REVIEWS OF GEOPHYSICS, VOL. 24, NO. 1, PAGES 27-53, FEBRUARY 1986

SPHERICAL SHELL TECTONICS: EFFECTS OF SPHERICITY AND INEXTENSIBILITY ON THE GEOMETRY OF THE DESCENDING LITHOSPHERE

Koshun Yamaoka and Yoshio Fukao

Department of Earth Sciences, Nagoya University, Nagoya, Japan

Mineo Kumazawa

Geophysical Institute, University of Tokyo, Tokyo, Japan

Abstract. The shape of a deep seismic zone is thought to represent that of the descending slab of lithosphere. The lithosphere before subduction is a spherical shell, and the shape of the descending slab is the result of the deformation of the spherical lithosphere at the subduction zone. Upon bending a spherical shell often deforms in a very different way from a simple plate. We examine whether the actual shape of the descending slab can be explained by a simple bending of an inextensible spherical shell, which shows little surface deformation under moderate stress. This examination is made region by region for most of the subduction zones in the world by means of an analogue method. The lithosphere is simulated by an inextensible spherical shell made of polyvinyl chloride resin. The Wadati-Benioff zone is shaped by plaster by referring to the reliable hypocentral data selected from the International Seismological Centre (ISC) bulletins. The spherical shell is forced to fit the miniature of the Wadati-Benioff zone. Fitting is first attempted only by bending. If a good fit is not attainable and if a discontinuity or gap in seismic activity is observed in the relevant region, the spherical shell is torn along this discontinuity or gap, and the goodness of fit is reexamined. The results of the analysis are summarized as follows: (1) The shape of the Wadati-Benioff zone can be simulated largely by a simple bending of a spherical shell without surface deformation. (2) In almost all of the regions of poor fit with bending, a good fit can be achieved by tearing the spherical shell along the trace of low seismicity. The sphericity of the lithosphere and the inextensibility upon deformation are the two essential factors in controlling the slab shape. This means that the lateral constraint is most important for understanding the geometry of the downgoing slab of lithosphere and the stress state within it. Further, several problems related to the deformational characteristics of the spherical lithosphere are also reviewed and discussed in connection with subduction tectonics.

Introduction

The earth's lithosphere is literally a "spherical shell," and its mechanical behavior can be very different from that of a simple "plate." The lithospheric plate, however, has often been treated as a plate rather than a spherical shell. In this study we refer to "plate tectonics" as "spherical shell tectonics" to emphasize the importance of sphericity in the lithospheric deformation.

Brotchie and Silvester [1969] analyzed the deformation of an elastic spherical shell by filling it with incompressive liquid to investigate the intraplate deformation due to glacier loading. They showed that the buoyancy force due to the deflection of the lithosphere is so large that the deformation is limited to such an extent that it is geometrically proportional to the load. The nonlinear terms in the governing equations can be omitted in this case of small deflection. The analysis of Brotchie and Silvester [1969] was later elaborated by Solomon and Head [1979, 1980], and by Head and Solomon [1981], who discussed the surface features of terrestrial planets. The tectonics using the theory of spherical shell of small deflection [Timoshenko and Woinowsky-Krieger, 1959; Dym, 1974] has also recently been argued by several authors [Liu, 1985; Lanzano, 1985].

The situation is, however, drastically different at subduction zones where the oceanic lithosphere descends into the asthenosphere. The density difference between the materials above and below the descending slab of lithosphere is so small that little buoyancy will act on it. The descending slab is therefore easy to deform, and the resultant large deformation causes an apparent sharp bend of the oceanic lithosphere at the trench. Large deformation of a spherical shell is notoriously difficult to analyze mathematically because of the inherent nonlinearity between the force applied and the bulk deformation of the shell. An intuitive two-dimensional analogy by means of a plane plate can be quite misleading for such a nonlinear problem. Although the configuration of the descending slab and the stress state within it have often been discussed in a cross-sectional view across the arc, such a discussion may lose some fundamental aspect of lithospheric deformation.

The three-dimensionality of the problem was first explicitly pointed out by Frank [1968], who noted that the trench axis is generally arcuate and convex oceanward. He regarded the lithospheric plate as a flexible but inextensible thin spherical shell. He then described the arcuateness of the trench axis as the effect of the push of a dent on a skin of a ping-pong ball; the downgoing slab behaves like the indented part of the ball. Only in this case, membrane stresses are absent in the downgoing slab [Strobach, 1973]. This punctured-ping-pong-ball

