Part I

Background and introductory material

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The big, the bad, and the curious

If you asked most seismologists for a brief summary of what they know about intermediate- and deep-focus earthquakes, they might write something like:

> Although nearly all of the world's earthquakes occur within the crust, there are a few with foci in the mantle having depths between 60 and 700 km. These so-called "deep earthquakes" occur near deep-ocean trenches within planar groups of hypocenters called Wadati–Benioff zones. In comparison with shallow-focus earthquakes, deep earthquakes tend to be smaller in size, have higher stress drops, more impulsive source-time functions, and few or no aftershocks. Generally, deep earthquakes aren't destructive because of their small size, distance from the surface, and tendency to occur in oceanic regions.

Unfortunately, most of the assertions in the above statement aren't strictly true; i.e., some are never true, some are true only sometimes, and some we aren't yet sure about. For example, in global earthquake catalogs about 25% of all earthquakes have reported focal depths exceeding 60 km (Table 1.1); the 75% that are shallower are hardly "nearly all." Moreover, even for very large earthquakes with M_W or m_B larger than 8.0, those with focal depths of 60 km and more make up about a quarter of all events.[1] Moreover, we shall see that not all deep earthquakes are associated with oceanic trenches; many important deep quakes occur as isolated events and not within planar groups. Whether deep quakes have higher stress drops and more impulsive source time functions is subject to debate. Finally, some deep earthquakes do have fairly numerous aftershocks and some deep earthquakes are highly destructive.

To illustrate some important characteristics of deep earthquakes, this chapter will present descriptions of several events. In different ways, each shows why the above statement is problematic. In addition, each of the quakes discussed is significant

[1] In the twentieth century, deep earthquakes are absent among very, very large events with M_W exceeding 8.5. However, until the Sumatra earthquakes of 26 December 2004 and 28 March 2005 there had been no earthquakes in the Harvard CMT catalog of any depth with M_W exceeding 8.5, and the largest m_B in the Abe catalog is only 8.3. Indeed, Abe assigned an m_B of 7.9 to both the 1960 Chile and 1964 Alaska earthquakes.

Table 1.1. *Fractions of shallow and deep earthquakes reported in the Harvard, Abe* (1981)*, and ISC catalogs.*

Catalog	Number; years	Shallow $h < 60\,km$	Deep $h > 60\,km$	Deep-focus $h > 300\,km$
Harvard; $M_W \geq 8.0$	13; 1977–2004	0.77	0.23	0.08
Abe; $m_B \geq 8.0$	13; 1897–1976	0.77	0.23	–
Harvard; $M_W \geq 7.0$	376; 1977–2004	0.73	0.27	0.09
Abe; $m_B \geq 7.0$	1110; 1897–1976	0.62	0.38	0.07
Harvard; $M_W \geq 5.6$	9403; 1977–2004	0.76	0.24	0.07
ISC; $m_b \geq 5.3$	18840; 1964–2000	0.70	0.30	0.05

because it is a celebrated representative of a particular category of deep earthquakes, or because it raises important questions about mantle dynamics.

1.1 The big: 9 June 1994 Bolivia

This earthquake was deep – Harvard assigned it a focal depth of 647 km – and really, really big, with a magnitude M_W of 8.2. Indeed, when it occurred it was the largest earthquake of any depth the world had experienced in the 17 years since the Sumbawa earthquake of 1977. It is also the largest earthquake ever recorded with a focal depth greater than 300 km.

A remarkable feature of South America is that it possesses a disproportionate fraction of the world's large very deep earthquakes (Table 1.2). For quakes with focal depths exceeding 300 km, South America has experienced the world's largest (1994 Bolivia), the second and third largest (Colombia, 1970; and northern Peru, 1922), and also the tenth, 13th, 15th, and 18th largest (Peru–Bolivia border: August 1963, November 1963, 1961, and 1958). Why such large earthquakes occur here and not elsewhere is a significant question. The answer isn't obvious, since the lithosphere subducting beneath South America is neither particularly old and fast (as in Tonga) nor particularly young and slow (as in the northwestern United States). What then, is special about South America?

