Subduction initiation at a strike-slip plate boundary: The cenozoic Pacific-Australian plate boundary, South of New Zealand

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[1] We first present a synthesis of the Macquarie Ridge Complex (MRC) tectonic structures as well as paleo-reconstruction models of the kinematic evolution of the Pacific-Australia plate boundary south of New Zealand, since the Eocene. We then ascertain the geodynamical conditions that preceded subduction initiation, and identify the nature and structures of the crust that first subducted, at the Puysegur subduction zone. This synthesis is used to produce a subduction initiation model for the Puysegur Region. Concomitant to inception of the Alpine Fault (ca. 23 Ma), a 150-km-wide transpressive relay zone developed along Puysegur Bank inherited structures, enabling localization of compressive deformation. Right-lateral motion at the relay zone has juxtaposed oceanic and continental crusts facilitating inception of subduction and controlling the subduction vergence. Subsequently, the Puysegur subduction zone initiated at the transpressive relay zone ca. 20 Ma. Upper and lower plate inherited structures guided and facilitated the lengthening of the subduction zone during the Neogene. The four individual segments of the MRC represent different stages of incipient subduction whose development depends on local geodynamical conditions and lithospheric heterogeneities. The example of the MRC demonstrates that subduction can initiate from an oceanic spreading center, through progressive changes in plate kinematics within a 10–15 Myr time frame. *INDEX TERMS:* 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 8155 Tectonophysics: Plate motions—general; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* subduction initiation, Pacific, Australia, plate motion, Cenezoic, Macquarie Ridge

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1. Introduction

[2] Subduction initiation is a major plate tectonic process that is yet to be fully understood. The geodynamical environment where subduction initiates, as well as lithospheric heterogeneities along which it occurs, have strong implications in the subsequent evolution of subduction processes. In particular, they control the subduction vergence and define whether the subduction will initiate as either intraoceanic or subcontinental.

[3] Initiating subduction requires rupture of the lithosphere. The rupture implies that compressive stress reaches the yield limit of the lithosphere. However, tectonic forces are weak compared with typical homogeneous lithosphere strengths [e.g., *McKenzie*, 1977; *Shemenda*, 1994]. Subduction initiation within a fractured lithosphere has been controversial [*Cloetingh et al.*, 1989; *Mueller and Phillips*, 1991], but recent mathematical models indicate that a subduction zone can develop along a preexisting dipping fault zone with ridge push forces alone [*Toth and Gurnis*, 1998]. A strongly favorable geodynamical environment for subduction initiation is the proximity of a nearby active subduction zone, in which case the overriding plate is already thermally and/or tectonically weakened. Consequently, tectonic stresses can be considerable, particularly following congestion of the subduction zone by underthrusting of buoyant material, or slab break [*Mueller and Phillips*, 1991; *Shemenda*, 1994]. Although subduction initiations are expected to take place along volcanic arcs, or within back arc

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basins, other zones of lithospheric weakness (in particular, passive margins, fracture zones, and transform faults) away from active subduction zones, cannot be discarded as favorable locations for subduction initiation to take place [*Mueller and Phillips*, 1991; *Toth and Gurnis*, 1998].

[4] South of New Zealand, between 43°S and 62°S, the dextral transpressive Pacific-Australia plate boundary runs along the intracontinental Alpine Fault (ca. 400 km long), the Fiordland-Puysegur oblique subduction zone (ca. 600 km long), and the intraoceanic Macquarie Ridge Complex (MRC) (ca. 1600 km long) (Figure 1). The MRC shows a variety of structural deformation style, which may be indicative of distinctive stages of subduction initiation [*Collot et al.*, 1995; *Hayes*, 1972; *Ruff et al.*, 1989] (Table 1).

[5] In this paper, we first synthesize the results from previous research (Table 2), from which we draw a comprehensive structural map of the Pacific-Australia plate boundary over the transition from the MRC to the Alpine Fault between South Island and 50°S (Figure 2) (see *Massell et al.* [2000] for the area south of 50°S). We then generate kinematic reconstruction models at key stages of the plate boundary history, in order to constrain its spatial and temporal tectonic evolution since the Eocene. Previous workers described the global kinematic evolution of the Pacific-Australia plate boundary south of New Zealand [e.g., *Kamp*, 1986a; *King*, 2000; *Molnar et al.*, 1975; *Sutherland*, 1995; *Walcott*, 1978; *Weissel et al.*, 1977] and the change from the Cenozoic Southeast Tasman-Emerald Basins (SETEB) spreading center into the present strike-slip plate boundary [*Lamarche et al.*, 1997; *Massell et al.*, 2000]. However, the mechanisms that controlled the evolution of the plate boundary at the transition between the SETEB spreading center and the New Zealand fault systems, together with the plate boundary evolution toward subduction, are yet to be understood. Our reconstruction models take into account the detailed structural evolution of SETEB and MRC, particularly in the Puysegur-Fiordland area. These models provide new constraints on the structures of the subducted lithosphere, and allow us to identify inherited structures that played a key role in the initiation of the Puysegur subduction. Finally, we discuss the geodynamical conditions that led to the initiation of subduction at the Puysegur-Fiordland subduction zone, and compare physical modeling of subduction initiation with the observed evolution of the MRC.

2. Tectonic Synthesis

[6] The study area divides into the New Zealand continental domain and the Pacific and Australian oceanic domains (Figures 1 and 2). The Australian oceanic domain includes the Eocene-Miocene southeast Tasman Basin and the Cretaceous-Paleocene Tasman Basin (Ano. 33 (74–79 Ma) to 24 (52–53 Ma) [*Cande and Kent*, 1992; *Weissel and Hayes*, 1977]), located south and north of the Resolution Ridge System (RRS), respectively. The Pacific oceanic domain includes the Eocene-Miocene Emerald Basin and Solander Trough. North of the Solander Trough lies the continental Solander, Waiau, and Te Anau basins. Southward, the Emerald Basin opens into the southwest Pacific Basin, where oceanic spreading has occurred since Cretaceous time [*Cande et al.*, 1995; *Molnar et al.*, 1975; *Weissel et al.*, 1977]. The southeast Tasman and Emerald basins are conjugated basins formed at a spreading center that separated the Pacific from the Australia Plate during the Eocene-Miocene time [*Lamarche et al.*, 1997; *Molnar et al.*, 1975; *Sutherland*, 1995; *Weissel et al.*, 1977]. We provide a review on the tectonic evolution, ages, and amount of displacement observed along the plate boundary (Table 3).

2.1. Transpressive MRC-Southeast Tasman and Emerald Basins (SETEB)

[7] The MRC consists of four ridges, named from north to south the Puysegur, McDougall, Macquarie, and Hjort ridges, southward. The ridges are 80–100 km wide and rise to 6500 m above the surrounding seafloor. Transpressive deformation concentrates within a nearly continuous 5–10 km wide fault zone extending along the ridge crest. Diffuse transpressive deformation is restricted to the ridge flanks, and saddles corresponding to step over basins mark the transition between ridges [*Massell et al.*, 2000]. The fault names relate with each ridge, i.e., the Hjort, Macquarie, McDougall, and Puysegur Faults.

[8] Curved fracture zones and oceanic spreading fabric observed in SETEB are identified from satellite altimetry and seafloor imaging [*Lamarche et al.*, 1997; *Massell et al.*, 2000; *Sutherland*, 1995] (Figures 1 and 2). Away from the MRC, fracture zones trend perpendicular to the SETEB margins, i.e., the Campbell Plateau margin to the east and RRS to the West. The curved shape of the fracture zones originates from the clockwise rotation of the spreading centers, in response to a progressive change of the orientation of the Pacific-Australia plate motion vector [*Lamarche et al.*, 1997; *Massell et al.*, 2000]. Coalescing fracture zones also indicate that individual spreading segments were shortened through time and eventually disappeared ca. 12 Myr ago [*Ducan and Varne*, 1988; *Lamarche et al.*, 1997] (Table 3), giving place to transcurrent motion along the MRC. This scenario implies that the MRC coincides with the relict SETEB spreading center. SETEB rifting propagated from the Southeast Indian Ridge northward into the New Zealand continent during late Eocene times, while the subsequent cessation of spreading first occurred to the north, and propagated southward [*Lamarche et al.*, 1997; *Massell et al.*, 2000].

2.2. Puysegur Subduction

[9] Between Resolution Ridge and 48°S, the subduction front is identified along the 5500-m-deep Puysegur Trench with no subduction-related tectonic accretion. Rather, the inner trench wall shows evidence of mass wasting. North of 47°30′S, seismic data revealed inner trench wall imbricated structures interpreted as past accretion [*Lamarche and Lebrun*, 2000; *Melhuish et al.*, 1999]. The lithosphere that entered subduction at Puysegur Trench has been translated northeastward beneath Fiordland owing to the 60° obliquity of the plate motion [*Davey and Smith*, 1983]. Inception of the Puysegur subduction is estimated to occur at ca. 10 Ma [*Davey and Smith*, 1983], an age we will reconsider in this paper (Tables 1 and 3).

[10] South of 48°S, the Puysegur Trench reaches a maximum depth of 6250 m and then shallows southward. Most of the deformation is concentrated along the Puysegur Fault at the ridge summit [*Collot et al.*, 1995] (Table 1). The Puysegur Subduction zone evolves southward along

