SEISMIC AND ASEISMIC SLIP ALONG SUBDUCTION ZONES AND THEIR TECTONIC IMPLICATIONS

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Abstract. Results of detailed mechanism studies of great earthquakes are used together with their repeat times to determine the amount of seismic slip along various subduction zones. Comparison of the seismic slip with the rate of plate motion suggests that, in Chile, and possibly Alaska, the seismic slip rate is comparable to the rate of plate motion while, in the Kuriles and Northern Japan, the seismic slip constitutes only a very small portion, approximately 1/4, of the total slip. In the Sanriku region, and to the south of it, the relative amount of seismic slip is even smaller. These results suggest that in Chile and Alaska the coupling and interaction between the oceanic and continental lithosphere are very strong, resulting in great earthquakes with a very large rupture zone, and in break-off of the undergoing lithosphere at shallow depths. In the Kuriles and Northern Japan, the oceanic and continental lithosphere are largely decoupled, so that the slip becomes largely aseismic, and the rupture length of earthquakes reduced. The reduced interaction at the inter-plate boundary may allow the oceanic lithosphere to subduct more easily and to form a continuous Benioff zone extending to depths. It may also facilitate ridge subduction beneath island arcs, which may play an important role in the formation of marginal seas such as the Japan Sea. The decoupling is also evidenced by silent or tsunami earthquakes [e.g., the 1896 Sanriku earthquake], great intra-plate normal-fault earthquakes [e.g., the 1933 Sanriku earthquake], and crustal deformation. A natural extension of this concept of inter-plate decoupling is the spontaneous sinking of the oceanic lithosphere with a consequent retreating subduction. Retreating subduction may be an important mechanism in the formation of marginal seas such as the Philippine Sea, and explains the complete lack of major shallow earthquake activity along some subduction zones such as the Izu-Bonin-Mariana arc.

Introduction

In the theory of plate tectonics, lithospheric subduction is one of the major tectonic processes related to the formation and evolution of island arcs. The deep and intermediate earthquake zones along island arcs delineate the geometry of the subducting lithosphere, and major shallow earthquake activity along island arcs is a manifestation of the mechanical interaction between the subducting and the overriding lithospheres. The geometrical agreement of focal mechanisms of earthquakes along the Circum-Pacific belt led McKenzie and Parker [1967] to the concept of rigid plates dividing the earth's surface. Isacks and Molnar [1969] used the geometry of the compression and tension axes of deep and intermediate earthquakes to infer the stress distribution in the descending lithosphere. Stauder [1968] found tensional mechanisms for earthquakes along the trench axis in the Aleutians and interpreted them as fractures due to bending of the oceanic lithosphere. Besides these geometrical arguments, studies of physical processes associated with large earthquakes provided important information concerning the dynamics of plate subduction [Plafker, 1972; Kanamori, 1971b; Abe, 1972]. Kanamori [1971b] proposed a model of gradual thinning and weakening of the ocean-continent lithospheric boundary to account for the differences in the maximum dimension of rupture zones among different island arcs. It was suggested that such differences in the coupling between the oceanic and continental lithospheres may control various tectonic processes at island arcs. The argument was based on detailed studies of great earthquakes through analysis of long-period surface waves (periods of 200 to 300 sec). Such long-period waves represent the overall crustal deformation at plate boundaries more directly than conventional short-period seismic waves. Kelleher et al. [1974] found a good correlation between the maximum dimension of rupture zones of great earthquakes and the width of the area of lithospheric contact at various subduction zones. This paper extends the previous paper [Kanamori, 1971b] by including more recent data from great earthquakes. Inclusion of these recent data strengthens the conclusions of the previous paper. It is almost certain that the degree of mechanical coupling (or decoupling) between the oceanic and continental lithospheres varies among different island arcs; along some subduction zones the coupling is very strong, so that the plate motion is almost entirely taken up by seismic slip. It is relatively weak elsewhere and the seismic slip represents only a very minor part of the plate motion. Along some subduction zones, the boundary is entirely decoupled and the plate motion seems to take place aseismically. It is proposed that such coupling and decoupling of plates may play an essential role in the evolution of island arcs and marginal seas.

Summary of Characteristics of Great Earthquakes along the Circum Pacific Belt

Figure 1 shows the rupture zones and the mechanisms of major earthquakes for which detailed studies were made by using long-period surface waves. Rupture zones of other major earthquakes have been mapped by Fedotov [1965], Mogi [1968a, b], Sykes [1971], and Kelleher et al. [1973]. Except for the 1933 Sanriku earthquake and the 1970 Peruvian earthquake, the mechanisms of these earthquakes suggest low-angle thrust faulting, which is consistent with the plate motion along the Circum Pacific belt. The 1933 Sanriku earthquake is an exceptionally large normal-fault earthquake which occurred beneath the axis of the Japan Trench [Kanamori, 1971a]. It is interpreted as a lithospheric normal-fault which cuts through the entire thickness of the lithosphere. The 1970 Peruvian earthquake is another normal-fault event [Abe, 1972] within the oceanic lithosphere. These two events are therefore intra-plate earthquakes and do not represent slip between the oceanic and continental lithospheres.

Two other important features in Figure 1 are (1) a remarkable regional variation of rupture lengths of great earthquakes despite their nearly identical earthquake magnitude, and (2) a nearly complete lack of large shallow activity along the Izu-Bonin-Mariana arc, despite its typical island arc features such as a deep trench, volcanic activity and a Benioff zone. Regarding (1), it is now widely known [e.g., Kanamori and Anderson, 1975] that earthquake magnitude M_S is not a meaningful parameter for very large earthquakes. The seismic moment M_O which represents the

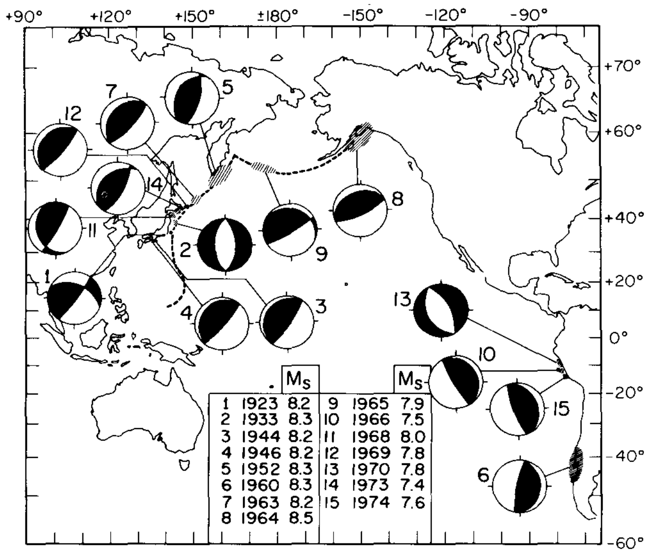

Figure 1. Mechanisms and rupture zones of large earthquakes along the Circum Pacific belt for which detailed studies of long-period waves have been made. Mechanism diagrams show the stereographic projection of the lower hemisphere. Dark and white quadrants indicate compression and dilatation respectively. References are: 1923 Kanto [Kanamori, 1971c]; 1933 Sanriku [Kanamori, 1971a]; 1944 Tonankai [Kanamori, 1972a]; 1946 Nankaido [Kanamori, 1972a]; 1952 Kamchatka [Kanamori, 1976]; 1960 Chile [Kanamori and Cipar, 1974]; 1963 Kurile Is. [Kanamori, 1970a]; 1964 Alaska [Kanamori, 1970b]; 1965 Rat Is. [Wu and Kanamori, 1973]; 1966 Peru [Abe, 1972]; 1968 Tokachi-Oki [Kanamori, 1971d]; 1969 Kurile Is. [Abe, 1973]; 1970 Peru [Abe, 1972]; 1973 Nemuro-Oki [Shimazaki, 1975a]; 1974 Peru [unpublished].

