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The Deep Earthquakes of 1997 in Western Brazil

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Introduction

We report here on three 1997 deep earthquakes in Western Brazil, which extend the Northern end of the Peru–Brazil deep cluster and close the spatial gap with the deep shocks of 1921–1922, previously studied by Okal and Bina (1994) (hereafter Article I).

Deep seismicity in South America has been described by many authors, most recently Kirby *et al.* (1995). It is characterized by significant lateral heterogeneity in the along-strike direction (generally north–south), with the activity arranged in clusters (see Figure 1). In particular, prior to the great 1994 Bolivian earthquake, no deep earthquakes were known between the southern termination of the Peru–Bolivia cluster at 13.5°S, 69.3°W and the northern end of the central Bolivia cluster at 16.8°S, 64.4°W. The great event of 09 June 1994, its aftershocks, and the subsequent earthquakes on 08 August 1994, 14 March 1995, and 28 November 1997 mapped an essentially continuous line along the Bolivian jog in the Benioff Zone, suggesting that the slab in that region is warped, rather than torn and fragmented (Kirby *et al.,* 1995). To the north, we described in Article I the three major shocks of 18 December 1921, 17 January 1922, and 31 July 1970 as isolated, with a gap of 265 km between the northern end of the Peru–Brazil cluster (then mapped at 6.67°S; 71.82°W) and the 1921–1922 hypocenters, and a further 238 km between the latter and the 1970 event to the North. The 1997 shocks essentially close the first of those two gaps.

The 1997 Events: Location

Event 1, at 09:42 on 07 March 1997, was located by the ISC at 6.43°S, 71.14°W, h = 628 km, the uncertainty of this location being ±4 km horizontally and ±8 km in depth. The root mean square (rms) residual is only 0.92 sec, and the solution uses 244 P-arrival times. Because of the quality of this location, there was no need to perform an independent relocation. The occurrence of this event prolonged the western Brazil cluster of deep seismicity 24 km to the north.

Two further earthquakes occurred in the same general location (we avoid the term *aftershocks,* which suggests that they took place on the same rupture zone). Event 2, on 10 May 1997 (m_b = 3.6), was reported by the ISC at 4.63°S, 71.59°W, and 645 km. Using the technique of Wysession *et al.* (1991), we relocated it at essentially the same epicenter (4.59°S, 71.54°W), but slightly shallower (628 km), achieving an rms residual of only 0.57 sec on 20 stations; its Monte Carlo ellipse (for Gaussian noise with σ_G = 1 sec) has a semimajor axis of only 30 km. Then, on 09 June 1997, event 3 took place between the previous two, with an ISC location of 5.90°S, 71.74°W; h = 640 km (m_b = 4.5). This solution, obtained on 127 P times with an rms residual of 0.81 sec did not warrant independent relocation. These results are summarized in Table 1, in which the relevant earthquakes are sorted from north to south, and in Figure 2.

Focal Mechanism

Figure 2 shows the CMT solution published for event 1 (Dziewonski *et al.,* 1998), like all deep shocks in the region,

