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The 9 June 94 Bolivian deep earthquake: An exceptional event in an extraordinary subduction zone

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Abstract. We investigate the physical setting of the Bolivian shock based on the history of the subducting Nazca plate, intraslab seismicity, deep seismic moment release, and seismic tomography. South America has two broad regions of reverse arc curvature. Subduction constrained to this unique geometry produces slab kinking contortions that may cause unusual slab thickening as they sink to the bottom of the transition zone and encounter resistance to penetration into the lower mantle. Such contortions are observed at intermediate depths "upstream" from the slab source regions of both the great 1970 Colombian and 1994 Bolivian events. Thickening helps explain how the Nazca slab accommodates large seismic source dimensions at depths of 625–650 km.

Introduction

The South American subduction zone (SZ) is one of the oldest and longest zones of continuous subduction, has the highest arc volcanoes and orogenic plateaus and produces a major fraction of the Earth's seismic activity. Many of the biggest earthquakes have occurred there, including the 635-km deep 9 June 94 event, the largest deep earthquake on record ($M_w = 8.2$). We discuss the setting of this shock and its Wadati-Benioff Zone (WBZ) based on an inferred physical history of the Nazca plate (NZ) prior to entering the trench, its descent and accompanying shape change, seismicity and tomography.

South American Deep Earthquakes

A homogeneous and comprehensive catalogue was produced by relocating 213 historical and modern deep events (1915–94) using a new algorithm [*Engdahl et al.*, 1995*a*]. We also augmented 35 Harvard CMT solutions (1977 to August 1994) with moment-tensor inversions for 20 pre-1977 deep events [*Huang et al.*, 1994].

The WBZ lacks any events in the depth range 325–520 km (Figs. 1 and 2*a*; [*Cahill and Isacks*, 1992]). WBZ geometry also changes from complexly curvilinear to a deep zone linearly segmented into three groups of shocks. Regional sections of these groups typically show marked changes in slab dip with depth (Fig. 3).

The northern group includes the great 1970 Colombia shock and the Peru-Brazil events (Fig. 3*a* inset), and is much more steeply dipping (~ 75°) than at shallower depths (Fig. 3*a*). Deep events of northern Argentina and southern Bolivia make up the southern group, whose structure (Fig. 3*c* inset) is more complex, with several "outboard" shocks, more easterly than expected from the trend of seismicity. An extreme example is the isolated 1989 shock 200 km east of the trend of the southern group [*Lundgren and Giardini,* 1994]. Excluding these shocks, the southern zone has an average dip of 80–90°. Focal mechanisms are remarkably consistent with the WBZ geometry of the northern and southern segments outlined above and with the results of earlier studies [*e.g., Cahill and Isacks,* 1992]: *P* axes tend to be down the dip of the local WBZ segment, *N* axes along strike and *T* axes normal to the zone (Figs. 1 and 3). The deepest events in the southern group (Fig. 3*c* inset) deflect eastward, suggesting that the slab becomes less steep with depth. A "jog" group of mostly big shocks, including the 9 June 94 event, begins near the Peru-Bolivia border and possibly includes three smaller events in central Bolivia. Although it has very sparse seismicity and hence the geometry is difficult to discern, their trend and the deep *P* directions in the jog (Fig. 3 inset) suggest a WNW strike and a dip ~60° to NNE.

This deep WBZ releases an unusually large fraction of the Earth's deep seismic moment (~58% of the CMT catalog through 1994). Seven of the ten largest deep events of known seismic moments occurred there, about 80% of the total release. These fractions are outsized even if one considers the length of the deep WBZ, the convergence rate and volume flux of slab into the transition zone [TZ] (~26% of the total flux [*Kirby et al.*, 1995]). Fig. 2*b* shows the heterogeneity in moment release: only a small fraction occurs in the main inclined zones; most is localized in isolated clusters at the northern end of the northern group and in the jog. About 40% of the moment release occurs in the western end of the jog representing ~5% of the deep WBZ length. Moment release is also concentrated at the greatest depths: events at 590–650 km comprise only ~50% of the deep shocks, but represent 90% of the total moment.