overall amount of displacement at the source is a more adequate parameter for the present discussion. Great earthquakes in Chile, Alaska, the Aleutians, and Kamchatka have very large rupture lengths and very large M_O ranging from 10^{29} to 10^{30} dyne-cm, while earthquakes in Peru and Japan have small rupture lengths and M_O, about 10^{28} dyne-cm. Kanamori [1971b] and Kelleher et al. [1974] argued that this remarkable difference in the characteristics of great earthquakes reflects regional differences in the contact zone between the oceanic and continental lithospheres. As regards (2), two mechanisms are possible. First, as a result of weakening and decoupling at the interface, the subduction has become nearly completely aseismic. In this case, the subduction is still taking place but without any major seismic activity. The second mechanism involves a buoyant oceanic lithosphere [Vogt, 1973; Kelleher and McCann, 1976]; part of the oceanic lithosphere is less dense than elsewhere and is not capable of subducting under the opposing lithosphere, and little or no subduction is now taking place. This mechanism is attractive in that it explains the arcuate feature of island arcs, some of the characteristic distributions of large earthquakes and volcanoes along island arcs and the regional variations in the shape of the Benioff zone [Kelleher and McCann, 1976]. However, these geometrical arguments alone are not enough to fully evaluate these possibilities. It is hoped that recent progress in long-period seismology will provide more direct clues to the understanding of these problems.

Seismic and Aseismic Slip

Among various subduction zones, historical earthquake data is most complete for southwest Japan. It is well known that along the Nankai trough in southwest Japan (Figure 2), large earthquakes have occurred very regularly in time (about once every 125 years) and space [Imamura, 1928; Ando, 1975a]. This regularity in time and space may justify the use of relatively recent data in estimating the seismic slip rate along various other subduction zones.

For Chile, along the rupture zone of the 1960 great Chilean earthquake, historic records suggest a repeat time of the order of a century [Lomnitz, 1970, Kelleher, et al., 1973]; large earthquakes occurred in 1970, 1837, 1737, and 1575. If we assume that these earthquakes involved a slip which is comparable, on the average, to that of the 1960 event (about 20 to 25 m), we can estimate the seismic slip rate. The amount of slip associated with the 1960 event is estimated on the basis of geodetic data [Plafker, 1972] and long-period surface-wave data [Kanamori and Cipar, 1974]. Dividing the seismic slip in each event by the repeat time gives the seismic slip rate. Figure 3a compares the seismic slip rate thus determined and the rate of relative plate motion between the South American plate and the Nazca plate, which is estimated to be about 11 cm/year [Morgan et al., 1969; Minster et al., 1974]. An uncertainty of ± 30% is attached to the estimate of the seismic slip. Although the plate slip rate seems to be slightly smaller than the seismic slip, this discrepancy is not significant in view of the large uncertainty in the magnitude of historical events. To the first order of approximation, we may conclude that the seismic slip rate is about the same order of magnitude as the rate of the plate motion.

For Alaska, there are no historical earthquake data from which we can estimate the repeat time. Plafker [1972] suggests on the basis of geomorphological data a repeat time

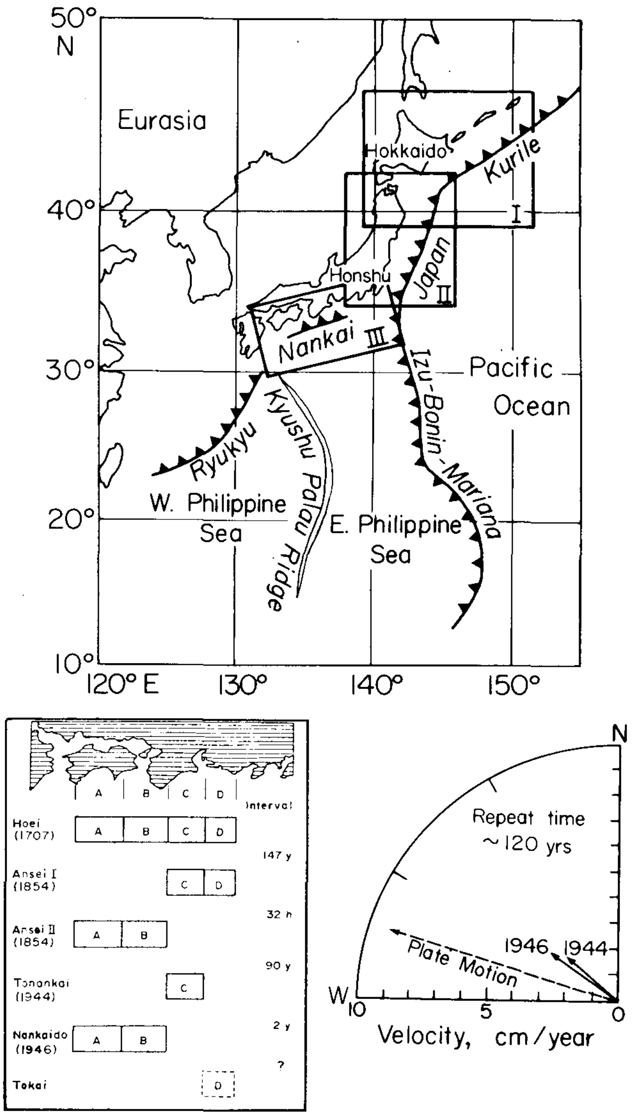

Figure 2. Index map (left) and historical seismicity along the Nankai trough, southwest Japan (Box III in the index map). Major earthquakes occurred in 1498, 1605, 1707, 1854, and 1944 to 1946 along this plate boundary. The last three sequences are shown in the upper right figure [after Ando, 1975a]. Arrows indicate the direction and the rate of seismic slip and the plate motion.

of 900 to 1350 years. There was a sequence of large earthquakes around the turn of the century near the rupture zone of the 1964 Alaskan earthquake [Sykes, 1971], but it is not very clear whether they occurred on the same fault as the 1964 event or not. If they indeed occurred on the same fault, the repeat time may be as short as 60 years, but Plafker's argument does not support it.

