 9A) suggests sediment thicknesses of around 500 m, while south of the Boundary there is no more than 250 m (Caress, 1991, profile C–C′; Karig, 1970b, profile D–D′; this study Fig. 9B). That is, despite the irregular topography, the deepest part of the trough basement north of the Boundary is 0.5–1.0 km shallower than south of it.

Thus, there are conflicting indications of the age of the trough. The greater sediment thickness north of the Boundary suggests the trough is older, whereas the greater depth to basement south of the Boundary suggests a more advanced stage of opening and crustal stretching and therefore perhaps a greater age. This contrast and apparent age conflict is discussed further below.

On both traverses the greatest depth and greatest sediment thickness is on the western side of the trough, furthest from the source of recent sediment supply, the Kermadec Ridge. The implication is that the trough is oldest in the west, and that much of the sediment may have been derived from the Colville Ridge. At its present depth (750 m and deeper) the ridge is unlikely to be yielding much sediment; therefore the implication is that deposition of the sediment may have pre-dated subsidence of the ridge. There is independent evidence for subsidence of the ridge (below).

7.6. *The Colville Ridge*

As noted earlier, the Colville Ridge displays contrasting forms north and south of the 32°S Boundary. Our two traverses were located north and south of the Boundary.

7.6.1. *Northern traverse*

On the northern traverse (Figs. 4 and 10) the Ridge is broad and onlapped by sediment. The eastern (backarc basin) flank supports a perched sedimentary basin at ca. 1 km water depth, containing up to 0.75 STWT of layered sediment. The sediment overlies an indistinct and irregular basement surface and onlaps westward to near the crest of the Ridge, and possibly also eastward onto lumpy terrain.

The pinnacled and stepped form of the crestal region suggests either seamounts, fault scarps or erosional notches. Cliff-like forms are present on the eastern slope at depths of 1000 and 750 m, separated by a step, and there are notches at similar depths on the western slope. The profile suggests that sediments of the perched basin onlap westward to the base of the deeper cliff.

Dredge haul 6 was taken from the deeper cliff-like feature at about 850 m water depth. It appeared to be a talus gravel containing a wide variety of igneous rocks and volcanic sediments, including basalt, dolerite, gabbro, vitroclastic breccia and tuff, and volcanic fine sandstones. Many of the clastic rocks have a carbonate cement or matrix; in most cases this is micritic, but some are calc–arenitic, indicating a shallow marine origin. This interpretation is supported by the presence of algal rhodoliths which must have formed within the photic zone at less than 120 m depth.

The rhodoliths and associated clasts could have been carried to their present depth by subsidence of the ridge or by gravity flows. We have no strong indications of gravity flow activity and, therefore, we conclude that, together, the landforms, the perched basin sediment fill requiring an abundant supply of sediment from the ridge, and the dredge haul, most probably indicate subsidence of the ridge by more than 700 m. This then raises the possibility of former subaerial exposure of the Colville Ridge, since the crest of the ridge on our profile is at about 750 m depth, while it is shallower than 750 m a short distance north of our traverse, at 30°S (CANZ, 1997).

Fossils in Dredge 6 samples indicate depositional ages for clasts in the range early Pliocene to Quaternary; fossils as old as early middle Miocene are present, indicating that older sedimentary rocks are exposed on the ridge. There is no evidence for the timing of probable subsidence, but it presumably post-dates cessation of volcanism on the ridge and the start of opening of the Havre Trough.