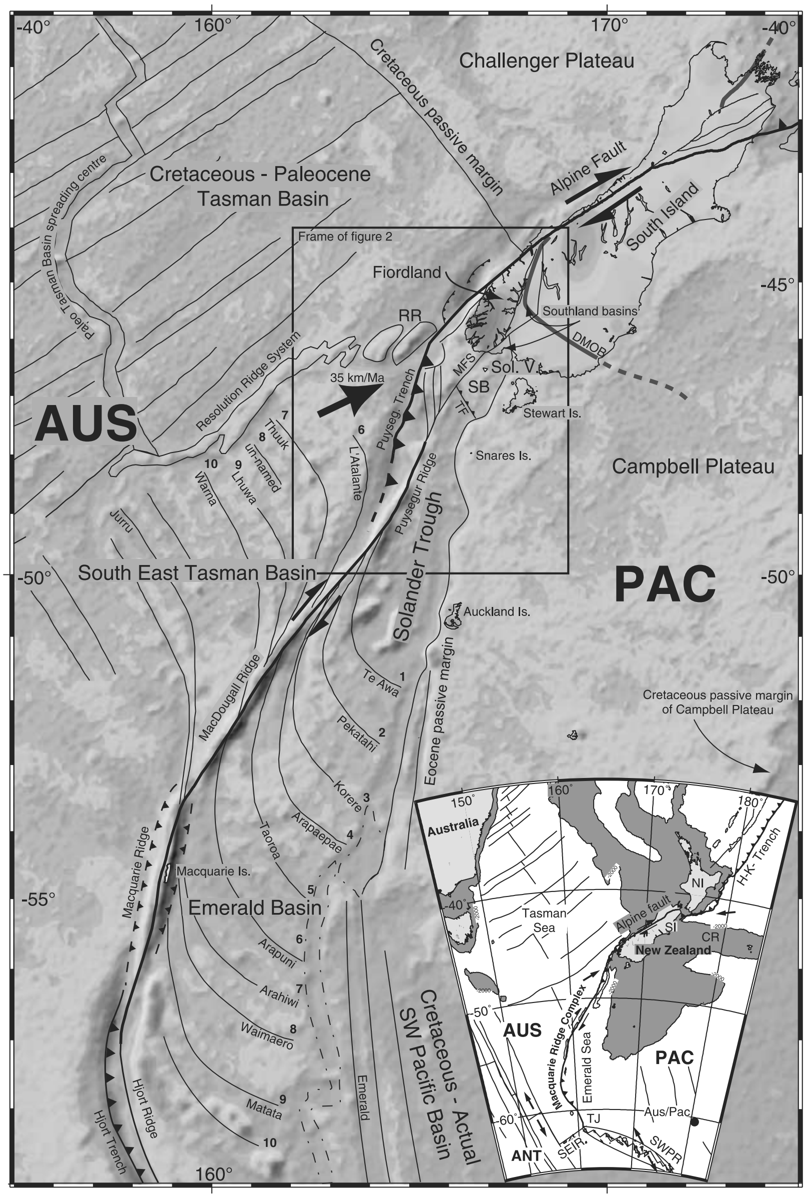

Figure 1. Global gravity anomalies (FAA) [*Sandwell and Smith*, 1997] and basin structures south of New Zealand. Numbers along fracture zones help to recognize conjugate fracture zone on either side of the plate boundary. Solander Trough corresponds to the basin limited southward by the Te Awa fracture zone and northward by the Tauru Fault. Very thick black line represents the Pacific-Australia plate boundary. Black lines represent other active structures. Thick continuous and dashed gray lines represent the Dun Mountain ophiolite belt and the offshore-associated magnetic anomaly, respectively. Thin lines represent inactive or secondary structures. Thin dot-dash line indicates the position of RRS prior to rifting of SETEB, as can be seen on gravity data [*Sutherland*, 1995]. Frame indicates location of Figure 2. DMOB, Dun Mountain ophiolite belt; MFS, Moonlight Fault System; RR, Resolution Ridge; SB, Solander Basin; Sol. V. Solander Volcano (Island size not at scale for better legibility); TF, Tauru Fault. Mercator projection. Insert: Location map. Large dot labeled “Aus/Pac” represents Nuvel 1A Australia relative to Pacific fixed pole of rotation [*DeMets et al.*, 1994]. Rotation occurs clockwise at 1.1°/Myr. Undersea landmasses are gray shaded. Thick lines represent plate boundaries, thin lines represent major fracture zones, the 2000-m bathymetric contour is indicated. ANT, Antarctic Plate; AUS, Australian plate; CR, Chatham Rise; H-K, Hikurangi-Kermadec Trench; NI, North Island; PAC, Pacific Plate; TJ, Aus-Pac-Antarctic Triple Junction; SEIR, Southeast Indian Ridge; SI South Island; SWPR, Southwest Pacific Ridge. See color version of this figure at back of this issue.

Table 1. Summary of Published Arguments Leading to Classification of Segments of the MRC Into Incipient or Mature Subduction Zone

Area	Published Arguments Showing Typical Subduction Characteristics	Arguments Showing That Subduction is Not Yet Developed or Lacks Some Typical Characteristic	Subduction Development Stage, Vergence and Geodyn. Context
Fiordland	sedimentary accretion in the trench [*Barnes et al.*, 2002; *Delteil et al.*, 1996b; *Lebrun et al.*, 2000]	margin deformation dominated by strike-slip deformation [*Barnes et al.*, 2001; *Lebrun et al.*, 2000]	incipient: mature stage
	150-km-deep Benioff Zone beneath Fiordland but entered subduction at Puysegur [*Anderson and Webb*, 1994; *Smith and Davey*, 1984; *Smith*, 1971]	little plate motion accommodated by the trench thrusts (<10 km to 15–30% of the plate motion) [*Barnes et al.*, 2002]	undercontinental
	earthquake data show plate motion partitioning [*Moore et al.*, 2000; *Reyners and Webb*, 2002]		Aus. beneath Pac.
N. Puysegur	imaged interplate décollement [*Melhuish et al.*, 1999]	lack of well-developed volcanic arc	mature subduction stage
	the Benioff Zone extends to northern Puysegur and is shaped like an inverted ploughshare [*Christoffel and Van Der Linden*, 1972]		
	Adakitic Solander volcano (inactive) located ca. 150 km landward [*Reay*, 1986; *Reay and Parkinson*, 1997; *Turnbull and Uruski*, 1993]		undercontinental
S. Puysegur	shallow earthquakes with both oblique thrust and strike-slip focal mechanisms [*Moore et al.*, 2000; *Ruff et al.*, 1989]	trench shallows and extends into a fracture zone southward [*Delteil et al.*, 1996a; *Massell et al.*, 2000]	early stage of incipient subduction
		limited oblique motion along a poorly developed subduction front [*Collot et al.*, 1995]	intraoceanic Aus. beneath Pac.
McDougall	diffuse shortening and crustal tilting [*Massell et al.*, 2000]	no past or present thrusting [*Massell et al.*, 2000]	transpressive ridge
			intraoceanic Pac. beneath Aus.?
Macquarie	crustal thickening [*Williamson et al.*, 1989]	earthquake focal mechanisms do not indicate active shortening [*Frohlich et al.*, 1997]	incipient stage but stopped
	thrust faults on either sides of the ridge [*Massell et al.*, 2000]		intraoceanic
	few kilometers of missing oceanic crust east of the ridge [*Massell et al.*, 2000]		Pac. beneath Aus. more developed
Hjort	geoid short wavelength anomalies and paired ridge/trench topography [*Ruff and Cazenave*, 1985; *Ruff et al.*, 1989]	no Benioff Zone	incipient stage probably ongoing
	magnetic anomalies adjoining the trench shorter than their counterpart [*Weissel et al.*, 1977]	lack of large thrust event [*Frohlich et al.*, 1997]	
	plate motion obliquity at Hjort trench = obliquity at Puysegur trench [*DeMets et al.*, 1994; *Massell et al.*, 2000]	no identified subduction-related volcanoes except alignment of seamounts at 120–140 km east from the trench (not sampled yet) (Figure 1)	intraoceanic
	identified strike-slip deformation at the ridge and compressive structures in the trench [*Bernardel et al.*, 2000]		Aus. beneath Pac.

Puysegur Trench from a mature stage north of 48°S to an incipient stage south of ca. 49°S [*Collot et al.*, 1995]. South of 50°S the deformation front continues as a fracture zone that eventually merges with the strike-slip plate boundary at McDougall Ridge (Figure 2). This suggests that the development and southward propagation of the subduction front is guided along a fracture zone that trends parallel to the ridge [*Collot et al.*, 1995; *Massell et al.*, 2000].

2.3. Puysegur Fault-Subduction Transition

[11] At ca. 48°S, the Puysegur Fault splays northward into a distributed zone of faulting that terminates against the Puysegur Trench [*Delteil et al.*, 1996a; *Lamarche and

Table 2. List of the Main Marine Geophysical Surveys Along the Pacific-Australia Plate Boundary South of New Zealand

Date	Ship-Cruise	Covered Area	Main Data	Reference
1966–1972	RV *Eltanin*	all MRC	global geoph. survey: core samples	*Hayes* [1972]
Early 1970s	petroleum companies	South Fiordland and Solander	seismic (drilling) mag. gravi.	Open files, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand
1974	DSDP Leg 29	south and north of Emerald Sea	drilling: holes 278 and 279	*Kennett et al.* [1974]
1993	RV *Lavrentiev*-Geodynz	W Fiordland-Puysegur	seismic	*Wood et al.* [1996]
1993	RV *L'Atalante*-Geodynz	W Fiordland-Puysegur	detail geoph. mapping	*Delteil et al.* [1996a]
1994	RV *Rig Seismic*-cruise 124	McDougall-Macquarie	detail geoph. mapping	*Coffin et al.* [1994]
1996	RV *Maurice Ewing*-cruise 9601	W Fiordland-Puysegur Bank	deep seismic	*Melhuish et al.* [1999]
1995–1996–1997	*Maurice Ewing*-cruise 9516 RVIB *R. Palmer*-cruises 9602 9702	Emerald and Southeast Tasman Sea	detail geoph. mapping	*Cande et al.* [1998]
1997	R/V *Tangaroa*	W Fiordland	seismic: cores	*Barnes et al.* [2001]
1990s	HMNZS Monowai	Puysegur Bank	single beam bathymetry	
1998	R/V *L'Atalante*-Austrea 2	Hjort	detail geoph. mapping	*Bernardel et al.* [2000]

Lebrun, 2000] (Figure 2). This zone separates Puysegur Ridge from Puysegur Bank, a shallow plateau that extends south of Fiordland massif. The fault zone geometry resembles a horsetail pattern and includes four major faults (from southwest to northeast): the Snares Faults; and the West, Central, and East Balleny Faults [*Lamarche and Lebrun*, 2000; *Melhuish et al.*, 1999]. These faults played distinctive tectonic roles in accommodating the transition from the Puysegur Fault to the Puysegur subduction zone.

[12] The Snares and West Balleny Faults trend north, obliquely to the N20°E Puysegur Trench, and show clear morphological expressions of active mature wrench faults with dextral motion. They form a transfer fault zone linking Puysegur Fault and Puysegur Trench [*Lamarche and Lebrun*, 2000]. Thrust-earthquake focal mechanisms reveal that slip vectors beneath Puysegur Bank are parallel to the predicted NUVEL1A plate motion vector [*Anderson et al.*, 1993; *Moore et al.*, 2000]. This illustrates that if motion partitioning occurs at the Puysegur Bank, it is restricted to the shallow levels of the upper plate edge [*Moore et al.*, 2000]. Consequently, relative plate motion accommodated at Puysegur Trench increases north of the Snares and West Balleny Faults.

[13] On Puysegur Bank, the Central Balleny Fault is marked by an alignment of morphologic scarps contrasting with the East Balleny Fault, which is partly buried by Miocene sediments [*Lamarche and Lebrun*, 2000; *Turnbull and Uruski*, 1993] (Table 3). These two faults appear subvertical on seismic profiles [*Melhuish et al.*, 1999; *Turnbull and Uruski*, 1993; *Wood et al.*, 1996] and trend at high angle with the offshore extension of the Alpine Fault on map view. A morphological scar in the inner trench wall (Figure 2) masks the relationships between the Central and East Balleny Faults, and the offshore extension of the Alpine Fault. Seismic stratigraphy and structural interpretations indicate that the Balleny Faults were initiated during the upper Oligocene-lower Miocene [*Turnbull and Uruski*, 1993]. They are interpreted as a transpressive relay between the Puysegur and Alpine faults [*Lamarche and Lebrun*, 2000] (Table 3).

[14] The location of the continent-ocean boundary south of Puysegur Bank remains speculative. From samples of MORB-like basalt, *Mortimer* [1995] inferred that the bank southern flank has an oceanic nature. However, these samples were all collected along the Snares and West Balleny wrench fault zones, suggesting that they may have been recovered from rock slivers transported from the Puysegur Ridge and are therefore not representative of Puysegur Bank nature (Figure 2). Seismic reflection data show buried Cretaceous and early Oligocene horst and graben structures beneath Puysegur Bank that extend southward from Fiordland [*Turnbull and Uruski*, 1993]. The Moho progressively rises from ca. 30 km beneath Stewart Island to ca. 20 km beneath the Puysegur Bank [*Melhuish et al.*, 1999] (Figure 2). These facts suggest that Puysegur Bank is continental and support the hypothesis of a continent-ocean boundary along the Balleny Faults.