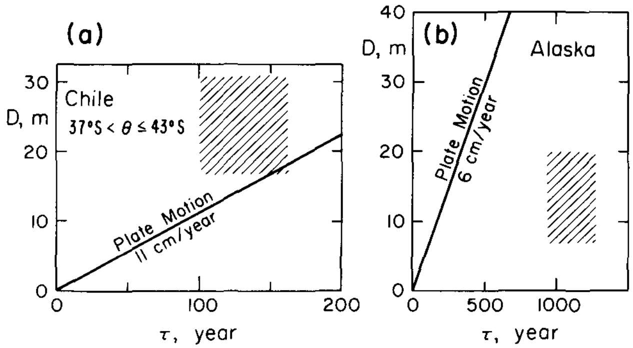

Figure 3. Seismic slip, repeat time of major earthquakes and the rate of plate motion for Chile and Alaska. Hatching indicates the range of seismic slip and the repeat time.

Along the Aleutian islands, the seismic activity is very high, and there seems to be two major seismic sequences during the past 60 years or so [Sykes, 1971; Anderson, 1974], one around the turn of the century and the other between 1957 and 1965. In view of this very high activity, a repeat time of about 1000 years seems somewhat too long. Figure 3b compares the seismic slip and the plate motion for Alaska. Plafker's [1972] repeat time of 930 to 1350 years is used. With this repeat time, the slip rate of the plate motion, 6 cm/year [LePichon, 1968; Minster et al., 1974] is several times larger than the seismic slip. However, if the repeat time is 60 years, the seismic slip becomes too large. If the repeat time is about 200 years or so, the seismic slip and the plate motion become comparable. In view of the fairly high seismic activity along the Aleutians, a repeat time of 200 years or so does not seem unreasonable, but the lack of reliable historical data does not permit more detailed discussion.

For the region from the Kurile Islands to Hokkaido, Japan, the historical data are more complete (Box I in Figure 2). As shown in Figure 4, during the 21 years from 1952 to 1973, six large earthquakes ($M_S > 7.5$) occurred along the arc, filling the entire seismic belt. Except for the 1958 event, detailed mechanism studies have been made for these events (for reference, see caption for Figure 1). These studies indicate that each of these earthquakes represents a slip of 2 to 3 m on a low angle thrust fault dipping 10 to 20 degrees NW (Figure 4). The slip direction agrees approximately with that of the Pacific plate with respect to the Eurasian plate. Thus, it is suggested that the Pacific plate subducted during the last 21 year period by 2 to 3 m along this plate boundary. Historical seismicity in this area shows that there was another sequence of major earthquakes along this zone from 1843 to 1918, as shown in Figure 4, indicating a repeat time of approximately 100 years [Utsu, 1972; Usami, 1966]. The seismic slip rate is therefore estimated to be 2.5 m/100 years = 2.5 cm/year, which is only 1/4 of the rate of the plate motion in this region, 9 cm/year [Minster et al., 1974]. Thus we may conclude that approximately 3/4 of the total slip must be taken up by aseismic slip, if the plate motion is uniform on this time scale. Independent evidence for such aseismic slip is found in the crustal deformation in Hokkaido. Figure 5 shows the subsidence in a coastal area of Hokkaido during the period from 1900 to 1955. Shimazaki [1974a] interpreted this subsidence to be the result of the drag caused by the underthrusting oceanic lithosphere. Shimazaki found that this subsidence can be explained if the continental lithosphere beneath Hokkaido is dragged at a rate of 2.7 cm/year. Since the rate of plate motion is 9 cm/year, this result suggests that about 3/4 of the slip takes place without causing crustal deformation, the interface being largely decoupled mechanically. Although the estimate of the seismic slip and the amount of the drag may be subject to some error, it is almost certain that a large part of the plate motion is taking place aseismically in the Kurile-Hokkaido region.

Farther to the south, in the Sanriku region (Box II in Figure 2), the evidence is more striking. In this region, two major earthquakes occurred in recent years, in 1896 (many large aftershocks occurred for several years following this event) and 1933 (Figure 6). Before 1896, only three major earthquakes are known to have occurred, in 1677, 1611, and 869 [Usami, 1966]. Although the historical data may not be very complete, it is clear that there is not a continuous zone of frequent thrust earthquake activity between the trench and the coast in this region (see Figure 6). As mentioned earlier, the 1933 event is a normal fault event with-

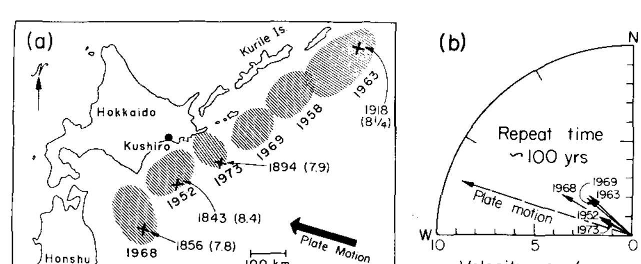

Figure 4. Seismicity, seismic slip and the plate motion in the Kurile Is.-Hokkaido region (Box I in Figure 2). Arrows indicate the direction and the rate of seismic slip and the plate motion.

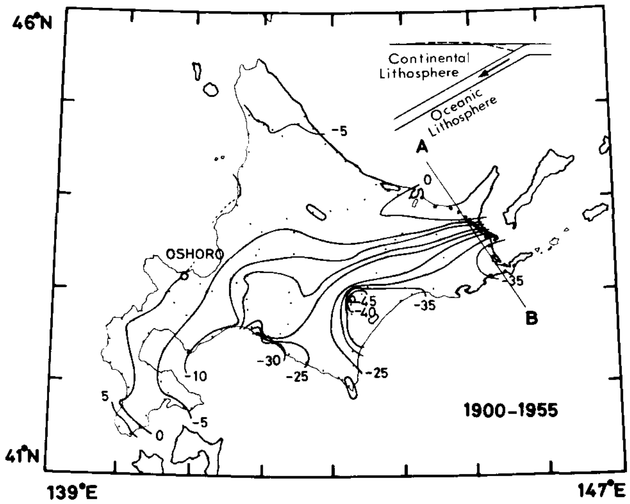

Figure 5. Vertical crustal deformation in Hokkaido, Japan, during the period 1900 to 1955 (unit:cm). Shimazaki's [1974a] model is schematically shown in the inset. Dotted curve shows the deformation due to the drag of the undergoing oceanic lithosphere.