Although the 1994 Bolivia earthquake was felt throughout much of South America, it caused only minor damage. It broke windows in tall buildings and caused some structural damage in La Paz, Cochabamba, and Oruro, all towns within about 500 km of the epicenter. It caused numerous landslides in southern Peru, which allegedly were responsible for numerous injuries and four deaths.

An unusual feature of the Bolivia earthquake was that it was felt in North American cities at distances of 50–80° from the epicenter (Fig. 1.1). For example,

Table 1.2. *Earthquakes with depths greater than* 300 *km and moments exceeding* 2.5×10^{20} *N-m occurring between 1906 and 2004. Source: Huang and Okal (1998) augmented by CMT catalog for events occurring since 1996.*

Rank	Date	Area	Depth (km)	Moment (N-m)	M_W	Environment
1	09 Jun 1994	Bolivia	647	2.6×10^{21}	8.3	bend
2	31 Jul 1970	Colombia	623	1.4×10^{21}	8.1	isolated
3	17 Jan 1922	North Peru	664	9.4×10^{20}	7.9	isolated
4	17 Jun 1996	Flores Sea	589	7.9×10^{20}	7.9	bend
5	29 Mar 1954	Spain	630	7.0×10^{20}	7.9	isolated
6	29 Sep 1973	North Korea	593	5.0×10^{20}	7.8	bend/edge
7	11 Jun 1972	Celebes Sea	332	4.7×10^{20}	7.7	
8	19 Aug 2002	Fiji	699	4.3×10^{20}	7.7	
9	26 May 1932	Fiji	560	4.0×10^{20}	7.7	bend
10	15 Aug 1963	Peru–Bolivia	573	3.9×10^{20}	7.7	bend
10	28 Feb 1950	Sea of Okhotsk	339	3.9×10^{20}	7.7	
12	25 May 1907	Sea of Okhotsk	548	3.7×10^{20}	7.7	
13	09 Nov 1963	Peru–Bolivia	573	3.5×10^{20}	7.7	
13	19 Aug 2002	Fiji	631	3.5×10^{20}	7.7	
15	19 Aug 1961	Peru–Bolivia	620	3.4×10^{20}	7.7	
16	09 Mar 1994	Fiji	563	2.7×10^{20}	7.6	
16	23 May 1956	Fiji	436	2.7×10^{20}	7.6	
18	26 Jul 1958	Peru–Bolivia	592	2.6×10^{20}	7.6	bend

the *Minneapolis Star Tribune* quoted a woman living on the 12th floor of a condominium who

> . . . felt her bed rocking and thought the wind must be blowing something fierce. “Then I looked outside the building, no wind,” she said. She went into the living room and asked her father whether he had felt the shock. He had, and the two of them hurried downstairs and into their car in the parking lot. They used a car phone to call the police. “The guy thought I was crazy,” the woman said.

Many of the felt reports came from people situated in buildings having three to twelve stories, and correspond to intensities of MM-I or MM-II.[2] Steel and concrete buildings with N stories have natural periods of approximately $0.08N$ (Kanai, 1983), which for buildings of 3–12 stories corresponds to frequencies of 1–4 Hz.

The 1994 Bolivia earthquake is the only deep-focus event to generate felt reports at such great distances. After the earthquake Anderson *et al*. (1995) evaluated these

[2] Felt reports at teleseismic distances are most often caused by surface waves from very large shallow earthquakes. For example, after the Alaska earthquake of 28 March 1964 ($M_W = 9.2$), newspapers widely reported water sloshing over the sides of swimming pools, and waves up to 1.8 meters high overturned small boats and caused minor damage 45° away in several channels along the Texas and Louisiana coasts.

