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Seismic anisotropy in the region of the Chile margin triple junction

Ruth E. Murdie[a,*], Raymond M. Russo[b]

[a]*Department of Earth Science, Keele University, Keele, Staffordshire, ST5 5BG, UK*
[b]*Department of Geological Sciences, Northwestern University, Evanston, IL 60208, USA*

Abstract

We have measured shear wave splitting at three temporary three-component short period stations that were deployed in southern Chile above the subducted Chile Rise spreading centre (Taitao Peninsula and environs). Subduction of the Chile Rise has been occurring beneath South America for at least the past 14 m.y. Previously published models of the ridge subduction posit the existence of 'slab windows', asthenosphere-filled gaps between subducted lithosphere segments of the spreading ridge, through which mantle might flow. Our preliminary results include two consistent fast polarization directions of splitting in the study region. Delay times between fast and slow split shear waves average around 1.0 s for all phases (ScS, PcS, SKS, and SKKS) that we measured. Fast-axis azimuths vary systematically among the three stations: near the coast, fast axes are parallel to the spreading ridge segments of the Chile Rise (approximately N-trending). This splitting fast-axis direction probably reflects either along-axis asthenospheric flow or results from the preferential attenuation effects of aligned pockets of melt at the subducted ridge segment. At one inland station above the slab window, we find two splitting fast-axis directions, one parallel to the subducted Chile Rise ridge segments, and a second trending NW–SE. We infer that upper mantle deformation in the vicinity of a well developed slab window is complicated and probably involves two superposed directions of upper mantle deformation. One of these directions (NW–SE) may indicate anomalous flow of asthenospheric mantle in the vicinity of the slab window gap. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Shear wave splitting results when shear waves pass through anisotropic media. Initially linearly polarised shear waves are split into orthogonally polarised fast and slow waves separated by a time delay (e.g., Ando 1984; Silver and Chan, 1991; Vinnik and Kind, 1993; Helffrich et al., 1994). Shear wave splitting principally occurs in the upper mantle where lattice preferred orientation of olivine crystals in aggregates is the primary source of seismic anisotropy (Hess, 1964; Gueguen and Nicolas, 1980; Nicolas and Christensen, 1987; Ribe, 1989; Mainprice and Silver, 1993). The fast polarisation direction, phi, ϕ, is aligned with the principle axis of extensional finite strain of the olivine. The delay time, δt, is dependent upon the length of the wave travel path through the anisotropic medium and on the strength of the olivine alignment (fabric) within the medium. Measurements of shear wave splitting have been used to deduce the degree and orientation of upper mantle anisotropy (Babuska and Cara, 1991), and hence the direction of upper mantle flow beneath either the receiver (Silver and Chan, 1991; Yang et al., 1995; Russo et al., 1996) or in the vicinity of the earthquake source, particularly beneath subducted lithospheric slabs (Kaneshima and Silver, 1992; Russo and Silver, 1994, Schoenecker et al., 1997). In this paper, we extend previous work on mantle flow by examining extant seismic data gathered at the site in southern Chile where the Chile Rise subducts beneath South America. Shear wave splitting observations of mantle flow here are of potentially great interest in that they may uniquely delineate asthenosphere–lithosphere interaction in a complex and interesting tectonic environment.

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* Corresponding author. Fax: +44-1782-715261.
E-mail address: gga22@keele.ac.uk (R.E. Murdie)

