

Back-Arc Opening and the Mode of Subduction

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Trench-arc systems (subduction zones) can be classified into two types depending on whether or not actively opening back-arc basins are associated with them. This suggests that subduction of an oceanic plate is not a sufficient condition for back-arc opening, though it may be necessary one. Mechanisms that cause the distinction between the two types have been investigated. Earthquake studies suggest that there is a significant difference in the mode of plate motion at interplate boundaries between the two types of trench-arc systems. Extreme cases are Chile, where plate motion is seismic, and the Marianas arc, where it is aseismic. This difference seems to indicate that the stress state in the back-arc area differs between the two types: compression in the Chilean type and tension in the Marianas type. This difference in the stress state is also manifested in other tectonic features, such as topography, gravity, volcanic activity, and crustal movement. Two possible mechanisms for the difference between the two types are suggested: (1) The nature of the contact zone between upper and lower plates changes from tight coupling (Chile) to decoupling (the Marianas) through the evolutionary process of subduction. The decoupling results in an oceanward retreat of the trench and back-arc opening. (2) The downgoing slab is anchored to the mantle, so that the position of a trench is also fixed with respect to the mantle. Since the motion in the mantle is slow compared to that of surface plates, it is the motion of the landward plate which controls the opening and nonopening of back-arcs.

INTRODUCTION

In plate tectonics, the fundamental process occurring under the trench-arc systems is the subduction of an oceanic plate. Small oceanic basins, such as the Japan Sea, Okhotsk Sea, and Philippine Sea are often found landward of arcs. The intent of the present paper is to discuss the genesis of these basins, called back-arc basins or marginal seas.

We first note the fact that not all the trench-arc systems have back-arc basins. The Peruvian and Chilean arcs do not have back-arc basins. The process of back-arc basin formation appears to be inactive at present in some arcs as in the case of the Japan Sea, whereas others are believed to have an actively opening back-arc basin, for example, the Mariana Trough [Karig, 1971a]. Any theory for the genesis of back-arc basins must account for this fact. Clearly, the subduction of an oceanic plate is not a sufficient condition for the formation of back-arc basins, although it may be a necessary one.

Several possibilities have been suggested to explain the origin of back-arc basins: (1) entrapment of a marginal part of preexisting ocean by the formation of an island arc: Aleutian Basin [Cooper *et al.*, 1976] and west Philippine Sea [Uyeda and Ben-Avraham, 1972], (2) back-arc spreading caused by or related to subduction: Lau Basin and Mariana Trough [Karig, 1970, 1971a], Scotia Sea [Barker, 1970], and Japan Sea [Karig, 1971b; Matsuda and Uyeda, 1971], (3) opening related to 'leaky' transform fault: Gulf of California [Wilson, 1965] and Andaman Sea [Curry *et al.*, 1979], (4) opening related to the subduction of a ridge: Japan Sea [Uyeda and Miyashiro, 1974], and (5) subsidence caused by oceanization of continental crust: Japan and Okhotsk seas [Belousov and Ruditch, 1961].

Among the above possibilities, 1 is probably the likeliest mechanism provided that the age of the basin is older than that of the arc. The Mesozoic sequence of magnetic lineations in the Aleutian Basin is a notable example provided that the identifications are correct. Possibilities 3 and 4 seem to be

closely correlated with each other because, from geometrical considerations, it is clear that a subduction boundary can easily change to a 'leaky' transform boundary upon a collision of a spreading center with the trench. In fact, the opening of the Gulf of California may be an example of the combined effects of 3 and 4. Until 20 m.y. B.P. the East Pacific Rise was situated to the west of Baja California [Atwater, 1970] while now it is in the gulf in the form of a series of ridges and transforms. The ridge possibly died during its collision with the trench that existed to the west of Baja and reappeared in the former back-arc region by jumping rather than migrating under the Baja. The Andaman Sea may be another example [Eguchi *et al.*, 1979]. Possibility 5 seems to have no petrological support.

Possibility 2 is our main concern in this paper. As we mentioned already, not all the subduction boundaries have back-arc basins, and not all subduction boundaries that have back-arc basins are presently actively opening. We will first classify the subduction boundaries by back-arc type and then demonstrate that the differences in back-arc type correlate with other phenomena which are presumed to be related to the tectonic stress state. We will next discuss the possibility that the difference in the tectonic stress state in back-arc regions may be caused by a difference in the mode of subduction and attempt to find out why such different modes of subduction occur.

CLASSIFICATION OF SUBDUCTION BOUNDARIES

Karig [1971b] classified marginal basins into active marginal basins (type 1), inactive marginal basins with high heat flow (type 2), and inactive marginal basins with normal heat flow (type 3). He postulated that types 2 and 3 were active in the past, type 2 in the more recent past than type 3. We use ideas more or less similar to Karig's to classify the subduction boundaries in Table 1. First, subduction boundaries (trench-arc-back-arc systems) are grouped into the continental arc and island arcs. Continental arcs, by definition, have no back-arc basins. The back-arc area of the Sumatra and Java arc is