Fig. 1.1 Felt reports at great distances (filled circles) for the 9 June 1994 Bolivia deep-focus earthquake. Plus (+) and (×) symbols indicate locations at distances greater than 1000 km from the epicenter where P and S waves respectively have maximum amplitude as they leave the focal region and reach the Earth's surface. The timing of the distant felt reports and their location nearer the local P-maximum suggests that P, and not S, was responsible. Plotted felt report data are from Anderson *et al*. (1995).

reports, and concluded that the reported times indicated that people were experiencing the arrival of P or PcP waves, rather than S or surface waves (Table 1.3). Moreover, seismograms at North American cities indicated that the highest accelerations were attributable to P rather than S or surface waves (Fig. 1.2), with peak accelerations in the frequency range of 0.5–5.0 Hz. The surface waves for this quake had low amplitudes because of its great focal depth. And, the quake's

Table 1.3. *Reported times in relation to estimated P and S arrival times for felt effects in North American cities following the 1994 Bolivian earthquake. Source for locations and times of felt effects is compilation by Jim Dewey of the U.S. Geological Survey, augmented by additional newspaper reports.*

Time reported	Number of observations
One hour or half-hour before P arrival	2
One minute before P arrival	1
Between P arrival and three minutes after	5
Between S arrival and five minutes after	0
Range of times reported includes both P and S arrivals	2
Long after S arrival	1

focal mechanism had an orientation that produced maximum-amplitude P in north central North America (Fig. 1.1).

A second peculiar feature of the Bolivia earthquake was its location beneath a part of South America where few deep-focus earthquakes had occurred previously (Fig. 1.3). To the northwest, the rare large and isolated deep quakes that occur beneath Colombia lie approximately along the extension of a linear trend of deep-focus activity that extends along the Peru–Brazil border, and the southern extension of this trend meets the Peru–Bolivia border. Then, to the southeast, a second linear group of earthquakes extends from central Bolivia into central Argentina. Both the northwest and southeast groups are in accord with the classical model of deep earthquake occurrence (Fig. 1.4) – that seismic activity occurs along a planar region, the Wadati–Benioff zone, which delineates the cold core of subducting oceanic lithosphere. However, this model doesn't fit the 1994 Bolivia hypocenter. It lies within a distinct gap between the northwest and southeast groups. One possible explanation is that it occurred within a kink in subducted lithosphere that connects the two groups.

What actually occurred in the mantle beneath Bolivia when the 1994 earthquake took place? Ihmlé (1998) modeled the rupture as a continuous process, and concluded that the rupture consisted of six pulses lasting about 50 seconds that released moment along a subhorizontal planar region (Fig. 1.5). He found slip of 4 meters over a region with dimensions of about 20×30 km^2, and slip of at least a meter over a roughly circular area with a diameter of 120 km. He concluded that the rupture front traveled with a velocity of 2 km/s or less. Ihmlé's results are generally consistent with other investigations of the rupture process that modeled the individual pulses as point sources (Beck *et al*., 1995; Estabrook and Bock, 1995; Goes and Ritsema, 1995; Silver *et al*., 1995; Antolik *et al*., 1996). However, because