The relationship of the perched basin fill to the extensional Havre Trough is unclear. A volcanically quiescent ridge situated at the present depth of the Colville Ridge is unlikely to be a source of voluminous sediment, and therefore we infer that the perched basin probably pre-dates subsidence of the ridge, and is shallow marine in origin. The basin could be either

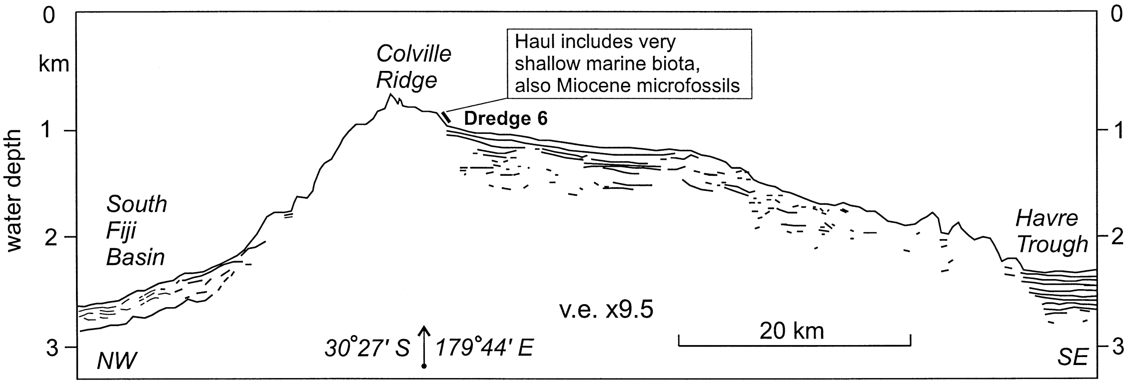
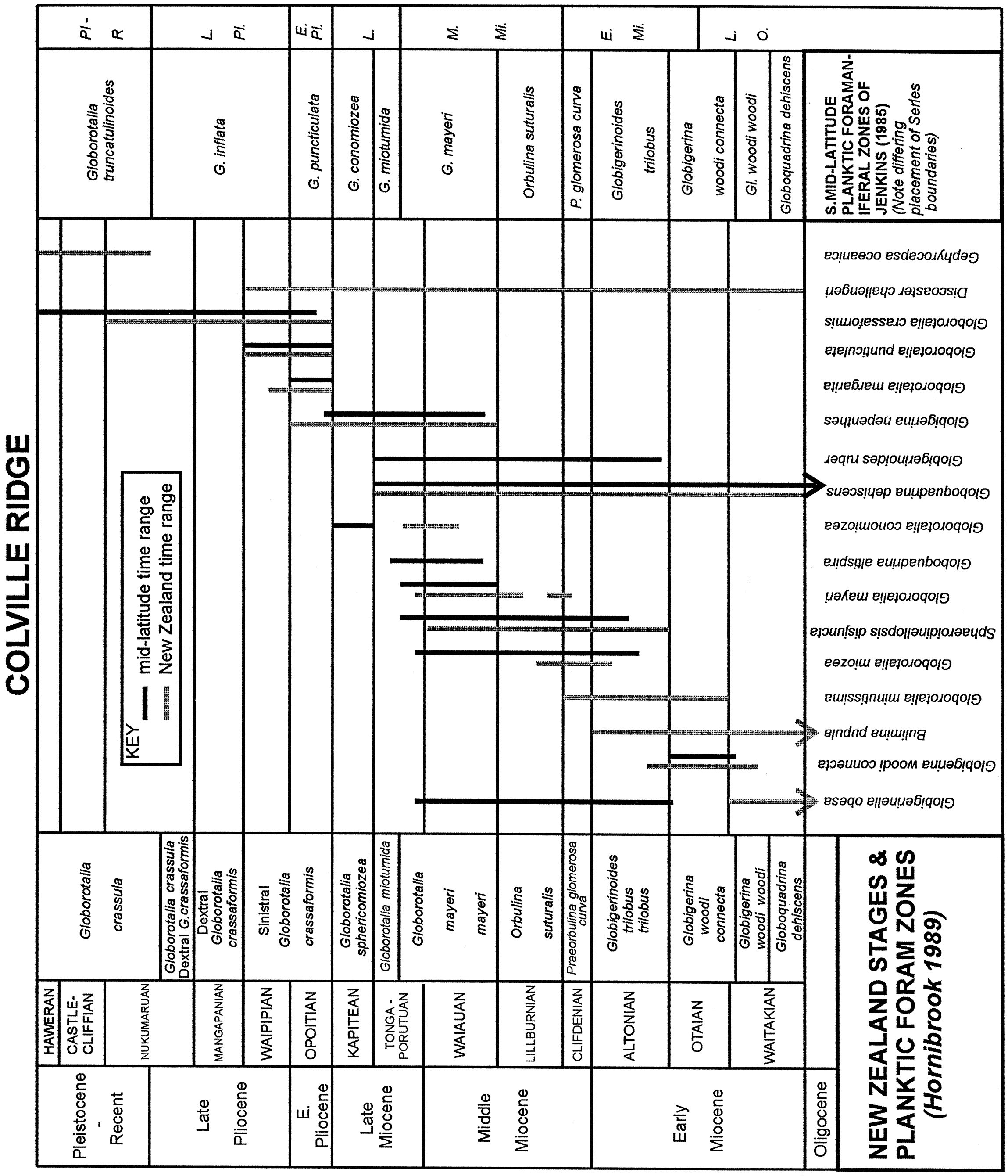