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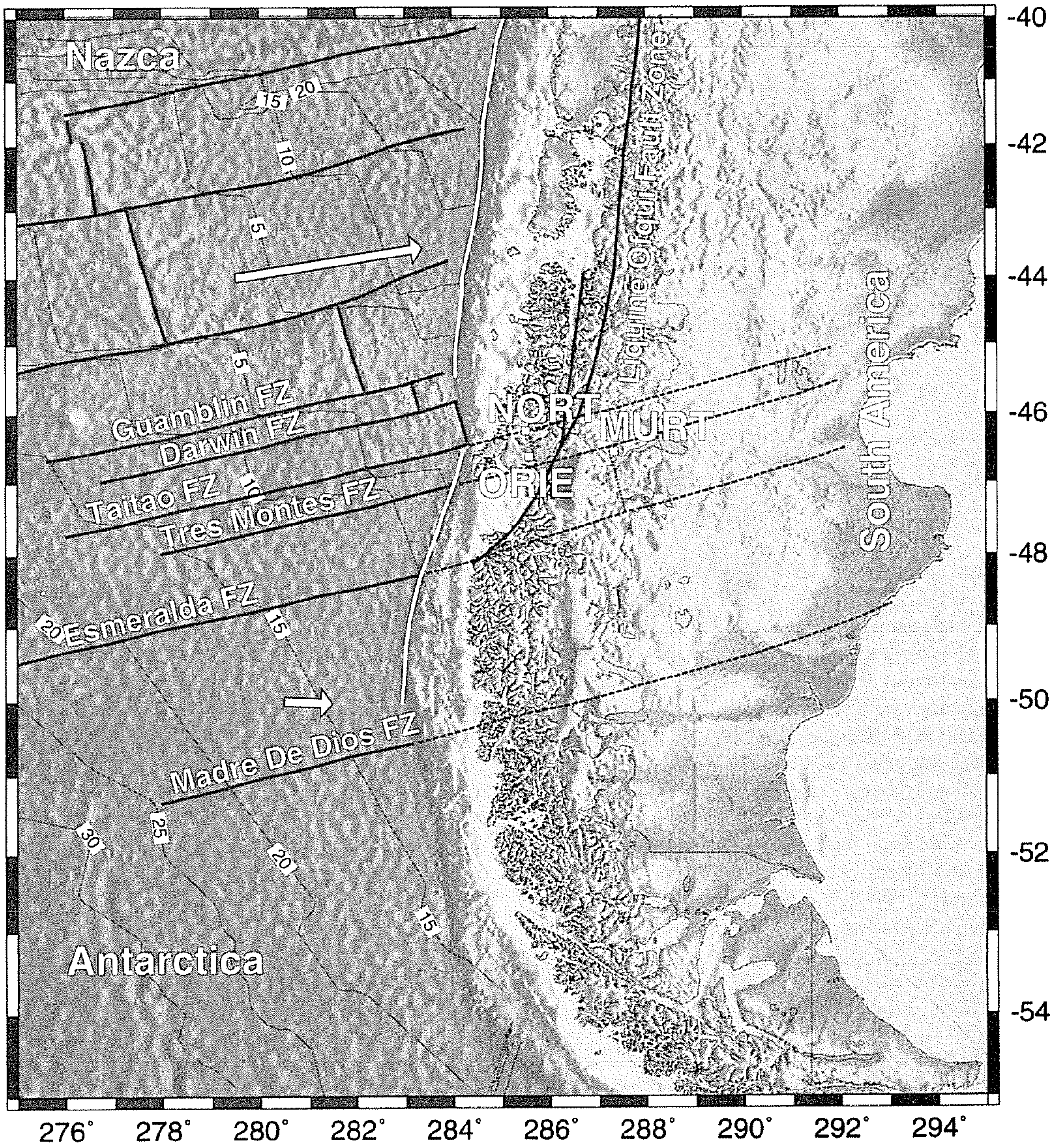

Fig. 1. Tectonic setting of the Chile Triple Junction showing the orientation of the Peru–Chile Trench, Chile Rise, and the subducted portions of the Chile Rise. Stations used in this study are labelled. Relative velocity vectors (NUVEL-1) of Nazca (top) and Antarctica (bottom) motion with respect to fixed South America are 8.3 and 2.1 cm yr^{-1}, respectively.

2. Tectonics of the study area

The Chile Margin Triple Junction at 46.5°S, 75.5°W (Fig. 1), is the best documented extant example of subduction of an active mid ocean ridge (Herron et al., 1981; Forsythe and Nelson, 1985; Cande and Leslie, 1986; Forsythe et al., 1986; Cande et al., 1987; Murdie et al., 1993; Bourgois et al., 1996). Subduction of the Nazca plate along the western coast of South America is well established on the basis of seismicity (e.g., Stauder, 1973; Barazangi and Isacks, 1976; Cahill and Isacks, 1992) and structure (Hasegawa and Sacks, 1981; Isacks, 1988; James and Snoke, 1994; Norabuena et al., 1994). However, because seismicity is less frequent (Fig. 2), subduction of the Antarctic plate beneath Patagonia is primarily indicated by large-scale plate motion studies, forearc and foreland morphology, and the active subduction related volcanism south of the triple junction. The Chile Rise has been converging with the Peru Chile Trench over the past 14 Ma (Cande et al., 1987). Convergence between the easternmost Chile Rise and South America at the trench (Fig. 1) is a bit over 8 cm yr^{-1} directed N79E (NUVEL-1 pole, DeMets et al., 1990). Subduction dip