2.4. Southland Basins and the Moonlight Fault System

[15] The Te Anau, Waiau, and Solander basins (collectively named Southland basins) are three inverted, northeast-southwest grabens, all fault bounded and located between Fiordland-Puysegur Bank and eastern margin of South Island and Stewart Island (Figure 2) [*Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993; *Sutherland and Melhuish*, 2000; *Turnbull and Uruski*, 1993]. The three basins are arranged in a right stepping en-échellon pattern along the Moonlight Fault System (MFS), which controlled their development during the Cenozoic (Figure 2). To the south, the Tauru Fault, which is a major lithospheric NNW-SSE fault, dips 30°ENE [*Sutherland and Melhuish*, 2000] and separates the continental Solander Basin from the oceanic Solander Trough. This fault does not extend west of the MFS onto Puysegur Bank. The MFS connects with the Alpine and Puysegur Faults to the north and south, respectively, so that Fiordland and Puysegur Bank define a sigmoidal faulted continental terranes between the Southland basins to the east, and the Alpine Fault and the Puysegur subduction front to the West [*Claypool et al.*, 2002; *Lamarche and Lebrun*, 2000].

[16] The MFS was part of the plate boundary prior to the Alpine Fault and Puysegur subduction initiation. Structural and stratigraphic studies [*Norris and Turnbull*, 1993; *Sutherland and Melhuish*, 2000; *Turnbull and Uruski*, 1993] showed that rifting was initiated in the Southland basins during the Eocene. During the Oligocene, transten-

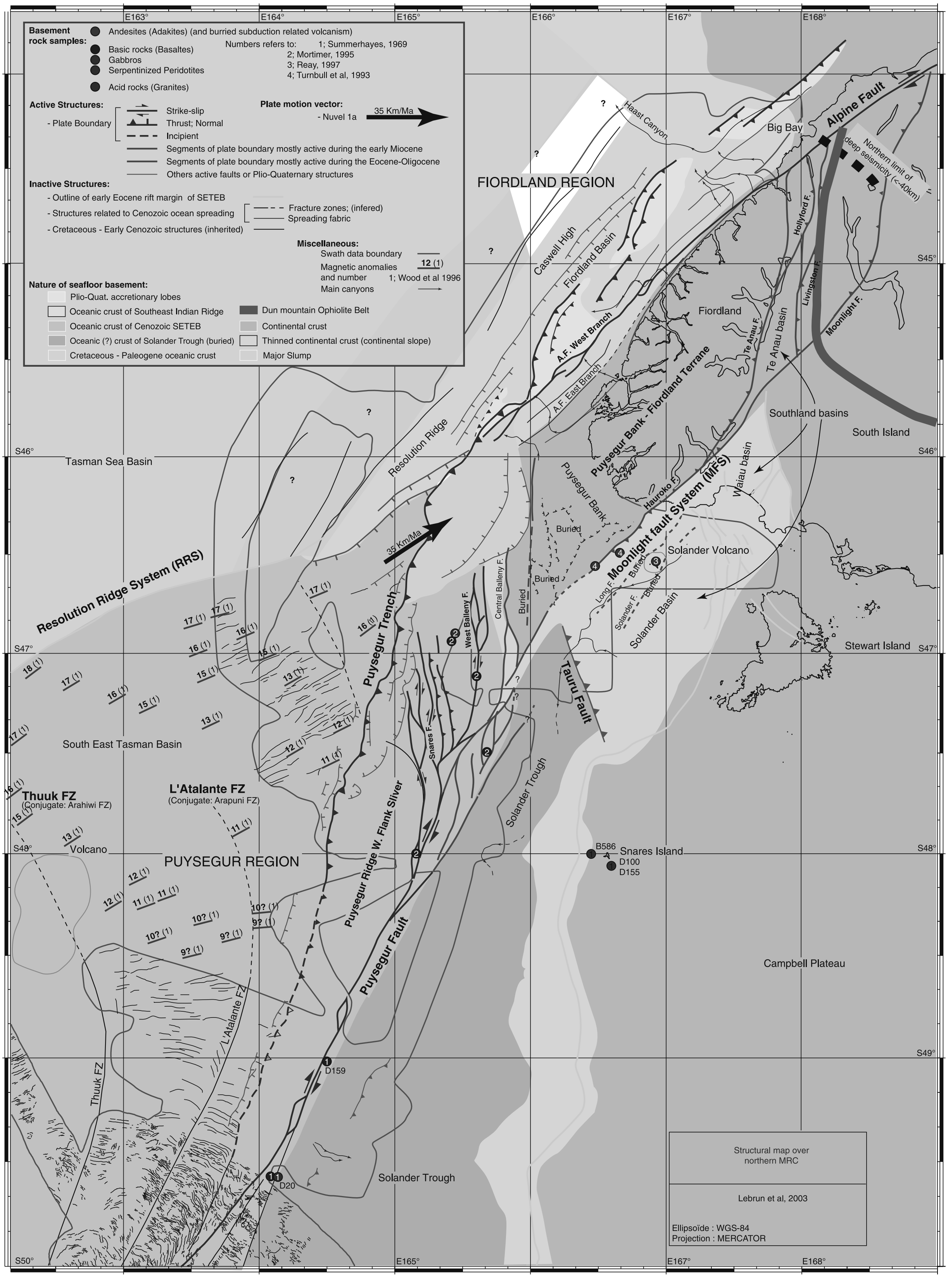

Figure 2. Tectonic map of the Puysegur-Fiordland Margin (northern Macquarie Ridge Complex), representing the area covered during the Geodynz-Sud survey, between 50°S and 44°S. Map characteristics on map caption. This plate complements the available structural map by *Massell et al.* [2000] for the region south of 50°S. See color version of this figure at back of this issue.

Table 3. Synthesis of the Tectonics Accommodated by the Major Structures in the Puysegur Fiordland and Southern South Island[a]

Structure Name	Inception	Cessation	Total Displacement	Tectonic Significance
SETEB	Ano. 18 (40.2–38.5 Ma) [*Cande and Kent*, 1992; *Weissel et al.*, 1977; *Wood et al.*, 1996]	9.7–11.5 Ma; MORB at Macquarie Island [*Ducan and Varne*, 1988]		oceanic spreading center
	45 Ma; best fit closure [*Sutherland*, 1995]	ca. 12 Ma; extrapolation of magnetic ano: [*Lamarche et al.*, 1997]		
Snares Faults		active	dextral	transfer fault zone between Puysegur Fault and Puysegur Trench
West Balleny Fault	upper Oligocene-lower Miocene; seismic-stratigraphy and structural interpretations [*Lamarche and Lebrun*, 2000; *Turnbull and Uruski*, 1993]	active	dextral	idem
Central Balleny Fault	idem	still active, probably secondary	dextral	transpressive relay between Puysegur Fault and Alpine Fault
East Balleny Fault	idem	buried by Miocene sediments [*Turnbull and Uruski*, 1993]	dextral	idem
MFS	Eocene: extensive		extension: Solander, 50–100 km; crustal stretching [*Sutherland and Melhuish*, 2000]; southwest South Island, ca. 10 km (estimation) [*Norris and Turnbull*, 1993].	Eocene: rifting
	Oligocene: transtensive to pure strike slip		lateral: dextral $-20 < x > 60-70$ km? [*King*, 2000; *Norris and Turnbull*, 1993; *Walcott*, 1998]	Oligocene: plate boundary.
	Miocene-quaternary: transpressive		shortening: Solander, 5–20 km; seismic profiles; up to 30 km north east of Fiordland [*Norris and Turnbull*, 1993; *Sutherland and Melhuish*, 2000; *Turnbull and Uruski*, 1993; *Walcott*, 1998]	early Mio.-present: coexists with Alpine Fault but secondary in terms of total amount of plate motion accommodated
	present day: compressive			
Alpine Fault	late Oligocene-early Miocene: offset DMO [*Adams and Cooper*, 1996; *Carter and Norris*, 1976; *Cooper et al.*, 1987; *Kamp*, 1986b].	active	lateral: dextral, 460 km; offset basement rocks [*Wellman*, 1953]	transform plate boundary
	Eocene: including bending of DMO [*Sutherland*, 1999].		ca. 800 km including bending of DMO [e.g., *Sutherland*, 1999].	
	shortening: ca. 12 Ma acquired mostly during the last 6.4 Ma (Southern Alps) [*Walcott*, 1998]		shortening:<70 km (south) to >110 km (north). [e.g., *Walcott*, 1998]	
Fiordland lobes	Pliocene-Quaternary [*Barnes et al.*, 2002]	active	shortening: >5.9 to <10.9 km [*Barnes et al.*, 2002]	subduction front

[a]DMO, Dun Mountain Ophiolite; MFS, Moonlight Fault System; MORB, mid-oceanic Ridge Basalts; SETEB, southeast Tasman and Emerald Basins.

sional tectonics progressively developed into strike-slip deformation. The MFS accommodated most of the Oligocene deformation in southern South Island. Subsequent to inception of the Alpine Fault in early Miocene times (Table 3), compressive tectonics inverted the Southland Basins with the peak of compression during the late Miocene. Tectonic deformation continued through Pliocene and Quaternary times with a decrease in strike-slip activity.

[17] *Lamarche and Lebrun* [2000] suggest a genetic link between the Puysegur Fault and the MFS, although the present-day continuity between the two fault zones is not clearly established [*Sutherland and Melhuish*, 2000]. The Puysegur Fault-MFS systems may have been continuous and active prior to the formation of the Puysegur-Balleny Faults, and seismic activity along the MFS indicates that some strike-slip motion is still presently transferred from the Puysegur Fault to the MFS [*Anderson et al.*, 1993]. However, geodetic measurements in Southland show dominant active compression suggesting that the strike-slip activity decreases northward [*Moore et al.*, 2000; *Pearson*, 1992; *Walcott*, 1978, 1984]. These observations demonstrate that most of the present-day lateral plate motion is transferred west of Fiordland through the Snares-Balleny Faults.

2.5. Alpine Fault-Puysegur Trench Transition

[18] The Alpine Fault is the most conspicuous structural feature in South Island, and regionally is best described as a N55°E linear dextral transpressive transform fault [*Berryman et al.*, 1992; *Wellman*, 1953]. South of Milford Sound, at ca. 44°30′S, the Alpine Fault extends offshore along the Fiordland coastline. At ca. 45°S (Figure 2), the fault runs obliquely through the margin and joins Puysegur Trench at the northeastern tip of Resolution Ridge (Figure 2) [*Barnes et al.*, 2002; *Lebrun et al.*, 2000]. The Fiordland Basin is characterized by late Pliocene-Quaternary accretionary lobes [*Barnes et al.*, 2002; *Delteil et al.*, 1996b] (Table 3 and Figure 2). Earthquake focal mechanisms suggest some plate motion partitioning between thrusts and the offshore extension of the Alpine Fault [*Anderson et al.*, 1993; *Barnes et al.*, 2002; *Delteil et al.*, 1996b; *Moore et al.*, 2000; *Reyners and Webb*, 2002]. The 10 km of estimated shortening at the Fiordland trench represents less than 15–30% of the total shortening accommodated across the plate boundary since the late Pliocene, whereas the offshore Alpine Fault accommodates all lateral plate motion [*Barnes et al.*, 2001, 2002].