Paper number 5R0711.
8755-1209/86/005R-0711$15.00

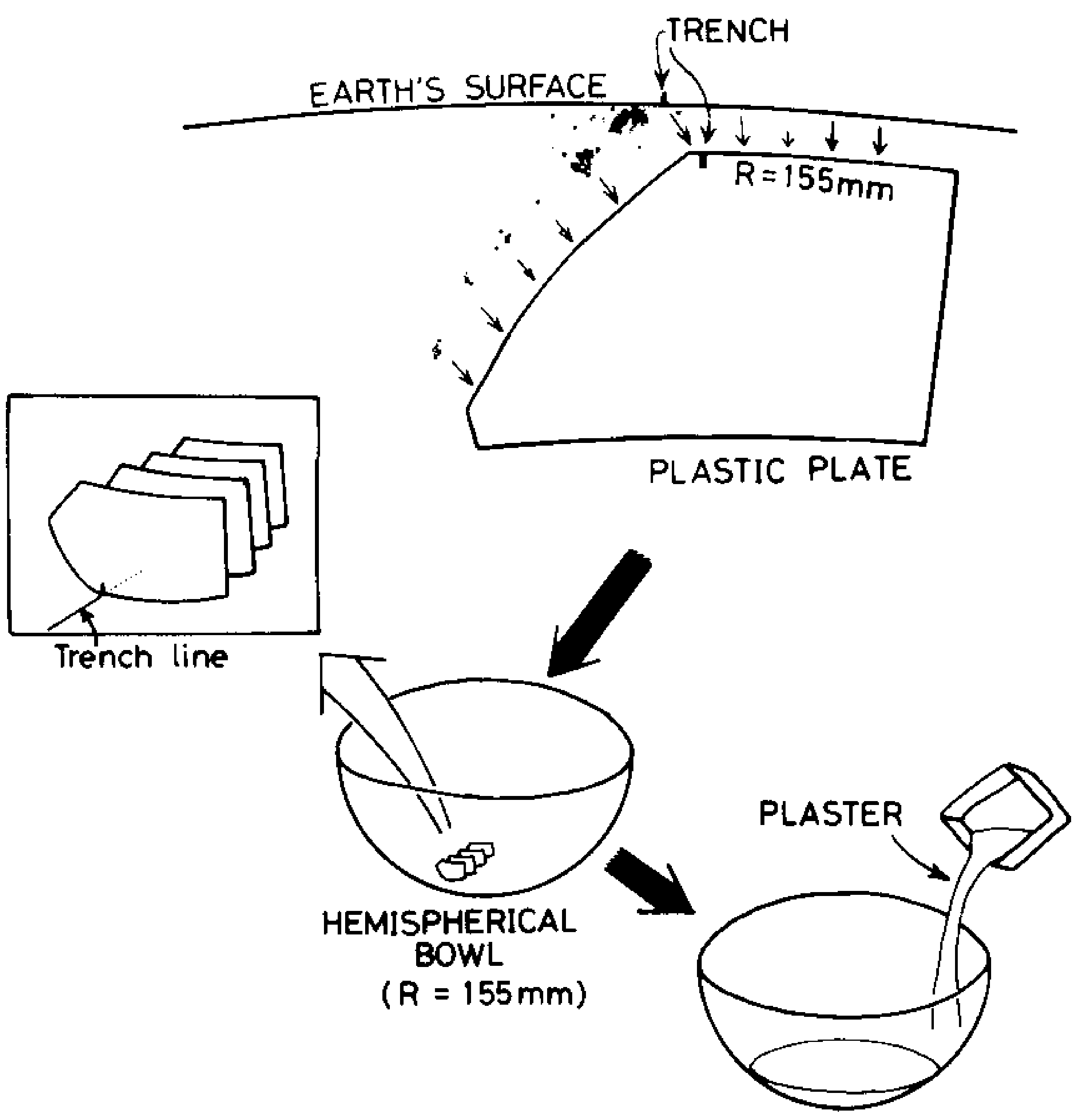

Fig. 1. Procedure for making miniatures of the Wadati-Benioff zone from plaster.

effect requires that the radius of an island arc be half of the dip angle of the slab [Frank, 1968].

This Frank's relation has been tested against the real subduction zones by many investigators [e.g., Strobach, 1973; Aoki, 1974a; DeFazio, 1974; Laravie, 1975; Tovish and Schubert, 1978]. They observed considerable deviations, though some arcs (e.g. Kuriles and Java) seem to satisfy this relation approximately. These deviations suggest either that Frank's basic assumption of inextensibility is invalid for lithospheric deformation or that descending slabs undergo considerable stresses parallel to their strike directions [Strobach, 1973]. Strobach [1973] cited the deep seismic zone of the Tonga-Kermadec arc as supporting the second alternative.

All the above authors have paid attention mainly to the slab configuration in a single arc. A subduction zone, however, usually consists of a chain of several arcs with their lithospheric slabs continuing from arc to arc (e.g., the Kurile-Northern Honshu-Izu-Bonin-Mariana arcs). The slab deformation is therefore in part controlled by mechanical interactions across the arc-arc junctions. This implies that the slab configuration could be fully understood only by viewing it as a whole along an entire subduction zone. The horizontal scale involved in the problem of slab geometry should be in this sense much greater than those considered by the previous workers.

We make the region-by-region analyses of slab configuration from the above point of view. Such analyses, besides providing the basis for our generalizations and inferences, yield information about the tectonic process now going on in each subduction zone.

Method

Our purpose is to examine the inextensibility of lithospheric deformation through region-by-region analyses. By inextensibility we mean the difficulty of deformation in extension, compression, and shear along the surface. The examination could be made in principle by numerical simulation. To avoid possible mathematical complexities, however, we adopt an analogue method; an inextensible spherical shell is deformed by bending so that it fits the real shape of a deep seismic zone. The model spherical shell is made of polyvinyl chloride resin with a thickness of about 0.2 mm, which is flexible but inextensible at room temperature.

We first prepare a metal hemispherical cap of 155 mm radius, inside of which an electric wire heater is installed. This metal cap is then mounted on the piston head of a hydraulic jack in a press frame. A plane vinyl sheet is firmly fixed at its rim to a horizontal circular frame so that the hemispherical cap pushes up the vinyl sheet from below as the piston moves upward. With appropriate heat supplied to the hemispherical cap the vinyl sheet slowly deforms into a hemispherical shell in about 10 minutes.

The spherical shell so formed is an analogue model of the lithosphere, which is to fit the miniatures of deep seismic zones. We make such miniatures using plaster in a scale consistent with the vinyl spherical shell. The detail of the procedure is shown in Figure 1. We first define the shape of a subducting slab by the hypocenters of earthquakes. The events with more or less reliable locations are selected from the International Seismological Centre (ISC) bulletins from 1971 to 1979. These hypocenters are projected onto the vertical planes striking nearly perpendicular to the local trend of the trench axis. The profiles are taken at about every 100 to 200 km interval along the trench axis. The shape of a subducting slab is determined by referring to these vertical cross sections. When it is difficult to define the slab shape uniquely because of a scattered hypocentral distribution, we attach more importance to the focal depths determined by pP-P time readings.

We next prepare plastic plates, each of which has an edge delineating the cross-sectional shape of a deep seismic zone with its seaward extension on the earth's surface. All such plates for a particular subduction zone are placed vertically in a consistent manner in a hemispherical container. Then plaster is poured and curdled to harden. To construct the miniature of a deep seismic zone and its seaward extension on the earth's surface, the excess plaster is removed by a knife by referring to the plates embedded in plaster.