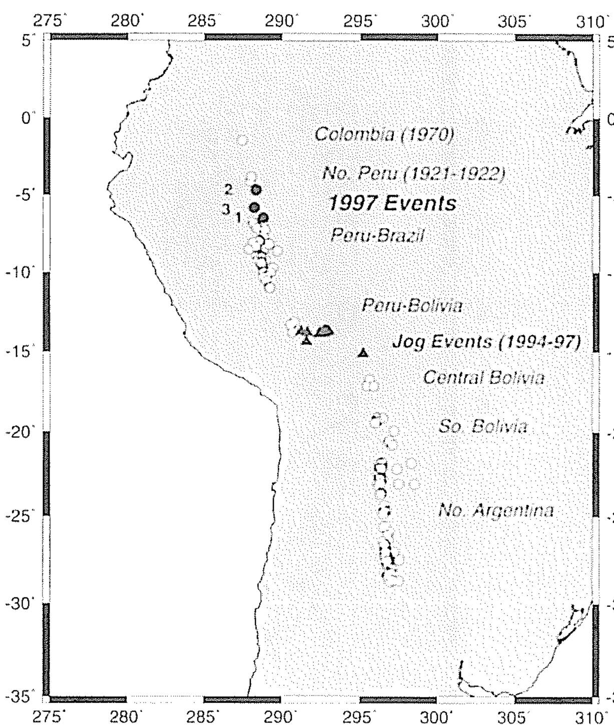

Figure 1. Map of South American deep seismicity (h > 400 km). The open circles are NEIC epicenters (1963 to present), complemented by the relocations of the 1921–22 shocks (Article I). The triangles show the great Bolivian earthquake of 1994, its aftershocks and subsequent events filling the jog between the Peruvian and Argentinian parts of the Benioff zone; no seismicity was known along that segment prior to 1994. The three solid dots are the 1997 events studied here.

Table 1
Deep Seismic Events North of the Peru–Brazil Cluster

Number	Date D M (J) Y	Origin Time GMT	Epicenter °N	Epicenter °E	Depth (km)	Magnitude (m_b)	Moment 10^{27} dyne cm	Focal Geometry ϕ, δ, λ (°)	Δ* (km)
			Large, Isolated Events to the North (Okal and Bina, 1994)						
	31 Jul (212) 1970	17:08	−1.46	−72.56	651		21†	148, 58, 261	
	17 Jan (017) 1922	03:50	−3.84	−71.98	660		6	44, 30, 307	238
	18 Dec (352) 1921	15:29	−4.11	−72.04	630		1.2	44, 30, 337	40
			New 1997 Events (This Study)						
2	10 May (130) 1997	19:49	−4.59	−71.54	628	3.6			48
3	09 Jun (160) 1997	14:20	−5.90	−71.74	640	4.5			131
1	07 Mar (066) 1997	09:42	−6.43	−71.14	628	4.8	0.0016	330, 65, 250	55
			Northernmost Events in Peru–Brazil Deep Cluster						
	21 Jan (021) 1972	19:18	−6.67	−71.82	571	5.4	Northernmost ISC location		62
	26 Mar (085) 1986	22:06	−7.12	−71.64	608	5.8	Northernmost NEIC location (Also Northernmost CMT solution)		59

†Furumoto and Fukao (1976), revised downward to 1.4×10^{28} dyne cm by Russakoff *et al.* (1997).
*Δ is the distance in three-dimensional space between an event and the one listed immediately above in the table.

