From Strike-Slip Faulting to Oblique Subduction: A Survey of the Alpine Fault-Puysegur Trench Transition, New Zealand, Results of Cruise Geodynz-sud Leg 2

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Abstract. The Geodynz-sud cruise on board the R/V *l'Atalante* collected bathymetric, side-scan sonar and seismic reflection data along the obliquely convergent boundary between the Australian and Pacific plates southwest of the South Island, New Zealand. The survey area extended from 44°05′ S to 49°40′ S, covering the transition zone between the offshore extension of the Alpine Fault and the Puysegur Trench and Puysegur Ridge. Based on variations in the nature and structure of the crust on either side of the margin, the plate boundary zone can be divided into three domains with distinctive structural and sedimentary characteristics. The northern domain involves subduction of probably thinned continental crust of the southern Challenger Plateau beneath the continental crust of Fiordland. It is characterized by thick sediments on the downgoing slab and a steep continental slope disrupted by fault scarps and canyons. The middle domain marks the transition between subduction of likely continental and oceanic crust defined by a series of en echelon ridges on the downgoing slab. This domain is characterized by a large collapse terrace on the continental slope which appears to be due to the collision of the en echelon ridges with the plate margin. The southern domain involves subduction of oceanic crust beneath continental and oceanic crust. This domain is characterized by exposed fabric of seafloor spreading on the downgoing slab, a steep inner trench wall and linear ridges and valleys on the Puysegur ridge crest. The data collected on this cruise provide insights into the nature and history of both plates, and factors influencing the distribution of strike-slip and compressive strain and the evolution of subduction processes along a highly oblique convergent margin.

Introduction

In the southwestern Pacific, the Australian-Pacific convergence plate boundary cuts the large continental block of New Zealand and the adjacent plateaus (Figure 1). The plate boundary consists of west-directed subduction beneath the North Island and east-directed subduction beneath Fiordland in the South Island. These subduction zones are connected by a major dextral reverse fault (the Alpine Fault) with about 500 km of horizontal, along-strike displacement (Wellman (1949) reported in Benson (1952)). At both ends of the Alpine Fault the transition to subduction is marked by a splaying of the fault into multiple traces (Lewis, 1980; Stevens, 1990; Turnbull and Uruski, 1993; Christoffel and Van der Linden, 1972; Anderson *et al.* 1992). Motion on the Alpine Fault has become increasingly compressional as the relative pole of rotation has migrated south during the last 38 My (e.g. Walcott, 1978). The plate margin changes strike off Fiordland, to the south becoming increasingly oblique to the relative plate motion (Figure 1, De Mets *et al.*, 1990).

Along the Fiordland margin, the Australian plate is being subducted beneath the continental crust of the Pacific plate. The southward extent of the continental crust is not known, but oceanic crust has been interpreted along the Macquarie Ridge from the geology of the Macquarie Island (Varne and Rubenach, 1972; Williamson, 1988). The downgoing Australian plate

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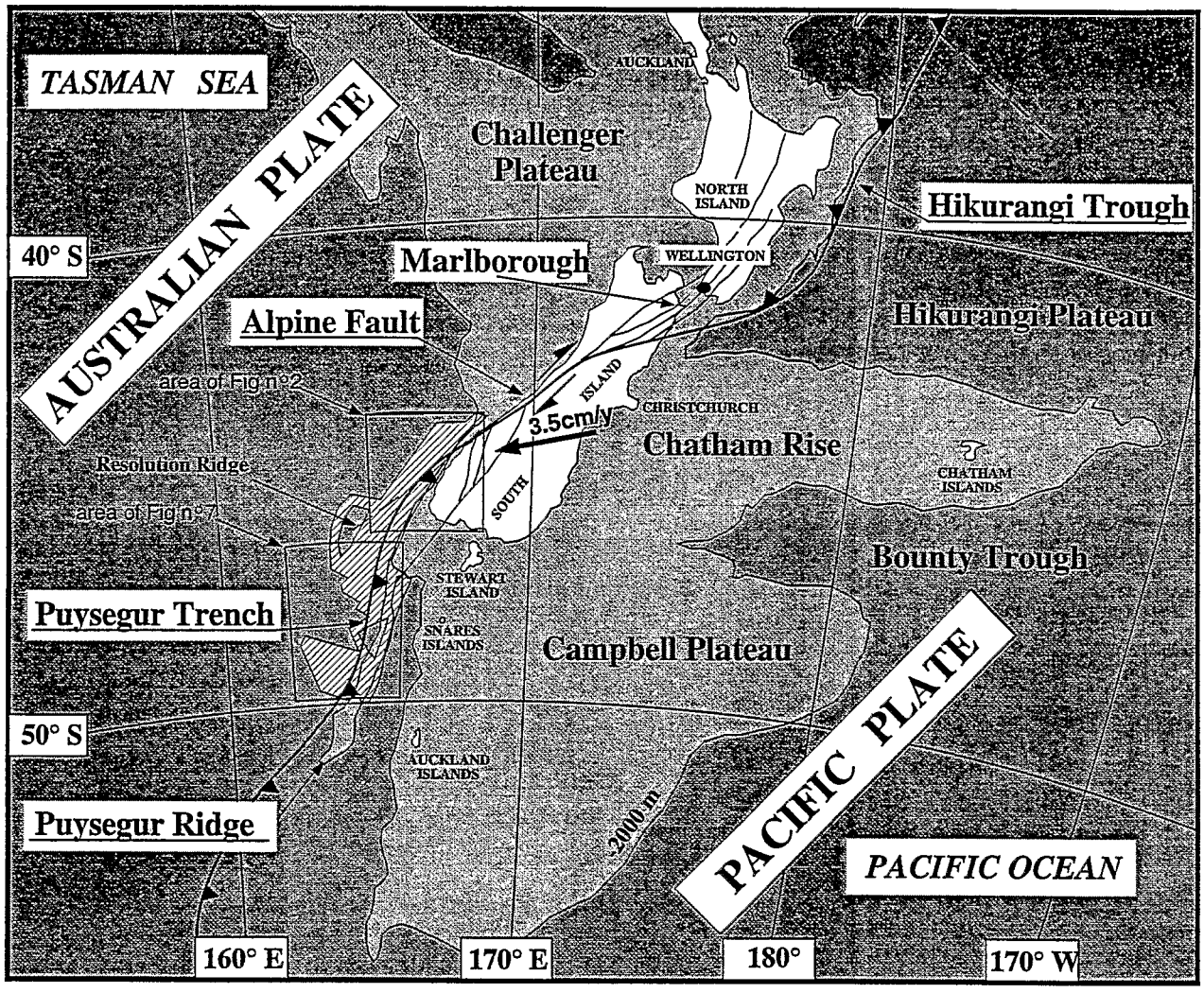


Fig. 1. Geodynamic setting of New Zealand and location of the area surveyed during the Geodynz-Sud cruise Leg 2 (hatched).

has been interpreted as oceanic crust (Weissel, *et al.*, 1977). Offshore Fiordland, this crust is thought to have formed by spreading in the Tasman Sea (Davey and Smith, 1983). Along the Puysegur Trench the oceanic crust is poorly known, but it has been inferred to be younger than that of the Tasman Sea (Weissel *et al.*, 1977).

Several structures on the Australian plate are significant for this study. The Caswell High is a flat-topped, oblong ridge 150 km long and 25 km wide, sub-parallel to the continental margin of Fiordland (Figure 2). The Resolution Ridge is one of a series of right-stepping en echelon ridges which are oblique to the margin and intersect the trench near the southern end of Fiordland. Resolution Ridge is 128 km long, 33 km wide and rises 2250 m above the surrounding seafloor. The junction of Resolution Ridge with the continental margin divides the plate boundary into three domains:

1. A northern domain from 44° to 45°40′ S (west of Fiordland, Figure 2).
2. A central domain from 45°40′ to 46°40′ S (Resolution Ridge – Fiordland margin junction, Figure 6).
3. A southern domain from 46°40′ to 49°42′ S (Puysegur Trench, Puysegur Bank and northern Puysegur Ridge, Figure 7).

