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Introduction to the special issue on the great Bolivian earthquake of 1994

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On June 9, 1994 the largest deep earthquake (M_W ~8.3, depth = 630 km) in recorded history occurred beneath Bolivia. This remarkable earthquake caused little damage in South America, but it was reported felt as far away as Montreal, Seattle, and San Diego (see the paper by *Anderson et al.*). Although deep earthquakes were first identified by Wadati in the 1920s, the mechanics of how they occur remains a fundamental question in Earth science. The Bolivian earthquake is extremely important for providing constraints on the mechanics of deep earthquakes, the dynamics and geometry of the Nazca plate subduction, and the structure of the Earth's interior. The earthquake was in some sense fortuitously timed; between the IRIS Global Seismic Network (GSN) and the Federation of Digital Seismic Networks (FDSN) there existed a fairly well populated global network of modern digital seismic instruments which provided excellent teleseismic coverage. Further, there were two portable experiments being conducted on the South American continent which provided timely high-quality regional data. One of the experiments, BANJO/SEDA (Broadband ANdean JOint/Seismic Exploration of the Deep Altiplano) was deployed only a few hundred kilometers south of the epicenter and recorded the mainshock on scale as well as aftershocks with magnitudes as small as $m_b = 2.3$ (see *Myers et al.*). The other experiment, BLSP (Brazilian Lithosphere Seismic Program), was deployed in Brazil approximately 2000 km to the east (see *Clarke et al.*). The combination of local, regional, and teleseisimc data for the Bolivian earthquake is unprecedented and has already advanced our understanding of deep earthquakes.

The 1994 earthquake occurred on a section of the Nazca plate which had not experienced any deep seismicity in the previous 50 years (see *Kirby et al.*). The deep Nazca Wadati–Benioff zone (WBZ) is defined by a roughly north-south trend of hypocenters north of 11°S; similarly, south of 16° the hypocenters define a linear trend. However, these lineations are offset by nearly 700 km beneath central Bolivia. Deep seismicity on this central, or offset, zone began on January 10, 1994 with a moderate-sized event ($M_W = 6.4$) at a focal depth of 600 km. Between January 10 and June 9 there were apparently no earthquakes on the offset section of the WBZ. The June 9 event occurred 200 km east of the January 10 event and had a fairly localized aftershock sequence which continued through at least August of 1994.

The source mechanism of the June 9 event appears to have occurred on a nearly horizontal plane (see *Wu et al.*, *Lundgren and Giardini*, and *Goes and Ritsema*). Analysis of the source time function indicates a total fault area of 30 km × 50 km, with a very low rupture velocity (see *Ihmlé and Jordan*, *Beck et al.*, *Chen*, and *Hara et al.*). Despite the large size of the event, the source process is fairly simple. The time function is approximately 45 s long, and there are three or four clear subevents. All the subevents have nearly identical source geometries (see *Wu et al.*), and the source can be described essentially as a pure double couple (i.e., with no isotropic component; see *Hara et al.*).

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In the 20 days which followed the mainshock, 45 aftershocks with magnitudes between 2.4 and 5.7 occurred in the vicinity of the mainshock hypocenter. The mainshocks define a tabular volume, mostly below and east of the mainshock (*see Myers et al.*). Most of the aftershocks have focal mechanisms with near-vertical P axes (see *Tinker et al.*). This represents a significant rotation from the January 10 and June 9 events. The largest aftershock ($m_b = 5.4$) occurred on August 8 and was located 100 km west of the mainshock (approximately half-way between the June 9 and January 10 locations) and had a focal depth of 590 km. The mainshock and aftershocks provide very significant constraints on the geometry of the Nazca WBZ (see *Myers et al.* and *Engdahl et al.*), which has some interesting implications for the evolution of the Altiplano (see *Creager et al.* and *Estabrook and Bock*). The January 10, June 9, and August 8 events define a lineament which could represent the seismogenic base of the Nazca plate. This interpretation suggests a smoothly bent slab between the well-defined north-south hypocenter lineation bracketing the offset WBZ beneath Bolivia.

Many of the seismic stations in the BANJO profile across southern Bolivia were equipped with 24-bit digitizers which provided on-scale recordings of the mainshock. These recordings appear to contain the signature of a static offset (see *Jiao et al.*). The waveforms are consistent with near-field synthetics which are calculated with either model sums (see *Ekström*) or ray theory (see *Jiao et al.*).

The location of the June 9 earthquake was ideal for studying Earth structure on many different scales. *ScS* reverberations were used by *Clarke et al.* to investigate the upper mantle beneath South America. In particular, they found that the "660 km" discontinuity was much deeper beneath the Altiplano (700 km) than beneath the Brazilian Shield (660 km). The earthquake produced an extraordinary set of free oscillations which are particularly sensitive to the aspherical structure of the deep mantle. Both spheroidal and toroidal free oscillations observations (see *Tromp and Zanzerkis*, *Resovsky and Ritzwoller*, and *Ritzwoller and Resovsky*) appear to validate recently developed 3-D Earth models.

This special issue contains 23 papers on various aspects of the Bolivia earthquake. This earthquake is truly one of the most important to occur in the last quarter century, and much of the research reported here is spawning new ideas about the mechanics of deep earthquakes. The fault dimensions and horizontal geometry of the Bolivian earthquake suggest that the entire width of the subducted Nazca plate was ruptured. Further, the earthquake appears to have been part of a series which occurred along a several hundred kilometer segment of Nazca plate which had a prolonged period of seismic quiescence.