

Apparent stress, fault maturity and seismic hazard for normal-fault earthquakes at subduction zones

George L. Choy¹ and Stephen H. Kirby²

¹US Geological Survey, Denver, CO 80215, USA. E-mail: choy@usgs.gov

²US Geological Survey, Menlo Park, CA 94025, USA

Accepted 2004 July 27. Received 2004 July 26; in original form 2003 November 26

SUMMARY

The behavior of apparent stress for normal-fault earthquakes at subduction zones is derived by examining the apparent stress ($\tau_a = \mu E_S / M_0$, where E_S is radiated energy and M_0 is seismic moment) of all globally distributed shallow (depth, $h < 70$ km) earthquakes with normal-fault mechanisms that occurred in or near subduction zones between 1987 and 2001 for which E_S and M_0 are available. Accurately determined hypocentres from the Engdahl–Hilst–Buland (EHB) catalogue establish the fine detail of the Wadati–Benioff zone. In many cases, we can relate trends in apparent stress to specific features within the subduction zone and compare these with trends for interplate-thrust earthquakes in the same subduction zones. There are two depth ranges over which τ_a for normal-fault earthquakes shows maxima. The highest and most anomalous values of τ_a are found in the deeper depth range from 35 to 70 km. The high- τ_a events (up to 5 MPa) are characteristically intraslab and in proximity to zones of intense deformation such as a sharp slab bend or where opposing slabs collide. High- τ_a events in the region of the shallower maximum (hypocentres between 10–35 km and $\tau_a > 1$ MPa) are also generally intraslab, but occur where the lithosphere has just begun subduction beneath the overriding plate. They usually occur in cold slabs near trenches where the direction of plate motion across the trench is oblique to the trench axis, or where there are local contortions or geometrical complexities of the plate boundary. Lower τ_a (< 1 MPa) is associated with events occurring at the outer rise (OR) complex (between the OR and the trench axis), as well as with intracrustal events occurring just landward of the trench. The average apparent stress of intraslab-normal-fault earthquakes is considerably higher than the average apparent stress of interplate-thrust-fault earthquakes. In turn, the average τ_a of strike-slip earthquakes in intraoceanic environments is considerably higher than that of intraslab-normal-fault earthquakes. The variation of average τ_a with focal mechanism and tectonic regime suggests that the level of τ_a is related to fault maturity. Lower stress drops are needed to rupture mature faults such as those found at plate interfaces that have been smoothed by large cumulative displacements (from hundreds to thousands of kilometres). In contrast, immature faults, such as those on which intraslab-normal-fault earthquakes generally occur, are found in cold and intact lithosphere in which total fault displacement has been much less (from hundreds of metres to a few kilometres). Also, faults on which high τ_a oceanic strike-slip earthquakes occur are predominantly intraplate or at evolving ends of transforms. At subduction zones, earthquakes occurring on immature faults are likely to be more hazardous as they tend to generate higher amounts of radiated energy per unit of moment than earthquakes occurring on mature faults. We have identified earthquake pairs in which an interplate-thrust and an intraslab-normal earthquake occurred remarkably close in space and time. The intraslab-normal member of each pair radiated anomalously high amounts of energy compared to its thrust-fault counterpart. These intraslab earthquakes probably ruptured intact slab mantle and are dramatic examples in which M_e (an energy magnitude) is shown to be a far better estimate of the potential for earthquake damage than M_W . This discovery may help explain why loss of life as a result of intraslab earthquakes was greater in the 20th century in Latin America than the fatalities associated with interplate-thrust events that represented much higher total moment release.

Key words: apparent stress, intraslab earthquake, seismic energy, seismic hazard, subduction zone.

1 INTRODUCTION

Normal-fault earthquakes occurring in subduction zones are generally recognized as the manifestations of downward deflection and descent of oceanic plates at convergent plate boundaries. Near the outer rise and the outer trench wall (OR and OTW, respectively), normal-fault earthquakes are induced by extensional failure from the downward bending of the subducted plate. On the landward side of trenches, thrust-fault earthquakes are the dominant mode of failure, arising from rupture of the frictional contact between the overriding and subducting plates. Also on the landward side, teleseismically large damaging normal-fault events can occur beneath the interface thrust zone and within the cold seismogenic part of the subducting lithosphere. The generally accepted mechanism that induces these intraslab earthquakes at shallow depths is plate bending and unbending. At greater depths, normal-fault events are often attributed to the tensional slab pull force, a negative buoyancy arising from the sinking of dense oceanic lithosphere into warmer mantle material (e.g. Spence 1987). In addition, densification caused by metamorphism of the oceanic crust to the eclogite mineral assemblage should produce normal faulting in the transformed slab crust at depths that depend on slab thermal structure (Kirby *et al.* 1996). Shallow normal-fault earthquakes behind the trench and above the subducting slab are intracrustal, arising as the overriding plate accommodates collision with the buoyant oceanic lithosphere.

Although they represent far less moment release than thrust-fault events at subduction zones, teleseismically large normal-fault events are responsible for a disproportionate share of earthquake damage and loss of life in Latin America (Kirby *et al.* 2002b). While the seismic slip along the plate interface occurs largely offshore for interplate-thrust earthquakes, the hypocentres of normal-fault earthquakes, especially those intraslab events nucleating at intermediate depth (approximately 35–70 km), are usually inland and, hence, more likely to be beneath population centres. Some large damaging events that have resulted in serious casualties and massive destruction with extensive economic repercussions include the 1939 M_W 8.0 intraslab shock beneath central Chile (Beck *et al.* 1998; Okal & Kirby 2002), the 1970 M_S 7.9 earthquake beneath coastal Peru (Abe 1972), and more recently the 1997 Coquimbo, Chile earthquake, the 1999 Oaxaca, Mexico earthquake, the 2001 March Nisqually, Washington earthquake and the 2001 January El Salvador earthquake.

Describing the spatial architecture of radiated energy release within subduction zones can enhance our ability to evaluate seismic damage potential, as well improve our understanding of slab mechanics. A useful indicator of stress is the apparent stress of an earthquake, τ_a :

$$\tau_a = \mu E_S / M_0, \quad (1)$$

where μ is the modulus of rigidity, E_S is seismic energy radiation and M_0 is seismic moment. McGarr (1999) has shown that τ_a is related to the absolute average level of shear stress, τ , causing fault slip according to

$$\frac{\tau_a}{\tau} \leq 0.06. \quad (2)$$

Moreover, as $M_0 = \mu A d$, where A is the area of the fault and d is the average displacement on the fault, τ_a can be viewed as being proportional to the radiated energy per unit rupture area per unit displacement or as being proportional to the radiated energy per unit of moment. Hence, our ability to characterize any class of earthquakes as having unusually elevated apparent stress for a given rupture size can lead to improving estimates of seismic hazards potential.

The deployment since the 1980s of global seismographic networks with broad bandwidth capabilities has enabled international reporting agencies to introduce into routine practice new parameters for describing the earthquake source that were previously impractical without broad-band data. Two such source parameters, which are requisites for estimating τ_a , are M_0 and E_S . Since the 1980s, the National Earthquake Information Center (NEIC) of the US Geological Survey has, in its Monthly Listings of the Preliminary Determination of Epicentres (PDE), routinely published the radiated energy and seismic moment for all large earthquakes. In the first part of this paper, we search the NEIC database for all events with predominantly normal-fault focal mechanisms for which both a moment and an energy have been computed. We select the subset of normal-fault earthquakes for which hypocentres are shallower than 70 km and that are located proximate to subduction zones. The first objective of this paper is to identify from plots of τ_a versus depth those normal-fault earthquakes with the highest τ_a and to investigate the specific tectonic factors that may have resulted in their anomalous energy release. The second objective of this paper is to identify any systematic variation of τ_a with depth of nucleation and distance from the trench axis. For each earthquake, a cross-section of seismicity is taken normal to the trench axis passing through the hypocentre. By using systematically relocated hypocentres of high quality, we are able to classify each normal-fault earthquake according to its local seismotectonic feature within the subduction zone complex (Fig. 1), such as the OTW, the subducting slab or the forearc. The identification of the characteristic τ_a for specific tectonic features would be a useful tool for improving seismic hazards evaluation as well as for gaining an insight into the mechanics of slab subduction.

2 DATA

Moments are obtained from the US Geological Survey's National Earthquake Information Center (NEIC) which, in its Monthly Listings of the PDE, routinely publishes seismic moments computed by two methods. The moments are from inversions using a body wave moment tensor (Sipkin 1982) and a centroid moment tensor (Dziewonski *et al.* 1981). Although in this paper we use only the moments from the centroid method for uniformity, the moments from the two methods are usually in agreement for earthquakes smaller than 10^{20} Nm (Sipkin 1986). Thus, on average, our conclusions are qualitatively unchanged regardless of whether the centroid or the body wave moments are used.

Since 1987, the NEIC has routinely published radiated energies for earthquakes with E_S greater than approximately 10^{12} Nm. These energies are computed directly from broad-band body wave data, rather than by empirical formulae based on magnitude or moment. The method used is that of Boatwright & Choy (1986) in which the energy flux in broad-band P waves is obtained by direct integration of velocity-squared records. Similar methods for computing energy have been proposed by others (e.g. Houston 1990; Newman & Okal 1998; Perez-Campos & Beroza 2001). We use the NEIC values because their computation has been continuous, uniform and concurrent with published M_0 values. The nominal uncertainty in M_0 (Sipkin & Ekstrom, private communication, 2004), as well as E_S is between 20–30 per cent. The important point is that M_0 and E_S are computed (using their respective methods) throughout the data set uniformly and consistently. Thus, the relative differences in apparent stress should be reliable.

Several types of depth determinations appear in the Monthly Listings: (i) a depth from conventional inversion of P -wave arrival times;

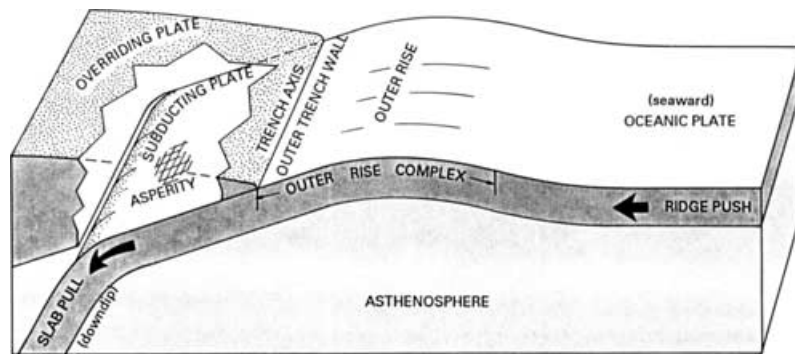


Figure 1. Schematic of a typical subduction zone from the outer rise and the outer trench wall (OR and OTW, respectively) to the subducted lithosphere and overriding plate.

(ii) a depth from body wave moment tensor inversion; (iii) a depth from centroid moment–tensor inversion; and (iv) a depth derived from broad-band waveforms. In order to ascribe a hypocentre to a specific feature in a subduction zone, the most reliable and well-resolved estimate of depth is required. The accuracy of a depth derived from P -wave arrival times alone is limited, at least for teleseismic computations, by the lack of vertical resolution. The moment–tensor solutions, which are generally derived from low-frequency data, reflect the gross properties of the rupture process and yield depths that may be averaged over tens of seconds or more. In contrast, the broad-band depths are determined from waveforms that have a flat response over the frequency range 0.01–5.0 Hz, which encompasses spectral information that brackets the corner frequency of teleseismically recorded earthquakes. The depth using the broad bandwidth has higher resolution and is essentially the depth of nucleation. Thus, the broad-band depths are most appropriate for our study. The spectral information from which they are derived is also commensurate with that used to compute E_S . Since 1985 October, the NEIC has been publishing a broad-band depth concurrent with estimates of E_S and M_0 . However, there is one significant correction that we make to the published values for depth. In the routine computation of depth from global data, it is common practice for reporting agencies to use a radially varying but spherically symmetric average earth model such as the Jeffreys–Bullen (Jeffreys & Bullen 1940) and iasp91 (Kennett & Engdahl 1991) models, which are appropriate for continental structure. In this paper, the depths of earthquakes with oceanic epicentres are redetermined using oceanic structure.

The focal mechanisms listed for the earthquakes in subsequent sections of the paper are also from the NEIC. In its Monthly Listings of the PDE, the NEIC publishes focal mechanisms derived from moment–tensor methods, P -wave first-motions and broad-band waveform modelling. In the computation of E_S , a correction for focal mechanism is applied (e.g. Boatwright & Choy 1986). The mechanism chosen is that which is most compatible with broad-band body waves, which is usually the one derived from broad-band modelling if available.

Finally, in the selection of events for analysis we eliminate those that do not satisfy the following criteria: (i) at least six well-distributed stations must have been used in the estimate of E_S ; (ii) a reliable focal mechanism (usually the broad-band determined focal mechanism) must have been available; and (iii) a broad-band depth is available. Thus, some of the events for which E_S are listed in the PDE do not appear in this study.

To interpret background seismicity in terms of the subduction-zone tectonics we plot seismic activity in cross-sections taken

normal to the trench axis. We use, whenever available, the relocated hypocentres from the Engdahl–Hilst–Buland (EHB) catalogue (Engdahl *et al.* 1998). By using later arrivals, including all depth phases, in addition to the usual regional and teleseismic P and S arrivals, the EHB algorithm returns hypocentres that are most suitable for resolution and definition of the Wadati–Benioff zone. The EHB catalogue is complete for events down to approximately M_W 5.2 from 1963 to 1999.

Shallow events whose epicentres are unequivocally seaward from the trench axis can be easily classified as occurring in the OR or OTW. Likewise, shallow events well above the Wadati–Benioff zone are easily categorized as intracrustal within the overriding plate. Deeper events far from the plate boundary and within the Wadati–Benioff zone can, likewise, be easily classified as intraslab. The classification of some events whose epicentres are near a nominal trench axis may be problematic. They are provisionally regarded as intraslab rather than intracrustal provided that: (i) their depths of nucleation are sufficiently deep to locate the earthquake well beneath the interplate boundary and (ii) their hypocentres are within the Wadati–Benioff zone delineated by the aggregate seismicity pattern as extrapolated towards the trench axis.

3 OBSERVATIONS OF APPARENT STRESS FOR EARTHQUAKES IN SUBDUCTION ZONE SETTINGS

In a comprehensive global survey of 397 earthquakes, Choy & Boatwright (1995) found a systematic variation in apparent stress with earthquake focal mechanism and tectonic setting. Mean apparent stress ($\langle \tau_a \rangle$) was highest among strike-slip earthquakes at oceanic intraplate and oceanic ridge–ridge transform faults (with $\langle \tau_a \rangle$ of 6.9 and 4.5 MPa, respectively), whereas it was lowest for the population of interplate–thrust–fault earthquakes at subduction zones (with $\langle \tau_a \rangle$ of 0.3 MPa). The mean apparent stress of normal–fault earthquakes was intermediate between those of subduction zone thrust and oceanic strike-slip events ($\langle \tau_a \rangle$ 0.6 MPa). Choy & McGarr (2002) demonstrated that additional constraints on the material conditions and mechanical processes that generate large earthquakes could be obtained by examining τ_a as a function of depth. In their plot of τ_a versus depth for 942 global shallow earthquakes (Fig. 2), a prominent maximum in the envelope of high- τ_a values can be seen in the depth range 10–35 km. They found that very high τ_a events ($\tau_a > 5.0$ MPa) were associated exclusively with strike-slip earthquakes in intraplate oceanic or ridge–ridge transform fault environments that were subject to intense plate deformation and/or

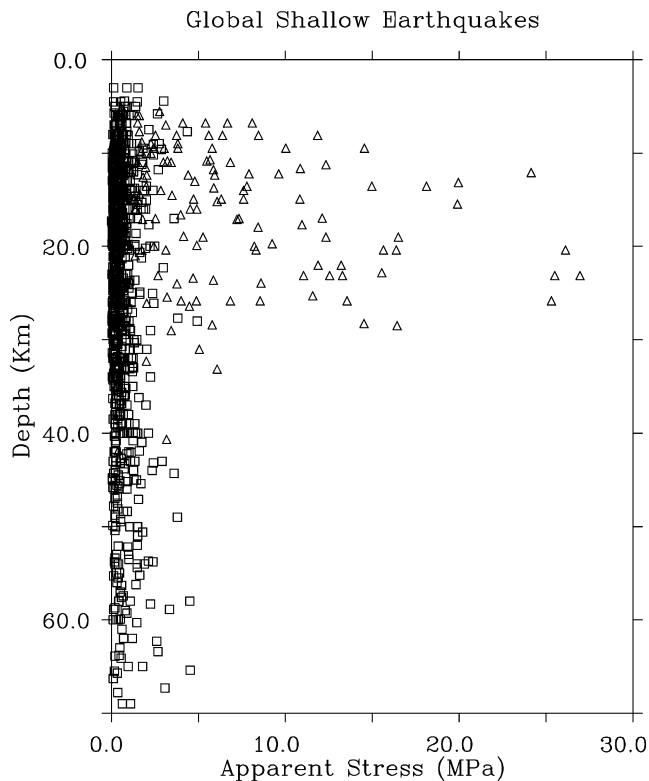


Figure 2. Apparent stress (τ_a) as a function of depth for the global set of 942 shallow-focus (depth ≤ 60 km) earthquakes with $E_S \geq 10^{17}$ N m that occurred between 1987 and 1998. Triangles indicate oceanic events with strike-slip focal mechanisms. The largest values of τ_a , which occupy a wedge-shaped portion of the plot in the depth range of approximately 10–30 km where maximum apparent stresses approach 25.0–30.0 MPa, are almost exclusively associated with oceanic strike-slip earthquakes (from Choy & McGarr 2002).

plate reorganization. Moreover, the events had depths that placed them in the oceanic mantle. From these systematics, they were able to infer a model for the strength of oceanic lithosphere.