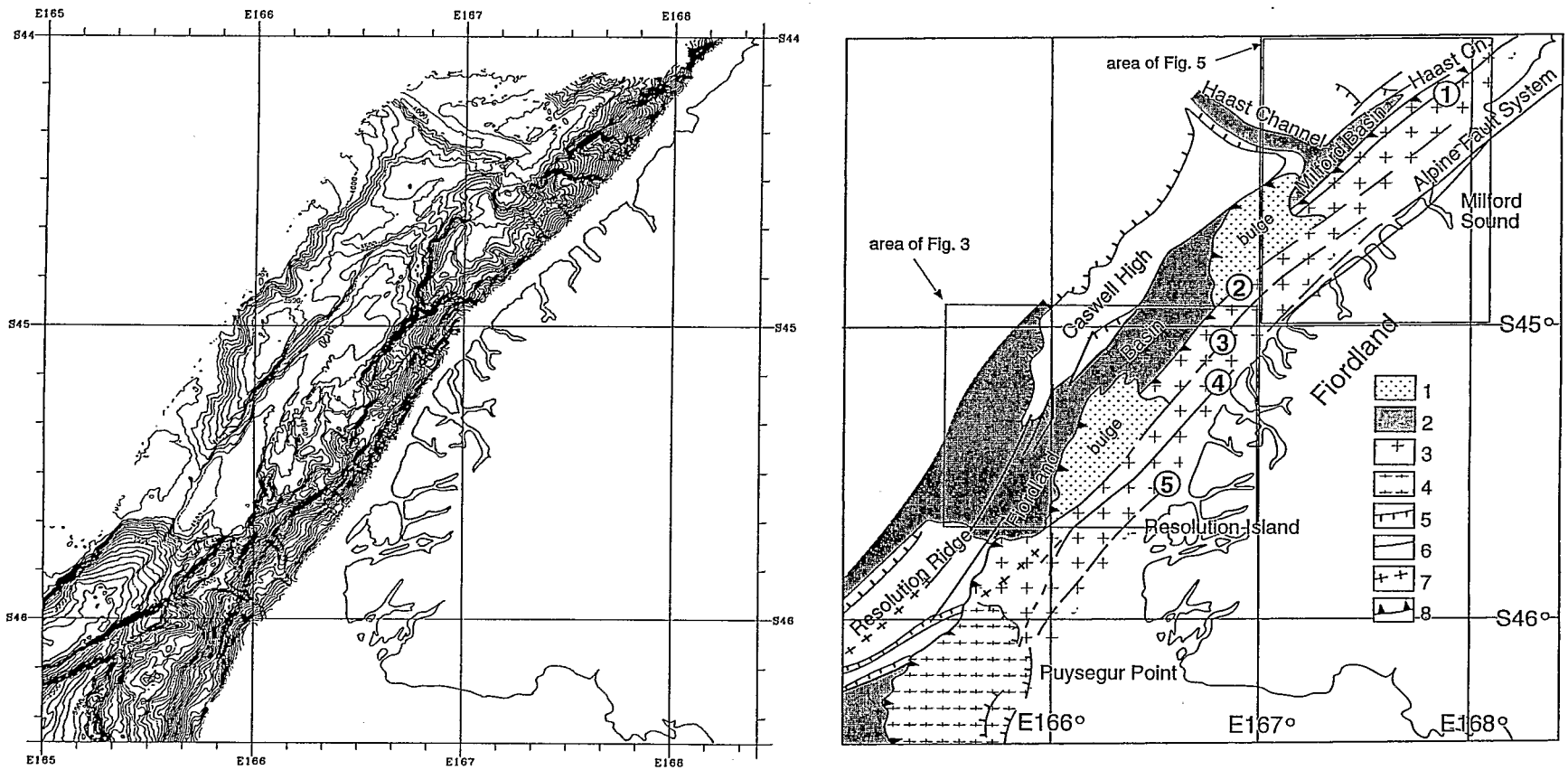


Fig. 2. Bathymetry of the Fiordland and Puysegur Bank margin. Contour interval: 100 m; 1: accreted sediment; 2: recent sediment of the Tasman Sea abyssal plain, Milford and Fiordland basins and northern Puysegur Trench; 3: Fiordland continental margin; 4: collapsed margin of Fiordland; 5: scarps; 6: fault traces (numbers in circles refer to faults mentioned in text); 7: ridge axis; 8: deformation front.

A detailed swath bathymetry and sonar imagery survey was undertaken over the Puysegur Trench and Ridge area during the Geodynz-sud leg 2 cruise of the *R/V l'Atalante*. This area extends from latitude 44° S, off Milford Sound where the Alpine Fault reaches the coast, to latitude 49°42′ S on the Puysegur Ridge (Figure 1). The purpose of the cruise was to investigate the transition between the transpressive regime of the Alpine Fault and the very oblique subduction along the Puysegur Trench and Ridge, the southern extent of continental crust on the Pacific plate, the nature of the oceanic crust of the Australian plate adjacent to the Puysegur Trench, the effects of changes in nature of the overriding and subducting plates on plate boundary structure, and the effects of subduction of en echelon ridges.

Structural and Sedimentary Features

Northern domain

The northern domain, off Fiordland, is characterized by a narrow shelf and a steep continental slope (Figure 2). At the base of the slope, the Fiordland and Milford basins are separated from the Tasman basin by the Caswell High. Two dominant structural grains can be defined:

1. Long linear fault scarps that outline troughs, ridges and steps which give both the inner trench slope and the ocean floor a strong coast-parallel morphologic grain.
2. Erosional canyons and channels that cross-cut the inner trench slope.

A bulge in the sediments of the lower continental slope separates the Milford and Fiordland basins. Another bulge further south almost divides the Fiordland Basin. A major submarine canyon – the Haast Channel – separates the Caswell High from the continental rocks of the Challenger Plateau to the north (Wood, 1993).

The continental slope is broken into southwestward-inclined steps up to 1500 m high by at least four major, long fault scarps which traverse it obliquely (Figure 2). A fifth scarp cuts the upper slope at the southern end of this domain. Three of these major scarps and a subordinate one are shown in detail in Figure 3. The westernmost step disappears at the northern end of the bulge between the Milford and Fiordland basins. The structural contact is obscured by canyon erosion but the buried block is evident beneath the overlying sediments in seismic profile (at 21h00 in profile MO 72–93 of Figure 4). The 3rd and 4th scarps are well defined and trend across a saddle towards two major scarps of similar strike but opposite throw on the Resolution Ridge (Figure 2). The terminus of the 5th scarp is considered later.

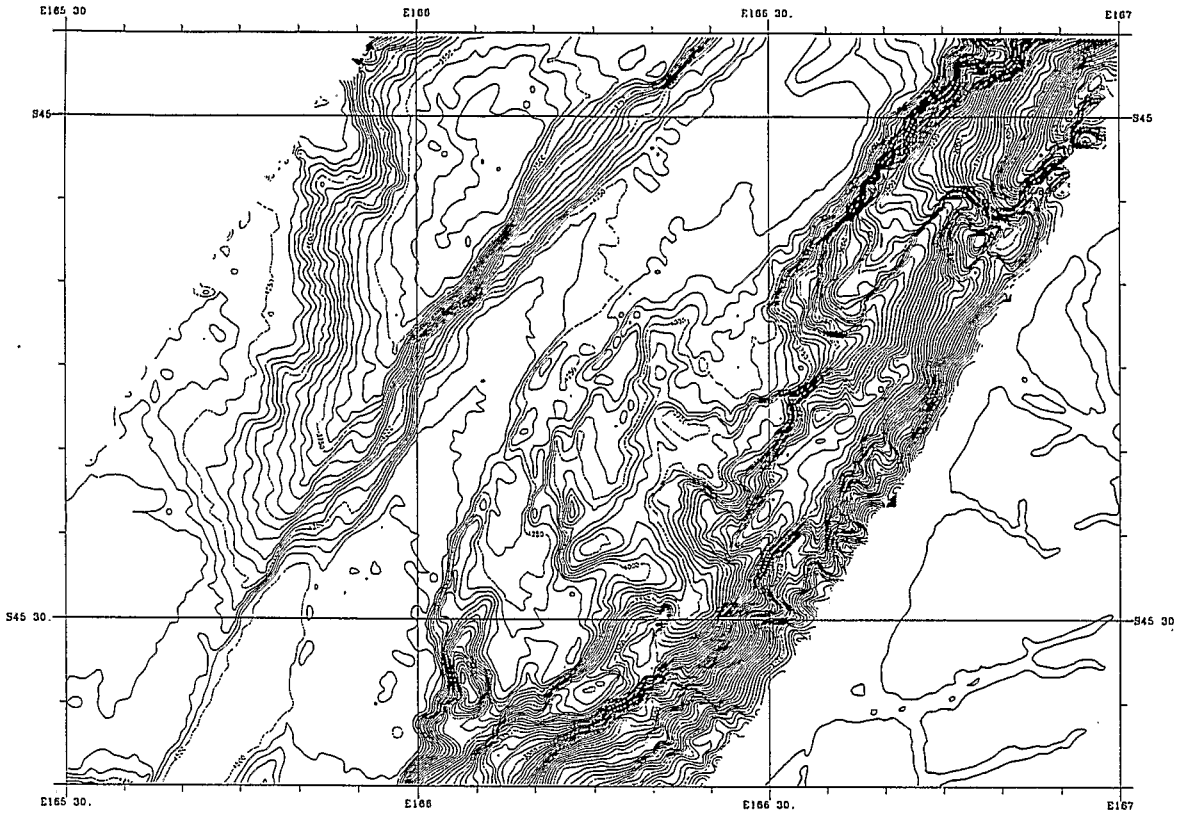
Submarine canyons occur along the Fiordland continental slope and are most frequent in the north (Figures 3 and 5). There, they cover approximately 75% of the area of the slope, and severely disrupt the scarp-step morphology. The upper scarps are particularly degraded by the many branches of these canyons.

