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Tectonic control of the subducting Juan Fernández Ridge on the Andean margin near Valparaiso, Chile

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Abstract. Near the latitude of Valparaiso, Chile, a fundamental change in configuration of the Benioff Zone, volcanic arc activity, and the structure of the continental margin occurs opposite the subducting Juan Fernández Ridge. Upper plate tectonics related to subduction of the ridge were studied by an international group of geoscientists in the two-degree segment offshore Valparaiso, extending from the shelf edge seaward across the eastern end of Juan Fernández Ridge. Near the O'Higgins group of seamounts, the Juan Fernández Ridge strikes northeast rather than continuing its east-west trend across the Pacific Basin. The ridge uplifts the upper plate, and sediments of the Valparaiso Basin are deformed against its southern flank. This deformation is consistent with the southward migration required by an oblique trending ridge and the nearly trench-normal vector of plate convergence. In the trench axis, the ridge forms a basement barrier behind which sediments 2.5 km deep have ponded. The lower slope over the ridge appears eroded, whereas the margin not yet affected by ridge subduction is fronted by an accretionary prism about 25 km wide. Nazca Plate relief clearly influences tectonism of the margin where it subducts beneath thin continental crust; its relation to deeper processes segmenting the Andean Orogen appears to involve prior tectonic events.

Introduction

The influence of the subducting oceanic plate on tectonism of continental margins is generally accepted, but the tectonic interactions are poorly understood. The Andes afford an outstanding opportunity to better understand the relation between subduction processes and continental tectonism. It has long been recognized that the exposed Andean Orogen is segmented [cf. *Steinmann*, 1930; *Aubouin and Borrello*, 1966; *Gansser*, 1973; *Sillitoe*, 1974; *Jordan et al.*, 1983; *Corvalán*, 1989; *Mpodozis and Ramos*, 1989] corresponding to segmentation of subduction zone earthquake patterns in the deep crust (Figure 1) [cf. *Barazangi and Isacks*, 1976]. An influence of subducted ocean floor morphology on earthquake nucleation has been inferred to explain patterns of relocated earthquake hypocenters [*Kirby et al.*, 1996]. Most segment boundaries on the continent are opposite ridges or fracture zones on the subducting oceanic plate [*Nur and Ben Avraham*, 1981; *Pilger*, 1981]. However, contemporary asperities sometimes subduct opposite older and therefore unrelated continental features Perhaps at some segment boundaries, asperities on the descending plate interact with preexisting structures of the upper plate [*Jordan et al.*, 1983].

A prime objective of the Chilean Offshore Natural Disaster and Ocean Environmental Research (CONDOR) Program is to study the affect of irregularities in a subducting plate on continental margin tectonism. For instance, do subducted ocean ridges with a thickened crust and thermal anomalies form earthquake asperities? Are they the cause for a decrease in depth of the subducting Nazca Plate? Is the singular Valparaiso midslope forearc basin a product of ridge collision? The area near Valparaiso contains a segment boundary (Figure 1) which involves a fundamental crustal change from a normal to a shallow amagmatic subduction zone.

The German Research Vessel Sonne was the platform for data acquisition between March and July 1995. The CONDOR program was constructed as a coordinated progression of multidisciplinary investigations that began with bathymetry, magnetics, and high-resolution seismics and progressed through sampling [*von Huene et al.*, 1995a] and land-sea crustal seismic experiments [*Flueh et al.*, 1995] and ended with deep-reflection acquisition [*Hinz et al.*, 1995]. Because of the sparse precruise information in the study area, successive legs were planned based on results of the preceding ones. This was optimized by processing data onboard during the acquisition. Data presented here were mostly processed at sea, and teams of scientists from the international community participated in legs devoted to their speciality (Table 1). Many have now sought support from their national funding sources to conduct postcruise investigations Onboard data reduction allowed the study to advance faster than usual, and here we report a major tectonic framework only partially or not at all recognized prior to the Sonne's entry into this area.

Regional Setting

Offshore Valparaiso, the Juan Fernández Ridge and its seamounts interrupt an otherwise monotonous Pacific ocean basin (Figure 1). This 900-km-long low rise supports a chain of 11 seamount groups that extend from the present hot spot west of Alexander Selkirk Island to the O'Higgins Seamounts (Figure 1). Satellite-derived gravity anomalies [*Sandwell and Smith*,

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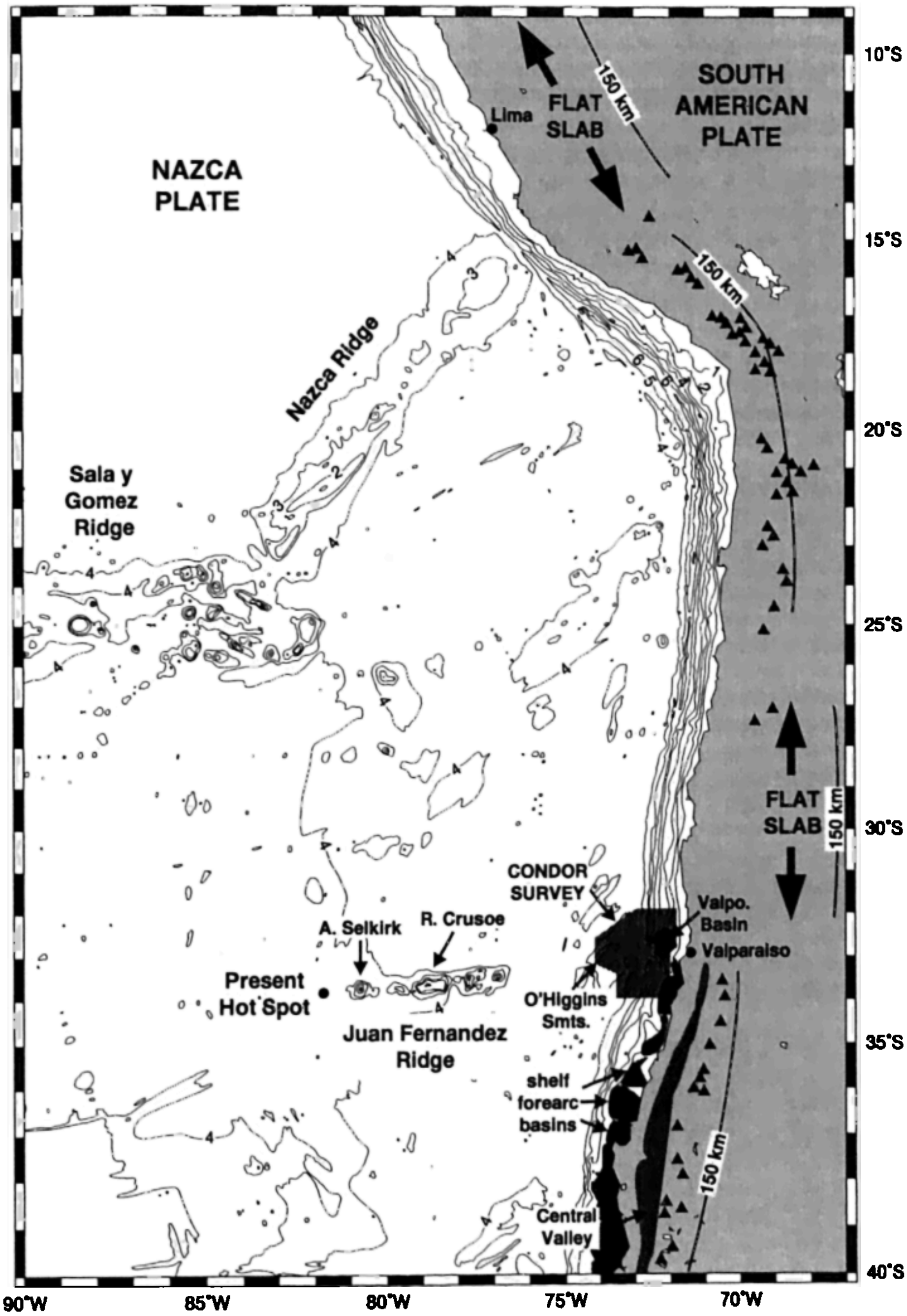

Figure 1. Morphology of the convergent margin along South America showing location of the Chilean Offshore Natural Disaster and Ocean Environmental Research (CONDOR) survey area, the northern ends of the Quaternary volcanos (solid triangles), the Central Valley, and the forearc basins on the shelf. The 150-km Benioff depth contour is indicated. From the beginning of the "flat slab" area to Valparaiso Basin marks the segment boundary opposite Juan Fernández Ridge which subducts beneath Chile. A similar boundary is associated with the subducting Nazca Ridge.

