Morphostructure of an incipient subduction zone along a transform plate boundary: Puysegur Ridge and Trench

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ABSTRACT

Multibeam bathymetric and geophysical data reveal a major strike-slip fault that extends along the summit of the Puysegur Ridge east of the Puysegur Trench. The northward structural development of this ridge-trench system illustrates the evolution of an incipient subduction zone along a transform plate boundary that has been subjected to increasing transverse shortening during the past 10 m.y. At the southern end of the trench, where subduction has not yet started, the Puysegur Ridge has a narrow (<50 km) steep-sided cross section, and the axial strike-slip fault separates a shallow (125–625 m), flat-topped eastern crest from a deeper (400–1600 m) western crest; these characteristics indicate differential uplift during the initial stage of shortening. On the lower plate an incipient, 5.2-km-deep trench developed in conjunction with normal and reverse faults, suggesting strong interplate coupling across the trench. Northward, the ridge broadens linearly to 80 km wide, its western flank has locally collapsed, and the ridge summit has subsided, possibly by 1.5 km, suggesting that the interplate coupling decreases and that a Benioff zone is being formed. Concomitant to the northward ridge evolution, the trench deepens to 6.2 km and normal fault throws increase along its outer wall, indicating greater flexure of the downgoing plate.

INTRODUCTION

The mechanisms that govern the initiation and development of subduction are not well understood, in part because of a lack of morphostructural observations. The Macquarie Ridge complex, part of the Pacific-Australian intraoceanic plate boundary south of New Zealand (Fig. 1), was interpreted by Ruff et al. (1989) as a possible incipient subduction zone propagating south along a transform plate boundary in conjunction with the southwestward migration of the Pacific-Australian rotation pole since about 10 m.y. (Walcott, 1984).

The northern segment of the Macquarie Ridge complex, between lat 51°S and 47°S, is the 3–5-km-high Puysegur Ridge, flanked to the west by the 6-km-deep Puysegur Trench and to the east by the sedimented 3.5-km-deep Solander Trough (Summerhayes, 1967; Van der Linden and Hayes, 1972). In this region, the NUVEL-1 model predicts a 3.2–3.5 cm/yr relative plate motion trending N52°–59°E, oblique to the N15°–20° trending trench (De Mets et al., 1990). According to Ruff et al. (1989), the oblique convergence at 49°–50°S is accommodated by a dual-rupture mode of relatively small (4.5 < M < 5.1) thrust earthquakes on shallowly dipping faults followed by a greater (M > 7) strike-slip earthquake on a subvertical fault.

We acquired multibeam bathymetry (Fig. 1), side-scan sonar imagery, and seismic reflection and geopotential data during the Geodynz-sud cruise of the R.V. *L'Atalante* along the Puysegur Ridge, Puysegur Trench, and adjacent Australian plate between 49°45′ and 47°S. This cruise was designed to investigate the structure and dynamics of this immature subduction margin.

MORPHOSTRUCTURE OF THE AUSTRALIAN PLATE AND PUYSEGUR TRENCH

The sea floor of the Australian plate shows a complex primary oceanic fabric with a structural grain that rotates from N120°E in the southern part of the survey area to N60°E in the north. Near 49°S, this pattern is cut perpendicularly by a ridge that trends N20°–30°E, which we interpret as a fracture zone (l'Atalante fracture zone; Fig. 2). Similar fractures zones may have played a significant role in the development of the plate boundary.

Extension related to flexure of the plate as it descends into the trench has affected the Australian plate within 10 km of the trench. Trench-parallel normal faults developed north of 49°15′S. The throws increase and the trench deepens from 5250 to 6250 m to the north, indicating that the plate flexure also increases to the north.

Reverse faults with small throws appear to deform the Australian sea floor as far as 65 km west of the trench near 47°S, indicating that primary oceanic structures were recently reactivated by shortening. Near 48°30′–49°S, reverse faults may indicate transpression along a trench-parallel zone, suggesting relatively strong interplate coupling.