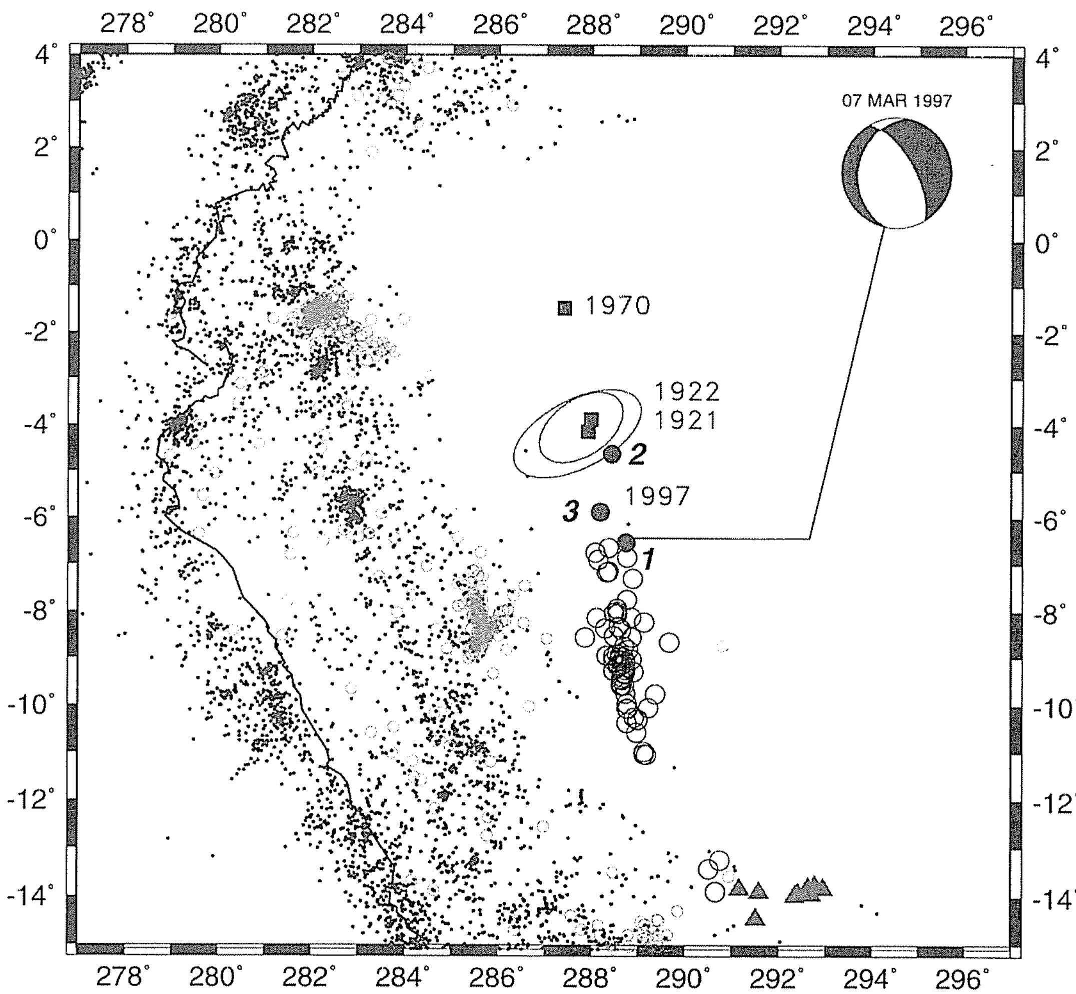

Figure 2. Close-up of epicentral area of the 1997 events. In addition to the deep seismicity (same symbols as on Figure 1), this map also shows the background shallow (small solid dots) and intermediate (half-tone open circles) seismicity, as well as the 95%-confidence ellipses for the 1921 and 1922 shocks (adapted from Figure 2 of Article I).

it features normal faulting ($\phi = 330°; \delta = 65°; \lambda = -110°$) but its P axis (dip 64°; azimuth 207°) dips to SSW and thus deviates significantly from the presumed down-dip direction of the slab, which should sink eastward. In the formalism of Kagan (1991), this mechanism is rotated 42°, 61°, and 67° from the 1970, 1922, and 1921 solutions, respectively, and from 35° to 55° from its eight immediate neighbors in the Peru–Brazil deep cluster, north of 9°S. By contrast, the 1970 geometry was in much better agreement with the latter (from 6° to 36°).

Discussion

Taken together, the three events partially fill the gap between the 1921–1922 hypocenters and the northern end of the Peru–Brazil deep cluster. While there remains a gap of 131 km between events 2 and 3, the along-strike pattern of seismicity at the bottom of the slab is reminiscent of that along the Bolivian jog and can be regarded as extending continuously to the 1922 epicenter at 4°S. In this respect, event 2 is particularly remarkable in that it is only 48 km from the inverted hypocenter of the 1921 shock and sits on the 95%-confidence ellipse (Fig. 2) of the older shock. We conclude that the 1921 and 1922 shocks are not isolated, but rather belong to a line of seismic activity extending continuously to the Peru–Brazil cluster. Whether or not the remaining gap between the 1921–22 locations and the 1970 Colombian earthquake is seismic remains an open question.