TABLE 1. Classification of Trench-Arc-Back-Arc Systems

Classification	Subduction Boundary	Location		
<i>Continental Arc</i>				
Continents	Peru-Chile	Andes		
	Middle America	Middle America (semi-active?)		
	Proto-North America	Basin and Range Province (semi-active?)		
	Alaska	Alaska Range		
	Sumatra-Java	Sunda Shelf		
<i>Island Arc</i>				
Back-arc active	Mariana Ryukyu Tonga Scotia New Hebrides Bonin Philippine	Mariana Trough		
		Ryukyu Trough		
		Lau Basin		
		Scotia Sea		
		?		
		?		
		?		
		Leaky transform	Proto-Baja California Andaman-Nicobar Melanesian Borderlands New Hebrides	Gulf of California
				Andaman Sea
				Bismarck Sea, New Guinea
Fiji plateau?				
Back-arc inactive Inactivated	Antilles West Aleutian Kurile Japan Proto-Izu-Bonin Proto-Mariana	Grenada Trough?		
		Kamchatka Basin		
		Kurile Basin		
		Japan Basin, Tsushima Basin		
		Shikoku Basin		
		Parece Vela Basin		
		Trapped	Aleutian Proto-Mariana Proto-Tonga Middle America	Bering Sea
				West Philippine Sea?
				South Fiji Basin?
				Caribbean Plate

water covered, but this arc is grouped with the continental arcs because most of the back-arc area has only shallow water depth (about 100 m) and presumably a continental crust. Conversely, the Middle American arc, though included in the continental arcs, might be better grouped with the back-arc spreading type because of the extensional volcanic grabens found in Middle America [Plafker, 1976]. A similar argument may hold for the Proto-North American arc, which is sup-

posed to have existed before the collision of the East Pacific Rise with the North American continent [McKenzie and Morgan, 1969; Scholz *et al.*, 1971]. Island arcs are classified into those with active back-arc basins and those with inactive back-arc basins. Active and inactive refer to whether the opening of the basin is presently in progress or not. A back-arc basin which has rift topography and/or fault structure suggestive of tectonics is considered to be actively opening if it shows one or more of the following characteristics: (1) thin sediment cover of very young age over rugged volcanic basement relief, (2) shallow water depth comparable to that of active midoceanic ridges, (3) high heat flow or highly variable heat flow [Watanabe *et al.*, 1977], or (4) magnetic lineations with zero age.

The actual classification in Table 1 was made using the references indicated in the legend of Figure 1. Figure 1 summarizes this information regarding the time and rate of opening.

Typical examples of the actively spreading back-arc basins are the Mariana Trough and the Lau Basin. Among those that are supposed to be actively spreading, magnetic lineations of very young age have been documented for the Scotia Sea. On the whole, the magnetic lineations in the back-arc basins are much less well developed than those in oceans [Watts and Weisell, 1975; Weisell and Watts, 1975; Kobayashi and Isezaki, 1977; Lawver and Hawkins, 1978], suggesting that either the mode of spreading in the two cases is different or the back-arc spreading corresponds to the very early stage of oceanic spreading.

The Fiji Plateau, behind the New Hebrides arc, satisfies the above criteria for an active back-arc basin, but there the polarity of the subduction is anomalous; polarity reversal occurred in the late Miocene (10 m.y. B.P.), when the Ontong Java Plateau collided with the now extinct trench [Chase, 1971;

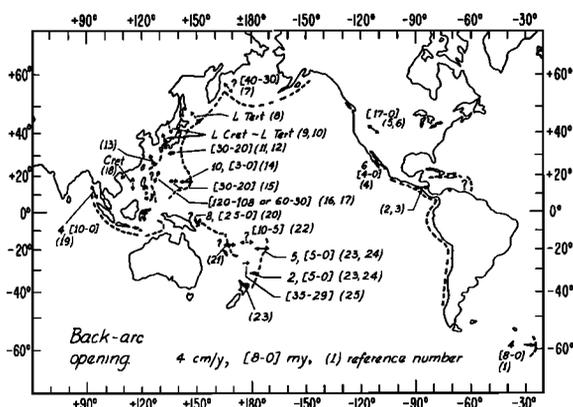


Fig. 1. Summary of back-arc opening activities. Reference numbers are as follows: 1, Barker and Griffiths [1972]; 2, Malfait and Dinkelman [1972]; 3, Plafker [1976]; 4, Larson [1972]; 5, Scholz *et al.* [1971]; 6, Christiansen and Lipman [1972], Smith [1977]; 7, Cormier [1975]; 8, Belousov [1968]; 9, Hilde and Wageman [1973]; 10, Uyeda and Miyashiro [1974]; 11, Tomoda *et al.* [1975]; 12, Watts and Weisell [1975]; 13, Herman *et al.* [1979]; 14, Karig [1971a]; 15, Heezen *et al.* [1971]; 16, Loudon [1976]; 17, Shih [1978]; 18, Ben-Avraham and Uyeda [1973]; 19, Curray *et al.*, [1979]; 20, Connelly [1976]; 21, Karig and Mammerickx [1972]; 22, Chase [1971]; 23, Karig [1970]; 24, Karig [1971b]; and 25, Weisell and Watts [1975].

been concentrated on the central portions of plates rather than on peripheral areas.