[19] Resolution Ridge is a continental fragment of the Campbell Plateau carried on the Australian Plate during the formation of SETEB [*Christoffel and Van Der Linden*, 1972; *Sutherland*, 1995] (Figure 2). The crust underlying the Fiordland Basin is inferred to be thinned continental in origin, with the oceanic crust of the Tasman Sea being further to the west of Caswell High [*Wood et al.*, 2000] (Figure 2). To the east, the crust obliquely subducted beneath the Fiordland Massif is that of the oceanic Southeast Tasman Basin. Therefore the RRS represents the Eocene passive margin between western New Zealand-Tasman Sea and SETEB. *Lebrun et al.* [1997] and *Sutherland et al.* [2000] suggested that the development of the Alpine Fault was controlled by Eocene inherited rift structures carried by the downgoing Australian plate. *Lebrun et al.* [2000] suggest that the offshore Alpine Fault coincides with a lithospheric scale structure within the Australian plate that enables the abrupt transition from the Puysegur subduction to the Alpine strike-slip fault. This is supported by three-dimensional flexural modeling across the Fiordland Margin, which requires a zone of mechanical decoupling within the subducted slab to explain the topography and the gravity anomalies [*Furlong et al.*, 2001; *Malservisi*, 2002]. An alternative model from *Reyners and Webb* [2002], suggests that the transition from very oblique subduction to oblique continental collision along the Alpine Fault is spatially distributed and that the offshore Alpine Fault is an entirely upper plate structure whose development is the result of the plate motion partitioning.

[20] The Benioff zone reaches 150 km deep beneath Fiordland. The deep seismicity (>40 km) does not extend further north than 44°20′S at the latitude of Big Bay (Figure 2) [*Anderson and Webb*, 1994; *Eberhart Phillips and Reyners*, 2001; *Reyners et al.*, 2002; *Smith*, 1971]. Earthquake studies show that the slab changes orientation at 45°20′S, striking N23°E to the south and N40°E to the north. It is noteworthy that the slab is unusually steep in the trench-parallel direction, particularly north of 45°20′S where it is vertical below 50 km within 60 km of the Fiordland Basin. The unusual shape of the slab is interpreted as a consequence of the obliquely converging subducted plate having to bend around a high-velocity zone located immediately to the east, in the Pacific Plate mantle [*Eberhart Phillips and Reyners*, 2001; *Reyners et al.*, 2002].

2.6. MRC-Alpine Fault Transition

[21] The transition between the intraoceanic MRC and the intracontinental Alpine Fault occurs through a 150-km-wide left step between the Alpine and Puysegur Faults. The step results in a complex zone of deformation extending from 50°S to 44°S. Our kinematic reconstructions (next section) demonstrate that the Puysegur subduction has developed along this plate boundary as a left stepping system. The western flank of Puysegur Ridge forms an exotic oceanic block tectonically bounded by the Puysegur Fault and Puysegur Trench to the east and west, respectively, and therefore is best described as an oceanic terrane. It is separated from Puysegur Bank to the northeast by the Balleny Faults. The kinematic reconstructions illustrate the development of the plate boundary until formation of Fiordland-Puysegur Bank continental terrane, inception of the Puysegur subduction zone, and formation of the Puysegur oceanic terrane.

3. Plate Kinematic Reconstruction

[22] All kinematic reconstructions were carried out in the Pacific Plate frame of reference, i.e., with the plate in its present-day position (Figures 3a–3h). The part of the South Island located on the Australian Plate (i.e., west of the present-day Alpine Fault), as well as Challenger Plateau, Resolution Ridge, and Caswell High, are rotated with the Australian Plate, regardless of any Cenozoic deformation that could have occurred in northwest South Island. These characteristic topographic elements are used to constrain the position of other structural features without any assumptions on paleogeography. We calculated the finite rotations from stage poles given by *Sutherland* [1995]. *King* [2000]

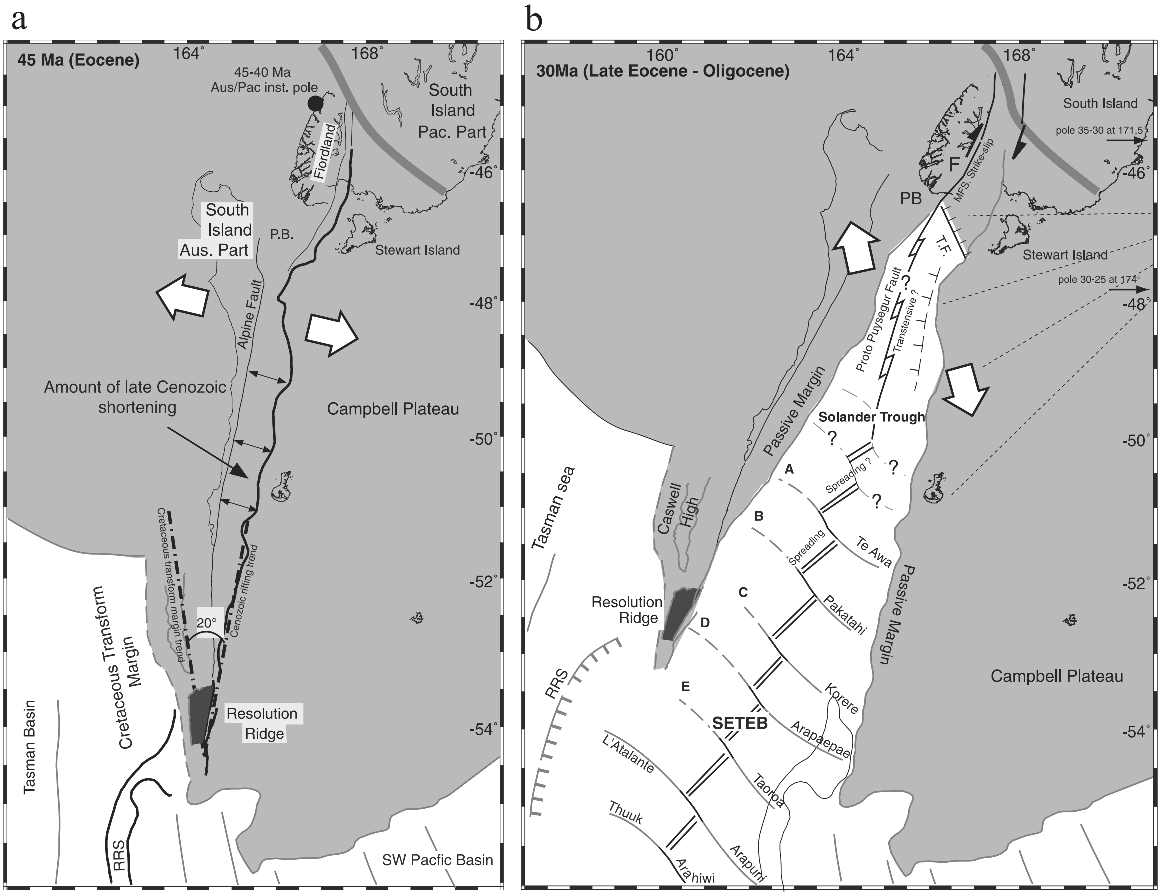

Figure 3. Kinematic reconstruction of the southern Pacific-Australia plate boundary at 45, 30 Ma and by steps of ca. 5 Myr until present. In this reconstruction, spreading centers (doubled black line) in SETEB are located between adjacent fracture zone about halfway between basin margins. Spreading centers point toward a stage pole located halfway between the pole representing the rotation for 5 Myr before the time of reconstruction (e.g., the 35–30 Myr instantaneous pole of rotation for the 30-Ma reconstruction) and the pole representing the rotation for 5 Myr after the time of reconstruction (e.g., the 30–25 Myr pole for the 30-Ma reconstruction). Thin dash lines point toward this position. Large white arrows show the average direction of relative plate motion for 5 Myr following time of reconstruction as they are perpendicular to the great circle that points toward the instantaneous pole of rotation for this period. Except for the best fit reconstruction, poles of rotation plot SE of the frame of the figure. Their latitude is indicated by an arrow, and a label gives their exact position. Thick black lines represent active structures at the time of reconstruction (plate boundary). Gray lines represent inherited structures (inactive). Tick lines represent normal faults, teeth lines are reverse faults. Lines with diamond are transpressive faults. Structures with question marks in the Solander Trough are hypothetical (see text). The very thick gray line shows the shape of the Dun Mountain Ophiolite Belt [from *Sutherland*, 1999]. Thick dashed gray lines in SETEB, labeled "A" to "E" are flow lines calculated to represent the Australian part of fracture zones observed on the Pacific Plate side. The thick dashed black line represents the present-day trace of the Puysegur Trench on the Australian plate. PB, Puysegur Bank; BF, Balleny Faults; F, Fiordland; MFS, Moonlight Fault System; RRS Resolution Ridge System; SV, Solander Volcano; TF, Tauru Fault. (a) Kinematic reconstruction at 45 Ma (Eocene). The angle between the Cretaceous transform margin and the Eocene rift direction is indicated by thick dot-dashed black lines. Double side arrows indicate amount of crust underthrusted beneath the Southern Alps since late Miocene. Labeled black dot is the Pacific-Australia instantaneous 45–40 Ma pole of rotation. (b) Kinematic reconstruction at 30 Ma (late Eocene-Oligocene). (c) Kinematic reconstruction at 25 Ma (Oligo-Miocene transition). (d) Kinematic reconstruction at 20.2 Ma (early Miocene). Dark shaded area represents the unfolded aseismic subducted crust (see text). Thick dash line shows the position of the present-day Puysegur Trench. (e) Kinematic reconstruction at 15 Ma (mid-Miocene). (f) Kinematic reconstruction at 11 Ma (late Miocene). (g) Kinematic reconstruction at 5 Ma (Mio-Pliocene transition). (h) Present-day situation. Thin frame shows location of Figure 4.