Most of the canyons in the north are short and trend more or less directly downslope with little or no evidence of structural control. The floors of the larger canyons are unusually wide for their short length, and effectively constitute seaward-sloping sedimentary ramps (4°–10°), separated by eroded spurs. The floors steepen slightly where they cross the scarps; above and below these points transverse topographic sections vary from u-shaped though flat to convex. Seismic profiles reveal that the convex floors are mounds of sediment, probably fans. The present day locations of the major canyons bear no obvious relationship to the major fiords.

The canyons cutting the continental slope in the south, with one exception, are narrow and clearly influenced by the slope-parallel structural grain: hooking left at the base of each scarp to follow the southwestward inclination of the succeeding tread and turning basinward again down the next scarp (Figure 3). One canyon located at latitude 45°50′ S (Figure 2), has a right offset upslope at the base of the 5th scarp, but it hooks left again downslope at the base of the 4th scarp. Another wide canyon, at 45°27′ S (Figure 3), drains a long back-tilted area between scarps 3 and 4, which is fed by numerous short, steep canyons descending the upper continental slope.

The two sawtooth bulges at the base of the continental slope that project into the basins are made up of linear to arcuate ridges and terraces (Figure 2). The northern bulge is a flat massif with a terrace on its southern and western sides. A scarp and linear ridges are in the saddle where the bulge abuts the Caswell High. In profile MO 72–93 at 23h30 (Figure 4), the ridges are seen to be west-verging thrust anticlines, while the massif and terrace are an overthrust duplex. The southern bulge is made up of three main arcuate

Fig. 3. Morphostructures of the southern Fiordland margin. Contour interval: 50 m; 1: accreted sediment; 2: recent sediment of the Fiordland Basin; 3: Fiordland continental margin; 4: scarps; 5: east-facing normal faults; 6: inferred strike-slip faults (numbers in circles refer to faults mentioned in text); 7: fold axes in accreted sediment; 8: canyons. →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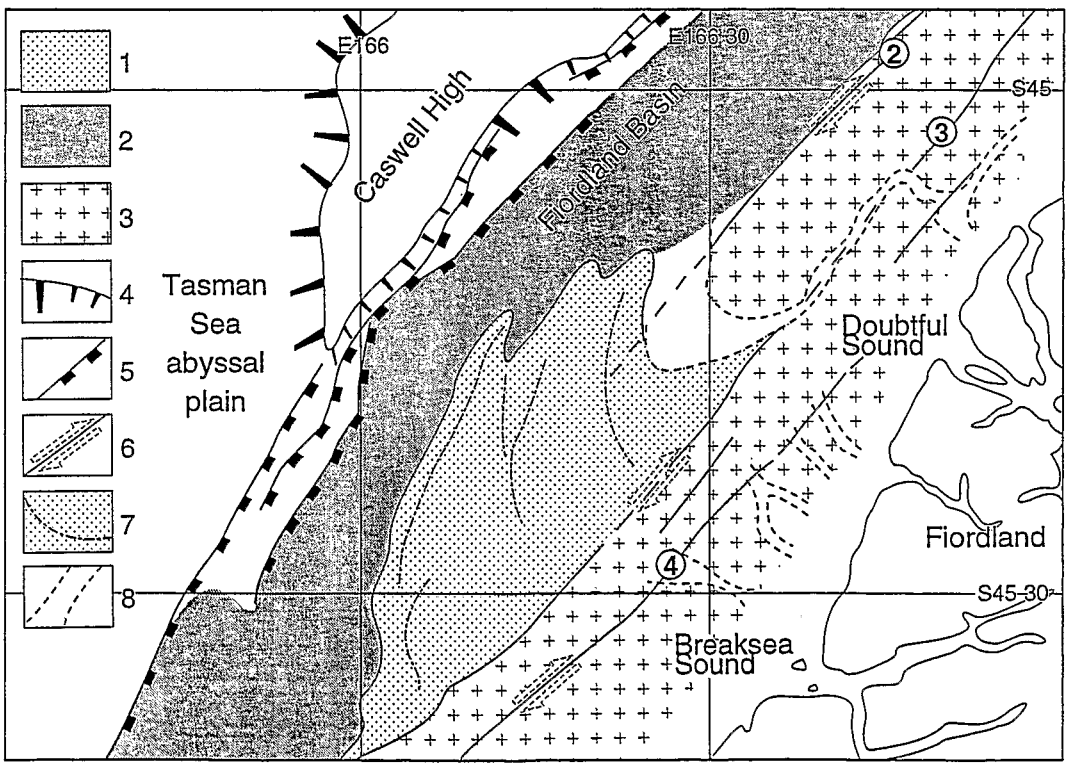
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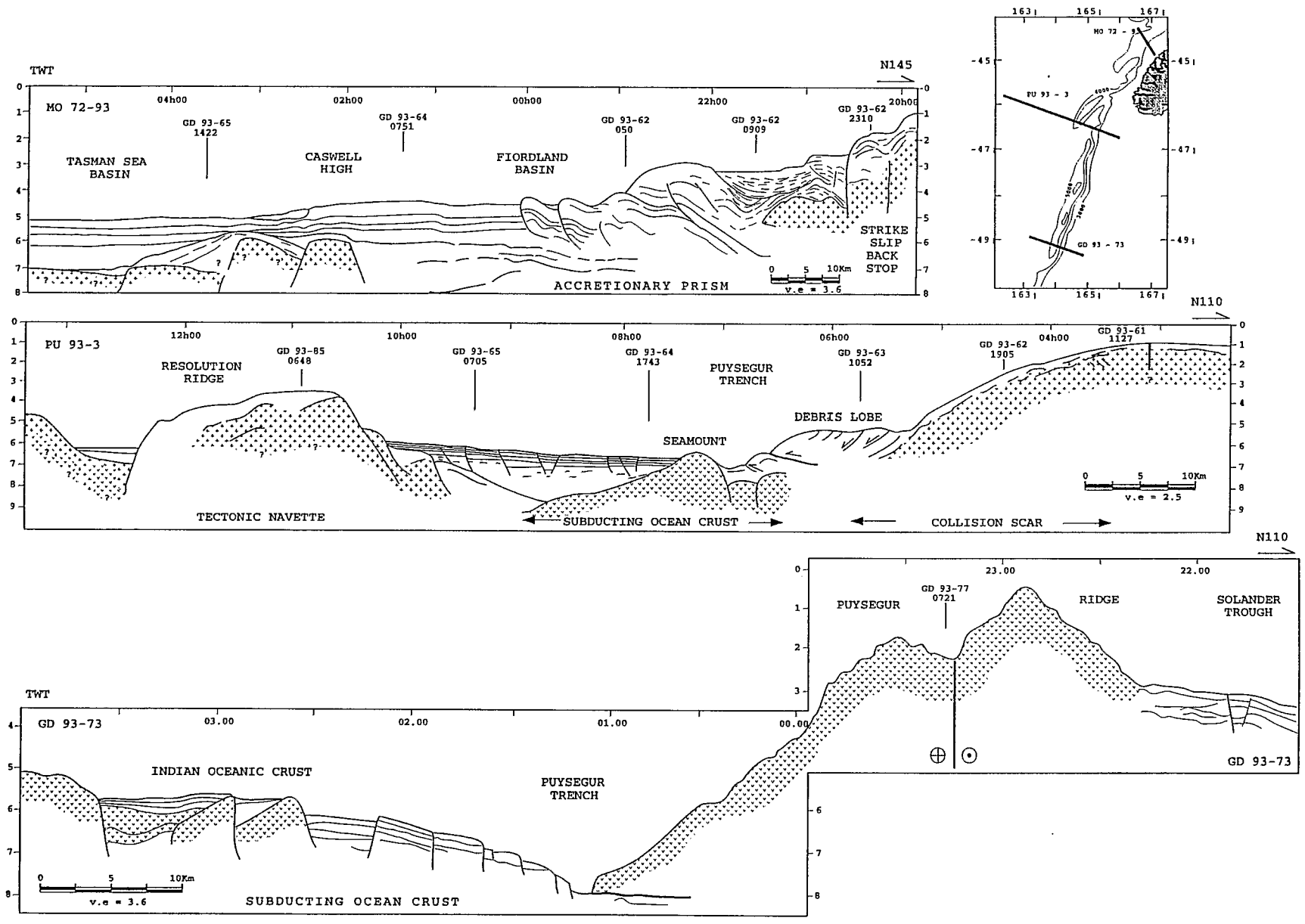


Fig. 4. Line drawings of three seismic lines transverse to the plate boundary. MO 72–93: line Mobil 93; PU 93–3: line Puysegur Trench Survey 3, R/V Lavrentyev; GD 93–73: line Geodynz-Sud 73, R/V L'Atalante.