Among the speculative mechanisms proposed in Article I to explain the patterns of seismicity at the 1921–22 hypocenters, we can now rule out the detached blob; this supports the conclusions of Okal (2001), where we showed that most earthquakes described as "detached" are actually linked to the main Benioff zone by a thermally and hence mechanically continuous piece of slab. Also, the trace of the Mendaña Fracture Zone on the slab can no longer be regarded as the northern boundary of deep seismicity in the Peru–Brazil region; it marks, however, the boundary between a regime of regular, relatively abundant seismicity to the south, which as argued in Article I could be associated with the presence of Nazca Ridge hotspot material on the slab, and more scattered seismicity to the North, involving another, as yet undefined, mechanism of seismogenesis.

Having established that the deepest part of the slab is continuously seismic to 4°S, events 2 and 3 now define a down-dip gap in seismicity between depths of 292 km to 628 km (shown in Figure 3), which raises the question of the mechanical continuity of the slab over that gap. Focal mechanisms for the 1921, 1922, and 1970 events would generally argue in favor of mechanical continuity, but we were unsuccessful in an attempt to use several other methods of investigation of the upward paths from their hypocenters: we could find no T waves generated into the Pacific Ocean from any of the three 1997 events; they could have been proxies for the thermal continuity of the slab (Okal and Talandier, 1997, 1998); we note, however, that the size of event 1 would have prevented observing its T waves had it taken place in other sections of the South American subduction system (Okal, 2001). Nor could we analyze the spectra of S waves traveling up-slab, since the 1997 shocks were not recorded in Ecuador (M. Segovia, personal comm., 1999), and the IRIS station at Santa Fe de Bogotá was discontinued in August 1996. If the slab is continuous, this down-dip gap in seismicity between 292 km and 628 km depth may reflect low stress levels in the slab, perhaps arising from depth variations in buoyancy forces (Bina, 1997) or in the strengths of minerals (Chen *et al.*, 1998).

Finally, the temporal relationship between the three 1997 events is intriguing and could suggest triggering through stress transfer; it is reminiscent of the situation along