In Fig. 3, we have plotted τ_a versus depth for the global subset of events with predominantly normal-fault focal mechanisms that occurred from 1987 to 2001 with epicentres in the vicinity of the subduction zones. The source parameters of these 139 events are listed in the Appendix. A polynomial fit to extremal points (dotted line) defines the envelope of maximum τ_a with depth down to 70 km. It shows maxima in τ_a over two depth ranges. The maximum at greater depth, from approximately 35 down to 70 km, contains the most extreme values of τ_a , approaching 5 MPa. A secondary maximum, from the 10 down to approximately 35 km, has peak values of τ_a of approximately 3 MPa.

The average τ_a for all subduction zone normal-fault earthquakes is 0.58 MPa with a first standard deviation of ± 0.37 MPa. The upper limit of the τ_a distribution is 0.95 MPa. If we round off this limit to 1.00 MPa, we find that only 20 per cent of the subduction normal-fault events have τ_a greater than 1 MPa. We adopt the value of 1 MPa as the criterion for distinguishing normal-fault earthquakes with typical values of τ_a from those with exceptionally high values. Moreover, if values with exceptionally high τ_a are regarded as outliers, we can obtain the average τ_a for the majority of OR/subduction normal-fault events by applying a 0.20 trim before taking an average. The resulting mean for the population of average subduction zone normal-fault earthquakes (for which $\tau_a <$

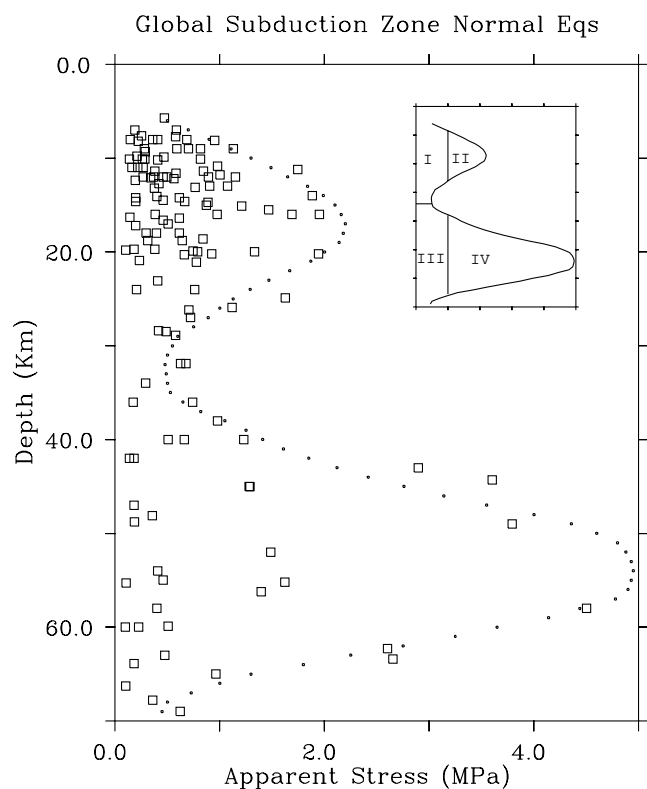


Figure 3. Apparent stress (τ_a) as a function of depth for the subset of 139 normal-fault shallow (depth ≤ 70 km) earthquakes with epicentres in the vicinity of a subduction zone. A polynomial fit to the extremal points defines the τ_a –depth envelope. Between the depth ranges of 10–35 and 35–70 km, there are two maxima in the envelope. Thus, we take 35 km as the demarcation of very shallow versus deeper populations. The standard deviation for τ_a is at approximately 1.0 MPa. Thus, we take 1.0 MPa as the demarcation between normal or average values of τ_a and high or elevated values of τ_a . The four quadrants are shown in the inset and defined in Table 1.

1.0 MPa) is 0.6 MPa. Thus, we can now further investigate the characteristics of earthquakes in four τ_a –depth quadrants as defined in the inset of Fig. 3: (I) shallower (<35 km) events with average τ_a (<1.0 MPa); (II) shallower events with exceptionally high τ_a (≥ 1 MPa); (III) deeper (>35 km) events with average τ_a ; and (IV) deeper events with exceptionally high τ_a . Events having $\tau_a > 2.5$ MPa are very rare. There are only five such events, all of which are deep and intraslab. The term anomalous is reserved for apparent stresses exceeding 2.5 MPa. We should also keep in mind that the τ_a of the average subduction zone normal-fault earthquake is still higher than the τ_a of the average subduction zone thrust event (for which $\langle \tau_a \rangle$ is 0.3 MPa). Finally, to facilitate the discussion in the next few sections of this paper, we outline in Table 1 our major findings for earthquakes in each quadrant. In particular, we find that average or exceptional values of τ_a are associated with specific seismotectonic features of subduction zones.

4 DEEPER INTRASLAB EARTHQUAKES WITH EXCEPTIONALLY HIGH APPARENT STRESS

There are 12 events in the τ_a –depth quadrant (Table A1) having exceptionally high τ_a (>1.0 MPa) that occur in the deeper interval (35–70 km). Their average τ_a is 2.36 MPa with a standard deviation

Table 1. Summary of the tectonic settings generally found in each τ_a -depth quadrant (see Fig. 3).

	Average τ_a (< 1.0 MPa)	Exceptional τ_a (≥ 1.0 MPa)
Shallower population (depth < 35 km)	I. Outer rise and outer trench wall, intracrustal (overriding plate). Some intraslab	II. Intraslab, behind axis of subduction
Deeper population (depth 35–70 km)	III. Warm intraslab, flat slab geometry	IV. Cold intraslab, near sharp change in slab geometry or near duelling slabs

of 1.31. Earthquakes of this group appear to be exclusively intraslab events occurring only in: (i) cold slabs [i.e. older lithosphere descending at moderate to fast rates (Kirby *et al.* 1996)]; (ii) zones of intense deformation such as at sharp bends or changes in the sign of slab curvature (concave downward to upward); or (iii) the collisional juncture of oppositely subducting slabs, a phenomenon that we term duelling slabs. These normal-fault earthquakes have two other unique attributes. First, they include the only events in the source-parameters database (from 1987 to 2003) that have occurred as paired sequences of interface-thrust/intraslab-normal fault earthquakes. Secondly, they include the only normal-fault earthquakes with anomalous apparent stresses ($\tau_a > 2.5$ MPa). Because of their rarity compared with the abundance of data in the other quadrants, we now discuss the tectonic attributes of all 12 events in this quadrant.

4.1 Interplate-thrust and intraslab-normal coupling

We found two examples where a major normal-faulting intraslab earthquake was followed within a few months by a major interplate-thrust event. The proximity of the earthquakes in each pair provides optimum conditions for comparison of the radiated energies associated with these different types of faulting where the tectonic setting is otherwise the same.

4.1.1 The 1997 Coquimbo, Chile earthquakes

The source parameters and macroseismic reports for two events that occurred in Chile are summarized in Table 2. The initial event of 1997 July was a shallow interplate event (M_W 6.9, M_e 6.1) with a thrust focal mechanism, while the subsequent event of 1997 October (M_W 7.1, M_e 7.6) was an intraslab event with a normal focal mechanism (Fig. 4a). The epicentres are separated by less than 1° in distance and by approximately 4 months in time. The Wadati–Benioff zone delineated by a cross-section of seismicity taken normal to trench axis at the hypocentre of the normal-fault event (Fig. 4b) defines a slab shape (enclosed by dashed lines) with a change in the sign of the curvature. Slab flattening behind the coast of Chile at 30° S is a very conspicuous feature that has long been recognized from seismicity cross-sections (e.g. Barazangi & Isacks 1976). The slab is concave downward on the trench side to a depth of approximately 60 km, concave upward from 60 to approximately 115 km, and reverts to concave downward below 115 km. The 1997 October normal-fault earthquake occurs at the first change in curvature beyond which seismicity also suddenly becomes more sparse. Its focal mechanism is consistent with concave-upward bending with failure below the neutral surface; its occurrence probably reflects the high strain rates and stresses accompanying the change in curvature

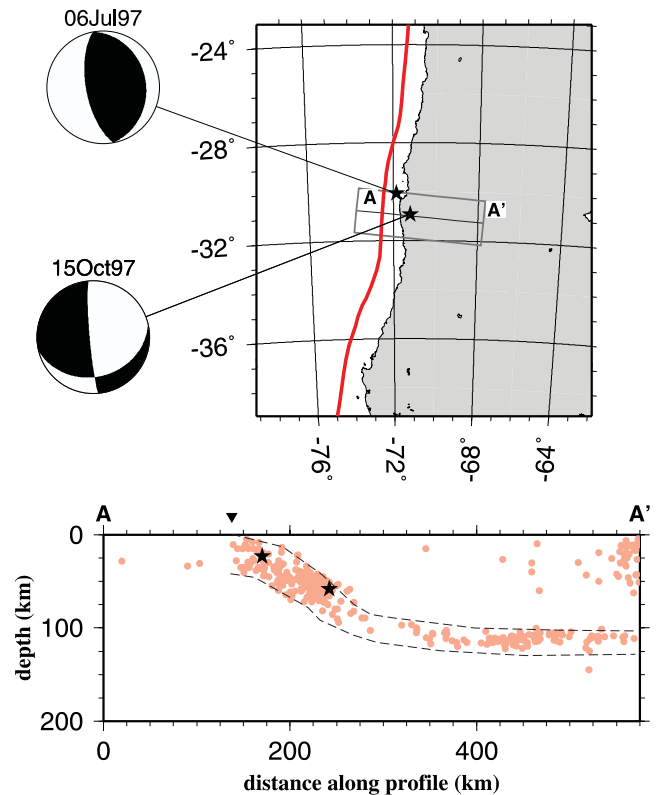


Figure 4. (a) Map of the coastal region of central Chile showing the epicentres and focal mechanisms (listed in Table 2) of the Coquimbo, Chile earthquake pair. The first event was the 1997 July 6 interplate-thrust-fault earthquake. The second event was the 1997 October 15 intraslab-normal-fault earthquake. A–A' is the line along which a seismicity cross-section is taken. The width of the cross-section is indicated by the rectangle. In Figs 4–20, plate boundaries are indicated by red (for trench axes), green (for ridge axes) or blue (for transform faults). (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A' to delineate the Wadati–Benioff zone of the subducted lithosphere. The dashed lines delimiting seismicity of the Wadati–Benioff zone show slab bending. The normal-fault earthquake is the deeper hypocentre and is located near a bend in the slab where seismicity suddenly decreases. In Figs 4–20, the position of the trench axis along A–A' is indicated by the inverted triangle.

near 60 km depth. The τ_a of 4.4 MPa was the highest τ_a of all the normal-fault events that we studied.

As seen in Table 2, the two earthquakes have virtually the same M_S and M_W in addition to having similar spatial and temporal locations. Nevertheless, the intraslab earthquake caused much greater damage than the interplate event (Choy *et al.* 2002; Okal & Kirby 2002). While the first (thrust) earthquake was merely felt, the second (normal) earthquake caused extensive damage and some loss of life. The disparity in macroseismic effects cannot be discerned from their respective M_W values, which are nearly identical. However, their energy magnitudes, M_e , were dramatically different (where $M_e = (2/3) \log E_S - 2.9$, from Choy & Boatwright 1995). The M_e 7.6 of the intraslab earthquake, which caused much greater damage, is 1.5 magnitude units larger than the M_e 6.1 of the interplate event. M_W , which is proportional to the low-frequency asymptote of displacement spectra, was not as successful in quantifying macroseismic effects as M_e . In contrast, M_e , which is derived from the higher frequencies of velocity spectra, was commensurate with the disparity in macroseismic effects. Most of the damage caused by the 1997 October intraslab event was to small structures; hence, the higher

Table 2. Source parameters and macroseismic reports for the 1997 Coquimbo, Chile earthquakes (Choy *et al.* 2002).

Date	Lat. (°)	Long. (E)	Depth (km)	M_e	M_W	m_b	M_S	τ_a (MPa)	Faulting type
1997 Jul 6 ⁽¹⁾	−30.06	−71.87	23.0	6.1	6.9	5.8	6.5	0.1	Interplate-thrust
1997 Oct 15 ⁽²⁾	−30.93	−71.22	58.0	7.6	7.1	6.8	6.8	4.4	Intraslab-normal

⁽¹⁾Felt (III) at Coquimbo, La Serena, Ovalle and Vicuna.

⁽²⁾Five people killed at Pueblo Nuevo, one person killed at Coquimbo, one person killed at La Chimba and another died of a heart attack at Punitaqui. More than 300 people injured, 5000 houses destroyed, 5700 houses severely damaged, another 10 000 houses slightly damaged, numerous power and telephone outages, landslides and rockslides in the epicentral region. Some damage (VII) at La Serena and (VI) at Ovalle. Felt (VI) at Alto del Carmen and Illapel; (V) at Copiapo, Huasco, San Antonio, Santiago and Vallenar; (IV) at Caldera, Chanaral, Rancagua and Tierra Amarilla; (III) at Talca; (II) at Concepcion and Taltal. Felt as far south as Valdivia. Felt (V) in Mendoza and San Juan Provinces, Argentina. Felt in Buenos Aires, Catamarca, Cordoba, Distrito Federal and La Rioja provinces, Argentina. Also felt in parts of Bolivia and Peru.

Table 3. Source parameters and macroseismic reports for the Kodiak Island, Alaska sequences of earthquakes of 1999–2000 (Choy *et al.* 2002).

Date	Lat. (°)	Long. (E)	Depth (km)	M_e	M_W	m_b	M_S	τ_a (MPa)	Faulting type
1. 1999 May 7 ⁽¹⁾	56.42	−152.94	20.0	5.8	6.3	5.7	6.1	0.2	Interplate-thrust
2. 1999 Dec 6 ⁽²⁾	57.41	−154.49	52.0	7.0	7.0	6.8	—	1.7	Intraslab-normal
3. 1999 Dec 7 ⁽³⁾	57.36	−154.1	45.0	6.4	6.5	6.5	6.1	1.5	Intraslab-normal
4. 2000 Jul 11 ⁽⁴⁾	57.60	−154.51	49.0	6.8	6.7	6.3	6.3	2.5	Intraslab-normal

⁽¹⁾No felt reports.

⁽²⁾Slight damage (VI) at Larsen Bay and Old Harbor. Felt strongly at Akhiok and Kodiak. Felt (III) at Homer and Chignik; (II) at Anchorage, Palmer and Willow. Also felt at Dillingham, Eagle River, Fairbanks, Kasilof, Nelson Lagoon and Nikiski.

⁽³⁾Felt at Anchorage, Ekwok, Homer, King Salmon, Kodiak and Old Harbor.

⁽⁴⁾Some minor damage on Kodiak. Felt throughout southern Alaska and as far north as Fairbanks.

amplitudes at high frequency from the 1997 October event are probably a significant factor in explaining the difference in damage from the 1997 July interplate event.

4.1.2 The 1999–2000 Kodiak, Alaska earthquakes

The source parameters and macroseismic reports for another sequence of coupled interface–intraslab events are given in Table 3. The sequence at Kodiak, Alaska began with a thrust event in 1999 May (M_W 6.3, M_e 5.8). Three large ($M_W \geq 6.5$, $M_e \geq 6.4$) normal-fault earthquakes followed, starting in 1999 December and ending in 2000 July (Fig. 5a). A cross-section of seismicity normal to the trench axis and passing through the hypocentre of the first large normal event is shown in Fig. 5(b). As with the paired interplate–intraslab events of 1997 in Chile, the normal earthquakes here occur near a sharp change in the slab curvature, seen in Fig. 5(b) as a sharp increase in the dip of the Wadati–Benioff zone (dashed lines). This type of slab bend has been documented for many subduction zones and is particularly well established for Alaska (e.g. Spence 1987).

The spatial and temporal proximity of the events is not as dramatic as it was for the Coquimbo, Chile sequence. The distance between the interplate-thrust and intraslab-normal events is approximately 160 rather than 60 km, and the time interval is approximately 7 to 14 months rather than 4 months. On the other hand, as with the Chile sequence, the disparity in reported damage between interplate-thrust and intraslab-normal earthquakes is very pronounced (Table 3). The macroseismic effects associated with the normal–intraslab earthquakes are in sharp contrast with the lack of reports of earthquake effects from the interplate-thrust earthquake. As the M_S values of the events are very similar, they are not adequate discriminants for the wide range of macroseismic effects. Moreover, although M_W for the interplate-thrust event and the intraslab-normal events are comparable (notably between events 1 and 3), the M_e differs by

0.6 magnitude units. As with the Coquimbo, Chile sequence, the range of macroseismic differences are more effectively quantified by M_e than by M_W .