A spherical vinyl shell is bent to fit the miniature of the deep seismic zone. The shell is first capped on the miniature, and they are adhered to each other in the portion corresponding to the earth's surface. The circumference free edge of the shell is then pulled downward by several narrow adhesive tapes to fix it to the miniature Wadati-Benioff surface. The bent portion of the vinyl shell is cut off at the length corresponding to the leading edge of the deep seismic zone, assuming that the subducting slab does not extend further beyond this leading edge. The fit is examined by using two criteria: We first force the spherical shell to fit the miniature only by bending. If it is

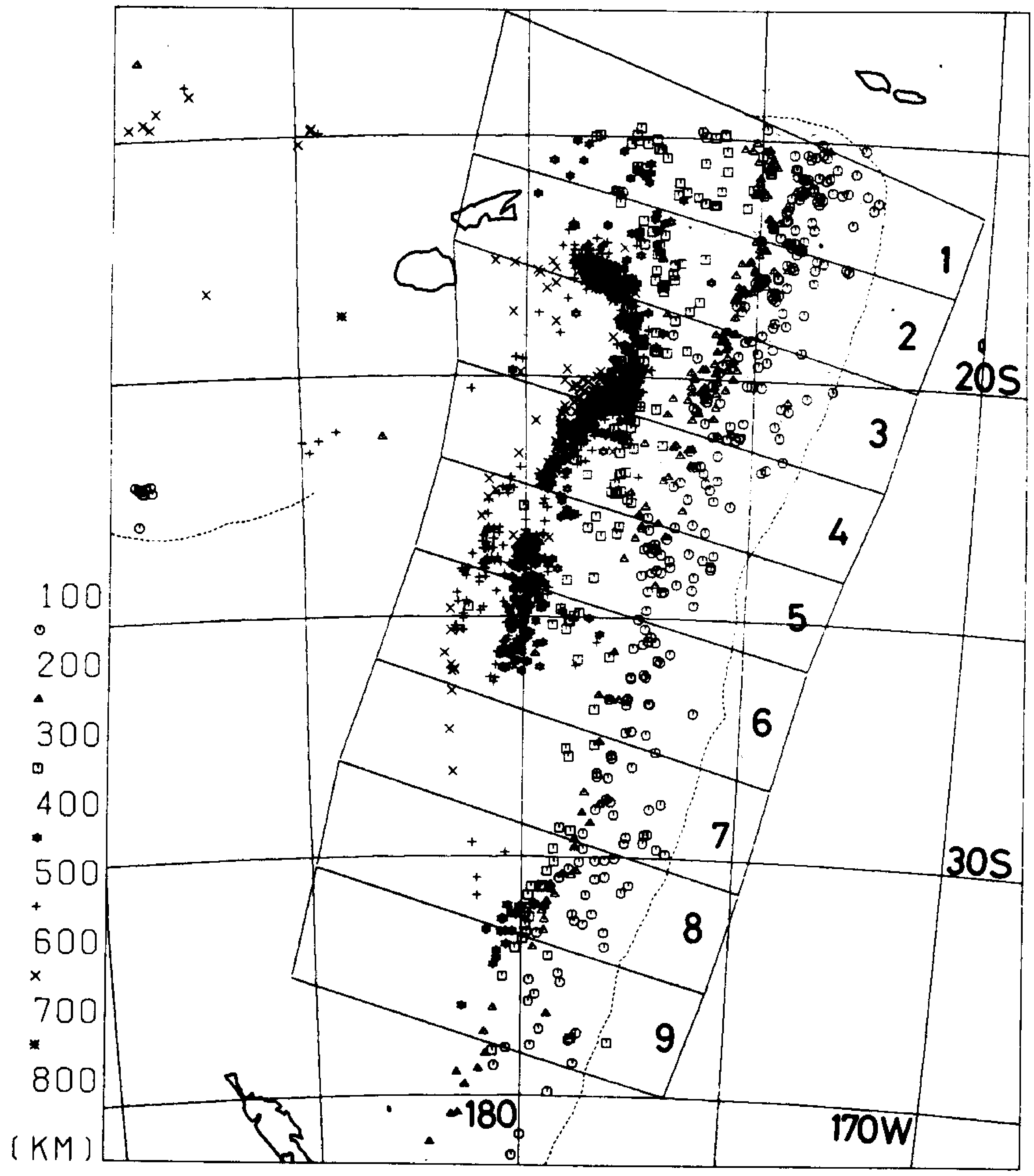

Fig. 2a. Tonga-Kermadec arc.

Fig. 2. Seismicity maps of subduction zones. Rectangular frames are the sites for which the vertical sections of hypocentral distribution are shown in Fig.4. Dashed lines show the tears introduced in the spherical shells. (a) Tonga-Kermadec arc, (b) New Britain-Solomon-New Hebrides arcs, (c) Indonesian arc, (d) Ryukyu arc, (e) Kamchatka-Kuril-Japan-Izu-Bonin-Mariana arcs, (f) Aleutian arc, (g) West Indies arc, (h) Middle American arc, (i) Peru and Chile arcs, (j) South Sandwich arc.

impossible to obtain a good fit, and if a gap in seismicity is observed there, we next tear the spherical shell by referring to this seismic gap and try fitting again. The poor fit appears as a separation of the vinyl shell from the miniature or a strong contortion of the shell. The goodness or poorness of fit after and before the introduction of the tear is shown in Figure 4. This figure clearly shows how the introduction of a tear in one place gives a good fit over a great distance along the arc and, therefore, how the slab geometries are laterally affected by each other.

The shell fitting test is performed on all the major subduction zones: the Aleutian, Kurile-Kamchatka, Northern Honshu, Izu-Bonin-Mariana, New Britain-Solomon-New Hebrides, Tonga-Kermadec, South Sandwich, Peru-Chile, Middle America, and West India. The subduction zones around the Philippine Sea and the Mediterranean Sea are excluded from our examination because of the complexity and smallness in size. The subduction zones whose slabs are considered to be continuous across the arc-arc junctions are analyzed together. Such subduction zones include the Kurile to Mariana arcs and the New Britain-Solomon-New Hebrides arcs.