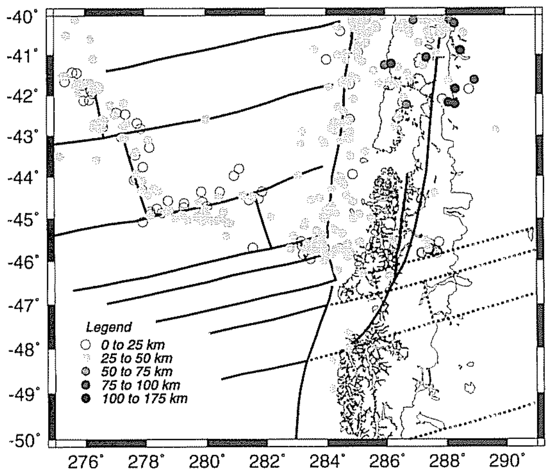

Fig. 2. Seismicity of the study region, data from US National Earthquake Information Center, 1963–1996.

where the Rise enters the Nazca Trench is very shallow, 10–15° (Bangs et al., 1992). The overall trend of the Rise is WNW, with ridge segments striking slightly west of N, and transforms that strike ENE. Thus, ridge segments approach the trench at a very shallow angle, just anticlockwise of parallel to the trench, and Chile Rise transforms enter the trench at a very high angle. This has meant that as subduction of the ridge proceeds, the triple junction between the Nazca, Antarctic, and South American plates has migrated rapidly northwards during subduction of ridge segments, but it has migrated slowly southwards during episodes of subduction of transforms, yielding a net northward triple junction migration. Subduction of both ridges and transforms, in sequence and diachronously along the Patagonian subduction zone, has had a profound impact on the structure and tectonics of the continental margin (Cande and Leslie, 1986; Cande et al., 1987).

The most recent subduction of a ridge segment, now occurring just offshore of the Taitao-Tres Montes Peninsulas (Fig. 1), has been associated with: variable structure of the continental forearc (Cande and Leslie, 1986; Cande et al., 1987); obduction of a Plio-Pleistocene ophiolite sequence (Forsythe and Nelson, 1985; Nelson et al., 1993; Bourgois et al., 1996) and recent volcanism on the Tres Montes Peninsula anomalously close to the trench (Forsythe et al., 1986; Lagabrielle et al., 1994); a gap in the active Patagonian volcanic arc (Cande and Leslie, 1986; Ramos and Kay, 1992); eruption of plateau basalts in western Argentina (Charrier et al., 1979; Ramos and Kay, 1992; Gorring et al., 1997); important differences between structures, morphology, and evolution in foreland areas north and south of the present triple junction (Ramos, 1989; Flint et al., 1994; Ray, 1996); and anomalous isotopic signatures from rocks dredged from Chile Rise ridge segments at or adjacent to the trench (Klein and Karsten, 1995; Karsten et al., 1996).

Studies of ridge subduction invoke the concept of a 'slab window' to frame discussions of the tectonics of

