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A narrowly spaced double-seismic zone in the subducting Nazca plate

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[1] High-precision relocations of intermediate-depth earthquakes (80–130 km) below the Central Andes reveal a fine-scale double-layered Wadati-Benioff zone (WBZ). Upper and lower band of seismicity are separated by about 9 km and occur at the top of the oceanic crust and in the uppermost oceanic mantle, respectively. Analysis of focal mechanisms and waveform similarities indicate that fluid processes are causing the events. Earthquakes in the oceanic crust occur on pre-existing normal faults due to hydraulic embrittlement from metamorphic dehydration, and on subvertical faults that connect the two layers in a narrow depth range. Extensional faulting predominates in both layers, indicating that slab pull forces are the dominant stress source superseding possible unbending forces in this segment of the Nazca plate. *INDEX TERMS:* 7218 Seismology: Lithosphere and upper mantle; 7220 Seismology: Oceanic crust; 7230 Seismology: Seismicity and seismotectonics; 8123 Tectonophysics: Dynamics, seismotectonics; 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Rietbrock, A., and F. Waldhauser (2004), A narrowly spaced double-seismic zone in the subducting Nazca plate, *Geophys. Res. Lett.*, *31*, L10608, doi:10.1029/2004GL019610.

1. Introduction

[2] While it is generally accepted that metamorphism in the down going lithosphere plays an important role in the generation of intermediate depth earthquakes in the WBZ [*Kirby et al.*, 1996; *Dobson et al.*, 2002; *Hacker et al.*, 2003a, 2003b], views differ on how and where exactly within the subducting plate such processes may cause brittle failure. A major impediment in understanding WBZ seismicity is the limited accuracy with which we know the location of the hypocenters. In general, uncertainties in hypocenter locations are larger than the scale-length of the tectonic units in which they occur (a few km for oceanic crust), with depth more poorly constrained than the epicenter. This is mainly because of the complex velocity structure of subduction zones, and the limited amount and quality of locally recorded WBZ earthquakes. Therefore, most previous analyses of intermediate depth WBZ seismicity at the crustal scale were based on focal mechanisms and inferred stress-depth profiles in the subducting oceanic lithosphere [*Fujita and Kanamori*, 1981; *Comte and Suarez*, 1994; *Igarashi et al.*, 2001]. By combining precise relative locations, seismic reflection data, and receiver function models, *Cassidy and Waldhauser* [2003] showed that earthquakes in the subducting Juan de Fuca plate occur in both the oceanic crust and in the uppermost oceanic mantle, indicating a narrowly spaced (<10 km) double-seismic zone.

[3] In recent years several temporary local seismic arrays have been deployed to study the geometry of the WBZ below South America. Evidence for a conventional widely spaced (>20 km) double-layered WBZ (DWBZ) was found near Arica at approximately 19°S latitude [*Comte et al.*, 1999]. Near Antofagasta at about 24°S latitude, *Comte and Suarez* [1994] proposed a DWBZ (also with a separation >20 km) based on focal mechanisms and assuming that different stress regimes exist in the upper and lower seismic zone. Later studies, however, using more and higher quality data, could not support this result [*Rudloff*, 1998]. In this paper we present and discuss precise relative locations of intermediate-depth seismicity near the top of the subducting Nazca plate that show a DWBZ with a clear separation of less than 10 km.

2. Data and Method

[4] Between 20°S and 23°S latitude, covering the forearc as well as the western part of the Altiplano Plateau in Northern Chile and Southern Bolivia, the seismic array of the ANCORP 1996 experiment [*Rietbrock et al.*, 1997], which was part of the steep-angle ANCORP profile [*ANCORP Working Group*, 1999], recorded 1050 local events between December 1996 and February 1997 with magnitudes (M_L) between 1.0 and 4.7 (Figure 1). These data, consisting of manually picked P- and S-wave arrival times, were used in a full inversion for 3-D velocity structure and hypocenter locations, revealing a rather complex three-dimensional structure of the downgoing Nazca plate [*Rietbrock and Haberland*, 2001]. We chose an undisturbed part of the slab near 22°S latitude (red box in Figure 1) containing 240 earthquakes (M_L = 1.3–4.7) to study in detail the seismic processes associated with subduction. Even though the 3-D located seismicity in the selected area shows a relatively sharp 16 km wide, dipping band of seismicity, no detailed internal structure was resolved, although some indication of a separation into two seismicity bands can be observed in some areas (Figure 2).