Fig. 10. The Colville Ridge on the northern profile, north of the 32°S Boundary. Note the perched sedimentary basin, and the stepped nature of the ridge crest. See Fig. 9 for the profile of the ridge on the southern profile, south of the 32°S Boundary.


COLVILLE RIDGE
KEY
mid-latitude time range
New Zealand time range
NEW ZEALAND STAGES & PLANKTIC FORAM ZONES (Hornibrook 1989)
S.MID-LATITUDE PLANKTIC FORAMANIFERAL ZONES OF JENKINS (1985) (Note differing placement of Series boundaries)
Pleistocene - Recent
Late Pliocene
E. Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
HAWERAN
CASTLECLIFFIAN
NUKUMARUAN
MANGAPANIAN
WAIPIPIAN
OPOITIAN
KAPITEAN
TONGA-PORUTUAN
WAIAUAN
LILLBURNIAN
CLIFDENIAN
ALTONIAN
OTAIAN
WAITAKIAN
Globorotalia crassula
Globorotalia crassula Dextral G.crassaformis
Dextral Globorotalia crassaformis
Sinistral Globorotalia crassaformis
Globorotalia sphericomiozea
Globorotalia miotumida
Globorotalia mayeri mayeri
Orbulina suturalis
Praeorbulina glomerosa curva
Globigerinoides trilobus trilobus
Globigerina woodi connecta
Globigerina woodi woodi
Globoquadrina dehiscens
Globorotalia truncatulinoides
G. inflata
G. puncticulata
G. conomiozea
G. miotumida
G. mayeri
Orbulina suturalis
P. glomerosa curva
Globigerinoides trilobus
Globigerina woodi connecta
Gl. woodi woodi
Globoquadrina dehiscens
Pl - R
L. Pl.
E. Pl.
L.
M. Mi.
E. Mi.
L. O.
Gephyrocapsa oceanica
Discoaster challengeri
Globorotalia crassaformis
Globorotalia puncticulata
Globorotalia margaritae
Globigerina nepenthes
Globigerinoides ruber
Globoquadrina dehiscens
Globorotalia conomiozea
Globoquadrina altispira
Globorotalia mayeri
Sphaeroidinellopsis disjuncta
Globorotalia miozea
Globorotalia minutissima
Bulimina pupula
Globigerina woodi connecta
Globigerinella obesa

an older arc–crest basin, pre-dating opening of the Havre Trough, or it could be an early expression of the extension preceding opening of the Havre Trough.

The western side of the Colville Ridge forms a long, concave slope down to the South Fiji Basin. South Fiji Basin sediments, up to 1 STWT thick, lap onto the Ridge up to a water depth of about 1.6 km. The irregular topography of the upper 2 km of the slope may result from mass movement.