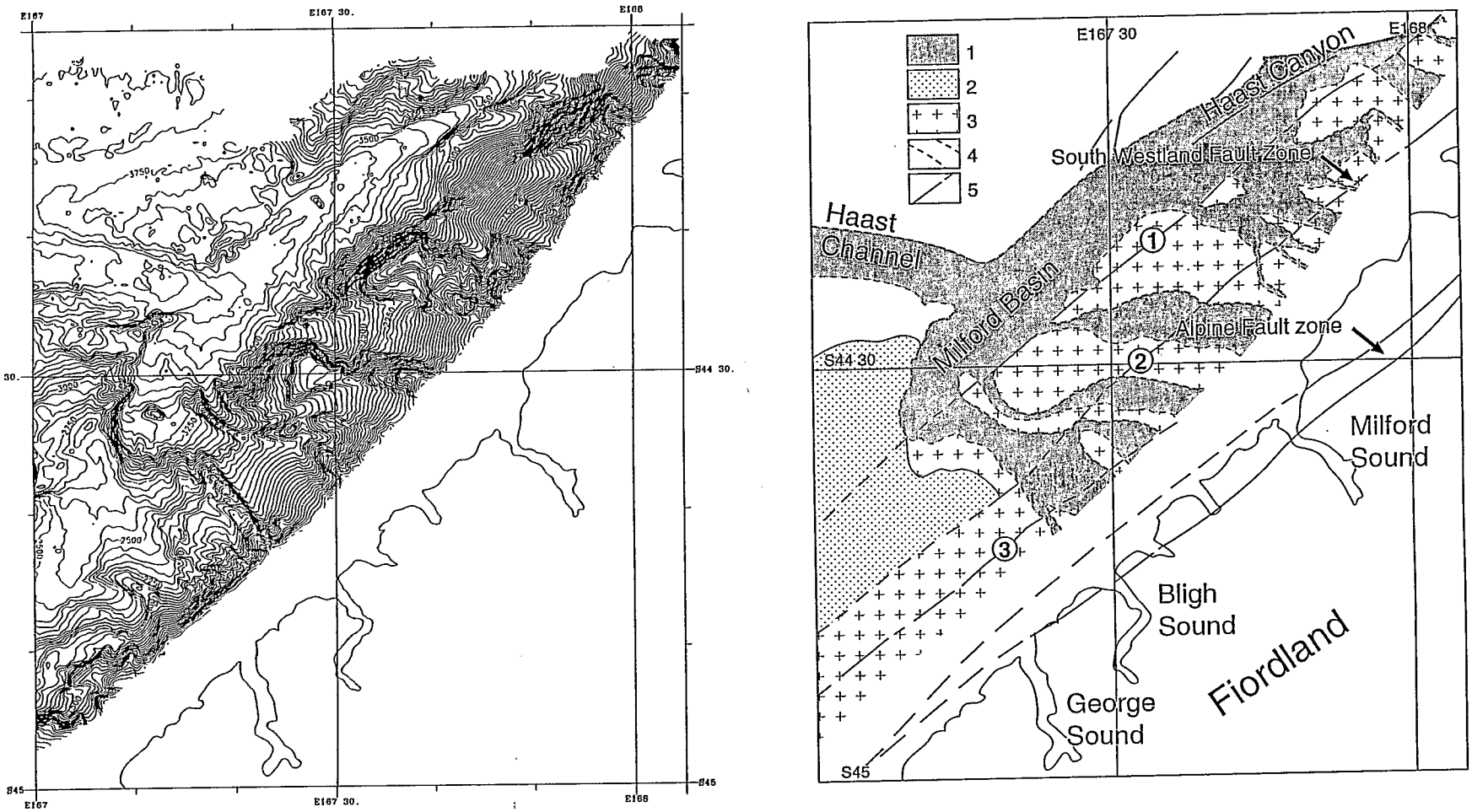


Fig. 5. The northern Fiordland margin. Contour interval: 50 m; 1: recent sediment of Milford Basin and canyons; 2: accreted sediment; 3: Fiordland continental margin; 4: canyons; 5: fault traces (numbers in circles refer to faults mentioned in text).

ridges, concentrically disposed and convex towards the southwest (Figure 3). In seismic profiles, these are seen to be south- and west-verging anticlines and thrusts developed in Tertiary Fiordland basin sediments.

The Milford and Fiordland basins are bounded to the east by the high scarps at the base of the continental slope and to the west by a system of east-facing scarps that also defines the edge of the Caswell High. Milford basin lies at a depth of about 3750 m (Figure 2). The floor is flat and underlain by 1100 to 2300 m of sediment (all sediment thicknesses are estimated using a 2.2 km/s average velocity). The basin narrows to the northeast and terminates to the southwest against the northern lower slope bulge (Figure 5). Here, a curved wall appears to have been cut in the bulge by a wide canyon descending from the shelf near Sutherland and Bligh Sounds. The Haast Canyon breaches the west margin of the basin. The Fiordland Basin deepens southward from 4000 to 4250 m just north of Resolution Ridge (Figure 2). It is also flat-floored and is underlain by 1900 to 2700 m of sediment.

The Caswell High lies west of the basins (Figure 2) and is composed of at least 1.5 km of flat-lying sediments (Profile MO 72–93 of Figure 4). The Haast Channel breaches its northern end and separates it from the Challenger Plateau to the north. The Caswell High terminates to the south in a series of parallel normal faults with a N 30° E strike.

The sides of the Caswell High are formed by fault-controlled scarps. The western side is a gentle scarp, incised by valleys that appear to be erosional. The eastern side of the high is composed of normal fault scarps dipping into the Fiordland and Milford basins. These faults have a dominant strike of N 30° E and a subsidiary strike of N–S. The main fault extends southwest into Resolution Ridge (Figure 3).

Central domain

The central domain includes the southwestern end of Fiordland and the western part of Puysegur Bank (Figure 6). It is dominated by the abutment of Resolution Ridge with the continental slope. The continental slope here is about twice as wide as that to the north, and includes a broad (22 km wide) lower slope terrace in an amphitheatre-like concavity above a well-defined trench. The subducting slab is visible beneath this terrace in some seismic profiles (i.e. profile PU 93–3, 06h30, Figure 4). Submarine canyons are rare and smaller than the main canyons in the northern domain, and they disappear south of Fiordland. Linear escarpments are both parallel and oblique to the trench and are found mainly on the Resolution Ridge.

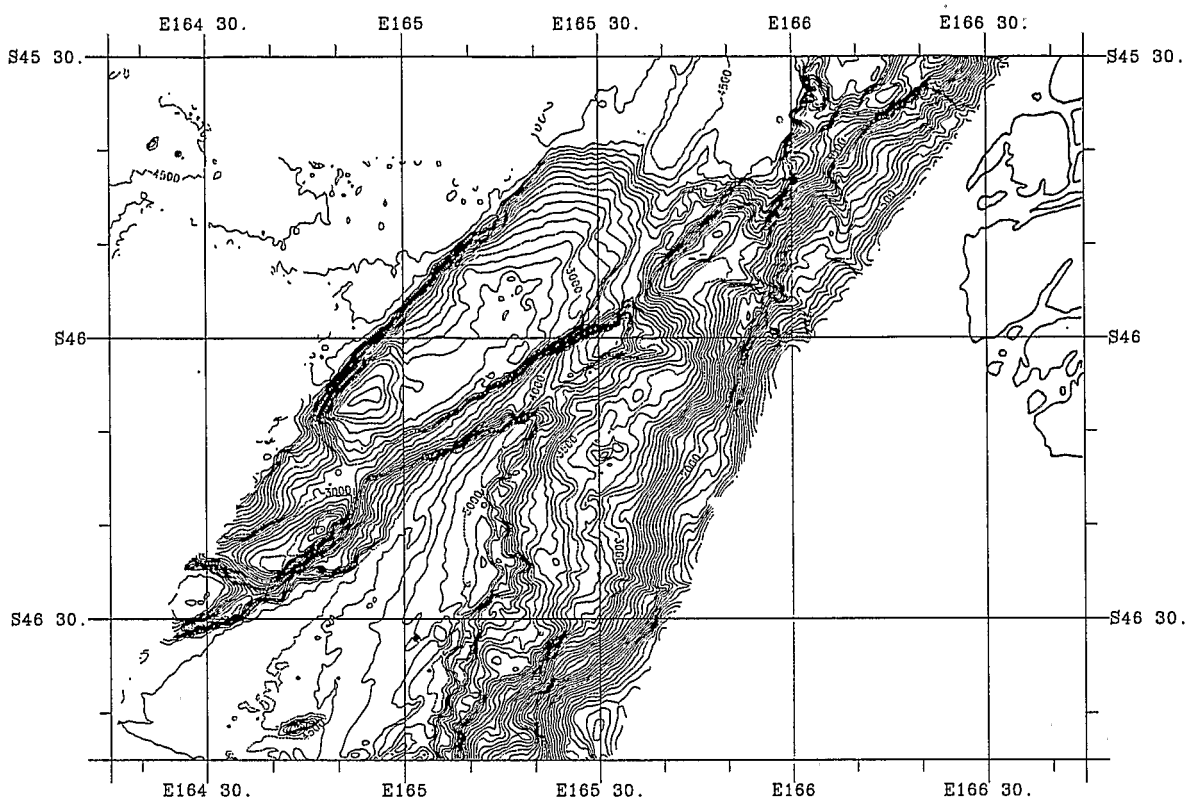
The Resolution Ridge (Figure 6) is a large, tabular, 2250 m high, non-magnetic, northeast-trending massif on the Australian plate. It is one of a series of en echelon ridges that extends southwestward from the plate margin. The sides of the ridge are onlapped by undeformed sediments and the flat top is covered with 200–1200 m of sediments (Wood *et al.*, in prep.). West of the ridge, the Tasman Sea floor is probably Late Cretaceous in age (Weissel *et al.*, 1977) and covered by 1–2 km of sediment (Wood *et al.*, in prep). South of the ridge the seafloor is possibly Eocene to Oligocene in age (Weissel *et al.*, 1977) and the primary ocean crust fabric is partially exposed at 46°40′ S, 134°45′ E (Figure 6).

