Comparison of Wadati-Benioff Zone Geometry and Distribution of Earthquake Generating Stress beneath Northeastern Japan and Those beneath Western South America

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Abstract: Beneath northeastern Honshu Wadati-Benioff zone is composed of two seismic planes which are parallel to each other. This double-planed deep seismic zone appears in the depth range from about 70 km to 150 km. The upper seismic plane is characterized by down-dip compression and lower plane by down-dip extension. Wadati-Benioff zone beneath Hokkaido is also double-planed in nearly the same depth range. However stress state within the descending Pacific plate is slightly different from that beneath northeastern Honshu. The upper seismic plane is not down-dip compression but has various types of focal mechanisms. Down-dip extensional stress is predominant in the lower seismic plane as the case of northeastern Honshu. Beneath western South America Wadati-Benioff zone does not separate into two seismic planes but consists of a continuous single plane. Down-dip extensional stress is predominant in this single-planed deep seismic zone.

Such variations in Wadati-Benioff zone geometry and in stress state within the subducting slab are considered to be caused by several interdependent factors. Single-planed deep seismic zone and down-dip extension predominating stress in western South America are caused mainly by higher absolute velocity of the upper plate toward the trench and the subduction of younger oceanic plate than those in northeastern Japan. The difference in stress state within the double-planed deep seismic zone between northeastern Honshu and Hokkaido is perhaps due to the difference in the age of the descending Pacific plate.

1. Introduction

Northeastern Japan and western South America are the only two major subduction zones which have low dip angles of the descending oceanic plates and deep earthquakes within them.

In the northeastern Japan arc, the Pacific plate subducts at an angle of about 30°. Within the descending Pacific plate is formed a double-planed deep seismic zone in the depth range from about 70 km to 150 km (*e.g.* Tsumura, 1973; Umino and Hasegawa, 1975; Hasegawa *et al.*, 1978). The upper seismic plane of the double-planed deep seismic zone is characterized by down-dip compressional stress and the lower seismic plane by down-dip extensional stress. The separation between the two planes is from 30 to 40 km.

The western South America subduction zone is divided into five major segments by its subduction zone geometry (Barazangi and Isacks, 1976). In Ecuador, southern Peru and northern Chile, and southern Chile, the Nazca plate descends at an angle of about 30°. Subduction zone geometries beneath northern and central Peru and central Chile are different from those beneath the above-mentioned regions. The Nazca plate dips at an angle of about 30° for the first 100 km of descent and then the dip of the descending Nazca plate becomes nearly horizontal (Hasegawa and Sacks, 1981). The stress state within the descending plate is characterized by down-dip extension in all the segments of western South America (*e.g.* Stauder, 1973, 1975).

Northeastern Japan and western South America, except northern and central Peru and central Chile, have the similar dip angles of the descending oceanic plates but have the different stress states within the plates. To know the factors affecting the subduction zone geometries and stress states within the subducting plates beneath these two subduction zones is important in order to understand the mechanics and dynamics of the subduction process.

2. Shallow Seismicity along the Plate Boundary

Most of large earthquakes in the world occur along the main thrust zone between downgoing and upper plates in subduction zones. Shallow seismicity along this main thrust zone is related to the mechanical coupling between the descending plate and the upper one (*e.g.* Kanamori, 1971; Ruff and Kanamori, 1980).

Fig. 1 shows rupture areas of large shallow earthquakes occurred beneath the Pacific Ocean in and around the northeastern Japan subduction zone (Nagumo, 1973). The locations of fracture zones estimated from the offsets of magnetic anomaly lineations (Hilde *et al.*, 1976) are also shown in the figure. We can see that, in many cases, rupture areas of these earthquakes are bounded by the landward extensions of the fracture zones. For example, southern and northern ends of the focal area of the 1968 Tokachi-oki Earthquake (M 7.9) are located along the landward extensions of the fracture zones FZ A and FZ B, respectively.

The similar feature is also seen in the western South America subduction zone. Fig. 2 shows estimated rupture areas of large shallow earthquakes ($M>7.7$) that occurred in this century (Kelleher, 1972). The locations of ridge, fracture zone and spreading axis (University of Concepcion, 1982) are also shown in the figure. As in the case of the northeastern Japan and southern Kurile subduction zones (Fig. 1), northern and southern ends of the rupture area of the 1960 Great Chilean Earthquake are bounded by the landward extensions of two fracture zones.

Fig. 3 is the epicenter distribution of shallow microearthquakes ($M>2.0$, $h<100$ km) located in northern Japan by using the seismic network data of Tohoku University. The locations of fracture zones are also shown in the figure. Although all the microearthquakes located at depths shallower than 100 km are plotted in this figure, most of these events are considered to have occurred along the main thrust zone between the downgoing Pacific plate and the upper plate. It is seen that microseismicity pattern along the main thrust zone changes across the landward extensions of the fracture zones. For