The aftershocks of the first and largest of the normal events (event 2, M_W 7.0) were relocated by Hansen & Ratchkovski (2001) and shown in their fig. 7. Their aftershock hypocentres delineate a thin nearly vertical zone that begins at the top of the Wadati–Benioff zone, passes through the hypocentre of the main (normal-fault) event and then below the Wadati–Benioff zone defined by prior seismicity. The apparent expansion of aftershock activity downwards suggests that the intraslab earthquake could have ruptured into the upper mantle of the subducted lithosphere or, alternatively, that it could have stressed the upper mantle sufficiently to induce secondary activity. The focal mechanism of event 2 has a near-vertical nodal plane with a northeast–southwest strike that is subparallel to the horizontal distribution of the aftershocks. The distribution of aftershocks suggests that the steep nodal plane was the plane of rupture. The normal-fault earthquake in the Chile sequence also had a vertical fault plane. In Fig. 4(b), a vertical fault plane rupturing downwards would bracket the active patch of seismicity at the bottom of the dipping slab just before the bend where the slab flattens out.

4.2 Duelling Slabs

There are eight other deep events with elevated τ_a . All occurred in complex tectonic environments involving continent–arc or arc–arc collision. We use the term duelling slabs to describe the situation where the slabs within a few degrees of each other have been or still are converging. The high level of seismic activity, broad zones of seismicity and sharp changes in curvature in the Wadati–Benioff zone all suggest that high levels of seismic strain rate are present in these environments.

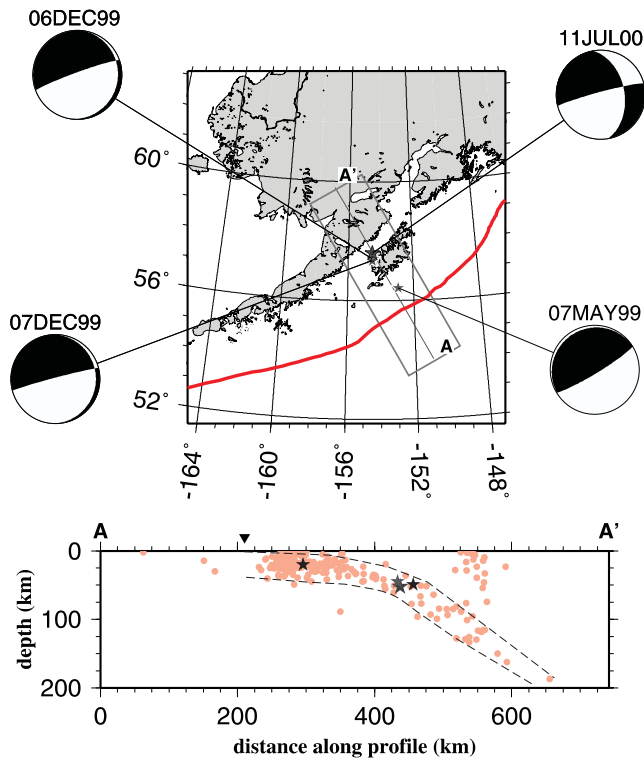


Figure 5. (a) Map of the Kodiak Island region off the coast of Alaska showing the epicentres and focal mechanisms (listed in Table 3) of the 1999–2000 Kodiak earthquake sequence. The first event was the 1999 May 7 interplate-thrust-fault earthquake. The subsequent three events were the 1999 December 6, 1999 December 7 and 2000 July 11 intraslab-normal-fault earthquakes, respectively. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A' to delineate the Wadati–Benioff zone of the subducted lithosphere. The three normal-fault earthquakes, which are the deeper events, occur near a sharp bend in the slab, which is delineated by the dashed lines bounding the seismicity of the Wadati–Benioff zone.

4.2.1 The Muertos Trough, northern Caribbean

A deep high- τ_a (2.6 MPa) normal-fault event occurred near the Mona Passage between Hispaniola and Puerto Rico on 1989 June 18. The seismicity in the cross-section taken normal to the Puerto Rico trench delineates two inclined zones of seismic activity corresponding to opposing subduction at the Muertos trough (Caribbean Plate) and the Puerto Rico trench (North American Plate). The existence of two convergent subduction zones arises from the interaction between the Caribbean and North American plates (Byrne *et al.* 1985; Dolan *et al.* 1998). Active subduction along the southern boundary of the Hispaniola and Puerto Rico microplates, represented by the Muertos trough, was a response to oblique subduction near the Puerto Rico trench.

The high- τ_a earthquake occurred within the seismic activity associated with subduction along the Muertos trough rather than the Greater Antilles slab (Fig. 6). The intense, broad and clustered nature of these two inclined seismic zones that are rooted in the Muertos and Puerto Rico trenches suggest that the two slabs may be currently colliding and the 1989 event may be a part of trans-slab rupture in the subducting Caribbean Plate.

4.2.2 Southern Philippines

Another example of a high- τ_a earthquake in a duelling slab environment is the 1989 August 12 Mindanao earthquake of (Fig. 7).

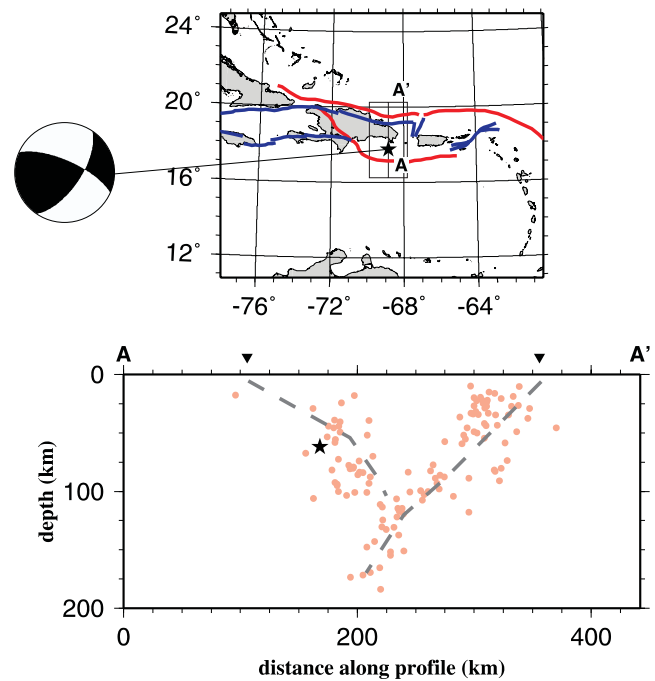


Figure 6. (a) Map of the plate boundaries at the northern Caribbean Plate showing the epicentre and focal mechanism of the 1989 June 18 deep ($h = 62$ km) intraslab earthquake just north of the Muertos trough. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The earthquake occurs in the Muertos slab rather than the Greater Antilles slab.

It occurred in a complex region involving very late Cenozoic subduction motions that saw a change from subduction of the Sunda Plate (an eastern Eurasia microplate) eastwards under the western Philippines to subduction of the Philippine Plate westwards under the Philippine islands south of Luzon at the Philippine trench (e.g. Roeder 1977; Bird 2003; Ozawa *et al.* 2004). This new west-dipping subduction system was apparently initiated when two inactive island arcs (now the Palawan and Sulu ridges) on the Sunda Plate began subducting and colliding with the western Philippine margin. Cardwell *et al.* (1980) note that although no eastward-dipping earthquake zone is resolved in the western Philippine margin, earthquakes to the west of the main westward-dipping Wadati–Benioff zone occur to depths of 50–80 km in the mantle under western Mindanao, indicating the presence of slab material there. Their inferences are consistent with the cross-section in Fig. 7 and suggests to us that the two slabs are colliding at a depth of approximately 75 km where the level of intraslab seismicity is high. The 1989 high-apparent-stress event occurred in this complex, seismically-active region of opposing subduction.

4.2.3 Melanesian region

Two high- τ_a normal-fault events occurred in the region of convergence between the Australia Plate and the Pacific or Caroline plates. Since the late Cenozoic, this region from Papua New Guinea to the Solomon Islands has undergone extensive plate reorganization, arc reversal and the accompanying creation of numerous microplates in response to the collision of Australia with New Guinea and with the Ontong Java plateau on the Pacific Plate. Among the expressions of the complex interaction of these plates are numerous leaky transform faults, propagating backarc spreading centres, overridden or

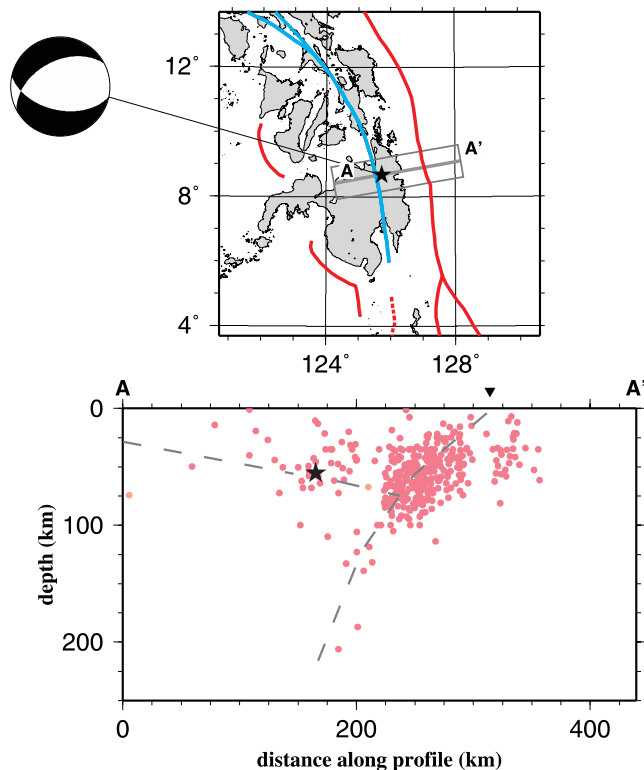


Figure 7. Map of southern Philippines region showing the epicentre and focal mechanism of the 1989 August 12 earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The seismicity defines opposing subduction or duelling slabs representing former east-dipping subduction from the Sunda Plate and active west-dipping subduction at the Philippine trench.

migrating trenches, duelling (opposing) slabs, divergent slabs and reversals in subduction polarity (e.g. Cooper & Taylor 1987; Milsom *et al.* 1992).

The two high- τ_a events in this region both occurred at the junctures of two slabs. The 1988 April 25 Solomon Islands event (Fig. 8) occurred in the slab corresponding to the formerly subducting Pacific Plate that dips SSW. The Australia Plate is currently subducting at the active Solomon trench in the opposite direction. The two zones of seismicity do not actually impinge, but the broad seismicity associated with subduction at the Solomon trench suggests some level of stress interaction between these two slab systems. The 1995 December 19 Irian Jaya event (Fig. 9) occurred in the zone of convergence of the Australia and Caroline plates involving two or more intervening microplates (Bird 2003). Oblique subduction occurs at the New Guinea trench, in addition to continental convergence in the Highlands and a possible fossil slab associated with a trench overridden by collision between New Guinea and Australia. The earthquake occurred where the Wadati–Benioff zone corresponding to the active New Guinea trench appears to impinge on another slab or region of underthrusting continent. Indeed, the cluster of north-dipping seismicity, with event depths down to at least 50 km, is likely to be the manifestation of rupture in slab material rather than mantle lithosphere (Cardwell *et al.* 1980).

4.3 Additional regions with complex subduction

The remaining events in this τ_a -depth quadrant occurred in regions of complex plate interaction, which are conducive to plate deforma-

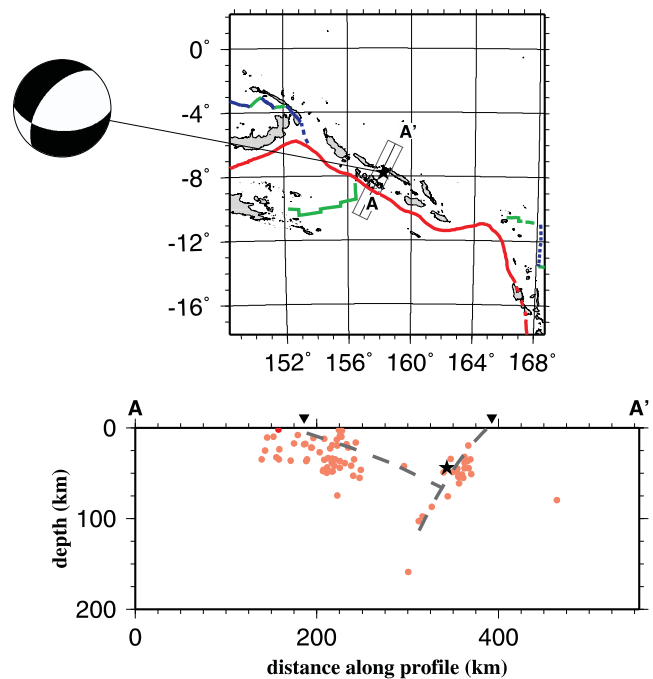


Figure 8. (a) Map of Solomon Islands region showing the epicentre and focal mechanism of the 1988 April 25 earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The seismicity defines opposing subduction or duelling slabs representing active subduction at the Solomon trench and former subduction at the Manus trough (a fossil trench not shown). The hypocentre is at the projected juncture of the two trenches.

tion. The 1996 September 11 eastern Honshu earthquake occurred beneath the Honshu Plate near the Pacific/Okhotsk/Philippine-sea triple junction. The contortions at the triple junction arise as the Philippine Plate is being subducted northwards between the overriding Okhotsk (Eurasian) Plate and the underlying Pacific Plate. The high- τ_a deep normal-fault earthquake found here is an expression of locally intense deformation. Severe internal plate deformation occurs at shallow depth as well, as Choy & McGarr (2002) found the apparent stresses of four intraoceanic earthquakes in this region were among the highest in the world for strike-slip earthquakes (with $\tau_a > 8.4$ MPa).

The 1999 February 4 northern Sumatra earthquake occurred beneath the Burma microplate bounded locally by the northern Sunda trench and the northernmost Sumatra fault, a right-lateral strike-slip boundary. The hypocentre is at a slab bend as evidenced by flattening of the Wadati–Benioff zone. A strong oblique component of subduction, manifested by the development of the arc-parallel Sumatra fault (Fitch 1972; Curray *et al.* 1979, 1982; Bird 2003), imposes additional deformational forces on the subducting slab.

The 1988 March 10 Trinidad earthquake occurred at the south-eastern corner of the Caribbean Plate where underthrusting along the Lesser Antilles arc is terminated by a series of faults in the Los Bajo–El Soldado fault zone, which becomes the El Pilar transform fault to the west (Perez & Aggarwal 1981; Dewey & Suarez 1991). The hypocentre is located behind an extrapolated bend in the descending slab at the collision of the South American and Caribbean plates, which may represent an old and dense oceanic lithosphere that has been overrun by the South American continent (VanDecar *et al.* 2003).

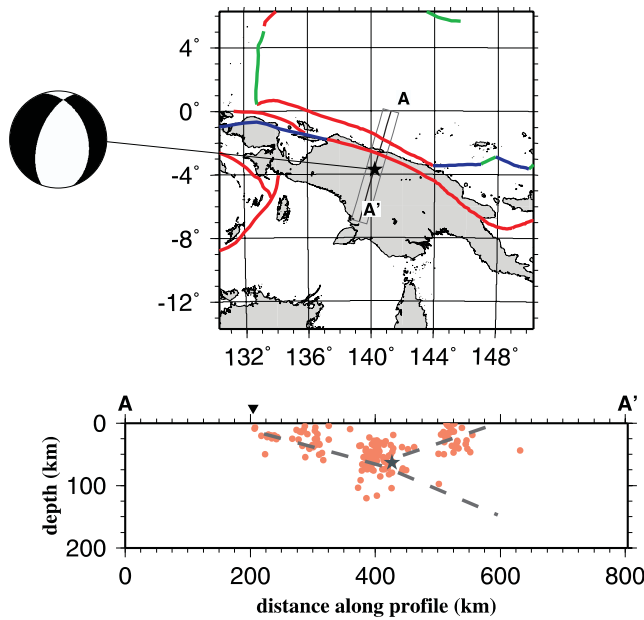


Figure 9. (a) Map of Irian Jaya region showing the epicentre and focal mechanism of the 1995 December 19 earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. Southward dipping seismicities are associated with a slab being subducted at the active New Guinea trench. The events in the cluster of northward dipping seismicity (toward the right side of the figure) have depths down to at least 50 km, which imply activity in a former subducting slab rather than rupture in mantle lithosphere (Cardwell *et al.* 1980). The hypocentre is near the juncture of the colliding slabs.

The 1999 December 29 Guerrero earthquake occurred in the slab subducted near the triple junction of the Middle America trench and the East Pacific rise. The intense slab deformation may arise from the eastward spreading ridge and northeastward subduction of the Cocos Plate. Unlike all the earthquakes previously discussed, however, this earthquake occurred in a relatively warm slab. The τ_a for this one event that did not occur in cold slab was 1.2 MPa, which is at the low end of our cut-off (1.0 MPa) for typical and high- τ_a events.