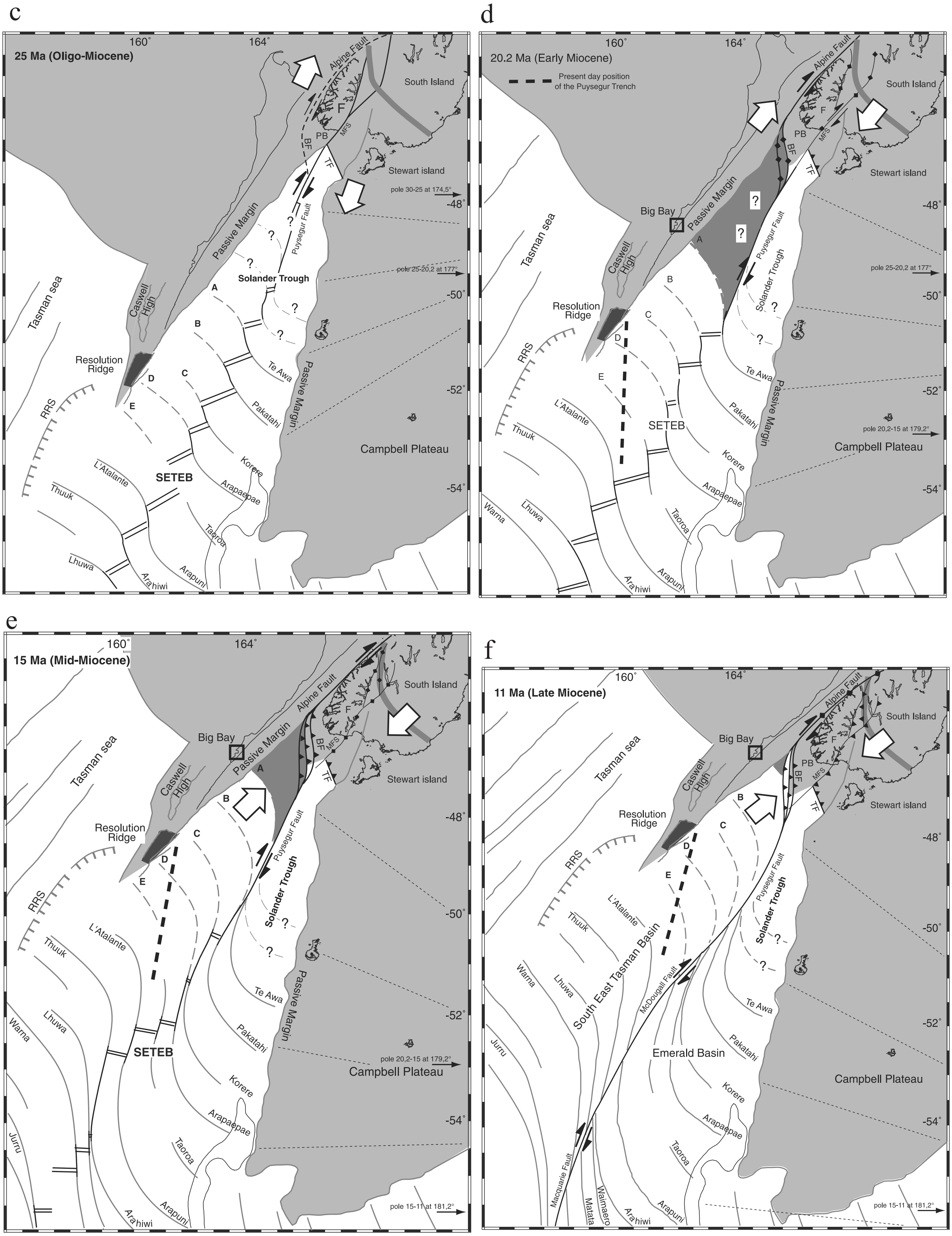

Figure 3. (continued)

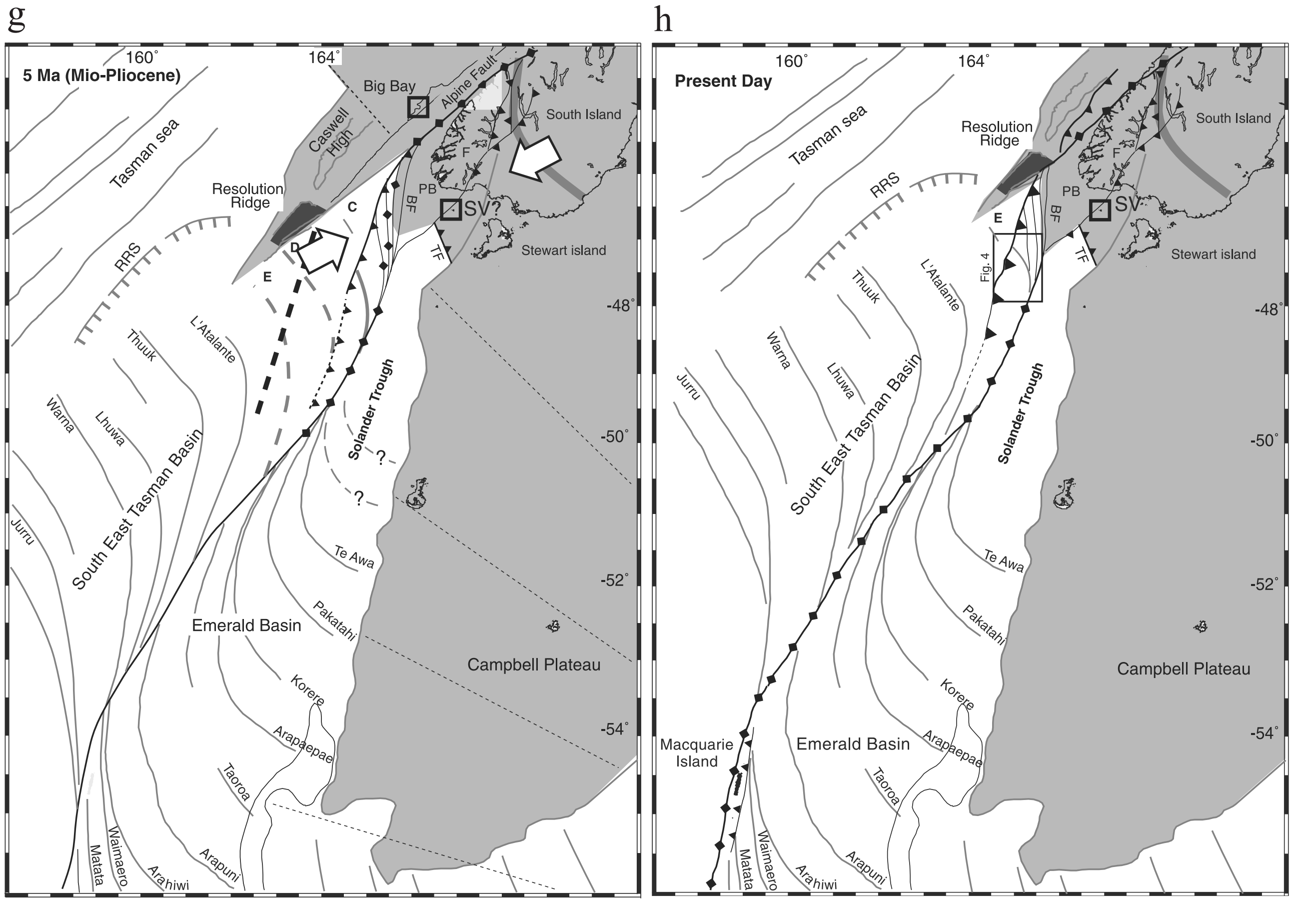

Figure 3. (continued)

provided details on timing of tectonic events along the plate boundary in New Zealand based on sedimentary evolution of inland basins. South of New Zealand, dating of structures is too incomplete to properly constrain absolute timing, while results obtained inland [*King*, 2000] cannot be extrapolated southward because of rapid lateral variations in tectonic events along the plate boundary. Therefore we adopted a 5 Ma interval between stages for our kinematic reconstructions.

3.1. Best Fit Rotation: Eocene (45 Ma) (Figure 3a)

[23] The best fit rotation enables reconstruction of New Zealand continent prior to Pacific-Australia plate boundary initiation; all structures of SETEB were removed. The Australian Plate portion of the South Island, Challenger plateau, and RRS, were restored against the Campbell Plateau western margin, so that Tasman Sea and the Southwest Pacific Basin adjoin. This reconstruction defines the general trend of the western SETEB passive margin that is presently thrusted beneath the Southern Alps. We propose a best fit position of Fiordland-Puysegur Bank along the northern Campbell Plateau Margin at the latitude of Stewart Island.

[24] Motion of the Fiordland-Puysegur Bank terrane was independent from that of the neighboring plates. Fiordland best fit position is poorly constrained and previous publications did not take into account Puysegur Bank [e.g., *King*, 2000]. Thus unrealistic overlaps appeared along the margin when Puysegur Bank was included in the reconstructions. In our best fit rotation, we translated Fiordland-Puysegur Bank ca. 40 km southward along the MFS, a value that is consistent with lateral displacement estimated along fault systems in southern New Zealand (Table 3), and we rotated the terrane ca. 20° counterclockwise. This resulted in a good fit between the Campbell plateau margin at Stewart Island and the Fiordland-Puysegur Bank eastern margin along MFS, and avoided overlap between the Australian portion of the South Island and Puysegur Bank.

3.2. Ocean Spreading: Late Eocene-Oligocene (30 Ma) (Figure 3b)

[25] During late Eocene-Oligocene times, the Pacific-Australia pole of instantaneous rotation migrated southeastward but remained close to the northern part of SETEB, resulting in oceanic spreading in SETEB and strike-slip motion along the MFS. *Massell et al.* [2000] mapped and named all fracture zones in SETEB (Figure 1), and *Lamarche et al.* [1997] described the organization of spreading centers and fracture zones in southern SETEB. These authors suggested a transition to strike-slip tectonics northward. However, conjugate fracture zones i.e., originating from the same transform fault, have not been identified across the MRC. Such identification is required to properly reconstruct crustal structures of the subducted part of SETEB. In the 30 Ma reconstruction, we rotated Fiordland together with the Australian Plate over a distance of ca. 100 km northward along the MFS in agreement with structural data [*Sutherland and Melhuish*, 2000]. By doing so we assume that no motion occurred west of Fiordland.

[26] The plate kinematic reconstruction at 30 Ma allows the alignment of all Australian plate fracture zones with their conjugates on the Pacific Plate (identified with equal numbers on Figure 1). In this model, the L'Atalante Fracture zone, which is the northernmost fracture zone on the Australian plate, is the conjugate of the Arapuni fracture zone (Pac). From our model, we identified five fracture zones north of Arapuni fracture zone in the Emerald Basin (Pac) with no matching conjugates on the Australian Plate (see also on Figure 1). We infer that the "missing fracture zones" developed on the piece of oceanic crust that has since subducted beneath Fiordland. Their locations on the Australian plate, labeled A to E in Figure 3b were extrapolated from the five Pacific Plate fracture zones. No fracture zone has been identified in Solander Trough (Figures 1 and 2). *Sutherland and Melhuish* [2000] suggested that seafloor spreading probably occurred up to the latitude of the Tauru Fault at 48°S. Our model shows that small circles around the instantaneous pole of rotation became subparallel to the plate boundary ca. 30 Ma.

[27] This geodynamic setting is comparable to that of the present northern Gulf of California. The most striking resemblance with northern SETEB 30 Myr ago is the succession of short segments of spreading centers separated by long transform fault segments. The obliquely opening Gulf of California extends northward into a transtensive fault zone with pull-apart basins in southern California, eventually connecting with the San Andreas Fault [e.g., *Wallace*, 1990]. We suggest that a similar transition existed 30 Myr ago between the strike-slip MFS along the Southland basins western margin and the northernmost spreading ridge in SETEB. We propose that the transtensive fault zone represents the proto-Puysegur Fault.

3.3. Plate Boundary Reorganization: The Oligo-Miocene Transition (25 Ma) (Figure 3c)

[28] The Oligocene-Miocene transition is a key period as it marks a major reorganization of the plate boundary in southern New Zealand. At this time, transcurrent motion initiated west of Fiordland along the Alpine Fault. The Balleny Faults on the Puysegur Bank developed as a transpressive relay zone between the Puysegur and Alpine faults [*Lamarche and Lebrun*, 2000] and isolated the Fiordland-Puysegur Bank terrane from neighboring plates. Oceanic spreading was still active in SETEB, but plate motion became more and more oblique to the plate boundary regional trend. Strike-slip motion may have initiated in the north along the Puysegur Fault. Spreading progressively ceased and strike-slip motion propagated southward, resulting in lengthening of the Puysegur Fault. We placed Fiordland 30 km southwest of its present-day position in agreement with geological data indicating ca. 20–30 km of strike-slip motion along MFS since the Miocene [*Norris and Carter*, 1980; *Norris and Turnbull*, 1993; *Uruski*, 1992].