[5] To study the internal seismicity structure in more detail we use the double-difference (DD) algorithm *hypoDD* [*Waldhauser and Ellsworth*, 2000; *Waldhauser*, 2001] to remove remaining path effects from event locations that were derived from 3-D tomography, and to maximize the value of cross-correlation data. The DD method minimizes residuals between observed and calculated travel-time differences for pairs of closely located earthquakes, assuming that ray paths from such events to a common station are similar enough to allow common mode travel-time errors to be removed. Travel-time differences from manually picked P- and S-phases (for events less than 15 km apart from each

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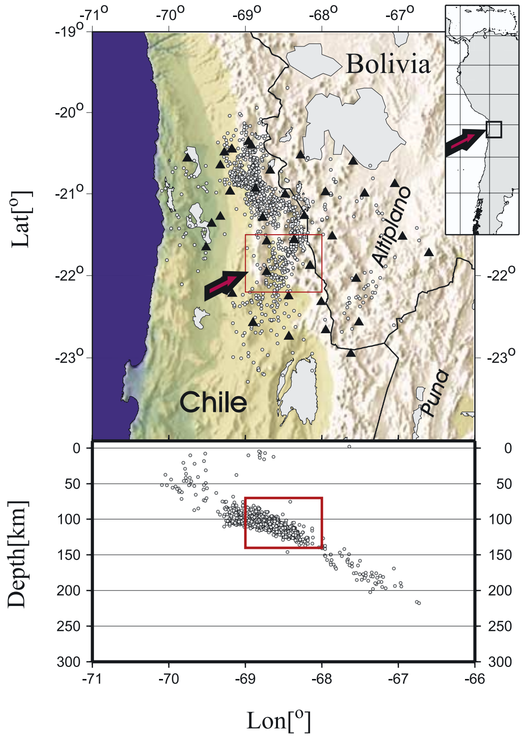

Figure 1. Map of the Central Andes, showing passive seismic stations of the 1996 ANCORP experiment (black triangles). 1050 locally recorded seismic events (open circles) were manually inspected and located. Lower panel shows a depth section of the seismicity located using a 3-D velocity model [*Rietbrock and Haberland*, 2001]. Red squares include the events analysed in this study.

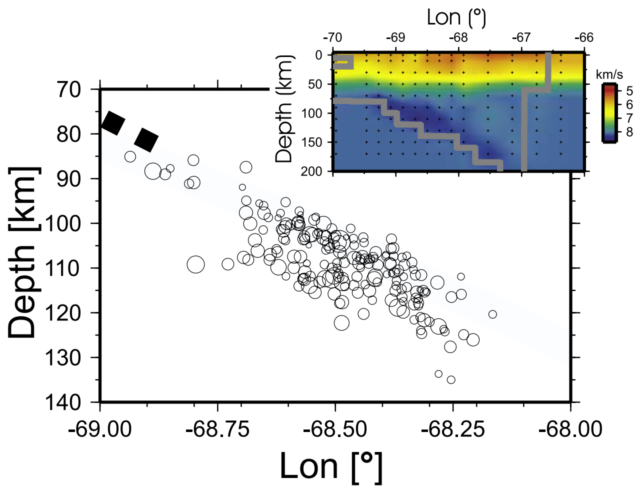

Figure 2. 240 earthquakes located by a 3-D tomographic inversion of P- and S-phase arrival times. Inset shows the P-wave velocity model for the corresponding cross section. Events between 21.5°S and 22.2°S were projected onto the section (see red box in Figure 1). Size of circles corresponds to event magnitude ranging from M_L 1.3 to 4.7.