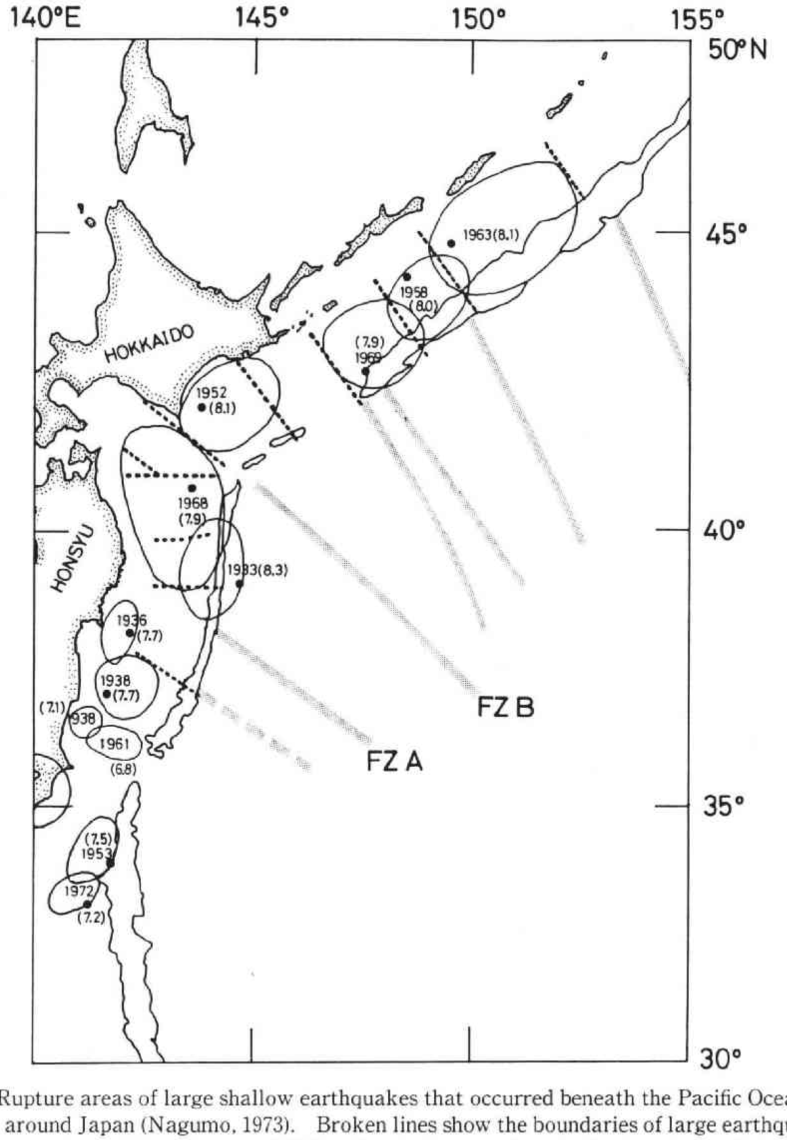

Fig. 1 Rupture areas of large shallow earthquakes that occurred beneath the Pacific Ocean in and around Japan (Nagumo, 1973). Broken lines show the boundaries of large earthquake blocks estimated by Nagumo (1973). Hatched zones donote the locations of fracture zones by Hilde *et al.* (1976).

example, landward extensions of fracture zones FZ A and FZ B in Fig. 3 are coincident with the zones where the seismicity along the shallower and deeper portions of the main thrust zone changes.

The fact that the rupture areas of large shallow events are bounded by the landward extensions of fracture zones indicates that the subducted fracture zones along the plate boundary behave as the barrier (Das and Aki, 1977) at which the rupture propagation will be stopped and that the strength of coupling between the descending oceanic plate and the upper one changes across the subducted fracture zone. The change in the strength

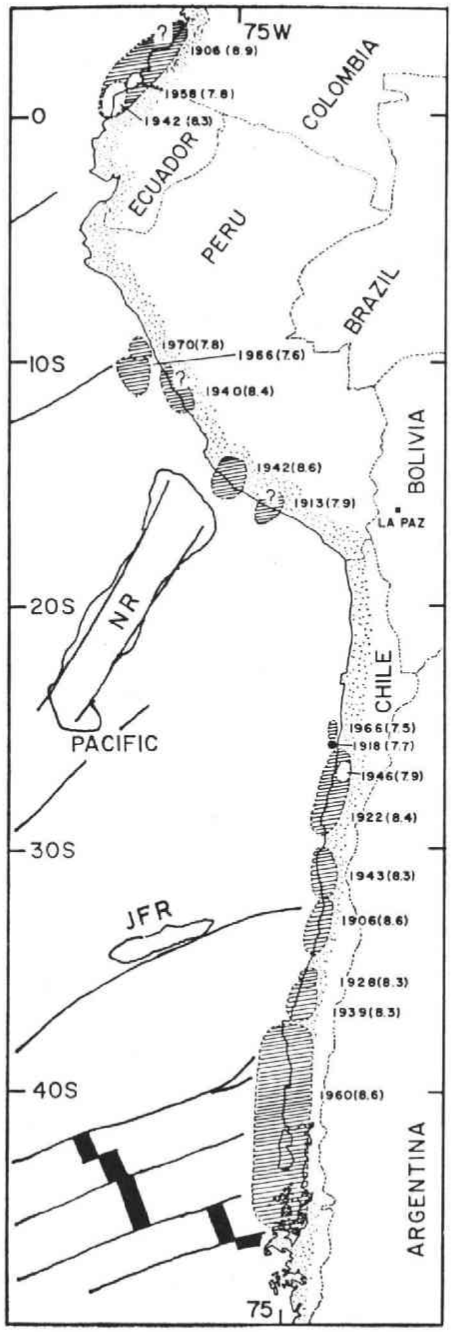

Fig. 2 Rupture areas of large shallow South American earthquakes of this century (Kelleher, 1972). Locations of fracture zones, ridges, and spreading axis (University of Concepcion, 1982) beneath the Pacific Ocean are also shown.