Morphology of the Resolution Ridge is controlled by two primary fault sets: one striking N 45° E and the other striking N 60° E (Figure 6). The main block dips at about 3° beneath the Fiordland Basin to the northeast. The fault scarps on the southeastern side of the Resolution Ridge delimit a ramp that slopes gently northeastwards down the side of the ridge into a small, deep, closed basin in the trench at the foot of the continental slope. This closed basin is one of a chain of basins which define the axis of the Puysegur Trench.

In addition to the main block, there are several smaller blocks separated from the main one by faults (Figure 6). One of these blocks, located at 46°20′ S, is a small right triangle in plan, bounded by straight sides trending N 45° E, N 60° E, and N 120° E. A narrow ridge extends southwest of the triangular block. Two blocks of similar size occur to the west of it, out of the present survey area, (Van der Linden and Hayes 1972; Wood *et al.*, in prep. seismic line 3). Together they form a right-stepping relay in the en echelon ridge system. The continental slope in the central domain shows little sign of canyon erosion. There are only two canyons, both narrow (Figure 6). The northern one (described earlier in Figure 2) shows a right offset at the base of the uppermost scarp on the slope and a left offset at the base of the slope, whereas the southern one descends directly into the saddle between Resolution Ridge and the continental slope.

The saddle formed by the junction of the ridge with the continental slope separates the 4500 m deep Fiordland Basin to the north from the 5200 m deep Puysegur Trench to the south.

Fig. 6. The Resolution Ridge – Fiordland Margin junction area. Contour interval: 100 m; 1: Fiordland continental margin; 2: collapsed margin; 3: recent sediment of the Tasman Sea abyssal plain; Fiordland basin and northern Puysegur Trench, 4: accreted sediment; 5: slump scars; 6: canyons; 7: scarps; 8: fault traces (numbers in circles refer to faults mentioned in text); 9: ridge axes. →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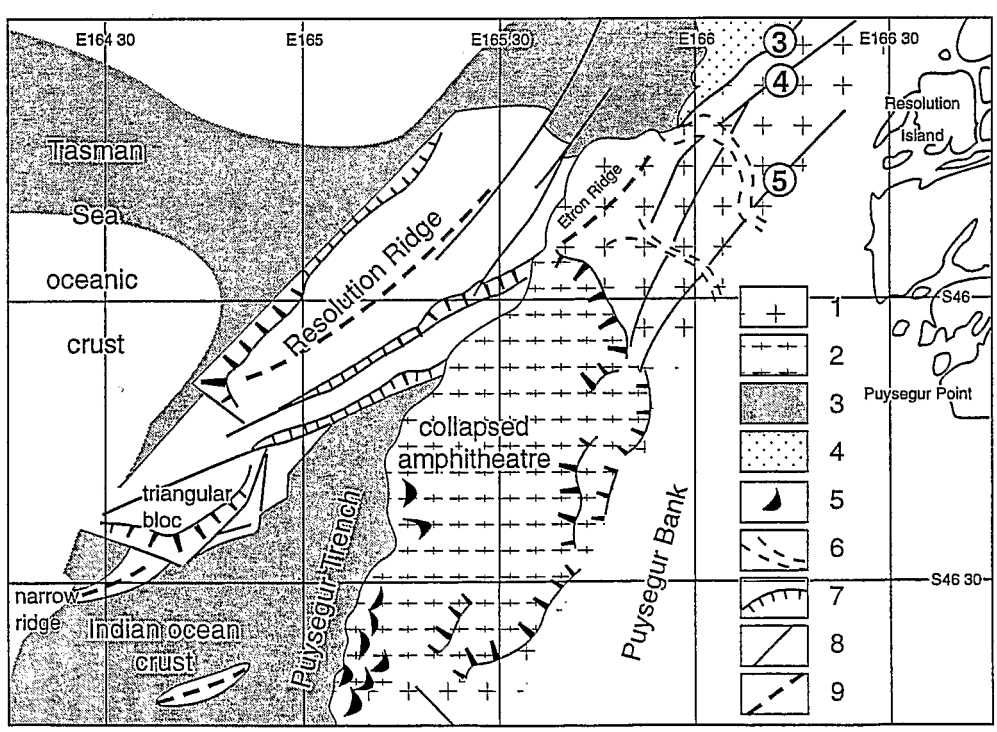
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The morphologic aspects of the continental slope opposite and south of this junction are very different: seaward convex in plan at the junction with the ridge, seaward concave south of the junction. Above the saddle, the continental lower slope is steep, the mid-slope is gently inclined and the upper slope is very steep. The 3rd and 4th scarps of the northern domain, and the two major southeast-facing fault scarps of the Resolution Ridge, have different strikes but appear to intersect in the saddle. In the middle of the saddle, at the apparent intersection of these faults, is a short round-topped NE-trending ridge: the Etron Ridge (Figure 6).

South of the saddle, there is a well developed trench characterized by mild down-faulting of the Australian plate. The sediment here is of the order of 2200 m thick (Wood *et al.*, in prep.), and almost completely buries the basement which shows the fabric of primary oceanic crust (this fabric, which is better featured in the southern domain, is described below). Although this area is generally more sediment covered than the region to the south, little young trench fill seems to be present since two ridges of the ocean crust, visible in the trench at 46°30′ S, 165° E and 46°42′ S, 164°43′ E, enclose unfilled basins.

Here the upper continental slope is concave or amphitheatre in shape, while the lower slope is formed by an uneven terrace that descends abruptly into the trench, giving the trench axes a sinuous trace. Several gentle scarps curve south and southeast across this terrace. Seismic profiles (Wood *et al.*, in prep.) reveal that the terrace is formed of acoustically transparent material without coherent internal structure. The top of the subducting slab can be followed southeast beyond the trench for 11 km under the terrace.

Southern domain

The southern domain (Figure 7) is characterized by subduction of Indian ocean crust of the Australian plate along the Puysegur Trench. The inner trench wall west and southwest of Puysegur Bank is complex. The ridge summit is a southward-tapering zone of linear ridges, scarps and perched basins. South of Puysegur Bank there is a transition via very complex bathymetry to the Puysegur Ridge, an intra-oceanic oblique subduction ridge.