A compilation of the published results of the few available source mechanism solutions is shown in Figure 2. In the Chilean and Peruvian arcs, the mechanisms of upper plate shallow earthquakes obtained by *Stauder* [1973, 1975] are mostly thrust and strike slip, but the direction of the compressional stress in both cases is perpendicular to the strike of the arc (Figure 2). The situation is the same for the Kurile and Japan arcs, which have inactivated back-arcs. On the other hand, upper plate shallow earthquakes in the typically active back-arc basins, such as Mariana Trough, Lau Basin, and Andaman Sea, and in similar types of regions, such as the Gulf of California, the Basin and Range Province, and Middle America, show normal faulting. Here again, there are strike slip earthquakes in these regions, but the directions of compression and tension are consistent with those inferred from the normal fault events. Immediately behind the New Hebrides arc, the one available solution is a reverse fault [*Chung and Kanamori, 1978*] and argues against the active opening of this area. In view of general evidence for extensional features in the back-arc region [*Dugas et al., 1977*], the New Hebrides arc is an enigma for us at this moment. The stress arrows immediately behind the Aleutians and in the middle of the Bering Sea are estimates, based on the distribution of flank eruptions, which can be considered as natural hydrofractures [*Nakamura et al., 1977*]. The stress is compressional in the immediate back-arc, as expected for an inactive back-arc, but that in the Bering Sea is tensional. A tensional earthquake mechanism was reported in the western tip of Alaska [*Sykes and Sbar, 1974*]. This may mean that the compressive stress in the volcanic arc is not transmitted several hundred kilometers inward, or there is an intrinsic mechanism that generates a tensional tectonic stress regime behind the arcs [*Scholz et al., 1971*; K. Nakamura, private communication, 1977]. Although the amount of information is small and there are arcs, like the Scotia and Sunda arcs, where no information is available, it appears that tensional and compressional stress regimes dominate in the active and inactive back-arc regions, respectively. In the following, we will call these two types of back-arc regions 'Mariana' type and 'Chilean' type for simplicity.

INTERPLATE EARTHQUAKES AND MODE OF SUBDUCTION

Why are there different stress regimes behind subduction boundaries? Could this difference be caused by some important difference in the subduction process itself? Interplate thrust type earthquakes, that are caused by interaction between the subducting and overthrusting plates, should provide pertinent information on this point. As is well known, a majority of the earthquakes that occur are interplate thrust events at subduction boundaries. An examination of world seismicity maps [e.g., *Barazangi and Dorman, 1969, Tarr, 1974*] shows that epicenters are more or less evenly distributed along subduction boundaries. No systematic difference is obvious between the Mariana and Chilean type boundaries. The same is true for the convergence rate at the boundaries (Figure 3): Although the convergence rate seems higher at Chilean type boundaries than at Mariana type ones, the distinction is not completely clear.

The distinction is, however, very clear in the rate of earthquake energy release. To demonstrate this, we use the seismic energy released in great earthquakes. The conventional earthquake magnitude, M , [*Gutenberg and Richter, 1954*] suffers saturation for great earthquakes ($M > 7.5$) and becomes un-

TABLE 2. Ten Greatest Earthquakes During 1904–1976

Earthquake	Year	M_s	M_w	W_0
Chile	1960	8.3	9.5	1.1×10^{26}
Alaska	1964	8.4	9.2	4.0×10^{25}
Aleutian Islands	1957	8.25	9.1	2.8×10^{25}
Kamchatka	1952	8.25	9.0	2.0×10^{25}
Ecuador	1906	8.6	8.8	1.0×10^{25}
Aleutian Islands	1965	7.75	8.7	7.1×10^{24}
Assam	1950	8.6	8.6	5.0×10^{24}
Kurile Islands	1963	8.1	8.5	3.5×10^{24}
Chile	1922	8.3	8.5	3.5×10^{24}
Banda Sea	1938	8.2	8.5	3.5×10^{24}

suitable as the meaningful scale of the size of earthquakes. This happens when the size of the rupture surface becomes comparable or larger than the wavelength of the seismic wave used for M determination. For such a great earthquake, since more energy is released by lower-frequency waves, the 'energy' meaningful to tectonics may better be estimated from static source parameters such as seismic moment. *Kanamori* [1977a] used this approach for the world's great earthquakes since 1904. The seismic moment ($M_0 = \mu \bar{D}S$, where μ is rigidity, \bar{D} is average displacement on the fault, and S is fault area) was evaluated for each great earthquake from long-period body wave, surface wave, free oscillation, and geodetic data, and the energy release W_0 was obtained by

$$W_0 = (\Delta\sigma/2\mu) M_0$$

where $\Delta\sigma$ is the stress drop. W_0 is considered to be a good estimate of the energy released in seismic waves. Using W_0 , a new magnitude M_w , which is meaningful even in the range $M \gtrsim 8.0$, was calculated using Gutenberg and Richter's formula:

$$\log W_0 = 1.5M_w + 11.8$$

Table 2 (from Table 2 of *Kanamori* [1977a]) lists the 10 largest earthquakes that occurred between 1904 and 1976. Two points should be noted: (1) These 10 large earthquakes released more than 90% of the world's total seismic wave energy released during 1904–1976, and (2) none of these really great earthquakes occurred at the Mariana type boundaries. This is true for the 40 largest earthquakes listed by *Kanamori* [1977a], which cover more than 95% of the total seismic energy (see Figure 4). Although there are a few great earthquakes in the Assam and Mongolia areas, all the truly great thrust interplate earthquakes occur exclusively at the Chilean type subduction boundaries. At the Mariana type boundaries, subduction must be going on essentially aseismically if the convergence rate shown in Figure 3 represents the present-day motion [*Kanamori, 1977b*]. Figure 4 shows that Chilean type boundaries have great earthquakes.

Thus, in general, at a Chilean type margin the slab appears to force itself into the mantle overcoming the strong resistive interaction with the upper plate, whereas in the Mariana type margin the slab falls into the mantle relatively freely. The gradation from the former to the latter may be observed in Figure 4 from Alaska to the Marianas via the Kurile, Japan, and Izu-Bonin arcs.