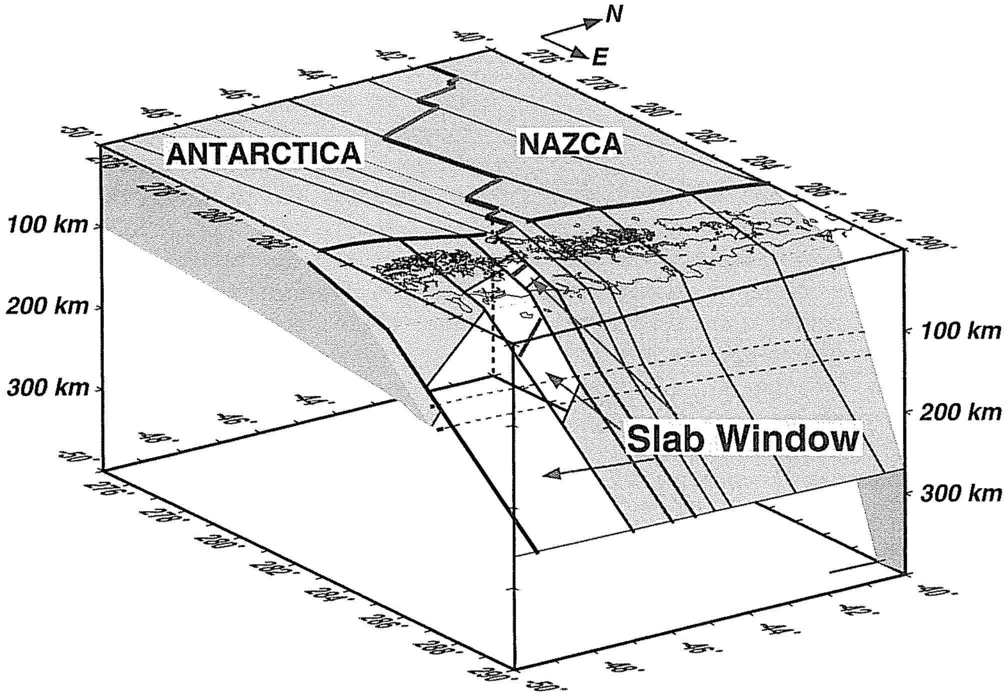

Fig. 3. Schematic of slab window tectonics. View is from the SE looking NW.

Table 1
Earthquakes studied and splitting parameters

Event	Date	Time (UT)	Latitude (degrees)	Longitude (degrees)	Depth (km)	Magnitude (m_b)	Station	Phase	Result	ϕ	δt
92013	13.01.92	09.37.43	−20.930	−178.717	575	5.6	MURT	SKS	Null	11 ± 23	
92025	25.01.92	17.11.12	−50.432	−72.168	33	5.1	NORT	ScS	Null	36 ± 23	
92027	27.01.92	09.52.58	−21.488	−68.001	146	5.0	MURT	ScS	Measured	353 ± 5	1.4 ± 0.12
92036	05.02.92	02.32.04	−23.217	−66.661	201	4.6	MURT	ScS	Measured	306 ± 6	0.64 ± 0.8
92036	05.02.92	05.33.14	45.185	150.896	54	5.6	NORT	SKKS	Measured	348 ± 3	1.28 ± 0.1
92037	06.02.92	03.14.58	−40.114	−74.867	35	5.0	MURT	PcS	Null	357 ± 2	
92042	11.02.92	23.56.08	−22.553	−67.412	159	4.7	MURT	ScS	Measured	350 ± 15	0.88 ± 0.8
92042	11.02.92	23.56.08	−22.553	−67.412	159	4.7	ORIE	ScS	Measured	23 ± 13	1.12 ± 0.12
92044	13.02.92	17.28.21	−24.433	−66.977	169	4.1	MURT	SKS	Measured	297 ± 4	3.3 ± 0.4
92044	13.02.92	17.28.21	−24.433	−66.997	169	4.1	ORIE	ScS	Null	1 ± 14	

asthenospheric mantle regions of the subduction zone and of the overriding lithospheric plate (Delong and Fox, 1977; Dickinson and Snyder, 1979; Ramos and Kay, 1992; Kay et al., 1993; Thorkelson and Taylor, 1989; Thorkelson, 1996; Gorring et al., 1997). Implicit in the slab window idea is the assumption that spreading between the two sides of the subducted ridge continues after subduction, but that no new lithosphere is formed after subduction, leading to a progressively widening asthenospheric mantle-filled gap between the two edges of the former ridge (Fig. 3). Obviously, formation of a slab window of this type requires a highly mobile fluid mantle to fill the increasing volume of the window. Although the exact form of slab window mantle flow is unknown, such mantle flow should be detectable via shear wave splitting analysis, and we have attempted to characterise the Chile Rise subduction slab window flow field using splitting observations.

3. The network

An array of nine three-component Willmore seismometers recording on Reftek Digital Acquisition Systems was set out in Southern Chile between 45.4° and 46.6°S and 72.1° and 74.6°W for two three-month periods, January to March, 1991 and 1992. These stations were set to record continuously sampling at 25 samples per second. From this dataset, high quality seismograms of nine earthquakes were selected for shear wave splitting analysis from three of these stations. Because the short period recording band of the seismometers is not ideal for recording S waves, and because the recording periods were short, our useful data set is limited.