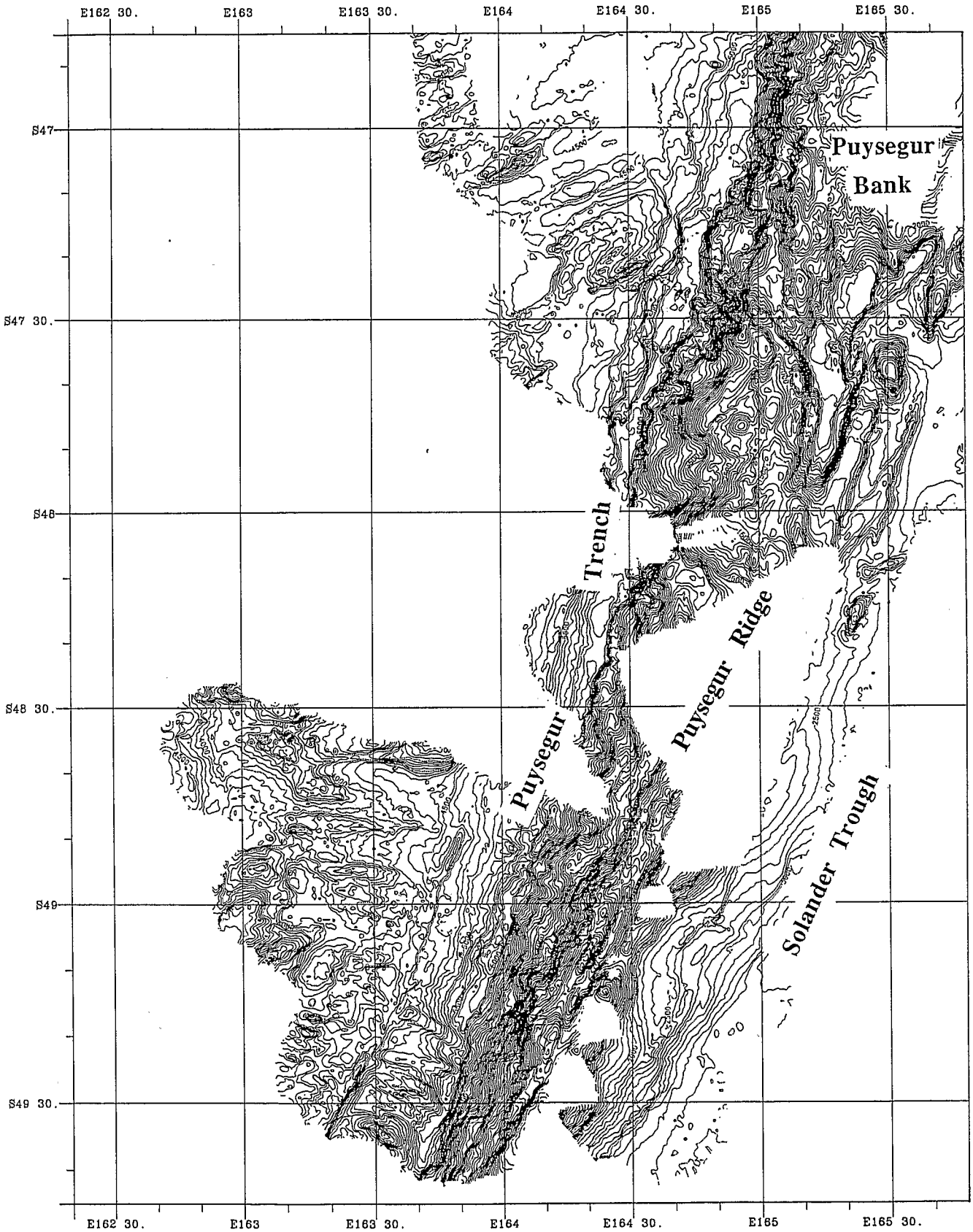
The sediment cover on the Australian plate thins rapidly south of Resolution Ridge and a strong N 65° E ridge-and-trough fabric is apparent on the seafloor south of latitude 47° S. This trend continues southwards to at least 47°40′ S where there is a gap in the data. Further south, from 48°27′ S to 49°40′ S, the trend of the fabric is N 120° E and includes a number of small seamounts, as well as an orthogonal fracture zone parallel and adjacent to the trench. Seismic profiles (profile GD 93–73 on Figure 4, and Wood *et al.*, in prep.) show that the oceanic basement topography is rugged and that the troughs are filled with more than 1 km of sediment. Where the N 65° E fabric obliquely intersects the trench, faults parallel and orthogonal to the ridges appear to be active. Together, these reactivated faults form a saw-tooth pattern of steps on the outer trench wall that defines the bending of the plate into the subduction zone. Further south, where the fabric is orthogonal to the trench, only trench-parallel faults have formed on the outer wall.

From the central domain to 48°35′ S, the trench floor is smooth and slopes gently southwards to the deepest part of the Puysegur Trench at 6200 m. South of the flat-floored area, the trench axis is gently sinuous, virtually devoid of sediment, and consists of a chain of left-stepping, en echelon closed basins. North of 49°22′ S these basins are separated by undulations of the lower inner wall, and south of this latitude, in the extreme south of the survey area, by the intersection of the ridges on the subducting plate with the inner trench wall.

The inner trench wall and ridge summit change markedly in character in the southern domain. They can be divided into three areas: (1) a northern area from the south end of the amphitheatre to the southern end of Puysegur Bank (46°35′ S to 47°30′ S); (2) a middle area covering the transition between the Puysegur Bank and the Puysegur Ridge (47°30′ S to 48°15′ S); and (3) a southern area covering the southern Puysegur Ridge (48°15′ S to the limit of the survey area at 49°42′ S).

1. In the northern area the base of the inner trench wall is uneven but appears to consist of indistinct right-stepping N–S to N 10° E-trending linear segments (Figure 7). The wall shallows rapidly from the trench to 3000 m in a series of continuous trench-parallel linear scarps and terraces scalloped by small, arcuate depressions. The upper wall is less steep and shows two structural trends. North of 47°10′ S, N 115° E-trending lineaments exhibit displacement down to the SW but do not appear to offset the trench-parallel scarps. South of 47°10′ S the upper wall is incised by a series of narrow valleys and ridges with directions splaying away from the ridge crest towards the north and northwest.

Fig. 7. Bathymetry of southern Puysegur Bank to Puysegur Ridge. Contour interval 100 m. →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Puysegur Trench
Puysegur Ridge
Solander Trough

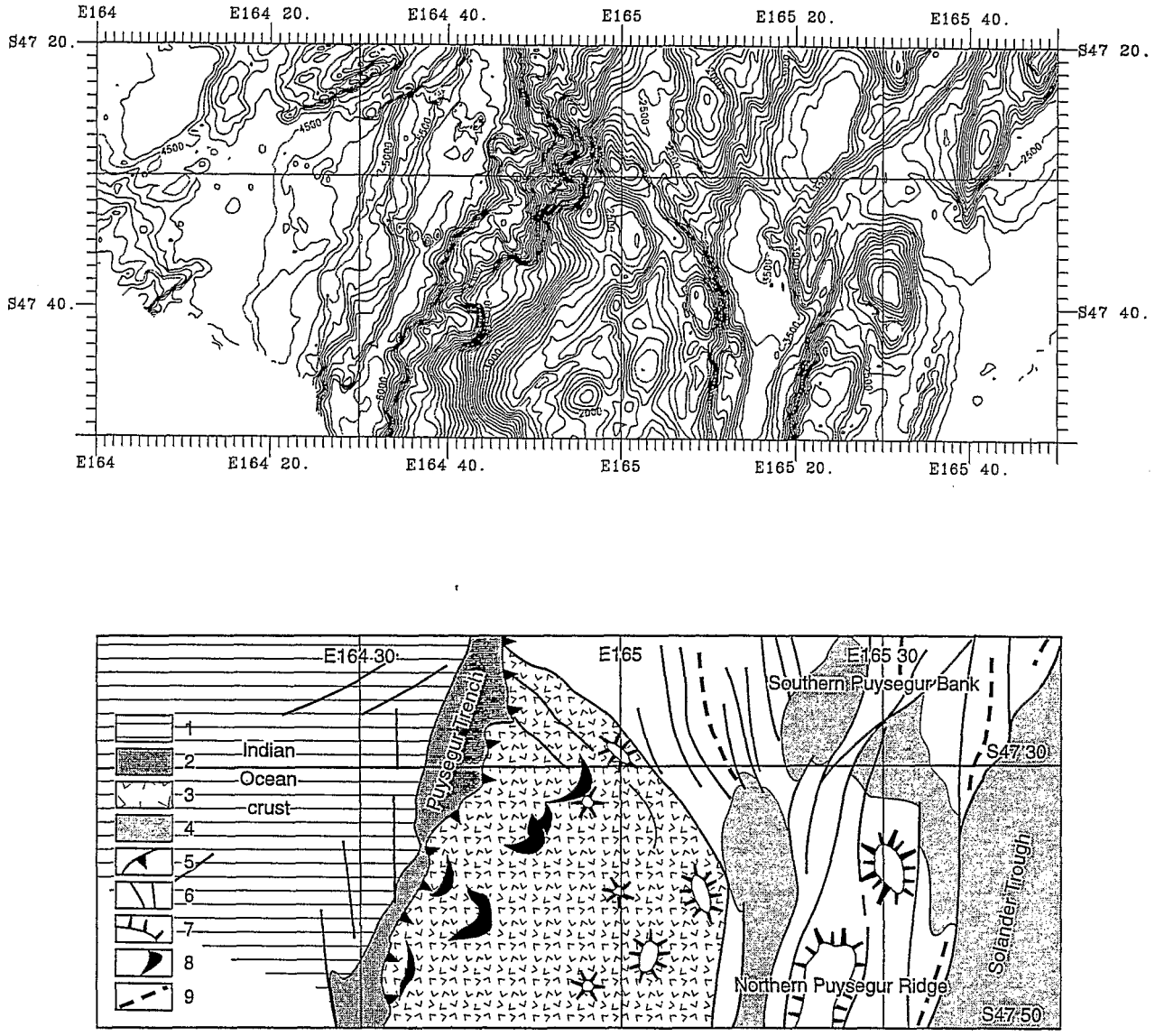

Fig. 8. Morphostructures at the Puysegur Bank – northern Puysegur Ridge junction. Contour interval: 100 m; 1: Indian Ocean crust; 2: sediment of the Puysegur Trench; 3: elliptical massif topped by conical seamounts; 4: basins and terraces of the overriding plate; 5: deformation front; 6: fault traces; 7: scarps; 8: slump scars; 9: ridge axes.