There is ample evidence that subducting lithosphere is subjected to plastic deformation. The very existence of earthquakes shows some plastic deformation of the subducting slab. Upon subduction the slab bends first and next unbends, as manifested by the slab geometry. This bending-unbending process may involve plastic deformation. Heat conduction from the surrounding hot mantle causes thermally induced strain besides mechanically induced strain. Our experiment ignores these complicated factors to simplify the subduction of lithosphere as the bending of an inextensible spherical shell.

Tonga-Kermadec Arc

The shape of the descending slab of the Tonga-Kermadec arc gives one of the simplest

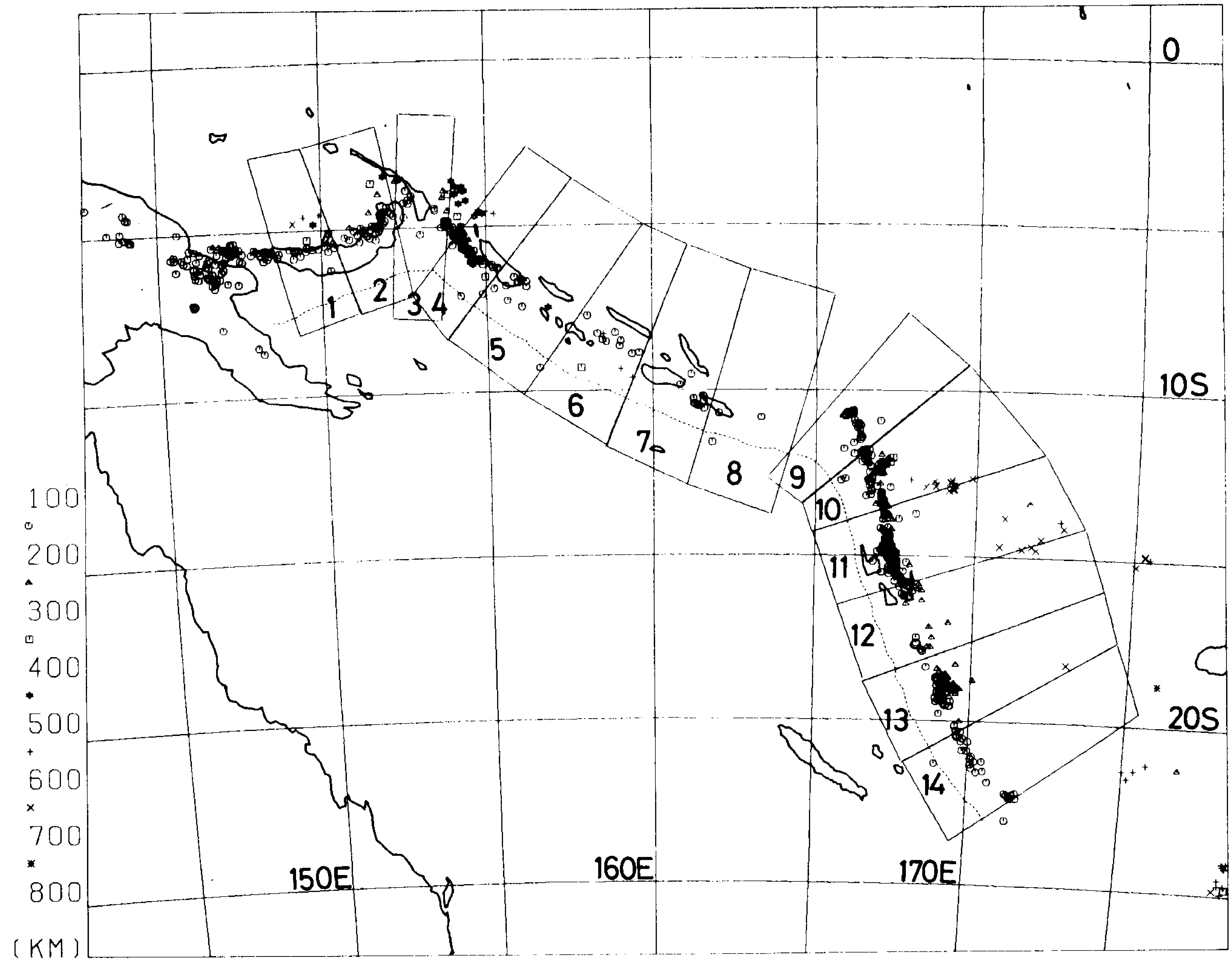

Fig. 2b. New Britain-Solomon-New Hebrides arcs.

examples of showing the effect of the earth's sphericity.

The Pacific plate subducts at this trench westward beneath the Indian plate. The hypocentral distribution of intermediate- to deep-focus earthquakes is shown in Figure 2a. The events whose focal depths are less than 100 km are omitted to show the deep seismicity clearly. The earthquakes plotted are selected from the ISC bulletins from 1971 to 1979 so that their magnitudes are greater than 4.5 and their hypocenters are determined by more than 10 stations. The plots illustrate a high activity in deep earthquakes and a relatively simple figure of the deep seismic zone.

A striking feature of this subduction zone is a contrast between the near straightness of the trench axis and the laterally wavy contortion of the deep seismic zone. Another intriguing feature is a sharp westward bend of the seismic zone at its northern edge. The leading edge of the deep seismic zone becomes in general progressively shallower southward from Tonga to New Zealand.

The laterally wavy contortion of the deep seismic zone was first explained by Strobach [1973] in terms of inward bending of the lithospheric shell. When the inextensible lithospheric shell is bent inward at a dip angle less than twice the radius of the curvature of the trench axis, the bent portion has to show a curtain-like folding along the trench axis [Strobach, 1973]. This is the case of the Tonga-Kermadec Trench, where the radius of the arc curvature is about 90° whereas the dip angle of the slab is only about 50° - 60°.

The model spherical shell is forced to fit the miniature of the Tonga-Kermadec slab only by bending. A good fit is, however, difficult to obtain at the northern end of the deep seismic zone as shown by the dotted lines in Figure 4a, where a remarkable gap in seismicity is observed (Figure 2a). We then tear the spherical shell at this portion so that the opening of the torn portion is consistent with the observed gap in seismicity. Such a tearing is possible to achieve, as shown in Figure 3a. This result suggests that the downgoing slab is detached at its northern end from the surface lithosphere further northward [Isacks et al., 1969]. The northern end of the slab is presumed to be free from lateral constraint. The hinge fault mechanisms of shallow earthquakes at the northern end of the arc are consistent with this idea [Isacks et al., 1969].