MORPHOSTRUCTURE OF THE PUYSEGUR RIDGE

The Puysegur Ridge widens and deepens from south to north. It can be divided near lat 48°30′S into a linear, N30°E-trending southern half, with a subsymmetrical cross section, and a more complex, asymmetrical, N15°E-trending northern half. The southern half widens from less than 50 km to more than 75 km wide and is sheared along its summit by a sharply localized fault zone. The northern half is 80 km wide and shows a complex set of northward-diverging faults. We first discuss the data from the ridge apex that are critical to locating the strike-slip fault zone and to understanding the nature of the ridge basement. We then examine the ridge flanks, which show structural features relevant to the development of the subduction zone.

Puysegur Ridge Summit

The summit of the Puysegur Ridge, between 48°40′ and 49°40′S, is bisected by a linear, N26°E-trending axial valley, 800–2500 m deep and 2–4 km wide. The valley is 18–30 km east of the trench and separates a massive, 15–20-km-wide, shallow (125–625 m), flat-topped eastern crest from a less developed, 400–1600-m-deep, 2–6-km-wide western crest. Immediately north of 49°S the valley consists of two parallel, narrow troughs that overlap along the strike of the ridge, isolating an axial crest. Both axial and western crests have narrow (2–6 km), 10–25-km-long, stretched tectonic lenses, suggesting strike-slip deformation along a fault zone within the axial valley (Fig. 2). North of 48°S, this fault zone shifts farther from the trench and splits into a fan-shaped set of locally sinuous faults, ridges, and troughs