The ridge summit is a 33 km wide complex of linear N 10° E to N 40° E-trending scarps and lens-shaped ridges enclosing elongated terraces and perched basins of ponded sediment. Some of the basin sediments show evidence of compression along the basin margins. East of the ridge summit the seafloor drops away into the Solander Trough, a basin with thick sediment fill. Folds seen on multibeam and seismic data reflect compression along the west margin of the Solander Trough.

2. In the middle area, the inner wall between 5750 and 4750 m is convex towards the west and has a steep slope. Above 4750 m, the slope is heavily scalloped by large 5–6 km wide slump scars. The ridge summit is divided into a western elliptical massif and an eastern series of linear NNE-trending ridges and basins (Figure 8). The massif is sharply bounded to the east by an arcuate, east-facing major scarp. The scarp is 250 to more than 1000 m high and dominates the eastern area of NNE-trending ridges and basins.

The elliptical massif is surmounted by seven small knolls with both acute and flat summits. The knolls near the eastern edge of the massif are elongated parallel to the bounding scarp.

The ridge summits and basins floors east of the massif are flat and are delimited by steep (38°) linear scarps. The scarps trend N 15°–20° E and are continuous or en echelon with those to the north. The easternmost ridge is narrower and lower than those to the west. It thins northward and rises 300 m above the smooth surface of the Solander Trough.

3. In the southern area, the structures of the inner trench wall and ridge are better organised than those to the north (Figure 9). The entire trench wall (approximately 4000 m high) is steep (12°) and relatively smooth with broad transverse N 145° E trending undulations. On the lower trench wall these undulations result in a sinuous trace of the trench. Poorly defined terraces are scattered from 5500 m to 1750 m, over most of the inner wall. In the northern part of the area a subdued slope break occurs at approximately 3500 m, the base of a steeper upper inner wall.

The N 25° E-trending Puysegur Ridge is a twin-ridged summit 100 to 1500 m below sea level, narrowing toward the south from about 45 to 35 km wide. The twin ridges are narrow (about 2 km wide) and very linear (Figure 9). The higher eastern ridge was only partly covered by the survey. It shows a series of flat-topped summits at varying depths from 49°15′ S northwards (450 m at 49°15′ S, 1400 m at 49°06′ S and 650 m at 48°56′ S). The western ridge consists of 24 to 45 km long aretes and troughs arranged in relays. Both aretes and troughs are discontinuous features, merging and overlapping along the Puysegur Ridge summit. The eastern flank of the Puysegur Ridge slopes steeply to about 1750 m and then more gently toward the thickly sedimented (1.3 km) Solander Trough. NE-trending, east-dipping fault related ridges are seen on seimic profiles across this slope.

Discussion

Northern Domain

Seismic reflection data west of Caswell High show typical oceanic crust sedimentary and basement structure. Weissel *et al.* (1977) identified magnetic anomaly 33 in this region, and it is therefore likely that basement is Late Cretaceous oceanic crust, formed during seafloor spreading in the Tasman Sea. Davey and Smith (1983) modelled the subduction of oceanic crust along the Fiordland margin, but our data suggest that this may not be the case.

The Challenger Plateau and Lord Howe Rise are continental fragments which extend north and west of this region (e.g. Shor *et al.*, 1971). Their western margin is characterized by large basins, continental fragments and horst and graben structure (e.g. Wood, 1994), indicating complex initiation of rifting in the Tasman Sea. Rifting in the New Caledonia Basin and Taranaki appears to have propagated along the west coast of the South Island shortly after rifting began in the Tasman Sea (e.g. Laird, 1994).

Basement structure interpreted from seismic reflection data indicates that the Caswell High is a fragment of continental crust, a southern extension of the Challenger Plateau, and that the Milford and Fiordland basins are rift basins similar to those seen elsewhere along the Tasman margin. Therefore, it is not old oceanic crust which is being subducted beneath Fiordland, but rather thinned continental crust with high relief. Both Tasman Sea and Taranaki/West Coast rifting probably influenced the development of these basins (e.g. Laird, 1994), but the relative importance of the two events is not yet determined. The Haast Canyon may mark the structural transition between Tasman Sea rift structures and West Coast transform-rift structures.

The faults which form the eastern margin of the Caswell High offset the seafloor and extend south across the Fiordland Basin and into the Resolution Ridge. They are parallel to the plate margin and are located 10–20 km from the toe of the slope. Farther north on the Challenger Plateau, Wood (1994) postulated a flexural bulge 100 km from shore. If the recently-active faults identified here are similarly associated with flexure, then their location must reflect structural control or a difference in effective crustal strength.

The linear features on the continental slope are probably splays from the Alpine Fault and the South Westland Fault Zone of Seward and Nathan (1990). Although strike-slip deformation has therefore probably extended across what is today the slope, there is no evidence of recent dextral deformation of the canyons or other features. The canyons are not aligned with the fiords, however, their spacing suggests that there may be about 20 km of dextral offset on a fault located near the coast on the shelf. If the down-going slab is comprised of a series of basins and ridges, then the present slope morphology may represent both splaying of strike-slip motion across the continental margin and collapse following the arrival of basins at the margin.

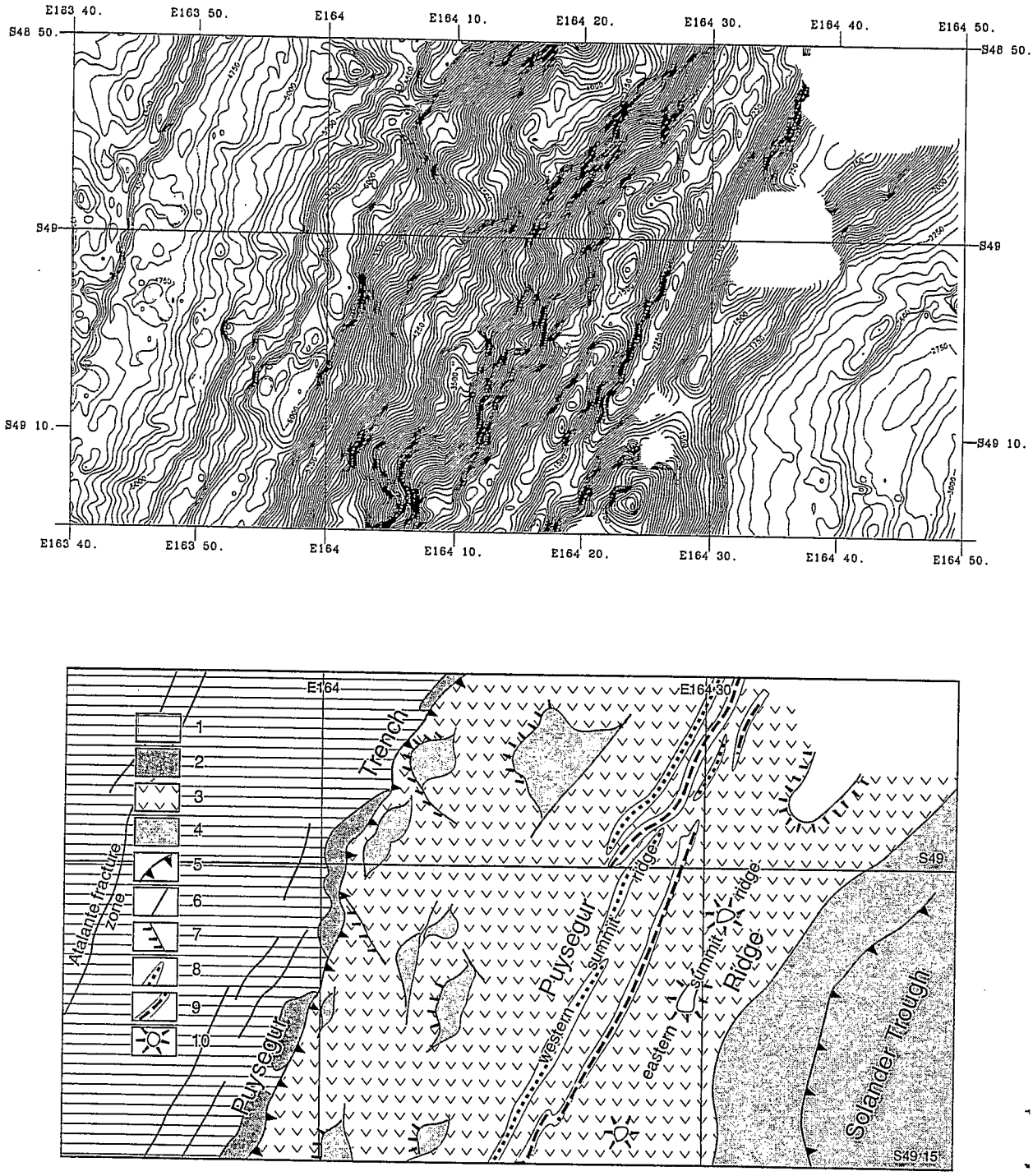

Fig. 9. Morphostructure of the Puysegur Ridge. Contour interval: 50 m; 1: Indian Ocean crust; 2: sediment of the Puysegur Trench; 3: Puysegur Ridge basement; 4: basins and terraces of the overriding plate; 5: thrusts; 6: fault traces; 7: scarps; 8: en echelon aretes of the western summit ridge; 9: en echelon summit valleys; 10: flat-topped highs of the eastern summit ridge.