1995] show a negative anomaly presumed to indicate crustal flexure from loading associated with seamounts and indicate a crustal root. Thus the normal oceanic crust entering the Chilean subduction zone may include a welt of thicker crust beneath an east-west hot spot chain of seamounts. Juan Fernández Ridge is entirely on the Nazca Plate, so its subducted end has no mirror image west of the East Pacific Rise as occurs for the Nazca Ridge [*Pilger*, 1981].

Once the oceanic crust enters the subduction zone, the upper plate north and south of the ridge display unlike structure. In the

Table 1. List of Shipboard Scientists and Credits

SO 101			SO 103		SO 104	
Name	Institution	Leg	Name	Institution	Name	Institution
von Huene, R.	GEOMAR	1, 2, 3	Flueh, E.R.	GEOMAR	Hinz, K.	BGR
Weinrebe, W.	GEOMAR	1, 2, 3	Bialas, J.	GEOMAR	Block, M.	BGR
Klaeschen, D.	GEOMAR	2	Biegling, A.	GEOMAR	Damm, V.	BGR
Diaz Naveas, J.L.	GEOMAR	1, 2, 3	Diaz Naveas, J.L.	GEOMAR	Fritsch, J.	BGR
Ranero, C.R.	GEOMAR	1, 2	Gerdom, M.	GEOMAR	Neben, S.	BGR
Harms, G.	GEOMAR	1, 2, 3	Hojka, A.M.	GEOMAR	Reichert, C	BGR
Spiegler, D.	GEOMAR	3	Hoppenworth, R.	GEOMAR	Schreckenberger, B.	BGR
Biebow, N.	GEOMAR	3	Husem, S.	GEOMAR		
Locker, S.	GEOMAR	3	Krastel, S.	GEOMAR		
Kriiger, D.	University Bochum	1, 2, 3	Kukowski, N.	GEOMAR		
Morales, E.	University Valpariso	3	Morawe, M.P.	GEOMAR		
Vergara, H.	SHOA	1, 2, 3	Diaz Munoz, A.E.	DGF		
Yañez, G.	SERNAGEOMIN	2	Lefmann, A.K.	GIUC		
Corvalán, J.	SERNAGEOMIN	3	Vidal, N.M.	CSIC		
Valenzuela, E.	University Chile	3	Zelt, C.	Rice		
Wall, R.	SERNAGEOMIN	3				
Korstgard, J.	University Aarhus	2				
Trinhammer, P.	University Aarhus	2				
Laursen, J.	University Aarhus	2				
Scholl, D.	USGS	2				
Kay, S.	Cornell University	3				
Domínguez, S.	University Montpellier	1, 2, 3				
Segl, M.	University Bremen	3				
Beese, D.	University Bremen	3				
Lamy, F.	University Bremen	3				

Complete addresses listed in appendix. Data processing generally done on shore was instead accomplished onboard. Magnetic data were processed by C.R. Ranero, G. Yáñez, and J.L. Naveas Diaz. High-resolution seismic data were processed by D. Klaeschen and C.R. Ranero. Bathymetric data were processed by W. Weinrebe, S. Domínguez, and D. Krueger. Processing of the deep-seismic reflection data was done on shore by C.R. Ranero. ERS 1 satellite gravity anomalies were processed at GEOMAR by N. Didden. Preliminary modeling of the wide-angle data was accomplished by C. Zelt, N. Vidal, and A. Lefman [*Zelt and Smith*, 1992]. Argon/argon dating of samples from O'Higgins Guyot was done after the cruise by J. O'Connor, GEOMAR.

trench axis, the Juan Fernández Ridge forms a barrier to sediment transport [*Lawrie and Hey*, 1981; *Schweller et al.*, 1981] which impounds deep trench axis sediment transported from the south and leaves little trench sediment to the north. The adjacent continental margin includes Valparaiso Basin and a series of shallow forearc basins on the shelf extending far to the south [*González*, 1989]. On land is the Central Valley which characterizes central and southern Chile, and in the adjacent Andes are the first active volcanoes of the southern volcanic zone. Central and southern Chile are underlain by a "normal" steep dipping Benioff Zone [*Barazangi and Isacks*, 1976] (Figure 1). North of the area, the dip of the Benioff Zone decreases (the "flat slab" area), volcanism is inactive, the Central Valley is absent, and the narrow shelf is without basins. Changes also occur in the back arc area at this latitude [*Mpodozis and Ramos*, 1989]. A broad boundary separates these tectonically different segments of the Andean Orogen.

Questioned is the relation between the subducted ridge and patterns of earthquakes and the linkage between the flat slab and ridge subduction history. A similar relation between a flat slab and amagmatic volcanic arc with an oblique subducting ridge is found at Nazca Ridge and at Louisville Ridge along the Tonga Trench. Cocos Ridge off Central America is also associated with a decrease in slab dip and termination of contemporary volcanism. However, a nearly orthogonal orientation of Juan Fernández Ridge to the continental margin would not produce the rapid southward migration of a subducting ridge proposed as a condition for development of the flat slab at Nazca and Louisville ridges. Another conflicting consideration is the decrease in dip of the subduction zone beginning in middle Miocene time which is a favored explanation for the geochemistry of arc volcanism beginning south of the segment boundary [*Kay et al.*, 1991]. A fundamental question is whether subduction of a ridge affected the configuration of the Benioff Zone.

Data Acquisition

Several geophysical techniques in addition to core and dredge sampling were employed during the study. Swath mapping of a large area, magnetic anomalies, and high-resolution seismic reflection data were first obtained to examine regional features followed by deep penetration multichannel reflection techniques and wide-angle seismic observations. The specifics of each leg are contained in cruise reports for legs SO 101, SO 103, and SO 104 [*von Huene et al.*, 1995a; *Flueh et al.*, 1995; *Hinz et al.*, 1995].

Precruise information for planning included gravity from satellite altimetry [*Sandwell, and Smith*, 1995; N. Didden, unpublished ERS 1 data, 1995], conventional bathymetry [*Schweller and Prince*, 1980], and swath mapping of San Antonio Canyon [*Hagen et al.*, 1996]. During SO 101, leg 1 (Table 1), hydrosweep and magnetic data were acquired along 8300 nautical miles (15,380 km) of ship's track. Hydrosweep data were edited onboard (mb-system software, authors D.W. Caress and D.N. Chayes) and displayed with the General Mapping Tool (GMT) software [*Wessel and Smith*, 1991]. Data were not filtered to assure preservation of the geologic detail that is lost when swath map data are smoothed. The resulting track noise from overlapped parts of adjacent swaths remain in high-resolution perspective presentations (Figure 2a and b) and provide a visual calibration of maximum noise level.

Some morphologic points of reference in the following sections include the O'Higgins Seamounts, the Valparaiso Basin, and the southern wide-floored sediment "flooded" trench axis which contrasts with the northern narrow-floored sediment "starved" trench. Valparaiso Basin is bounded to the north by the diagonal Punta Salinas Ridge, and to the south, San Antonio Canyon cuts a striking zigzag path across the margin (Figure 3).

Total field magnetic anomalies observed concurrent with the swath mapping were corrected during the second leg with the diurnal variation recorded simultaneously onshore. Contouring and interpretive modeling were accomplished onboard (Figure 4) (G.A.Yáñez et al., A tectonic interpretation of magnetic anomalies across a segment of the convergent margin of the southern central Andes (32°-34° S) submitted to *Journal of Geophysical Research*, 1996) (hereinafter referred to as Yáñez et al., submitted manuscript, 1996).

The second leg (Table 1) was devoted to high-resolution seismic reflection surveying using the Parasound transducer system and the reflection system of Aarhus University. The latter consists of a 24-channel, 150-m-long active streamer and a four-sleeve gun array seismic source. Of the 2000 line km of seismic reflection data acquired, one third were processed onboard through stacking for quality control and to help plan the next legs. These data were used to locate the deep penetration and wide-angle seismic experiments and sampling.

During the third leg of SO 101 (Table 1), 11 core stations 23 dredge stations were occupied, but examination has not advanced much beyond onboard analysis. The dredges in San Antonio Canyon to sample deep rock outcrops recovered only Miocene and younger sediment, and much more consolidated sedimentary rock was recovered to the north. Preliminary onboard paleontology guided this part of the program.