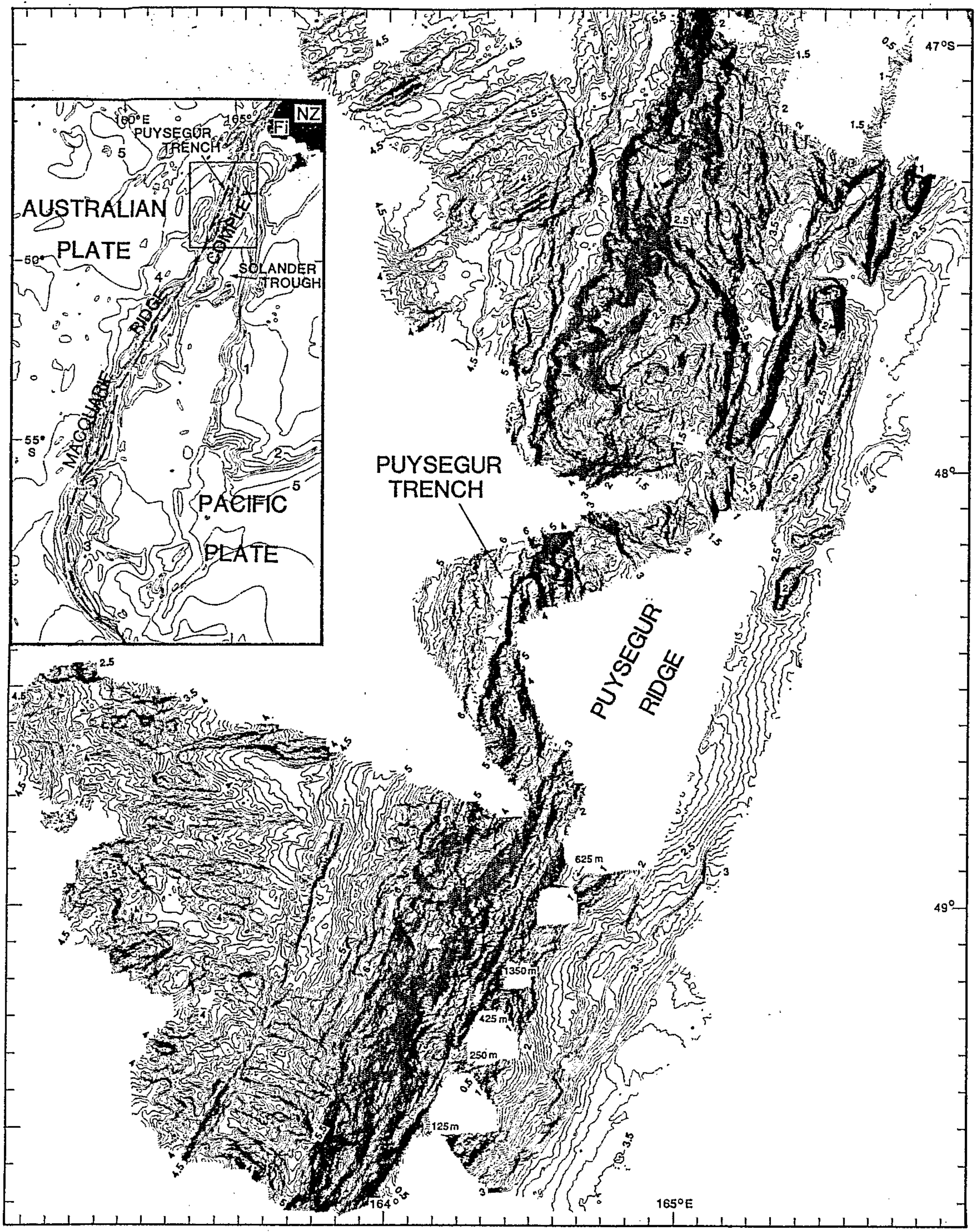

Figure 1. Multibeam bathymetric map of Puysegur Ridge and Trench; bathymetric contour interval is 50 m. Inset: Location of study area along Macquarie Ridge complex; NZ—New Zealand; Fi—Fiordland.

trending N20°E to N40°W. The single valley is replaced by a series of 3250–3800-m-deep, structurally controlled axial troughs that split the northern termination of the Puysegur Ridge into two flat-topped, 1750–2000-m-deep eastern ridges and a western sigmoidal-shaped 2000-m-deep plateau. Reverse and normal faults along the axial troughs in combination with the sinuous nature of the fault traces and the ridge and trough morphology indicate strike-slip deformation.

The flat tops of the eastern crest and ridges suggest wave-base erosion. Northward deepening of the flat-topped ridges indicate that a large (possibly up to 1500 m) subsidence of the Puysegur Ridge summit followed its uplift.

Sidescan sonar and geopotential data indicate that the ridge comprises oceanic crust. Highly reflective horizontal surfaces are probably associated with basement outcrops. Large (500–1000 nT) peak-to-peak amplitude magnetic anomalies over the ridge crests reveal shallow magnetic sources of igneous origin, and 140–235 mgal gravity anomalies may indicate uncompensated volcanic and ophiolitic rocks such as those seen on Macquarie Island (Varne and Rubenach, 1972).

Puysegur Ridge Flanks

The flanks of the Puysegur Ridge have different morphologies, which change northward as the ridge broadens. The west flank of the southern half of the ridge has a linear and steep (12°) slope cut by N150°–160°E

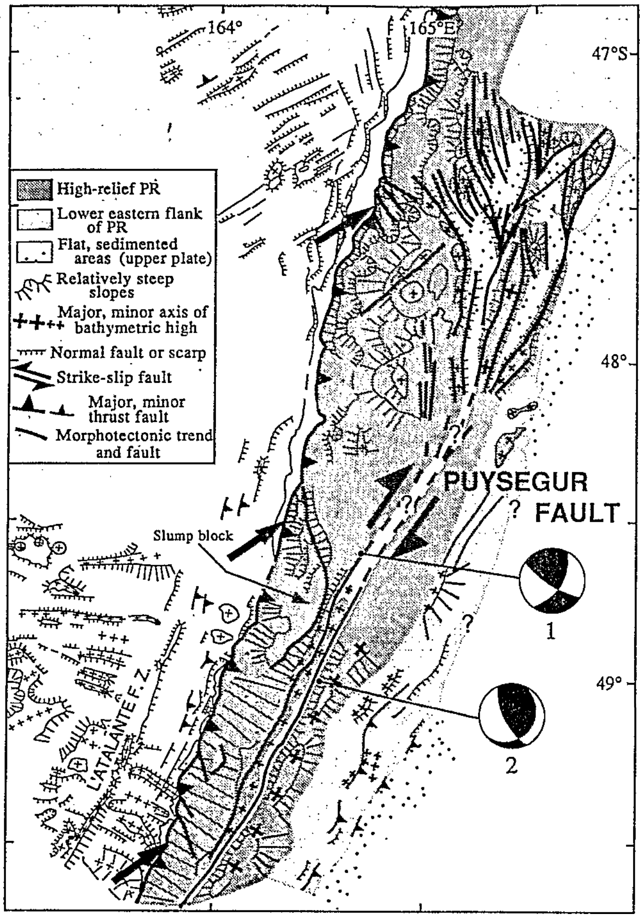

Figure 2. Structural interpretation of Puysegur Ridge (PR) and Trench. Large arrows are relative plate motion vectors (De Mets et al., 1990). Focal mechanisms for 7.6 magnitude, May 25, 1981, earthquake (1) and 6.9 magnitude, September 12, 1964, earthquake (2) (Ruff et al., 1989; Anderson, 1990) are shown.