[29] The 25-Ma reconstruction model shows that the Balleny Faults developed across the Southeast Tasman Basin passive margin in the vicinity and approximately parallel to the NNW-SSE trending Tauru Fault. Furthermore, *Sutherland and Melhuish* [2000] demonstrated that the Tauru Fault developed along inherited Mesozoic structures. Such NNW-SSE trending structures exist beneath Puysegur Bank immediately north of the Balleny Fault (Figure 2). We believe that a deep, shallowly dipping, lithospheric structure similar to the Tauru Fault played a significant role in localizing the deformation along the Balleny relay.

3.4. Presubduction Stage: Early Miocene (20.2 Ma) (Figure 3d)

[30] By the early Miocene, ca. 20 Myr ago, the Pacific-Australia relative plate motion became subparallel to the trend of the SETEB passive margin. Lateral motion at the Balleny Faults zone had progressively aligned the passive margin with the Alpine Fault. Hence the Alpine Fault started to develop along the margin as it represented a weakness zone in the Australian plate [*Lebrun*, 1997; *Sutherland et al.*, 2000]. At the Balleny relay, oceanic crust was translated against the continental Puysegur Bank. Shortening increased across the MFS, which progressively became a secondary fault system in as much as the majority of the plate motion was transferred along the Alpine Fault. Oceanic spreading was still active in southern SETEB. By the early Miocene, Fiordland-Puysegur Bank was located ca 20 km to the WSW of its present position.

[31] Our model suggests that the Puysegur subduction was initiated at the toe of the Puysegur Bank dissected by the Balleny faults system ca. 20 Myr ago concomitantly with, or immediately following, inception of the Alpine Fault (see also Figure 3e). This timing is about 10 Myr earlier than previous estimates of the age of the subduction initiation [*Davey and Smith*, 1983; *House et al.*, 2002; *Walcott*, 1998]. As the development of the Alpine Fault was controlled by the SETEB passive margin structure, the oceanic lithosphere located east of the passive margin and lying along the Balleny relay zone must have, since, underthrusted the New Zealand continent. When compared to the reconstruction at 15 Ma (Figure 3e), a ca. 200-km-long piece of oceanic crust measured along strike, must have disappeared beneath the Puysegur Bank, so that the lithosphere that first subducted is the conjugate of the Solander Trough lithosphere.

[32] The lithosphere that extended between the Puysegur Bank and the projection of the present-day position of Puysegur Trench on the 20.2-Ma reconstruction stage (Figure 3d) has been subducted. The shape of this slab of oceanic lithosphere was an elongated trapezoid with 100–170 km wide bases and 550–600 km long sides [*Lebrun*, 1997; *Sutherland et al.*, 2000]. This slab represents about twice the area of the Fiordland Benioff zone. The present leading edge of the Benioff zone in the direction of the plate motion (i.e., to the northeast) projects at the latitude of Big Bay (Figure 2). Our 20.2 Ma model shows that fracture zone "A" extends from Big Bay southeastward. This suggests that the present Benioff zone seismicity occurs within oceanic lithosphere located south of fracture zone A. The subducted lithosphere that formed north of fracture zone A must underlie the South Island but is presently aseismic.

3.5. Subduction Stage: Middle Miocene, Present (Figures 3e–3h)

[33] Paleo-reconstructions for the last 20 Myr include four steps ending with the present-day geodynamic setting. Subduction at the toe of the Balleny fault system progres-

sively absorbed the Southeast Tasman lithosphere while the Alpine Fault continued to accommodate lateral motion. With the progressive decrease in plate convergence obliquity, oceanic spreading ceased in SETEB at ca. 10 Ma [*Lamarche et al.*, 1997; *Massell et al.*, 2000] (Figures 3e and 3f). The strike-slip plate boundary propagated southward along transform segments of the MRC, and through extinct spreading centers while transpressive deformation started along the Alpine Fault [*Lamarche et al.*, 1997; *Massell et al.*, 2000; *Walcott*, 1998]. Transpressive motion eventually extended to the entire MRC during the late Miocene-Quaternary period as indicated by the acceleration of the uplift of Fiordland and the Southern Alps at ca. 6.5–10 Ma [*House et al.*, 2002; *Walcott*, 1998] and emergence of the Macquarie Island during the mid-late Pleistocene [e.g., *Massell et al.*, 2000] (Figures 3g and 3h). The Challenger Plateau passive margin migrated northeastward by strike-slip motion, sweeping along the southern end of the Alpine Fault, and eventually moved away from the Fiordland Margin (Figures 3g and 3h). During the last 5 Myr, the thick continental crust of the Challenger Plateau was progressively replaced west of Fiordland by the thin continental crust of Resolution Ridge and other crustal slivers. Subsequently, the Fiordland massif started to overthrust the Fiordland Trench as evidenced by the development of accretionary lobes at the toe of the margin during the Quaternary [*Barnes et al.*, 2002; *Delteil et al.*, 1996b; *Lebrun et al.*, 2000] (Figure 3h).

[34] Sometime during the last 5–10 Ma the subduction front jumped westward from the Balleny Fault system into the present-day Puysegur Trench. This jump probably occurred when a fracture zone approached the trench. Today the Puysegur subduction front development is guided by a fracture zone carried by the Australian Plate [*Collot et al.*, 1995] (Figures 1, 2, and 3g). This process resulted in formation of a terrane by capture of the western flank of the Puysegur Ridge by the Pacific Plate. To the northeast the terrane is separated from a 3500-m-deep Snares Trough and the Snares Fault by a 1500-m-high scarp (Figure 4). The scarp splays off the Puysegur Fault, curves westward, and terminates at the inner trench wall. This curved scarp appears extraneous in the tectonic context of the Puysegur Ridge because the eastern flank of the terrane departs from the general trend of the fault pattern in the area and does not appear to be dissected or offset by any faults (Figure 4). We infer that the northeastern arcuate border of the tectonic sliver formed as a curved fracture zone on the Australian plate. This fracture zone is concave to the west as all others fracture zones in SETEB (Figures 3h and 4) and now lies east of the Puysegur Trench. This substantiates the argument of the formation of an oceanic terrane by the capture of the western flank of the Puysegur Ridge by the Pacific Plate.

4. Discussion

[35] Analyzing the evolution of the plate boundary in the southern New Zealand region and the kinematics prevailing at the MRC during the Cenozoic, provide new insights on the mechanisms of subduction initiation. We first discuss the nature and location of the crust that first entered subduction at the Puysegur Trench, which is presently aseismic. We then analyze the geodynamics that led to the development of an oblique subcontinental subduction zone at a strike-slip plate boundary (Puysegur-Fiordland subduction zone) and compare the evolution of the Fiordland Margin with the evolution of the Balleny Margin. This leads us to discuss the timing of initiation of subduction at the Puysegur-Fiordland subduction zone. Eventually, we analyze the conditions for initiation of intraoceanic subduction elsewhere along the transpressive MRC and propose a model for the development of subduction at a former mid-oceanic spreading center.

4.1. Geodynamical Conditions Prevailing During the Puysegur Subduction Initiation

[36] We identify four geodynamical factors that controlled the initiation of subduction at the Puysegur margin which are (1) The development of the 150-km-wide Balleny transpressive relay zone, which favored the localization of compressive deformation and reactivation of lithospheric faults. This factor determines the nucleation point of the subduction. (2) Lateral tectonic transport along the Balleny relay zone juxtaposed different lithospheres with variable thickness and densities. Crustal thickness and density contrasts, as well as lithospheric heterogeneities contribute to determine the subduction vergence; (3) Favorably oriented lithospheric faults facilitated and guided the propagation of the subduction zone by reducing the compressive forces needed to rupture the lithosphere; and, (4) A progressive increase of the trench-orthogonal compressive component of the relative plate convergence provided additional forces to trigger the subduction, i.e., to rupture the lithosphere along shallow-rising splays at the toe of subvertical strike-slip faults.

[37] Up until now, the present-day location of the aseismic lithosphere that first entered subduction along the Balleny relay zone (and that was transported northeastward beneath Fiordland) has remained an enigma. Our reconstructions identified this crust as the conjugated part of the Cenozoic crust of the Solander Trough (e.g., Figure 3d). *Sutherland et al.* [2000] suggested that this lithosphere remained along western South Island and is now beneath the Southern Alps or that it sank in the mantle and lies beneath the Benioff zone, i.e., at a depth greater than 150 km. Alternatively, we propose that the aseismic lithospheric slab could be detached and underplated beneath the southwestern part of South Island. The high-velocity zone beneath the southern New Zealand that forces the Fiordland slab into its abnormally vertical position, is usually interpreted as the westward dipping lower crustal layers of the continental Pacific Plate [*Eberhart Phillips and Reyners*, 2001; *Reyners*, 1995; *Reyners et al.*, 2002; *Waschbusch et al.*, 1998]. We suggest that part of the high-velocity zone could represent an underplated piece of the Australian lithosphere. We calculated that at the latitude of the Solander Trough the spreading center was very slow with rates lower than 5 km/Ma. Very slow (<5 mm/yr) spreading centers such as the slowest segments in the mid-Atlantic Ocean, or those that gave birth to the Ligurian Thetys ocean [*Ricou et al.*, 1985] created abnormal crusts. Such a crust is characterized by the absence or very thin gabbro and/or basalt layers overlying a serpentinized peridotitic mantle that widely crops out at the seafloor [*Lagabrielle and Cannat*, 1990; *Lagabrielle and Lemoine*, 1997]. This was probably the nature of the crust that first entered subduction