In summary, all 12 of the deep high- τ_a events are located in regions of the subduction zone that are undergoing severe internal deformation, such as slab bends, duelling slabs and kinked slabs. All but the 1999 Guerrero earthquake occurred in relatively cold-slab environments.

5 DEEPER EARTHQUAKES WITH AVERAGE APPARENT STRESS

There are 26 events in the τ_a -depth quadrant (Table A1) defined as having average τ_a (<1.0 MPa) and occurring relatively deep (>35 km). Their average τ_a is 0.43 MPa with a standard deviation of 0.27. Every event in the group occurred in a warm-slab environment. All but three events occurred in clearly flat sectors of subducting slab; the remaining three events are in the vicinity of a slight change in curvature but not sharp bends. Only two of 26 events are in regions with a nearby duelling slab.

5.1 Near the upper limit of the Wadati–Benioff zone

14 events occurred near the upper limit of the Wadati–Benioff zone. The characteristics of this subset are typified by the 1987 December

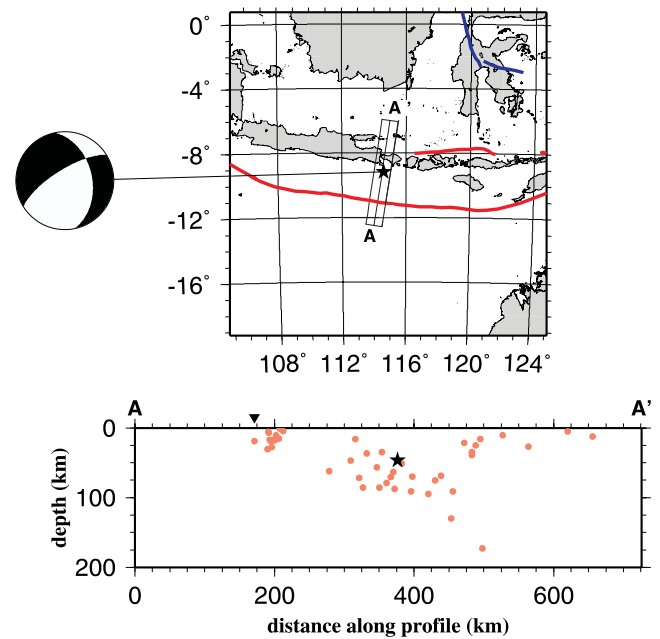


Figure 10. (a) Map showing the region of the epicentre and focal mechanism of the 1987 December 17 Bali Sea earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The hypocentre is clearly located near the top surface of the Wadati–Benioff zone. It is far from a bend, although there is a seismic gap seaward of this event as well as seamounts from the Christmas rise off the trench.

17 Bali Sea earthquake (Fig. 10). Although oblique convergence develops in the Sunda arc to the west and duelling slabs exist to the east, the hypocentre itself is located where the slip vector is approximately normal to the trench axis. In cross-section, the Bali Sea earthquake, as with all the earthquakes in this subset, is quite removed from sharp changes in curvature. There is also an absence of seismic activity between the trench axis and intermediate depths where the Wadati–Benioff zone resumes. Such gaps in seismic activity at various distances from the trench axis to the hypocentre are not uncommon. Most earthquakes in this subset are located at plate boundaries lacking significant oblique convergence. Their focal mechanisms have at least one arc-parallel nodal plane with dip between approximately 40° and 70° . The mechanism of the Bali Sea earthquake is an exception. Its T-axis is perturbed away from the trench axis. The perturbation may be the result of the affect of a series of seamounts from the Christmas rise, which are being subducted just up-dip of the hypocentre.

5.2 Intraslab-normal/arc-parallel strike-slip coupling

The subset of events near the top surface of the Wadati–Benioff zone includes a normal-faulting intraslab earthquake that is worth special discussion because it occurred close in space and time to a strike-slip earthquake.

5.2.1 The 2001 El Salvador earthquake sequence

The source parameters and macroseismic reports for two events that occurred in El Salvador are summarized in Table 4. The epicentres are separated by less than 1° in arc distance and by exactly 1 month in time. The initial January 13 M_W 7.7 event was a large

Table 4. Source parameters and macroseismic reports for the 2001 El Salvador earthquakes.

Date	Lat. (°)	Long. (E)	Depth (km)	M_e	M_W	m_b	M_S	τ_a (MPa)	Faulting type
2001 Jan 13 ⁽¹⁾	13.05	−88.66	38.0	7.8	7.7	6.4	7.8	1.0	Intraslab-normal
2001 Feb 13 ⁽²⁾	13.67	−88.94	11.0	6.5	6.6	5.5	6.5	0.5	Arc-parallel strike-slip

⁽¹⁾At least 844 people killed, 4723 injured, 108 226 houses destroyed and more than 150 000 buildings damaged in El Salvador. Approximately 585 of the deaths were caused by large landslides in Nueva San Salvador and Comasagua. Utilities and roads damaged by more than 16 000 landslides. Damage and injuries occurred in every department of El Salvador. Eight people killed in Guatemala. Felt from Mexico City to Colombia.

⁽²⁾At least 315 people killed, 3399 injured and extensive damage. The most severe damage occurred in the San Juan Tepezontes–San Vicente–Cojutepeque area. Landslides occurred in many areas of El Salvador. Felt throughout El Salvador and in Guatemala and Honduras.

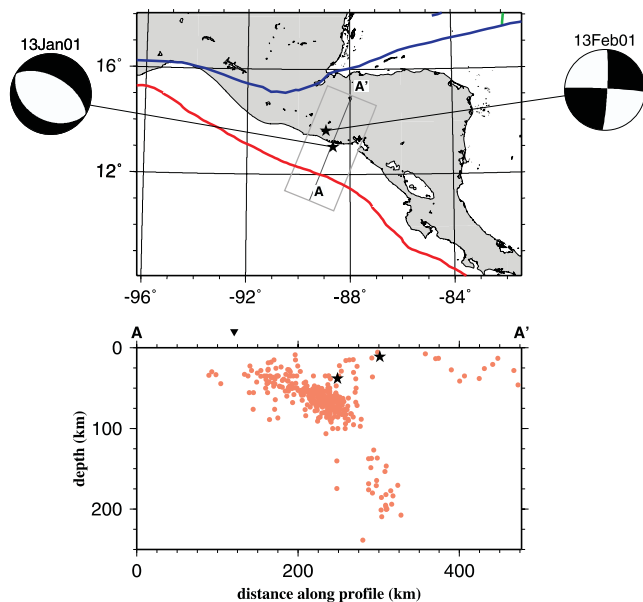


Figure 11. (a) Map showing the region of the epicentres and focal mechanisms of the 2001 El Salvador sequence (listed in Table 4). The first event was the 2001 January 13 intraslab-normal-fault earthquake. The second event was the 2001 February 13 intra-arc strike-slip earthquake. A–A' is the line along which a seismicity cross-section is taken. The width of the cross-section is 1.0° , sufficiently wide to include both hypocentres. (b) Seismicity cross-section using earthquakes within a 1.0° width about the line A–A' to delineate the Wadati–Benioff zone of the subducted lithosphere. The intraslab-normal-fault earthquake is the deeper hypocentre; the intra-arc strike-slip earthquake is the shallower hypocentre.

normal-fault earthquake within the deeper earthquake population (depth 38 km; Fig. 11). It was followed on February 13 by a shallow M_W 6.6 intra-arc strike-slip earthquake. As seen in the cross-section of seismicity, the hypocentre of the normal-fault event, which occurs within the diffuse Wadati–Benioff zone, does not appear to be in a region of sharp bending. Surface rupture that could be associated with the January 13 strike-slip earthquake occurred on a major east–west fault that defines the northern margin of the central graben in central El Salvador (Crone, private communication, 2001) and is also along the volcanic arc (White 1991). Near the Middle America trench, the plate interaction involves largely the Cocos and Caribbean plates. Locally complex zones of deformation may exist in the vicinity of the Caribbean–North America–Cocos triple junction. The strike-slip earthquake may have occurred on the arc-parallel northern boundary of a forearc sliver within the Caribbean Plate, which accommodates the slight oblique subduction between

the Caribbean and Cocos plates (White 1991) or the aforementioned Caribbean–North America motion.

The spatial and temporal proximity of these two earthquakes raises the possibility of a causal relationship. The initial normal-faulting event may have reduced the curvature of the slab, thereby reducing the coupling between the subducting and overriding plates. The occurrence of the strike-slip event would consequently be facilitated by the reduction in normal stress across the volcanic arc.

The seismic potential of a normal-fault earthquake should not be underestimated because its τ_a falls within our definition of average (i.e. $\tau_a < 1$ MPa). The τ_a (0.98 MPa) for the El Salvador earthquake is near the upper limit separating the average from the exceptionally high- τ_a earthquake populations. Indeed, as noted in Table 4, this normal-fault earthquake caused devastating damage to life and property. In general, the τ_a of the typical normal-fault earthquake still exceeds the τ_a of the typical interplate-thrust event.

5.3 Within and near the bottom limit of the Wadati–Benioff zone

Another eight events were located near the bottom limit of the Wadati–Benioff zone. Two earthquakes whose characteristics are representative of the earthquakes in this group are discussed here. These events were also chosen because they affected large population centres.

5.3.1 The 2001 February 28 Nisqually, Washington earthquake

The deep normal-fault earthquake occurred beneath the Puget Sound region at a depth of 54 km. A seismicity cross-section taken normal to the Cascadia subduction zone (Fig. 12) uses relocations from Stanley & Villasenor (2000) of microseismicity based on observations from the regional Pacific Northwest Seismic Network. The Nisqually earthquake occurred within and near a subtle change in dip of the Wadati–Benioff zone defined by the prior seismicity. The young age of the Juan de Fuca Plate, the moderate convergence rate and the shallow dip of the Wadati–Benioff zone indicate that Cascadia is a warm-slab environment (Kirby *et al.* 1996, 2002a). The τ_a for this event was 0.4 MPa, not anomalously high. This finding suggests that earthquakes in warm slabs do not have high apparent stresses, regardless of spatial changes in slab geometry and deformation.

5.3.2 The 1999 September 30 Oaxaca, Mexico earthquake

This deep normal-fault event occurred beneath coastal Mexico at a depth of 40 km. The subducted lithosphere of the Cocos Plate has

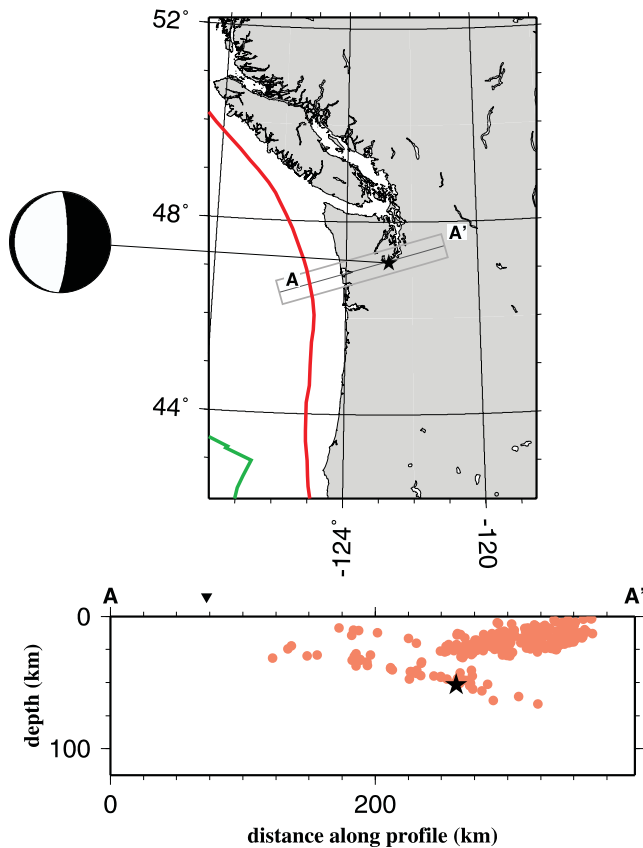


Figure 12. (a) Map showing the region of the epicentre and focal mechanism of the 2001 February 28 Nisqually, Washington earthquake. A–A' is the line along which a seismicity cross-section is taken with a width of 0.5° . (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The seismicity data are from Stanley & Villasenor (2000).

a generally shallow dip of approximately 15° . The earthquake is intraslab, being situated deep within the Wadati–Benioff zone (Singh *et al.* 2000) as seen in the seismicity cross-section (Fig. 13). The regional slab morphology changes from weakly concave downward at shallow depths to concave upward at approximately 50 km (Pardo & Suarez 1995; Singh *et al.* 2002) where it becomes horizontal. This normal-fault shock, like its 1931 M8 predecessor near Oaxaca (Singh *et al.* 1985) could be a mantle event at a depth below the neutral fiber in the concave upward slab geometry. The hypocentre is also situated just before a downdip gap in seismicity occurs in the Wadati–Benioff zone. The proximity of the East Pacific rise spreading centre and the shallow dip make this subduction zone a warm-slab environment (Stanley & Villasenor 2000). The τ_a for this event was 0.51 MPa, average for this population.

In summary, events in the population of deeper earthquakes with average τ_a occur in warm-slab environments. They generally occur in portions of the slab that are either geometrically smooth or in regions that have only subtle downdip changes in slab geometry. The warm-slab thermal states in these regions, making slabs thin and weak, may tend to reduce slab deformation rates and stresses and suppress high-apparent-stress events.

6 SHALLOWER EARTHQUAKES WITH AVERAGE APPARENT STRESS

There are 88 events (Table A3) in the τ_a -depth quadrant defined by typical τ_a (<1.0 MPa) that occurred at relatively shallow depth

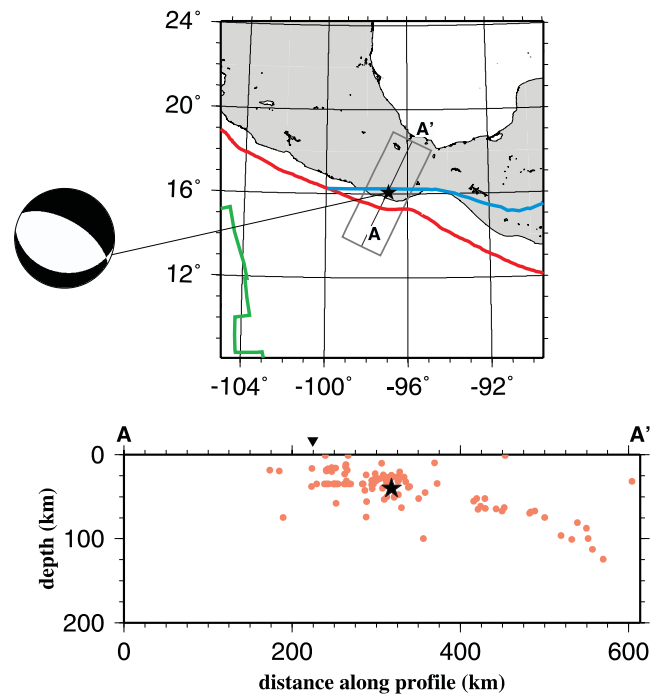


Figure 13. (a) Map showing the region of the epicentre and focal mechanism of the 1999 September 30 Oaxaca, Mexico earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The hypocentre is deep within the Wadati–Benioff zone. The slab has a shallow dip and flat geometry.

(<35 km). Their average τ_a is 0.51 MPa with a standard deviation of 0.29. The majority of these hypocentres are either well within the OR and OTW or are intracrustal within the overriding plate (i.e. clearly seaward or landward of the trench axis, respectively). The tectonic environment of a few of these events, being located beneath or just landward of the trench axis, could not be easily categorized as their hypocentres were in the region where the seismicity from the Wadati–Benioff zone overlaps with that of the overlying crust. We describe the salient features of the major subsets.

6.1 Outer rise and outer trench wall

We found that all but one of the 31 events occurring in the OR complex (OR/OTW) are characterized by average τ_a . In this region of the lithosphere, just prior to subduction, seismicity patterns are of two types. In one type, there is a gap in seismicity between events seaward of the trench axis and those landward of the trench axis. The other type of seismic behavior is characterized by continuous seismic activity from the OR to the zone of subduction behind the trench axis.

The majority of OR/OTW events is characterized by the first type of activity, in which seismicity near the trench axis is geographically separated from down-slab activity. Typical cross-sections are shown for the 1989 April 11 Kuril earthquake and the 1993 November 11 Andreanof earthquake (Figs 14 and 15, respectively). This behavior is generally found at trenches with classically simple geometry (in the sense that forearc strike-slip faults are either non-existent or poorly developed). Examples would be the trenches along the coasts of South and Central America, the eastern Aleutians and the Kurils. The focal mechanisms for these events generally have one nodal plane that is parallel to the strike of the arc.

