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Double seismic zones and stresses of intermediate depth earthquakes

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Summary. Data from Japanese local seismograph networks suggest that the stresses in double seismic zones are in-plate compression for the upper zone and in-plate tension for the lower zone; the stresses do not necessarily appear to be down-dip. It may therefore be possible to identify other double seismic zones on the basis of data which indicate that events with differing orientations of in-plate stresses occur in a given segment of slab.

A global survey of published focal mechanisms for intermediate depth earthquakes suggests that the stress in the slab is controlled, at least in part, by the age of the slab and the rate of convergence. Old and slow slabs are under in-plate tensile stresses and the amount of in-plate compression in the slab increases with increasing convergence rate or decreasing slab age. Young and fast slabs are an exception to this trend; all such slabs are down-dip tensile. Since these slabs all subduct under continents, they may be bent by continental loading. Double seismic zones are not a feature common to all subduction zones and are only observed in slabs which are not dominated by tensile or compressive stresses.

Unbending of the lithosphere and upper mantle phase changes are unlikely to be the causes of the major features of double zones, although they may contribute to producing some of their characteristics. Sagging or thermal effects, possibly aided by asthenospheric relative motion, may produce the local deviatoric stresses that cause double zones.

Introduction

The zone of seismic activity dipping under a convergent plate margin, commonly referred to as the Benioff zone, is believed to be located within the subducting oceanic plate and to be representative of the gross structure of the slab. The thickness of these seismic zones, for those convergent margins where good hypocentral determination is possible, ranges between 10 and 30 km (Isacks & Barazangi 1977; Engdahl 1977) and, until recently, the hypocentres were thought to form a single zone in the coldest part of the slab (e.g. Sleep 1973).

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This view has been challenged in the last few years with the discovery of the two-layered seismic zone at intermediate depths in the Japanese arc (Tsumura 1973; Umino & Hasegawa 1975) of which the upper layer appears to coincide with the conversion plane for *ScSp* (Okada 1977; Hasegawa, Umino & Takagi 1978b), i.e. the upper boundary of the slab. Examination of teleseismically determined earthquake hypocentres in the Kurile Islands also suggests the presence of a two-layered seismic zone (Sykes 1966; Veith 1974, 1977) and had led to speculation that the double zones are a general feature of Benioff zones worldwide. However, in the Aleutians, where a local seismograph network (hereafter, local network) is in operation, and in the New Hebrides, where teleseismic and local network studies have been conducted, no clear evidence for a true double zone has been found (Topper 1978; Pascal *et al.* 1978). Thus, double seismic zones appear to be restricted only to certain convergent margins and are not a global phenomenon.

The origin of the double zone has been discussed by many authors who have suggested such causes as unbending of the subducted lithosphere (Isacks & Barazangi 1977; Engdahl & Scholz 1977; Yoshii 1977, 1979), sagging of the slab in a less viscous asthenosphere (Yoshii 1977, 1979; Sleep 1979), upper mantle phase changes (Veith 1974, 1977), and thermally induced stresses (Yang, Toksöz & Smith 1977; Hamaguchi, Goto & Wada 1977).

The distribution of double zones should provide some insights and possible constraints on the causes of their development. The purpose of this paper, therefore, is to discuss the characteristics of double zones, provide a survey of intermediate depth earthquake mechanisms from arc-trench regions, relate the distribution of double zones to parameters of convergent plate margins, and discuss possible causes for the formation of double zones. In the next two sections, we outline the characteristics of the best studied double seismic zones. First we consider the characteristics of their seismicity followed by their earthquake mechanisms.

Distribution and seismicity characteristics of double zones

The two most prominent characteristics of double zones are the depth range at which they are observed and the separation between the two seismic layers. On the basis of these criteria, we consider as reliable identifications those double zones observed in Tohoku, Japan (Umino & Hasegawa 1975; Yoshii 1979), Kanto, Japan (Tsumura 1973), and the southern Kuriles (Sykes 1966; Veith 1974, 1977). The double planed structure has been observed in these arcs through the use of local networks, whose location capability is to within 10 km both in epicentre and focal depth (Fedotov *et al.* 1971; Tsumura 1973; Hasegawa, Umino & Takagi 1978a). Double zones have also been reported in central Hokkaido (Suzuki & Motoya 1978), the northern and central Kuriles (Veith 1974, 1977), and an indication of a double zone in Kamchatka can be seen in the cross-sections of Fedotov (1968). These identifications are slightly less reliable since the location accuracy of the Hokkaido and Kamchatka local networks are less than that of those noted earlier, perhaps 10–20 km (Fedotov 1968; Suzuki & Motoya 1978), while the hypocentral distribution in the central Kuriles is constrained only by source-region station-time corrected teleseismic locations of Veith (1974). However, we consider all of these to be true double seismic zones (Table 1).

Topper (1978) has shown that the double zone postulated for the central Aleutians (Engdahl & Scholz 1977) is probably an artifact of the projection used. He concludes that there is a tear and bend in the subducting slab which offsets one segment's earthquakes with respect to the other when a vertical cross-section is produced. For reasons discussed further below, this zone is termed a 'stress-segmented seismic zone'.

In all the zones that we consider true double zones, the two-layered structure of the seismic zone is observed between about 65 and 185 km in depth and the two layers are separated by 30–40 km (Table 1); this separation is two to three times the location accuracy of the local networks.

The local network studies in the Tohoku district have been supplemented by examining large earthquakes. Workers at Tohoku University relocated events of magnitude greater than 3, which had been detected by the network of the Japan Meteorological Agency (JMA), using the same travel time tables as had been used for local network determinations and observed a clear two-layered structure between 75 and 100 km depth (Umino & Hasegawa 1975). Yoshii (1977, 1979) independently used *pP–P* times reported by the International Seismological Centre (ISC), considered the phases identified as *pP* to be the water reflection, *pwP*, and noted that a separation into two layers existed between 80 and 120 km. Examination of JMA located hypocentres in the period 1947–56 by Hasegawa & Iizuka (1969) also suggests, although with less confidence, the possible existence of a double zone in the Kanto district.

Table 1. Characteristics of double seismic zones.

Region	Depth range (km)	Separation (km)	Mechanism solutions	Location method	Reference
Double seismic zones					
Tohoku, Japan	64-181	25-30	Composite	Tohoku microearthquake	Umino & Hasegawa, 1975
	75-100	30	Composite	JMA relocated	Umino & Hasegawa, 1975
	77-120	35	Individual	pwP constrained ISC	Yoshii, 1979
Kanto, Japan	85-155	30	None	ERI microearthquake	Tsumura, 1973
Kuriles (Etorofu)	110-170	40	None	Teleseismic WWSSN	Sykes, 1966
	60-169	40	None	South Kurile network	Fedotov et al., 1971
Kuriles (entire)	73-186	26-32	Individual	SRST corrected WWSSN	Veith, 1974, 1977
Kamchatka	88-180	40	None	Kamchatka network	Fedotov, 1968
	98-154	29	Individual	SRST corrected WWSSN	Veith, 1974, 1977
Hokkaido	66-160	30	None	Hokkaido microearthquake	Suzuki & Motoya, 1978
Stress-segmented seismic zones					
Aleutians (Adak)	118-190	25	Composite	Adak microearthquake	Engdahl & Scholz

Although we have listed the double seismic zone noted by Susuki & Motoya (1978) under the Hidaka Mountains of central Hokkaido as being a double zone, the scatter in their data is particularly large. In addition, Moriya (1978), who studied the seismicity slightly further east, observes no double zone. Since Hokkaido is located near the junction of the Kurile and Honshu arcs, the possibility of a contorted or segmented slab exists. Therefore, although there are data to support the existence of a double zone, considerable ambiguity remains.

In the observed double zones, the level of seismic activity in the two layers varies greatly. In the Tohoku district, the lower zone is considerably less active (E. R. Engdahl 1980, private communication) and has fewer teleseismically detected events (Umino & Hasegawa 1975; Yoshii 1979). On the other hand, the data of Veith (1974) suggests that although the upper zone of the Kuriles has more events, the lower zone events are, on the average, about 1/2 magnitude greater in size. The vertical section of Fedotov *et al.* (1971) across Etorofu suggests a similar magnitude distribution; however, the lower zone appears to be more active and have larger events at depths less than 100 km, while the upper zone dominates below that depth. Thus, the frequency distribution by magnitude in a given layer of the seismic zone varies from arc to arc.

Stresses of double zone earthquakes

Prior studies using composite focal mechanisms from *P*-wave first motions for all events in the Tohoku district had concluded that the events between 60 and 100 km depth were caused by down-dip tension while the events at depths greater than 110 km were caused by down-dip compression (Koyama, Horiuchi & Hirasawa 1973). A similar study by Horiuchi *et al.* (1975) on the Kurile–Kamchatka earthquakes concluded that the northern end of the arc was in down-dip compression at intermediate depths while the southern end was in down-dip tension.

Umino & Hasegawa (1975) and Hasegawa *et al.* (1978a), however, produced composite mechanisms using local network first motions for each of their two seismic layers separately. Their results for the region where their data were most reliable, between 39° N and 40° N, suggested that the upper zone was in down-dip compression and the lower zone was in down-dip tension (Fig. 1). An identical result was obtained from composite and individual mechanisms of teleseismically detected events (Umino & Hasegawa 1975; Yoshii 1979). The results were also consistent with that of Veith (1974) who had determined focal mechanisms for individual teleseismically located events in the Kuriles. It has, therefore, become generally accepted that the upper zone is characterized by down-dip compression and the lower zone by down-dip tension (e.g. Isacks & Barazangi 1977; Sleep 1979).

Examination of the error estimates of Umino & Hasegawa (1975), however, suggest that the above characteristics may be inaccurate. The error estimates, defined as the range of alternate solutions for the *P* and *T* axes if an additional 10 per cent of the first motions are allowed to be inconsistent, show that the variation in possible solutions can be as much as ± 50° from the down-dip direction; they are, however, constrained to within about ± 20° of the plane of the slab (Figs 1 and 2). In addition, since the composite mechanisms are determined from local stations, there is poor control in the centre of the focal sphere. Mechanisms determined by Yoshii (1979) for teleseismically detected events are roughly down-dip, however, only about half of the other solutions determined in the area are such (Appendix A).

Hasegawa & Umino (1978) divided each of the two layers into 10 km (horizontal distance) increments down the slab and computed composite mechanisms for each segment. A portion of their results are presented in Fig. 2. The numbers denote the percentage of first motions for a particular mechanism that are inconsistent for each depth interval. As an

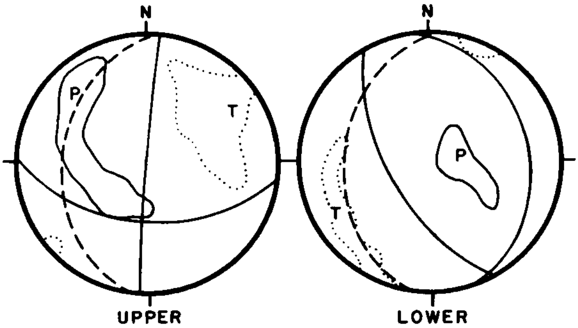

Figure 1. Composite lower hemisphere focal mechanisms from the Tohoku Microearthquake Network for the two planes of the double-zone. Nodal planes and *P*- and *T*-axes shown are for the solution with the minimal number of inconsistent stations. The solid line surrounding the *P*-axis and the dotted line surrounding the *T*-axis are the range of solutions possible if an additional 10 per cent of the stations are allowed to be inconsistent. The dashed curve denotes the dip of the subducting slab (after Umino & Hasegawa 1975).