A fourth leg on Sonne cruise SO 103 was devoted to wide-angle seismic observations [*Flueh et al.*, 1995] along two lines. One crossed the undisturbed margin in the south, and the other crossed the margin affected by the subducted Juan Fernández Ridge to the north. Ocean bottom hydrophones (OBH) at nominal 15-km spacing recorded shots at a 100-m interval from

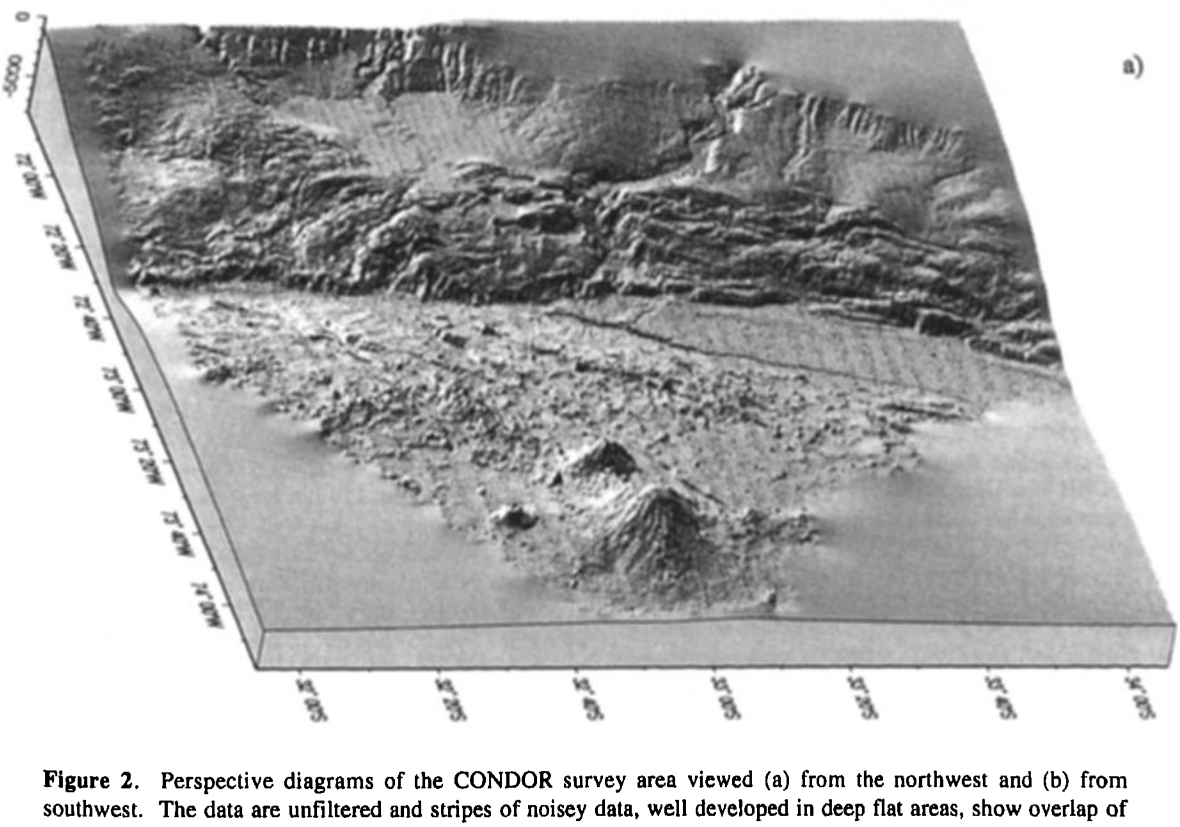

Figure 2. Perspective diagrams of the CONDOR survey area viewed (a) from the northwest and (b) from southwest. The data are unfiltered and stripes of noisey data, well developed in deep flat areas, show overlap of outer beams of adjacent swaths. Stripes are a measure of maximum noise which varied with sea state and depth. Figure 2a shows a regional overview of the area surveyed, Figure 2b emphasizes the aparent southward step of Juan Fernández Ridge.

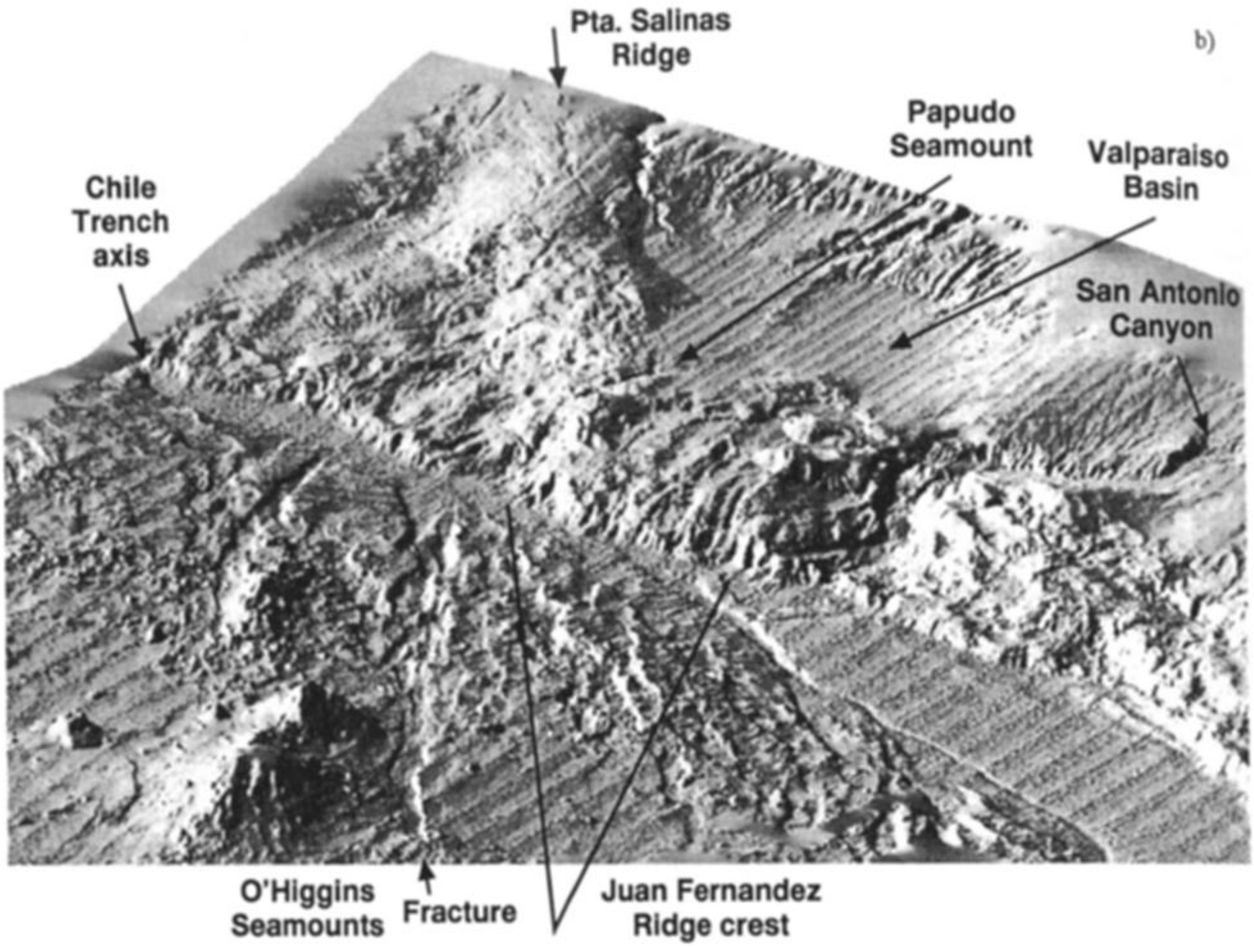

Figure 2. (continued)

an up to 96 L (6000 cubic inch) air gun source. An additional network of ten intersecting lines in a pentagonal figure was acquired for a three-dimensional imaging experiment across the Punta Salinas Ridge and Valparaiso Basin [*Flueh et al.*, 1995]. The marine survey was extended on land with more than 12 mobile instruments. Data processing and preliminary two-dimensional modeling was accomplished onboard.

Deep reflection data were acquired on SO 104 along the wide-angle OBH lines [*Hinz et al.*, 1995]. The seismic signals were generated using two tuned linear arrays of 20 air guns with a total volume of 51.2 L (3123 cubic inches). Interpretations of onboard monitor records [*Hinz et al.*, 1995] were modified on shore after processing through prestack depth migration.

