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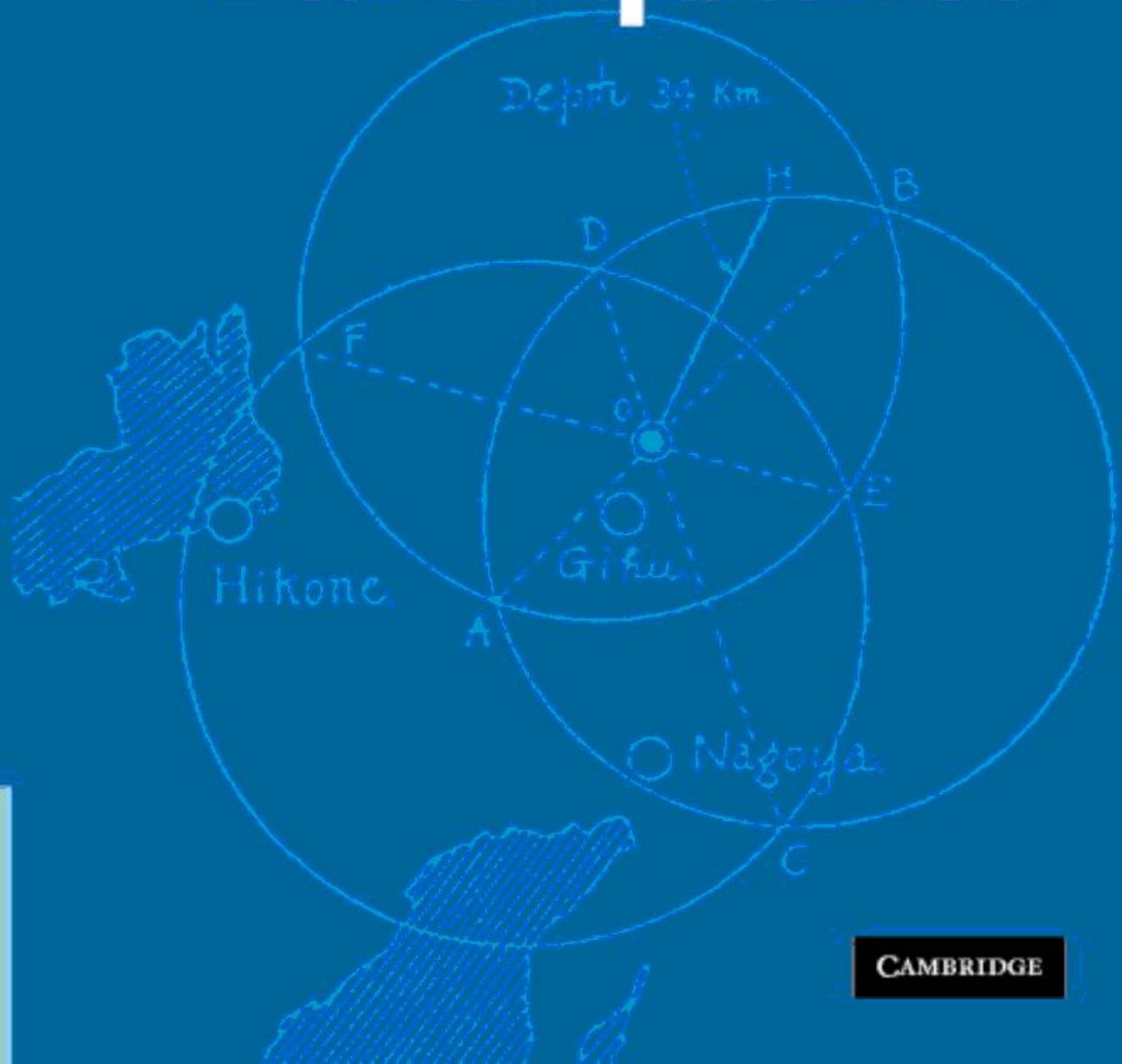
# Deep Earthquakes

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# 1

# 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* $2.5 \times 10^{20}$ *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 | $2.6 \times 10^{21}$ | 8.3 | bend |
| 2 | 31 Jul 1970 | Colombia | 623 | $1.4 \times 10^{21}$ | 8.1 | isolated |
| 3 | 17 Jan 1922 | North Peru | 664 | $9.4 \times 10^{20}$ | 7.9 | isolated |
| 4 | 17 Jun 1996 | Flores Sea | 589 | $7.9 \times 10^{20}$ | 7.9 | bend |
| 5 | 29 Mar 1954 | Spain | 630 | $7.0 \times 10^{20}$ | 7.9 | isolated |
| 6 | 29 Sep 1973 | North Korea | 593 | $5.0 \times 10^{20}$ | 7.8 | bend/edge |
| 7 | 11 Jun 1972 | Celebes Sea | 332 | $4.7 \times 10^{20}$ | 7.7 | |
| 8 | 19 Aug 2002 | Fiji | 699 | $4.3 \times 10^{20}$ | 7.7 | |
| 9 | 26 May 1932 | Fiji | 560 | $4.0 \times 10^{20}$ | 7.7 | bend |
| 10 | 15 Aug 1963 | Peru–Bolivia | 573 | $3.9 \times 10^{20}$ | 7.7 | bend |
| 10 | 28 Feb 1950 | Sea of Okhotsk | 339 | $3.9 \times 10^{20}$ | 7.7 | |
| 12 | 25 May 1907 | Sea of Okhotsk | 548 | $3.7 \times 10^{20}$ | 7.7 | |
| 13 | 09 Nov 1963 | Peru–Bolivia | 573 | $3.5 \times 10^{20}$ | 7.7 | |
| 13 | 19 Aug 2002 | Fiji | 631 | $3.5 \times 10^{20}$ | 7.7 | |
| 15 | 19 Aug 1961 | Peru–Bolivia | 620 | $3.4 \times 10^{20}$ | 7.7 | |
| 16 | 09 Mar 1994 | Fiji | 563 | $2.7 \times 10^{20}$ | 7.6 | |
| 16 | 23 May 1956 | Fiji | 436 | $2.7 \times 10^{20}$ | 7.6 | |
| 18 | 26 Jul 1958 | Peru–Bolivia | 592 | $2.6 \times 10^{20}$ | 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