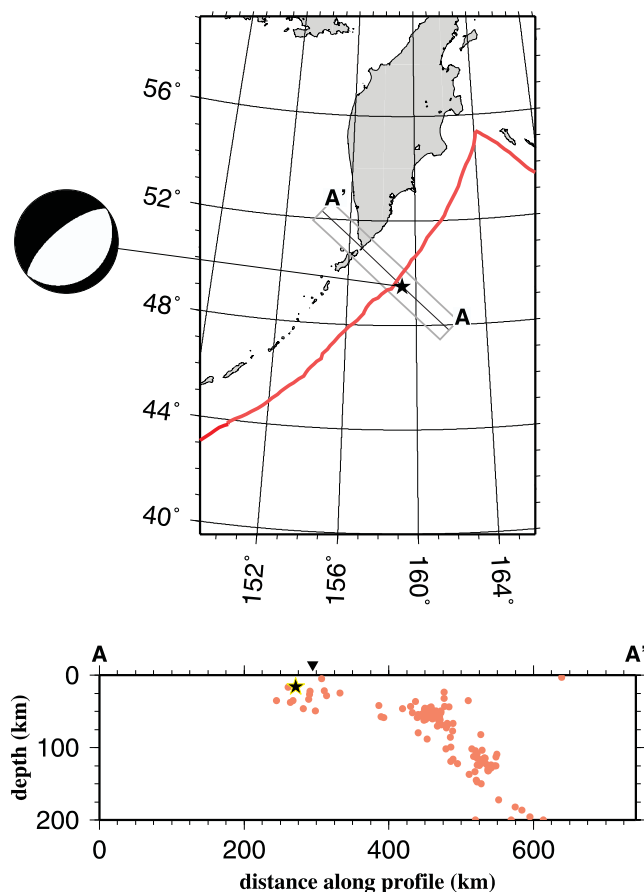


Figure 14. (a) Map showing the region of the epicentre and focal mechanism of the 1989 April 11 Kurils earthquake. The epicentre is clearly located in the outer rise/outer trench wall (OR/OTW) region. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The gap in seismicity between activity in the OR complex and down-dip activity is typical at geometrically simple subduction zones.

The second type of activity, in which seismicity is continuous from the OR down past the axis of subduction, is usually found in subduction systems of the southwest Pacific and the Java trench, where complex multislabs tectonics and/or strong oblique convergence often occur at the plate boundaries. A typical cross-section is exemplified by the 1993 April 2 Tonga earthquake (Fig. 16). The difference in the two types of cross-section may be connected to the presence or absence of oblique convergence at plate boundaries. In contrast to simple plate geometries, there are now oblique stresses superimposed on stresses from simple plate flexure.

The only OR event that did not conform to the above phenomenology was the 1997 March 11 Philippine Sea earthquake. Although its epicentre is clearly in the OR/OTW setting, its τ_a of 1.9 MPa is high. The high τ_a , however, is consistent with reports of damaged buildings inland and felt reports as far inland as Davao. Its focal mechanism has a very strong strike-slip component reflecting the strong oblique convergence between the Philippine and the Sunda (Eurasia microplate) plates (Bird 2003). This suggests that the tectonic origin of this earthquake may be more akin to intra-oceanic deformation that causes highly energetic strike-slip earthquakes (Choy & McGarr 2002) than to plate flexure causing normal faulting.

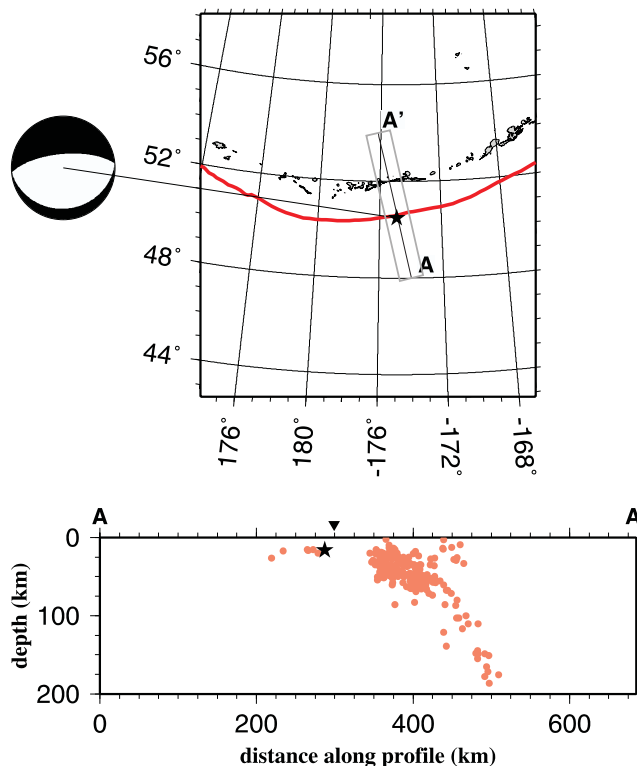


Figure 15. (a) Map showing the region of the epicentre and focal mechanism of the 1992 August 19 Andean Islands earthquake. The epicentre is clearly located in the outer rise/outer trench wall (OR/OTW) region. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. There is a gap in seismicity between activity in the OR complex and down-dip activity.

6.2 Intracrustal within the overriding plate

The epicentres of 35 events are located landward of the trench axis. By virtue of their shallow depths and spatial separation from nearby Wadati–Benioff zones, these events are clearly located within the overriding plate. All events occurred in the vicinity of extinct or active volcanism. A typical example is the 1993 December 29 Vanuatu earthquake, which is located behind the New Hebrides trench (Fig. 17). Moreover, the majority of these events are near strike-slip faults in the back-arc region. All have a significant strike-slip component in their focal mechanism. An example is the 1994 February 15 southern Sumatra earthquake, which is near the SE terminus of the Great Sumatra strike-slip fault behind the Sunda trench (Fig. 18). As noted earlier, major strike-slip faults behind subduction zones are often the result of partitioning of oblique plate motion into trench-parallel and convergent trench-normal motion (Fitch 1972; Avé Lallemont & Oldow 2000).

6.3 Near the trench axis

We found 22 events that are nominally located near or just landward of the trench. The locations for 13 events are sufficiently within the Wadati–Benioff zone to be provisionally regarded as intraslab. The locations of the other nine of these events cannot be conclusively attributed to either the very shallow forearc crust or the top of the subducted slab at the axis of subduction because of the uncertainty in their locations and the shallowness of their depths. However, the tip of the forearc crust is thin and not likely to support the frictional

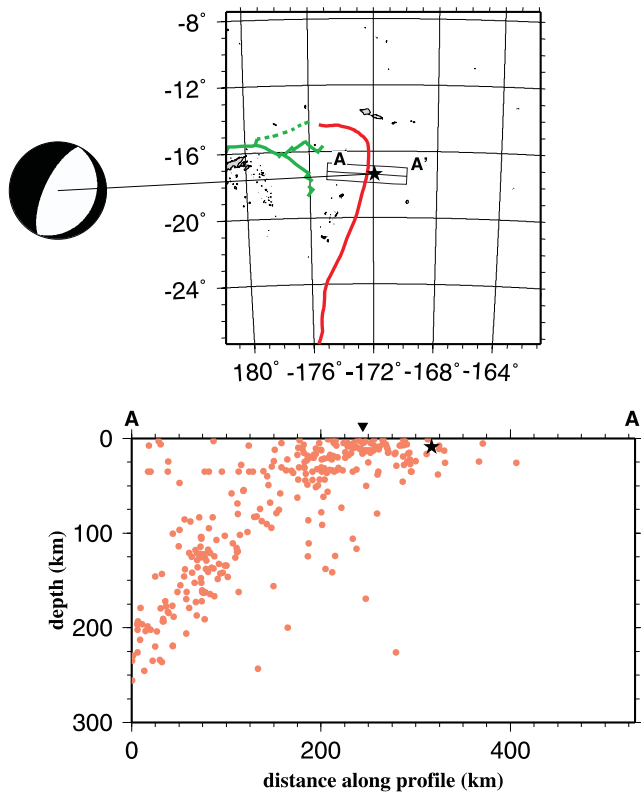


Figure 16. (a) Map showing the region of the epicentre and focal mechanism of the 1993 April 2 Tonga earthquake. The epicentre is clearly located in the outer rise (OR) complex. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. Seismicity activity is continuous between the OR complex and the downdip slab.

stress needed for large (i.e. teleseismically recordable) earthquakes. These events are also more likely to be within the slab or along the interplate-thrust boundary. If these events are indeed intraslab, the similarity in values of τ_a with OR events (<1.0 MPa) would imply that the plate flexural forces that dominate normal-fault failure in the OR and OTW may persist in lithosphere at least down to the vicinity of the trench axis.

7 SHALLOWER EARTHQUAKES WITH EXCEPTIONALLY HIGH APPARENT STRESS

There are 13 events in the τ_a -depth quadrant (Table A4) defined by exceptionally high τ_a (>1.0 MPa) and by relatively shallow depth (<35 km). Their average τ_a is 1.45 MPa with a standard deviation of 0.33. Three events are within the Wadati–Benioff zone landward of the trench axis (for example, the 1994 May 2 event southwest of Sumatra, shown in Fig. 19). The shallow depths of these events reflect the shallow dip of the subducted lithosphere. Nine events are located in diffuse seismicity behind the trench axis. On the basis of their depths (generally greater than 10 km beneath the ocean floor), it is reasonable to assume these events occurred within the subducting slab rather than in the shallow forearc. In summary, all but one of these high- τ_a events is probably within the subducting slab.

The geographical distribution of these earthquakes provides the best clue as to why their τ_a values are higher than those for OR/OTW events. As noted earlier, normal-fault earthquakes in the vicinity of

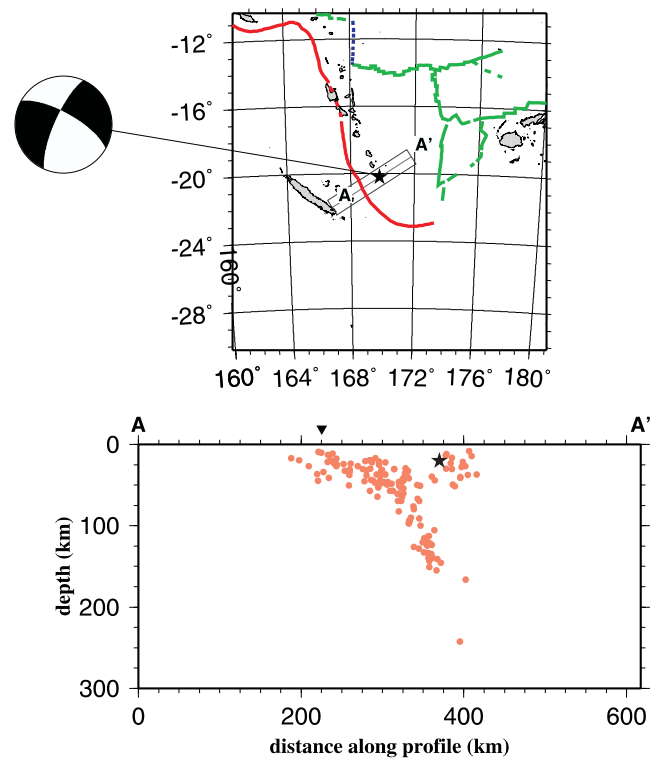


Figure 17. (a) Map showing the region of the epicentre and focal mechanism of the 1993 December 29 Vanuatu earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The hypocentre is clearly located in seismicity of the overriding plate just beneath the Vanuatu Islands rather than in the Wadati–Benioff zone.

the trench axis are generally thought to arise from stresses associated with plate bending and unbending. Moreover, failure can in some settings occur by reactivation of planes of weakness that were imprinted long ago during seafloor spreading. In the vicinity of the trench, a good indicator of seafloor fabric would be the trend of magnetic anomalies rather than the strike of the nearest active mid-ocean ridge. All of the events in this high- τ_a group occurred where the offshore magnetic anomalies are not parallel to the trench. This suggests that τ_a is elevated relative to events at the OR when OR/OTW faulting must create rupture surfaces that are not optimally aligned with the original fabric of the seafloor. An example is the 1994 May 2 earthquake southwest of Sumatra (Fig. 19).

Non-optimal alignment of stresses with the seafloor fabric can also arise where convergence at a plate boundary is oblique or where normal convergence is perturbed by an irregularity at a plate boundary. An example is the 1991 November 11 Volcano Islands earthquake (Fig. 20). The concave-seaward geometry of the trench is thought to be related to the subduction of numerous seamounts from the Marcus ridge (Vogt *et al.* 1976).

8 DISCUSSION

8.1 Fault maturity and apparent stress

The global study of Choy & Boatwright (1995) was the first to find that patterns of energy release and variations in apparent stress could be related to faulting type and tectonic setting. The dependence of τ_a on focal mechanism type was reconfirmed by Perez-Campos & Beroza (2001). Choy and Boatwright found that the population with

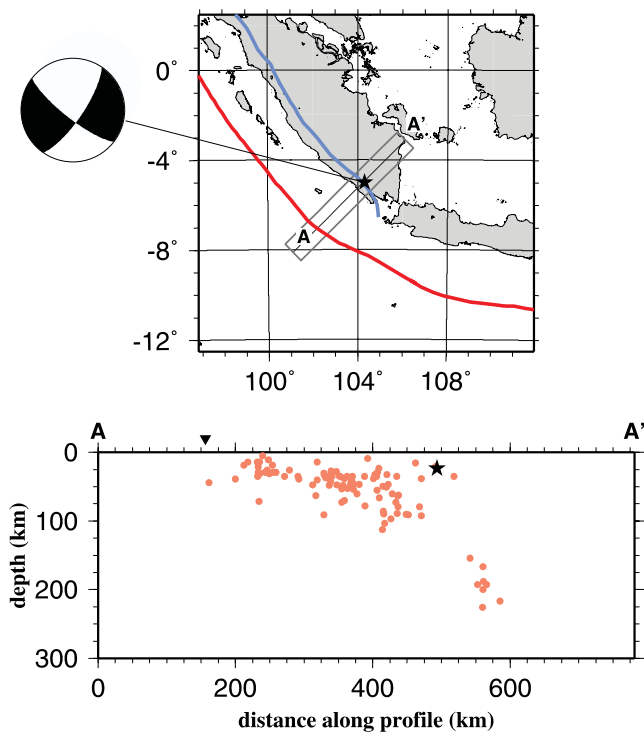


Figure 18. (a) Map showing the region of the epicentre and focal mechanism of the 1994 February 15 southern Sumatra earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The hypocentre is clearly located in seismicity of the overriding plate just beneath the southeast terminus of the right-lateral strike-slip Great Sumatra fault.

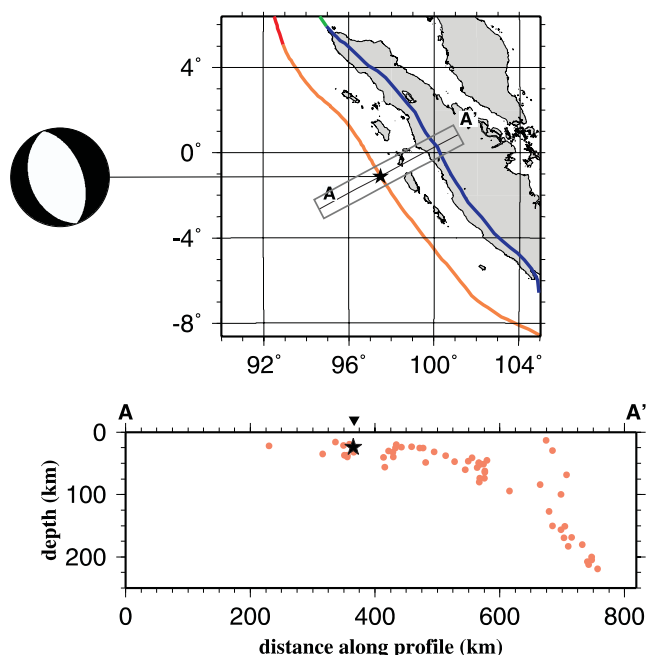


Figure 19. (a) Map showing the region of the epicentre and focal mechanism of the 1994 May 2 earthquake southwest of Sumatra. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. As a result of its location in the Wadati–Benioff zone, the earthquake is likely to be within the subducting slab rather than the overriding plate.