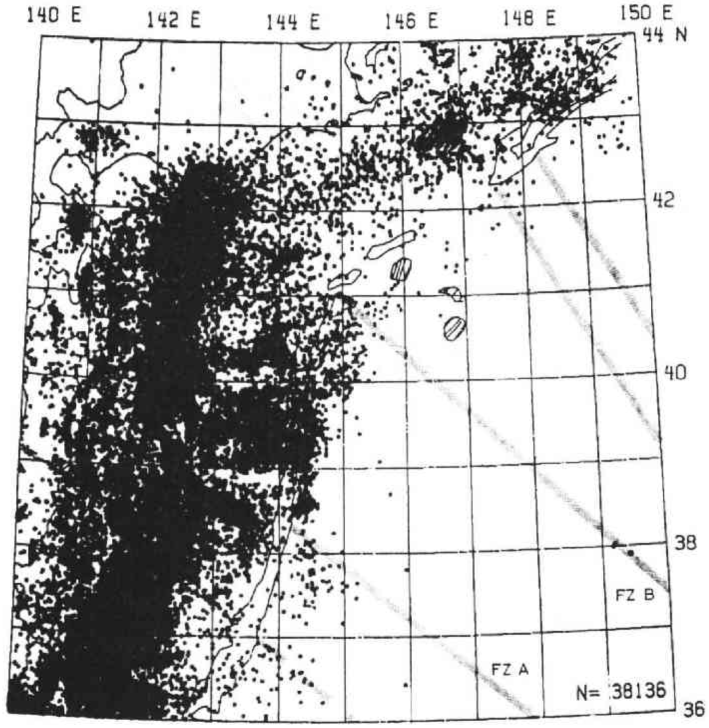

Fig. 3 Epicenter distribution of shallow microearthquakes located by the local seismic network of Tohoku University. Locations of the fracture zones are also shown by hatched zone.

of mechanical coupling aross the subducted fracture zone is also suggested from the change in the pattern of the shallow microseismicity (Fig. 3). Since the age of the subducted plate changes discretely across the fracture zone which is estimated from the offset of magnetic anomaly lineations, these facts indicate that the age of the descending plate plays an important role in the degree of seismic coupling between the plates in subduction zones. In fact, characteristic size of large shallow earthquakes in western South America, where the young oceanic slab is descending, is much larger than that in northeastern Japan, suggesting the stronger seismic coupling in western South America.

3. Wadati-Benioff Zone Geometry

In the northeastern Japan arc the deep seismic zone dips at an angle of about 30°. The shallower portion of the deep seismic zone (70-150 km depth range) is composed of two seismic planes which are parallel to each other. Precise investigation on seismic activity beneath Hokkaido and northern Honshu made by using 35 stations of three local seismic networks reveals that the double-planed deep seismic zone is continuously distributed in the whole area of Hokkaido and northern Honshu including the junction between the northeastern Japan arc and the Kurile arc (Hasegawa *et al.*, 1983 ; Suzuki

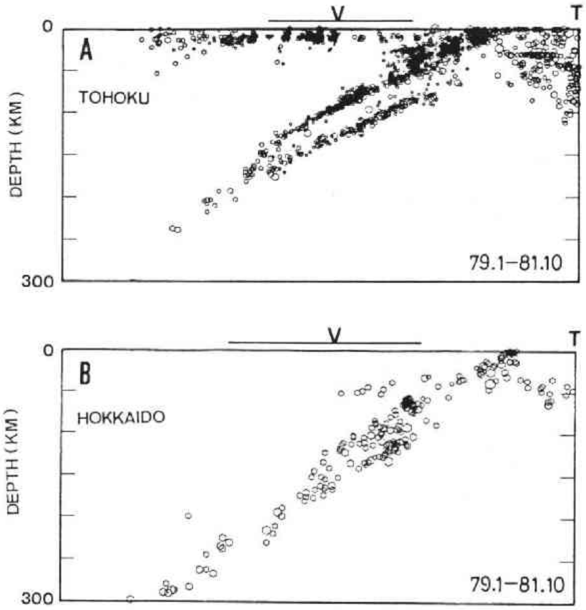

Fig. 4 Vertical cross sections of microearthquakes located (A) in northeastern Honshu (Tohoku) and (B) in Hokkaido (Hasegawa *et al.*, 1983). T and V represent the locations of the trench axis and the volcanic front, respectively.

et al., 1983).

Vertical seismic sections in northeastern Honshu (Tohoku) and Hokkaido are shown in Fig. 4. Geometry of the double-planed deep seismic zone beneath northeastern Honshu and Hokkaido is illustrated in Fig. 5 by contour lines (Hasegawa *et al.*, 1983). At the junction between the northeastern Japan arc and the Kurile arc, the deep siesmic zone is contorted but is still double-planed at least in the upper 150 km depth range. Beneath central and eastern Hokkaido, located at the southwestern end of the Kurile arc, the upper seismic plane disappears at depths deeper than about 120 km (Fig. 4(B) and Fig. 5) (Suzuki and Motoya, 1981), whereas the upper plane seismicity beneath the northeastern Japan arc is still active in this depth range (Fig. 4(A)).