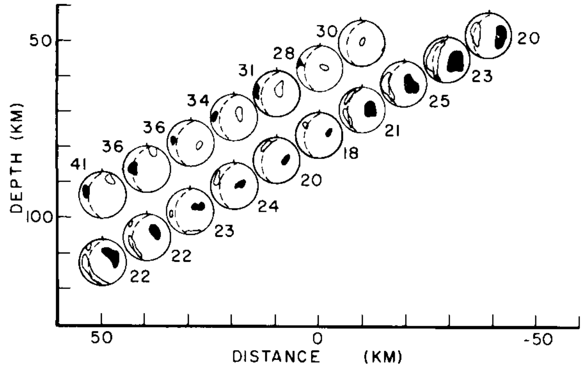

Figure 2. Composite lower hemisphere focal mechanisms from the Tohoku Microearthquake Network at 10 km intervals for the upper and lower planes of the double zone. Numbers denote the percentage of inconsistent first motions for the best solution. The dashed curve shows the dip of the subducting slab. The black areas denote the range of solutions possible for the *P*-axis if five more stations are allowed to be inconsistent; white regions represent the same for the *T*-axis. The zero point for the distance scale is at the aseismic front (after Hasegawa & Umino 1978).

average, nearly 33 per cent of the upper layer first motions and 22 per cent of the lower layer first motions are inconsistent. The maximum percentage of inconsistent first motions for any segment is 41 per cent for the upper layer and 25 per cent for the lower layer; the percentage increases, for the upper layer, as one proceeds to greater depths.

The error bounds shown in Fig. 2 are the ranges in which the *P* and *T* axes could vary if five additional first motions (1–3 per cent) are allowed to be inconsistent. The error bounds are also located approximately in the plane of the slab (especially for the upper layer). These observations lead to the conclusion that the principal axes of stress are not necessarily down-dip but can vary considerably within the plane of the subducting slab. Therefore, rather than characterizing stresses in double zones as being down-dip compression or tension, we suggest that, given the presently available data, it is more appropriate to refer to the upper zone as being in-plate compressive and the lower zone as in-plate tensile.

Engdahl & Scholz (1977) used, as supporting evidence for a central Aleutian double zone, the fact that the first motions at local stations were consistent with a compressive upper zone and a tensile lower zone. Composite and individual event focal mechanisms of these events, however, showed that the mechanisms are largely strike-slip and indicate that the slab itself is neither strongly in tension or compression along the dip direction (Topper 1978). Composite mechanisms from small clusters of earthquakes suggest that, contrary to true double zones, the presumed 'lower zone' of Engdahl & Scholz (1977) is characterized by in-plate compressive stresses and their presumed 'upper zone' more by in-plate tensile stresses. Mechanisms for teleseismically located events in the Aleutians show a mixture of compressive and tensile events (L. House 1978, private communication; Engdahl, Sleep & Lin 1977); however, the hypocentres nowhere appear to form a true double zone with two layers of seismicity in the same segment of the arc. Since the stress orientation is different in two adjacent sections of the slab and forms only a single plane in each segment, we consider the Aleutians to be a 'stress-segmented seismic zone' – one in which in-plate compressive and tensile events are found in close proximity, but in different segments of the arc each with only one seismic layer.

Mechanisms of intermediate depth earthquakes

Standard teleseismic hypocentre determinations are too inaccurate to be used in locating double seismic zones through hypocentre distributions unless the data are of particularly high quality (Barazangi & Isacks 1979b). Such high quality data, however, are scarce and of insufficient number to produce cross-sections in most cases. Poorer quality data are biased by the effect of the slab on *P*-wave travel times. These effects are not uniform to all stations; thus, not all events will be mislocated in the same manner, but rather as a function of station distribution and position of the event within the slab.

Present accurate relocation procedures either require large amounts of computation time, e.g. seismic ray tracing (Julian & Gubbins 1977), or require the calibration of the specific arc being studied (Veith 1974; Fujita 1979). Joint hypocentre determination (JHD) and master event techniques, however, are thought to give good relative locations (Dewey 1972) capable of resolving a double zone. In the two arcs where JHD has been extensively used for intermediate depth earthquakes, Tonga and the New Hebrides, no clear evidence of a double zone has been observed from hypocentre distributions (Pascal *et al.* 1978; Billington 1980).

In this paper, we do not include the double seismic zones suggested by Isacks & Barazangi (1977) in Peru and by Samowitz & Forsyth (1979) in the Marianas. The Peruvian events are all located at depths of less than 70 km, which is less than the thickness of the continental crust. The double zone in the Marianas is defined by a localized cluster of only three events which are located by teleseismic data. At present it is not clear whether these 'double zones' represent a part of the continuous double zones, down to depths of 150 km, discussed in this paper. These events, however, have focal mechanisms similar to double zone events; we discuss them further in the section on the origin of double zones.

Until such a time when local networks are established in each of the subduction zones around the world, or some simple way of calibrating the relocating subduction zone earthquakes with certainty can be developed, the identification of double zones is dependent on identifying in-plate compressive and tensile events in close proximity to each other. Even then, we must also be able to separate true double zones from stress-segmented zones.

It has generally been believed that intermediate depth mechanisms are tensile in most island arcs (Isacks & Molnar 1971) since the slab at these depths is sinking under its own weight (Isacks & Molnar 1969). For the purposes of this study, published focal mechanisms of intermediate depth earthquakes are tabulated and considered by island arc or, for arcs with plentiful data or complex structures, arc segment.

The upper depth limit was chosen at 70 km to avoid inclusion of mislocated thrust zone events and the lower depth limit was chosen at 230 km. These limits were not definitive and some shallower events have been included while some within the bounds have been omitted depending on error bounds and whether or not depth phases were used in determining the focal depth. The lower limit was chosen 40 km below the deepest double zone yet identified since the higher velocity of the slab results in deeper focal depths; a depth error of 40 km is observed for thrust zone earthquakes for a 300 km long slab, thus an error of the same magnitude is expected for earthquakes at 200 km depth for a 500 km deep slab. For older solutions, where depths were given as fractions of the Earth's radius, events between $0.005R$ and $0.030R$ (65–223 km) were considered. The teleseismic depth determinations for intermediate depth earthquakes are probably not accurate to more than 30 km at best and epicentres may be in error by nearly 100 km, especially for the older events. However, since intermediate depth take-off angles are relatively insensitive to variations in hypocentres by these amounts, less than 1° at teleseismic distances, these errors will affect mechanism solutions only marginally.

Focal mechanism solutions based on data reread by various researchers from long-period WWSSN stations were used in as many cases as possible. These were supplemented by solutions determined using bulletin reported first motions. The method used for determining the mechanisms tabulated are given in the column headed QU in Appendix A.

Solutions determined using computer minimum inconsistency programs, i.e. those of Wickens & Hodgson (1967) and Ichikawa (1971), were usually omitted since their accuracy has been questioned since the solutions differ greatly from visual solutions by other authors (Stevens & Hodgson 1968). Also generally omitted were mechanisms for Kurile events determined by Aver'yanova (1973) and Veith (1974) since the solutions were not published and the quality of the solutions were uncertain. The few events from these sources that were used were consistent with other sources which presented the data. In general, we restricted our data set to mechanisms for which the actual solution has been published. The solutions by Veith (1974) were also used as an independent comparison to the data tabulated here; we assume that the general character of the solution, whether tensional or compressive, is correct even though the exact trend and plunge of the axes may not be.

Twenty pre-WWSSN focal mechanisms for which individual station data were available, either in the International Seismological Summary (ISS) or in the publications of the Dominion Observatory (e.g. Hodgson & Stevens 1958), were redetermined using *P*-wave first motions and *S*-wave polarization angles (Stauder 1962; Udias & Stauder 1964). These bulletin reported first motions should be more consistent than their WWSSN short-period counterparts since the response curves of many pre-WWSSN instruments were more broadband.

As noted previously, mechanisms are relatively insensitive to hypocentral locations, thus no attempt was made to relocate events and USGS or ISC determinations are used in the tables. Magnitudes were preferentially taken from Gutenberg & Richter (1954), Rothe (1969) and Ichikawa (1971), or, when otherwise unavailable, from the ISC bulletin.

Events occurring near known major bends in the slab, e.g. the Hokkaido corner or the Kanto district, were omitted since the local stresses due to the bend affect the focal mechanisms (Sasatani 1976; Cardwell & Isacks 1978). Solutions from the Himalayan arc, Burma, Hindu Kush and the Carpathians were also omitted since these regions are presently continent–continent convergence zones and the nature of subduction may be significantly different from that occurring at continent–ocean convergence zones.

Two hundred and forty-three focal mechanisms, or about 2.5 times the amount available to Isacks & Molnar (1971), were found or determined and are listed in Appendix A. Again, we note that there is considerable variation in the confidence to be attached to individual mechanisms. However, the general character of the solutions is probably reliable. These events were grouped into 24 arcs or arc segments which are listed in Table 2. The segments were chosen on the basis of variations in the strike of the arc, convergence rate, age of subducting crust, and dip of subducting slab. Thus, for example, the South American arc was divided into five segments showing variations in strike and dip of the slab. The number of events per segment varies from 1 (Caribbean) to 27 (Central America) and the events span a wide range of magnitudes, from 4.4 to 8.0, averaging around 6.

For each segment, the *P*- and *T*-axes were plotted on an equal-area lower hemisphere projection in a manner similar to that used by Isacks & Molnar (1971). Representative lower hemisphere equal-area projections showing *P*- and *T*-axes and the orientation of the subducting slab are shown in Fig. 3; plots for other arcs, for which five or more mechanism solutions are included, have been relegated to Appendix B. The earthquakes were then divided into six classes based on the orientation of the *P*- and *T*-axes with respect to the plane of the slab: down-dip compressive, down-dip tensile, in-plate compressive, in-plate tensile, both axes in-plate, and neither axis in-plate. Down-dip is defined as having the determined azimuth of a principal axis within 20° of the azimuth of the maximum dip of the slab and being in-plate. In-plate is here defined as having a principal axis of stress determined to be within 25° of the dip angle of the slab at maximum dip or an equivalent

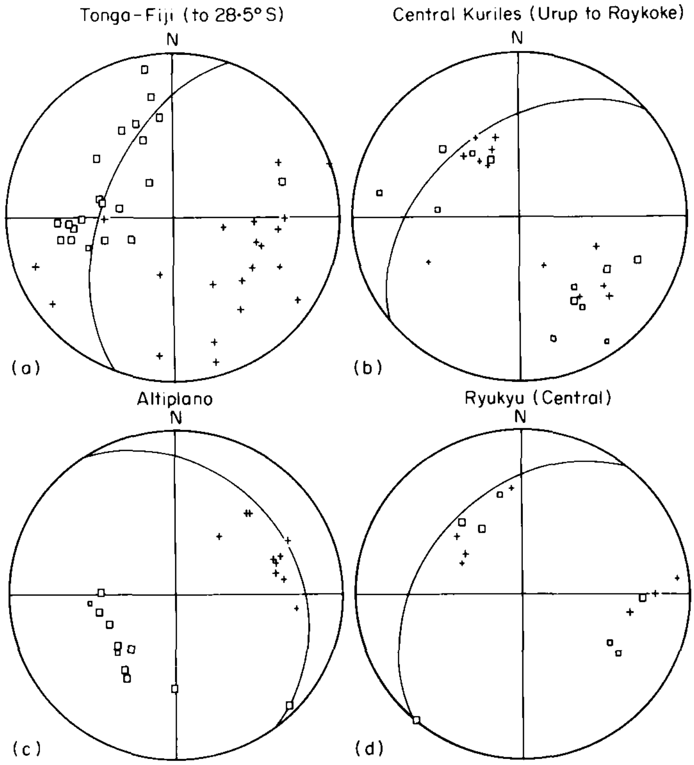

Figure 3. Representative equal area lower-hemisphere projections showing *P*- and *T*-axes for (a) a compressive arc (Tonga), (b) a mixed arc (central Kuriles), (c) a tensile arc (Altiplano) and (d) a possible double or stress-segmented seismic zone (Ryukyu). □ = *P*-axes, + = *T*-axes.