in the oceanic lithosphere, which does not represent slip on the inter-plate boundary. The location of the 1896 Sanriku earthquake is not known accurately, but macro-seismic data and some instrumental data strongly suggest that this is a tsunami earthquake, or, in more general terms, a silent earthquake [Kanamori, 1972b]. A tsunami earthquake refers to an earthquake which generates very extensive tsunamis but relatively weak seismic waves, indicating that a very slow source process is involved. The 1896 event generated one of the most disastrous tsunamis in Japanese history while its earthquake magnitude is only 7 to 7 1/2. It is suspected that this earthquake represents a large aseismic event. It is interesting to note that tsunami earthquakes occasionally occur in the Hokkaido-Kurile region too, although they are not as striking as the 1896 Sanriku earthquake. Shimazaki [1975b] found a very low stress drop earthquake (therefore of aseismic character) which occurred in 1968 within the fault zone of the major 1969 Kurile Island earthquake (Figure 4), thereby contributing significantly to the overall plate motion along the Kurile arc. Another striking example is shown in Figure 7. On June 10, 1975, a $M_s = 7.0$ ($m_b = 5.8$) earthquake occurred within the rupture zone of the 1969 Kurile Island earthquake. This earthquake was followed by an aftershock on June 13, 1975, which occurred essentially at the same location as the main shock. Figure 7 compares the seismograms of the main shock and the aftershock recorded by short-period, intermediate period, and ultra-long period seismographs at Pasadena. On the short-period records, the aftershock is slightly larger than the main shock, but on the ultra-long period records, the main shock shows a very clear long-period phase while the aftershock has no energy in this frequency range. Similar results were found at Japanese stations [Suzuki and Sugimoto, 1975; Nagamune and Chiurei, 1976; Tsujiura, 1975] and WWSSN stations [Shimazaki, personal communication, 1976]. The long-period excitation of the main shock was anomalously large for an earthquake of this magnitude ($m_b \sim 5.8$). This earthquake generated a tsunami as high as 90 cm along the Japanese coast which is very anomalous for a $m_b \sim 5.8$ event. This event may be considered as a tsunami earthquake which reflects a weakened coupling between the oceanic and continental lithosphere there.

To the south of the Sanriku region, a series of moderate-size ($M_s \sim 7.1$ to 7.7) earthquakes (Shioya-Oki earthquakes) occurred in 1938 (see Figure 6). A recent detailed study by Abe [1976] showed that this sequence consists of three thrust and two normal-fault earthquakes having a total seismic moment of about 2 X 10^{28} dyne-cm. However, historical data suggest that there was no major earthquake in this region at least for the past

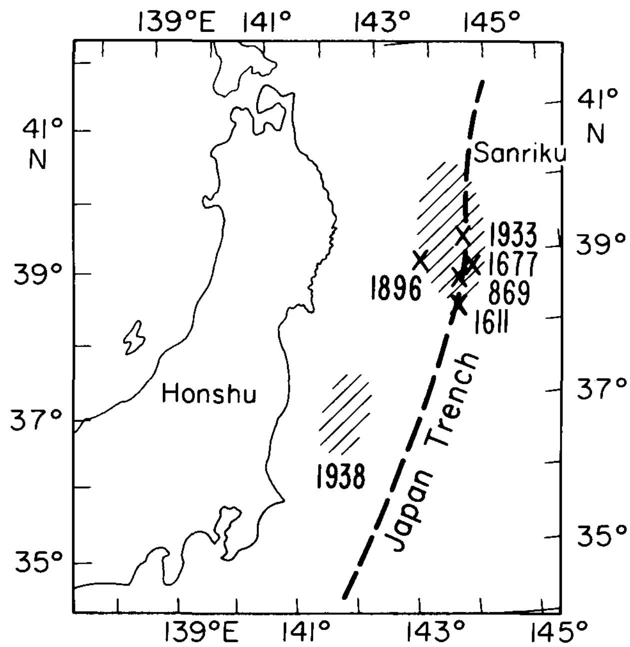

Figure 6. Sanriku earthquakes of 1896 and 1933 and Shioya-Oki earthquakes of 1938 [Abe, 1976] (Box II in Figure 2). Historical earthquakes larger than $M_s > 8.0$ between 36°N and 40°N are also included.

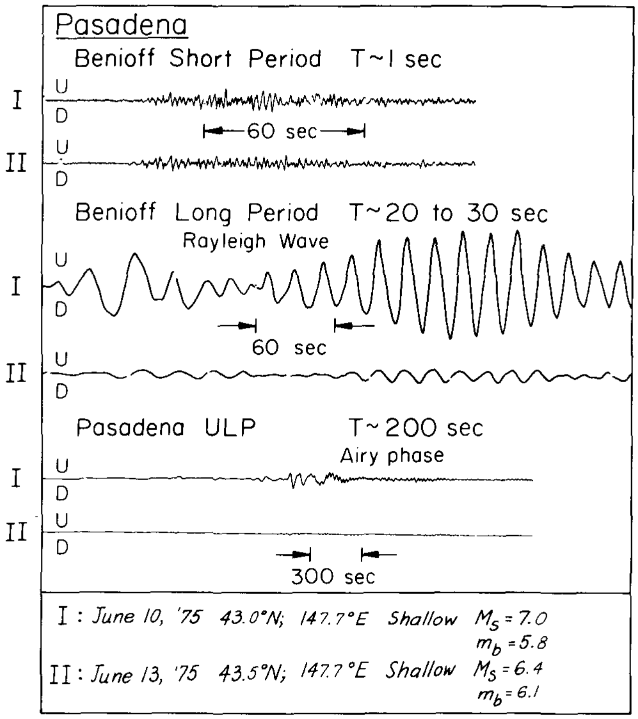

Figure 7. Seismograms of a tsunami earthquake recorded at Pasadena. The main shock on June 10, 1975 (tsunami earthquake) and one of the aftershocks on June 13, 1975 (regular earthquake) are compared at three different periods. Note that the amplitude ratio of the main shock to the aftershock becomes progressively larger as the period increases.

800 years. Abe [1976] concluded that the seismic slip rate there is about 0.4 cm/year suggesting that the plate motion is largely aseismic. This finding is very consistent with the above model of plate decoupling.