Seismic Tomography

Engdahl et al. [1995*b*] present high-resolution tomographic images of the seismic velocity under South America. High-velocity slab structure is well resolved and generally includes the position of the WBZ. Some high-velocity material is also resolved in the seismicity depth gap, suggesting that the slab is at least locally con-

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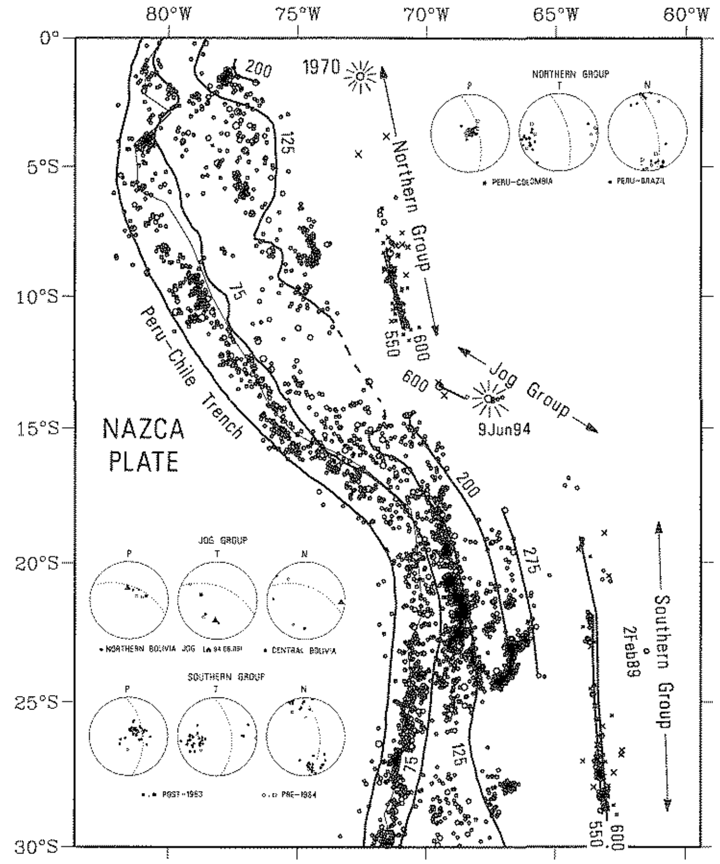

Figure 1. South American earthquakes. O: 1964-94 events. ×: historical deep earthquakes (1915-63). WBZ depth contours shown in km. Events < 50 km in depth are stripped from the figure east of the 75 km contour. Note sharp contortions in the slab near 2–3°S and 15°S. Stereograms show mechanisms of deep shocks.

tinuous but aseismic there. A broad Nazca slab anomaly is present in the lower mantle beneath a large fraction of the deep seismic zone [see *Grand,* 1994]. Apparent broadening but no deflection of the velocity anomaly occurs at the bottom of the TZ in the source region of the 9 June event. However, as in other deep slabs, the tomographic inversion technique cannot determine if this broadening is real or if real, whether it occurs near the bottom of the TZ or near the top of the lower mantle [van der Hilst, pers. comm.]. Lastly, a regional deflection of the slab anomaly is seen in part of the TZ of the southern region, consistent with the existence of several "outboard" shocks (Fig. 3*c* inset) and with our interpretation that the deepest events in the group at 24–29°S are also deflected eastward, suggesting some level of resistance to penetration into the lower mantle.