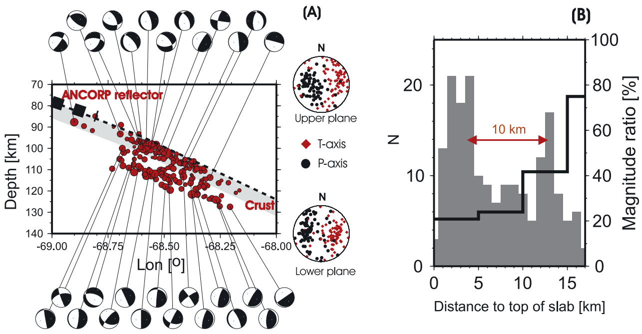

Figure 3. (a) Relocated seismicity of Figure 2) and fault plane solutions based on first-motion polarities (lower hemisphere projection). Individual mechanisms are shown for events with magnitude $M_L > 2.5$. P-axes (pressure) and T-axes (extension) are shown in a combined stereographic plot for both the upper and lower band seismicity. Superimposed on the seismicity is the thickness of the oceanic crust as derived from offshore refraction profiles [*Patzwahl et al.*, 1999]. The top of the Nazca plate (dashed line) is inferred from steep-angle reflection profiles to the north [*ANCORP Working Group*, 1999] and south [*Yoon et al.*, 2003]. (b) Depth distribution of the relocated events with respect to the top of the Nazca plate (gray bars) and precentage of earthquakes with $M_l \geq 2.5$ (black line).

other) and accurate differential times derived from cross-correlating 2.56-second windows around the P-wave train are combined and simultaneously inverted for separation distance in an iterative weighted least-squares procedure. Inter-event distance and residual misfit weighting are applied after each iteration to optimize data quality dynamically during the relocation process. We use the 3-D tomographic velocity model of *Rietbrock and Haberland* [2001] (Figure 2) to predict travel-time differences and partial derivatives for the event locations in the strongly heterogeneous structure of the subducting slab. We find, however, that differences between solutions based on the 3-D and a layered 1-D model are small (<1 km on average),

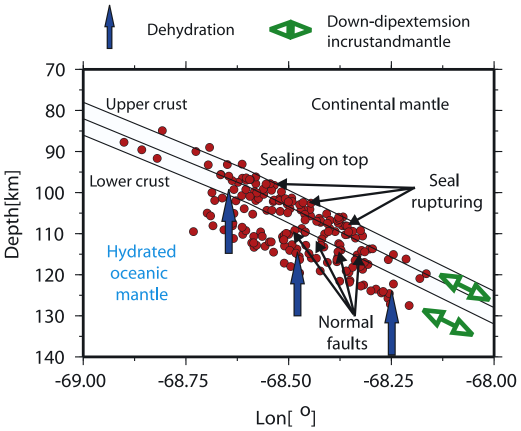

Figure 4. Interpretive cross section based on our findings. The upper oceanic crust is intensively fractured and hydrated leading to seismic events with strongly correlated waveforms. The lower crust exhibits only patches of seismicity in localized areas aligned at deep penetrating outer rise faults [*Peacock*, 2001; *Seno and Yamanaka*, 1996]. Uprising fluids from the mantle increase the fluid pressure and enable brittle failure on these faults. The oceanic mantle shows a more widely distributed seismicity, which we infer to be linked to the deep penetrating faults.

indicating that inter-event distances for linked events are smaller than the scale length of the tomographic velocity variation. Both formal least squares errors and errors from a bootstrap analysis show average horizontal and vertical relative errors of about 0.3 km. These errors are much smaller than the scale of the structures we like to resolve.