Table 2. Stresses of intermediate depth earthquakes.

Name of arc	N	Avg. mag.	Down-dip %	In-plate compressive* %	m	In-plate tensional* %	m	Age (Myr)	Velocity (cm/yr)
Dominantly Compressive									
South Scotia (S of 58.2S)	2	6	100	100		0		27	2.0
Tonga (N of 28.5S)	21	6	52	95	6.0	5	5.5	120	9.7
Kamchatka	27	5	100	95	5.0	5	6.4	80	8.8
	5	6	100	80		20			
Ogasawara (Bonin)	5	6	20	80		20		150	6.7
Mixed									
Tohoku, Japan	12	5 1/2	55	73	5.7	27	5.4	130	8.4
Northern Kuriles	24	5	100	68	4.8	32	5.4	85	8.8
(Shiashkotan-Shumshu)	11	6 1/4	91	36	6.3	64	6.1		
Aleutians	13	5 3/4	62	62	5.8	38	6.0	60	4.9
Central Kuriles	29	5	100	52	4.9	48	5.1	95	8.5
(Urup-Raykoke)	12	6 1/4	75	42	6.3	58	6.2		
Alaska	2	5 3/4	100	50		50		40	3.2
Ryukyu (central)	7	6 1/4	71	43	6.4	57	6.2	60	4.8
Southern Kuriles	41	5	100	41	4.7	59	5.1	100	8.5
(Hokkaido-Etorofu)	7	6 1/2	57	14	6.3	86	6.4		
Dominantly Tensional									
Java (106-124E)	6	6	83	17	6.0	83	6.0	135	6.4
North Peru (N of 7S)	7	6 1/4	57	14	6.8	86	6.3	30	9.8
New Hebrides	15	6	60	13	5.6	87	6.1	60	--
Central America	27	5 3/4	96	4	5.5	96	5.6	45	8.7
North Scotia (N of 58.2S)	12	6	29	0	--	100	6.0	55	2.0
North Chile (20.1-27.0S)	12	6 1/4	42	0	--	100	6.3	45	10.4
Altiplano (14.0-20.1S)	11	6 1/4	91	0	--	100	6.1	45	9.7
Kermadec (S of 28.5S)	6	6 1/2	83	0	--	100	6.5	120	6.0
Central Chile (27.0-33.6S)	6	6 1/4	17	0	--	100	6.2	32	10.2
Marianas	5	6 1/4	40	0	--	100	6.2	150	3.7
Peru (7.0-14.0S)	5	6 1/4	80	0	--	100	6.3	40	9.5
Sumatra (W of 106E)	4	6 1/4	83	0	--	100	6.0	80	5.8
Caribbean	1	5 1/2	0	0	--	100		100	2.0

Notes: * – includes down-dip and in-plate events. *N* – number of events. *m* – average magnitude of events used.

distance from the great circle describing the slab on an equal-area lower hemisphere projection ($\pm 0.28R$, where R is the radius of the projection). This broad definition is used to account for errors in take-off azimuth and angle due to slab structure (Engdahl *et al.* 1977; Sleep 1973; Fujita 1979), uncertainties in the dip of the slab (Hasegawa *et al.* 1978b), and ambiguities in determining nodal planes, usually thought to be around 15° (Isacks, Sykes & Oliver 1969; Minster *et al.* 1974). If both axes were in-plate, but one was down-dip, the event was considered to have down-dip stresses.

Of the tabulated mechanisms, six were found to have both axes in-plate with neither in the down-dip direction, and six others were found to have neither axis in-plate. The remaining 231 mechanisms are used in the discussion that follows and are assumed to be representative of the types and relative abundances of mechanisms of intermediate depth earthquakes in non-contorted oceanic plates.

Discussion

Table 2 and Fig. 4 summarize the distribution of stresses in each arc for the events listed in Appendix A. As can clearly be seen, the percentage of in-plate compressive events ranges from zero in the South American arcs to nearly 100 in the Tonga and southern Scotia arcs.

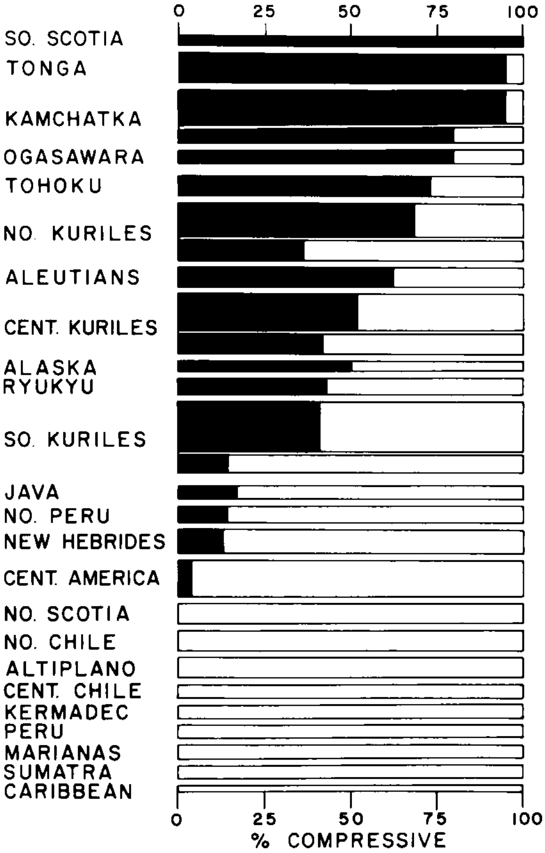

Figure 4. Distribution of in-plate stresses (including down-dip) in the various arcs. For the Kurile and Kamchatka arcs, the upper bar is for the data of Veith (1974), while the lower bar is from our tabulation. The relative number of events for which focal mechanisms have been determined is represented schematically by the width of the bars.

Two sets of data are provided for the Kurile and Kamchatka arc segments to show the effects of using data sets with different average magnitudes. The first set is obtained from the results of Veith (1974) excluding the events described as being ‘transverse’, while the second set is derived from our tabulation. In all of these cases, Veith’s (1974) data show a greater number of compressive events; this is expected since events of the lower zone are of greater magnitude and Veith’s (1974) data set uses events with an average magnitude 1.25–1.5 units less than our study, thus our study includes fewer upper zone (compressive) events. The difference in the worst case is about 30 per cent, which can be taken as a rough indicator of the maximum error on the percentages used herein if data from events averaging one magnitude unit smaller had been uniformly available; since the magnitude/frequency-type of mechanism relationship varies from arc to arc, the sign of the difference is unknown.

We define arcs with less than 20 per cent compressional events as being ‘dominantly tensile’ and arcs with greater than 80 per cent compressional events as being ‘dominantly compressive’; the rest are considered ‘mixed’. By this definition, the Kurile arc segments are all mixed, regardless of the data set used, with the exception of the southern Kuriles segment. We utilize Veith’s (1974) data and consider the southern Kuriles arc segment mixed. However, since our data for this segment have the highest average magnitude (6.5) of any of our regions, a decrease in that average would presumably add more compressive events. All other arcs which have only one compressive event are considered to be tensional since the average magnitude of the events in those segments are lower. The new Hebrides arc is also considered tensional since there are a sufficient number of events that the addition of a small number of solutions, even if compressive, will not affect the overall percentage significantly.

Isacks & Molnar (1969) suggested that the stress type for intermediate and deep focus earthquakes is related to the maximum depth of penetration of continuous lithosphere. Their results suggest that, in general, the deeper the penetration, the greater the compression within the slab as the bottom enters material of increasing viscosity. They point out, however, that their data indicate compression in the Aleutian and Ryukyu arcs, where tension is predicted, and that their hypothesis fails to explain why both compressional and tensional events exist in the Kuriles and north-eastern Japan; they ascribe the anomalies in the Ryukyu and Aleutian arcs to horizontal compression due to acute slab curvature.

Fig. 5 shows a plot of slab penetration depth against the percentage of events which are compressive. Although there is some indication of a positive correlation, especially if one ignores the Alaska and southern Scotia arcs for which the data are poor, there are major

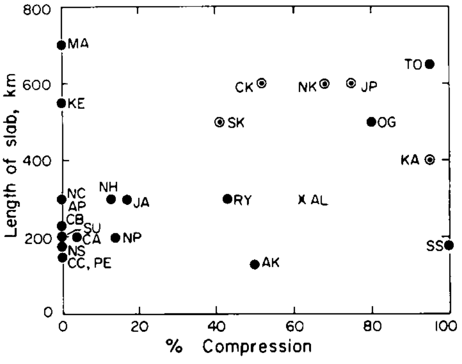

Figure 5. Relationship of maximum depth of slab penetration and percentage of compressive events. Double circles are known double zones, X’s are known stress-segmented zones. Abbreviations are as in the event identifications of Appendix A.

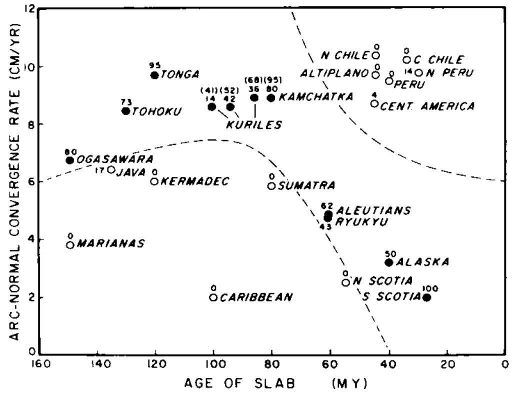

Figure 6. Correlation between the arc-normal convergence rate, the age of the subducting lithosphere, and the percentage of in-plate compressive events. Dashed lines separate tensile arcs (open circles) from mixed to compressive arcs (solid circles). The numbers indicate the percentage of compressive events; for the Kurile–Kamchatka arcs, the number in parenthesis is for the data set of Veith (1974).

inconsistencies. The Mariana and Kermadec arcs are entirely tensile, although the slab penetration exceeds 500 km. On the other hand Kamchatka and the Aleutians have mostly compressional events, although their slabs do not penetrate to especially great depths. In addition, there are double zones in many, but not all, of the long slabs.