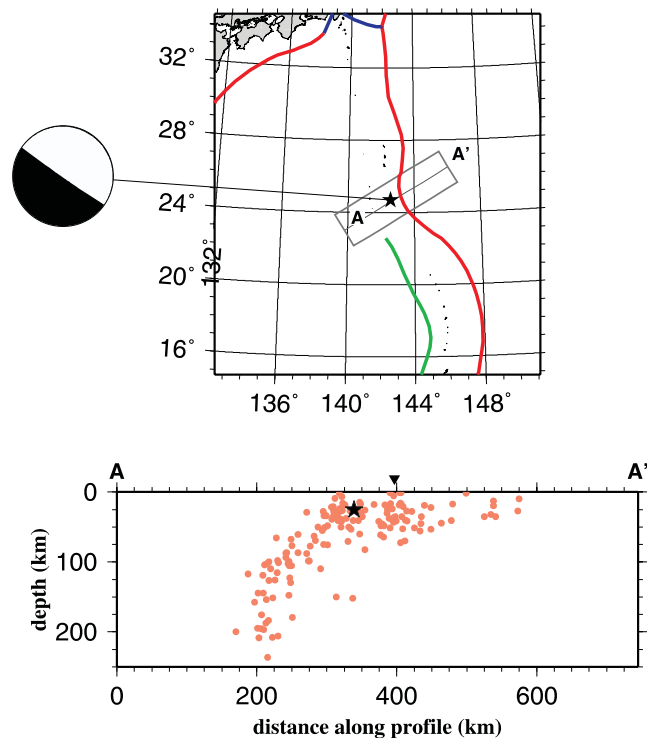


Figure 20. (a) Map showing the region of the epicentre and focal mechanism of the 1991 November 11 Volcano Islands earthquake. A–A' is the line along which a seismicity cross-section is taken. (b) Seismicity cross-section using earthquakes within a 0.5° width about the line A–A'. The Marcus ridge just east of this earthquake is currently being subducted at the Bonin trench.

the smallest average τ_a is that of global interplate-thrust-fault earthquakes at subduction zones (0.3 MPa); the population with the highest average τ_a is that of global strike-slip earthquakes (3.6 MPa); the average τ_a for the population of global normal-fault earthquakes is intermediate between the thrust and strike-slip populations (0.5 MPa). In this paper, we have found that correlations between τ_a and tectonic setting could be refined further still within subsets of normal-fault earthquakes at subduction zones. The level of τ_a appears to be related to the degree to which lithosphere can sustain strain accumulation before rupture. We now examine correlations among τ_a , focal mechanism and tectonic setting with fault maturity, a measure of the total offset accumulated by a fault. The most mature faults would have large cumulative total displacements. An example would be the plate interface at a subduction zone. These plate interfaces are presumably made smoother by large cumulative displacements (say, from hundreds to thousands of kilometres). On the other extreme, the least mature faults would involve rupture in intact fresh rock. The faults involved would have had little to no previously accumulated displacement and, hence, they should have maximum fault roughness.

We start with the tectonic settings of the earthquakes with the largest average τ_a . Choy & McGarr (2002) found that the apparent stresses of earthquakes with strike-slip mechanisms in intraplate oceanic lithosphere were the highest τ_a of any tectonic setting (an average of 6.9 MPa, but with individual earthquakes having τ_a up to 27 MPa). The nodal planes of oceanic intraplate events generally are neither parallel to the nearest fracture zones nor to regional magnetic anomalies. This implies that their ruptures are not on reactivated faults created at mid-ocean ridges or along transforms. The depths of these events are in the range 10–35 km. In addition, all

of the high- τ_a strike-slip events of Choy and McGarr that occurred on active oceanic transforms have depths between 5 and 20 km. For both oceanic intraplate and oceanic transform events, the depths of nucleation suggest that fracturing at mantle depths is an important factor in promoting high apparent stress.

The category with the next highest τ_a is that of normal-fault earthquakes at depths of 35–70 km occurring in regions of intense slab deformation. In at least one example, the 1999–2000 Kodiak earthquake sequence, the aftershock distribution appears to have ruptured downwards into the subducted oceanic mantle. Moreover, the seismicity in regions of duelling slabs occur over broad, complex seismic zones. This suggests that collision may have caused rupture through a slab and, hence, involved mantle rupture. Those shallow normal-fault earthquakes with comparably high τ_a are found intraslab, landward of the trench and usually at subduction zones having significant oblique convergence. This suggests that τ_a may be elevated when the dominant regional stress is not favorably oriented to utilize the pre-existing weakness in the fabric of the original seafloor. The nodal planes of these earthquakes generally cut across the trend of seaward magnetic anomalies.

Lowest in the hierarchy of τ_a for normal-faulting events are shallow earthquakes occurring from the OR/OTW region just seaward of the trench axis. Their focal mechanisms have nodal planes that are generally parallel to the trend of local magnetic anomalies. Earthquakes here probably are produced largely by flexural stresses at shallow depths that can mechanically exploit weaknesses in seafloor spreading fabric.

The mean τ_a for the normal-fault events at the OR and OTW is still higher than the mean τ_a of interplate-thrust events. Material at the OR and OTW is generally colder and more intact than material at the interface. In contrast, thrust-fault earthquakes and aseismic slip occur repeatedly on the frictional interface between the overriding and subducting plates in the course of subduction. The result is that contact between the overriding plate and oceanic lithosphere probably becomes smoothed by frictional wear and shear-zone thickening as total displacement accumulates.

From all the above we can begin classifying the events in oceanic lithosphere and slabs or along oceanic plate boundaries according to fault maturity, i.e. a measure of cumulative fault offset. Mature faults would have large cumulative total displacements (from hundreds to thousands of kilometres) and tend to have low apparent stresses. Immature faults would have small cumulative displacement (from hundreds of metres to as much as a few kilometres) and, hence, they should have higher amplitude fault roughness at short wavelengths. Earthquakes on these faults should radiate more high-frequency energy and have higher τ_a . Thus, in increasing order of apparent fault maturity and decreasing order of the degree of new rupture in the mantle, we have:

- (i) non-transform intraoceanic strike-slip events with little or no expression in seafloor morphology that must rupture through previously unbroken mantle lithosphere or involve additional slip on a small-offset fault;
- (ii) intraslab events of the deeper normal-fault population that likely rupture through unfractured mantle or on fractures with small offsets;
- (iii) shallow OR/near-trench axis events that, by rupturing on faults that cut across seafloor fabric (as indicated by magnetic anomalies), must create new rupture surfaces or involve slip on rough faults;

(iv) OR/near-trench axis intraslab events that occur by reactivating and growing faults at shallow depths in oceanic lithosphere that is cold and intact, along which cumulative total fault displacements are hundreds of metres to as much as 1 km (Masson 1991);

(v) interplate-thrust earthquakes along boundaries that may have hundreds to thousands of kilometres of cumulative displacement.

[The generalization that the main controlling factor for the apparent stress is the maturity of the fault, is not violated by strike-slip earthquakes on oceanic transform faults which have τ_a that are comparable to the high τ_a of intraoceanic strike-slip earthquakes. In the data set of Choy & McGarr (2002), less than half of all large strike-slip events in the oceans actually occurred on transform faults. Most large non-transform strike-slip events occurred in the vicinity (less than a couple of degrees) of ridges and transforms, but were generally labelled as intraplate because of their location just off a plate boundary. Among events on oceanic transforms, almost all occurred on short-offset transforms. Virtually all occurred near the inside corner of the ridge–transform intersection. Most had depths that put their hypocentres in the oceanic mantle. The cumulative observations of (i) the high apparent stress, (ii) the proximity of intraplate earthquakes to the ridge–transform system, (iii) the location of transform events predominantly at or near the ridge–transform corner and (iv) the rupture depths of the events being in the mantle (much deeper than originally conceived in the plate-tectonic paradigm) suggests these oceanic strike-slip events represent new ruptures or slip on faults with small cumulative displacements, at least for regions pertaining to the Choy and McGarr data set.]

8.2 Other tectonic implications

As we noted earlier, some normal-fault earthquakes at the OR/OTW can occur on faults by reactivation of spreading structures formed at the oceanic ridges. However, it has long been noted that at oceanic spreading systems, the number of large magnitude earthquakes occurring on transform faults greatly exceeds the number occurring at ridge axes (e.g. Isacks *et al.* 1968). For example, between 1987 and 2001, the total energy radiated by large strike-slip earthquakes at oceanic transforms exceeded that by normal-fault earthquakes at oceanic ridges by a factor of 1000. In the same time period, the total moment for large strike-slip earthquakes at oceanic transforms exceeded that of normal-faulting earthquakes at oceanic ridges by nearly 2 orders of magnitude. Normal-faulting seismicity at the spreading ridge is dwarfed even by seismicity at the OR complex. In the years between 1987 and 2001, there were only nine teleseismically recorded normal-fault spreading-ridge events compared to 31 global OR normal-fault events. Both the total moment and the total energy of the OR events exceeded those of the ridge events by a factor of 100. This suggests a significant number of normal faults in the ocean basins are created not by spreading at the ridge axis, but by plate bending at the OR and OTW. Nevertheless, a deeper ingrained weakness that can permeate the oceanic lithosphere can be introduced at the ridge through aseismic dike intrusion. By the time the oceanic lithosphere approaches the OR region, it has cooled sufficiently to undergo brittle fracture at a greater depth. Moreover, the lithosphere is fairly intact, having rarely been ruptured since its creation at the ridge. Thus, although the ingrained weakness is exploited preferentially by plate flexure, the τ_a of normal-fault earthquakes between the OR and the trench axis is on average higher than thrust events at the more mature interplate-thrust boundary.

8.3 Slab mechanics

At depths where changes in slab curvature and, hence, flexural stresses may be less important, the occurrence of intraslab-normal-fault events is often attributed to the tensional slab pull force, a negative buoyancy arising from the sinking of dense oceanic lithosphere into warmer mantle material. Also, slab metamorphism (densification) of oceanic crust can produce extension in the densified crust and compression in the underlying material (Kirby *et al.* 1996). The depth at which slab metamorphism occurs depends largely on the thermal structure of the slab. Fortunately, the characteristics of the slab associated with average and exceptionally high values of τ_a are very distinctive. Elevated τ_a (>1.0 MPa) is usually associated with earthquakes occurring in cold-slab environments undergoing intense deformation. The source of deformation has been associated with either a sharp change (even reversal) in slab curvature or the collision of duelling (opposing) slabs. The cold-slab environment may be sufficiently strong that faulting can occur even within the oceanic mantle, as indicated by the apparent penetration of the aftershocks of the 1999–2000 Kodiak earthquake sequence beneath the usual Wadati–Benioff zone (Hansen & Ratchkovski 2001). On the other hand, τ_a tends to be average for normal-fault earthquakes in warm slabs that generally have low-dip geometries and less pronounced changes in slab curvature. This suggests that the sinking force is smaller for warm (less dense) slabs and deformation resulting from slab pull is negligible.

8.4 Remote stress adjustments

The phenomenon of multiple large earthquakes occurring in close temporal and spatial proximity, separated by days and kilometres, has long been known. That stress adjustments may occur over distances of tens of kilometres and separated by many days or weeks has been recently recognized with the occurrence of the 1992 Landers and Big Bear, California earthquakes and the 1999 Izmit and Düzce earthquakes (Parsons *et al.* 2000). The interplate–intraslab sequences we discussed demonstrate the possibility of additional modes of stress adjustment: (i) stress adjustments propagating tens of kilometres vertically as well as horizontally; (ii) stress adjustments influencing non-contiguous faults; and (iii) stress adjustments inducing events with completely different focal mechanisms. The 1997 Coquimbo and 1999 Kodiak sequences strongly suggest that critical stresses can also be transmitted within a slab. The occurrence of the 2001 El Salvador sequence, involved a deep slab event and a shallow strike-slip event at a non-contiguous boundary of a forearc sliver. Numerous slab earthquake sequences are also recognized in the pre-digital-data era.

8.5 Seismic hazard implications

It is quite possible for earthquakes with identical M_W to have vastly different macroseismic effects. For high-apparent-stress events, M_e (energy magnitude) is a more appropriate description of seismic potential. Energy, being derived from velocity power spectra, is a better measure of seismic potential for damage to small man-made structures prone to shaking damage at high frequency. In contrast, moment, being derived from the low-frequency asymptote of the displacement spectra, is related to the final static displacement. High energy-to-moment ratios mean that intensity of radiated energy at high frequencies is large relative to the size (measured by moment) of an earthquake. Such a condition can lead to extreme damage to structures prone to ground motion effects at high frequencies.

Normal-fault intraslab earthquakes comprise but a small fraction of the large-earthquake population, yet they are responsible for a disproportionate amount of destruction worldwide, especially in Latin America (Kirby *et al.* 2002b). In contrast to shallow interplate-thrust earthquakes, which often rupture largely offshore, deeper normal-fault events are more likely to be located inland and beneath population centres. At least two characteristics of deep normal-fault earthquakes have been identified that may have profound consequences in evaluating earthquake potential. These characteristics are that the high-energy events tend to occur (i) in cold-slab environments and (ii) in regions of intense slab deformation (such as near a change in slab curvature or near the collision of opposing slabs). Much of the direct damage and loss of life in Latin America caused by these earthquakes, such as the effects of the 1939 Chile event and the 1970 Peru event, has occurred in small adobe structures lacking steel reinforcement. The high apparent stress associated with the 1997 Coquimbo event described here suggests that these earlier intraslab events also had high apparent stress. For these intraslab events, M_e is a more appropriate description of seismic potential.

Warm-slab earthquakes at depth appear to release less energy per unit of moment than their cold-slab counterparts. However, their geographic location landward of the trench and their enhanced likelihood of occurring beneath populated regions should be viewed as potential indicators for seismic damage. The 2001 Nisqually, Washington earthquake is an example where, despite damages estimated between \$1bn and \$4bn, the destructiveness was not as extensive as would have been expected for an M_W 6.8, perhaps as a result of reduced ground motions expected for this event at 55 km depth.

9 CONCLUSIONS

We have investigated the apparent stresses for 139 normal-fault earthquakes that occurred at subduction zones. We used precise depths of nucleation and a global data set of high-quality relocated hypocentres to associate each earthquake with a tectonic regime and a value of apparent stress. We found that the level of τ_a for normal-fault earthquakes is a function of depth and distance from the axis of subduction. The level of τ_a can be associated with specific tectonic features of the subduction zone as well as slab geometry. In the depth range 0 to 35 km, average τ_a (<1.0 MPa) is associated with events in the OR/OTW region and in the overriding plate. In the depth range 35–70 km, the level of τ_a is associated with very distinctive tectonic environments. Elevated τ_a (≥ 1.0 MPa) is found for events in cold slabs near regions of intense slab deformation; lower τ_a events generally occur in warm slabs with shallow dip or flat-slab geometry. The hierarchy of apparent stresses for strike-slip, normal and thrust earthquakes can be interpreted in terms of the difference in the likely roughness spectra of faults as a result of differences in total cumulative fault displacement (fault maturity). Earthquakes occurring on immature (low cumulative displacement) faults are more likely to have more roughness at short fault wavelengths and, hence, radiate more energy per unit of moment than earthquakes occurring on smoother, more mature faults. Together with the apparent stresses found for interplate-thrust earthquakes and intraplate oceanic earthquakes near subduction zones, we have been able to develop a general profile of the level of apparent stresses expected for various earthquakes across the subduction zone.

We have established the value of using energies to complement moment in describing earthquake hazard. First, high energy-to-moment ratios mean that intensity of radiated energy at high frequencies is large relative to the size (measured by moment) of an earthquake. Such a condition can lead to extreme damage to

structures prone to ground motion effects at high frequencies. Differences in moment alone may be insufficient to distinguish these macroseismic differences. Secondly, stress adjustments can occur over considerable depth. The spatial and temporal connection between destructive events in the 1997 Chile, 1999–2000 Kodiak and 2001 El Salvador sequences demonstrates various modes of coupling between deep normal-fault earthquakes and shallow strike-slip or thrust earthquakes that also can be highly destructive.

ACKNOWLEDGMENTS

The authors thank A. Beck, J.W. Dewey, P. Earle and R. Tibi for careful reviews of the manuscript, as well as J. Boatwright, A. McGarr, and E. Okal for many enlightening discussions. P. Byrd provided many invaluable comments. A. Villaseñor kindly provided unpublished hypocentre data for the 2001 Nisqually earthquake. We thank S. Beck for initially bringing our attention to the 1997 Chile earthquakes. We are indebted to P. Earle, M. Donnelly and M. Zirbes for invaluable assistance in the construction of the map and cross-section plots.