Major Features Revealed in the Survey Data

Lower Plate Structure

The O'Higgins group of seamounts (Figures 1 and 2) are the most apparent expression of the Juan Fernández Ridge in this area. On regional bathymetric and satellite altimetry maps, the Juan Fernández volcanic ridge across the Pacific Basin is roughly aligned with the O'Higgins Seamounts and Valparaiso Basin. However, at larger scales the O'Higgins seamount group displays a strong northeasterly trend that also characterizes seafloor morphology to the trench axis. Swath maps resolve a northeast alignment in the seamount group including the ridge between the guyot and the smaller volcano (Figure 3); the O'Higgins Ridge is composed of many small roughly aligned cones. Southeast of the seamounts some unusually long fractures dominate the morphology (Figure 2b). The O'Higgins fracture (Figure 3) is 110 km long, and near the trench axis, scarps are as much as 1 km high. The fractures do not offset magnetic anomalies of the Nazca Plate that trend at almost right angles to them (Figure 4). Parallel trend of fractures and volcanic features show the change in trend of the Juan Fernández Ridge; however, in the surveyed area its southeast boundary is unclear (Figures 2 and 3).

A "total fusion" age from O'Higgins Guyot is 8.5±0.4 Ma (J.M. O'Connor, manuscript in preparation, 1996). The age-distance relation from the active hot spot of Juan Fernández is essentially the same as that from the hot spot to the 8-Ma sample from the Sala y Gomez volcanic chain off Peru [*O'Connor et al*, 1995]. The Sala y Gomez chain bends slightly and steps south at 8 Ma, indicating a change in Nazca plate motion but not in convergence rate

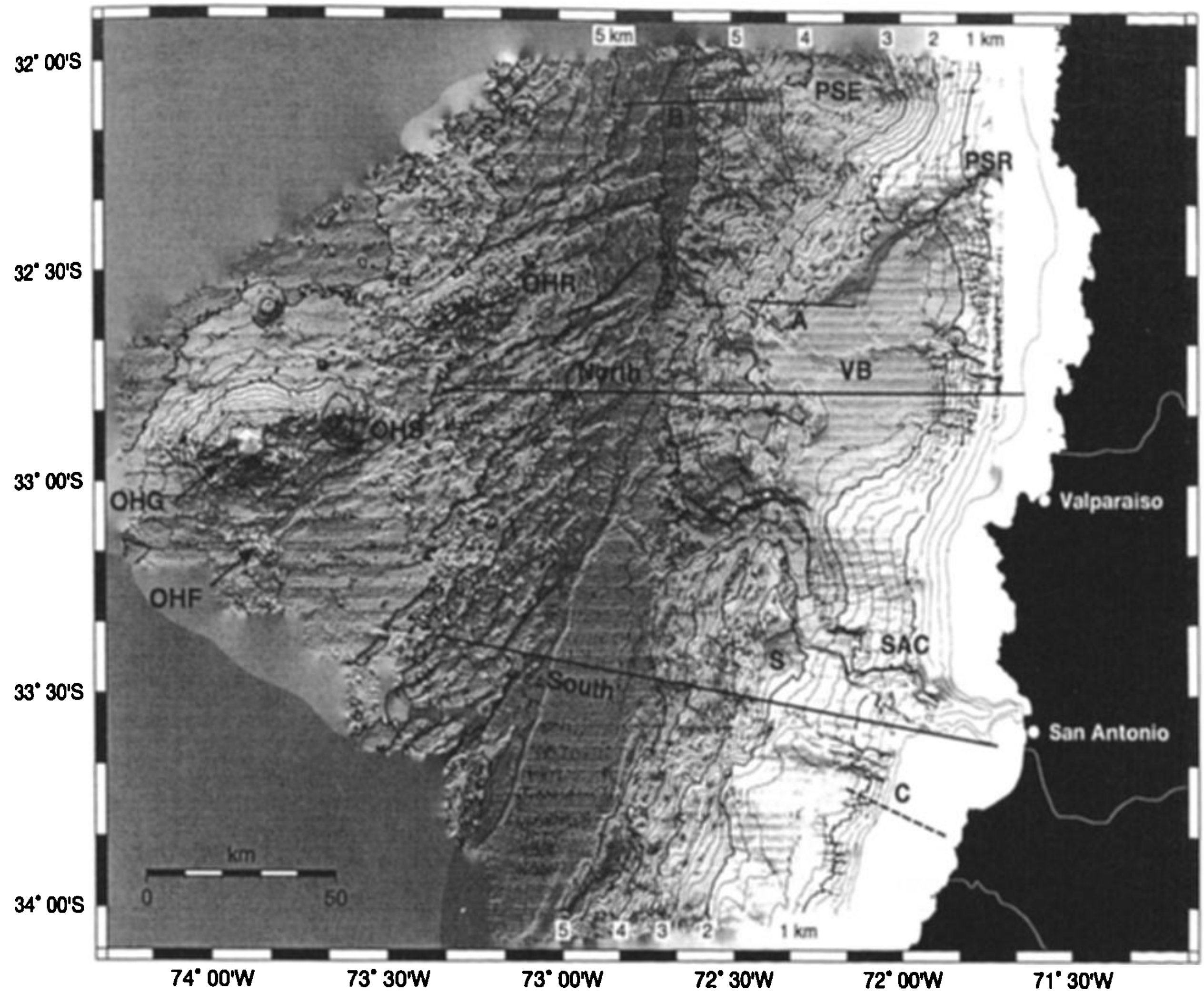

Figure 3. Swath map data at 1000-m contour intervals over a shaded relief image. Where mapping was within the 12-mile zone, contours were digitized from nautical charts to show the head of San Antonio Canyon. Long lines "north" and "south" show location of wide-angle and deep-/ seismic reflection profiles; lettered short lines are the two high-resolution records in Figure 5. Line C south of San Antonio Canyon locates a seismic record of *González* [1989]. Abbreviations are as follows: SAC, San Antonio Canyon; VB, Valparaiso Basin; PSR, Punta Salinas Ridge; PSE, Punta Salinas Embayment; OHG, O'Higgins Guyot; OHS, O'Higgins Seamount; OHR, O'Higgins Ridge; OHF, O'Higgins Fracture.

The first seismic data in this area [*Lawrie and Hey*, 1981; *Schweller et al.*, 1981; R. von Huene and D.W. Scholl, unpublished data, 1968] showed a major barrier to axial sediment transport from the Juan Fernández Ridge crest. The buried southern flank of the ridge extends 2.5 km deep beneath the trench axis along the south seismic transect (Figure 3). Seventy-five kilometers north over the ridge crest, the trench axis is narrowest and has little trench-fill sediment. North of the ridge crest is a modestly wider trench floor (Figures 2 and 3) where the axial sediment is ponded behind a small seamount and thickens to about 1 km (Figure 5). The 2.5-km relief across the ridge is considerably greater than the seafloor relief where no seamounts occur west of the O'Higgins Seamounts (Figure 1)

A thickened oceanic crust beneath Juan Fernández Ridge is indicated by the wide-angle seismic data (Figure 6). Along the northern profile, the crust is approximately 1.5-2 km thicker than the southern profile which is less than expected. Here, however, the gravity anomalies display a much shallower negative than to the west [*Sandwell and Smith*, 1995], suggesting a shallower root than elsewhere beneath the ridge.

Upper Plate Structure

South of Juan Fernández Ridge, continental crust extends to the middle slope, and the accretionary prism is about 25 km wide. Near Valparaiso, coastal outcrops expose rocks of Paleozoic and Mesozoic age which are covered unconformably

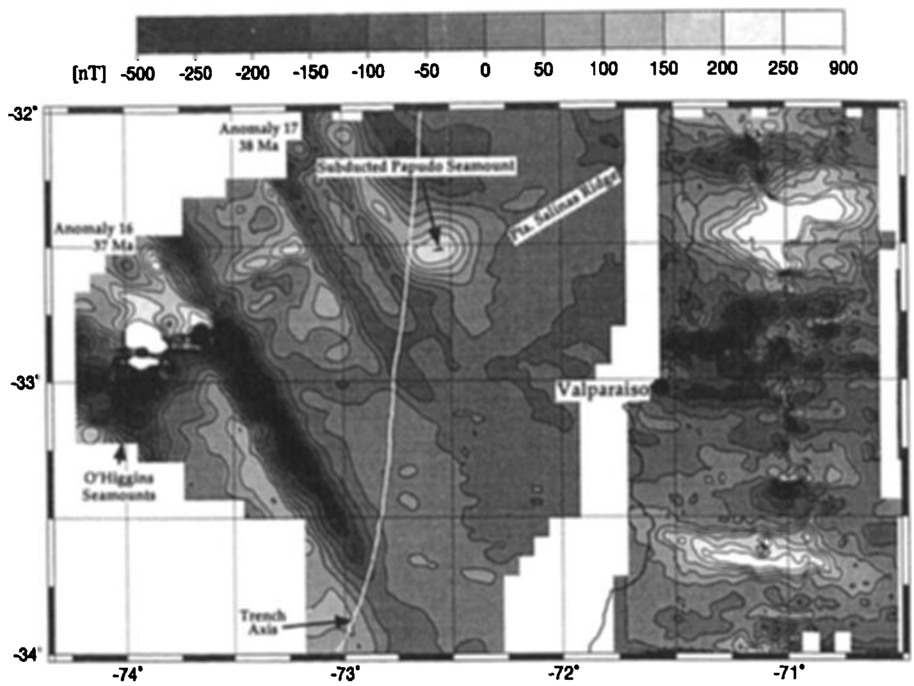

Figure 4. Oceanic and continental magnetic anomalies corrected for International Geomagnetic Reference Field and diurnal variation. Data on continent from Servicio National de Geologia y Mineria. Trench axis position shown by heavy white line, 12-mile zone indicated by blank area along the coast.