Figure 3a is an overview of how the inextensi-

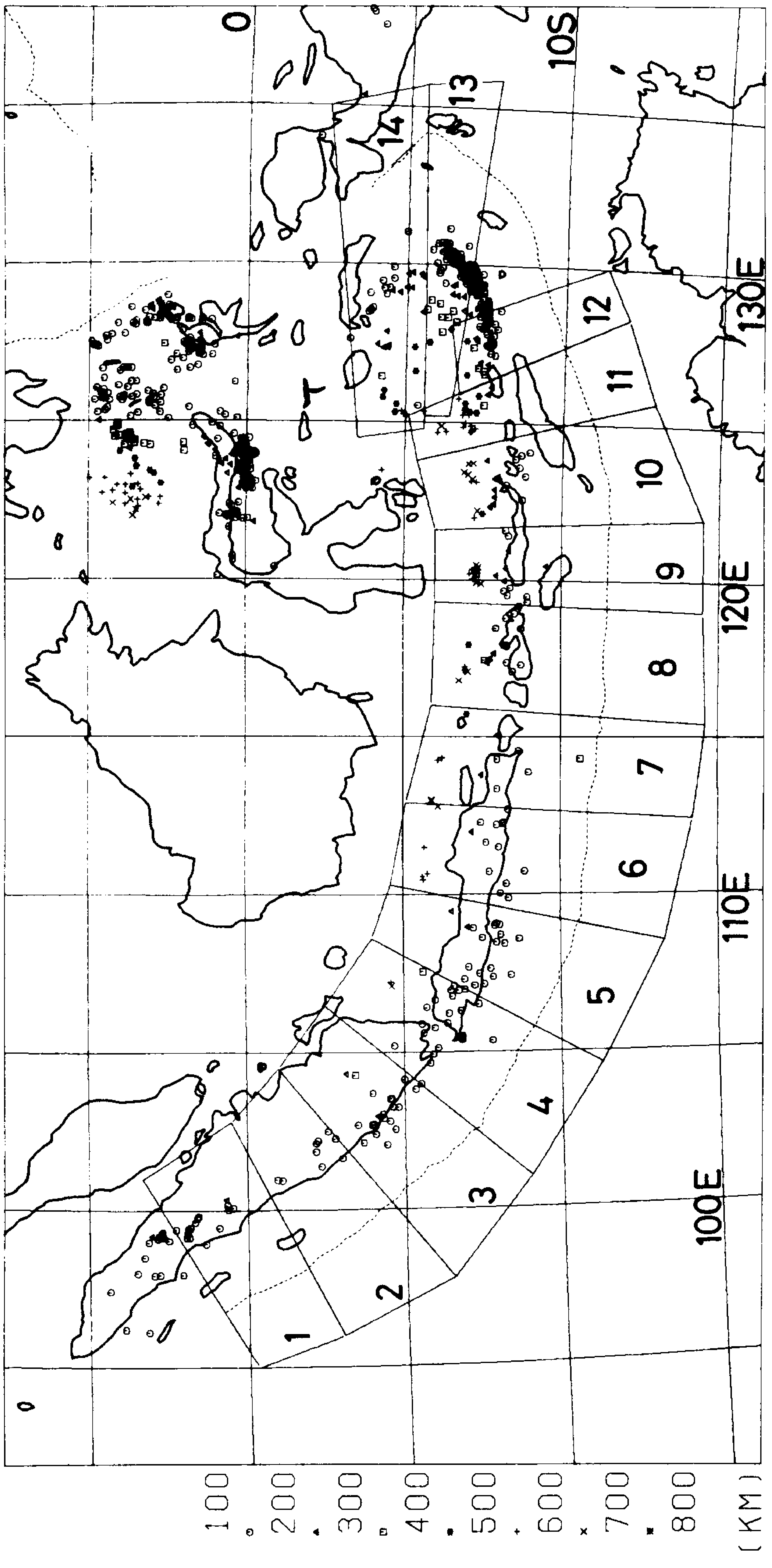

Fig. 2c. Indonesian arc.