3. Results

[6] Out of the 240 selected earthquakes 238 could be relocated and the results show a clear separation into two bands of seismicity (Figure 3a). The distribution of depths, calculated from the top of the upper seismic layer, indicates a distance between the two layers of 8–10 km (Figure 3b). The top of the upper seismic layer correlates with a dipping reflector (Nazca-reflector) that was imaged at somewhat shallower depths to the west between 80–85 km (Figure 3a), and considered to represent the top of the subducted Nazca plate [*ANCORP Working Group*, 1999; *Yoon et al.*, 2003]. Thus, seismicity in the upper band occurs near the top of the down going oceanic crust, just beneath its interface with the South American continental mantle. Since the crustal thickness of the subducting Nazca plate, determined by wide-angle reflection profiles, is about 8 km [*Patzwahl et al.*, 1999], we infer that the lower seismicity band is in the uppermost subducting oceanic mantle. Because there are uncertainties associated with the absolute location of the earthquakes (3–5 km) and with the vertical position of the ANCORP reflector in the study area we cannot completely rule out the possibility that the upper and lower seismic bands are located in the continental mantle and lower oceanic crust, respectively. We can rule out, however, the possibility of both bands laying in the oceanic crust.

[7] Between the two bands of seismicity, a zone of approximately 5 km width with low seismic activity exists. This zone appears to correspond to a less than 5 km thick low-velocity layer (-7%) observed from the analysis of guided waves in this region down to 160 km depth [*Martin et al.*, 2003]. Such a low-velocity zone may represent untransformed lower oceanic crust, supporting our interpretation that all of the seismic activity occurs in the oceanic plate.

[8] Focal mechanisms based on P-wave first motions [*Reasenberg and Oppenheimer*, 1985] for events with $Mw > 2.5$ show predominantly extensional faulting for both crustal and mantle events (Figure 3a). Pressure (P) and tensional (T) axes for all events indicate clear down dip extensional regimes in both seismic layers. In the upper band, the P-axes are aligned predominantly normal to the slab, while the T-axes are oriented in many slab-parallel directions. In the lower band, P-axes are distributed in a plane perpendicular to the down-dip direction of the slab, while the T-axes are predominately down-dip. These observations are in contrast with findings from Northeast Japan (a cold slab environment), where events with down-dip tension occur near the slab surface, and more numerous down-dip compression events occur 5–20 km below the slab surface [*Igarashi et al.*, 2001].

4. Discussion

[9] A generally accepted mechanism for the generation of intermediate depth seismicity is dehydration of hydrous minerals. Such minerals are believed to form in oceanic crust by hydrothermal circulation at mid-ocean ridges. Hydration processes in the mantle may be stimulated by normal faulting beneath outer rises [*Peacock*, 2001], the existence of volatile rich mantle plumes [*Seno and Yamanaka*, 1996], and/or the cooling history of the oceanic plate [*Wang*, 2002]. This water is subsequently released during subduction by dehydration of hydrous minerals, which can lead to high pore pressures and reduction of effective normal stress, and hence promote faulting by dehydration embrittlement [*Kirby*, 1995].

[10] In the subducting oceanic crust at intermediate depths, eclogite formation is the most dominant source for water. This transformation is accompanied by a density increase and thus up to 10% volume reduction that induces a stretching deformation in the oceanic crust [*Kirby et al.*, 1996]. The stretching deformation is accomplished by nearly randomly oriented pre-existing fractures in the oceanic crust (in plane distribution of the T-axes), resulting in normal faulting events.

[11] In the uppermost mantle the down-dip alignment of T-axes indicates that slab-pull forces are the dominant stress source, superseding possible unbending forces in this segment of the Nazca plate. Given the contradictory observation by *Igarashi et al.* [2001] below NE Japan it appears, therefore, that normal faulting events in the oceanic crust occur regardless of the apparent stress field in the underlying oceanic mantle. It is possible that the metamorphic strain rates are much higher than any bending or unbending forces that might act on the slab [*Wang*, 2002; *Cassidy and Waldhauser*, 2003]. Crustal densification can introduce some compressional stresses in the underlying mantle [*Kirby et al.*, 1996] but they cannot offset the stresses introduced by slab-pull forces. *Wang* [2002] proposed a model of unbending combined with dehydration embrittlement for the generation of double and triple seismic zones in cold slabs, but young and warm slabs may work differently.