4. Shear-wave splitting measurements

We have used two seismic phases to deduce the anisotropy of the mantle in the region of the Chile Margin Triple Junction. SKS or SKKS phases from earthquakes at epicentral angles between 87 and 150°, and ScS or PcS phases from earthquakes between 0 and 30°, are suitable for splitting analysis. The SKS and SKKS phases pass through the core as compressional (P) waves and on leaving the core convert to shear waves with radial polarisation only. Hence any splitting detected at the receiver will be due to anisotropy of the mantle below the receiver only. PcS is similarly useful because of its conversion from P to S at the core–mantle boundary (CMB), although no assumptions about the polarity of the phase can be made, as is possible for SK(K)S. ScS can also be used to deduce anisotropy at the receiver, although the phase may also be split during its downward passage through the mantle from the earthquake source to the CMB. Source information for the all the earthquakes we used are given in Table 1.

We used the method of Silver and Chan (1991) to determine splitting parameters ϕ, (fast polarisation azimuth) and δt (the delay time), for the small data set we have. This method is based on the assumption that the symmetry axis of upper mantle olivine linear preferred orientation is horizontal, which imposes a limitation on our interpretations. However, observations of splitting indicate that this assumption is generally valid, since steeply plunging symmetry axes should yield no observed splitting for steeply incident waves such as SKS and ScS. Because the data were recorded on short period seismometers, in some cases we altered the maximum allowable delay time in the grid search for splitting parameters to 1 s (instead of their standard 4 s) to avoid spurious delay time estimates from cycle skipping. Example waveforms are shown in Fig. 4, results from each earthquake which gave a usable S phase are given in Table 1, and a map of the results is shown in Fig. 5. Several of the measurements were 'nulls', indicating that there is either no splitting or that the fast or slow polarisation azimuths are parallel or perpendicular to the phase polarisation. Currently there is no way to distinguish between these two possibilities. Nulls are shown on Fig. 5 as crosses with branches in the two possible ϕ directions.

At station MURT (Fig. 5), three ScS ϕ measurements have polarization azimuths in the northwest quadrant (events 92027, 92036, and 92042). Two of the measurements are very similar (ϕ of 353 ± 5 and 350 ± 15, δt of 1.4 ± 0.1 and 0.9 ± 0.8), but the third is quite different (ϕ of 306, δt of 0.6 ± 0.8). All three measurements were made on ScS phases, which means that complications from source-side splitting are a distinct possibility. However, a fourth measurement, a clear observation of splitting of an SKS phase has a ϕ direction of 297 ± 4 and a δt of 3.3 ± 0.4 s. The fast axis azimuth for this measurement is very similar to the third ScS measurement mentioned above, but the delay time is grossly inconsistent with the small delay (0.6 ± 0.8 s) estimated for that event. The delay time of the ScS event is poorly constrained and both delay time measurements may be adversely affected by filtering of the data. Nonetheless, the consistency of the two groups of ϕ directions we obtain for these measurements is reasonably good evidence that the measurements are accurate in fast angle estimation. Two other readings at MURT are nulls (events 92013 and 92037) from an SKS phase and a PcS phase. Neither phase carries source-side splitting information and both have potential ϕ directions close to N–S, similar, within estimated errors, to the slightly west of north ϕ directions of events 92027 and 92042.

For station NORT (Fig. 5), closer to the coast than station MURT, we have a single measurement from event 92036, an SKKS phase from the Kurile Islands. The ϕ is 348 ± 3, and δt is 1.3 ± 0.1 s, similar to one