REFERENCES

- Abe, K., 1972. Mechanisms and tectonic implications of the 1966 and 1970 Peru earthquakes, *Physics of the Earth and Planetary Interiors*, **5**, 367–379.
- Avé Lallemont, H.G. & Oldow, J.S., 2000. Active displacement partitioning and arc-parallel extension of the Aleutian volcanic arc based on Global Positioning System geodesy and kinematic analysis, *Geology*, **28**(8), 739–742.
- Barazangi, M. & Isacks, B.L., 1976. Spatial distribution of earthquakes and subduction of the Nazca Plate beneath South America, *Geology*, **4**, 686–692.
- Beck, S., Barrientos, S., Kausel, E. & Reyes, M., 1998. Source characteristics of historic earthquakes along the central Chile subduction zone, *Journal of South American Earth Sciences*, **11**, 115–129.
- Bird, P., 2003. An updated digital model of plate boundaries, *Geochemistry Geophysics Geosystems*, **4**, 1027, doi:10.1029/2001GC000252.
- Boatwright, J. & Choy, G.L., 1986. Teleseismic estimates of the energy radiated by shallow earthquakes, *J. geophys. Res.*, **91**, 2095–2112.
- Byrne, D., Suarez, G. & McCann, W.R., 1985. Muertos Trough subduction-microplate tectonics in the northern Caribbean, *Nature*, **317**, 420–421.
- Cardwell, R.K., Isacks, B.L. & Karig, D.E., 1980. The spatial distribution of earthquakes, focal mechanism solutions, and subducted lithosphere in the Philippine and northern Indonesian Islands, *Am. geophys. Un. Monogr.*, **23**, 1–35.
- Choy, G.L. & Boatwright, J.L., 1995. Global patterns of radiated seismic energy and apparent stress, *J. geophys. Res.*, **100**, 18 205–18 228.
- Choy, G.L. & McGarr, A., 2002. Strike-slip earthquakes in the oceanic lithosphere: observations of exceptionally high apparent stress, *Geophys. J. Int.*, **150**, 506–523.
- Choy, G.L., Boatwright, J. & Kirby, S., 2002. The radiated seismic energy and apparent stress of interplate and intraslab earthquakes at subduction-zone environments: Implications for seismic hazard estimation, in *The Cascadia subduction zone and related subduction systems—Seismic structure, intraslab earthquakes and processes, and earthquake hazards*, Open-File Report 02–328, pp. 107–114, eds Kirby, S.H., Wang, K. & Dunlop, S., US Geological Survey, Menlo Park, CA.
- Cooper, P. & Taylor, B., 1987. Seismotectonics of New Guinea: a model for arc reversal following arc-continent collision, *Tectonics*, **6**(1), 53–67.
- Curry, J.R., Moore, D.J., Lawver, L.A.E., Emmel, F.J., Rait, R.W., Henry, M. & Kieckhefer, R., 1979. Tectonics of the Andaman Sea and Burma, in *Geological and Geophysical Investigations of Continental Margins*, pp. 189–198, eds Watkins, J., Montadert, L. & Dickerson, P., AAPG, Tulsa, OK.
- Curry, J., Emmel, F.J., Moore, D.G. & Raitt, R.W., 1982. Structure, tectonics and geological history of the northeastern Indian Ocean, in *The Indian Ocean, the Ocean Basins and Margins*, pp. 399–450, eds Naim, A.E.M. & Stehli, F.G., Plenum, New York.
- Dewey, J.W. & Suarez, G., 1991. Seismotectonics of Middle America, in *Neotectonics of North America*, pp. 309–321, eds Slemmons, D.B., Engdahl, E.R., Zoback, M.D. & Blackwell, D.D., Geological Society of America, Boulder, CO.
- Dewey, J.W., White, R.A. & Hernandez, D.A., 2003. Seismicity and tectonics of El Salvador, in *Natural Hazards in El Salvador*, pp. 363–378, eds Rose, W.I. *et al.*, Geological Society of America, Boulder, CO.
- Dolan, J.F., Mullins H. & Wald, D., 1998. Active tectonics of the north-central Caribbean: oblique collision, strain partitioning, and opposing subducted slabs, in *Active strike-slip and collisional tectonics of the northern Caribbean plate boundary zone*, pp. 1–61, eds Dolan, J. & Mann, P., Geological Society of America, Boulder, CO.
- Dziewonski, A.M., Chou, T.A. & Woodhouse, J.H., 1981. Determination of earthquake source parameters from waveform data for studies of global regional seismicity, *J. geophys. Res.*, **86**, 2825–2852.
- Dziewonski, A.M., Hales, A.L. & Lapwood, E.R., 1975. Parametrically simple earth models consistent with geophysical data, *Phys. Earth. planet. Inter.*, **10**, 12–48.
- Engdahl, E.R., van der Hilst, R. & Buland, R., 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. seism. Soc. Am.*, **88**(3), 722–743.
- Fitch, T.J., 1972. Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and the western Pacific, *J. geophys. Res.*, **77**, 4432–4460.
- Hansen, R.A. & Ratchkovski, N.A., 2001. The Kodiak Island, Alaska Mw 7 earthquake of 6 December 1999, *Seismological Research Letters*, **72**(1), 22–32.
- Houston, H., 1990. Broadband source spectra, seismic energies, and stress drops of the 1989 Macquarie Ridge earthquake, *Geophys. Res. Lett.*, **17**, 1021–1024.
- Isacks, B., Oliver, J. & Sykes, L., 1968. Seismology and the new global tectonics, *J. geophys. Res.*, **73**, 5855–5899.
- Jeffreys, H. & Bullen, K.E., 1940. *Seismological Tables*, British Association for the Advancement of Science, London.
- Kennett, B.L.N. & Engdahl, E.R., 1991. Travel times for global earthquake location and phase identification, *Geophys. J. Int.*, **105**, 429–465.
- Kirby, S., Engdahl, E.R., & Denlinger, R., 1996. Intermediate-depth intraslab earthquakes and arc volcanism as physical expressions of crustal and uppermost mantle metamorphism in subducting slabs, *AGU Monogr.*, **96**, 195–214.
- Kirby, S., Engdahl, E.R. & Villaseñor, A., 2002a. Warm-slab subduction as a global process, in *The Cascadia Subduction Zone and related subduction systems—Seismic structure, intraslab earthquakes and processes, and earthquake hazards*, Open-File Report 02–328, pp. 79–80, eds Kirby, S., Wang, K. & Dunlop, S., US Geological Survey, Menlo Park, CA.
- Kirby, S., Wang, K., Choy, G. & Okal, E., 2002b. Recent developments on intraslab earthquakes in warm-slab environments that are relevant to seismic hazard appraisal with applications to the Cascadia system, *EOS, Trans. Am. geophys. Un.*, **83**, F1074.
- McGarr, A., 1999. On relating apparent stress to the stress causing earthquake fault slip, *J. geophys. Res.*, **104**(B2), 3003–3011.
- Masson, D.G., 1991. Fault patterns at outer trench walls, *Marine Geophysical Researches*, **13**, 209–225.
- Milsom, J., Masson, D., Nichols, G., Sikumbang, N., Dwiyanto, B., Parson, L. & Kallagher, H., 1992. The Manokwari trough and the western end of the New Guinea trench, *Tectonics*, **11**(1), 145–153.
- Newman, A.V. & Okal, E.A., 1998. Teleseismic estimates of radiated seismic energy: The E/Mo discriminant for tsunami earthquakes, *J. geophys. Res.*, **103**, 26 885–26 898.
- Okal, E.A. & Kirby, S.H., 2002. Energy-to-moment ratios for damaging intraslab earthquakes; preliminary results on a few case studies, in *The Cascadia subduction zone and related subduction systems—Seismic structure, intraslab earthquakes and processes, and earthquake hazards*,

- Open-File Report 02–328, pp. 117–121, eds Kirby, S.H., Wang, K. & Dunlop, S., US Geological Survey, Menlo Park, CA.
- Ozawa, A., Tagami, T., Listanco, E.L., Arpa, C.B. & Sudo, M., 2004. Initiation and propagation of subduction along the Philippine Trench: evidence from the temporal and spatial distribution of volcanoes, *Journal of Asian Earth Sciences*, **23**, 105–111.
- Pardo, M. & Suarez, G., 1995. Shape of the subducted Rivera and Cocos plates in southern Mexico; seismic and tectonic implications, *J. geophys. Res.*, **100**(7), 12 357–12 373.
- Parsons, T., Toda, S., Stein, R.S., Barka, A. & Dieterich, J.H., 2000. Heightened odds of large earthquakes near Istanbul: An interaction-based probability calculation, *Science*, **288**, 661–665.
- Perez, O.J. & Aggarwal, Y.P., 1981. Present-day tectonics of the southeastern Caribbean and northeastern Venezuela, *J. geophys. Res.*, **86**(b11), 10 791–10 804.
- Perez-Campos, X. & Beroza, G., 2001. Is there a focal mechanism dependence to radiated seismic energy?, *J. geophys. Res.*, **106**, 11 127–11 136.
- Roeder, D., 1977. Philippine arc system—collision or flipped subduction zones?, *Geology*, **5**, 203–206.
- Singh, S.K., Suarez, G. & Dominguez, T., 1985. The great Oaxaca earthquake of 15 January 1931: Lithosphere normal faulting in the subducted Cocos Plate, *Nature*, **317**, 56–58.
- Singh, S.K. *et al.*, 2000. The Oaxaca earthquake of 30 September 1999 ($M_{\text{sub w}} = 7.5$): a normal-faulting event in the subducted Cocos Plate, *Seismological Research Letters*, **71**(1), 67–78.
- Singh, S.K., Kostoglodov, V. & Pacheco, J.F., 2002. Intraslab earthquakes in the subducting oceanic plates below Mexico, in *The Cascadia Subduction Zone and related subduction systems—Seismic structure, intraslab earthquakes and Processes, and Earthquake Hazards*, Open-File Report 02–328, pp. 87–91, eds Kirby, S., Wang, K. & Dunlop, S., Menlo Park, CA.
- Sipkin, S.A., 1982. Estimation of earthquake source parameters by the inversion of waveform data: synthetic seismograms, *Phys. Earth planet. Int.*, **30**, 242–259.
- Sipkin, S.A., 1986. Interpretation of non-double-couple earthquake mechanisms derived from moment tensor inversion, *J. geophys. Res.*, **91**, 531–547.
- Spence, W., 1987. Slab pull and the seismotectonics of subducting lithosphere, *Rev. Geophys.*, **25**(1), 55–69.
- Stanley, W.D. & Villasenor, A., 2000. Models of downdip frictional coupling for the Cascadia megathrust, *Geophys. Res. Lett.*, **27**(10), 1551–1554.
- VanDecar, J.C., Russo, R.M., James, D.E., Ambeh, W.B. & Franke, M., 2003. Aseismic continuation of the Lesser Antilles slab beneath continental South America, *J. geophys. Res.*, **108**(B1).
- Vogt, P.R., Lowrie, A., Bracey, D.R. & Hey, R.N., 1976. *Subduction of aseismic oceanic ridges: Effects on shape, seismicity, and other characteristics of consuming plate boundaries*, Special Paper 172, Geological Society of America, Boulder, CO, p. 59.
- White, R.A., 1991. Tectonic implications of upper-crustal seismicity in Central America, in *Neotectonics of North America*, pp. 323–338, eds Slemmons, D.B. *et al.*, Geological Society of America, Boulder, CO.

APPENDIX A: SOURCE PARAMETERS OF THE NORMAL-FAULT EARTHQUAKES

Source parameters of 139 normal-fault earthquakes that occurred from 1987 April to 2001 June selected from the Monthly Listings of the PDE published by the NEIC of the US Geological Survey. Given are date of the event, epicentre, radiated energy (E_S); seismic moment (M_0); energy magnitude (M_e , where $M_e = (2/3) \log E_S - 2.9$ from Choy & Boatwright 1995), apparent stress (τ_a), depth and the focal mechanism [given by strike (θ), dip (δ) and slip (λ)]. Depths of oceanic epicentres, recomputed using a PEM-O oceanic crust (Dziewonski *et al.* 1975), are referenced to the sea bottom. The following tables (Tables A1–A4) list the events found in each of the four quadrants of the τ_a -depth plot (Fig. 3) as defined in Table 1. The global distribution of these events is shown in Fig. A1.

Table A1. Events in the quadrant of deeper depth (35–70 km) and exceptionally high τ_a (≥ 1.0 MPa).

Date	Lat. (°)	Long. (°)	E_S (N m)	M_0 (N m)	M_e	M_W	τ_a (MPa)	h (km)	θ (°)	δ (°)	λ (°)
1988 Mar 10	10.40	−60.59	0.23E+15	0.11E+20	6.7	6.7	1.40	56.2	252	58	−32
1988 Apr 25	−7.79	158.26	0.13E+15	0.24E+19	6.5	6.3	3.60	44.3	92	51	−50
1989 Jun 18	17.76	−68.81	0.70E+13	0.18E+18	5.7	5.5	2.60	62.3	34	64	−22
1989 Aug 12	8.68	125.72	0.18E+14	0.74E+18	5.9	5.9	1.62	55.2	242	47	−120
1995 Dec 19	−3.70	140.23	0.23E+15	0.58E+19	6.7	6.5	2.66	63.4	343	39	−103
1996 Sept 11	35.54	140.94	0.37E+14	0.20E+19	6.1	6.2	1.23	40.0	254	52	−145
1997 Oct 15	−30.93	−71.22	0.33E+16	0.49E+20	7.4	7.1	4.50	58.0	175	85	−120
1999 Feb 4	4.03	95.28	0.27E+14	0.62E+18	6.1	5.9	2.90	43.0	320	80	−40
1999 Dec 6	57.41	−154.49	0.78E+15	0.35E+20	7.0	7.0	1.49	52.0	250	85	−81
1999 Dec 7	57.36	−154.51	0.97E+14	0.50E+19	6.4	6.5	1.29	45.0	0	10	−165
1999 Dec 29	18.24	−101.43	0.16E+14	0.83E+18	5.9	5.9	1.28	45.0	135	70	−135
2000 Jul 11	57.37	−154.21	0.37E+15	0.65E+19	6.8	6.5	3.79	49.0	255	85	−45

Table A2. Events in the quadrant of deeper depth (35–70 km) and average τ_a (< 1.0 MPa).

Date	Lat. (°)	Long. (°)	E_S (N m)	M_0 (N m)	M_e	M_W	τ_a (MPa)	h (km)	θ (°)	δ (°)	λ (°)
1987 Dec 17	−9.17	114.61	0.79E+13	0.12E+19	5.7	6.1	0.44	46.0	238	72	−50
1990 Jan 4	−15.40	−172.85	0.10E+15	0.67E+19	6.4	6.6	1.00	53.5	140	60	−90
1990 Jul 10	−10.35	161.12	0.67E+13	0.44E+19	5.7	6.4	0.10	66.3	100	85	−45
1992 Jun 9	−8.47	111.10	0.44E+13	0.16E+19	5.5	6.1	0.18	63.9	320	15	−42
1993 Jan 20	3.14	97.63	0.97E+13	0.18E+19	5.8	6.2	0.36	67.8	50	32	−150
1994 May 6	−4.68	153.10	0.20E+13	0.72E+18	5.3	5.9	0.19	48.8	30	50	−90
1994 May 23	18.17	−100.53	0.45E+13	0.28E+19	5.5	6.3	0.11	55.3	315	55	−90
1994 Jun 6	28.60	129.10	0.41E+12	0.28E+18	4.8	5.6	0.10	60.0	152	64	−47
1994 Dec 5	−8.58	159.83	0.14E+13	0.18E+18	5.2	5.5	0.52	49.2	95	68	−90
1994 Dec 10	18.14	−101.38	0.28E+14	0.52E+19	6.1	6.5	0.36	48.1	247	15	−146
1995 Sept 23	−10.68	−78.58	0.44E+14	0.58E+19	6.2	6.5	0.51	59.9	3	73	−90
1996 Aug 5	−15.27	−173.13	0.23E+14	0.11E+20	6.0	6.7	0.14	42.0	130	73	−60
1997 Apr 5	−6.49	147.41	0.52E+14	0.56E+19	6.2	6.5	0.62	69.0	245	55	−60
1997 Apr 8	18.32	120.95	0.34E+13	0.60E+18	5.5	5.9	0.38	68.0	285	30	−60
1997 May 22	18.68	−101.60	0.22E+14	0.65E+19	6.0	6.5	0.23	60.0	279	76	−98
1998 Apr 20	18.52	−101.20	0.60E+13	0.10E+19	5.6	6.0	0.40	58.0	300	70	−90
1999 Jun 6	13.90	−90.77	0.27E+14	0.27E+19	6.1	6.3	0.66	40.0	120	75	−150
1999 Jun 15	18.39	−97.44	0.22E+15	0.31E+20	6.7	7.0	0.48	63.0	300	40	−105
1999 Jun 21	18.32	−101.54	0.85E+13	0.31E+19	5.7	6.3	0.18	47.0	360	10	−45
1999 Sept 30	16.06	−96.93	0.13E+16	0.17E+21	7.2	7.5	0.51	40.0	300	60	−80
2000 Jan 26	−17.27	−174.00	0.20E+14	0.29E+19	6.0	6.3	0.46	55.0	5	79	−90
2000 Feb 26	9.41	−78.53	0.23E+14	0.16E+19	6.0	6.1	0.96	65.0	345	65	−120
2000 Nov 29	−24.87	−70.89	0.38E+14	0.34E+19	6.2	6.4	0.74	36.0	350	80	−65
2001 Jan 13	13.05	−88.66	0.68E+16	0.46E+21	7.7	7.8	0.98	38.0	300	55	−90
2001 Feb 28	47.15	−122.73	0.11E+15	0.18E+20	6.5	6.8	0.41	54.0	2	79	−90
2001 Mar 24	34.08	132.53	0.55E+14	0.20E+20	6.3	6.9	0.18	42.0	160	65	−90

Table A3. Events in the quadrant of very shallow depth (<35 km) and average τ_a (<1.0 MPa).