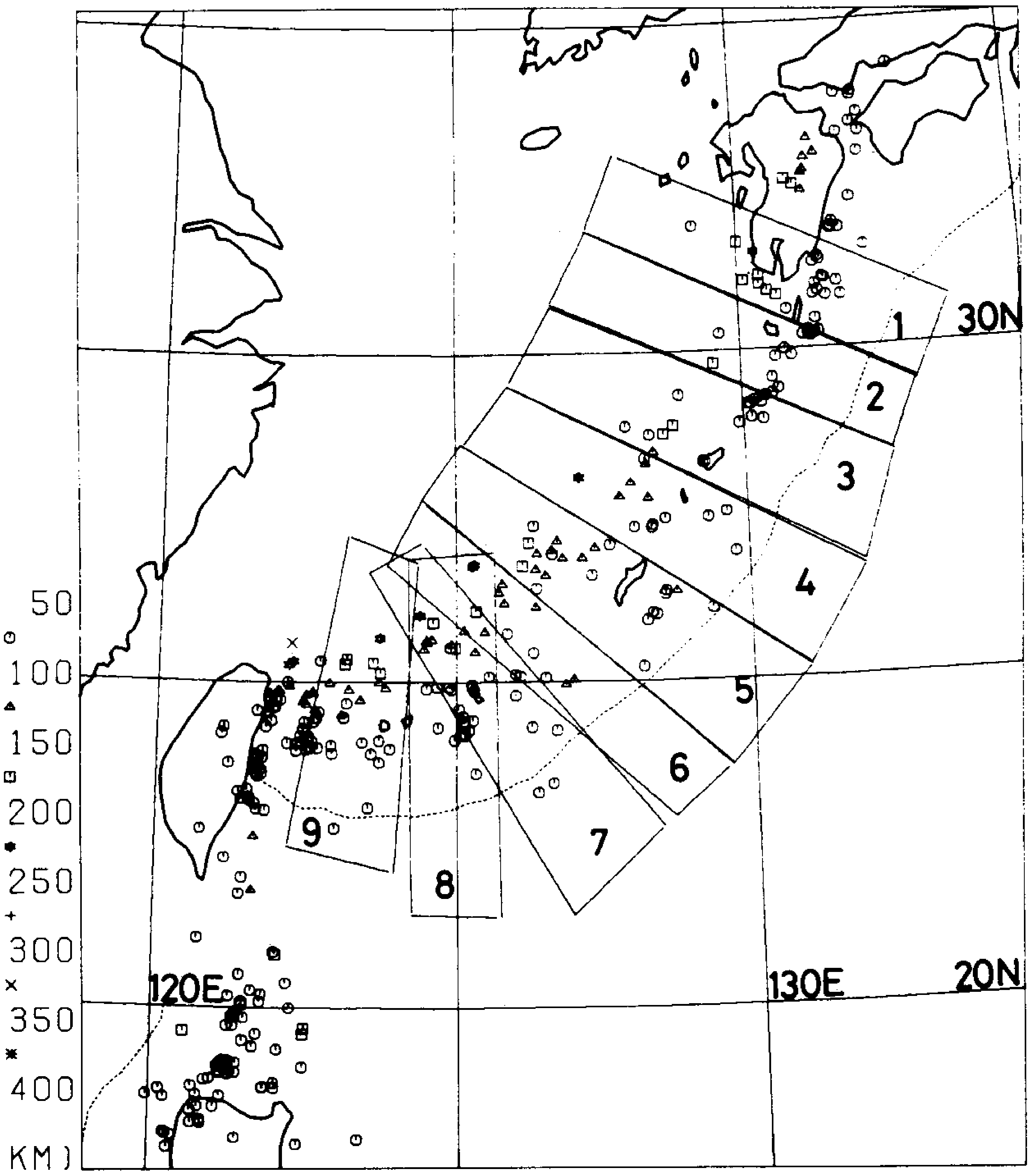

Fig. 2d. Ryukyu arc.

ble spherical shell fits the miniature of the deep seismic zone. Figure 4a is a cross-sectional view of the fit. The fit is reasonably good along the entire arc. The shape of the deep seismic zone of the Tonga-Kermadec arc is thus explained, to a good approximation, by bending alone except at the northern end of the arc, where tearing is introduced. Our experiment directly demonstrates that the lateral contortion of the downgoing slab at its deep portion is a natural consequence of the inward bending of the inextensible spherical lithosphere as first pointed out by Strobach [1973]. This demonstration warns against a conventional two-dimensional analysis of the slab shape based on a cross sectional view of seismicity. The three dimensionality is an essential factor for considering the slab shape.

In Figure 4a the shallow seismicity is scattered in the northern portion of the arc, probably because of the inaccuracy in hypocentral determination, particularly in focal depths. Although the miniature of the deep seismic zone is referred in this portion to the deeper bound of the scattered seismic zone, the bent spherical shell coincides rather well with the shallower bound when a good fit is required for all other portions (see Figure 4a). It would be interesting to examine whether or not a more accurately determined hypocentral distribution converges into the shallower bound as expected from our fitting experiment. This may be a good test to check our interpretation for the slab shape.

New Britain-Solomon-New Hebrides Arcs

Along the New Britain-Solomon-New Hebrides Islands, the Indian plate of lithosphere subducts beneath the Pacific plate. Unlike all the other circum-Pacific arcs, these arcs are convex to the south and face away from the Pacific basin. These arcs form sharp corners at their arc-arc junctions. The southeastern end of the New Hebrides arc curves eastward toward the Tonga arc.

Complex tectonic features in the New Britain-Solomon regions appear in the mechanism solutions of large earthquakes [Lay and Kanamori, 1980]. Along the New Britain trench, directions of slip vectors for thrusting events are oriented approximately NNW, while they are oriented NNE for events along the Solomon trench. To explain this difference, the Bismark plate just to the north of the New Britain trench has been proposed [Johnson and Molnar, 1972]. The presence of the Bismark plate does not affect our examination, however. Several authors proposed a spreading center along the Woodlark ridge [Milson, 1970; MacDonald et al., 1973; Luyendyk et al., 1973]. If this spreading center is in fact active, we may have to discuss the slab systems eastward and westward of the Woodlark ridge separately. We