Discussion

These unique features of the deep seismicity of the Nazca slab reflect its thermal and deformation history. Although outwardly similar to the plate-tectonics setting of other SZs with deep shocks, two large-scale features of the Nazca system are unusual. First, Tertiary-age lithosphere is currently entering the trench over the latitude range of the deep WBZ. Apart from Melanesia, where a history of Cenozoic arc reversals and back-arc spreading have complicated deep slab ages, no other deep WBZ has such young lithosphere currently subducting [*Kirby et al.,* 1991, 1995]. *Engebretson and Kirby* [1992] suggest that the Nazca slab is composite in age and thermal structure, with cold Mesozoic lithosphere comprising the deep slab. *Okal and Bina* [1994] show that the slab material presently in the northern end of the deep WBZ was probably created by Pacific:Farallon (PA:FA) spreading ~50–65 Ma b.p. Despite much uncertainty in spreading history (PA:FA, PA:NZ) and finite motions (SA:FA, SA:NZ), this suggests that the age of material entering the trench 10–20 Ma ago (and now at 500–700 km depth) was considerably greater than at present.

Older lithosphere and hence lower temperatures in the deep Nazca slab would favor both high strength [*Wortel,* 1984] and large kinetic hindrance of spinel-forming reactions as slab peridotite enters the TZ [*Rubie,* 1993].

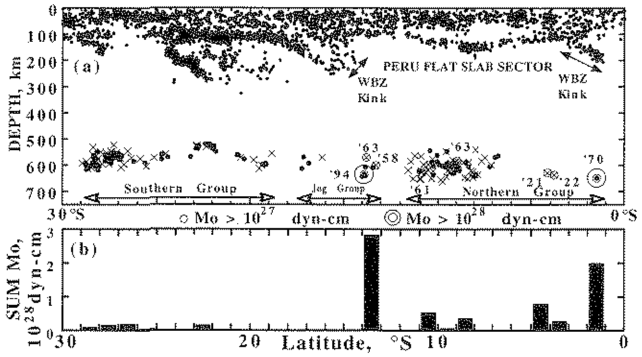

Figure 2. N-S variation in deep seismic activity: *(a)* Depths. *(b)* Seismic moment release.

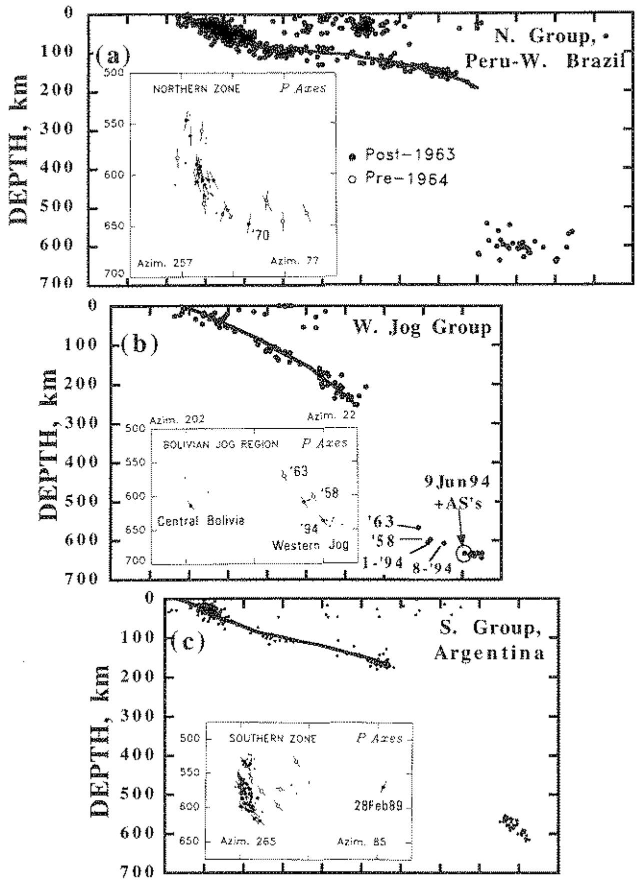

Figure 3. Cross-sections using curvilinear projections with origin at center of curvature of volcanic arc or trench. *(a)* Northern group. *(b)* Western jog group. *(c)* Southern group. Detailed deep cross sections oriented perpendicular to the 3 linear segments of deep seismic activity of Fig. 1 are also shown. They include all deep shocks with focal mechanisms and all the post-1963 events (symbols as in Fig. 1). Lines through symbols are *P* directions.