by shallow water Miocene sediment. In seismic records, the offshore forearc basins south of Valparaiso (Figure 3, profile C) contain Pliocene sediment overlying a 1000-m-thick Oligo-Miocene section resting in turn on Mesozoic basement [*González*, 1989]. Seismic data acquired during CONDOR show the continuation of this continental section about 70 km across the shelf and down the slope. A continental magnetic anomaly pattern and basement velocities continue to the lower slope (Yáñez et al., submitted manuscript,1996). Continental crust extends to the lower slope as inferred previously [*Mordojovich*, 1974, 1981; *Gonzàlez*, 1989; *von Huene*, 1989; *Behrmann et al.*, 1994] and forms a backstop for accretion. None of the presently processed seismic data clearly image the backstop boundary, but it is constrained to a 2- to 3-km-wide area (Figure 7).

The accreting prism is marked in morphological data by continuous long ridges which are folds in seismic section. Developing folds which produce low ridges on the trench floor above thrust faults mark the deformation front (Figures 2 and 7). Up slope, the seismic image of accretionary structure ends at a change in the morphology from long ridges subparallel to the trench to a smooth slope over the unfaulted sediment section (Figure 2).

Deformation Above Juan Fernández Ridge

From San Antonio Canyon to the northern end of the survey area, the margin morphology is modified from that observed in the south. The accretionary prism morphology with its long trench-parallel ridges is absent although seismic reflection profiles show an accretionary structure beneath the lower slope The foot of the slope is characterized by an escarpment about 1 km high with many slump scars cutting transverse morphology (Figures 2 and 3). Above the escarpment, the lower slope morphology is less systematic than to the south with short ridges and scarps subparallel to the trench disrupted by transverse and diagonal structures (Figure 2). The northern deep seismic image shows a 15-km-wide accretionary mass beneath the lower slope which is covered by slope-parallel reflections 0.4 s thick (Figure 7). Sampling 11 km landward of the deformation front in an embayment exposing deeper rock yielded well-consolidated sedimentary rocks consisting of strongly fractured siltstone, and fine- to coarse-grained sandstones of a character unknown onshore.

The crest of the Punta Salinas Ridge north of Valparaiso Basin has a fragmented morphology, including many abandoned canyons and rills. High-resolution seismic data indicate mostly disturbed sediment. At the base of the continental slope, a low-rounded ridge crosses all morphological elements upslope (Figure 5a, line 5 and Figure 2).

In contrast to the lower slope, the upper slope morphology includes many rills and canyons which indicate tectonic stability long enough for channels to form. This is consistent with the coherent and little-deformed upper slope Tertiary sediment sequence in seismic records. Only in the middle slope of Valparaiso Basin is active tectonism apparent in the folded sedimentary strata that impinge against Punta Salinas Ridge. Strata in basins on the shelf are little deformed [*González*, 1989].

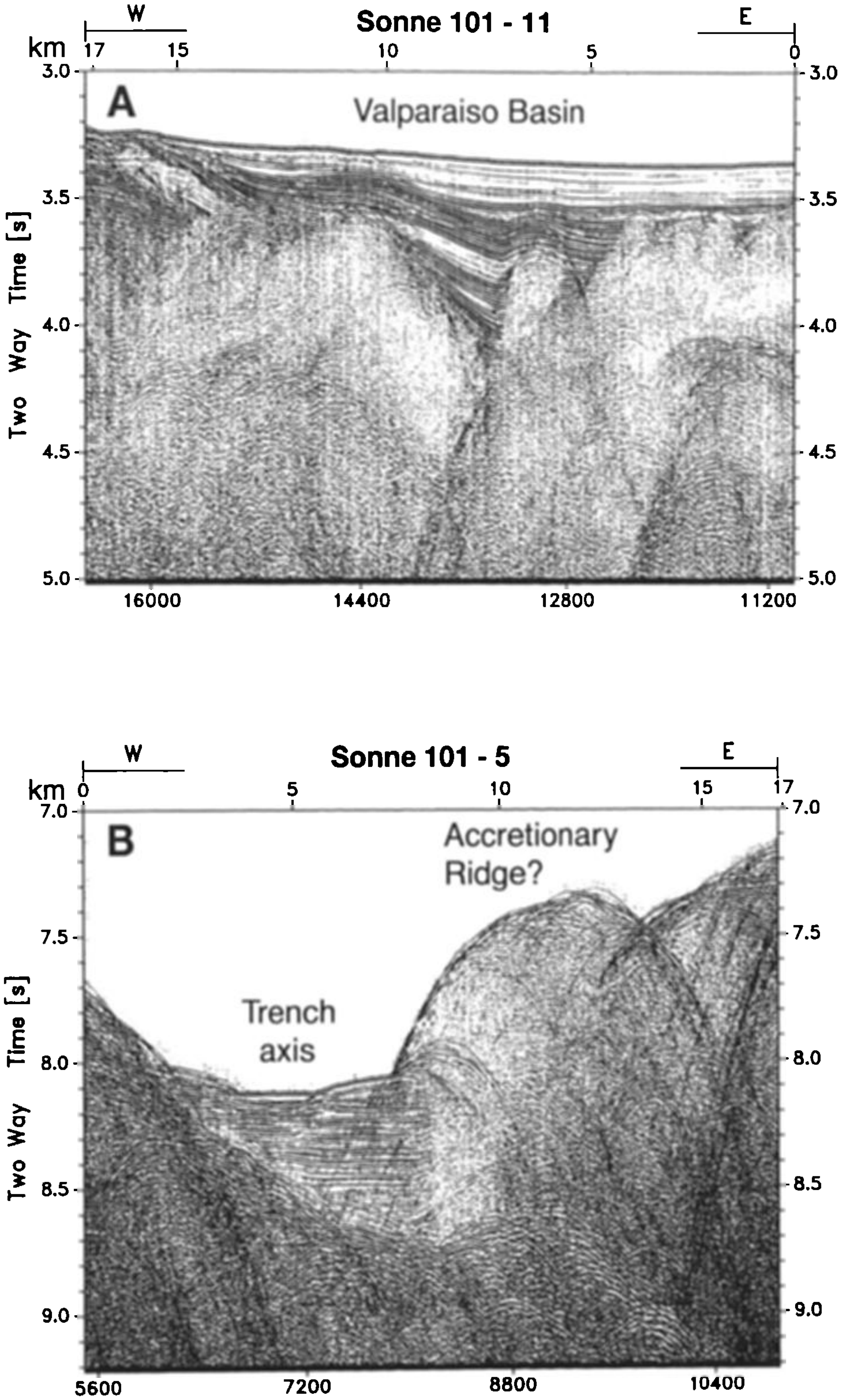

Figure 5. High-resolution seismic records showing (a) folding of sediment against Punta Salinas Ridge and (b) trench axis with sediment at northern end of surveyed area and presumed accretionary fold. Locations shown in Figure 3.