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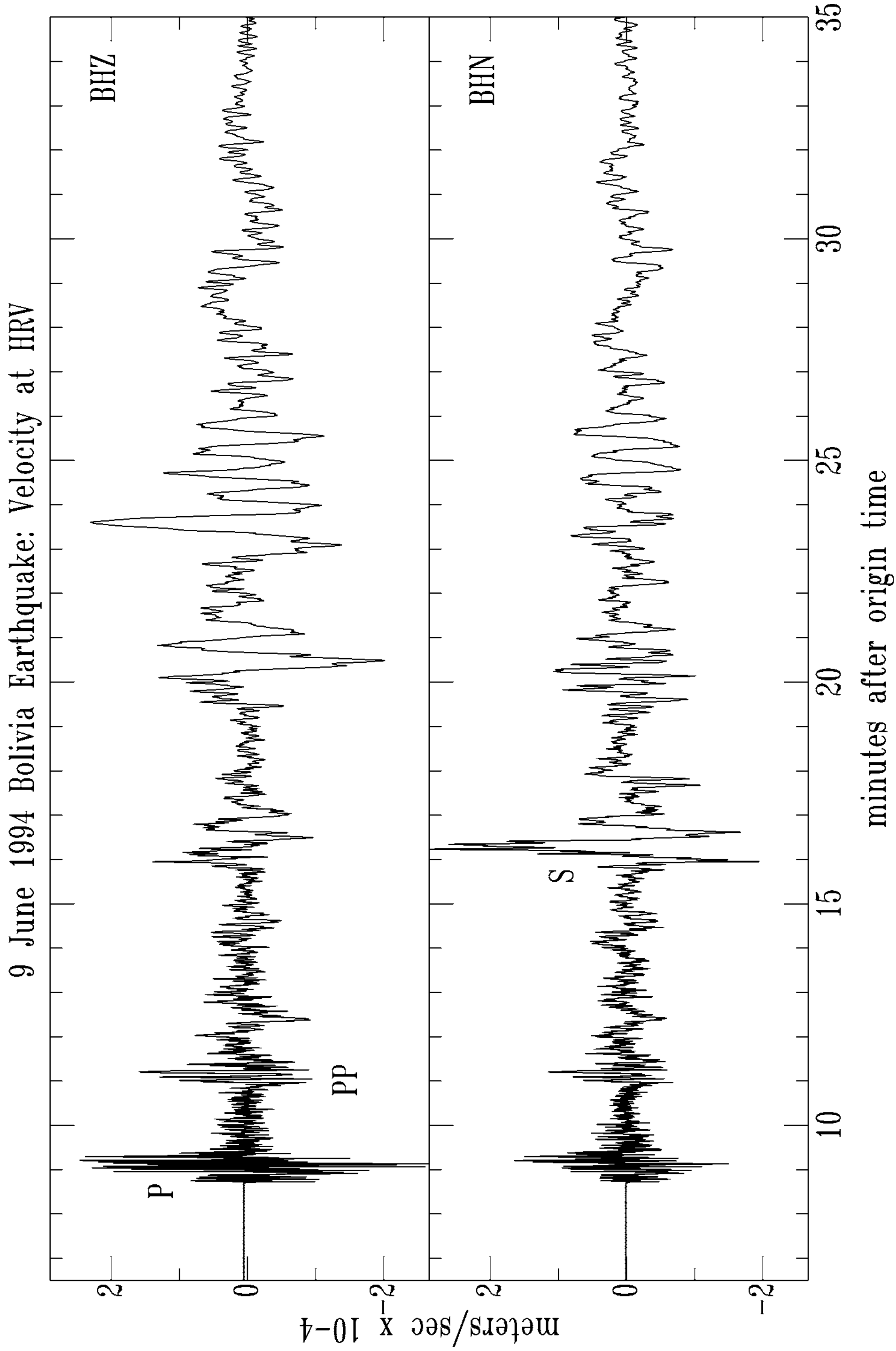
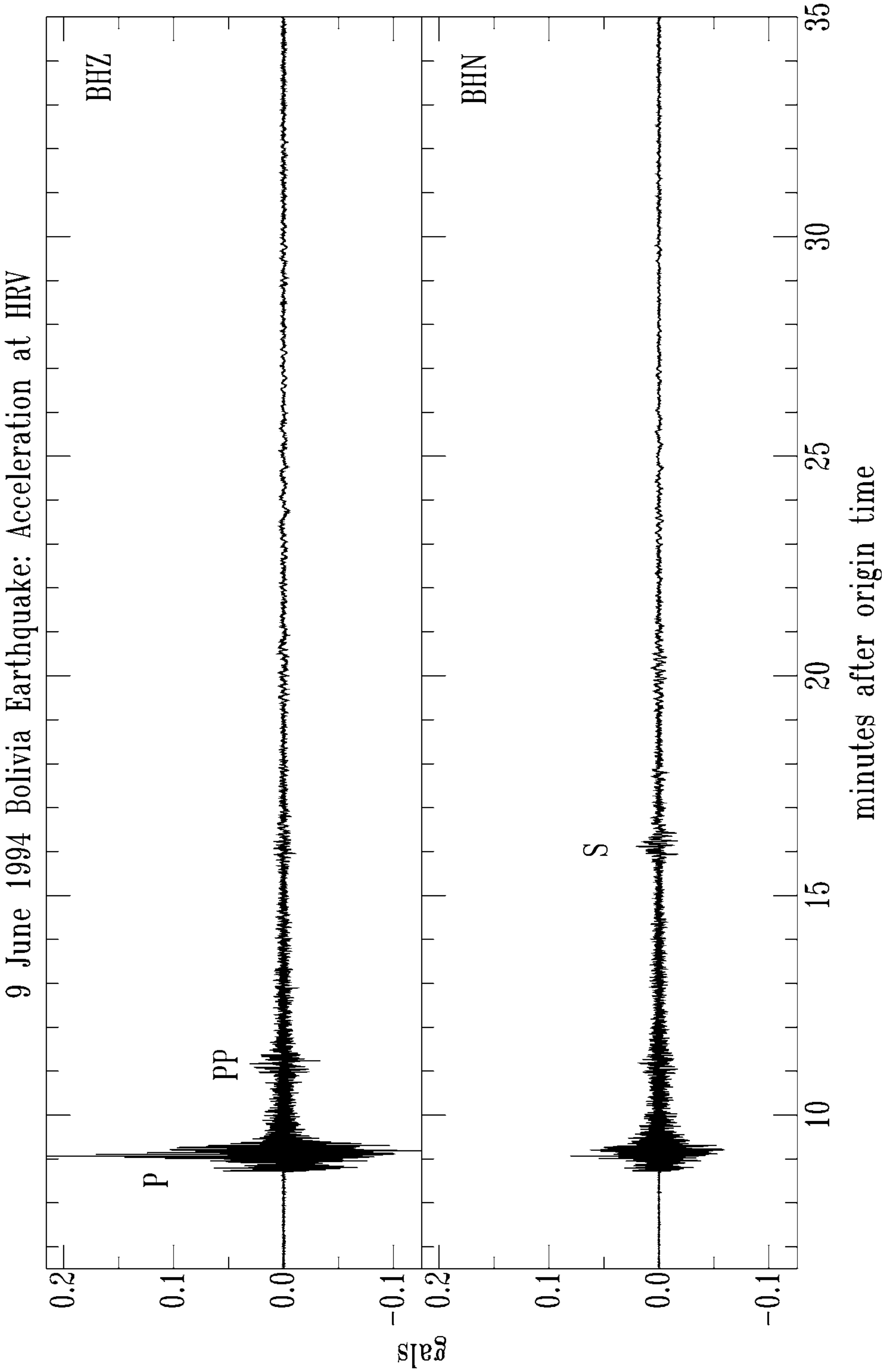