Olivine metastability is a necessary condition for transformational faulting, a high-pressure shear instability observed in some strongly exothermic polymorphic phase changes [*e.g., Kirby et al.,* 1991]. Dehydration embrittlement [*e.g., Raleigh,* 1967] also depends upon serpentine survival in deep slabs and hence requires low slab temperatures. These two mechanisms are leading candidates for the deep-earthquake faulting instability [*Frohlich,* 1994]. A composite thermal structure for the Nazca slab (Fig. 4*a*) could also explain the prominent depth gap in seismic activity. Lithosphere now at 520-660 km depth may have been too cold, for example, for minerals such as olivine to react swiftly enough to keep pace with the descent rate through the TZ. Hence, peridotite may have persisted metastably well into the transition zone in the coldest core of the Nazca slab. Later, as younger, warmer parts of the slab entered the TZ, spinel was produced near the equilibrium boundary, pinching off the region of metastability that now may exist only at 520–660 km depth. Earthquakes could occur by transformational faulting in the region of peridotite metastability but not at shallower depths in transformed material. This reconciles the existence of the seismic depth gap with the roughly continuous slab inferred from tomography.

The Nazca SZ is also unusual from the presence of two broad sectors of reverse curvature of the Peru-Chile trench (concave seaward): the Arica sector at 15–23°S and the Ecuador-Colombia sector north of ~3°S. This condition requires along-strike slab compression in order for the spherical-shell geometry of the plate west of the trench to conform to the WBZ geometry during descent [*e.g., Burbach and Frohlich,* 1986]. *Creager et al.* [1995] estimate that ~10% compression is required in the Arica sector to achieve this geometrical "conformation strain" to depths of 600 km. It is significant that the WBZ shows sharp contortions at intermediate depth "upstream" of both the 1970 Colombia and 1994 Bolivia deep earthquakes (Fig. 1) and many of the events in those contortions have complex focal mechanisms. We suggest that these slab contortions, which define the SE and NW boundaries of the Peruvian flat slab sector [*Cahill and Isacks,* 1992; *Burbach and Frohlich,* 1986], may also be expressions of "kinking" localization of these conformation strains at the northern margin of the Arica sector and the southern margin of the Ecuador-Colombia sector.