7.6.2. Southern traverse

The Colville Ridge on the southern traverse, at 32°06′S, 179°03′E is narrow and steep (Fig. 9B). It presents a 2.5-km scarp face to the Havre Trough, but passes westward into the South Fiji Basin by way of a concave, somewhat hummocky slope like its counterpart on the northern traverse. The dredge samples from the scarp (50, 51, 52) contain basalts, dolerites, albitised gabbro, and a wide variety of volcanic rudites and sandstones, some of which contain what appear to be felsic clasts. None were K–Ar dated.

7.6.3. Age of Colville Ridge

As with Kermadec Ridge samples, there is much mixing of different-aged fossils. Fig. 11 shows a compilation of taxa selected to illustrate the age range of derived fossils. While the depositional age of individual rock samples is difficult to determine because of the large number of derived microfossils, the microfossils clearly establish the existence of the Colville Ridge, like the Kermadec Ridge, from at least the early Miocene. They also indicate more-or-less continuous sedimentation and resedimentation on the ridge since the early Miocene.

The basalt clast from 35°S dated at 5.4 ± 0.1 Ma (Adams et al., 1994) indicates continuing volcanism at that time, and is here presumed to show that the Havre Trough had not begun to open at 5.4 Ma.

7.7. South Fiji Basin

Our northern traverse extended 150 km west of the Colville Ridge into the South Fiji Basin, which is a marginal basin believed to have opened during the Oligocene (Burns et al., 1973; Andrews et al., 1975; Malahoff et al., 1982) (Fig. 3). This portion of the Basin is outside the part surveyed aeromagnetically, but would fall on the projection of anomaly 9 by Malahoff et al. (1982; basaltic crust of late Oligocene age).

We dredged firm micritic ooze, bored and manganese-encrusted, from near the crest of a prominent unnamed ridge at 29°41S, 178°09E (Figs. 3 and 4). A diverse assemblage of planktic foraminifera and calcareous nannoplankton included some forms with restricted ages in the New Zealand sequence (Hornibrook et al., 1989), for example mid-middle Miocene (*Orbulina suturalis* Bronimann), middle Miocene (*Globorotalia miozea* Finlay), middle to late Miocene (*Discoaster calcaris* Gartner), latest Miocene–early Pliocene (*Globorotalia sphericomiozea* Walters). Other taxa were longer-ranging forms, but all were typical of Neogene ages. We infer that the ridge has existed since at least the middle Miocene.

The mixing of taxa of different ages suggests that processes of exposure of older materials and redeposition operate on the ridge. The fact that this firm, bored ooze is at outcrop is also suggestive of removal of recent ooze cover near the summit.

The single-channel seismic profile indicates a sediment thickness of up to 1 STWT in the South Fiji Basin. Sediment thins towards the Colville Ridge (Fig. 3).

8. Brief history of the Kermadec arc system at 30–33°S

We have presented abundant microfossil evidence from both the active and remnant arcs (Kermadec and Colville Ridges, respectively) of sedimentation taking place from at least the early Miocene. The various hand samples with inferred Miocene, Pliocene and Quaternary depositional ages, in con-

Fig. 11. Age ranges of selected microfossil taxa obtained from dredged rock clasts from the Colville Ridge. The age ranges are taken from either or both of the New Zealand faunas (Hornibrook et al., 1989) and the mid-latitude faunas (Jenkins, 1985). Like the Kermadec Ridge, derived microfossils indicate that the Colville Ridge has been in existence since at least the early Miocene.

junction with the many derived microfossils of all ages from early Miocene to early Quaternary, imply a record of continuous sedimentation through the Neogene on both ridges (Figs. 8 and 11). Since the sediment enclosing the microfossils is in all cases volcaniclastic and/or carbonate, we infer that volcanic activity has been taking place on (and by further inference forming) the two ridges for much or all of the time since the earliest Miocene.