These deviations suggest that other parameters besides slab penetration depth affect the state of stress at intermediate depths. Ruff & Kanamori (1980) have noted a correlation between the amount of inferred coupling between the subducting and overriding plates, as evidenced by the maximum size of earthquakes and marginal sea formation, and the rate of convergence of the slab and the age of the subducting lithosphere. Although this coupling itself may not contribute to the stress field at all depths and in all arcs, strong coupling may result from properties of the slab that also cause the stress in the slab at intermediate depths to be different from weakly coupled slabs.

In Fig. 6, we present a correlation between the arc-normal convergence rate, the age of subducting lithosphere, and the percentage of in-plate compressive events. The arc-normal convergence rates are computed from the AM1 model of Minster *et al.* (1974) except for the Philippine plate for which the results of Fitch (1972) are used. The Kurile–Japan ages are extrapolated from Hilde, Isezaki & Wageman (1976), while the Scotia ages are taken from Brett (1977), and the Ryukyu age from Louden (1976). The other ages were determined from Pitman, Larson & Herron (1974). The arc-normal convergence rate, as opposed to the rate of convergence between the plates, was used since we are considering stresses that operate in the general direction of maximum dip; in the event, there is little difference in the broad features of the relations and the differences only affect the relative distribution of the most closely spaced points.

Even if the maximum possible errors in slab ages and convergence rates are taken into account, it can be seen that old and fast slabs and young and slow slabs are mixed or dominantly compressive. This can be seen in Fig. 6 as a region of maximum compression, bounded by the dashed lines, that includes the points for Tonga, Kamchatka, the Aleutians and southern Scotia.

The convergence rates for the Scotia arc segments are not clear due to the complicated distribution of plates in the area (Forsyth 1975). The Scotia ridge is currently spreading at a full rate estimated between 7 and 9 cm yr^{-1} (Barker 1972). Since the Scotia plate appears to represent a zone of deformation between the south American and Antarctic plates

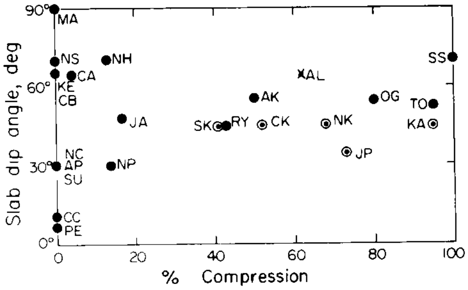

Figure 7. Distribution of double zones (double circles) and stress-segmented seismic zones (X's) with respect to slab dip angle and percentage of compression. Abbreviations are as in the event identifications of Appendix A.

(Forsyth 1975), the relative velocities and poles of rotation between the three plates are difficult to constrain. We use here the Antarctic–South America convergence rate from Minster *et al.* (1974) for the Scotia convergence rate and recognize its uncertainty. An increase in the arc-normal convergence rate to about 4.5 cm yr^{-1} would not affect our conclusions and should the crust in the northern section be 10 Myr older, an increase up to nearly 7 cm yr^{-1} would still be consistent with the dashed lines drawn in Fig. 6. At present, too little is known about the tectonics of the region to refine the data further. The New Hebrides arc has been omitted from the figure and is discussed in the next section.

It is also noted that the confirmed double zones (Tohoku, Kuriles) occur in old and fast slabs. In contrast, the one known stress-segmented seismic zone, the Aleutians, occurs in a young and slow slab. This suggests that the other young and slow slabs, with mixed mechanisms, may also be stress-segmented.

Finally, Fig. 7 shows the distribution of the amount of compression in an arc with respect to the dip angle of the Benioff zone, at depths between 100 and 150 km, perpendicular to the strike of the arc. In addition to other factors discussed herein, all known double zones occur in slabs with a dip angle between 30 and 45°; this may be an important datum in determining the causes of double zones. If this is a general rule, the kind of seismic zone present in the Ryukyus becomes ambiguous; the dip angle suggests a double zone but the age–rate relation suggests a stress-segmented zone.

Tectonics of intermediate depth earthquakes

The distribution of compressive and tensional arc segments in relation to the age of the subducting lithosphere and the arc-normal convergence rate suggests that these parameters do indeed affect the tectonic processes at intermediate depths as well as at the surface. We suggest that the stresses in the downgoing slab are controlled by the rate at which the plate moves at the surface and the rate at which the subducted slab would tend to sink into the mantle were it not attached to the surface portion of the plate. In old and slow slabs, the slab tends to sink at a faster rate than the rate at which the slab moves at the surface; thus the surface plate is being pulled and the slab is dominantly in tension. With decreasing slab age, which reduces the negative bouyancy, or as the surface convergence rate increases, the amount of tension decreases, resulting in mixed stress slabs. Finally, young and fast slabs should be dominantly compressive since the surface plate is moving faster than the slab tends to sink. These factors should result in tension at the lower left corner of Fig. 6 and compression in the upper right corner with mixed stresses in between. This trend is observed except that the young and fast slabs (upper right) are dominantly tensile instead of compressive as anticipated. We now discuss each group of slabs, examining the consequences of the stress regime, and also seek to explain why young and fast slabs are an exception to the predicted trend.

OLD AND SLOW SLABS

The state of stress in old and slow slabs is controlled by the sinking of the slab into the mantle in a manner analogous to that proposed by Isacks & Molnar (1969, 1971). These slabs would tend to sink at a rate faster than the rate of surface convergence. This creates tensional stresses in the upper segment of the slab. These tensile stresses dominate in the slab, therefore double zones are not observed (Fig. 8, top).

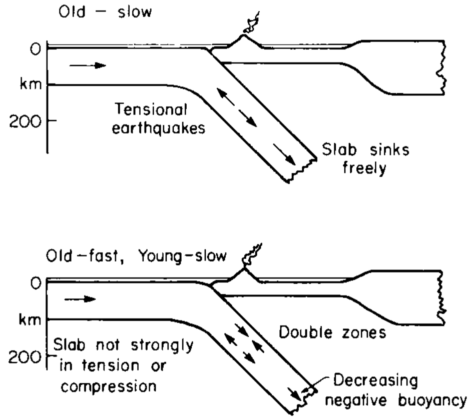

Figure 8. Schematic diagram showing the state of stress in (top) old and slow slabs, and (bottom) old and fast and young and slow slabs.

OLD AND FAST, AND YOUNG AND SLOW SLABS

Old and fast slabs and young and slow slabs show mixed to dominantly compressive states of stress. In general, the dominantly compressive slabs appear to be at greater convergence rates than mixed slabs. Since there are slabs of various lengths with mixed to compressive mechanisms, the compression is not due to the depth of slab penetration. It is suggested that driving forces other than that due to slab pull, e.g. ridge push, mantle drag, etc. (Forsyth & Uyeda 1975), result in a surface convergence rate equal to, or greater than, the rate at which the slab would tend to sink. This results in a slab that is neither strongly in tension or compression. Younger slabs, which are warmer and have less of a density contrast with the ambient mantle, would exhibit compression with a slower rate of convergence than for old slabs.

When the slab is, on the average, neither dominantly in tension or compression, local stresses, e.g. slab flexure, thermal stresses, etc., which are obscured by compression or tension in other arcs, represent the major component of the deviatoric stress causing earthquakes. In these cases, double and stress-segmented seismic zones may be observed (Fig. 8, bottom).

In older slabs, the lithosphere is still sufficiently thick even at intermediate depths that differing states of local stress can exist within one segment of arc. These slabs can then exhibit double zones. On the other hand, younger slabs are thinner and less rigid. Thus, it becomes easier for tensile or compressive stresses to dominate short segments of the slab with no one segment exhibiting both. This results in short segments with differing stresses in close proximity, i.e. stress-segmented seismic zones.

YOUNG AND FAST SLABS

Young and fast slabs represent a different mechanism. Since they are fairly short, the Isacks & Molnar (1969, 1971) mechanism can be applied to explain the dominance of tensional stresses. On the other hand, their tendency to sink is expected to be small, since the slabs are young and have a small negative bouyancy, while the convergence rate is large; these factors taken together should cause compression. In addition, it is noted that although the nodal planes of the mechanism solutions vary greatly in other arcs from event to event, all of the young and fast arcs have nodal planes parallel to the strike of the trench and at roughly 45° angles to the dip of the slab (e.g. Fig. 3c).

Portions of the South American subduction zones are characterized by an extremely low subduction angle (Barazangi & Isacks 1979a), although this interpretation has been questioned by James (1978). From the near horizontal geometry of the Benioff zone in Peru, Barazangi & Isacks (1979a) suggest that the slab is in approximate contact with the base of the overriding lithosphere. The fact that the slab does not descend to depths of greater than 200 km for a horizontal distance of 600 km from the trench suggests that if the continent were not present, the slab would not sink very much, if at all. The presence of the continent, however, forces the slab down to a depth of 100 km in only 200 km, horizontal distance, from the trench axis. Since the slab is very strongly coupled to the continent (Uyeda & Kanamori 1979; Ruff & Kanamori 1980), it is possible that the slab would bend or wrap around the lower boundary of the continental lithosphere, with the neutral plane at the slab–continent interface, resulting in dominantly tensile stresses in the slab. Other South and Central American slabs have a much greater dip angle (30°–60°), presumably due to greater negative bouyancy and/or slightly slower convergence rates. These slabs, however, could still be forced to greater depths closer to the trench axis due to the thick continental crust overriding them and to which they are strongly coupled. A suggestion of this effect is visible in the Benioff zone geometry in southern Peru by Barazangi & Isacks (1979a). The asthenospheric eastward drift, postulated by Uyeda & Kanamori (1979), may also contribute to this effect (Fig. 9).

From the above discussion, it is suggested that double zones would only be observed in the small number of island arc regions where the slab is not strongly in overall tension or compression. Therefore, the causes of the double zone's characteristic stresses need not be so large as to be greater than the gravitational stress due to negative bouyancy or to those caused by loading.

At present, too few mechanisms have been determined in Alaska to determine why two types of focal mechanisms occur there. In the Ryukyus, however, seven mechanisms have been determined and all the compressive events are located towards the Taiwan end of the

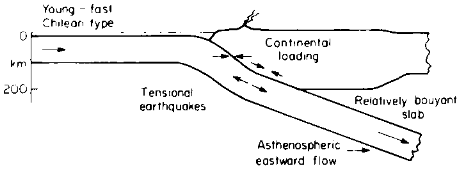

Figure 9. Schematic diagram of stresses in South American (young and fast) arcs.

arc while the tensile mechanisms are located towards Kyushu. Shiono, Mikumo & Ishikawa (1979) suggest that the boundary between the stress regimes lies in the Tokara channel. This suggests that the Ryukyus represent, like the Aleutians, a stress-segmented seismic zone. Alternatively, two different ages of crust and/or convergence rates may exist. Further study of Ryukyu and Alaskan mechanisms is required. Furthermore, the data sets for the Indonesian, Marianas and Caribbean arcs need to be expanded to confirm their tensional character.