According to Barazangi and Isacks (1976, 1979), high-quality hypocenter data beneath western South America define five major segments of deep seismic zone, in each of which the deep seismic zone has relatively uniform dip angles. The two segments beneath northern and central Peru (about latitude 2° to 15° S, section B-B in Fig. 6) and beneath central Chile (about latitude 27° to 33° S, section D-D in Fig. 6) have very small dip angles of about 10°. On the contrary, the other three segments beneath southern Ecuador (about latitude 0° to 2° S, section A-A in Fig. 6), beneath southern Peru and northern Chile (about latitude 15° to 27° S, section C-C in Fig. 6), and beneath southern Chile (about latitude 33° to 45° S, section C-C in Fig. 6) have steeper dip angles of about 30°.

Hasegawa and Sacks (1981) made a detailed reinvestigation of seismicity in the

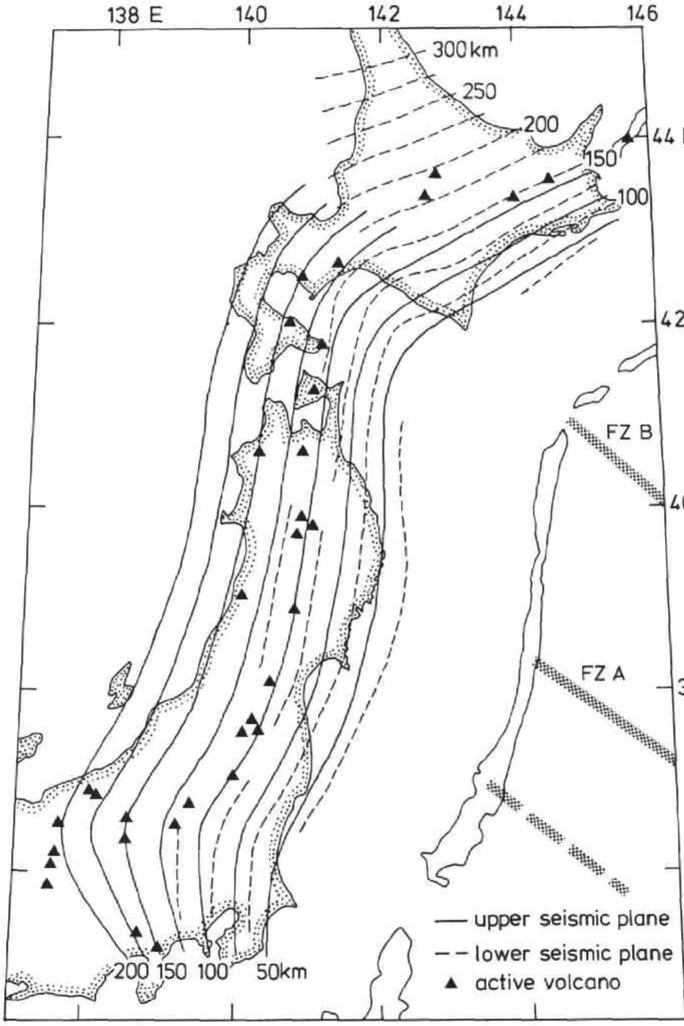

Fig. 5 Geometry of the Wadati-Benioff zone beneath northeastern Honshu and Hokkaido (Hasegawa *et al.*, 1983). Solid and broken lines show the depth to the upper and lower seismic planes, respectively. Hatched zones and triangles denote the fracture zones (Hilde *et al.*, 1976) and active volcanoes, respectively.

southern half of Peru by using local seismic network data and showed that for the first 100 km of descent the Nazca plate in the central Peru segment enters at a normal dip angle near 30° and that below this depth it is bent to a nearly horizontal angle. Between the 30° dipping plate in the southern Peru segment and the horizontal profile in the central Peru segment, there is a contortion over a 100-km-wide continuous lateral section of the descending plate. In this transition zone between the two segments the subducting Nazca plate is not torn but is contorted at least in the upper 150 km depth range (Fig. 7), though Barazangi and Isacks (1976, 1979) pointed out that it was torn.

This continuous deformation model of the descending Nazca plate in the transition