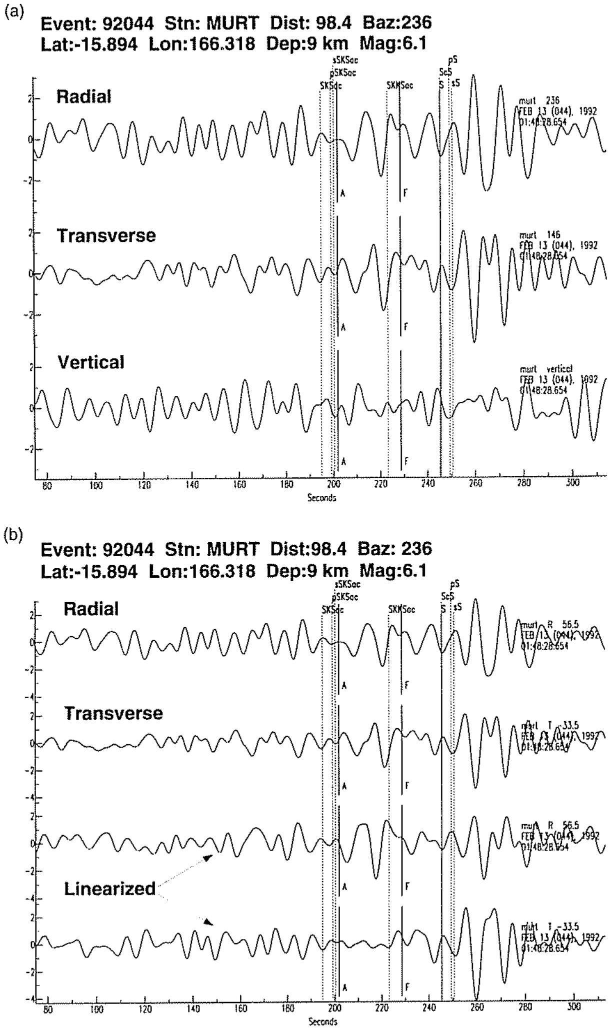

Fig. 4. Splitting measurement for event 92044 at station MURT. (A) SKSphase in the fast-slow motion frame. (B) Same as (A), delay removed; note good waveform coherence. (C) Elliptical particle motion corresponding to waveforms in fast-slow frame (A). (D) Linearized particle motion after delay time correction (B). (E) Result of grid search for best ϕ and δt values. Star is the best estimate of splitting parameters. Double contour is 95% confidence interval.

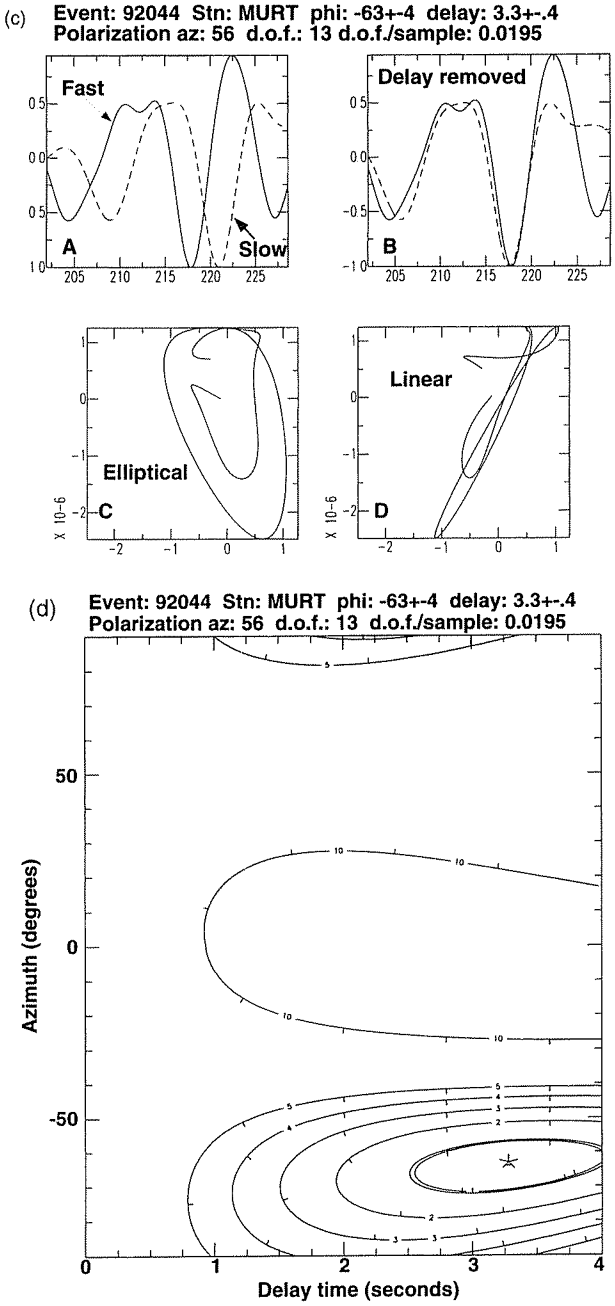

Fig. 4 (*continued*)

group of the consistent measurements and the nulls at MURT. The other measurement at NORT is a null with possible ϕ angles to the northwest and northeast. This null derives from an ScS phase, and given the consistency of the null and the measurement phi directions, it is unlikely that this ScS phase carries a significant source-side signal.

Station ORIE lies about 30 km south of NORT (Fig. 5). We made two measurements on ScS phases recorded at this station. Event 92042 gives a ϕ of 23 ± 13 and a delay time of 1.3 ± 0.1 s, and event 92044 is a null with possible fast directions trending N–S. The measurement and the null are reasonably consistent in indicating a N–S ϕ azimuth for this station.