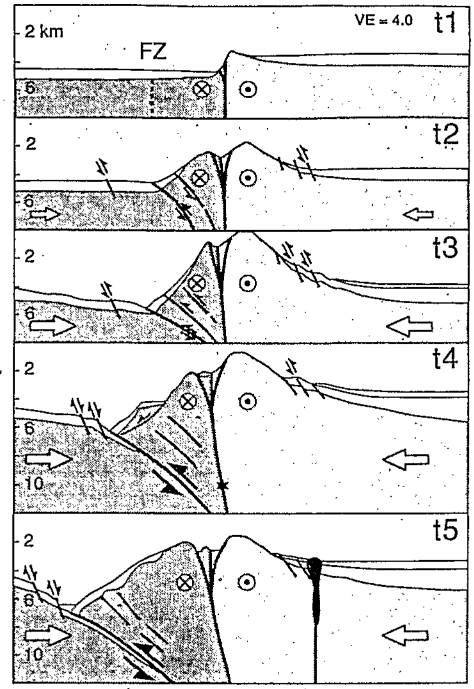

Figure 3. Schematic diagram showing stages of development of incipient subduction along strike-slip ridge (see text for explanation). White arrows indicate horizontal compressive stress. Crossed circle denotes motion away from viewer. Dotted circle denotes motion toward viewer. Star in t4 is May 25, 1981, earthquake.

trending lineaments that appear to offset the tectonic front left-laterally. Some of the offsets coincide geographically with the eastern termination of small, N120°E trending oceanic ridges on the Australian plate, showing that these ridges have collided obliquely with the Puysegur Ridge lower slope and have affected structures on the inner trench wall. On seismic reflection lines, coherent reflections extending eastward from the trench beneath the Puysegur Ridge lower slope for about 10 km suggest underthrusting of oceanic strata. Slope failures south of 49°S that are 10 km wide contrast with a probable large slump block at 48°35′S, a 3500-m-deep terrace bounded to the east by a 70-km-long scarp (Fig. 2). Numerous slump scars indent the steep (15°–20°) and irregular lower slope north of 47°45′S and indicate an increasing degree of mass wasting to the north as the ridge broadens.

The east flank of the southern half of the ridge shows a slope break near 2000 m. The slope break separates a steep (11°) upper slope from a gently dipping (2°–3°) lower slope. The lower slope is underlain by stratified sediments of the Solander Trough that are tilted eastward and deformed by folding and west-verging reverse faults. The faults are associated with 10–25-km-long, asymmetric sea-floor bumps, attesting to recent tectonic activity. The attitude of the strata and the reverse faults shows that the eastern ridge flank has been uplifted recently by compression. Along the northern half of the ridge, the east flank is underlain by faulted, east-dipping sediment and shows magnetic ridges and seamounts with a highly reflective sea floor, suggesting igneous intrusions along faults.

DISCUSSION

According to Christoffel and Van der Linden (1972) and Smith and Davey (1984), the earthquake pattern from the Puysegur Ridge to beneath Fiordland can be interpreted as oblique subduction of the Australian plate, from near-zero subduction at 50°–51°S to a 150-km-deep, 80°SE dipping Benioff zone beneath Fiordland. A sole Quaternary andesitic volcano near 46°30′S is associated with this subduction (Reay, 1986). Earthquakes south of 47°S substantiate east-northeastward underthrusting and trench-parallel, strike-slip motion (Ruff et al., 1989; Anderson, 1990), although the existence of a Benioff zone cannot be proven and no volcanic arc is recognized. The data that we present are consistent with two well-constrained earthquake focal mechanisms (1 and 2 in Fig. 2): one is 10 km deep and indicates dextral strike-slip motion along a trench-parallel, subvertical fault beneath the ridge axial valley; the other is 10 ± 5 km deep and shows northeastward oblique slip along a southeastward shallowly dipping thrust.