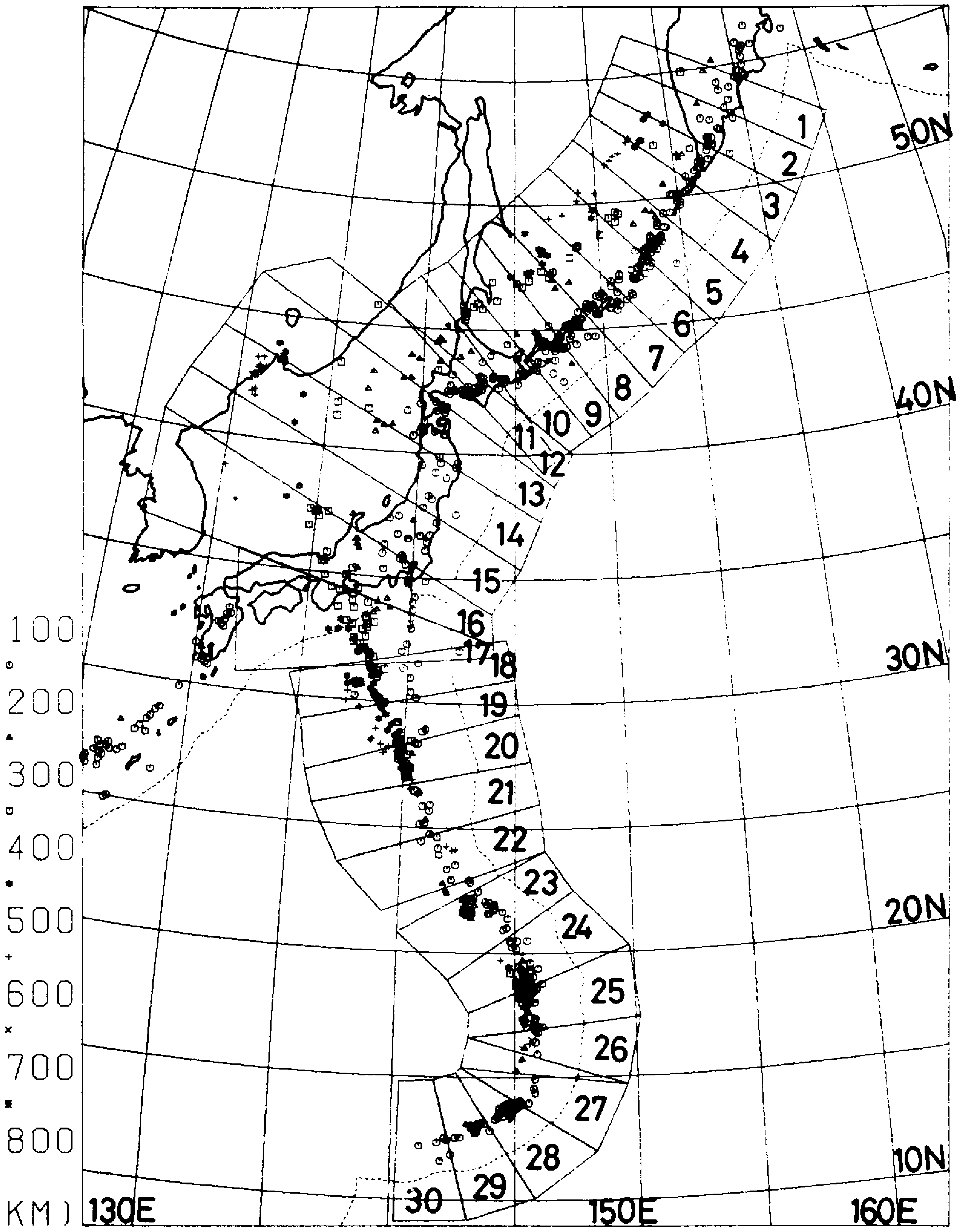

Fig. 2e. Kamchatka-Kuril-Japan-Izu-Bonin-Mariana arcs.

ignore this possibility, as the Wadati-Benioff zone northward of the Woodlark ridge is so short, reaching only a depth of 150 km (Figure 2b), that such a separate treatment would not affect our conclusion significantly.

In the New Britain region and in the northwestern Solomon region, the seismic zone seems to be continuous from shallower to deeper portions without a distinct gap (Figure 2b). In the southeastern Solomon region, the seismic activity is restricted to shallow depths of less than 150 km. In the New Hebrides region, there is a clear seismic gap between the intermediate-depth and the deepest seismic activities (sections 10-13 of Figure 4b). The intermediate-depth activity constitutes a slab-like seismic zone extending downward from the trench axis to depths of about 300 km. On the other hand, the deepest activity is confined in a nearly horizontal planar zone. The trends of these two activities are quite different from each other (Figure 2b). Pascal et al. [1973] suggested from a study of seismic wave propagation that there is no lithospheric slab between them. The deepest events appear to occur within a detached slab of lithosphere. We therefore exclude the deepest activity from our consideration.

Figures 3b and 4b show the result of the shell fitting. The fit is quite good along the whole arcs. To maintain a good overall fit, sharp