OTHER PHENOMENA POSSIBLY RELATED TO THE TWO MODES OF SUBDUCTION

The differences in the mode of subduction suggested in the previous section have other possible consequences. We will

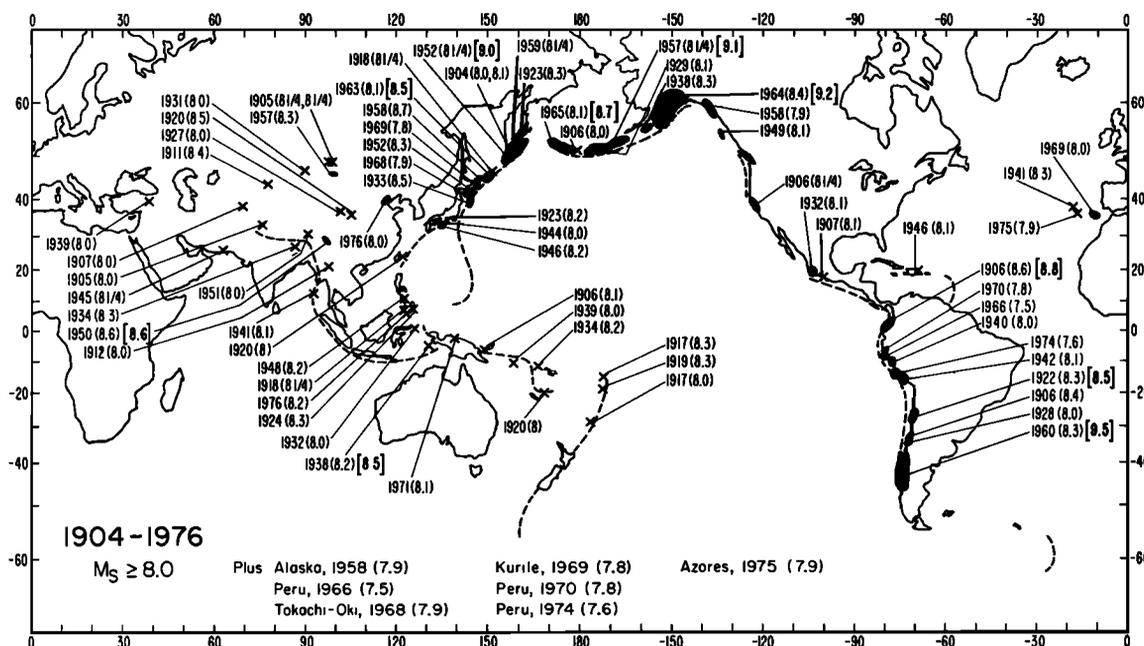


Fig. 4. Great earthquakes during 1904–1976 [after Kanamori, 1978]. Conventional magnitudes are in parentheses, and new magnitudes are in brackets. Black areas are rupture zones.

examine some of them in this section. They are, in our view, promising but need further elaboration to be conclusive.

Outer Gravity High and Outer Topographic Rise

It is well known that often there exist a positive gravity anomaly belt and topographic rise just outside of trenches. Hanks [1971] and Watts and Talwani [1974] interpreted these features as a result of the oceanic plate being compressed

horizontally before subduction. One feature to be noted is that both gravity and topographic highs are wide and prominent off the Aleutian and Kurile trenches but become gradually less wide and less prominent toward the south from the Japan trench to the Marianas trench [Watts and Talwani, 1974, Figure 1]. The previously noted similarity [Kanamori, 1977b] to the trend of diminishing great earthquakes is interesting. Outer gravity highs around the circum-Pacific region are summarized in Table 3 and Figure 5 [Getts, 1975; Watts et al., 1976]. Figure

TABLE 3. Outer Gravity High

Trench	References*	Outer Gravity High	Δg, mGal	Width, km
<i>Continental Arc</i>				
Peru-Chile	1, 2	Well developed south of 18°S	40–60	300–400
Middle America	1	Exists but not well defined		
Alaska	1, 3	Well developed	50	600
Sumatra-Java	1	Well developed	50	200
Nankai	1	Not clear
<i>Trapped Back-Arc</i>				
Aleutian	1, 3	Well developed	50–60	350–500
<i>Inactivated Back-Arc</i>				
Kurile	1, 3, 4	Well developed	40	300–400
Japan	1, 3	Well developed	30	300
<i>Leaky Transform</i>				
Andaman-Nicobar	1	Not developed
<i>Back-Arc Spreading</i>				
Mariana	1, 3	Not developed		
Tonga	1, 3	Not developed north of 24°S	40–20	70
Kermadec	1, 3	Developed		
Ryukyu	1, 3	Not developed	–30	100
<i>Unidentified</i>				
Bonin	1, 3	North, developed; south, not developed	40	150
Philippine	1, 3	Well developed	60	400

*References are 1, Watts and Talwani [1974]; 2, Getts [1975]; 3, Watts et al. [1976]; and 4, Hanks [1971].

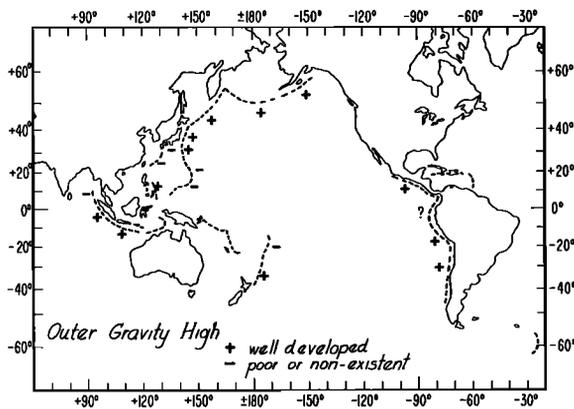


Fig. 5. Distribution of trench outer gravity high [after *Watts and Talwani, 1974; Getts, 1975; Watts et al., 1976*].

5 shows substantial correspondence with the two modes of subduction.

We realize that there are problems in both observations and models of the outer gravity and topographic highs [e.g., *Caldwell et al., 1976*]. Therefore, although the first-order effect may be meaningful, final conclusions must await further investigation.