Along the Izu-Bonin-Mariana arc, there is no evidence for great earthquakes at shallow depths during this century [Gutenberg and Richter, 1954]. This lack of shallow activity, together with the foregoing arguments may lead one to the conclusion that the plate motion there is entirely aseismic. However, one difficulty arises. The Izu-Bonin-Mariana arc constitutes a boundary between the Pacific plate and the Philippine Sea plate. The Philippine Sea plate is subducting underneath southwest Japan along the Nankai Trough and the Ryukyu arc (Figure 2). The rate of the plate motion between the Pacific and the Eurasia plates has been determined to be about 9.2 cm/year [LePichon, 1968; Minster et al., 1974]. However, neither the slip rate between the Pacific and the Philippine Sea plates nor that between the Philippine Sea and the Eurasia plates is known independently. It is therefore necessary to consider the Nankai trough and the Marianas simultaneously. As shown in Figure 2, historical seismicity in this region shows a remarkably regular repeat time of major earthquake sequences along the Nankai trough [Imamura, 1928; Ando, 1975a]. The last three sequences are shown in the figure. The average repeat time is about 120 years. The amount of slip for each seismic event is about 2 to 5 m [Kanamori, 1972a, Ando, 1975b] indicating a seismic slip rate of about 3.5 cm/year. Since the seismic slip rate along the Marianas is practically zero, this value represents the total seismic slip rate between the Pacific and the Eurasia plates. Since the rate of plate motion is about 9 cm/year, the difference, 5.5 cm/year, must be absorbed either at the Marianas or along the Nankai trough as aseismic slip. If we include the possible inter-arc spreading [Karig, 1971] along the Marianas, the amount of aseismic slip would be even larger. Two extreme cases are possible: (1) The slip along the Nankai trough is largely seismic and that along the Marianas is aseismic. (2) There is little slip along the Marianas and the slip along the Nankai trough consists of 3.5 cm/year seismic and 5.5 cm/year or more of aseismic slip. There will also be cases which lie between these two extreme cases. In any event, it is important to note that a substantial part of the slip must be aseismic, if the plate motion is uniform on this time scale. If, as proposed by Kelleher and McCann [1976], the Pacific basin to the east of the Marianas is buoyant and the subduction along the Marianas has recently either decelerated or ceased, (2) would be the case. However, in view of the evidence for gradual decoupling of the plates in the Hokkaido and Sanriku regions, it seems natural to postulate complete decoupling as an important mechanism for the lack of major shallow activity along the Marianas. Although we prefer case (1) on these grounds, it is still possible that the buoyancy of the subducting lithosphere is playing an important role in modifying the mode of subduction along the Marianas. This point will be discussed further in relation to the origin of the Philippine Sea.

Model of Plate Coupling and Decoupling

On the basis of the seismological results presented in the previous section, a model of plate coupling and decoupling is proposed in an attempt to understand the fundamental physical mechanisms operating in various subduction zones. This model is basically the same as that proposed by Kanamori [1971b], but some refinements and modifications have been made on the basis of more recent data. The idea is schematically shown in Figure 8. Figure 8a shows the oceanic lithosphere which is underthrusting beneath the continental lithosphere and opposed by the latter. Because of its strength, the oceanic lithosphere is unlikely to bend very sharply and low-angle (10° to 20°) thrusting occurs. The stress in the oceanic lithosphere is compressive. We consider that this stage corresponds to the Chilean and possibly the Alaska type structure (if the repeat time is much shorter than the geomorphological evidence suggests). At this stage, the width of the contact zone is very large and the coupling is very strong, so that when slippage occurs it results in a major earthquake such as the 1960 Chilean earthquake, involving an extensive crustal deformation and

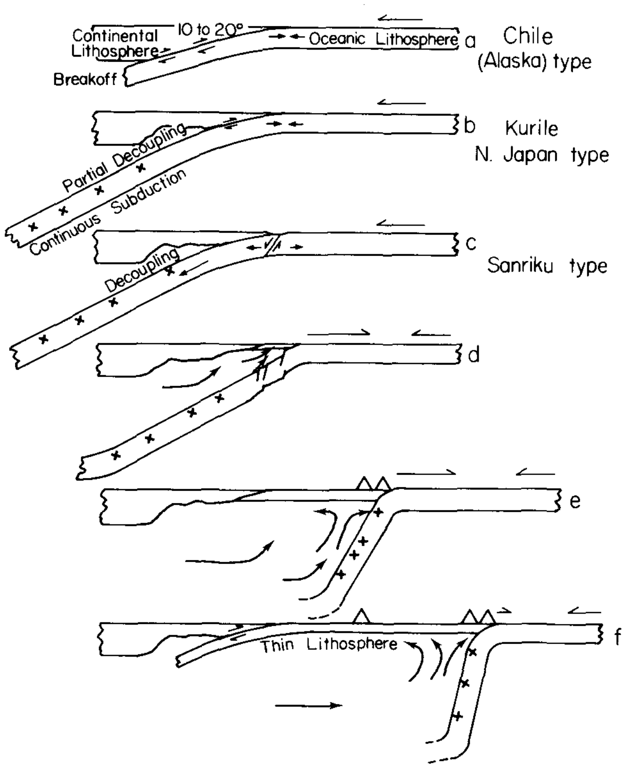

Figure 8. Schematic model of inter-plate coupling and decoupling, sinking and retreating subduction. a. Strong coupling between the oceanic and continental lithospheres results in great earthquakes and break off of the subducting lithosphere at shallow depths. b. Partial decoupling results in smaller earthquakes and continuous subduction. c. Further decoupling results in aseismic events and intra-plate 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.

rupture zone. The lack of deep earthquakes below 200 km in these regions may indicate an absence of the downgoing plate at these depths. It is possible that where the inter-plate coupling and interaction are very strong, the downgoing oceanic lithosphere itself is substantially fractured and tends to break off, at relatively shallow depths, into pieces which sink into the mantle.

As the underthrusting proceeds further, both the strength and width of the interface decrease because of various effects of the plate interaction such as extensive fracturing, formation of gouge, water injection, and possible partial melting (Figure 8b). This stage corresponds to the Kurile to Hokkaido region where the reduced coupling results in smaller rupture zones of earthquakes, large aseismic slip, and occasional occurrence of silent or tsunami earthquakes. The stress in the oceanic lithosphere is still compressive. Because of the reduced interaction at the inter-plate boundary, the oceanic plate can subduct smoothly, without breaking off into pieces, to form a well defined continuous deep seismic zone. Thus a continuous Benioff zone may be an indication of partially or completely decoupled lithospheric plates.

Subduction of a ridge, which is often considered to be a major tectonic event [e.g., Wilson, 1973; Uyeda and Miyashiro, 1974], may take place more easily under these conditions. When the interface is further weakened, the continental and the oceanic lithospheres are nearly completely decoupled so that no major thrust earthquake can occur along the interface (Figure 8c). Because of the reduced coupling, the tensional force caused by the gravitational pull of the denser downgoing lithosphere may be transmitted to the oceanic lithosphere and may cause a large intra-plate normal-fault earthquake. We consider that this stage corresponds to the Sanriku region. The 1896 tsunami earthquake and the 1933 lithospheric normal-fault earthquake reflect, respectively, the decoupling of the interface and the intra-plate tensional fracture [Kanamori, 1972b]. At this stage the stress within the oceanic lithosphere is largely tensional. The above process is in general consistent with the model proposed by Kelleher [1974], who showed that the width of the contact zone controls the maximum length of the rupture zones of great earthquakes in various island arcs.