5. Discussion

Of the six measurements we made, three have ϕ azimuths just west of north, whereas two are to the northwest (event 92036 at MURT). The null measurements all have one of two possible splitting fast axes

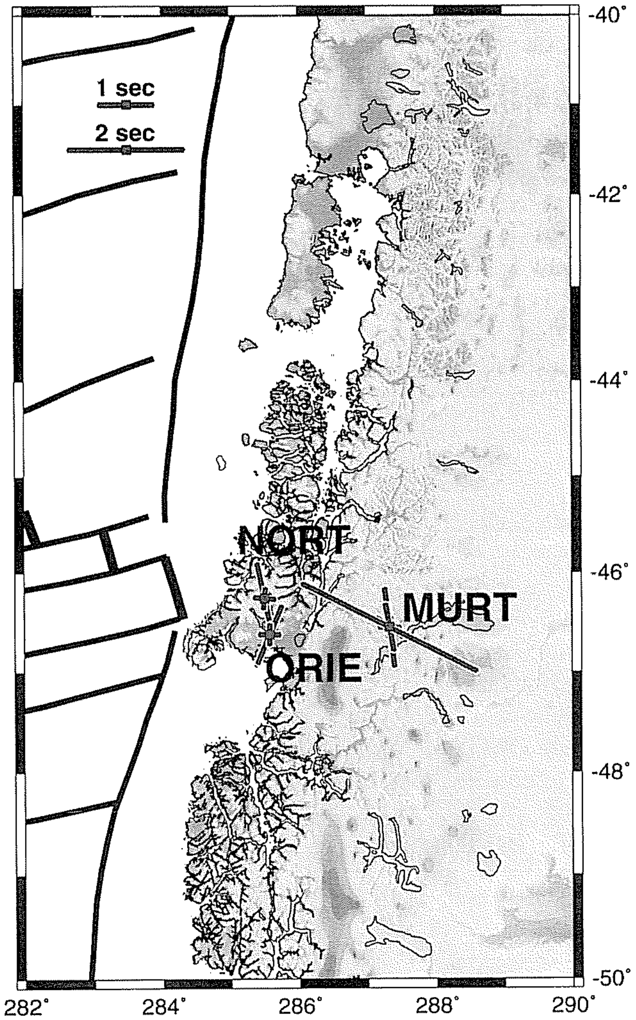

Fig. 5. S-wave splitting fast polarisation directions. Splitting parameters are plotted as a vector, length proportional to delay time (see scale) and azimuth parallel to ϕ, at the three station sites.

trending N–S, generally consistent with co-located observed measurements. Our data set is limited in both the number of events and in the recording frequency of the seismometers, and therefore this splitting data set can only be regarded as very preliminary. Nevertheless, the overall consistency of the measurements is encouraging: most of the fast axis measurements lie parallel to the trend of the Chile Rise, and the nulls are either parallel or perpendicular to the orientation of the Chile–Peru trench. The second, northwestern ϕ direction we obtain at station MURT (events 92036 and 92044) probably results from a superposition of differently deformed mantle beneath that station.

In order to correctly interpret our results, it is necessary to discuss briefly potential sources of anisotropy beneath the three recording stations. In our Southern Chile study region, the subsurface volume sampled by shear waves travelling to the network includes South American continental crust and mantle, the crust and mantle of the subducted Nazca and Antarctic plates, and asthenospheric mantle in the slab window and perhaps in the mantle wedge overlying the subducted slab(s). We rule out significant contributions to the observed splitting from the South American continental crust, and from the supra-slab upper mantle wedge, where it exists, because observed splitting along crustal and mantle wedge paths from up-going shear waves leaving the subducted Nazca slab in the northern and central Andes is restricted to very small delay times (0.1–0.2 s; Shih et al., 1991; Kaneshima and Silver, 1995; Polet et al., 1996), whereas, the delay time estimates we are confident of are around 1–1.4 s. Thus, although it has been shown that anisotropy can develop quite strongly within subduction zone mantle wedges (Ribe, 1989), this is apparently not observed along the Nazca subduction zone. Also, beneath the network we used, the dip of the subducting plates is so shallow (15° according to Bangs et al. (1992)) that there is very little mantle wedge overlying the slab at the longitude of the network, and none at all for near-trench stations ORIE and NORT (Fig. 5). Hence, any splitting we see is most likely imparted in the mantle beneath the subducted oceanic plates, or in the asthenospheric slab window, or both.