Dip of Benioff-Wadati Zones

The dip of Benioff-Wadati zones may be shallower for the Chilean type subduction than for the Mariana type subduction. Simplified Benioff-Wadati zones from various sources including *Isacks and Barazangi [1977]*, are shown in Table 4 and Figure 6, in which mainly features deeper than 100 km are represented. When the Benioff-Wadati zone is shallow, as in the case of the Andaman-Nicobar, Middle America, Aleu-

tians, Alaska, and Lesser Antilles, features shallower than 100 km are shown, but the problems related to the shallower features [*Karig et al., 1976*] will be touched upon later. Figure 6 testifies that the dip of the Benioff-Wadati zone is definitely shallow for the Peru-Chile arc and Sumatra arc and deep for the Mariana, Kermadec, and Scotia (not well constrained) arcs. Here again, the grouping typified by the Chilean and Mariana arcs seems to hold.

Some arcs, that are considered to have inactive back-arcs, also have steep Benioff-Wadati zones: for example, Java, New Britain, Philippine, Solomon and possibly New Hebrides arcs. However, these Benioff-Wadati zones tend to be discontinuous in the direction of dip as indicated by broken lines in Figure 6. This may mean that the downgoing slab is disrupted in these subduction zones.

Nature of Volcanism

The compositions of volcanic rocks are different for different tectonic settings [*Miyashiro, 1975*]. Generally speaking, the representative volcanics are midoceanic ridge type tholeiites at diverging boundaries, alkali basalts and tholeiites in midplate volcanism, and andesites in addition to tholeiites at converging boundaries. The origin of andesite itself is one of the major problems in igneous petrology, but here we attempt to compare the abundance of andesites for different subduction boundaries. The reason for such a comparison is that, for example, in western North America, andesitic volcanism was dominant in early Tertiary, when the west coast of North America was a subduction boundary; the volcanism changed to the basalt-rhyolite type after the collision of the Pacific-Farallon ridge with the then existing trench [*Dickinson, 1970*].

Scholz et al. [1971] suggested that the stress field changed from compressional to tensional in western North America

TABLE 4. Dip of Benioff-Wadati Zones

Arc	Approximate Position of Plate Boundary, deg	Strike of Section, deg	Maximum Depth, km	Dip, deg	References
Scotia	58°S, 24°W	EW	180	70	E. R. Engdahl, personal communication (1977)
South Chile	40°S, 72°W	N100°E	160	30	<i>Isacks and Barazangi [1977]</i>
Central Chile	30°S, 70°W	N100°E	150	11	<i>Isacks and Barazangi [1977]</i>
North Chile	20°S, 70°W	N70°E	290	30	<i>Isacks and Barazangi [1977]</i>
Peru	10°S, 78°W	N60°E	150	8	<i>Isacks and Barazangi [1977]</i>
Middle America	12°N, 87°W	N45°E	200	65	<i>Dewey and Algermissen [1974]</i>
Lesser Antilles	15°N, 60°W	EW	230	65	<i>Sykes and Ewing [1965]</i>
Alaska	59.5°N, 150°W	N73°W	150	55	<i>Lahr [1975]</i>
Central Aleutians	51°N, 180°E	NS	260	65	<i>Engdahl et al. [1977]</i>
Kuriles	45°N, 153°E	N40°W	650	50	<i>Engdahl et al. [1977]</i>
Northeast Japan	40°N, 144°E	EW	600	40	<i>Ishida [1970]</i>
Ryukyu	24°N, 126°E	N30°W	300	45	<i>Katsumata and Sykes [1969]</i>
Philippine (Mindanao)	5°N, 128°E	EW	600	55	<i>Hamilton [1974]</i>
Izu-Bonin	30°N, 143°E	N100°W	500	65	<i>Katsumata and Sykes [1969]</i>
Marianas	18°N, 148°E	EW	700	90	<i>Katsumata and Sykes [1969]</i>
Tonga	21°S, 173°W	N70°W	650	53	<i>Isacks and Barazangi [1977]</i>
Kermadec	33°S, 178°W	N70°W	550	65	<i>Isacks and Barazangi [1977]</i>
New Zealand	40.5°S, 177°E	N48°W	300	67	<i>Ansell and Smith [1975]</i>
New Hebrides	17°S, 167°E	N70°E	300, 530	70	<i>Isacks and Barazangi [1977]</i>
					<i>Dubois [1971]</i>
New Britain	6°S, 147°E	N40°W	200, 600	65	<i>Isacks and Molnar [1971]</i>
Solomons	6°S, 154°E	N40°E	150; 550 in northwest corner	70	<i>Isacks and Molnar [1971]</i>
Andaman	12°N, 92°E	EW	100	50	<i>Eguchi et al. [1979]</i>
Sumatra	5°S, 100°E	N60°E	200	30	<i>Fitch [1970]</i>
Java	10°S, 113°E	NS	300, 600	55	<i>Fitch [1970]</i>
Banda Sea	7°S, 130°E	N30°W	400	55	<i>Fitch [1970]</i>

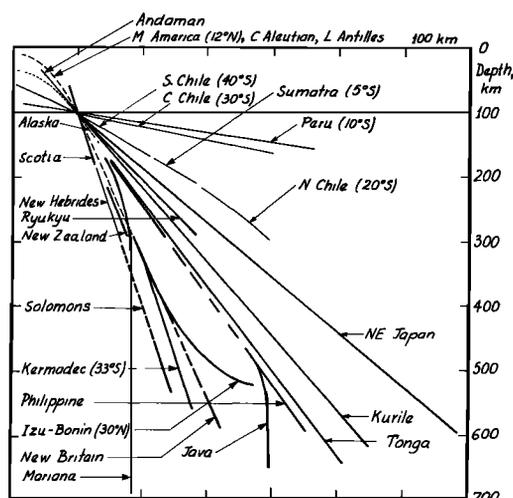


Fig. 6. Dip of Benioff-Wadati zones (after the references listed in Table 4).

when the Pacific-Farallon ridge collided with the subduction zone. The change in the nature of volcanism may be explained as follows (K. Nakamura, personal communication, 1977): The parental basaltic magmas can ascend and erupt more easily in a tensional stress field than in a compressional environment. In the latter situation, the magma, while forcing its way to the surface, tends to stay longer in the crust and is more prone to react with the surrounding rocks to produce andesitic rocks.