Our data provide further insight into the structural evolution of the Puysegur Ridge. One possibility, based on earthquake patterns and focal mechanisms, is that the evolution is driven by the northward development of subduction along a strike-slip plate boundary. On the basis of morphostructural data, a simple model of subduction initiation can be proposed (Fig. 3).

The initial stage is a strike-slip fault zone (t1 in Fig. 3). We think that the plate boundary developed preferentially along a preexisting fracture zone similar in direction to the L'Atalante fracture zone. Many oceanic fracture zones show a 1–4-km-high ridge formed by crustal uplift along the fracture valley. Bonatti (1978) showed that compression is the major factor of the ridge formation. We suggest that the ridge at 49°–50°S formed by compression (t2 in Fig. 3).

However, the primary linear aspect of the ridge indicates that the ridge development has been influenced by the axial strike-slip motion. Thus, shearing and thermal uplift of oceanic crust along the strike-slip zone may also have contributed to the ridge development. The 1 km vertical offset across the ridge-trench system indicates that lithospheres of different density are in contact along the ridge. Moreover, subduction likely began beneath Fiordland, where oceanic crust abutted continental crust, and therefore where the density contrast was greatest. According to Matsumoto and Tomoda (1983), this density contrast could potentially generate a new subduction zone over a period of several tens of millions of years. The subduction development was likely accelerated when the plate boundary was subjected to increasing transverse shortening during the southward migration of the Pacific-Australian pole of rotation.

The development of subduction requires a progressive adjustment of the strike-slip plate boundary. This adjustment involved the development of the ridge by internal thrusting, differential uplift of the crustal blocks located on either side of the vertical fault (t2, t3 in Fig. 3), and transpressive deformation and downwarping of the oceanic plate at the toe of the deeper crustal block to form an incipient trench. These adjustments, consistent with the high, shallow seismicity near the southern end of the Puysegur Ridge, may have been facilitated by development of reverse faults along a fracture zone at the trench location, as shown by analogue plate models of Shemenda (1992). Although thrust faults are not seismically imaged beneath the ridge western flank, the reverse faults along its eastern flank attest that compressive stress is transmitted across the ridge.

Subsequent to initiation of shortening, the ridge eventually emerged, as indicated by its flat top (t3 in Fig. 3). As shortening increased, the trenchward slope of the ridge tended to oversteepen and collapse (t4 in Fig. 3). Additional deformation stemmed from oblique collision between the ridge and oceanic features, contributing to the seaward migration of the tectonic front. These processes appear to contribute to the asymmetric development of the ridge. We suggest that when the thrust rupture areas increase and coalesce to form an incipient Benioff zone, more elastic stress is released and the ridge subsides and collapses trenchward (t4 in Fig. 3). This collapse may contribute to transverse extension and trigger the intrusion of subduction-related magma on the faulted landward flank of the ridge, as indicated by the volcanic ridges and seamounts near 48°S. Subcrustal tectonic erosion associated with interplate thrust rupture would also contribute to ridge subsidence. At this stage of underthrusting, mass wasting and possibly subcrustal erosion shaped the trenchward slope of the ridge into a generally convex cross section (t5 in Fig. 3).

CONCLUSIONS

Subduction and strike-slip deformation occur synchronously along the Puysegur Ridge plate boundary, but they are geographically distinct. Morphologic, seismologic, and kinematic data, however, indicate that the subduction is immature and is currently propagating southward at the southern tip of the ridge where the trench and strike-slip fault may coalesce. The northward morphostructural evolution of the ridge-trench system reflects more advanced underthrusting of the Australian plate. We propose that the plate boundary formed along an oceanic fracture zone. As shortening began, a ridge formed by internal thrusting and differential uplift of the crustal blocks located on either side of the strike-slip fault zone; as shortening increased, the eastern block rose above sea level, the seaward flank of the ridge steepened and collapsed, and the landward flank developed by reverse faulting. Synchronously, an incipient trench formed at the flexure of the Australian plate where the outer trench wall was subject to transpressive deformation. Subsequent subsidence and broadening of the ridge may reflect formation of a shallow Benioff zone and loosening of the interplate coupling. The ridge cross section then became asymmetric, with a convex-seaward flank and a landward flank dominantly affected by faulting and probably minor volcanism.

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