Although the data set is small and preliminary, there does appear to be a consistent fast polarisation direction sub-parallel to the trend of the ridge segments of the Chile Rise, and to the subduction trench. This result is counter to expectations based on assumed two-dimensional flow fields at spreading ridges (Blackman et al., 1993), and also does not fit models of mantle deformation in a decoupling asthenosphere, which should yield fast anisotropy axes parallel to absolute plate motion (Vinnik et al., 1989; Russo and Okal, 1998). Both these processes, assuming splitting results primarily from development of moderate lineation fabrics of upper mantle olivine, should result in generally east–west mantle flow and phi directions, given (1) the generally east–west spreading direction along the Chile Rise (Cande et al., 1987); and (2) the velocities of the subducting plates relative to the hotspots, which are towards the east at a rate of 7 cm yr^{-1} for the Nazca plate and 2 cm yr^{-1} for the Antarctic plate (Gripp and Gordon, 1990).

Splitting data from Russo and Silver (1994) show that along the South American margin, shear wave splitting phi trends often lie parallel to the Nazca trench. Those authors proposed that slab lithosphere and its underlying mantle are largely decoupled, and that asthenospheric mantle is displaced and diverted around South America as the Nazca slab retreats westward yielding net mantle flow along strike of the slab. The slab in this case acts as a solid boundary between the Pacific and South American mantles. However, at the latitudes of Southern Chile, the slabs are very young, buoyant, and dip very shallowly (Bangs et al., 1992). Also, as the Chile Rise has entered the subduction zone, the Nazca and Antarctic plates have continued to separate leaving a slab window (Thorkelson and Taylor, 1989; Thorkelson, 1996; Gorring et al., 1997). The slab window could act as a pathway for sub-Nazca slab mantle to flow eastward. It is possible that the NW–SE trending fast polarisation directions we observed at station MURT indicate mantle flow towards the southeast, potentially through the well-developed slab window beneath that station (Figs. 1 and 3).

The ridge-axis parallel fast polarisation directions could be considered odd if flow in the vicinity of the ridge is assumed to be strictly two-dimensional. Normally, one would expect to see fast axes of anisotropy trending in the spreading direction at a mid ocean ridge (Nishimura and Forsyth, 1988; Montagner and Tanimoto, 1990; Tommasi et al., 1996). However, studies of ophiolites commonly show evidence for along-axis asthenospheric flow (Nicolas, 1989; Boudier and Nicolas, 1995; Nicolas and Boudier, 1995), and such flow has been inferred from seismic studies of mid ocean ridges (Blackman et al., 1993; Wolfe and Solomon, 1998). Alternatively, it is thought that asthenospheric upwelling at the site of the subducted mid ocean ridge continues after subduction, although new crust is no longer formed. Thus, mantle flow in the vicinity of the ridge could be predominantly two-dimensional upwelling overturning to flow perpendicular to the ridge, and the splitting we see could be due to magma-filled dikes or cracks trending along the ridge segments (Gao et al., 1997). Finally, it has been suggested that a weak plume lies under Southern Chile (Abbott, 1996) and has been responsible for the eruption of Tertiary plateau basalts (Gorring et al., 1997). Anomalous low gravity in the area has also been attributed to a possible thermal anomaly (Murdie et al., 1999). It is possible that the shear wave splitting we observe reflects flow associated with a weak hotspot.

6. Conclusions

Although our data are preliminary, we have found two consistent fast polarisation directions of splitting in the region where the Chile Ridge subducts beneath South America. These measurements show that there is anisotropy within the mantle in the region of the Chile Triple Junction. Near the coast, the dominant orientation of the splitting appears to lie parallel to the subducted portions of the Chile Rise. This splitting fast-axis direction may reflect either three-dimensional flow, including a significant along-axis component, at the subducted spreading ridge; or the effects of ridge-aligned pockets of melt; or flow associated with a weak hotspot in this area. Further inland, we find two splitting fast-axis directions, one parallel to the subducted Chile Rise ridge segments, and a second trending NW–SE. Vertical flow of mantle can not be constrained by this method. However the splitting directions we observe are not parallel to the subduction direction as may be expected and we infer that upper mantle deformation in the vicinity of this well developed slab window is complicated and may involve two superposed directions of upper mantle deformation.

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