Fig. 1.2 Velocity and acceleration seismograms for the Bolivia earthquake of 9 June 1994 recorded at HRV (Harvard, MA; $\Delta = 56°$, azimuth = 356°). While peak velocities for P and S are about the same, the highest peak accelerations accompany the higher-frequency P arrival.


9 June 1994 Bolivia Earthquake: Acceleration at HRV
BHZ
BHN
P
PP
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gals
0.2
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−0.1
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35
minutes after origin time

Fig. 1.2 (*cont.*)

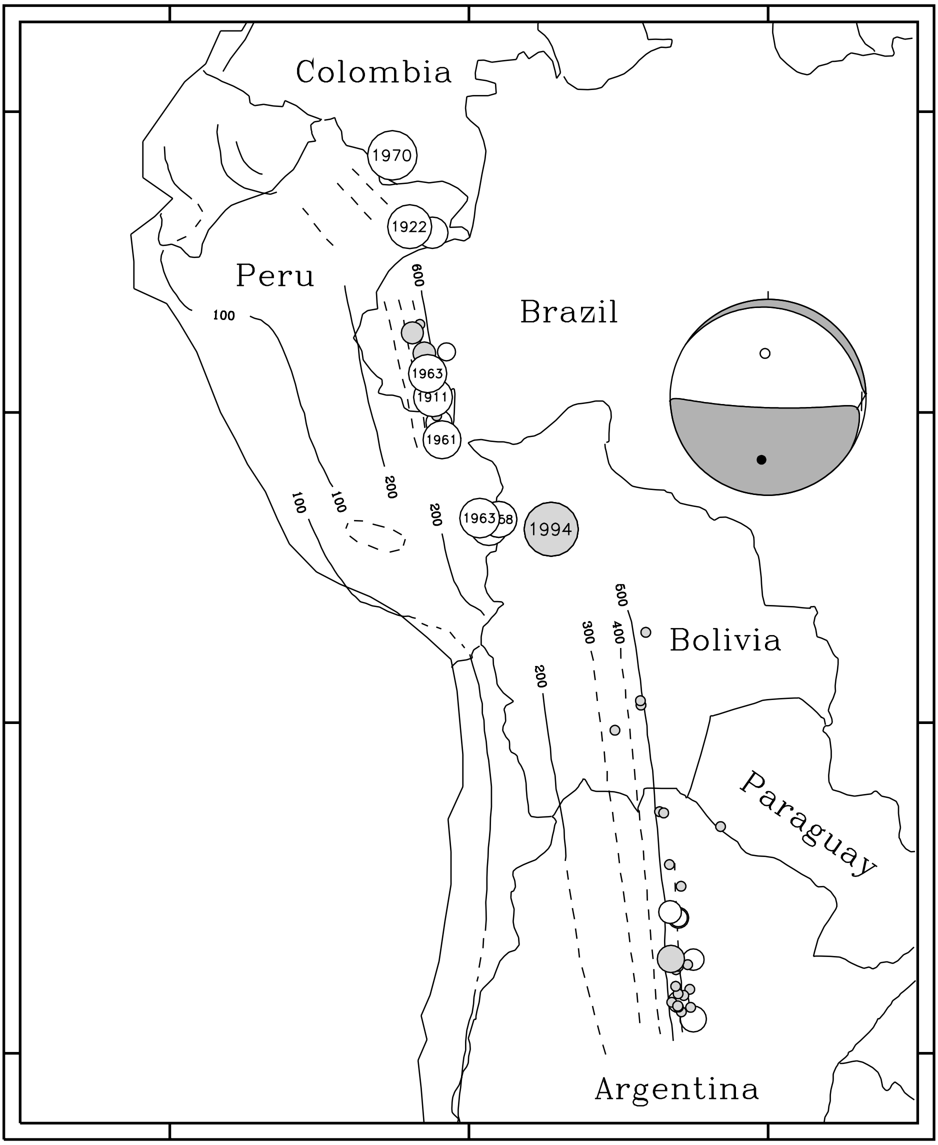

Fig. 1.3 Relation of the 1994 Bolivia deep-focus earthquake to previous deep earthquakes in South America, and focal mechanism reported by Harvard (right). Circles are earthquakes with depths exceeding 300 km occurring before 1977 (open circles) and after 1977 (filled circles) in the Harvard CMT catalog, the CMT historical catalog, the EV Centennial catalogs (see Chapter 10), and from Okal and Bina (2001). Events labeled with dates have M_W of 7.5 or greater. Small numbers label depth contours of the Wadati–Benioff zone from Burbach and Frohlich (1986). Note that the 1994 earthquake occurred in a region where no Wadati–Benioff zone was evident, approximately midway between the better-defined zones in western Brazil and Bolivia–Argentina.