The presence of a few species whose time ranges extend back from early Miocene into the Oligocene (Figs. 8 and 11), in conjunction with the calcareous nannoplankton form *Chiasmolithus* sp. (Paleocene through Oligocene) on the Kermadec Ridge, raises the possibility that there was some deposition on the ridge(s) prior to the earliest Miocene. Additional evidence is needed to confirm this possibility.

The two ridges were joined as a single ridge before the opening of the Havre Trough. Our K–Ar ages from basalt clasts have a smaller age range than the fossils (7.8 to 0.04 Ma). The predominance of ages less than 2 Ma, and the lack of any ages between 2 and 7.8 Ma (Table 1) may imply a hiatus in volcanism related to the opening of the Havre Trough, similar to the hiatuses in both Tonga (5–3 Ma) and New Zealand (4–2 Ma) (below).

9. Discussion

9.1. Inception of the Tonga–Kermadec–New Zealand Neogene arc

Within the limits of precision afforded by biostratigraphic and radiometric dating, the time of inception of arc activity on all three sectors is closely similar. It took place in the late Oligocene to earliest Miocene, between 28 and 24 Ma. Synchroneity is to be expected, since all sectors of the arc respond to the Pacific and Australian plates, which have been interacting in broadly the same way for most of the Cenozoic (Stock and Molnar, 1987; Sutherland, 1995; Hall, 1997).

The inception of arc activity seems to have been a response to a relatively minor change in plate motions. Using changes in direction of hotspot seamount chains as a proxy for changes in plate motion that were either positive or negative in terms of the convergence vector at the plate boundary, there were minor positive changes in both plates at about 25 Ma (Lonsdale, 1988; McDougall and Duncan, 1988) which together amounted to an increase in convergence of about 20°. In combination with a progressive southerly retreat of the Pacific–Australia pole of rotation, causing acceleration of convergence (Sutherland, 1995), this seems to have been sufficient to trigger widespread arc activity in the southwest Pacific (Ballance, in press).

9.2. Subsequent arc evolution

Initially, there was a complex arc configuration, with north-trending sectors on the Norfolk–Three Kings Ridge (Mortimer et al., 1998; i.e., before the splitting of the ridge by the opening of the early Miocene Norfolk backarc basin), a northwest-trending sector in northern New Zealand–Reinga Ridge (Herzer, 1995; Herzer and Mascle, 1996; Herzer et al., 1997), and a NNE-trending Colville Ridge–Lau Ridge sector (this paper; Ballance, in press). It is postulated by Ballance (in press) that the initial complexity of subduction systems was an inheritance from a Paleogene regime of slow, oblique and magma-free subduction.

At about 15 Ma, the system simplified to a single arc, which was the Lau–Colville line with the addition of a 500-km southwestward prolongation across the North Island of New Zealand as the new Coromandel–Hauraki and Taranaki arc (Fig. 1) (Herzer, 1995). Simultaneously, the other sectors became extinct. The simplification at 15 Ma was probably a response to the progressive southerly retreat of the pole of rotation.

The period between 15 and about 5 Ma was marked on the Colville–Lau arc by stability. There is no known backarc basin of this age.

9.3. Inception of the Lau–Havre backarc basin

The next change occurred around 5.6 Ma, when the Lau backarc basin began to form (Clift et al., 1994; Parson and Wright, 1996). External causes which may have contributed to the change include a further shift of the Pacific–Australia pole of rotation, but to the southwest rather than south as before (Sutherland, 1995); and a possible acceleration of convergence related to Pacific-wide changes in hotspot tracks (Pollitz, 1986).