The situation in the New Hebrides is unclear. Although the slab is about 60 Myr old, there is great uncertainty in the convergence rate. If the Fiji plateau is assumed to be part of the Pacific plate, the AM1 model of Minster *et al.* (1974) predicts a convergence rate of about 10 cm yr^{-1}. However, if the Fiji plateau is considered to be a separate microplate, Ruff & Kanamori (1980) estimate a rate of about 2 cm yr^{-1}, assuming that the Fiji plateau is stationary in the absolute frame. The slab is 87 per cent tensile, however, and has a very steep dip. Therefore, a slower convergence rate, given our models, is suggested. Although teleseismic relocations using JHD suggest a double zone between 135 and 160 km with a spacing of 10 km, the number of events is small and the separation considerably less than in other arcs. Since local network hypocentral determinations, which should be more accurate, show no such double zone (Pascal *et al.* 1978), it seems doubtful that a double zone exists.

The number of mechanisms that are down-dip do not appear to correlate with any of the parameters considered here. Thus, the factor determining the exact orientation of the stress axes within the plate is probably local. As a global average, 65 per cent of the intermediate depth events are down-dip.

Origin of double seismic zones

Numerous authors (e.g. Engdahl & Scholz 1977; Isacks & Barazangi 1977; Samowitz & Forsyth 1979) have suggested that the double seismic zone is caused by the unbending of the lithosphere after passing the position of maximum curvature. They theorize that as the plate subducts, it behaves with an elastic-plastic rheology causing permanent deformation and tensile earthquakes at the top of the plate and compressive earthquakes in the lower part (Chapple & Forsyth 1979; McAdoo, Caldwell & Turcotte 1978). Subsequent to subduction, the plate unbends elastically at first. As the stress level about the neutral plane increases, faulting will occur with an opposite sense of stresses than before subduction, i.e. compression at the top of the plate and tension below, creating the double zone.

Sleep (1979), however, has noted that if the aseismic region between the two seismic zones represents an elastic core, a stress on the order of 30 kbar would exist at its edges, assuming the material to be perfectly elastic. Such a stress is an order of magnitude greater than that implied by surface topography and is close to, or may even exceed, the fracture strength of the entire slab. For more realistic stresses, the elastic core can not exceed a few kilometres in thickness, thus the two seismic zones would be closer together and probably inseparable through seismicity studies. Samowitz & Forsyth (1979) suggest that the earthquakes do not occur on the edges of an elastic zone but on the outer edges of a semi-brittle zone about the neutral plane, thus the zones could be further apart.

Since large earthquakes of the lower zone are particularly clustered at about 100 km depth in the Tohoku double zone, it is possible that some of the seismicity at about 100 km, where the slab straightens out, occurs as a result of unbending. Samowitz & Forsyth (1979) have noted tensile events at about that depth in the Marianas, below the main thrust plane, and compressive events at a somewhat shallower depth are observed in Peru (Isacks & Barazangi 1977). We note, however, that if double zones are due to unbending, they should be observed in all subduction zones; this is not the case. In addition, teleseismically detectable earthquakes occur at depths greater than 100 km in the Kuriles and the double zone continues essentially linearly in Tohoku to depths of about 180 km (Hasegawa *et al.* 1978a). These observations suggest that a continuous stress acts on the slab long after it has passed the time point of unbending. Unless the unbending stress is released over an extremely long time span, about 1.3 Myr for Tohoku and the Kuriles, some other continuous force must be present to cause the double zone earthquakes.

Veith (1974, 1977) suggests that the olivine–spinel phase transition, which is normally presumed to occur at 397 km depth, is elevated by nearly 275 km and causes the colder inner part of the slab, which has undergone the transition, to be in tension, and the outer and upper portion, which has not gone through the transition, to be in compression. Since the temperature difference between the ambient mantle and the interior of the slab is about 1000°C at 400 km (Toksöz, Sleep & Smith 1973), a dP/dT for the transition of 60 to 75 bar $^\circ\mathrm{C}^{-1}$ is required to raise the transition depth up to 150 km. Recent experimental work by Akimoto *et al.* (1976) suggests that a dP/dT for this transition, for presumed mantle compositions, is about 33 bar $^\circ\mathrm{C}^{-1}$. Independently, Solomon & U (1975) used observed travel time residuals from Tongan earthquakes to suggest an elevation of the olivine–spinel transition by 100 ± 15 km and, therefore, an implied dP/dT of 32 bar $^\circ\mathrm{C}^{-1}$, which is in good agreement with the experimental results. Therefore, we consider this phase transition to be an unlikely cause of the double zone.

Sleep (1979) has proposed that a continuous stress could be applied due to the sagging of the slab into the asthenosphere while being supported above by the oceanic and arc lithosphere and below by a more viscous mesosphere. The slab itself need not physically sag any noticeable amount and the double zone is caused solely by the presence of a moment due to its being supported above and below. His numerical models suggest that the occurrence of stresses which could cause the double zone are solely dependent on the viscosity of the mesosphere. These stresses would not be extremely large since they are only observed in slabs which are neither strongly in compression or tension. At present, this model, and the thermal stresses suggested by Yang *et al.* (1977) and Hamaguchi *et al.* (1977) are tenable explanations for the double zone, although other possibilities cannot yet be

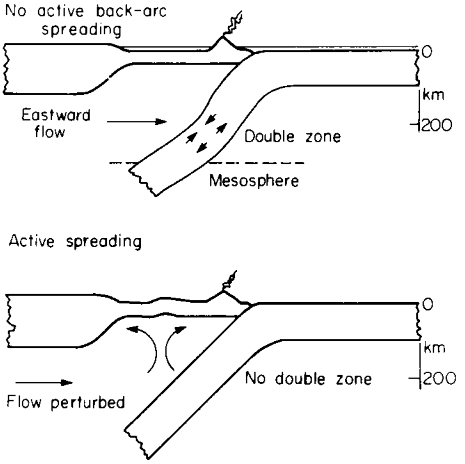

Figure 10. Schematic diagram showing (top) the possible effect of eastward asthenospheric relative flow in forming double seismic zones, and (bottom) the possible perturbation effects of back-arc spreading to cancel out the drift.

excluded. We suggest one additional factor which may, very speculatively, contribute to the stress regime at intermediate depths.

Uyeda & Kanamori (1979) noted that the AM1 model of Minster *et al.* (1974) yielded a general westward drift of the plates with respect to the asthenosphere. If this is the case, then a horizontal eastward stress could be applied to a west-dipping slab by this relative motion. If the mesosphere is approximately stationary relative to the lithosphere, then the eastward flow would cause a bending of the slab in a manner analogous to that postulated by Sleep (1979) except due to horizontal, rather than vertical, stresses (Fig. 10, top).

Evidence for relative westward motion of the lithosphere with respect to the asthenosphere, which is different from return flow, exists in the asymmetry of the angles of subducting slabs on the west and east edges of the Pacific (Nelson & Temple 1972) and in the revised AM2 model of Minster & Jordan (1978). The causes and magnitudes of such asthenospheric relative motion are not known and will remain a matter for future investigation.

Not all island arcs of the western Pacific, however, show double zones. For example, the Mariana and Tonga arcs do not. These arcs are the sites of presently active back-arc spreading (Karig 1971). It is possible that the eastward flow is perturbed by the back-arc convection (Fig. 10, bottom) so that no direct flow falls on the slab.

Conclusions

Double seismic zones can be characterized as having two layers of seismicity between about 60 and 190 km in depth and separated by about 35 km. The upper layer is dominated by in-plate compressive events while the lower layer is dominated by in-plate tensile events. Although a bias could be introduced due to magnitude differences in the events used in the data sets for different arcs, intermediate depth stress regimes in slabs can be divided into four general categories as a function of slab age and convergence velocity. Old and slow slabs are tensile because the slab tends to sink at a rate faster than the plate convergence rate. Old and fast slabs are, in general, mixed stress slabs and exhibit double seismic zones. Young and slow slabs are also mixed stress slabs but because of their warmer temperature exhibit stress-segmented zones. Finally, young and fast slabs, specifically those subducting under the South American continent, are tensile due to being bent by continental loading. Double seismic zones are not a feature common to all subduction zones and appear to exist only in old and fast slabs. The Ryukyu and Alaskan arcs are suggested as being possible double or stress-segmented seismic zones. The stress characteristics may be useable in constraining estimates of convergence rate and slab age where estimates from other sources are lacking.

Unbending of the lithosphere and phase changes within the slab are not likely to be the cause of the primary features of double zones. Unbending stresses, however, may cause increased seismicity at about 100 km depth. Thermal stresses or sagging, due to horizontal and/or vertical stresses, remain possible explanations for the formation of double seismic zones.

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Appendix A

This appendix lists all known focal mechanisms for intermediate depth events. Only one entry per event is given although numerous authors may have determined solutions. Preference has been given to solutions determined using reread long-period first motions and solutions using surface waves. The events are grouped by arc-segment; the down-dip direction (in degrees east of north) and dip angle (in degrees downwards from the horizontal) are given for the subducting slabs immediately in front of the arc-segment name.

The origin time is given in GMT, north latitude and east longitude are positive, and depth (Z) is in km. The P, T and B axes are given as trend/plunge with trend in degrees east of north. TY gives the mechanism type, T being in-plate tensile and P being in-plate compressive; the prefix D indicates the event is also down-dip. QU indicates the source of data for the solution; First column, W reread data, B bulletin, C computer solution; second column, L long period, S short period, A mixed; third column, P P-wave first motions, S S-wave polarizations, A P- and S-wave data, and L surface waves.