The fault splays form narrow wedges which trend obliquely down the slope. Two of these dive beneath the sediment bulges in the Fiordland Basin. The southern bulge presents the clearer surface and subsurface picture. It shows a pattern of arcuate south- and west-verging anticlines and thrusts, concentric around the block which dives beneath it. This pattern suggests that the block has acted like a plane and the basin sediments have been uplifted and deformed by relative transpressive dextral motion between the basin and the slope. The bulges could conceivably have originated from slumps, but the pattern of internal structure supports sediment accretion. Accretion would imply that dextral strain is not entirely localised along the coastline, but is also taking place at the base of the slope.

The Milford and Fiordland basins both serve as depocentres for sediments transported across the margin. The Milford Basin has a clear sediment path, with sediment derived from the Haast and other slope canyons and leaving the basin via the Haast Channel. The Fiordland has no clearly defined exit; sediment is transported along down-slope canyons and disperses across the basin and through the relatively broad gap between Caswell High and Resolution Ridge. Transport is at least periodically interrupted by faulting across this gap.

Central Domain

The Resolution Ridge is the dominant feature of the Australian plate in this domain. The ridge is unsampled, but the local presence of sedimentary structure, the lack of magnetic anomaly, and the inferred complexity of Tasman Sea breakup suggest that it is another continental fragment. Its shape indicates that it has been strongly influenced by faulting and tilting rather than volcanism.

The Resolution Ridge is one of a right-stepping en echelon series of ridges extending ESE from the plate margin. North of these ridges is Cretaceous and Paleogene oceanic crust formed by seafloor spreading in the Tasman Sea (Weissel *et al.*, 1977). South of the ridges is younger oceanic crust, discussed later in this paper. It is likely that these ridges are continental tectonic lenses distributed along a major transform boundary active during Tasman Sea rifting. Modern earthquake activity at the Resolution Ridge is compressional and suggests either obduction of the ridge or bending of the subducting plate (Anderson *et al.*, 1993). Bending of the Australian Plate, which appears farther north, where it is evidenced by the N 35° E-trending normal faults, may be expressed here by the trenchward tilting of the ramp on the southern side of the ridge.

The continental slope adjacent to the Resolution Ridge has been uplifted, separating the Fiordland Basin from the Puysegur Trench. The amphitheatre-shaped area just south of this saddle suggests a large collapse structure on the lower slope. Similar slope collapse has been reported as a result of seamount subduction (Collot and Fisher, 1991). Relative plate motion is almost parallel to the Resolution Ridge (Figure 1; De Mets *et al.*, 1990), so collapse could not have resulted from sweeping of an eastern extension of the ridge beneath the plate boundary. However, subduction of another right-stepping en echelon ridge is possible.

The lack of slope canyons probably reflects a change in hydrologic regime and a decline of sediment input south of Fiordland.

Southern Domain

The sediment cover on the Australian plate thins to the south, and by 47° S a linear fabric of basement basins and ridges is apparent on the seafloor. This fabric appears to be the product of NW–SE seafloor spreading. This is similar to the Oligocene-Miocene spreading direction predicted for this region by Weissel *et al.* (1977). Further south, at 48°40′ S, the basement fabric is consistent with a N–S direction of seafloor spreading similar to that of the Southeast Indian Ridge. It then changes gradually to the south so that by 49°30′ S it is consistent with NE–SW spreading. Orthogonal ridges in this southern area, such as the "l'Atalante Fracture Zone" (Figure 9), are associated transform fracture zones.

The structural fabric of the basement influences the morphology of the trench and faulting on the downgoing slab. In the north, where the N 65° E fabric intersects the trench, the faults have been reactivated in response to plate trenchward bending and form a sawtooth pattern of steps on the outer trench wall. Farther south, trench-parallel transform fracture zones have been reactivated. The effects of this bending are observed along the entire area covered by this survey, suggesting that subduction occurs along the entire obliquely convergent plate boundary.

There is little sediment in the trench south of Resolution Ridge, and no sign of accretion. Numerous slump scars and west-facing scarps on the inner trench wall suggest collapse of the trench wall, perhaps in response to tectonic erosion.

Between the Puysegur Bank (about 47°15′ S) to the Puysegur Ridge (about 48°15′ S), is a zone of transition between continental crust to the north and oceanic crust to the south. This transition zone shows

a very complex bathymetry with two distinctive areas. An elliptical massif is on the western side of the ridge and is topped by volcano-like knolls and bounded to the east by a large, seaward concave, arcuate scarp. A series of northwest-trending splays tends to parallel the arcuate scarp and dies out downslope to the northwest. The volcano-like knolls are too close to the trench to be subduction-related. One possibility is that the knolls could be due to mud volcanism although their heights seem to be too large. Another possibility is that the knolls could be oceanic volcanoes passively transported on top of the elliptical massif and accreted or docked with their basement to the margin. The latter eventuality is supported by the arcuate scarp that bounds the elliptical massif to the east and distorts, to the northeast, the trend of adjacent structures. This is where a series of ridges and basins that splays northwest, and dies out downslope, tends to parallel the arcuate scarp. This pattern suggests a diffuse area of strike-slip deformation and that the elliptical massif is an allocthonous unit sutured to the margin.

Other series of north- and northeast-trending scarps are located east of the massif, do not change strike and appear to be components of the primary plate boundary system. The well-expressed northeast-trending scarps are in line with the southwestern tip of Fiordland where the main branch of the Alpine Fault is thought to lie (e.g. Christoffel and van der Linden, 1972).

South of 48°15′ S, the Puysegur Ridge summit consists of a double chain of elongated, braided lens-shaped aretes and valleys related to the Puysegur Fault (Collot *et al.,* 1995). The symmetry of the aretes in section and map view, and their steady trend, strongly evoke an intermediate to mature strike-slip zone (Sylvester, 1988). A series of flat-topped peaks along the eastern Puysegur Ridge must be of wave-cut origin. Variations in depth of the eroded summits suggest vertical undulations along the strike-slip zone.

Conclusions

The very oblique convergence along the Fiordland margin – Puysegur Ridge/Trench system has produced variations in deformation style which reflect changes in the nature and structure of the overlying and downgoing plates.

The Pacific plate is continental in the north of the survey area and oceanic in the south. The continent-ocean transition appears to be located near the southern end of the Puysegur Bank.

The Australian plate is probably thinned continental crust west of Fiordland, and certainly oceanic crust west of the Puysegur Trench. The boundary between the two crusts is marked by the Resolution Ridge System, a series of right-stepping, en echelon ridges, probably continental in nature. The oceanic crust west of Puysegur Trench formed by spreading along different apparent directions: NW–SE in the north and N–S to NE–SW in the south.

Discontinuous tectonic accretion resulting from transpressive deformation is restricted to the toe of the Fiordland margin. Southward, along the Puysegur Trench, slumping, collapse and mass wasting of the inner trench wall, support an interpretation of frontal tectonic erosion.

Strike-slip tectonic features are recognized along this entire margin. Although we see evidence on the Fiordland margin for strike-slip faults which were previously active, the present strike-slip component is in part accomodated by transpressive deformation at the toe of the slope and the remainder must be accomodated by faults near the Fiordland coast. Active strike-slip deformation is strongly expressed at the Puysegur Fault along the crest of the Puysegur Ridge, but we see no clear evidence for a strike-slip component along the Puysegur Trench.

Strike-slip motion must be transferred between an offshore extension of the Alpine Fault and the Puysegur Fault – across the Puysegur Bank and the continent-ocean transition zone of the Pacific plate. However, the diffuse zone of strike-slip deformation near the inferred location of the continent-ocean transition, indicates that there is a discontinuity in the well-organised strike-slip fault pattern. An anomalous unit which may be an accreted oceanic terrane is also present on the Pacific plate at this location and may contribute to the interpreted strain distribution.

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