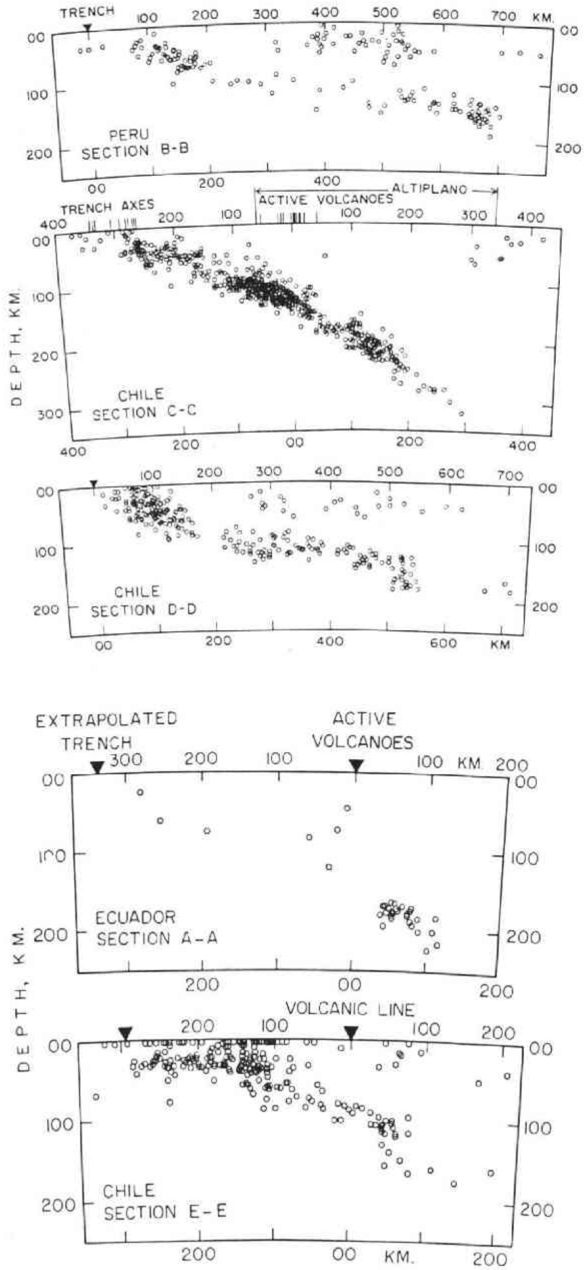

Fig. 6. Vertical seismic sections showing the Wadati-Benioff zone beneath western South America (Berazangi and Isacks, 1976).

zone between the two segments (Hasegawa and Sacks, 1981) is reaffirmed by Boyd *et al.* (1984) and Grange *et al.* (1984) using local seismic network data and by Bevis and Isacks (1984) using teleseismic data. Teleseismic data also suggest that the deformation of the Wadati-Benioff zone in the other transition zones between the segments is continuous at

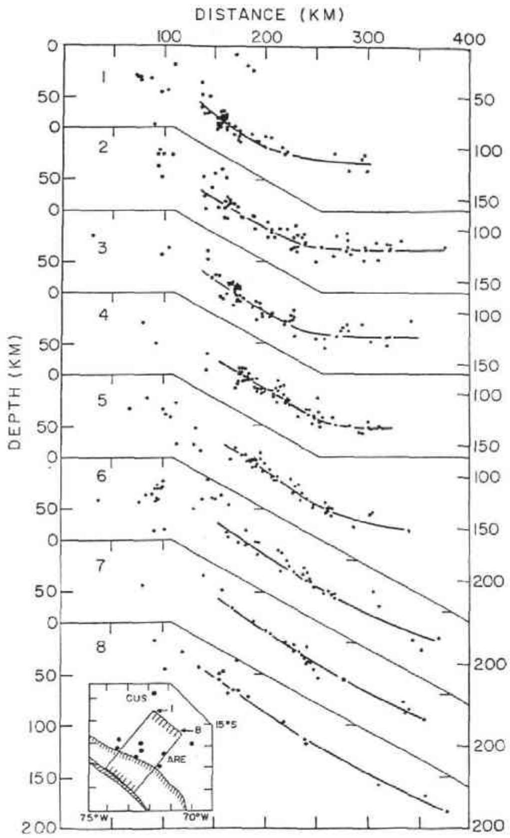

Fig. 7. Vertical cross sections of earthquakes located in southern Peru using local seismic network data (Hasegawa and Sacks, 1981).

least in the upper 150 km depth range rather than it is torn and divided into two separate tongues (Bevis and Isacks, 1984). Wadati-Benioff zone geometry beneath western South America is shown in Fig. 8 by contour lines.

4. Stress State within the Descending Slab

In northeastern Honshu (Tohoku) the shallower portion (shallower than about 150 m) of the Wadati-Benioff zone consists of two seismic planes which are parallel to each other. The separation of the two planes is about 30-40 km. Stress states in these two seismic planes are reversed: the upper seismic plane is characterized by down-dip compression and the lower seismic plane by down-dip extension. Fig. 9 shows the directions of pressure and tension axes, projected on the vertical seismic sections, for the events occurred in the upper and lower seismic planes of the double-planed deep seismic zone (Umino *et al.*, 1984). Not only in northeastern Honshu (region A in the figure) but also at the junction between the northeastern Japan arc and the Kurile arc (region B in the figure), the upper seismic plane is characterized by down-dip compressional stress and the lower seismic plane by down-dip extensional stress. The events occurring in the

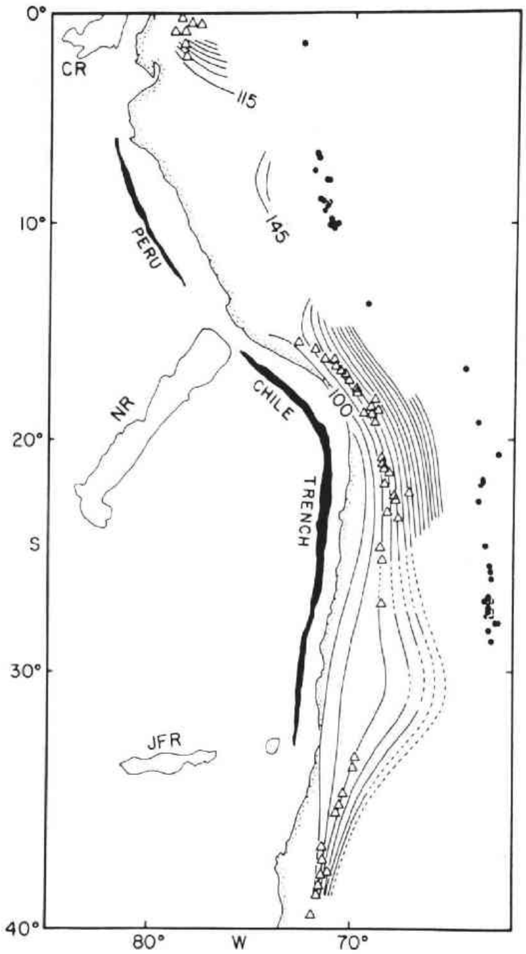

Fig. 8. Geometry of the Wadati-Benioff zone beneath western South America (Bevis and Isacks, 1984). Triangles and solid circles represent the Quaternary volcanoes and deep earthquakes, respectively.

shallower portion (shallower than 60 km) of the upper seismic plane have low-angle thrust fault type, delineating the interface between the descending Pacific plate and the upper continental plate.