In association with the initial opening of the backarc basin there appears to have been a 2 million-year hiatus in volcanism in both Tonga (5 to 3 Ma) (Clift et al., 1994) and New Zealand (4 to 2 Ma) (Takagi et al., 1993; Adams et al., 1994). Our biostratigraphic age information from the Colville–Kermadec sector does not relate directly to volcanic activity, and therefore cannot be used to establish a similar age gap, but our K–Ar ages (7.84, 2.04 to 0.04 Ma) are compatible with a similar age gap, though they are too few to prove it.

In both Tonga and New Zealand the new late Pliocene arcs were established in new geographic locations, and were not superimposed on the older arcs. In the Colville–Kermadec sector, on the other hand, the new arc was built on top of half of the older arc.

9.4. Age of the Havre Trough

The inception of the Havre Trough both north and south of the 32°S Boundary is unconstrained by direct age data. Our oldest K–Ar date from the trough is 1.37 ± 1.55 Ma (Fig. 9B), but is unreliable because of the large error factor. Our limestone sample with derived Miocene microfossils is readily explained as a relic from the Colville–Kermadec ridge before it split; if it was formed within the trough, the implied age of source rocks is far older than any other indicator we have for the trough.

The time of cessation of volcanism on the Colville Ridge might be a proxy for the time of inception of the Havre Trough, but our biostratigraphic data record only the existence of a ridge, not the precise timing of volcanic activity. A K–Ar date of 5.4 Ma from the southernmost Colville Ridge (35°S) (Adams et al., 1994) indicates that the arc had not split at that time.

9.5. Origin(s) of the 32°S boundary

The 32°S Boundary (Fig. 4) was defined by Pelletier and Dupont (1990) primarily to separate what they inferred to be different regions of the trench slope, with tectonic erosion north of the boundary and accretion south of it. As noted, other authors (Ruppel et al., 1994; Collot and Davy, 1998) have offered different opinions as to regions of the inner trench slope that are undergoing accretion and tectonic erosion. Thus, the 32°S Boundary appears to have little significance in respect of the inner trench slope, though a prolongation of the Boundary on Fig. 4 does coincide with a left-step of the trench axis of about 10 km.

The Boundary marks significant changes in the Kermadec Ridge, Havre Trough and Colville Ridge, which include: southward narrowing and deepening of both ridges; southward deepening of the Havre Trough basement, such that it becomes the deepest backarc basin in the Pacific rim (Pelletier and Dupont, 1990); a 10-km left-step of the Kermadec Ridge; a change of trend on both ridges (Colville Ridge from 015° north of the line to 030° south of it; Kermadec Ridge from 018° north of the line to 025° south of it); and marked changes in the bounding slopes of the Havre Trough, from diffuse and without evident faulting north of the line, to steep, sharply delineated and fault-controlled south of the line.

Such changes clearly imply regional tectonic control. The regional tectonic factor highlighted by Pelletier and Dupont was the approximate coincidence of the 32°S Boundary with an abrupt southward shallowing of the deep limit (the tip) of the seismogenic subducting slab, from > 500 km north of the line to < 300 km south of it (Fig. 4). Seismic tomography indicates that a cold aseismic slab extends far beyond those depths (van der Hilst, 1995), thus, implying that subducting Pacific plate lithosphere extends beyond the seismogenic tip. All other known parameters (angle of slope on the seismic interface (Pelletier and Dupont, 1990), slab thickness from seismic tomography (van der Hilst, 1995)) are maintained across the 32°S Boundary, and thus, the only factor that is known to change is the depth of seismicity. It is not clear how this change might relate to the Boundary.