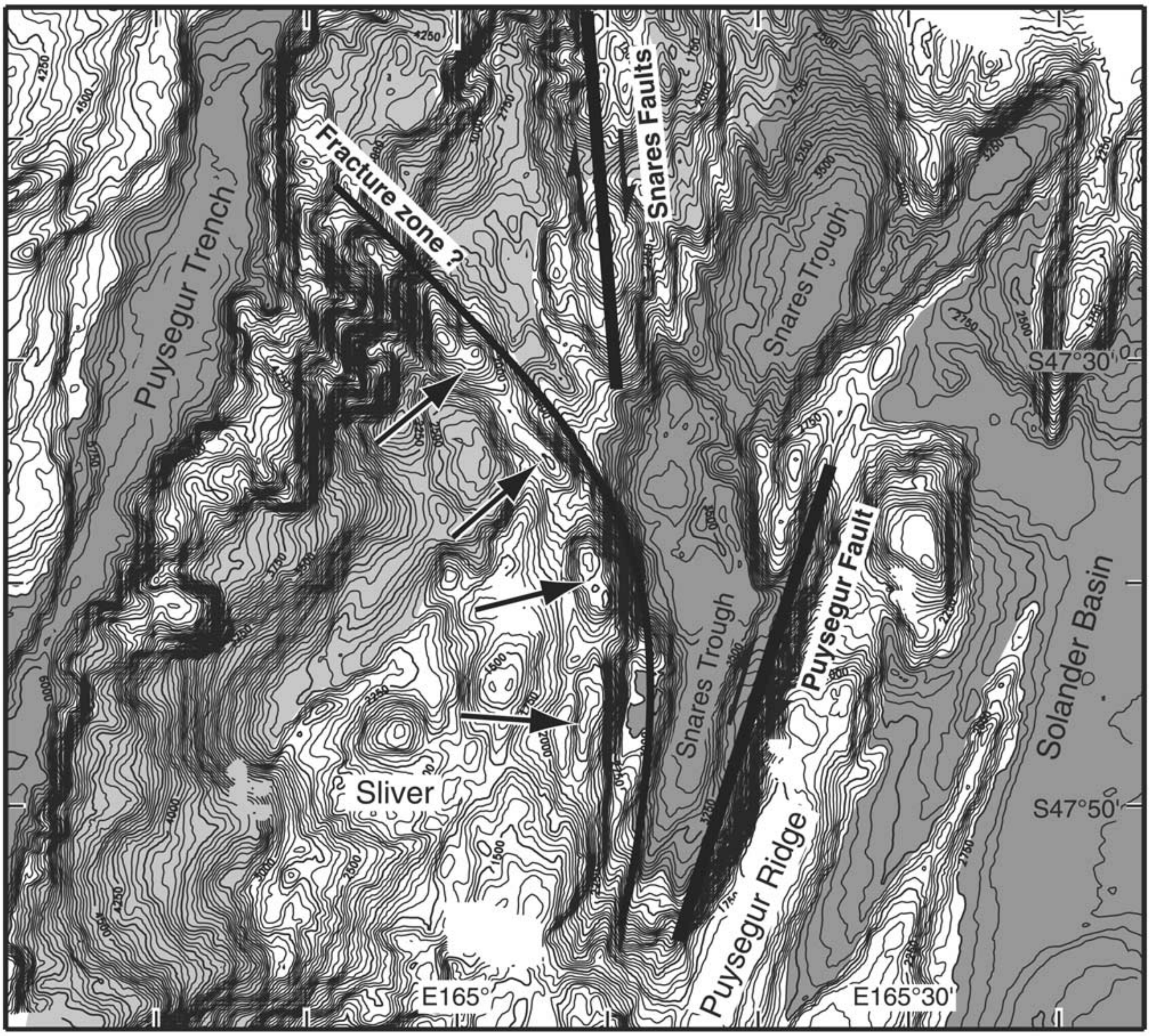

Figure 4. Bathymetry of the northern Puysegur Ridge. Location on Figure 3h. Arrows show the piece of fracture zone captured from the Australian plate on the Pacific Plate. Dark gray shading represents very low reflective seafloor of conformable sediments. Light gray represents irregular reflective seafloor composed of imbricated sediments. White areas are very reflective seafloor of basement outcrop or steep scarps. Seismic reflection data over the sliver, at ca. 47°30 show highly reflective basement with some imbricated sediments at the toe of the trench wall [*Lamarche and Lebrun*, 2000]. The nature of the sliver seafloor contrasts with the thick sedimentary (up to 3s TWT) imbricated structures observed from the trench to the top of the margin immediately north of the sliver [*Melhuish et al.*, 1999].

at Puysegur Trench. The difference in nature (continental versus oceanic as well as thickness) between the seismic and the aseismic subducted lithosphere can be responsible for their different behaviors with regard to the mechanisms of the subduction.

4.2. Fiordland Margin as a Modern Analogue to the Oligo-Miocene Balleny Relay

[38] The geodynamic setting and evolution of the Fiordland Margin during the last 5–10 Ma are comparable to the situation that prevailed during the early and mid-Miocene along the margin segment that contained the Balleny relay zone. Both margins juxtaposed thick Australian plate continental crusts when transpression was initiated (Figures 3c and 3f). Subsequently, in the wake of the thick continental crusts that migrated laterally, thin continental/oceanic crusts were transported against the Fiordland and Balleny margins (Figures 3d and 3f). Eventually, oblique convergence resulted in thrusting of the Pacific Plate continental margin over the thin continental/oceanic crusts. The tectonic evolution of the Fiordland Margin shows that transpression led to the development of a positive flower structure at the

offshore Alpine Fault with very shallow rising fault splays on the ocean side of the strike-slip fault [*Barnes et al.*, 2002; *Lebrun et al.*, 2000]. Earthquake slip-vector distribution [*Reyners and Webb*, 2002] indicates that some plate motion partitioning is occurring and that the shape of the plate interface from the Benioff zone to the frontal thrust is relatively smooth [*Barnes et al.*, 2002; *Reyners and Webb*, 2002]. However, the alignment of the SETEB passive margin with the offshore Alpine Fault demonstrates that the lower plate structures that controlled the Alpine Fault development since ca 25 Ma are not yet overthrusted by the Fiordland Margin. This shows that the strike-slip Alpine Fault remains the dominant plate interface. Providing that convergence persists, thrust structures should develop at the expense of the strike-slip faults that will become trapped on the upper plate.

[39] Timing of the development of the subduction at southwestern New Zealand differs by at least 10 Myr between the Fiordland and the Balleny margins. *House et al.* [2002] dated inception of the Fiordland Margin surrection at 10 Ma. They demonstrated that surrection started first in southern Fiordland and 5 Myr later in northern Fiordland. This result agrees well with the timing of the clearance of the Fiordland Margin by the Challenger Plateau passive margin. At the Balleny relay, sedimentary records over the Puysegur Bank show that surrection was initiated at the Oligo-Miocene transition [*Lamarche and Lebrun*, 2000; *Turnbull and Uruski*, 1993]. Thus we conclude that uplift at the Puysegur Bank relates to subduction initiation at the Puysegur Trench ~20 Ma ago, and that inception of convergence at the Fiordland Margin started ca. 10 Ma later.

4.3. MRC is a Natural Example of an Incipient, Thousands of Kilometers Long Subduction, at a Former Spreading Center

[40] Initiation of large intraoceanic subduction zones, such as the Tonga-Kermadec or Marianna trenches has often been related to tectonic inversion at extinct spreading centers [e.g., *Hawkins*, 1994; *Jolivet et al.*, 1989]. However, this process requires a rapid tectonic inversion, otherwise the lithosphere would cool and strengthen, thus preventing subduction to initiate at the spreading center. A rapid tectonic inversion can be achieved in back arc basins as congestion of a nearby subduction zone can quickly invert the tectonic regime at the spreading center. However, such inversion from extension to compression seems more difficult to achieve rapidly along mid-oceanic spreading centers. At the MRC, progressive changes in plate motion from divergence at spreading centers to transpression and localized compression at segments of a continuous plate boundary accounted for the development of a large oceanic subduction zone in about 10–15 Myr (Figure 5).

[41] Along the MRC, subduction appears to have nucleated asynchronously at multiple locations along the plate boundary and with opposite vergences. The various segments of the plate boundary had different obliquities relative to the plate motion. Thus the total amount of shortening varies from one segment to another. The northern Puysegur and most probably Hjort segments have undergone all stages of subduction initiation (Table 1), whereas the McDougall and Macquarie segments are in incipient stages (Table 1). Local geodynamical conditions and structural heterogeneities that prevail along the different segments of the plate boundary may influence the subduction development, vergence in particular. The northern Puysegur subduction is undercontinental. At the intraoceanic McDougall and Macquarie Ridge segments, the structural environment implies an east verging subduction development. The McDougall segment has the deepest trough developed on the pacific side and is bounded by fracture zones trending parallel to the ridge (Figure 1). At the Macquarie Ridge segment, thrusts are better developed on the eastern side of the ridge [*Massell et al.*, 2000]. The crust of the Pacific Plate carries many fracture zones trending parallel to the ridge (Figure 1) whereas to the west of the ridge, the crust, which formed at the Southeast Indian Ridge segment [*Cande et al.*, 2000], carries no fracture zone (Figure 1).

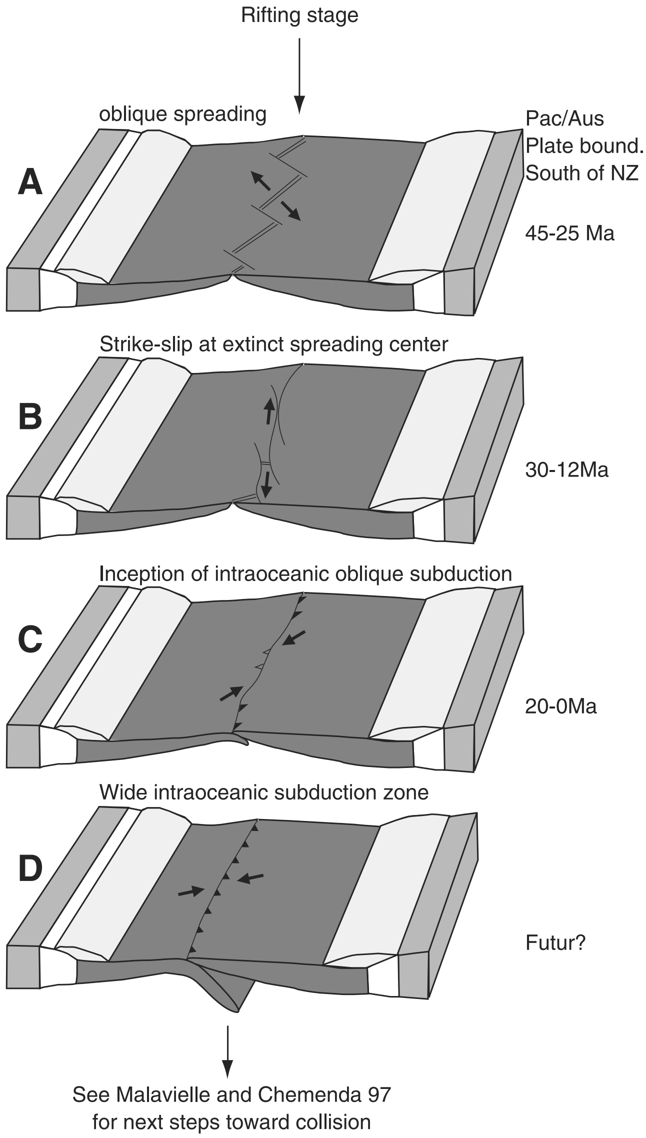

Figure 5. Sketches showing the evolution of the Pacific-Australia plate boundary from oceanic spreading to subduction initiation. Dark gray, oceanic crust; light gray, continental crust; pale gray, sediments over passive margins; white, thin continental crust at the passive margin.

At the Hjort subduction, the Australian plate subducts beneath the Pacific Plate.

[42] The evolution of the Puysegur subduction zone shows that, following inception along a short segment, the subduction has subsequently lengthened. The Puysegur subduction developed along a 150-km-wide step over of the Pacific-Australia plate boundary. Lengthening of the subduction zone beneath the continental Fiordland massif to the north, and the oceanic Puysegur Ridge to the south, tended to smooth the step over, by aligning the Alpine Fault and the MRC, and progressively shortcutting the Puysegur Fault. This process is still occurring and progressively individualizes the Puysegur terrane. Today, the Puysegur subduction zone extends from ca. 44°30′S to ca. 49°S (Figures 1 and 2) which represents a threefold increase in length of the segment along which subduction nucleated. It is conceivable that the tectonic environment at the southern termination of the Macquarie Ridge is favorable to the northward propagation of the Hjort subduction, in a similar fashion as to that of the southward propagation of the Puysegur subduction. South of 48°S, the Puysegur subduction is guided by inherited structures at the toe of Puysegur Ridge [*Collot et al.*, 1995]. Comparatively, the Hjort Trench could actively extend north of ca. 56°S along the thrust belt located at the toe of the Macquarie ridge. At the MRC, the eastward dipping subduction segments are the most developed and are actively lengthening. In physical models, continuing compression causes the most developed subduction segments to lengthen and coalesce, the subduction zone adopting a unique vergence in the absence of the development of a transform fault between segments of opposite dip [*Shemenda*, 1994].