Date	Lat. (°)	Long. (°)	E_S (N m)	M_0 (N m)	M_e	M_W	τ_a (MPa)	h (km)	θ (°)	δ (°)	λ (°)
1987 Apr 21	-22.74	170.26	0.37E+14	0.17E+19	6.1	6.2	0.67	14.6	116	42	-55
1988 May 16	-13.94	166.34	0.15E+14	0.12E+19	5.9	6.1	0.38	16.0	355	45	-90
1988 Jul 23	-6.53	152.78	0.48E+15	0.32E+20	6.9	7.0	0.46	16.6	104	40	-92
1989 Feb 14	-10.45	161.37	0.96E+14	0.58E+19	6.4	6.5	0.68	31.9	359	87	-90
1989 Apr 11	49.49	159.18	0.30E+15	0.15E+20	6.8	6.8	0.61	16.4	230	68	-90
1989 Oct 9	51.78	171.87	0.79E+13	0.46E+18	5.7	5.8	0.71	26.2	174	27	-76
1990 Feb 19	-15.47	166.38	0.19E+15	0.17E+20	6.6	6.8	0.34	12.1	246	35	-7
1990 Apr 5	15.13	147.60	0.44E+16	0.16E+21	7.5	7.5	0.84	11.4	84	38	-44
1990 Apr 9	-25.81	-176.06	0.33E+13	0.90E+18	5.4	6.0	0.25	22.3	353	31	-102
1991 Feb 9	-9.93	159.14	0.24E+15	0.28E+20	6.7	7.0	0.26	18.0	270	25	-90
1991 May 7	39.43	144.71	0.35E+14	0.11E+19	6.1	6.0	0.98	16.0	30	40	-45
1991 Aug 26	42.10	144.63	0.70E+13	0.40E+18	5.7	5.7	0.72	28.6	79	33	-90
1992 May 7	41.17	144.70	0.15E+14	0.11E+19	5.9	6.0	0.42	12.7	107	46	-49
1992 May 27	-11.12	165.24	0.40E+15	0.39E+20	6.8	7.1	0.31	18.8	227	40	-37
1992 May 28	47.63	155.56	0.65E+13	0.50E+18	5.6	5.8	0.40	14.1	219	69	-90
1992 Jun 21	-37.69	176.86	0.23E+14	0.26E+19	6.0	6.3	0.27	12.0	260	55	-110
1992 Aug 19	50.50	-174.92	0.26E+14	0.17E+19	6.0	6.2	0.47	9.9	265	68	-90
1992 Oct 31	-2.32	141.26	0.95E+14	0.62E+19	6.4	6.5	0.47	5.7	230	58	-130
1993 Jan 5	-26.70	-70.92	0.90E+14	0.64E+19	6.4	6.5	0.58	28.9	249	11	-27
1993 Mar 17	-37.69	-74.94	0.61E+13	0.31E+18	5.6	5.7	0.60	9.2	224	30	-37
1993 Apr 2	-17.37	-171.92	0.70E+13	0.74E+18	5.7	5.9	0.29	9.3	205	67	-90
1993 Jul 22	6.47	-71.21	0.21E+14	0.13E+19	6.0	6.1	0.66	20.3	352	46	-115
1993 Aug 16	12.97	144.97	0.74E+13	0.97E+18	5.7	6.0	0.23	18.3	218	62	-120
1993 Sept 26	10.00	138.22	0.29E+14	0.31E+19	6.1	6.3	0.29	10.1	168	32	-82
1993 Nov 11	50.20	-177.45	0.23E+14	0.11E+19	6.0	6.0	0.64	18.8	75	50	-115
1993 Dec 29	-20.23	169.79	0.95E+15	0.37E+20	7.1	7.0	0.79	20.0	204	75	-20
1994 Feb 15	-4.97	104.30	0.22E+15	0.22E+20	6.7	6.9	0.41	23.1	128	77	-164
1994 Mar 15	11.11	-88.08	0.21E+14	0.14E+19	6.0	6.1	0.46	14.5	330	73	-90
1994 Apr 4	-15.47	-173.01	0.11E+14	0.48E+18	5.8	5.8	0.70	9.0	122	24	-32
1994 Apr 10	23.71	126.85	0.20E+14	0.15E+19	6.0	6.1	0.41	10.2	230	75	-140
1994 Apr 13	22.77	123.63	0.40E+13	0.58E+18	5.5	5.8	0.21	9.8	260	55	-65
1994 Apr 13	-3.14	135.97	0.69E+14	0.58E+19	6.3	6.5	0.49	28.5	138	82	-153
1994 May 3	10.24	-60.76	0.25E+13	0.95E+18	5.4	6.0	0.11	34.0	245	37	-90
1994 May 24	23.96	122.45	0.31E+14	0.66E+19	6.1	6.5	0.14	16.3	260	83	-86
1994 Jun 15	-10.34	113.66	0.34E+14	0.14E+19	6.1	6.1	0.75	19.9	292	80	-90
1994 Jul 4	14.89	-97.32	0.35E+14	0.54E+19	6.1	6.5	0.20	14.6	320	72	-90
1994 Jul 14	-16.58	167.45	0.29E+13	0.86E+18	5.4	6.0	0.10	19.8	340	72	-130
1994 Sept 5	46.78	155.23	0.57E+13	0.31E+18	5.6	5.7	0.56	12.2	233	65	-140
1994 Sept 16	22.53	118.71	0.30E+15	0.12E+20	6.8	6.7	0.77	13.1	280	52	-125
1994 Oct 5	43.59	147.45	0.11E+14	0.90E+18	5.8	6.0	0.38	13.2	255	58	-146
1995 Feb 5	-37.76	178.75	0.11E+16	0.58E+20	7.1	7.2	0.78	21.1	210	62	-126
1995 Feb 13	-1.28	127.44	0.18E+14	0.28E+19	5.9	6.3	0.20	14.2	152	32	-142
1995 Feb 13	-1.31	127.43	0.11E+14	0.17E+19	5.8	6.2	0.20	17.2	28	60	-90
1995 Feb 13	-1.32	127.44	0.24E+15	0.12E+20	6.7	6.7	0.61	14.2	67	33	-50
1995 Mar 8	16.56	-59.56	0.62E+14	0.20E+19	6.3	6.2	0.95	8.1	185	78	-90
1995 Mar 13	-2.79	134.38	0.44E+13	0.61E+18	5.5	5.9	0.22	8.2	163	70	-142
1995 Apr 16	-9.80	159.58	0.16E+13	0.28E+18	5.2	5.6	0.23	20.9	151	10	-30
1995 May 16	-23.01	169.90	0.88E+16	0.39E+21	7.7	7.7	0.93	20.2	290	65	-90
1995 May 17	-23.03	170.11	0.67E+14	0.54E+19	6.3	6.5	0.38	19.7	156	27	-59
1995 May 22	-22.80	170.01	0.41E+14	0.15E+19	6.2	6.1	0.84	18.6	334	30	-68
1995 Jul 12	-23.26	170.87	0.66E+14	0.53E+19	6.3	6.5	0.38	11.4	277	78	-90
1995 Jul 19	-22.72	169.78	0.16E+14	0.84E+18	5.9	5.9	0.58	11.6	115	68	-155
1995 Sept 17	-35.56	-74.17	0.51E+13	0.27E+18	5.6	5.6	0.58	7.7	35	60	-90
1995 Oct 18	27.93	130.18	0.58E+15	0.57E+20	6.9	7.2	0.42	28.4	206	76	-90
1995 Oct 19	28.09	130.15	0.89E+14	0.15E+20	6.4	6.8	0.18	19.7	86	23	-16
1996 Jan 12	-23.26	170.80	0.20E+14	0.69E+18	6.0	5.9	0.89	14.7	110	55	-50
1996 Jan 22	-60.61	-25.90	0.18E+14	0.21E+19	5.9	6.2	0.26	10.1	110	40	-30
1996 Feb 17	-0.92	136.23	0.11E+15	0.72E+19	6.5	6.6	0.63	31.9	30	45	-121

Table A3. (Continued.)

Date	Lat. (°)	Long. (°)	E_S (N m)	M_0 (N m)	M_e	M_W	τ_a (MPa)	h (km)	θ (°)	δ (°)	λ (°)
1996 Feb 19	-42.13	-75.28	0.91E+13	0.11E+19	5.7	6.0	0.25	7.6	35	70	-55
1996 Jul 20	36.15	27.10	0.15E+14	0.24E+19	5.9	6.3	0.19	7.0	195	45	-50
1996 Sept 2	12.32	143.81	0.17E+14	0.76E+18	5.9	5.9	0.69	8.0	145	55	-50
1996 Nov 6	28.00	143.54	0.21E+15	0.79E+19	6.6	6.6	0.82	9.0	138	65	-110
1996 Nov 20	16.35	120.53	0.25E+14	0.86E+18	6.0	6.0	0.89	12.0	210	61	-168
1997 Mar 11	7.74	127.65	0.14E+16	0.22E+20	7.2	6.9	1.95	16.0	205	72	-35
1997 Apr 22	11.11	-60.89	0.22E+15	0.11E+20	6.7	6.7	0.61	18.0	145	75	-20
1997 Jun 17	51.35	-179.33	0.22E+14	0.44E+19	6.0	6.4	0.21	24.0	177	73	-90
1997 Jul 8	23.80	142.70	0.10E+14	0.54E+18	5.8	5.8	0.76	24.0	100	80	-120
1998 Apr 1	-40.32	-74.87	0.11E+15	0.12E+20	6.5	6.7	0.28	9.0	350	65	-90
1998 Aug 23	11.66	-88.04	0.18E+15	0.12E+20	6.6	6.7	0.46	12.0	327	72	-70
1998 Aug 30	17.09	148.13	0.41E+14	0.34E+19	6.2	6.4	0.37	12.0	45	40	-60
1998 Sept 9	40.03	15.98	0.15E+13	0.33E+18	5.2	5.7	0.14	10.1	131	41	-95
1998 Nov 25	-7.86	158.62	0.15E+14	0.21E+19	5.9	6.2	0.29	34.0	85	80	-85
1999 Apr 29	28.87	131.15	0.86E+13	0.89E+18	5.7	6.0	0.30	18.0	200	75	-70
1999 May 5	14.36	-94.67	0.54E+14	0.19E+19	6.3	6.2	0.87	15.0	310	75	-30
1999 Jun 29	-9.47	147.85	0.10E+14	0.34E+18	5.8	5.7	0.90	13.0	315	45	-105
1999 Aug 22	-40.51	-74.76	0.58E+14	0.45E+19	6.3	6.4	0.40	18.0	120	35	-105
1999 Oct 10	-1.99	134.28	0.40E+14	0.15E+19	6.2	6.1	0.82	10.1	70	70	-35
1999 Oct 25	31.97	142.25	0.73E+13	0.51E+18	5.7	5.8	0.98	10.9	50	55	-45
2000 May 2	17.44	147.52	0.13E+14	0.11E+19	5.8	6.0	0.36	8.0	150	65	-130
2000 May 6	-11.30	165.43	0.58E+14	0.36E+19	6.3	6.4	0.49	12.0	340	80	-90
2000 Jun 9	-5.55	102.68	0.16E+14	0.91E+18	5.9	6.0	0.72	27.0	184	30	-12
2000 Jun 15	29.37	132.08	0.15E+14	0.17E+19	5.9	6.2	0.27	11.0	195	29	-96
2000 Jul 21	9.42	-85.33	0.81E+14	0.49E+19	6.4	6.5	0.51	17.0	281	78	-155
2000 Jul 31	-16.70	174.54	0.57E+13	0.20E+19	5.6	6.2	0.20	12.4	45	70	-90
2000 Sept 10	-1.11	129.33	0.27E+14	0.14E+19	6.1	6.1	0.59	9.0	270	55	-90
2000 Dec 20	-39.01	-74.66	0.29E+14	0.55E+19	6.1	6.5	0.16	11.0	5	50	-90
2001 Mar 3	-38.77	-74.56	0.34E+13	0.72E+18	5.5	5.9	0.15	8.0	0	60	-90

Table A4. Events in the quadrant of very shallow depth (<35 km) and exceptionally high τ_a (≥ 1.0 MPa).

Date	Lat. (°)	Long. (°)	E_S (N m)	M_0 (N m)	M_e	M_W	τ_a (MPa)	h (km)	θ (°)	δ (°)	λ (°)
1987 Oct 6	-17.94	-172.23	0.49E+16	0.89E+20	7.6	7.3	1.69	16.0	307	64	-151
1990 Apr 6	15.18	147.60	0.11E+15	0.23E+19	6.5	6.2	1.47	15.5	159	70	-167
1991 Jan 3	-7.18	148.54	0.92E+14	0.15E+19	6.4	6.1	1.88	14.0	260	75	-25
1991 Nov 11	24.70	142.57	0.21E+14	0.53E+18	6.0	5.8	1.63	24.9	267	44	-119
1992 Oct 17	-19.23	169.55	0.19E+15	0.58E+19	6.6	6.5	1.01	11.8	200	68	-22
1994 May 2	-1.12	97.49	0.67E+14	0.17E+19	6.3	6.2	1.21	15.1	340	52	-90
1994 Jun 3	3.52	-78.78	0.21E+14	0.57E+18	6.0	5.8	1.13	9.0	230	55	-40
1994 Jun 3	-10.36	112.89	0.24E+15	0.88E+19	6.7	6.6	1.12	25.9	51	55	-137
1994 Jun 4	-10.78	113.37	0.33E+15	0.58E+19	6.8	6.5	1.75	11.2	305	60	-35
1995 Apr 18	-2.06	140.46	0.71E+14	0.15E+19	6.3	6.1	1.94	20.2	260	62	-42
1996 Jun 14	12.81	125.06	0.56E+14	0.16E+19	6.3	6.1	1.07	13.0	118	68	-29
1997 Mar 11	7.74	127.65	0.14E+16	0.22E+20	7.2	6.9	1.95	16.0	205	72	-35
1999 Jan 25	4.46	-75.72	0.96E+14	0.20E+19	6.4	6.2	1.47	17.0	110	75	-165
1999 Apr 2	-19.90	168.19	0.75E+14	0.20E+19	6.4	6.2	1.15	12.0	222	26	-49
2000 Jul 8	-5.41	102.70	0.30E+14	0.69E+18	6.1	5.9	1.34	20.0	40	75	-135

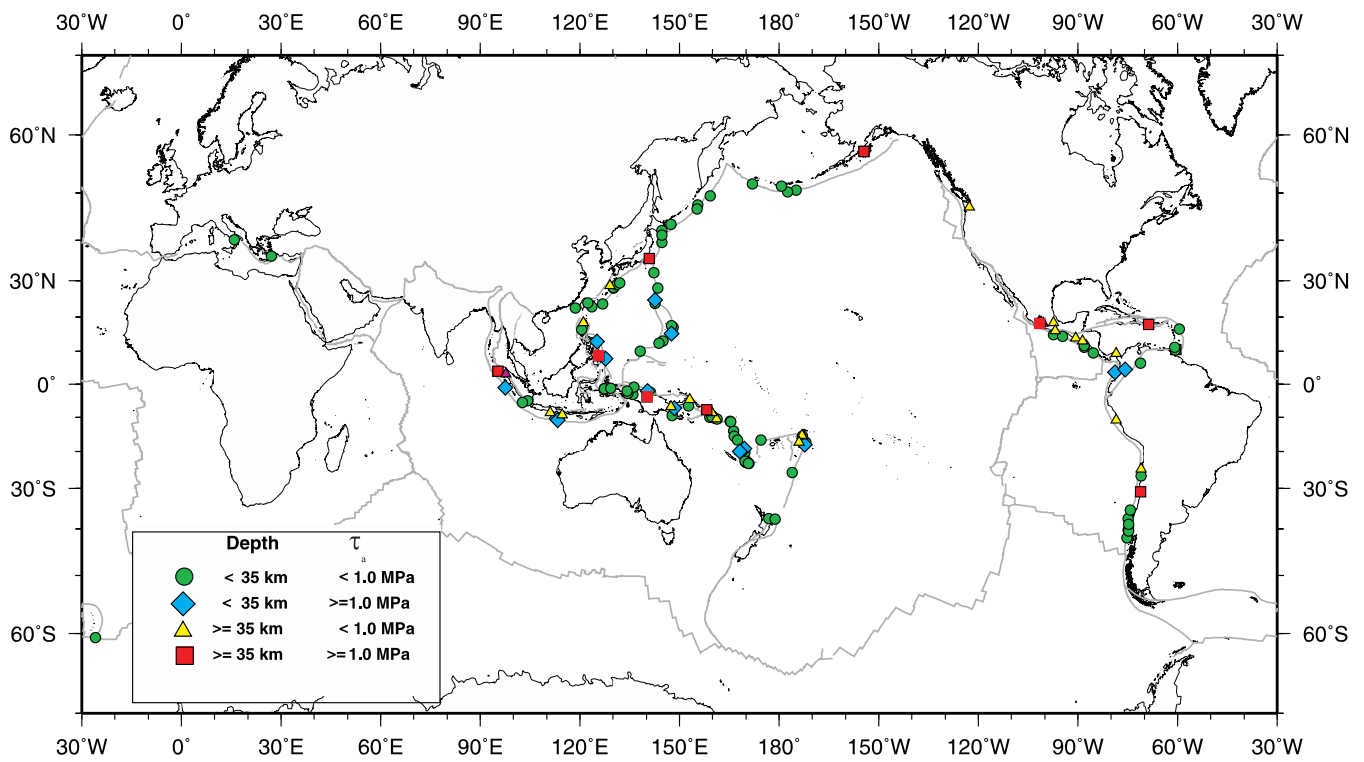


Figure A1. Global distribution of normal-earthquakes in this study.