[12] In general more and smaller events are occurring in the oceanic crust, while fewer and larger events are in the mantle (Figure 3a). A higher percentage of events with $M_l \geq 2.5$ occur in the lower band compared to the upper band (Figure 3b). Although the three-month observation period may not be long enough for a representative magnitude distribution, a similar observation over an 8-year period has been made for events in the subducting Juan de Fuca plate [*Cassidy and Waldhauser*, 2003]. It is possible that the interface between the oceanic crust and the continental mantle represents, beside a change in rheology, a low-permeability seal [*Davies*, 1999] that acts as a barrier against upwelling fluids released by dehydration processes in the down going mantle and crust. The increasing pore pressure at the top of the oceanic crust may cause periodic rupturing of the seal, causing many small earthquakes immediately beneath the interface (Figure 4). Such a process would explain the extremely sharp transition from seismicity to aseismicity at the interface between oceanic crust and continental mantle. We note that for the NE Japan subduction zone relatively few events seem to occur in the top band [*Igarashi et al.*, 2001], but this may be explained by a higher magnitude cutoff in this dataset that misses many of the smaller ($M_L < 2.5$) events.

[13] The high degree of waveform similarity for events in the oceanic crust suggests that fluids from dehydration move up along pre-existing faults. These faults fail by events with similar rupture characteristics by hydraulic embrittlement as increased pore pressure reduces the effective normal stress and brings the oceanic crust into the brittle regime. While high correlation coefficient (>0.75) are found for event pairs that parallel the top of the slab, nearly vertical structures are found for events in the lower crust and upper 5 km of the mantle. These sub-vertical structures seem to connect both seismicity bands and may be interpreted as deep penetrating faults, which are (re)activated by fluid flow in a depth range between 105 km and 115 km (Figure 4). Above and below this depth range only a few events occur in the intermediate (mostly aseismic) layer. Thus, dehydration embrittlement caused by hydrous minerals that are generated at the trench due to bend-faulting appears to occur in a narrow depth interval.

[14] It can be speculated that multiple layering of WBZ seismicity at intermediate depths is a much more common feature than previously thought. Such fine scale features are most likely buried in the large uncertainties generally associated with WBZ earthquake locations. Previous studies proposed the existense of double-seismic zones when bands of different stress regimes were observed. Here we presented precise relocations of earthquakes in the Nazca plate that delineate a narrowly spaced double-seismic zone, with similar stress regimes in both layers. We postulate, therefore, that in general intermediate-depth seismicity occurs in double WBZ, and known double WBZ are likely triple WBZ.

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References

ANCORP Working Group (1999), Seismic reflection image revealing offset of Andean subduction-zone earthquake locations into oceanic mantle, *Nature*, *397*, 341–344.

Cassidy, J. F., and F. Waldhauser (2003), Evidence for both crustal and mantle earthquakes in the subducting Juan de Fuca plate, *Geophys. Res. Lett.*, *30*(2), 1095, doi:10.1029/2002GL015511.

Comte, D., and G. Suarez (1994), An inverted double seismic zone in Chile—Evidence of phase-transformation in the subducted slab, *Science*, *263*, 212–215.

Comte, D., L. Dorbath, M. Pardo, T. Monfret, H. Haessler, L. Rivera, M. Frogneux, B. Glass, and C. Meneses (1999), A double-layered seismic zone in Arica, northern Chile, *Geophys. Res. Lett.*, *26*, 1965–1968.

Davies, H. (1999), The role of hydraulic fractures and intermediate-depth earthquakes in generating subduction-zone magmatism, *Nature*, *398*, 142–145.

Dobson, D. P., P. G. Meredith, and S. A. Boon (2002), Simulation of subduction zone seismicity by dehydration of serpentine, *Science*, *298*, 1407–1410.

Fujita, K., and H. Kanamori (1981), Double seismic zones and stress of intermediate depth earthquakes, *Geophys. J. R. Astron. Soc.*, *66*, 131–156.