After the plates are decoupled, several modes of deformation of the underthrusting lithosphere are possible. First, a complete detachment may take place in the form as suggested by Kanamori [1971b]. Second, the oceanic plate, having lost the mechanical support of the opposing continental lithosphere, may start sinking from the leading edge. Third, the above process may occur by discontinuous shear faulting, as suggested by Lliboutry [1969]. The overall pattern of the deformation may be similar between the second and third cases. In any event, once the plates are decoupled, there is no reason for them to be in contact. Although there is no seismological evidence that favors any particular one of these possibilities, the second or third one seems to explain more naturally the transition from the Sanriku type structure to the Izu-Bonin-Mariana type structure. In this case, the subduction zone retreats in the direction opposite to the direction of the plate motion as the leading edge sinks and falls off (Figure 8d). A counter flow may fill the opening between the continental lithosphere and the retreating subduction zone. This counter flow may take place in the form of episodic interarc spreading, with upwelling material eventually forming a thin lithosphere between the continental lithosphere and the retreating subduction zone (Figure 8e). Such a thin lithosphere has been found for the Philippine Sea by surface-wave studies [Kanamori and Abe, 1968; Seekins and Teng, 1976]. As this newly created lithosphere cools and becomes rigid, a new episode of subduction may commence at the boundary between this new lithosphere and the continental lithosphere (Figure 8f). The subduction along the Nankai trough, which is believed to have commenced very recently (1 to 4 m years ago) [Fitch and Scholz, 1971; Kanamori, 1972a], may correspond to this type. Once the relatively rigid lithosphere is formed, the coupling between this lithosphere and the oceanic lithosphere may be restored. Retreating subduction may be an important element in the formation of the Philippine Sea, and will be discussed more fully in the next section.

The above model is very consistent with the topographic and gravity highs seaward of trenches [Walcott, 1970; Hanks, 1971; Watts and Talwani, 1974]. A recent extensive study of Watts and Talwani [1974] is particularly intriguing in this context. Figure 9 shows some of the representative profiles perpendicular to the Aleutians, Kuriles, Bonin and Marianas. The topographic high and the gravity high are most conspicuous for the Aleutians and the Kuriles, but are not very obvious for the southern Bonin and Marianas. Watts and Talwani [1974] explained these features in terms of a flexural bending of the oceanic lithosphere due to compression and vertical loading at the trench. They found that a large compressive stress is required to explain the topographic and gravity highs for the Aleutians and Kuriles, but for the southern Bonin and Marianas, they can be

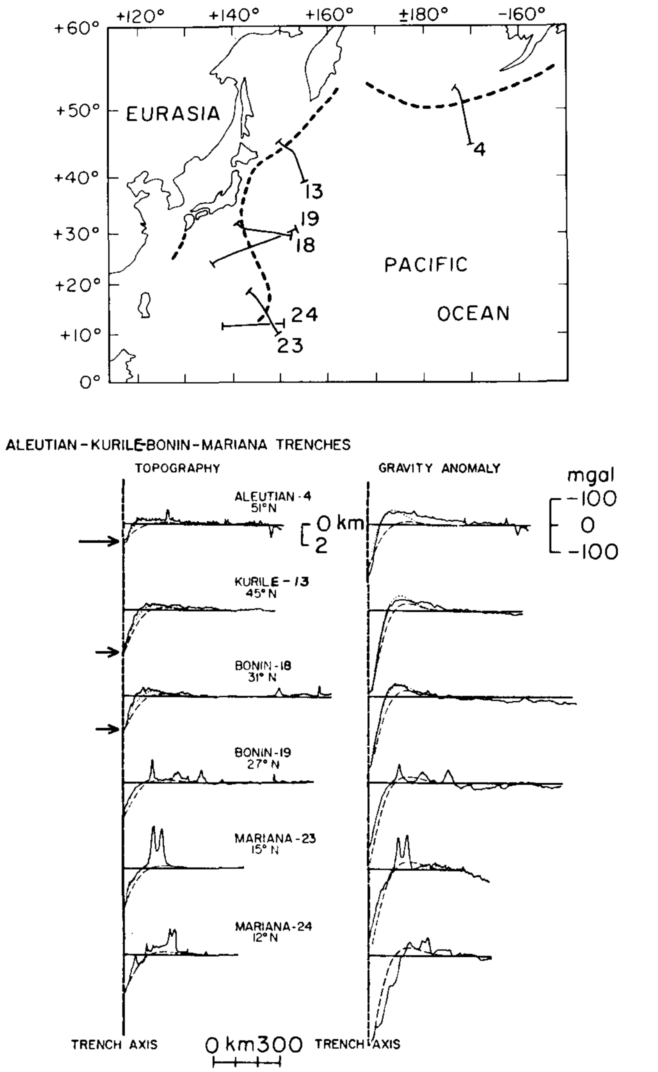

Figure 9. Topography and gravity anomaly along representative cross sections in the Pacific shown in the top figure. Solid curves show the observed profiles. Dashed curves are the profiles computed for a model with only vertical loading at the trench. Dotted curves are the profiles computed for a model with vertical loading and compression. The length of the arrows indicates the magnitude of the compressive stress [after Watts and Talwani, 1975].

explained without horizontal compressive stress; only vertical loading is necessary. Although the details may vary according to the assumptions, their results are qualitatively very consistent with the present model in which compressional coupling gradually weakens from the Aleutians to the Kuriles, and farther south to the Bonin-Marianas, where the plates are decoupled.

Retreating Subduction and the Philippine Sea

The Philippine Sea is a marginal sea between the Bonin-Mariana arc and the Ryukyu arc both of which are dipping westward (Figure 2). Several models have been proposed for the origin of the Philippine Sea [e.g. Karig, 1971; Uyeda and Ben-Avraham, 1972; Uyeda and Miyashiro, 1974]. Here we show how the concept of retreating subduction can be employed as one of the fundamental physical mechanisms of formation of island arcs and marginal seas. We take Uyeda and Ben-Avraham's [1972] model shown in Figure 10. Uyeda and Ben-Avraham [1972] postulated that the Kula-Pacific ridge subducted beneath Japan sometime in the late Cretaceous about 100 m years ago. As the Pacific plate changed its direction of motion from a NNW to a WNW direction, about 40 m years ago, subduction started along a transform fault which connected the Kula-Pacific ridge with the Philippine ridge (Figure 10). Subsequent interarc spreading as suggested by Karig [1971] along this subduction zone formed the present day Philippine Sea. It is assumed in this model that the direction of motion of the Kula plate did not change when the Pacific plate changed its direction of motion to allow subduction of the Pacific plate beneath the Kula plate. This assumption seems somewhat ad hoc. Introduction of a retreating subduction zone may offer an alternative model which is shown in Figure 11. Before 40 m years ago, both the Pacific and the Kula plates were subducting beneath the Kurile-Japan-Ryukyu arc. We assume that the plate decoupling began from the southwest end. Then a retreat of the subduction zone began and proceeded as shown in Figure 11b to form the Philippine Sea. The upwelling counter flow took place in the form of inter-arc spreading, filled the opening, and cooled to form the Philippine Sea plate (Figure 11c). When a reasonably rigid lithosphere was formed, a new episode of underthrusting began along the Nankai trough and the Ryukyu trench. The retreat and the upwelling may have been episodic resulting in various NW-SE trending features in the western Philippine Sea and N-S trending features in the eastern Philippine Sea.