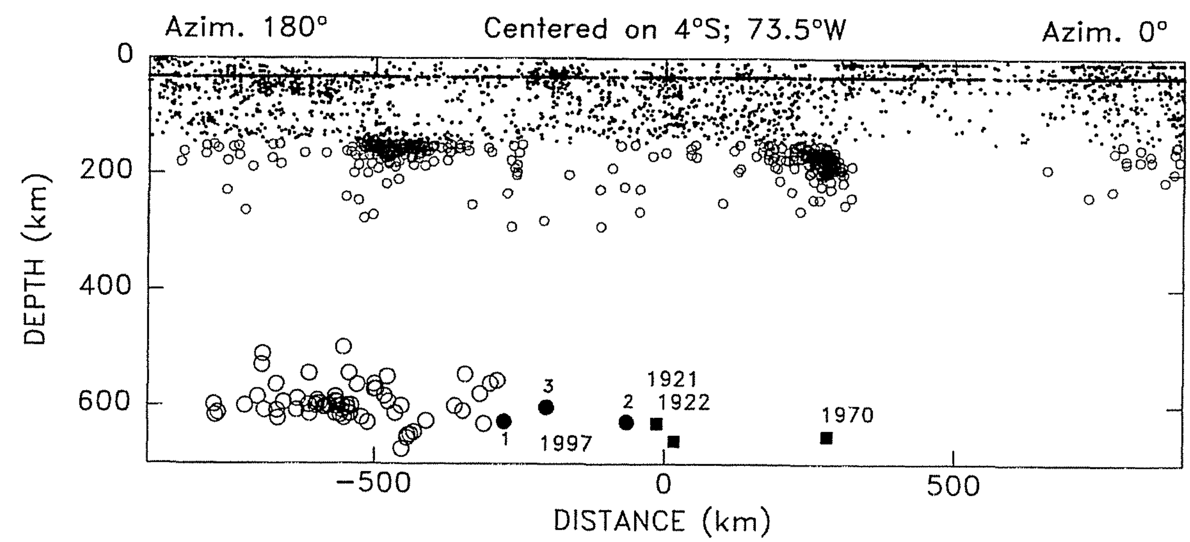

Figure 3. North-south cross-section of seismicity under northern Peru and Colombia. Symbols as in Figure 2.

the Bolivian jog where the seismic gap was closed by activity following the great Bolivian deep shock of 09 June 1994 (09 June 1994 [01:15 TU]; 08 August 1994; 14 March 1995; 28 November 1997), outside the rupture zone of the mainshock, as defined, for example, by Myers *et al.* (1995).

Acknowledgments

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References

Bina, C. R. (1997). Patterns of deep seismicity reflect buoyancy stresses due to phase transitions, *Geophys. Res. Lett.* **24,** 3301–3304.

Chen, J., T. Inoue, D. J. Weidner, Y. Wu, and M. T. Vaughan (1998). Strength and water weakening of mantle minerals, olivine, wadsleyite and ringwoodite, *Geophys. Res. Lett.* **25,** 575–578. Correction (1998) *Geophys. Res. Lett.* **25,** 1103–1104.

Dziewonski, A. M., G. Ekström, and N. Maternovskaya (1998). Centroid-moment tensor solutions for January-March 1997, *Phys. Earth Planet. Inter.* **106,** 171–179.

Furumoto, M., and Y. Fukao (1976). Seismic moments of great shocks, *Phys. Earth Planet. Inter.* **11,** 352–357.

Kagan, Y. Y. (1991). 3D rotation of double-couple earthquake sources, *Geophys. J. Intl.* **106,** 709–716.

Kirby, S. H., E. A. Okal, and E. R. Engdahl (1995). The 09 June 1994 great Bolivian deep earthquake: an exceptional deep earthquake in an extraordinary subduction zone, *Geophys. Res. Lett.* **22,** 2233–2236.

Myers, S. C., T. C. Wallace, S. L. Beck, P. G. Silver, G. Zandt, J. Vandecar, and E. Minaya (1995). Implications of spatial and temporal development of the aftershock sequence of the M_w = 8.3 June 9, 1994, deep Bolivian earthquake, *Geophys. Res. Lett.* **22,** 2269–2272.

Okal, E. A. (2001). "Detached" deep earthquakes: are they really?, *Phys. Earth Plant. Inter.,* in press.

Okal, E. A., and C. R. Bina (1994). The deep earthquakes of 1921–1922 in Northern Peru, *Phys. Earth Planet. Inter.* **87,** 33–54.

Okal, E. A., and J. Talandier (1997). *T* waves from the great 1994 Bolivian deep earthquake in relation to channeling of *S* wave energy up the slab, *J. Geophys. Res.* **102,** 27,421–27,437.

Okal, E. A., and J. Talandier (1998). Correction to "*T* waves from the great 1994 Bolivian deep earthquake in relation to channeling of *S* wave energy up the slab", *J. Geophys. Res.* **103,** 2793–2794.

Russakoff, D., G. Ekström, and J. Tromp (1997). A new analysis of the great 1970 Colombia earthquake and its isotropic component, *J. Geophys. Res.* **102,** 20,423–20,434.

Wessel, P., and W. H. F. Smith (1991). Free software helps map and display data, *EOS, Trans. Amer. Union* **72,** 441, 445–446.

Wysession, M. E., E. A. Okal, and K. L. Miller (1991). Intraplate seismicity of the Pacific Basin, 1913–1988, *Pure Appl. Geophys.* **135,** 261–359.

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