ID	TY	ORIGIN TIME	MAG	LAT	LONG	Z	P	T	B	QU	REF
044 35 CENTRAL AMERICA											
CA01	DT	55 08 28 20 13 36	6.8	14.0	-91.0	080	234/26	054/64	144/00	B P	44
CA02	DT	59 05 24 19 17 40	6.8	17.5	-97.0	080	259/70	042/10	134/12	B P	44
CA03	DT	63 02 24 13 34 16	5.9	14.6	-91.4	133	236/35	056/55	146/00	WLP	24
CA04	DT	64 04 24 14 40 28	5.5	13.7	-88.6	158	228/24	033/64	135/06	WLP	24
CA05	DT	64 12 15 12 13 24	5.4	14.7	-91.7	101	220/45	040/45	130/00	WLP	24
CA06	DT	65 03 01 21 32 12	6.1	15.4	-92.4	093	203/46	060/38	314/19	WLP	24
CA07	DT	65 10 20 23 54 30	6.0	12.5	-87.4	070	214/35	034/55	124/00	WLP	24
CA08	DT	66 12 10 13 06 32	5.6	14.3	-92.0	070	231/14	059/72	322/02	WLP	24
CA09	DT	67 08 27 13 08 57	5.2	12.2	-86.3	201	234/33	062/56	326/05	WLA	10
CA10	DT	67 10 15 08 00 50	6.2	11.9	-86.0	181	240/26	043/62	147/08	WLA	10
CA11	DT	68 02 03 15 40 44	5.5	16.6	-93.6	133	210/20	030/60	302/00	WLA	10
CA12	DT	68 06 11 05 52 35	5.3	14.0	-88.7	212	225/35	045/55	315/00	WLA	10
CA13	DT	68 09 25 10 38 38	5.7	15.5	-92.6	114	212/31	032/49	302/00	WLA	10
CA14	DT	69 03 14 08 47 16	5.6	12.7	-86.9	203	240/35	063/55	332/01	WLA	10
CA12	DP	69 04 21 02 19 07	5.5	14.1	-91.0	076	021/55	207/35	114/02	B P	44
CA16	DT	69 05 13 14 16 53	5.6	11.5	-86.4	075	214/20	024/70	123/03	WLA	10
CA17	DT	69 06 24 00 35 06	5.3	11.5	-85.9	154	239/49	059/41	330/00	WLA	10
CA18	DT	69 10 20 15 20 36	5.4	17.3	-95.2	074	242/65	062/25	332/00	WLA	10
CA19	DT	70 09 29 04 42 47	5.4	11.5	-85.5	220	236/31	056/59	326/00	WLA	10
CA20	T	70 12 24 08 00 38	5.6	16.0	-93.7	105	253/51	073/39	343/00	WLA	10
CA21	DT	71 05 28 14 12 08	5.4	14.7	-91.5	136	204/22	042/66	297/06	WLA	10
CA22	DT	72 01 22 13 08 50	5.5	14.0	-91.1	094	230/61	050/29	320/00	WLA	10
CA23	DT	72 03 11 03 50 46	5.1	13.4	-90.1	082	229/43	049/47	318/00	WLA	10
CA24	DT	72 08 31 02 24 12	5.4	13.1	-88.6	076	218/20	038/70	308/00	WLA	10
CA25	DT	72 10 05 10 48 19	5.4	13.8	-91.2	072	248/41	028/41	138/18	WLA	10
CA26	DT	74 03 06 01 40 26	5.8	12.3	-86.4	110	247/41	060/48	153/04	BSP	10
CA27	DT	74 04 10 22 43 01	5.4	14.5	-91.6	108	222/59	045/31	314/01	BSP	10
090 30 ECUADOR-NORTH PERU											
PN01	DP	50 06 07 16 52 34	6.8	-4.5	-77.0	100	110/40	209/09	309/48	B P	44
PN02	DT	63 04 13 02 20 58	6.7	-6.3	-76.6	125	022/68	262/16	166/18	W A	20
PN03	T	64 11 02 06 50 58	6.5	-4.1	-76.9	091	290/85	059/02	150/04	W A	20
PN04	T	65 09 17 11 13 56	6.6	-1.5	-77.7	191	234/59	039/30	133/07	WLA	33
PN05	DT	67 03 02 02 49 32	5.8	-0.3	-78.7	121	012/55	282/00	192/35	WLP	33
PN06	T	71 05 17 11 04 07	5.7	-1.6	-77.7	176	209/63	045/26	312/06	WLA	33
PN07	DT	71 07 27 02 02 50	6.3	-2.7	-77.4	135	194/65	094/04	004/02	WLA	33
055 08 PERU											
PE01	DT	63 09 17 05 54 34	6.4	-10.6	-78.2	061	192/77	066/08	334/10	W A	20
PE02	DT	63 09 24 16 30 16	7.0	-10.6	-78.0	080	261/56	039/27	139/20	WLA	33
PE03	T	66 05 01 16 22 56	5.7	-8.5	-74.3	165	251/54	117/27	015/22	WLA	33
PE04	DT	68 09 09 00 37 43	6.0	-8.7	-74.5	120	265/51	057/36	157/14	WLA	33
PE05	DT	68 09 28 13 53 35	6.4	-13.2	-76.4	070	257/57	059/32	154/08	WLA	33
055 28 ALTIPLANO											
AP01	DT	59 07 19 15 06 10	7.0	-15.0	-70.5	200	264/47	043/35	149/21	C	39
AP02	DT	64 01 26 09 09 34	6.6	-16.3	-71.7	116	181/43	064/26	313/36	W A	20
AP03	DT	65 12 30 06 16 04	6.0	-16.6	-71.1	118	257/51	070/38	163/03	W A	20
AP04	DT	70 06 17 04 44 21	5.9	-15.8	-71.8	091	219/55	041/35	310/01	WLA	33
AP05	T	49 04 25 13 54 59	7.3	-19.5	-69.4	100	225/49	097/28	351/27	B P	28
AP06	DT	63 12 29 17 15 39	5.5	-18.3	-69.5	113	271/53	070/34	165/09	W A	20
AP07	DT	65 07 30 05 45 16	6.1	-18.1	-70.8	072	211/41	078/39	325/25	WLA	32
AP08	DT	65 08 20 09 42 49	6.4	-18.9	-69.0	128	228/51	072/37	333/12	W A	20
AP09	DT	66 02 05 23 34 32	5.1	-19.1	-69.3	142	135/05	037/54	229/35	W A	20
AP10	DT	66 03 08 20 46 12	5.9	-20.0	-68.9	122	246/54	042/34	140/11	WLA	32
AP11	DT	66 08 24 07 17 18	5.5	-19.9	-69.1	100	214/44	082/35	332/26	WLA	32
092 30 NORTH CHILE											
CN01	T	53 12 07 02 05 42	7.1	-22.1	-68.7	110	226/42	122/14	018/45	B P	28
CN02	DT	62 08 03 08 56 17	7.1	-23.3	-68.1	071	307/66	076/16	172/18	WLA	32
CN03	DT	63 05 07 16 23 12	5.7	-22.0	-68.5	095	239/41	097/41	348/20	W A	20
CN04	T	64 09 11 04 23 56	5.3	-23.9	-66.6	195	286/39	038/25	152/41	BSP	25
CN05	DT	65 02 23 22 11 50	6.9	-25.7	-70.5	080	291/51	093/37	190/08	WLA	32
CN06	T	65 05 03 16 09 09	5.5	-24.3	-67.9	127	233/53	138/04	034/35	BSP	25
CN07	T	65 06 12 18 50 11	6.5	-20.5	-69.3	102	240/55	060/35	150/00	W A	20
CN08	DT	65 08 03 08 56 12	7.1	-23.2	-67.1	100	256/69	076/21	166/00	W P	20
CN09	T	67 05 11 15 05 17	6.1	-20.3	-68.5	115	209/59	068/25	330/17	WLA	32
CN10	T	67 12 27 09 17 56	6.4	-21.2	-68.3	135	215/77	064/10	334/07	W A	20
CN11	DT	68 10 08 14 53 39	5.6	-23.3	-66.5	221	242/68	077/21	345/05	WLA	32
CN12	T	70 06 11 06 02 55	6.3	-24.5	-68.5	112	189/69	054/15	320/15	WLA	32
100 10 CENTRAL CHILE											
CC01	T	63 03 10 10 51 47	6.1	-29.9	-71.2	070	250/48	051/40	149/09	WLA	32
CC02	T	65 03 28 16 33 15	7.4	-32.4	-71.3	072	246/55	066/35	156/00	W A	20
CC03	T	65 07 12 13 57 15	5.7	-28.4	-68.3	118	259/84	053/05	143/02	WLA	32
CC04	T	66 11 10 03 02 33	6.0	-31.9	-68.4	113	028/52	184/11	186/36	WLA	32
CC05	DT	67 09 26 11 11 24	5.8	-33.6	-70.5	084	315/47	116/42	215/10	WLA	32
CC06	T	70 03 15 12 39 18	6.0	-29.7	-69.5	119	090/70	252/20	344/06	WLA	32
287 55 ALASKA (S OF 62.25N)											
AK01	N	54 10 03 11 18 46	6.8	60.7	-150.3	065	001/39	264/14	156/48	B P	28
AK02	DP	73 05 26 23 04 38	4.4	60.2	-154.0	171	274/32	113/60	010/10	LSP	06
AK03	DT	75 01 01 03 55 12	5.9	61.9	-149.7	066	126/55	316/35	223/04	W	40
350 50 ALEUTIANS (M.GT.4)											
AL01	P	50 09 16 21 58 17	6.5E	52.0	177.1	100	320/45	140/45	050/00	B P	44
AL02	T	55 01 13 02 03 45	6.9	53.0	-167.5	75	186/11	277/12	053/74	W A	35