Although the change in the direction of the Pacific plate is not essential in this model, it may be related to the formation of the Kyushu-Palau ridge (Figure 2) which marks the boundary between the Western and Eastern Philippine Sea. When the direction of motion of the Pacific plate changed from NNW to WNW, the component of the velocity perpendicular to the subduction zone must have increased. Since the rate of retreat is determined by a balance between the rate of fall-off of the plate at its leading edge and the plate motion perpendicular to the subduction zone, a sudden increase in the plate velocity may have resulted in a substantial difference in the nature of the marginal sea formed by this process. An increase in the velocity of plate motion would also result in an increase of the dip of the Benioff zone. The nearly vertical Benioff zone in the southern end of the Marianas [Katsumata and Sykes, 1969] may have been caused by either an increase in the effective plate velocity, a decrease in the fall-off rate or both.

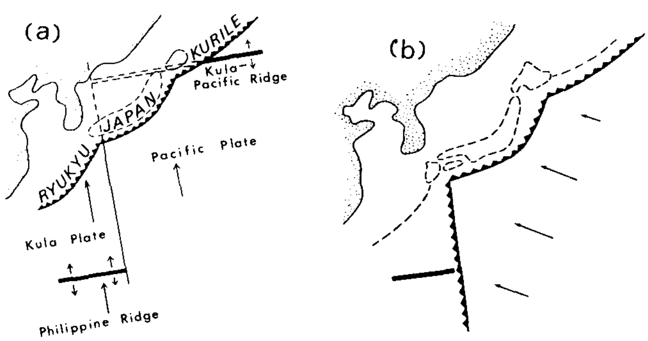

Figure 10. Schematic sketch of possible history of the Philippine Sea [after Uyeda and Ben-Avraham, 1972]. a. Kula-Pacific ridge descended beneath Japan 80 to 90 m.y. ago. b. About 40 m.y. ago, the direction of motion of the Pacific plate changed. The Kula plate did not change its direction of motion and subduction started along the transform fault.

Discussion and Conclusions

Although an attempt is made in the previous section to explain some of the details of the geological features of the Philippine Sea, the emphasis of the present paper is on the fundamental physical mechanisms operating in the formation of geological features. In constructing a model for a specific area, it would be necessary to arrange these fundamental mechanisms in appropriate temporal and spatial order. We emphasize that inferences from detailed studies of great earthquakes strongly suggest that inter-plate coupling and decoupling play a fundamental role in the formation and evolution of island arcs. Strong inter-plate coupling results in great earthquakes and disrupted Benioff zones. Partial and complete decoupling results in aseismic slip, continuous Benioff zones, gravitational sinking of the subducting lithosphere and finally, retreating subduction zones. Retreating subduction would imply a more disruptive process for formation of marginal seas than for ordinary ocean basins which are formed by spreading from a linear oceanic ridge. This difference may explain

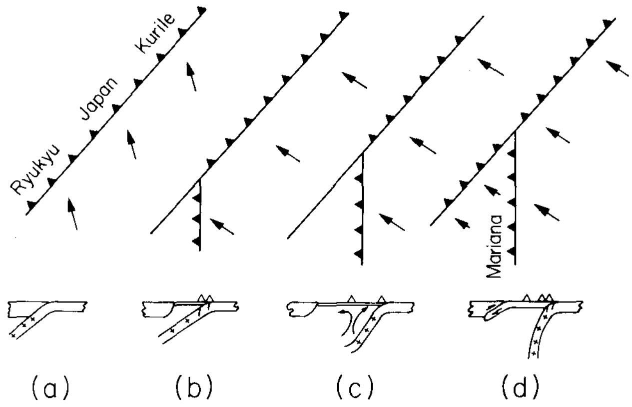

Figure 11. Schematic figure of possible history of the Philippine Sea. a. Before 80 to 90 m.y. ago. b. Before 40 m.y. ago. Retreat started and the Pacific plate changed its direction. c. Further retreat and formation of the eastern Philippine Sea. d. New subduction along the Nankai trough and Ryukyu arc and the present day Marianas.

the less distinct linear features in magnetic stripes and heat flow distribution in most marginal seas and the disparity in the water depth versus age relation [Sclater et al., 1976].

Although we believe that the inter-plate coupling and decoupling are the major factors that affect the mode of subduction and evolution of island arcs, aseismic ridges and buoyant lithospheres suggested by Vogt [1973] and Kelleher and McCann [1976] may still play an important role in modifying the mode of subduction. For example, if the lithosphere to the east of the Marianas is indeed buoyant, as suggested by Kelleher and McCann [1976], it may have prevented further fall-off of the lithosphere along the Marianas thereby terminating the retreat of the subduction.

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References

Abe, K., Mechanisms and tectonic implications of the 1966 and 1970 Peru earthquakes, Phys. Earth Planet. Interiors, 5, 367-379, 1972.

Abe, K., Tsunami and mechanism of great earthquakes, Phys. Earth Planet. Interiors, 7, 143-153, 1973.

Abe, K., Mechanisms of the 1938 Shioya-Oki earthquakes and their tectonic implications, to be submitted to Tectonophysics, 1976.

Anderson, D. L., Accelerated plate tectonics, Science, 187, 1077-1079, 1975.

Ando, M., Source mechanisms and tectonic significance of historical earthquakes along the Nankai trough, Japan, Tectonophysics, 27, 119-140, 1975a.

Ando, M., Long-duration faulting in the 1946 Nankaido earthquake (abstract), EOS, 56, 1067, 1975b.

Fedotov, S. A., Regularities of the distribution of strong earthquakes in Kamchatka, the Kurile Islands and northeastern Japan, Trans. Acad. Sci. U.S.S.R., Inst. Phys. Earth, 36, (203), 66-93, 1965 (in Russian).

Fitch, T. J., and C. H. Scholz, A mechanism for underthrusting in southwest Japan: A model of convergent plate interactions, J. Geophys. Res., 76, 7260-7292, 1971.

Gutenberg, B., and C. F. Richter, Seismicity of the Earth, 2nd Edition, Princeton University Press, Princeton, N.J., 310 pp., 1954.

Hanks, T. C., The Kuril trench-Hokkaido rise system: Large shallow earthquakes and simple models of deformation, Geophys. J., 23, 173-189, 1971.

Imamura, A., On the seismic activity of central Japan, Jap. J. Astron. Geophys., 6, 119-137, 1928.

Isacks, B., and P. Molnar, Mantle earthquake mechanisms and the sinking of the lithosphere, Nature, 223, 1121-1124, 1969.

Kanamori, H., Synthesis of long-period surface waves and its application to earthquake source studies-Kurile Islands earthquake of October 13, 1963, J. Geophys. Res., 75, 5011-5027, 1970a.

Kanamori, H., The Alaska earthquake of 1964: Radiation of long-period surface waves and source mechanism, J. Geophys. Res., 75, 5029-5040, 1970b.

Kanamori, H., Seismological evidence for a lithospheric normal faulting-The Sanriku earthquake of 1933, Phys. Earth Planet. Interiors, 4, 289-300, 1971a.

Kanamori, H., Great earthquakes at island arcs and the lithosphere, Tectonophysics, 12, 187-198, 1971b.