According to the synthesis of Miyashiro [1975], andesites are abundant in continental arcs and mature island arcs (island arcs with substantial continental crust, e.g., Japan), and rare in immature island arcs (island arcs without continental crust, e.g., the Marianas). Here we note that these correspond with our Chilean type and Mariana type arcs. This seems to suggest that the mode of development of arcs may also be controlled by the mode of subduction. In the Mariana type subduction boundaries, back-arc spreading will soon start to break the arc longitudinally [Karig, 1972], so that the arc becomes thin and pushed away from the continent, the source of terrigenous sediments, inhibiting the rapid growth of the accretionary prism (discussed later).

Sugisaki [1972, 1976] demonstrated that the abundance of andesite is controlled by the convergence rate: andesite is more abundant where the convergence rate is high. However, in his observation, the Tonga and Izu-Mariana arcs constitute notable exceptions where the convergence rate is high and andesite is scarce. Sugisaki's observation seems to be better explained by our interpretation.

Further, according to Nakamura *et al.* [1977], the structure of volcanoes is also dependent on the tectonic stress: large stratovolcanic edifices grow in the Chilean type environment, whereas small many monogenic volcanoes are found in the tensional environment. The series of monogenic cones in the Middle America arc are examples of the latter. Again, the difference is caused by the general ease of magma eruption under a tensional regime. These observations appear to confirm our notion of the two types of subduction, but certainly more thorough investigation is needed.

Sedimentary Structure on the Landward Wall of Trenches

It is now believed that an accretionary prism of sediments develops on the landward wall of trenches. The sediments are

probably of terrigenous origin or are scraped off pelagic sediments from the oceanic plate. The prism rises due to the compression and sometimes emerges above sea level to form the so-called outer arc such as Mentawasi Island off Sumatra and Middleton Island off the Aleutian Arc. Landward of the outer arc, sedimentary basins called deep sea terraces or fore-arc basins often develop. The development of those structures is controlled by various factors such as the supply of terrigenous material, the duration of subduction, and the history before the onset of subduction. Thus one would expect that the regional difference in the mode of subduction significantly affects the structure of the accretionary prism. In fact, the growth of accretionary prism appears more pronounced in our Chilean type boundaries than Mariana type ones [Karig and Sharman, 1975, Figure 5]. Often, one encounters exposures of basement in the wall of the latter type trenches. As a result of the growth of the sedimentary structure, the oceanic plate tends to be bent downward by the sediment load and thus creates the long shallow dipping slope at a shallow part (depth of <30 km) of the Benioff-Wadati zone [Karig *et al.*, 1976]. Karig and Sharman [1975] attribute the difference in the growth of fore-arc sedimentary structures to that of the sediment supply (supply rate times duration). Here we suggest that the difference in the mode of subduction may be an additional factor which gives rise to the difference in the structure of the accretionary prism. In the Chilean type boundaries, the strong mechanical coupling causes an extensive contortion and development of the accretionary prism, whereas in the Mariana type boundaries, because of the relatively weak coupling, subduction takes place without strong resistance from the upper plate, resulting in less contorted, or lack of, accretionary prisms. However, more detailed interpretation must await further investigations on the origin of the sediments that form the accretionary prism. The difference in the supply itself would, to a certain degree, ultimately be caused by the difference in the subduction mode as mentioned earlier, because the Mariana type arcs always tend to be at some distance from the continent.

As stated above, the outer arcs or frontal arcs are probably the raised sediments. Such a rise would have the same mechanism as that of the coastal uplifts estimated from coastal terraces and the actual coastal uplifts associated with major thrust earthquakes [Yonekura, 1975]. Such uplifts are also expected to be much more evident at the Chilean type subduction boundaries than the Mariana type. Although further investigations are required, preliminary literature surveys indicate that Quaternary coastal uplifts are prominent in Japan, Taiwan, Indonesia, western South America, Alaska, New Guinea, and New Hebrides [Ota and Naruse, 1977].

Although terraces are observed in Mariana and Tonga, the rate of uplift appears to be almost an order of magnitude smaller than in the Chilean type coasts [Taylor and Bloom, 1977; N. Yonekura, personal communication, 1978].