ID	TY	ORIGIN TIME	MAG	LAT	LONG	Z	P	T	B	QU	REF
AL03	DT	55 03 14 13 12 04	7.0	52.5	-173.5	75	212/25	030/65	121/01	C	39
AL04	DP	63 04 02 16 18 55	6.4	52.1	-171.7	157	348/57	251/05	158/24	W A	20
AL05	DT	69 06 20 02 37 --	5.5	56.3	-161.6	191	123/41	303/49	033/00	WLA	16
AL06	DP	70 02 28 10 52 31	6.1	52.6	-175.0	159	313/67	101/20	195/12	WLA	31
AL07	DP	71 04 05 09 04 --	5.8	53.3	-170.5	140	310/70	148/19	056/04	WLA	16
AL08	DT	71 09 04 15 53 --	5.7	54.9	-163.4	134	154/45	334/45	064/00	WLA	16
AL09	P	72 04 21 01 28 --	5.8	54.0	-166.8	104	356/49	176/41	086/00	WLA	16
AL10	P	73 03 19 11 41 08	5.8	52.8	173.8	081	355/32	175/53	085/00	W	40
AL11	P	75 01 27 21 33 33	4.9	52.2	-175.9	151	294/44	194/10	093/44	WSP	36
AL12	T	75 11 30 05 31 26	4.8	51.9	-176.0	099	009/15	274/15	141/70	WSP	36
AL13	DP	76 08 28 02 30 10	5.1	52.2	-175.0	138	343/63	163/28	253/00	BSP	14
306 45 KAMCHATKA PENINSULA											
KA01	DP	60 07 25 11 12 00	6.9	54.0	159.0	100	301/46	182/26	073/57	W S	37
KA02	DP	64 12 26 14 30 29	5.7	51.8	156.8	136	303/33	102/55	207/10	WLA	34
KA03	DP	66 01 28 22 38 14	5.7	51.6	157.0	124	278/48	130/36	038/03	BSP	44
KA04	DP	67 12 14 18 25 23	5.5	54.5	160.4	077	320/45	140/45	050/00	BSP	38
KA05	DT	71 11 24 19 35 29	6.3	52.9	159.2	106	131/40	302/50	037/05	WLA	34
306 50 NORTHERN KURILES (SHIASHKOTAN TO SHUMSHU)											
NK01	P	49 11 03 01 12 36	6.8	48.5	154.0	160	254/05	169/37	352/53	B P	44
NK02	DP	53 01 17 17 30 03	6.3	50.5	155.2	128	307/45	127/45	037/00	B P	44
NK03	DP	53 03 17 13 04 42	5.8	50.0	156.4	060	306/45	126/45	036/00	B P	44
NK04	DT	53 10 11 13 08 33	6.8	50.0	155.5	060	128/27	308/63	038/00	BLA	44
NK05	DT	61 01 19 17 22 17	5.7	49.3	156.4	050	099/26	339/44	209/34	BSP	44
NK06	DT	61 03 11 01 31 34	6.2	48.7	155.2	050	132/26	296/63	039/06	BSP	44
NK07	DT	63 01 29 09 21 14	6.2	49.7	155.0	143	108/32	317/55	207/14	WLA	34
NK08	DT	64 06 21 01 33 11	5.7	50.7	157.5	051	045/01	315/54	013/54	B A	43
NK09	DT	66 02 05 16 16 04	5.9	50.0	155.4	121	141/28	280/54	040/21	W A	20
NK10	DT	67 12 01 13 51 02	5.9	49.5	154.4	136	127/41	326/47	226/09	WLA	34
NK11	DP	72 03 22 10 27 42	6.3	49.1	153.6	134	311/59	114/30	208/08	WLA	34
320 45 CENTRAL KURILES (URUP TO RAYKOKE)											
KU01	DP	49 05 03 05 56 42	7.0	48.6	153.5	125	324/51	144/39	054/00	B P	44
KU02	DT	51 08 24 14 21 35	6.3	46.6	150.7	190	146/34	326/56	056/00	B P	44
KU03	DT	54 07 06 08 04 37	6.7	46.5	153.4	100	165/25	330/60	070/05	BSA	05
KU04	DT	56 10 11 02 24 33	7.6	45.9	150.7	100	143/45	332/45	238/04	B A	44
KU05	P	60 03 10 14 32 39	6.0	46.6	152.5	100	280/17	154/63	019/21	BSP	04
KU06	T	60 05 08 14 29 --	5.5	45.0	151.0	090	146/09	243/39	044/50	C P	18
KU07	P	61 08 17 21 16 30	6.7	46.4	149.3	160	275/50	130/35	027/18	B A	44
KU08	DP	64 08 04 17 24 29	5.9	46.6	151.3	086	312/39	112/49	214/10	WLA	34
KU09	DT	65 04 05 13 52 13	5.7	44.6	151.1	081	111/26	339/54	213/23	WLA	34
KU10	DT	69 08 20 07 50 06	5.8	47.9	153.6	101	147/39	344/49	244/08	WLA	34
KU11	DP	71 03 03 21 54 13	5.8	48.3	153.0	132	334/59	132/29	227/10	WLA	34
KU12	DT	72 03 25 00 56 05	5.8	48.0	153.2	134	122/39	319/49	219/08	WLA	34
326 45 SOUTHERN KURILES (HOKKAIDO TO ETOROFU)											
ET01	DT	34 06 13 01 51 01	7.0	44.2	147.4	096	147/59	327/31	057/00	WSA	29
ET02	T	51 02 10 08 38 14	5.5	43.9	146.2	100	099/51	285/39	193/03	C	39
ET03	T	61 02 12 21 53 44	6.9	43.2	147.9	045	095/43	266/47	000/05	B P	17
ET04	P	61 10 24 07 25 28	6.3	45.0	146.7	144	273/44	138/36	029/24	BSP	44
ET05	DT	64 06 23 01 26 37	7.6	43.3	146.1	077	152/36	351/52	249/09	WLA	34
ET06	DT	65 10 25 22 34 24	6.2	44.2	145.3	181	139/36	346/50	237/14	W A	20
ET07	DT	65 11 29 09 00 14	5.4	45.0	146.7	186	145/45	325/45	055/00	BSP	38
279 35 TOHOKU, JAPAN											
JP01	P	55 10 11 23 03 --	5.1	39.0	141.3	090	242/43	126/24	016/37	C P	18
JP02	DP	57 10 31 02 37 00	5.9	37.6	140.8	080	275/14	028/57	174/29	B P	17
JP03	T	59 01 24 05 08 38	6.4	37.4	141.2	086	151/65	331/25	061/00	C P	18
JP04	B	59 03 04 23 00 52	5.0E	37.6	138.7	219	340/23	246/07	141/67	B P	17
JP05	T	60 04 02 13 46 --	5.0E	37.2	140.6	090	117/44	015/12	091/43	B P	17
JP06	DP	60 04 15 11 39 01	6.0	40.9	141.6	130	286/19	181/36	038/48	C P	18
JP07	DP	60 10 09 09 00 42	6.2	40.8	141.4	125	279/29	189/00	099/61	B P	17
JP08	P	65 07 27 21 16 03	4.8	40.2	139.4	195	306/30	125/60	035/00	BSP	25
JP09	DP	70 03 23 00 20 55	5.8	40.2	140.3	145	283/25	118/64	016/06	W P	42
JP10	DP	70 04 01 14 23 25	5.8	39.8	141.9	067	290/23	110/67	200/00	W P	42
JP11	P	72 03 19 15 57 50	6.0	40.8	141.9	076	315/24	046/02	140/66	WLA	34
JP12	DT	73 02 14 21 45 43	4.9	39.1	141.5	110	096/61	276/29	186/00	W P	42
260 55 OGASAWARA (BONIN)											
OG01	T	53 11 25 17 48 54	8.0	34.1	141.9	060	051/64	210/24	304/08	B P	44
OG02	N	58 09 08 14 53 --	5.0E	33.7	139.1	080	355/54	265/00	175/36	B P	17
OG03	P	64 01 15 21 36 05	6.7	29.2	141.1	075	154/12	034/66	249/20	WAA	22
OG04	DP	65 05 01 02 16 12	4.5	33.5	139.0	230	302/62	072/27	172/20	BSP	25
OG05	P	65 07 07 21 38 52	5.2	32.9	139.0	226	169/22	077/04	337/68	BSP	03
OG06	P	70 12 07 21 35 22	6.0	29.7	140.0	179	320/57	125/34	220/07	W	40
MARIANAS (SLAB DIRECTION VARIES)											
MA01	T	57 05 21 01 12 04	7.0	21.5	144.0	113	030/70	125/00	220/20	BSA	05
MA02	T	65 01 02 13 44 19	6.5	19.1	145.8	136	043/60	177/22	276/20	WAA	22
MA03	DT	69 06 17 19 26 32	5.8	19.0	145.2	206	095/01	191/74	004/16	W	40
MA04	T	74 01 25 20 28 14	5.9	18.9	145.5	141	335/49	155/41	065/00	W	40
MA05	DT	74 03 24 04 21 05	5.9	12.6	144.3	079	161/61	340/28	071/00	W	40
070 65 NEW HEBRIDES (S. OF -12.5)											
NH01	T	63 03 30 01 53 29	6.3	-19.1	169.0	156	235/20	130/36	348/48	W A	20
NH02	T	63 05 01 10 03 20	7.0	-19.0	168.9	142	250/20	138/46	355/38	W A	20

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NH03DT 63 11 04 01 14 33 6.4 -15.1  167.4 123 275/05 095/85 005/00 W P 20
NH04DP 64 01 20 17 08 37 6.5 -20.7  169.9 139 093/63 340/12 244/24 W A 20
NH05DT 64 07 09 16 39 49 7.2 -15.5  167.6 121 263/09 083/81 174/00 W A 20
NH06 P 64 09 02 21 32 40 4.7 -18.6  169.3 223 120/24 217/07 323/64 BSP 25
NH07DT 65 08 04 08 47 09 6.0 -13.2  167.0 209 130/01 038/62 220/28 W A 20
NH08DT 65 09 12 06 58 35 5.1 -11.3  166.4 130 150/13 330/77 060/00 BSP 25
NH09 T 66 02 04 10 39 12 6.3 -15.9  167.9 183 244/24 136/30 006/50 W A 20
NH10 T 66 10 07 15 55 11 6.0 -21.6  170.6 160 239/00 328/30 148/60 W A 20
NH11DT 66 12 01 04 56 59 6.0 -14.0  167.1 132 249/03 122/86 339/04 W A 20
NH12DT 67 03 31 20 05 19 5.4 -15.4  167.5 132 253/05 073/85 163/00 W A 20
NH13 B 69 01 19 18 50 52 6.4 -14.9  167.2 107 030/30 144/35 271/40 WLP 09
NH14 B 69 07 29 06 29 23 5.3 -14.8  167.3 134 104/24 012/04 273/65 WLP 09
NH15DT 70 01 30 08 28 23 5.7 -14.6  167.5 177 238/03 140/67 329/23 WLA 26
NH16 T 71 08 14 00 15 18 5.5 -14.8  167.2 124 050/29 150/30 286/46 WLP 09
NH17DT 73 11 30 08 09 56 6.2 -15.2  167.4 124 284/06 086/83 194/02 WLP 09


290 55 TONGA-FIJI (TO 28.5S)
TO01 P 54 08 18 04 42 20 6.9 -21.5 -175.0 160 250/45 115/30 010/25 BSA 05
TO02 P 63 07 04 10 58 16 6.8 -26.3 -177.8 190 339/39 071/01 164/51 WLA 19
TO03DP 64 07 21 03 48 57 6.4 -26.0 -177.9 200 308/42 107/47 208/08 WLA 19
TO04DP 65 03 18 06 22 10 5.5 -19.9 -175.9 219 266/38 133/43 018/25 WLA 19
TO05DP 65 08 20 21 21 50 6.2 -22.9 -176.1 079 263/40 093/50 357/06 WLA 19
TO06DP 66 08 10 05 01 11 5.6 -20.2 -175.3 095 282/54 062/29 163/20 WLA 19
TO07 P 67 03 04 06 16 22 5.5 -18.4 -175.4 228 258/32 144/32 021/41 W P 07
TO08 P 67 08 12 09 39 46 5.8 -24.7 -177.5 134 350/27 193/61 085/10 W A 20
TO09 P 68 03 11 08 26 30 6.0 -16.2 -173.9 112 339/48 234/12 137/39 W A 20
TO10 N 68 08 01 00 14 16 5.6 -26.6 -177.5 123 305/03 210/44 039/46 WLP 27
TO11DT 68 08 15 06 50 39 5.5 -13.9 -177.2 186 072/32 268/56 166/08 W P 07
TO12DP 69 05 01 19 05 25 6.0 -16.7 -174.6 205 326/69 186/17 091/13 W A 41
TO13 B 69 10 26 06 37 56 5.8 -16.2 -173.9 127 334/02 239/72 065/18 W P 07
TO14 P 69 11 14 07 37 44 5.5 -19.7 -175.8 209 251/54 091/34 354/09 W P 07
TO15 P 70 01 20 07 19 51 6.5 -25.8 -177.3 080 330/39 150/51 060/00 W P 07
TO16DP 71 03 23 02 15 24 6.1 -22.9 -176.1 077 268/44 108/44 008/10 W P 07
TO17 P 71 12 12 08 06 53 5.8 -26.7 -177.1 101 349/10 102/65 255/23 WLP 27
TO18DP 71 12 27 11 00 57 5.6 -19.9 -175.8 224 267/32 162/22 044/50 W P 07
TO19 P 72 01 15 03 39 22 5.7 -18.3 -174.6 155 257/37 123/43 007/24 W P 07
TO20 P 72 03 07 07 45 21 6.2 -28.2 -178.3 192 352/39 250/14 144/48 W P 07
TO21DP 72 05 22 20 45 55 6.2 -17.7 -175.2 227 279/63 164/10 068/24 W P 07
TO22DP 72 09 22 11 45 55 6.2 -16.5 -174.5 186 284/53 096/37 199/04 W P 07
TO23DP 75 01 17 09 30 37 5.8 -17.9 -174.6 153 241/67 124/11 030/20 WLP 27


290 55 KERMADEC-NEW ZEALAND (FROM 28.5S)
KE01DT 49 11 22 00 51 52 7.3 -29.3 -178.2 191 071/60 294/22 197/18 B P 28
KE02 B 57 06 11 14 49 47 7.0 -30.0 -178.0 100 190/03 303/83 099/06 C   39
KE03DT 60 03 27 23 28 27 6.6 -39.1  174.9 228 089/25 243/62 354/11 W P 02
KE04DT 63 07 29 20 14 07 6.6 -30.3 -177.6 085 114/32 273/56 018/10 WLA 19
KE05DT 65 12 08 18 05 25 6.2 -37.1  177.5 156 042/15 288/57 140/30 W A 20
KE06DT 70 01 08 17 12 41 6.1 -34.7 -178.6 179 101/16 252/59 007/14 W P 07
KE07 B 70 08 28 10 06 04 5.7 -33.8 -179.8 090 248/08 339/08 114/78 W P 27
KE08 T 76 01 24 21 48 23 6.0 -28.6 -177.6 078 061/08 327/48 158/42 WLP 27