Beneath central and eastern Hokkaido, the southwestern end of the Kurile arc (region C in Fig. 9), the upper seismic plane of the double-planed deep seismic zone is not down-dip compression but has various types of focal mechanisms, although the shallower portion than about 60 km has low-angle thrust fault type as the case of northeastern Honshu (northeastern Japan arc) and the junction between the two arcs (regions A and B in Fig. 9). Down-dip extensional stress is predominant within the lower seismic plane, which is the same as the regions A and B. The deeper portion than about 150 km of the Wadati-Benioff zone beneath central and eastern Hokkaido is characterized by down-dip extensional stress, whereas that beneath northeastern Honshu by down-dip com-

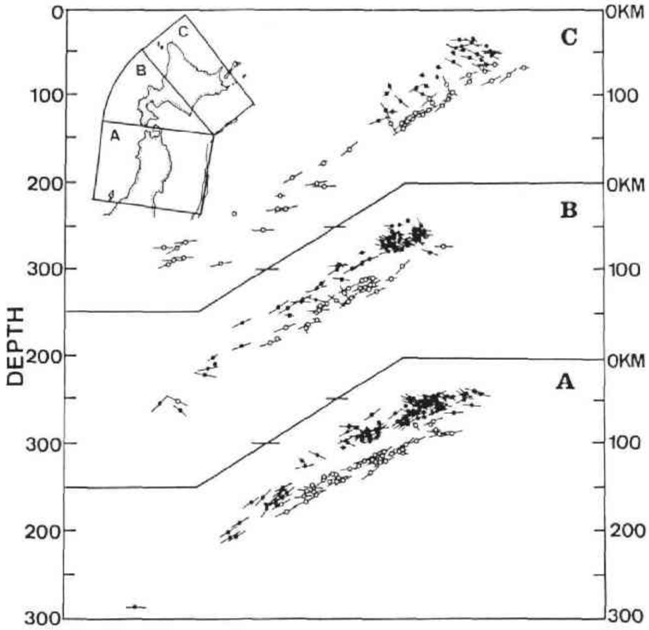

Fig. 9. Vertical cross sections showing the stress state within the double-planed deep seismic zone beneath northeastern Honshu and Hokkaido (Umino *et al.*, 1984). Pressure (open circles) and tension (solid circles) axes for events in the upper and lower seismic planes are projected on the vertical seismic sections.

pressional stress. Both in Hokkaido and Tohoku, the deepest part (deeper than about 300 km) of the Wadati-Benioff zone is characterized by down-dip compressional stress.

Distribution of earthquake generating stresses within the subducting Nazca plate under western South America is much simpler than the case of northeastern Honshu and Hokkaido. The Wadati-Benioff zone beneath western South America does not separate into two seismic planes (*e.g.* Hasegawa and Sacks, 1981; Fujita and Kanamori, 1981; Bevis *et al.*, 1984), although the double-planed deep seismic zone is clearly seen beneath northeastern Honshu and Hokkaido in the depth range from about 70 km to 150 km. In all the five segments of the western South America subduction zone, down-dip extensional stress is predominant within the underthrust Nazca plate (*e.g.* Isacks and Molner, 1971; Stauder, 1973, 1975). Even in northern and central Peru where the descending Nazca plate has flat geometry, intermediate-depth earthquakes within the plate have tension axes nearly parallel to the local dip of the plate (Hasegawa and Sacks, 1981).

5. Factors Affecting Wadati-Benioff Zone Geometry and Stress State within the Descending Slab

Variation in Wadati-Benioff zone geometry is caused mainly by four interdependent factors: combinations of (1) rapid absolute upper-plate motion toward the trench, (2) rapid relative plate convergence rate, (3) subduction of bouyant intraplate island-seamount chains, aseismic ridges, and oceanic plateaus, and (4) subduction of young lithosphere cause low-angle geometry of the descending oceanic lithosphere (Cross and Pilger, 1982).

Absolute upper-plate velocity, convergence rate and age of the descending lithosphere in northeastern Japan and those in western South America are listed in Table 1 together with dip angle of the Wadati-Benioff zone and stress state within the subducted plate. The descending oceanic plates beneath Tohoku (northeastern Honshu), Hokkaido, Ecuador, southern Peru and northern Chile, and southern Chile have nearly the same dip angles, although the three factors (convergence rate, absolute upper-plate velocity and age of descending lithosphere) are different to each other. Relatively low dip angles of about 30° of the Wadati-Benioff zone beneath these regions may be the results of combinations of these three factors: high convergence rate (especially in Tohoku and Hokkaido) and high absolute upper-plate velocity and active overriding of the young descending slab (beneath Ecuador, southern Peru and northern Chile, and southern Chile) may cause the low-angle subduction.