POSSIBLE MODELS OF THE TWO MODES OF SUBDUCTION

Summarizing the argument developed in the previous sections, there are two different modes of subduction. The extreme cases of each mode are represented by the Chilean arc and Mariana arc. At the Chilean type subduction boundaries, the mechanical coupling between the upper and lower plates is strong, whereas at the Mariana type boundaries the coupling is either much weaker or effectively nonexistent. The two types

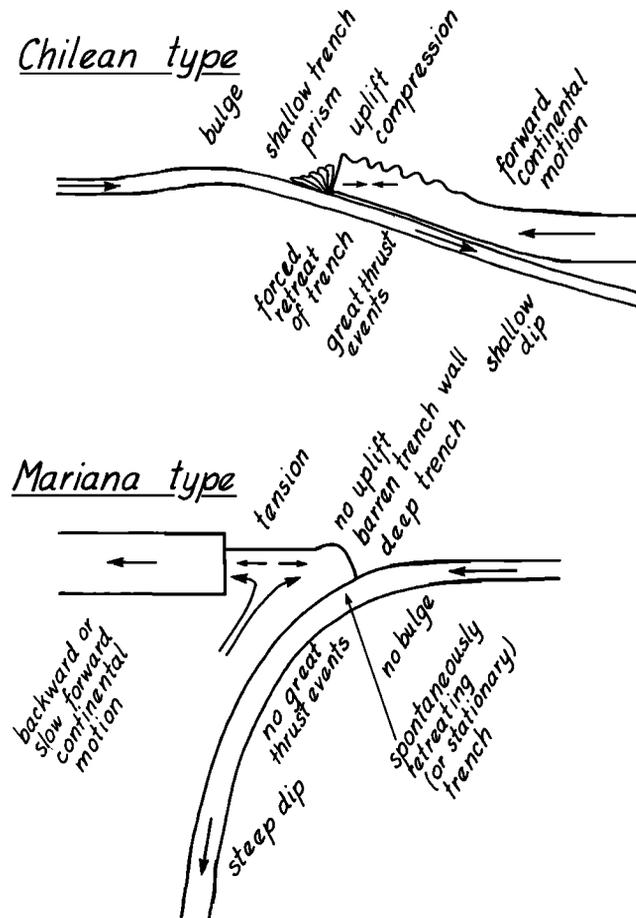


Fig. 7. Two kinds of subduction boundaries.

may be illustrated as shown in Figure 7. The difference in the subduction mode seems to be important not only for the problem of back-arc spreading but also for more general problems of orogeny.

Evolutionary Model

This model views the different modes of subduction as representing the different stages of a single evolutionary process of subduction [Kanamori, 1971a, 1977b]. As seen in Figure 8, the process of subduction starts with low-angle thrusting as in the case of the Alaska Trench. Here a wide contact zone between the upper and lower plates provides a strong coupling between the two plates, and great earthquakes occur at the interface. This is the mode that we call in this paper the Chilean type and that we regard as the first stage of subduction (Figure 8a). As the process goes on, the oceanic plate subducts to a greater depth in the mantle, and the contact interface is heavily fractured by repeating fault movements. This repeated fracturing may result in reduced coupling of the two plates through various processes such as formation of fault gouge, increased pore pressure, and possible partial melting. This may be the state of the Kurile arc (Figure 8b). If the process continues, the upper and lower plates will be almost completely decoupled so that there will be no more great earthquakes. The elongated tongue of the high-density slab will exert strong tension in the upper part of the slab to cause great normal fault intraplate earthquake (Figure 8c), like the 1933 Sanriku earthquake [Kanamori, 1971b]. Once decoupled, the slab may break by this type of intraplate earthquakes and sink

in pieces into the mantle. It may also be possible that under such circumstances, the oceanic plate loses its support at the end and starts sinking well before it reaches the trench. Such a collapse of the oceanic plate may lead to the formation of marginal seas (Figures 8d-8f). It has been suggested that the decoupling of the slab took place at the Ryukyu Trench at some time in the Tertiary and then the basins in the Philippine Sea were formed as the slab foundered and the trench retreated, as in the fashion suggested by *Elsasser* [1969] and *Moberly* [1972].

In such an evolutionary model, some explanation is needed to explain why progressively advanced stages are found successively from Alaska to the Ryukyu arc. One explanation is that as the subduction rate increases progressively from north to southwest along the northwestern Pacific margin, the evolutionary process has proceeded more rapidly along the margin. This explanation, however, may not apply to the South American margin, where a relatively early evolutionary stage is suggested in our model, yet the plate has been subducting for a long time with a high rate. It is possible that as *Molnar and Atwater* [1978] suggested, the age of the subducted plate is another factor that affects the mode of subduction.

Anchored Slab Model

This model is an alternative to the evolutionary model. The basic idea is very simple and similar to the one proposed by *Moberly* [1972] and *Hyndman* [1972]. It even resembles one of *Wegener's* [1924] postulates that marginal seas form in the rear of advancing continent.