5. Conclusion

[43] The Cenozoic evolution of the Pacific-Australia plate boundary south of New Zealand illustrates how a divergent plate boundary can evolve to generate favorable conditions for subduction initiation. The MRC example leads us to propose a conceptual model for development of wide intra-oceanic subduction zones along a spreading center (Figure 5). This model resembles a "Wilson Cycle" [*Wilson*, 1966] applied to mid-oceanic ridges. Following opening of the oceanic basin (Figure 5a), progressive rotation in relative plate motion results in the reorganization of the plate boundary in short individual spreading segments, while transform faults lengthen (Figure 5b). The process evolves until transform faults eventually coalesce to form a single, albeit discontinuous, transform plate boundary, along which plate motion becomes dominantly accommodated by strike-slip motion (Figure 5c). At that stage, subduction may nucleate in discrete locations representing discontinuities along the plate boundary, which are dominated by transpressive deformation (Figure 5c). Subduction vergence during inception of the subduction zone depends on local geodynamical conditions and heterogeneities. Progressively, the subduction segments lengthen and coalesce until subduction propagates to the entire plate boundary. If no transform fault develops between segments of opposite vergence, continuing compression will lead to the development of a subduction zone several thousands kilometers in length (Figure 5d). In this model the plate boundary remains at about the same location all along the cycle, i.e., similar to that of the spreading center, only it reorganizes to accommodate new tectonic regimes.

[44] The evolution of the Puysegur-Fiordland subduction zone leads us to conclude that juxtaposition of crusts of different natures, thickness, and densities together with structural heterogeneities on either side of the plate boundary, are parameters that help to localize the deformation and influence the vergence of the incipient subduction segment. This model of subduction nucleation along tectonic relay zones and propagation of the subduction zone, applied to individual ridge segments of the MRC, demonstrates that a ca. 2000-km-long subduction zone can develop in less than 10–15 Ma from a spreading plate boundary stage. This outcome dates the initiation of the Puysegur subduction 5–8 Ma older than that previously estimated.

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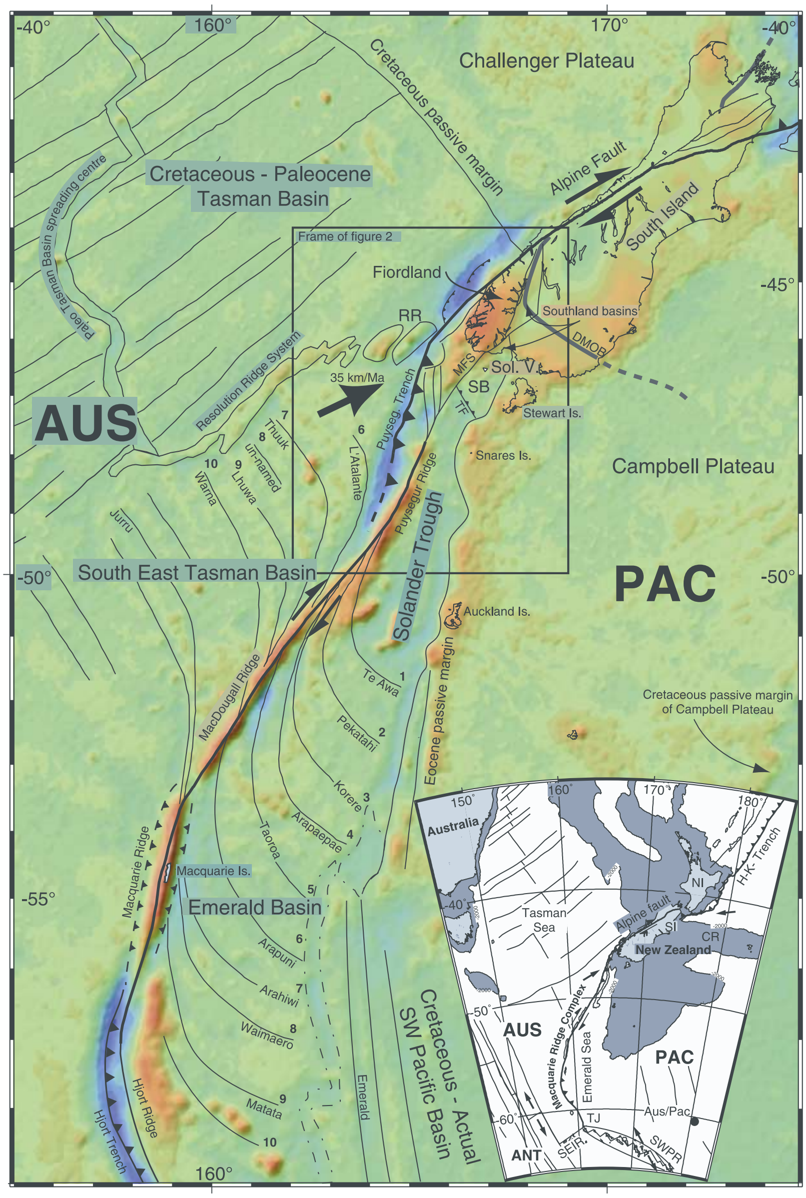

Figure 1. Global gravity anomalies (FAA) [*Sandwell and Smith*, 1997] and basin structures south of New Zealand. Numbers along fracture zones help to recognize conjugate fracture zone on either side of the plate boundary. Solander Trough corresponds to the basin limited southward by the Te Awa fracture zone and northward by the Tauru Fault. Very thick black line represents the Pacific-Australia plate boundary. Black lines represent other active structures. Thick continuous and dashed gray lines represent the Dun Mountain ophiolite belt and the offshore-associated magnetic anomaly, respectively. Thin lines represent inactive or secondary structures. Thin dot-dash line indicates the position of RRS prior to rifting of SETEB, as can be seen on gravity data [*Sutherland*, 1995]. Frame indicates location of Figure 2. DMOB, Dun Mountain ophiolite belt; MFS, Moonlight Fault System; RR, Resolution Ridge; SB, Solander Basin; Sol. V. Solander Volcano (Island size not at scale for better legibility); TF, Tauru Fault. Mercator projection. Insert: Location map. Large dot labeled "Aus/Pac" represents Nuvel 1A Australia relative to Pacific fixed pole of rotation [*DeMets et al.*, 1994]. Rotation occurs clockwise at 1.1°/Myr. Undersea landmasses are gray shaded. Thick lines represent plate boundaries, thin lines represent major fracture zones, the 2000-m bathymetric contour is indicated. ANT, Antarctic Plate; AUS, Australian plate; CR, Chatham Rise; H-K, Hikurangi-Kermadec Trench; NI, North Island; PAC, Pacific Plate; TJ, Aus-Pac-Antarctic Triple Junction; SEIR, Southeast Indian Ridge; SI South Island; SWPR, Southwest Pacific Ridge.

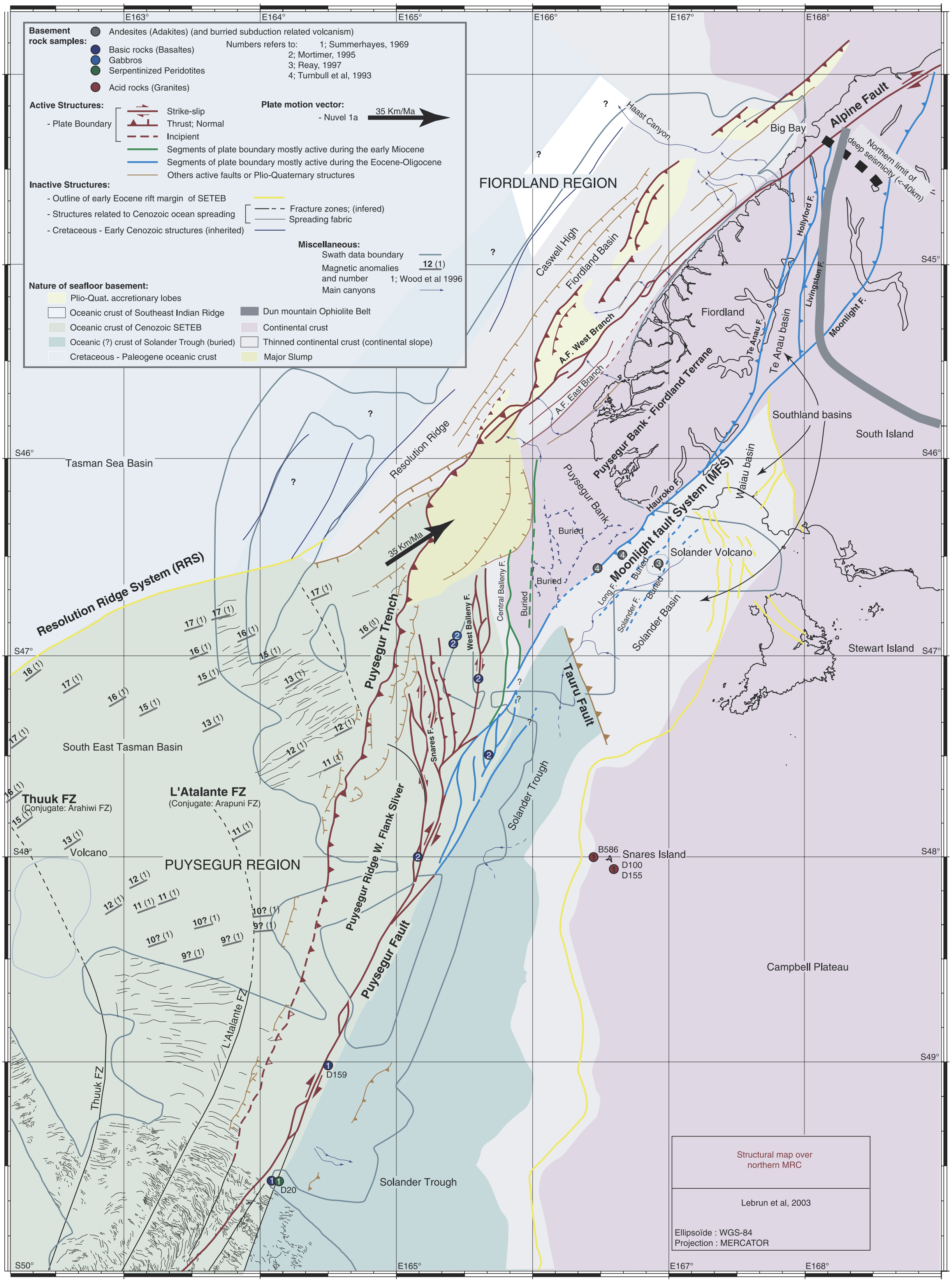

Figure 2. Tectonic map of the Puysegur-Fiordland Margin (northern Macquarie Ridge Complex), representing the area covered during the Geodynz-Sud survey, between 50°S and 44°S. Map characteristics on map caption. This plate complements the available structural map by *Massell et al.* [2000] for the region south of 50°S.