Anomalously flat geometry of the subducted Nazca plate beneath northern and central Peru and central Chile may be partly due to the young and relatively less dense subducted plate (Sacks, 1983). More important factor producing the flat geometry of the subduction for these two segments is considered to be the subduction of the aseismic Nazca Ridge and Juan Fernandez Ridge, because the age of the descending Nazca plate in the northern and central Peru and central Chile segments is not completely younger

Table 1. Subduction

Region	Relative plate velocity* (mm/yr)	Absolute velocity of upper plate normal to the trench* (mm/yr)	Age of descending plate* (10^6 yr)
Tohoku	105	2	125
Hokkaido	100**	2**	110**
Ecuador	84	32	30
North and central Peru	89	26	42
South Peru North Chile	92	30	51
Central Chile	92	28	45
South Chile	91	26	15

* Averaged value along the arc (after Peterson and Seno (1984)).

** Value in the Kurile arc.

than that in the other three segments in western South America. Pilger (1981) has revealed that the predicted continuations of the relatively bouyant Nazca and Juan Fernandez ridges to the subducted slab correspond well with the limits of the flat geometry segments beneath northern and central Peru and central Chile on the basis of symmetric sea-floor spreading models and plate-hotspot reconstructions.

Earthquake generating stresses within the descending oceanic plates beneath north-eastern Japan and western South America are summerized in Table 1 and schematically shown in Fig. 10(E)-(H). When the oceanic lithosphere subducts under the continental lithosphere it sinks into the asthenosphere under its own weight for the first descent of about 300 km but, below it, encounters resistance to its downward motion (Isacks and Molner, 1971). The depth of the olivine-spinel phase change (about 400 km depth) is thought to be elevated and that of the spinel-post-spinel phase transition (about 650 km depth) is presumed to be lowered within the subducted plate (*e.g.* Schubert *et al.*, 1975). The additional load of dense materical, due to the elevation of the shallower phase transition within the plate, further drives the lower portion of the plate. On the contrary, the depression of the deeper phase transition within the plate will generate an upward buoyant force, causing the resistance to the sinking of the plate below it. If this is the case, the shallower portion of the descending plate is characterized by down-dip extensional stress and the deeper portion by down-dip compressional stress. The critical depth at which the stress state changes from extension to compression depends

zone parameters

Dip of descending place (degree)	Stress state with the descending plate	
	(70-150 km depth)	(150-300 km depth)
30	down-dip compression (upper plane) down-dip extension (lower plane)	down-dip compression
30-40	mixed (upper plane) down-dip extension (lower plane)	down-dip extension
30	down-dip extension	down-dip extension
30 ($<$100 km) ~ 0 ($>$100 km)	down-dip extension	
30	down-dip extension	down-dip extension
30 ($<$100 km) ~ 0 ($>$100 km)	down-dip extension	
30	down-dip extension	

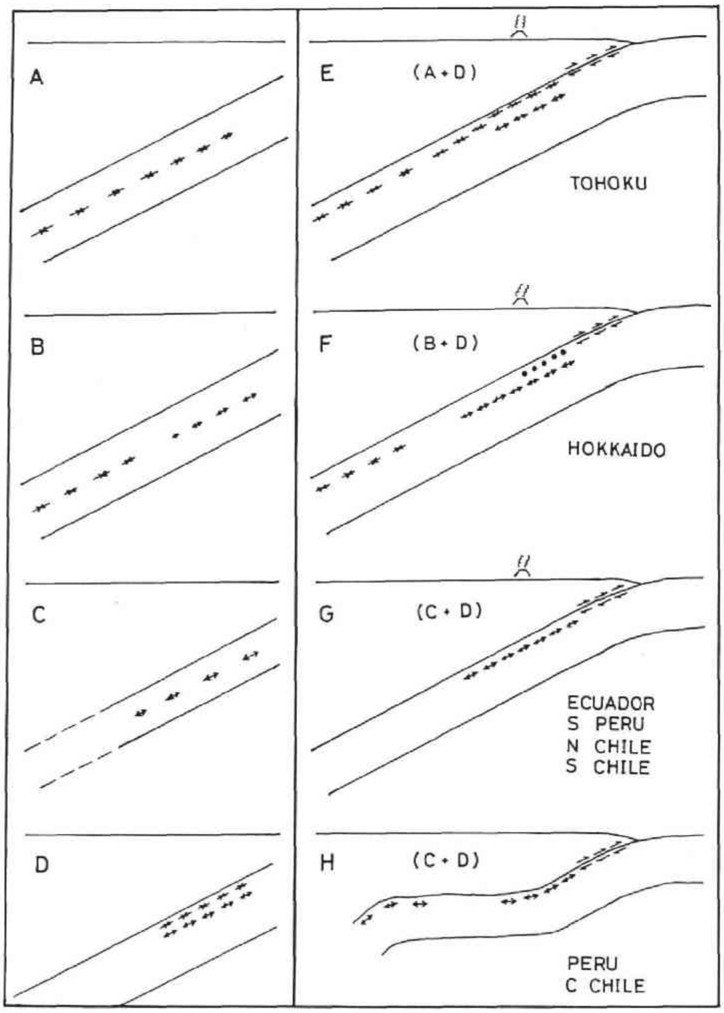

Fig. 10 Schematic illustration of stress state within the descending oceanic slab beneath northeastern Japan and western South America (see text for details).

on convergence rate, absolute velocity of upper plate, age of descending oceanic plate, and maximum penetration depth of subducted plate.