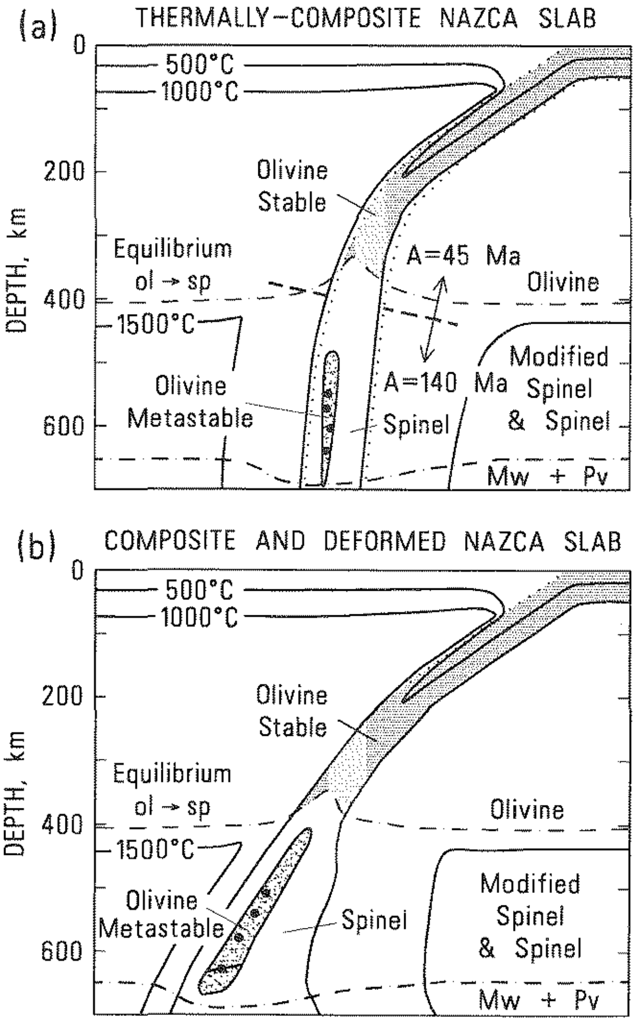

Figure 4. Conceptual models of the Nazca slab. *(a)* Composite plate age and thermal structure with older and colder material at the bottom of the transition zone and a region of olivine metastability (shown stippled) where deep earthquakes (dots) can occur by transformational faulting. *(b)* Similar to *(a)* but with large slab thickening produced by compression during descent.

What happens when such slab contortions reach the bottom of the TZ? Several lines of evidence suggest that slab deformation intensifies at such depths: (a) Some deep Nazca slab segments deflect toward a recumbent slab attitude (see above and results for other deep zones [*e.g., van der Hilst et al.*, 1991; *Lundgren and Giardini,* 1994]). (b) Apparent slab thickening occurs in the tomographic image of the 9 June source region. (c) Most seismic moment release is localized near the bottom of the TZ, perhaps reflecting a resistance to deeper slab descent. But why, then, is the deep seismic moment release so variable along strike? Descent of kinked regions of a slab to the bottom of the TZ has an interesting implication. If a kink meets resistance to descent into the lower mantle, then it could act as an upward-opening stiffening rib, resisting bending deflection, anchoring itself in the lower mantle, and producing localized down-dip slab compression, consistent with observed focal mechanisms. This conceptual model is also consistent with the disproportionate share of moment release occurring in the jog region near the bottom of the TZ and in the northern end of the northern group (Fig. 2*b*). The segmentation of the deep seismic zone into linear sections and the sharp jog near the Peru-Bolivia border may thus be a deep expression of the shallower heterogeneity in slab deformation. The outsized fraction of the global deep seismic moment release probably reflects the slab conformation deformation that evidently accompanies descent of these unusually broad segments of reverse trench curvature. Thick continental lithosphere has long made up the overriding plate in South America, and such a structure appears more likely to impose those geometrical constraints than with thinner overriding oceanic plates. This may explain why other deep WBZs with mostly oceanic overriding plates lack big reverse-curvature sectors and, in turn, why they do not release abundant seismic moment and display such large events.

The likelihood of locally marked thickening of the slab near the kink at the Peru-Bolivia border has significance for the problem of how such a large shock can occur in a slab that is slowly heating up and thus, in the simplest thermal models, has converging isotherms and a transversely diminishing source region near the bottom of the TZ (Fig. 4*a*). If the slab is locally thickened in the jog region, then the most straightforward structure expected would have splayed out isotherms and a thicker region of metastability (Fig. 4*b*). This speculative structure is consistent with the limited data on the deep kinked region near the Peru-Bolivia border and the rupture characteristics inferred for the 9 June 94 main shock indicating slip to the north on a horizontal plane rupturing in the ENE or NNE direction [*Kikuchi and Kanamori,* 1994; *Silver et al.*, 1995]. Our deformed slab model is an alternative to an even more speculative one involving the reactivation of a large postulated serpentinized normal fault inherited from shallower slab bending [*Silver et al.,* 1995]. That model is also subject to temperature constraints on mineral stability and thus poses the same question: how does a large fault fit between isotherms that converge with depth? *Kirby* [1995] argues that large-scale survival of serpentine to those depths is problematical given the stability relations of serpentine and the likely thermal structure of the Nazca slab.

Although knowledge of the physical slab environment of the great 9 June 94 deep earthquake is still sketchy at best, the limited observational constraints suggest that its source region has sustained large compressional deformation and slab thickening during descent.

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