Another external factor that may have a connection with the 32°S Boundary is subduction of the Hikurangi Plateau of oceanic igneous rocks (Fig. 2). The northern edge of the Plateau trends northwest and at the present time intersects the trench at about 36°S. Collot and Davy (1998), considering only the forearc, suggested that the narrowing of the Kermadec Ridge at 32° is related to the point of initial collision of the Plateau, and the subsequent southward sweep of its northern edge, and that a decrease in dip of the Benioff Zone associated with subduction of the bouyant Hikurangi Plateau caused the westward step of the Kermadec volcanoes south of 33°. In relation to the 32°S Boundary, the temporary addition of 12–15 km thickness of bouyant oceanic crust beneath the arc, and its subsequent removal as the northern edge of the plateau retreated southwards, superimposed upon normal backarc basin processes, may have brought about first uplift and then excessive subsidence of the whole arc–backarc basin–remnant arc system. However, it is necessary to assume an indefinite former extension of the present 135° trend of the northern boundary of the plateau, and in conjunction with known plate convergence vectors this would place the moment of plateau–trench collision at about 10 Ma (Collot and Davy, 1998). This is far earlier than current estimates of the earliest time of opening of the Havre Trough (around 5 Ma). Furthermore, Collot and Davy (1998) note geophysical evidence indicating that the subducted portion of the plateau at 36°S extends only as far as the middle of the Havre Trough. Thus, even where it is known to be being subducted, the Hikurangi Plateau does not yet underlie the whole of the Havre Trough, and therefore taking this in conjunction with the lack of logic in the timing there is little support for regarding the Plateau as a causal factor for the distinctive features of the trough and its adjacent ridges between 32 and 37°S.

9.6. Stages in development of the backarc basin

Parson and Wright (1996) proposed five stages in the development of the Lau–Havre backarc basin, from south to north ranging from incipient symmetrical rifting (Taupo Volcanic Zone of New Zealand), through distributed half-graben rifting and axial half-graben rifting, each with a basin width up to 130 km and an estimated β extension factor of up to three (Havre Trough), to two stages of oceanic spreading (Lau Basin). They infer that the stages represent an evolutionary sequence and that the basin is propagating southwards into the North Island of New Zealand.

However, neither the constant width of the Havre Trough between 26°S (130 km) and 37°S (120 km) (Parson and Wright, 1996; CANZ, 1997), nor the abrupt changes at the 32°S Boundary, fit easily into a simple scenario of progressive southward propagation. As noted above, there are conflicting indications concerning the age and evolution of the Havre Trough north and south of the 32°S Boundary, and the opening process seems to be quite different north and south of the Boundary. Some continuity of process is suggested by the fact that on both sides of the Boundary the same asymmetry exists, the western side of the trough being deeper, more sedimented, and presumably older. In the model of Parson and Wright (1996), this is explained by progressive trenchward retreat of the arc front.

Overall, the data suggest that processes are relatively uniform north of the 32°S Boundary as far as 25°S, and south of the Boundary as far as 36°S, but that there is a fundamental change at the Boundary. Southward propagation of a rift system, as proposed by Parson and Wright (1996), satisfactorily explains the broad regional aspects of the backarc basin, but is not sufficient to explain the many changes at the Boundary and the apparent uniformity north and south of it. Some other, equally important, tectonic factor is superimposed on the rift propagation processes north and south of the Boundary, though it is not yet clear what that factor is.

9.7. Nature and age of Kermadec arc substrate

Collot and Davy (1998) speculate that most of the forearc of the Kermadec Ridge, as far south as 37°, is underlain by a southward continuation of the Eocene volcanic terrain of the Tonga forearc (Fig. 5). The Eocene terrain in Tonga is exposed on ’Eua Island, was drilled in ODP hole 841, and is inferred elsewhere on the forearc by derived Eocene fossils in dredge samples (Ballance, 1991; Chaproniere, 1994b). In contrast, south of 26°S the forearc narrows and deepens significantly, and we have found no evidence of Eocene microfossils with the possible exception of rare Paleogene nannoplankton. It seems unlikely that the Eocene volcanic terrain of Tonga extends past 26°S.

Acknowledgements

We thank shipboard colleagues and crew for their assistance, and Andrew Stevenson, Ian Wright and an anonymous reviewer for comments on the paper. Louise Cotterall draughted the diagrams.

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