In northeastern Honshu the critical depth at which the stress state changes is considered to be extremely shallow and almost entire part of the subducted Pacific plate is under compression because of the deep penetration of the plate (down to about 600 km) and high convergence rate. Down-dip compressional stress is not so high in the shallower part and gradually increases with increasing depth as schematically shown in Fig. 10 (A). In Hokkaido the critical depth is considered to be deeper than that in northeastern Honshu due to the relatively younger descending lithosphere and partly due to the slightly lower convergence rate. Degree of mechanical coupling at the contact zone between the descending oceanic plate and the upper one strongly depends on the age of the descending plate (Ruff and Kanamori, 1980 ; Peterson and Seno, 1984). In fact, characteristic size of large shallow interplate earthquakes in Hokkaido is systematically larger than that in northeastern Honshu (Fig. 1). This is also suggested from the change in seismicity pattern across the subducted fracture zones as discussed in the previous section (Fig. 3). As a result of stronger mechanical coupling (and therefore more efficient locking of the plate interface) than that in northeastern Honshu, down-dip extensional stress (slab pull force) due to the gravitational force, although not so high, becomes dominant in the shallower portion of the subducted slab. This down-dip extensional stress gradually decreases with increasing depth and becomes zero at the critical depth. Below this depth down-dip compressional stress dominates and increases with depth due to the increased resistance of the surrounding mantle (Fig. 10 (B)).

In the three subduction segments of western South America (Ecuador, southern Peru and northern Chile and southern Chile) the critical depth is much deeper and almost entire part of the subducted Nazca plate is under tension, mainly because of the higher absolute velocity of the upper plate toward the trench and perhaps partly because of the shallower penetration of the descending plate. Down-dip extensional stress in the shallower part is relatively high and it decreases with increasing depth as schematically represented in Fig. 10(C).

In addition to the stress system mentioned above, another important one acting within the descending oceanic slab is that which generates the double-planed deep seismic zone in the shallower portion (70–150 km depth range) of the slab. The origin of the double-planed deep seismic zone has not been revealed yet. Four models have been proposed as possible causes for the formation of the double-planed deep seismic zone : they are unbending of the subducted oceanic plate (Isacks and Barazangi, 1977 ; Engdahl and Scholz, 1977), phase change within the plate (Veith, 1974), sagging of the plate in a less viscous asthenosphere (Sleep, 1979), and thermal stress within the plate (Yang *et al.*, 1977 ; House and Jacob, 1982 ; Goto *et al.*, 1983). In any case such a stress system as causes the double-planed deep seismic zone beneath Tohoku is perhaps actually acting within the descending oceanic slab of any subduction zones (*e.g.* Kawakatsu, 1986). This stress system is schematically shown in Fig. 10(D).

Variations of seismicities and earthquake generating stresses within the descending plates beneath northeastern Japan and western South America are formed by the superposition of the two kinds of stress systems mentioned above. Down-dip extensional stress (Fig. 10(C)), superimposed on the stress system generating the double-planed deep seismic zone (stress system (D) in Fig. 10), beneath western South America is high enough to erase the preexisting upper seismic plane of the double-planed deep seismic zone. Consequently the deep seismic zone is single-planed and is characterized by down-dip extensional stress (Fig. 10(G) and (H)).

On the contrary, down-dip compressional stress in the shallower portion of the descending slab beneath Tohoku (Fig. 10(A)) and down-dip extensional stress beneath Hokkaido (Fig. 10(B)), superimposed on the stress system (D) in Fig. 10, are presumed not to be so high as to erase the preexisting double-planed deep seismic zone. Seismicities and distributions of earthquake generating stresses, are affected by these superimposed down-dip compressional stress beneath Tohoku and down-dip extensional stress beneath Hokkaido. Down-dip extensional stress (slab pull force) in the shallower part of the slab beneath Hokkaido will intensify the preexisting down-dip extensional force in the lower seismic plane and weaken the down-dip compressional force in the upper seismic plane. Thus the seismicity of the upper seismic plane is much lower than the lower seismic plane (Suzuki and Motoya, 1981) and has various types of focal mechanisms. Moreover it is expected that the lower seismic plane with down-dip extensional stress extends to the deeper part (down to about 300 km depth), which is actually the case for Hokkaido (Fig.10(F)).

Beneath Tohoku down-dip compressional stress in the upper seismic plane will be intensified and down-dip extensional stress in the lower seismic plane will be weakened by the superimposed stress system (A) in Fig. 10. Thus it is the upper seismic plane that extends to the deeper part down to about 300 km depth, and relatively large events are occurring in the upper seismic plane. However the effect of down-dip compressional force within the shallower portion of the slab (Fig. 10(A)) is not so strong, and the stress state of the lower seismic plane remains down-dip extension (Fig. 10(E)).

Transition from Hokkaido-type subduction (Fig. 10(F)) to Tohoku-type (Fig. 10(E)) occurrs rather abruptly across the landward extension of the fracture zone (FZ B in Fig. 5), across which the age of the subducted lithosphere changes, indicating the relative importance of age of the subducted lithosphere for subduction process. Abrupt change in stress state from Hokkaido type to Tohoku type suggests a disruption of the descending Pacific plate into the two segments of the northeastern Japan arc and of the Kurile arc in the deeper part (at least deeper than about 200 km).

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