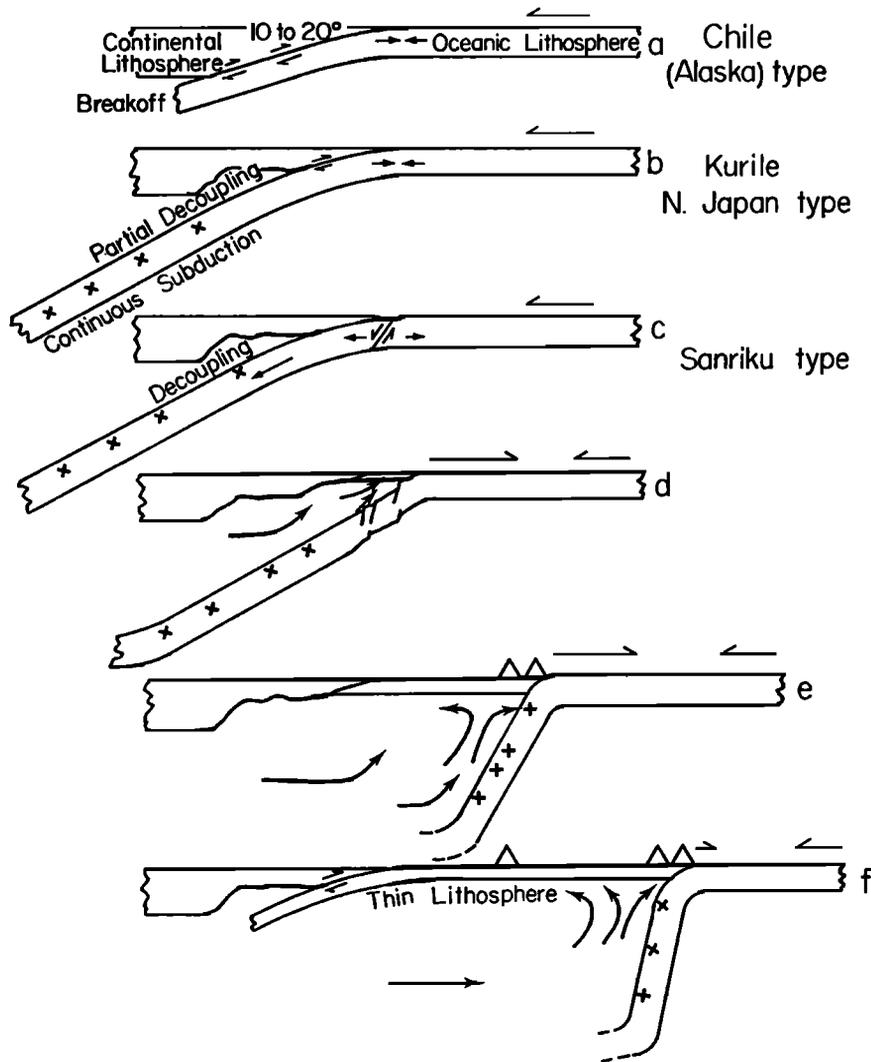


Fig. 8. Evolutionary model [Kanamori, 1977b]. (a) Strong coupling between the oceanic and continental lithospheres results in great earthquakes and breakoff of the subduction lithosphere at shallow depths. (b) Partial decoupling results in smaller earthquakes and continuous subduction. (c) Further decoupling results in aseismic events and intraplate tensional events. (d) Sinking plate results in retreating subduction and formation of a new thin lithosphere. (e) Episodic retreat and formation of ridges. (f) Decelerated retreat and commencement of new subduction.

Referring to Figure 9, three velocities, V_L , V_U , and V_T , are defined. V_L and V_U are the velocities of the lower and the upper plates, respectively. V_T is defined as the velocity of point T where the lower plate starts deflecting downward, i.e., the position of trench. The back-arc spreading can be formulated in terms of V_U and V_T . Namely, the condition for the back-arc

to open is $V_U < V_T$. In this model, V_L is not important except that V_U must exceed V_L for the boundary to be convergent. At this point, we assume that the position of the trench is fixed to the mantle. This assumption seems reasonable because it would be very difficult for the slab to move in the direction perpendicular to the strike of the trench. Thus the slab acts as an anchor [Talwani, 1969; Tullis, 1972]. In a frame of reference fixed to the mantle, we may put $V_T = 0$. In this case, the criterion for opening of back-arc basin would become

Opening

$$V_U < 0$$

Not opening

$$V_U > 0$$

This criterion is testable if we know the plate motions relative to the mantle, or 'absolute motions.' Figure 10 shows the absolute motions of upper plates at subduction zones computed from model AM1 of Minster *et al.* [1974]. Absolute motion of the Philippine Sea plate is not well determined,

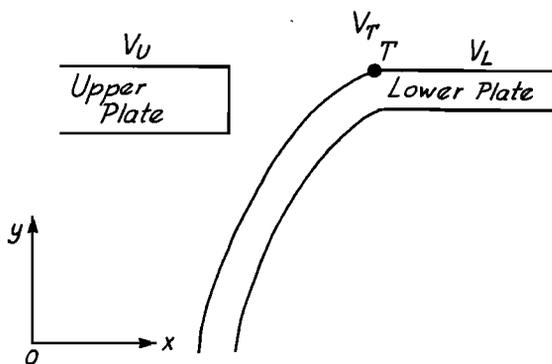


Fig. 9. Anchored slab model.

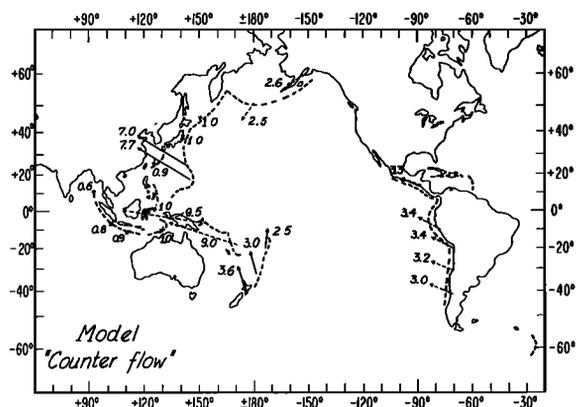


Fig. 12. Velocity vectors of landward (upper) plates relative to trenches in counter flow model. Units are centimeters per year.

CONCLUSIONS

Subduction plate boundaries can be classified into two groups according to whether their back-arc regions are actively spreading or not. The typical cases are the Mariana and the Chile boundaries. Intraplate earthquake mechanisms show that these two classes of back-arc regions are actually under tensional and compressional tectonic stresses. Great thrust type interplate earthquakes are occurring only along the latter type of subduction boundaries, indicating that there is a significant difference in the degree of coupling of the upper and lower plates between the Mariana type and the Chilean type boundaries. This in turn indicates that the mode of subduction is different in the two cases. The different cases are interpreted as caused by either differences in the stage of subduction process (evolutionary model) or differences in the motion of the landward plate (anchored slab model).

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