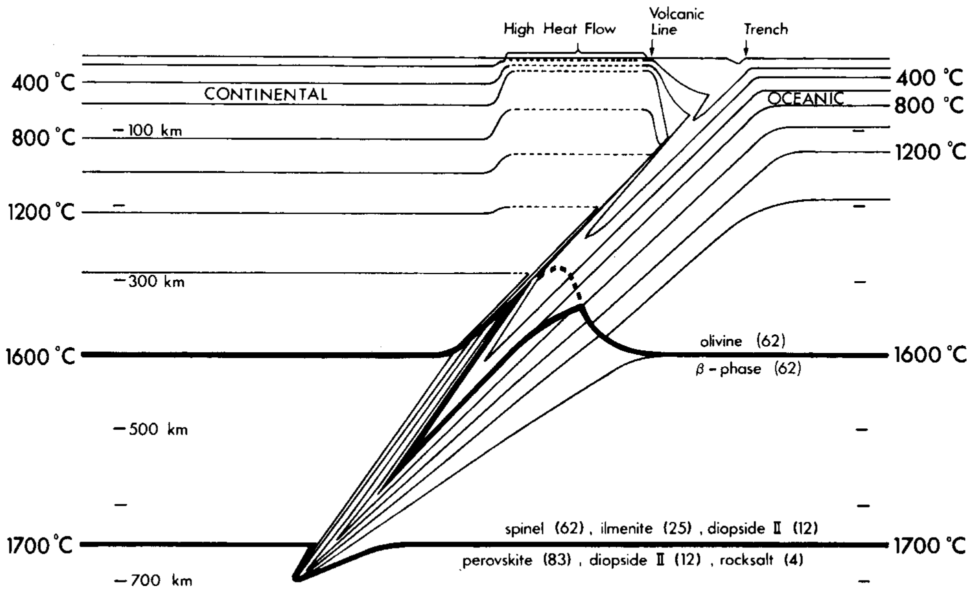

Fig. 1.4 A model of the thermal and petrological environment where subduction-zone deep earthquakes typically occur; thin lines denote isotherms, and the heavy lines represent the positions of the olivine–spinel and spinel-to-oxides phase transitions. As cold oceanic lithosphere penetrates the warmer mantle, its temperature changes because of conduction, because of frictional heating along its upper surface, and because of heat released or absorbed as subducting material undergoes phase transitions. Earthquakes occur within roughly planar zones where the stress is sufficiently high and the temperature sufficiently low. The model shown here is after Liu (1983).

he modeled rupture as occurring along a front rather than at a sequence of localized subevents, Ihmlé found that the subevent locations often did not coincide with the regions of maximum moment release (Fig. 1.6; and see Fig. 6.10).

Serendipitously, when the 1994 Bolivia earthquake occurred there were two temporary local networks operating in Peru, Bolivia, and Brazil, making it possible to detect 89 aftershocks occurring over a period of 20 days. Myers *et al.* [1995] located 45 of these and found them to occur within a slab-like region having a thickness of about 30 km, a lateral dimension of about 55–60 km, and dipping at approximately 45° to the northeast. Although the aftershocks' epicenters did correspond roughly to Ihmlé's zone of maximum slip, they did not delineate a plane coincident with either of the nodal planes of the mainshock. And the majority were situated beneath the mainshock hypocenter at depths up to 660 km. Tinker *et al.* [1995] determined focal mechanisms for 12 of the aftershocks and concluded that most had near-vertical P axes and all possessed mechanisms that were significantly different from that of the mainshock.