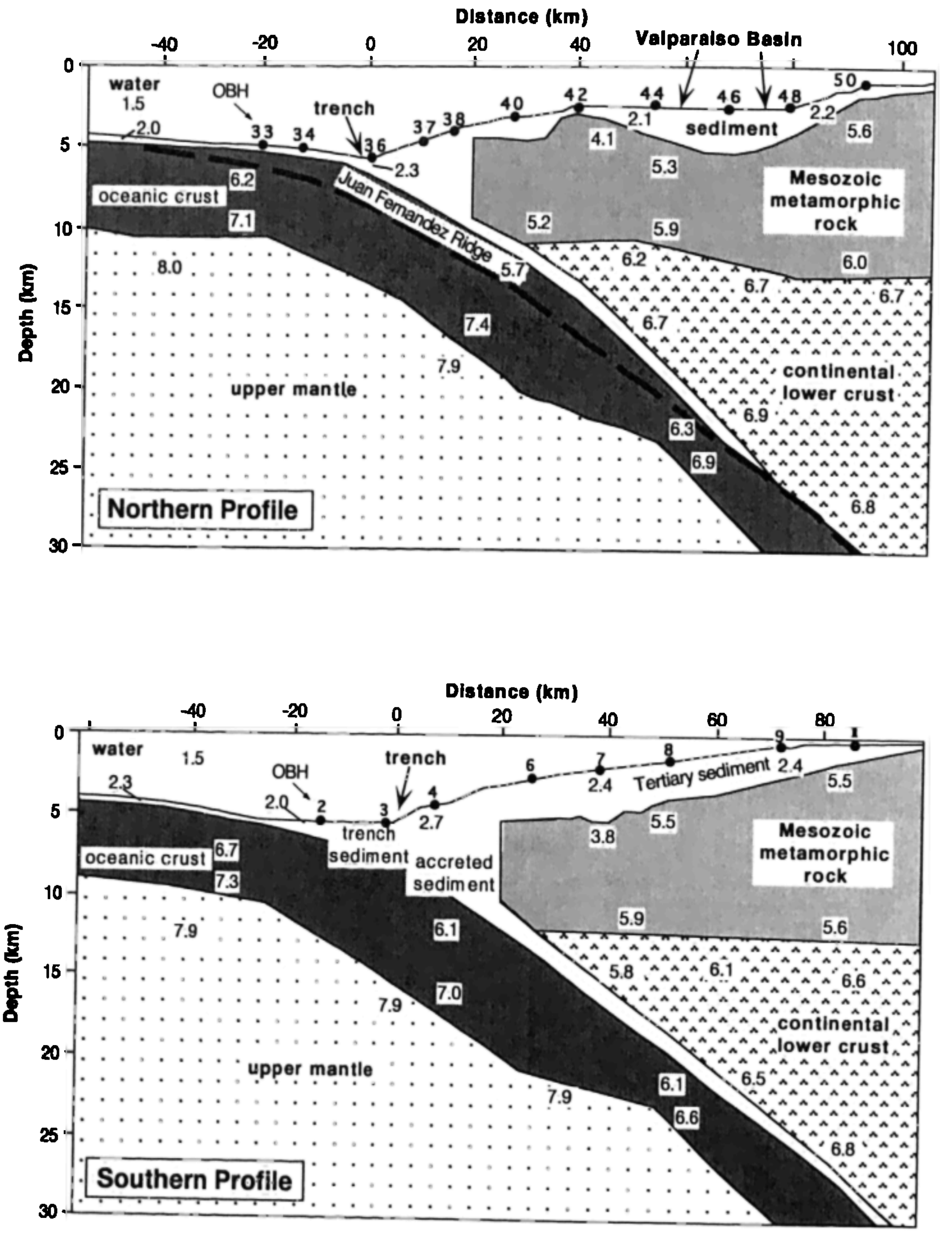

Figure 6. Sections constructed from preliminary wide-angle seismic data across the noncollisional and collisional areas. Locations shown in Figure 3. Position of backstop, area of accreted sediment, and interpretation of slope sediment are based on reflection data.

Subducted Seamounts and Sediment

The spacing of seamounts on the Juan Fernández Ridge would bring a seamount into the trench axis at an average rate of three per Ma. Magnetic anomalies (Figure 4) clearly show the underthrust Papudo Seamount which is about as large as O'Higgins Guyot (Yáñez et al., submitted manuscript, 1996). As it was underthrust, the seamount left a short indistinct trail in the lower slope morphology (Figures 2 and 3). Perhaps the indistinct character of this trail is a characteristic of seamount scars across more consolidated rock as was sampled from the lower slope here. Trails through recently accreted sediment are far more distinct [*von Huene et al.*, 1995b]. About 1 Ma, Papudo Seamount must have blocked the trench axis for about 1 Ma which may explain the indications of erosional channeling and the lack of a delta at the mouth of San Antonio Canyon Papudo Seamount rises about 3 km above the 4-km-deep lower plate, and it produces a seafloor dome about 400 m high. This attenuation of lower plate morphology through the upper plate is surprisingly large considering its rheology.

The mouth of San Antonio Canyon might be another seamount scar (Figure 2). Its steep and narrow active channel is

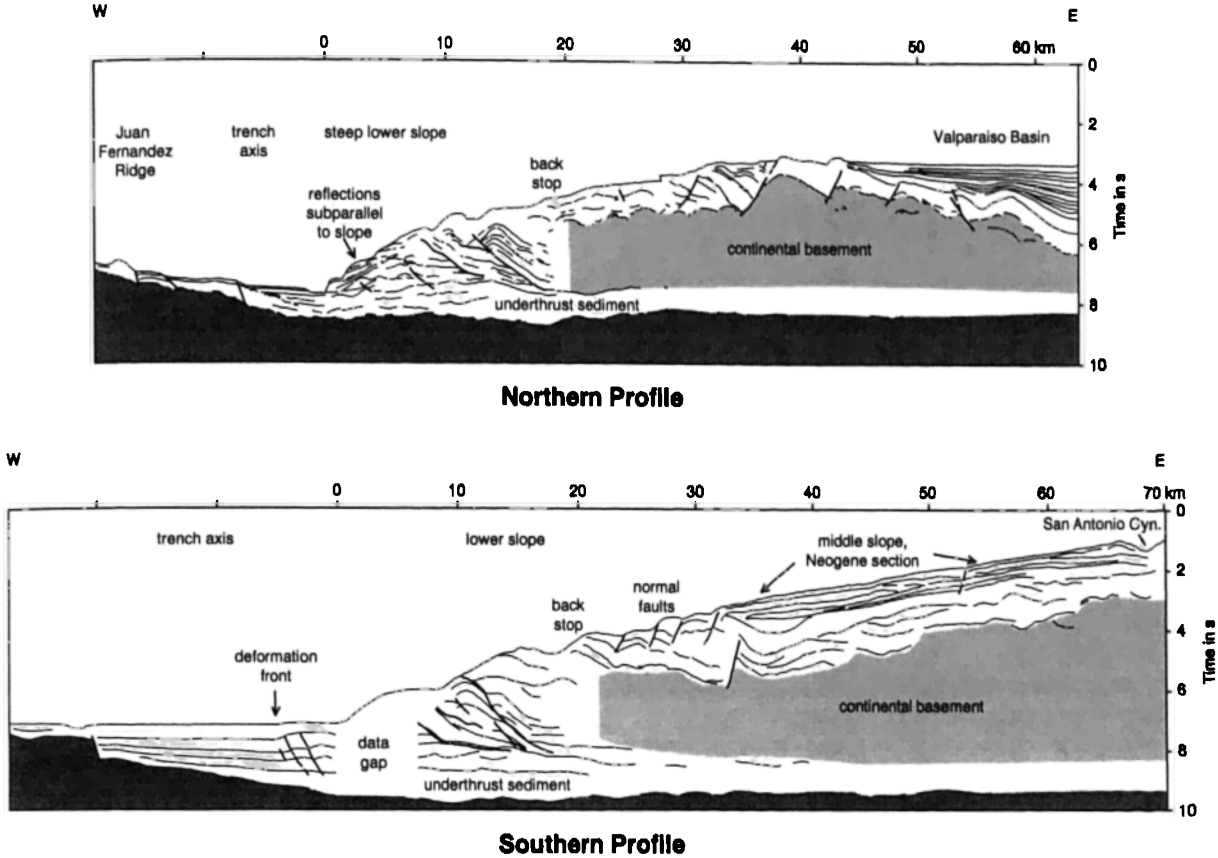

Figure 7. Line drawings of deep-seismic reflection time sections along the same lines on which wide-angle data were acquired (vertical axis two-way time). Processing included poststack time migration. Thickness of subducted sediment is inferred where no lines are present and only shaded area boundaries are presented. Neogene section is from *González* [1989], section C, Figure 3.

contained in a much broader U-shaped valley across the lower slope which is subparallel to the direction of convergence. The active channel is too small and deeply eroded to have produced the wide canyon mouth. Channel erosion would probably have been deflected from a straight path by ridges of the lower slope as occurs up slope. A deflected path is observed along the smaller canyon just south of San Antonio Canyon (Figures 2 and 3) which first makes a straight traverse across the upper and middle slope but becomes deflected across the lower slope.

The deep seismic reflection profiles image underthrusting of considerable sediment. Despite a data gap, the southern profile shows underthrust sediment beneath the accretionary structure about 15-18 km landward of the trench axis (Figure 7). The landward most image of underthrust sediment has a 1.5 s two-way travel time (TWT) or a thickness between 1.8 and 2.3 km.