Kanamori, H., Faulting of the Great Kanto earthquake of 1923 as revealed by seismological data, Bull. Earthquake Res. Inst. Tokyo Univ., 49, 13-18, 1971c.

Kanamori, H., Focal mechanism of the Tokachi-

Oki earthquake of May 16, 1968: Contortion of the lithosphere at a junction of two trenches, Tectonophysics, 12, 1-13, 1971d.

Kanamori, H., Tectonic implications of the 1944 Tonankai and the 1946 Nankaido earthquakes, Phys. Earth Planet. Interiors, 5, 129-139, 1972a.

Kanamori, H., Mechanism of Tsunami earthquakes, Phys. Earth Planet. Interiors, 6, 346-359, 1972b.

Kanamori, H., Re-examination of the earth's free oscillations excited by the Kamchatka earthquake of November 4, 1952, Phys. Earth Planet. Interiors, 11, 216-226, 1976.

Kanamori, H., and K. Abe, Deep structure of island arcs as revealed by surface waves, Bull. Earthquake Res. Inst. Tokyo Univ., 46, 1001-1025, 1968.

Kanamori, H., and D. L. Anderson, Theoretical basis of some empirical relations in seismology, Bull. Seismol. Soc. Am., 65, 1073-1095, 1975.

Kanamori, H., and J. J. Cipar, Focal process of the great Chilean earthquake, May 22, 1960, Phys. Earth Planet. Interiors, 9, 128-136, 1974.

Karig, D. E., Origin and development of marginal basins in the western Pacific, J. Geophys. Res., 76, 2542-2560, 1971.

Katsumata, M., and L. R. Sykes, Seismicity and tectonics of the western Pacific: Izu-Mariana-Caroline and Ryukyu-Taiwan regions, J. Geophys. Res., 74, 5923-5948, 1969.

Kelleher, J., and W. McCann, Buoyant zones, great earthquakes and dynamic boundaries of subduction, J. Geophys. Res., 81, 1976 (in press).

Kelleher, J., J. Savino, H. Rowlett, and W. McCann, Why and where great thrust earthquakes occur along island arcs, J. Geophys. Res., 79, 4889-4899, 1974.

Kelleher, J., L. Sykes, and J. Oliver, Possible criteria for predicting earthquake locations and their application to major plate boundaries of the Pacific and the Caribbean, J. Geophys. Res., 78, 2547-2585, 1973.

LePichon, X., Sea-floor spreading and continental drift, J. Geophys. Res., 73, 3661-3697, 1968.

Lliboutry, L., Sea-floor spreading, continental drift and lithosphere sinking with an asthenosphere at melting point, J. Geophys. Res., 74, 6525-6540, 1969.

Lomnitz, C., Major earthquakes and tsunamis in Chile during the period 1535 to 1955, Geol. Rundschau, 59, 938-960, 1970.

Mckenzie, Dan P. and R. L. Parker, The north Pacific: An example of tectonics on a sphere, Nature, 216, 1276-1280, 1967.

Minster, J. B., T. H. Jordan, P. Molnar, and E. Haines, Numerical modelling of instantaneous plate tectonics, Geophys. J., 36, 541-576, 1974.

Mogi, K., Development of aftershock areas of great earthquakes, Bull. Earthquake Res. Inst. Tokyo Univ., 46, 175-203, 1968a.

Mogi, K., Some features of recent seismic activity in and near Japan, 1, Bull. Earthquake Res. Inst. Tokyo Univ., 46, 1225-1236, 1968b.

Morgan, W. J., P. R. Vogt, and D. F. Falls, Magnetic anomalies and sea floor spreading on the Chile rise, Nature, 222, 137-142, 1969.

Nagamune, T., and M. Chiurei, On the magnitude of an earthquake off the east coast of Hokkaido which occurred on June 10, 1975, Quart. J. Seism., 40, 105-107, 1976 (in Japanese).

Plafker, G., Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implications for arc tectonics, J. Geophys. Res., 77, 901-925, 1972.

Sclater, J. G., K. Karig, L. A. Lawver, and K. Louden, Heat flow, depth, and crustal thickness of the marginal basins of the south Philippine Sea, J. Geophys. Res., 81, 309-318, 1976.

Seekins, L. C., and Ta-Liang Teng, Lateral variations in the structure of the Philippine Sea plate, J. Geophys. Res., in press, 1976.

Shimazaki, K., Pre-seismic crustal deformation caused by an underthrusting oceanic plate, in eastern Hokkaido, Japan, Phys. Earth Planet. Interiors, 8, 148-157, 1974a.

Shimazaki, K., Nemuro-Oki earthquake of June 17, 1973: A lithospheric rebound at the upper half of the interface, Phys. Earth Planet. Interiors, 9, 314-327, 1975a.

Shimazaki, K., Low-stress-drop precursor to the Kurile Islands earthquakes of August 11, 1969, EOS, 56, 1028 (abstract), 1975b.

Stauder, W., Tensional character of earthquake foci beneath the Aleutian trench with relation to sea-floor spreading, J. Geophys. Res., 73, 7693-7701, 1968.

Suzuki, S., and H. Sugimoto, 1975 Nemuro-Oki earthquake, abstract, Annaul Meeting of Seism. Soc. of Japan, 112, 1975.

Sykes, L. R., Aftershock zones of great earthquakes, seismicity gaps, and earthquake prediction for Alaska and the Aleutians, J. Geophys. Res., 76, 8021-8041, 1971.

Tsujiura, M., Spectral ratio of two earthquakes off the east coast of Hokkaido, on June 10 and 14, 1975, abstract, Annual Meeting of Seism. Soc. of Japan, 114, 1975.

Usami, T., Descriptive table of major earthquakes in and near Japan which were accompanied by damages, Bull. Earthquake Res. Inst. Tokyo Univ., 44, 1571-1622, 1966 (in Japanese).

Utsu, T., Large earthquakes near Hokkaido and the expectancy of the occurrence of a large earthquake off Nemuro, Rep. Coordinating Committee for Earthquake Prediction, 7, 7-13, 1972 (in Japanese).

Uyeda, S., and Z. Ben-Avraham, Origin and development of the Philippine Sea, Nature, 240, 176-178, 1972.

Uyeda, S., and A. Miyashiro, Plate tectonics and the Japanese Islands: A synthesis, Geol. Soc. Am. Bull., 85, 1159-1170, 1974.

Vogt, P. R., Subduction and aseismic ridges, Nature, 241, 189-191, 1973.

Walcott, R. I., Flexural rigidity, thickness, and viscosity of the lithosphere, J. Geophys. Res., 75, 3941-3954, 1970.

Watts, A. B., and M. Talwani, Gravity anomalies seaward of deep-sea trenches and their tectonic implications, Geophys. J., 36, 57-90, 1974.

Wilson, J. T., Mantle plumes and plate motions, Tectonophysics, 19, 149-164, 1973.

Wu, F. T., and H. Kanamori, Source mechanics of February 4, 1965, Rat Island earthquake, J. Geophys. Res., 78, 6082-6092, 1973.