310 40 RYUKYU (CENTRAL)
RY01 P 51 03 05 20 11 48 6.9  28.2  128.7 170 348/39 084/08 183/50 B P 28
RY02 T 53 12 01 05 08 50 6.8  29.1  128.4 224 120/40 355/36 240/31 B P 44
RY03DT 60 07 08 12 51 27 6.1  30.5  130.6 075 122/33 298/57 031/02 BSP 30
RY04DP 64 01 06 05 54 43 5.8  27.2  127.4 103 321/43 100/35 206/20 WLA 22
RY05DP 65 09 21 01 38 30 6.5  29.0  128.2 197 329/52 090/22 193/30 WLP 22
RY06DT 68 05 14 14 05 06 5.9  29.9  129.4 168 092/29 306/56 190/18 WLP 23
RY07DT 70 03 23 12 14 54 5.8  29.8  129.3 148 220/01 312/47 128/47 WLP 23


345 70 TIMOR
TI01DT 63 02 14 07 04 41 6.5  -7.4  128.2 197 268/11 020/62 174/25 WLA 12
TI02 T 65 11 20 15 05 39 6.2  -7.3  129.2 132 110/22 241/59 010/22 WLA 12
TI03 T 67 10 12 18 31 39 6.2  -7.1  129.8 086 029/02 296/49 122/41 W A 11
TI04DT 69 09 29 16 20 02 5.7  -7.3  128.8 139 240/04 346/74 148/15 WLA 08
TI05DT 71 07 08 19 07 07 6.3  -7.0  129.7 101 087/22 308/63 182/16 WLA 08
TI06DT 72 09 05 05 23 03 5.8  -7.0  129.7 108 068/12 304/69 162/18 WLA 08


000 48 JAVA (106 TO 124E)
JA01DT 59 06 28 19 43 30 6.4  -9.0  123.0  75 201/76 021/14 111/00 B P 44
JA02DT 61 05 07 04 32 15 5.8  -7.5  110.0 113 208/31 028/59 118/00 B P 44
JA03DP 63 05 22 21 53 04 6.0  -8.2  115.8 047 006/39 186/51 096/00 W A 11
JA04DT 64 02 29 23 49 41 5.8  -8.5  112.7 120 183/65 003/25 093/00 WLA 12
JA05 T 67 02 19 22 14 36 6.1  -9.2  113.1 080 229/53 051/37 140/00 W P 11
JA06DT 70 08 13 04 22 35 6.0  -9.0  118.0 099 135/21 340/66 228/10 WLA 08


050 47 SUMATRA
SU01DT 60 07 10 00 05 38 6.5   1.0   98.0 150 209/29 029/61 119/00 B P 44
SU02DT 63 06 30 06 45 39 5.5  -2.6  102.5 181 207/32 080/45 320/30 WLA 12
SU03 T 64 04 03 04 12 42 6.2   4.0   96.6 070 200/65 020/26 110/00 W A 11
SU04DT 67 05 21 18 45 13 6.3  -1.0  101.5 173 244/25 077/65 335/05 WLA 12


CARIBBEAN
CB01 T 64 08 20 08 37 47 5.5  14.9  -60.5 072 069/53 279/33 179/15 WLP 24


225 80 NORTH SCOTIA (55 TO 58.2S)
SN01 N 63 12 10 06 30 55 5.5 -58.1  -26.4 110 095/15 275/15 005/00 WAP 13
SN02 T 64 05 26 10 59 13 7.3 -56.5  -27.7 120 083/06 179/57 348/31 WLL 01
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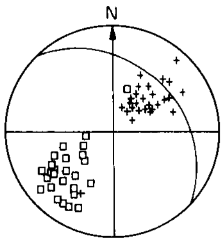
SN03	T	64	05	27	00	56	43	5.8	-56.1	-27.6	101	221/06	125/57	315/34	W A	20
SN04	DT	65	01	16	11	32	37	6.1	-56.6	-27.4	101	068/30	248/60	158/00	W A	20
SN05	T	65	05	26	19	44	11	6.7	-56.1	-27.6	120	052/00	146/50	322/39	W A	20
SN06	T	65	12	13	15	08	27	5.2	-56.1	-27.8	153	094/02	180/51	003/39	BSP	25
SN07	DT	67	02	02	06	25	50	5.8	-57.9	-25.4	079	070/16	277/72	162/08	WAA	13
SN08	T	67	03	22	21	17	37	5.6	-56.2	-27.7	085	071/03	162/56	347/41	WAA	13
SN09	T	68	10	04	06	04	32	5.9	-56.2	-27.0	090	021/34	180/54	283/10	WAA	13
SN10	T	69	01	18	03	02	39	5.9	-56.8	-26.8	141	064/04	160/55	330/35	WAA	13
SN11	T	70	05	20	20	03	42	6.0	-55.9	-28.3	080	216/09	120/32	317/55	WAA	13
SN12	DT	70	12	17	08	42	22	5.9	-56.0	-27.5	115	230/13	101/70	326/14	WAA	13
SN13	T	71	09	26	11	02	59	5.6	-56.7	-27.4	181	070/25	250/65	160/00	WSP	13
SN14	N	72	04	06	03	21	16	5.4	-57.9	-26.6	135	095/75	275/15	005/00	WSP	13
258 58 SOUTH SCOTIA (58.2 TO 61S)																
SS01	DP	67	06	17	05	00	12	6.1	-58.3	-26.6	140	272/64	073/24	167/08	W A	20
SS02	DP	69	12	01	20	35	05	5.6	-60.0	-28.5	150	308/74	096/12	187/07	WAA	13

References

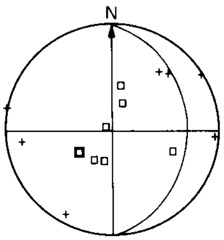
(1) Abe (1972); (2) Adams (1963); (3) Annaka (1977); (4) Aver'yanova (1973); (5) Balakina (1962); (6) Bhattacharya & Biswas (1979); (7) Billington (1980); (8) Cardwell & Isacks (1978); (9) Chung & Kanamori (1978); (10) Dean & Drake (1978); (11) Fitch (1970); (12) Fitch & Molnar (1970); (13) Forsyth (1975); (14) Fujita (1979); (15) Hirasawa (1966); (16) House (in preparation); (17) Ichikawa (1966); (18) Ichikawa (1971); (19) Isacks *et al.* (1969); (20) Isacks & Molnar (1971); (21) Ito & Annaka (1977); (22) Katsumata & Sykes (1969); (23) Mikumo (1972); (24) Molnar & Sykes (1969); (25) Oike (1971); (26) Pascal *et al.* (1978); (27) Richter (1979); (28) Ritsema (1964); (29) Ritsema (1965); (30) Shiono (1977); (31) Stauder (1972); (32) Stauder (1973); (33) Stauder (1975); (34) Stauder & Mualchin (1976); (35) Stauder & Udias (1963); (36) Topper (1978); (37) Udias & Stauder (1964); (38) Veith (1974); (39) Wickens & Hodgson (1967); (40) Wilson & Toldi (1978); (41) Wyss & Molnar (1972); (42) Yoshii (1979); (43) Zobin & Simbireva (1977); (44) New mechanisms from ISS or ISC first motions.

Appendix B

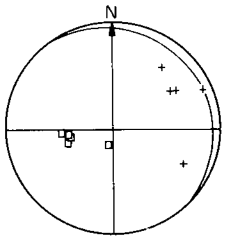
Central America



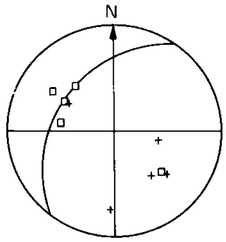
Ecuador - North Peru



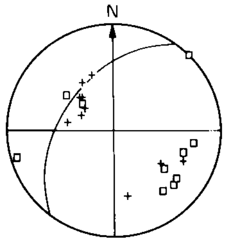
Peru



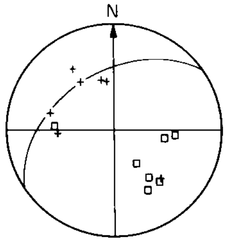
Kamchatka Peninsula



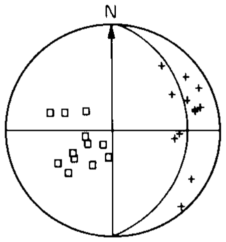
Northern Kuriles



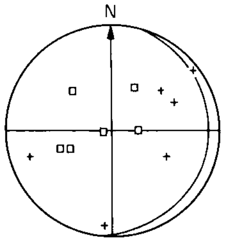
Southern Kuriles



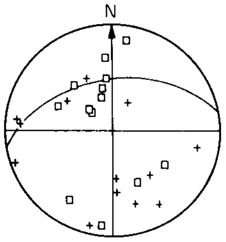
North Chile

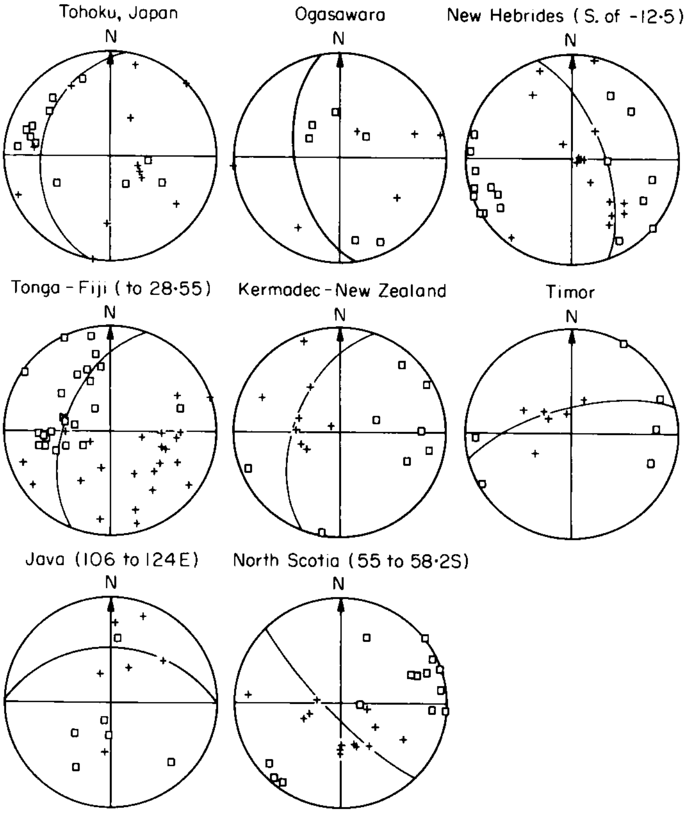


Central Chile



Aleutians (M.GT.4)




Tohoku, Japan
N
Ogasawara
N
New Hebrides (S. of -12·5)
N
Tonga - Fiji (to 28·55)
N
Kermadec - New Zealand
N
Timor
N
Java (106 to 124E)
N
North Scotia (55 to 58·2S)
N