The northern profile (Figure 7) indicates underthusting of the less than 1 s TWT trench axis section (~1 km thick). The underthrust sediment layer has a 1.5 s TWT 10 km farther landward. The top of the igneous oceanic crust can be followed clearly for 20 km landward from the trench axis. Underthrust sediment is also interpreted in a seismic record at about 40° S and 46° S latitude, but only thin underthrust sediment is interpreted in lines at 36° S and 38° S latitude [*Bangs and Cande*, 1997; *Behrmann et al.*, 1994].

Discussion

The east-west Juan Fernández Ridge changes trend to northeast near O'Higgins Seamount. Part of the bend in the Juan Fernández Ridge is hidden beneath the margin, but it might be configured similarly to the bend at the Nazca and Sala y Gomez ridges (Figure 1). The change in direction is not sharp, indicating the time required for complete plate motion readjustment. However, the 8-Ma bend in Juan Fernández Ridge appears much greater than the coeval bend in Sala y Gomez Ridge.

The Juan Fernández Ridge crest is offset near the trench (Figures 2 and 3). A line along Punta Salinas Ridge and through Papudo Seamount is offset from a line connecting the O'Higgins Seamounts or the trace of O'Higgins fracture (Figures 2b and 3). Perhaps major seamounts do not only erupt on the ridge crest but also off axis. At the 8-Ma segment of the Sala y Gomez Ridge, a major southward step is displayed in gravity anomalies [*Sandwell and Smith*, 1995]. Thus the apparent southward step in Juan Fernández may be common to Nazca Plate motion history.

The diagonal Juan Fernández Ridge segment beneath the margin is also indicated by gravity anomalies that cross the slope diagonally and coincide with Punta Salinas Ridge and Papudo Seamount. The anomaly is much larger than that caused by the low seafloor ridge and is unique to the Valparaiso area. The anomalies are sufficiently robust to show clearly in three independent compilations of gravity from satellite altimetry [*Andersen and Knudsen*, 1995; *Sandwell and Smith*, 1995; N. Didden, unpublished ERS 1 data, 1995]. Thus at least a 100-km ridge segment has subducted diagonally and swept along the Chile margin similar to the migration of Nazca Ridge along the Peru margin [*Nur and Ben Avraham*, 1981; *Pilger*, 1981].

A change in strike of the Juan Fernández Ridge at O'Higgins Seamount is significant for the tectonic history of the central Chile margin. With an essentially east-west strike and normal plate convergence, the point of ridge subduction remains fixed through time. With the north-east strike indicated by Punta Salinas Ridge, however, it migrated south along the trench at about 60 km/Ma, similar to the Nazca Ridge. Nazca Ridge migration is inferred to have caused the flat slab [*Nur and Ben Avraham*, 1981; *Pilger*, 1981]. The central Chile flat slab extends about 570 km north of the current position of the Juan Fernández Ridge crest beneath the arc (Figure 1).

To examine tectonism across the margin as the subducting ridge migrated south, the unaffected margin segment is compared with that affected by subduction of Juan Fernández Ridge. Along the unaffected margin segment, continental basement and the little deformed Neogene sedimentary sequence extend from the coast to the top of the lower slope; canyons continue uninterrupted from the shelf to the lower slope. These observations indicate a tectonically stable regime. Across the accretionary prism, the canyons become disrupted channels. The change in canyon morphology begins in the area of the contact between the prism and continental rock (backstop) in seismic records. At the base of the lower slope, thick trench sediment is accreted, of which about ~2 km is underthrust. Only lower slope structure indicates the intense tectonism associated with plate convergence.

Where the crest of the Juan Fernández Ridge subducts, the accretionary prism is cut by a steep cliff at the base of the continental slope. In the northern seismic profile, reflections parallel to the slope indicate mass wasting of the prism consistent with slump scars in the cliff and steep lower slope. If the 25-km-wide prism (southern line, Figure 7) represents the previously undisturbed prism north of San Antonio Canyon, subduction erosion has removed about 5 km of the prism at the northern seismic line. The long trench-parallel ridges of the active accretionary prism in the south are replaced over the Juan Fernández Ridge crest by fewer continuous morphological trends and derangement. Strike-parallel lineaments are cut by numerous transverse elements and local morphological features indicate mass wasting. The lower slope accretionary area is an erosional area where the ridge subducts.

A second difference associated with the subducted ridge is the extent of current tectonic deformation. Valparaiso Basin is the first significant forearc basin along the Chile margin south of the Peruvian border. Its position on the middle slope and deformed sediment make it a tectonic anomaly Basin sediment deformed in growth folds against the Punta Salinas Ridge, consistent with a southward ridge push during sedimentation of the upper section. The morphology is associated with the Punta Salinas Ridge itself includes crossing and disrupted trends (Figure 2b) The many well-established canyons descending the landward flank of Valparaiso Basin are absent to the north and were presumably destroyed as the ridge was uplifted. Where the ridge has subducted, current tectonism extends to the upper slope.

Large-scale tectonism from Juan Fernández Ridge is punctuated by local tectonism from smaller-scale subducting features. The recent breaching of the lower slope by the subducting Papudo Seamount left a trail across the margin. A size approximating the O'Higgins Guyot is indicated by its magnetic anomaly (Yáñez et al., submitted manuscript, 1996), but the interpretation of the seamount track is unclear without the circular magnetic anomaly (Figure 4). A possible track breaching the foot of the slope at San Antonio Canyon is suggested by its wide triangular mouth and deeply incised lower course subparallel to plate convergence. Here sedimentary rock of the accretionary prism was more easily disrupted than at Papudo Seamount. A subducting seamount explains the sudden change from a wide flat channel across the middle slope to the rough slump modified channel cutting the lower slope.

The tectonic effects of ridge subduction observed over relatively thin continental crust (middle and lower slopes) may be intensified by subsurface tectonism. As the Juan Fernández Ridge subducts, its relief increases dramatically (Figure 8). Perhaps the ridge had an original relief of almost 3 km before subduction, because its seaward extension exhibits high standing parts separated by a broad low section (Figure 1). Alternatively, the increased relief may result from differential crustal bending as the Nazca Plate is flexed into the subduction zone. In the wide-angle seismic crustal sections, the thickened crust of the ridge exhibits a broader plate-bending radius compared with the normal crust. Remarkably, the ridge is expressed at the seafloor on the upper slope. It seems unlikely that 4-km relief on a subducting plate some 20 km deep will cause a 200-m-high seafloor uplift. Attenuation through only 1-2 km of the upper plate reduced 4-km relief of Papudo Seamount to a dome only 0.4 km high. Tectonic increase of ridge relief appears likely, and the 3- to 4-km-high seamounts and a thinned layer of subducted sediment make the deeply subducted ridge a candidate for earthquake asperities in the seismogenic zone.

Tectonic changes along the Chilean continental slope associated with southward migration of Juan Fernández Ridge were only partially surveyed. Tectonic healing of the margin following disruption is assumed to occur north of the survey area. Tectonic healing of the Peruvian margin after disruption by Nazca Ridge subduction is associated with formation of Lima forearc basin on the middle slope and renewed accretion to replace the eroded precollision prism [*von Huene et al.*, 1996] At the foot of the slope in the northern part of the Chilean survey area, the beginning of renewed accretion is suggested by the rounded ridge that cuts all up-slope elements (Figures 2 and 5). A small middle slope basin in the Punta Salinas Embayment is positioned similar to Lima Basin. A better understanding of the complete tectonic process in central Chile requires further investigations to the north.