Hacker, B. R., G. A. Abers, and S. M. Peacock (2003a), Subduction factory: 1. Theoretical mineralogy, densities, seismic wave speeds, and H_2O contents, *J. Geophys. Res.*, *108*(B1), 2029, doi:10.1029/2001JB001127.

Hacker, B. R., S. M. Peacock, G. A. Abers, and S. D. Holloway (2003b), Subduction factory: 2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions, *J. Geophys. Res.*, *108*(B1), 2030, doi:10.1029/2001JB001129.

Igarashi, T., T. Matsuzawa, N. Umino, and A. Hasegawa (2001), Spatial distribution of focal mechanisms for interplate and intraplate earthquakes associated with the subducting Pacific plate beneath the northeastern Japan arc: A triple-planed deep seismic zone, *J. Geophys. Res.*, *106*, 2177–2191.

Kirby, S. H. (1995), Intraslab earthquakes and phase changes in subducting lithosphere, *Rev. Geophys.*, *33*, 287–297.

Kirby, S. H., E. R. Engdahl, and R. Denlinger (1996), Intermediate-depth intraslab earthquakes and arc volcanism as physical expressions of crustal and uppermost mantle metamorphism in subducting slabs (overview), in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 195–214, AGU, Washington, D. C.

Martin, S., A. Rietbrock, C. Haberland, and G. Asch (2003), Guided waves propagating in subducted oceanic crust, *J. Geophys. Res.*, *108*(B11), 2536, doi:10.1029/2003JB002450.

Patzwahl, R., J. Mechie, A. Schulze, and P. Giese (1999), Two-dimensional velocity models of the Nazca plate subduction zone between 19.5°S and 25°S from wide-angle seismic meassurments during the CINCA95 project, *J. Geophys. Res.*, *104*, 7293–7317.

Peacock, S. M. (2001), Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle?, *Geology*, *29*, 293–302.

Reasenberg, P., and D. Oppenheimer (1985), FPFIT, FPPLOT, and FPPAGE: Fortran computer programs for calculating and displaying earthquake fault-plane solutions, *U.S. Geol. Surv. Open File Rep., 85-739*, 1–109.

Rietbrock, A., and C. Haberland (2001), A tear in the subducting Nazca slab: Evidence from local earthquake tomography and high precision hypocenters, *Eos Trans. AGU*, *82*(47), Fall. Meet. Suppl., T31A-0822.

Rietbrock, A., C. Haberland, G. Asch, G. Chong, and P. Giese (1997), ANCORP'96-Seismicity along the ANCORP traverse in northern Chile, *Eos Trans. AGU*, *78*(46), F716.

Rudloff, A. (1998), Bestimmung von Herdflächenlösungen und detaillierte Spannungsinversionen aus ausgewählten Ereignissen des seismologischen Netzes PISCO '94 (Nord-Chile), *Sci. Tech. Rep. GFZ Potsdam 98/01*, pp. 1–142, GeoForschungsZentrum, Potsdam, Germany.

Seno, T., Y. and Yamanaka (1996), Double seismic zones, compressional deep trench-outer rise events, and superplumes, in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 347–355, AGU, Washington, D. C.

Waldhauser, F. (2001), hypoDD: A computer program to compute double-difference hypocenter locations, *U.S. Geol. Surv. Open File Rep., 01-113*, 1–25.

Waldhauser, F., and W. L. Ellsworth (2000), A double-difference earthquake location algorithm: Method and application to the northern Hayward Fault, California, *Bull. Seismol. Soc. Am.*, *90*, 1353–1368.

Wang, K. (2002), Unbending combined with dehydration embrittlment as a cause for double and triple seismic zones, *Geophys. Res. Lett.*, *29*(18), 1889, doi:10.1029/2002GL015441.

Yoon, M., S. Buske, S. Lüth, A. Schulze, S. A. Shapiro, M. Stiller, and P. Wigger (2003), Along-strike variations of crustal reflectivity related to the Andean subduction process, *Geophys. Res. Lett.*, *30*(4), 1160, doi:10.1029/2002GL015848.

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