The first-order effects of the subducting lower plate on the upper one involve entry of the ridge into the trench, erosion over

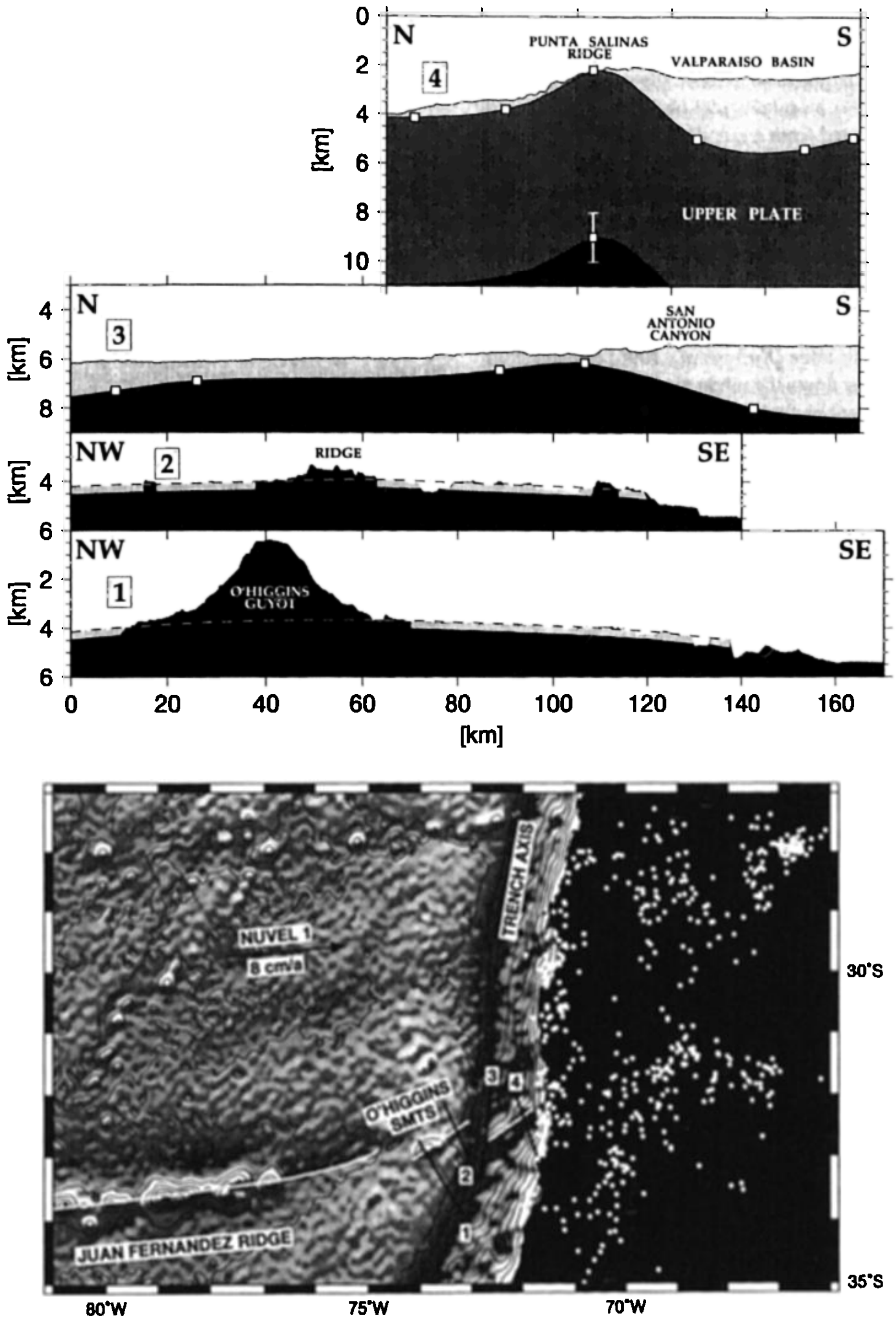

Figure 8. Profiles across the Juan Fernández Ridge. (top) Profiles 1 and 2 are across the ridge at O'Higgins Guyot and north of the seamount group. Light gray shading represents sediment, black represents basement. Profile 3 is along the Chile Trench axis showing (with squares) subsurface depths to basement along seismic profiles (V=2 km/s). Profile 4 is across Valparaiso Basin and Punta Salinas Ridge showing sediment depths. The depth of the Juan Fernández Ridge crest in wide-angle seismic data is indicated near 10 km depth. (bottom) Satellite altimetry of the Juan Fernández Ridge and adjacent continental margin (N. Didden, unpublished data, 1995) with Benioff Zone earthquakes [after *Kirby et al.*, 1996]. Lines indicate location of ridge crest from morphology and earthquakes.

its crest, and a return to normal subduction processes in its trailing wake. Features on the ocean crust impact the upper plate on two scales. When larger seamounts on the ocean floor enter the trench, they leave a morphological trail across the lower slope and can be detected from a circular magnetic anomaly to the middle slope. Conversely, the less obvious ridge itself, with its low seafloor profile, appears to gain relief as the ocean crust flexes into the trench axis to become an even more consequential tectonic element deeper in the subduction zone. It produces a diagonal transverse ridge across the seafloor bounding Valparaiso Basin where the plate boundary is from 15 km to 25 km deep (Figure 6). The elongate pattern of earthquakes through the seismogenic zone [*Kirby et al.*, 1996] extends from beneath the ridge farther down the subduction zone, suggesting a line of earthquake asperities from a subducted ridge (Figure 8). Also, Juan Fernández is one of three ridges (with Nazca and Louisville) that have swept along a margin where volcanic activity has recently stopped. All have a flat slab. Despite these arguments for the association of Juan Fernández Ridge with the Chilean flat slab, they have no clear cause and effect relationship. If the ridge continues down the subduction zone with the trend indicated by margin structure and the earthquake pattern, it would sweep the entire flat slab area in about 8 Ma. The volcanic history near 30°S indicates a decrease in volcanism associated with the flat slab beginning about 18 Ma which was complete at 9 Ma [*Kay et al.*, 1991]. The sequence of volcanic rock indicates increasing crustal thickness which by analogy to the present subduction zone is inferred to involve development of the flat slab. Reconstruction of past lithospheric configurations [*Kay et al.*, 1991] were chosen based on the southward progression of the contemporary flat slab behind Juan Fernández Ridge. The resulting model argues for an older development of the nonvolcanic margin. Thus the rapid migration of the Juan Fernández Ridge into the area as indicated in the preceding appears to conflict with evidence for much older changes in crustal configuration.

This dilemma has no clear solution but two possibilities are suggested as follows. (1) The observed change in trend is a local en echelon segment extending only across the continental slope without connecting with a feature nucleating the elongate swarm of earthquakes (Figure 8). This possibility has support from the smaller bend of the Sala y Gomez hot spot trace and the greater bend at the equivalent section of the Juan Fernández hot spot trace. The complexity of ocean crust affected by the much younger hot spot includes fractures, fossil ridges, and ridge jumps [*Cande and Haxby*, 1991; Yáñez et al., submitted manuscript, 1996]. Also, the Nazca Plate supporting the O'Higgins section of the ridge originates at the east Chile Rise and is separated by the Challenger Fracture zone from the plate originating at the East Pacific Rise [*Cande and Haxby*, 1991]. Unfortunately, most of the ocean basin containing magnetic anomalies needed for plate reconstruction is missing or subducted. (2) During subduction of a previous feature about 18 Ma, the subduction zone dip decreased. That feature was completely subducted about 9 Ma, and subsequent subduction of Juan Fernández Ridge modified an earlier flat slab or thickened crust [*Kay et al.*, 1991]. A multistage development of the flat slab and crustal thickening could be tested if a history of the accretionary prism north of this survey were known.

Conclusions

Juan Fernández Ridge strikes N80°E from its contemporary hot spot west of Alexander Selkirk Island in the Pacific Basin to the O'Higgins Seamounts. There morphology, gravity, and magnetics indicate a change in strike to N65°E The subducting ridge dams considerable sediment in the trench axis because it increases greatly in height. In the subduction zone, the ridge relief probably continues to increase and becomes asymmetrically steeper on its leading flank. Along the subducted ridge, a low dome on the seafloor over a circular magnetic anomaly locates the subducted Papudo Seamount The subducted ridge continues to be expressed at the seafloor as the 60-km-long diagonal trending Punta Salinas Ridge. Morphology over the ridge is disrupted, and Valparaiso Basin sediment is deformed against it. Continuing landward beneath the ridge is a linear pattern of earthquake epicenters with the same trend which suggests an earthquake nucleating feature extending through the seismogenic zone (Figure 8).

The Juan Fernández Ridge deforms the thin crust of the continental margin, but landward of the coast, its effects are deep seated. Features along the central Chile segment boundary such as the northern end of the Central Valley and structure in the back arc are difficult to relate to the arrival of Juan Fernández Ridge and probably have prior origins.

The diagonal trend of Juan Fernández Ridge to the direction of plate convergence entails southward ridge migration. Southward migrating tectonism as the underthrust ridge disrupts the thin upper plate is consistent with the observed deformation of forearc sediment and the altered continental margin morphology. The incompletely observed tectonism north of Juan Fernández Ridge may be similar to that of the Peru margin north of the Nazca Ridge. Accelerated erosion followed by accretion and the enlargement and destruction of forearc basins accompany subduction of the ridge. The resulting diversity of material input to the subduction zone north and south of thickened crust make this a likely area for a diagonal trending pattern of plate coupling and earthquake epicenters.

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