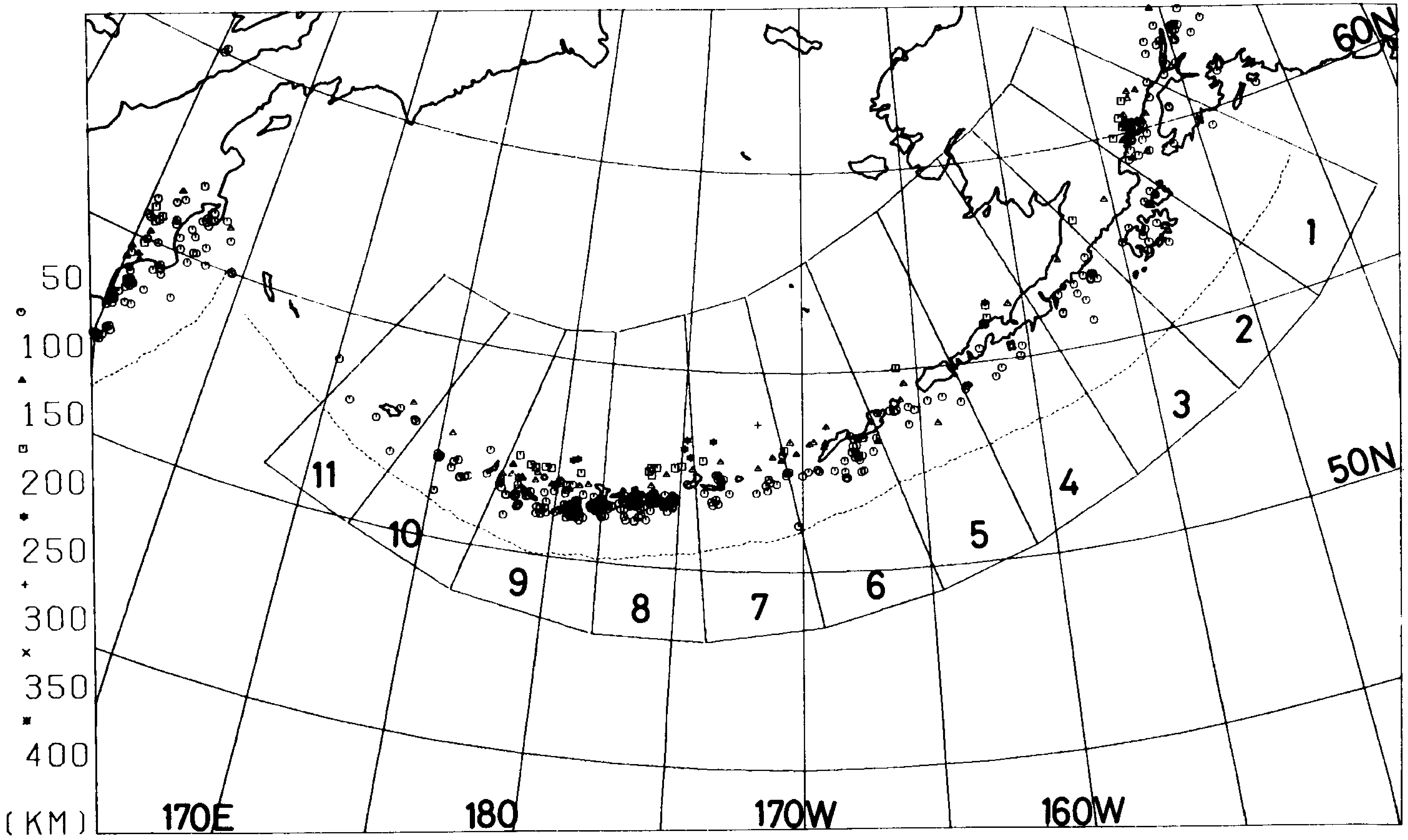

Fig. 2f. Aleutian arc.

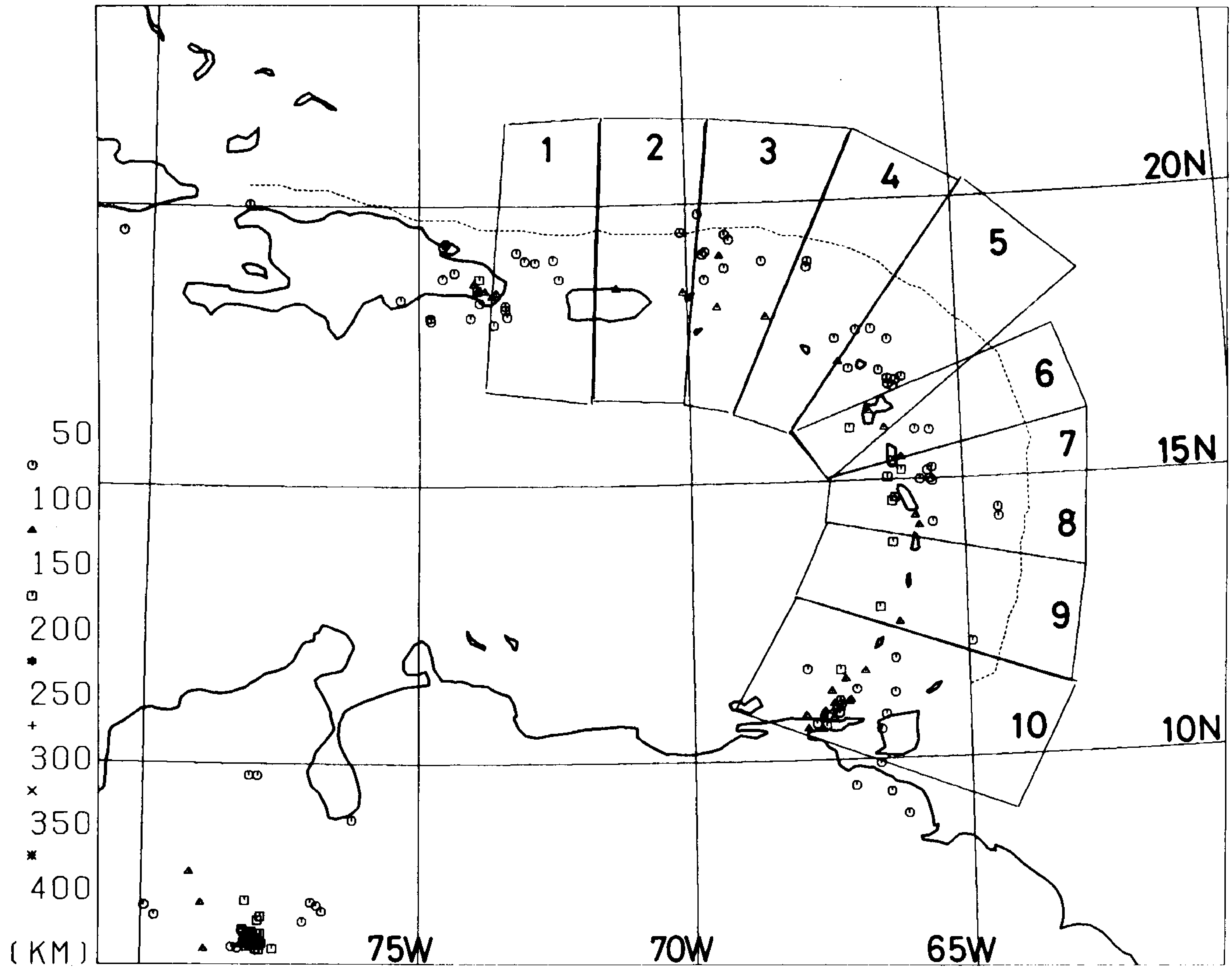

Fig. 2g. West Indies arc.

cusps take place at the corners of the bent portion of the shell corresponding to the arc-arc junctions. Such a cusp is in fact observed for the real seismic zone at the junction of the New Hebrides and the Solomon arcs (see Figure 2b) and is understood as a manifestation of lithospheric inextensibility. It is not clear whether or not the descending slab actually forms such a cusp at the junction of the Solomon and the New Britain arcs, since no deep activity is observed there (see Figure 2b). Although the corresponding vertical section shows some deep activity (section 3 of Figure 4b), this is an effect of finite interval sampling. The arc-arc junction itself lacks deep activity, a tendency more apparent at greater depths. A similar situation also occurs at the junction of the Izu-Bonin and the Mariana arcs, where the bent vinyl shell forms a sharp cusp in the absence of the corresponding deep seismic activity.

No trial of shell fitting is made for the southern end of the New Hebrides arc, where the trench axis bends abruptly eastward, as the seismic activity is confined to shallow depths (<100 km). If a shell fitting were attempted, however, it would be necessary to tear the vinyl shell at the southern end, just as in the case of the northern end of the Tonga arc. In fact, Johnson and Molnar [1972] and Pascal et al. [1978] obtained focal mechanisms of hinge fault type for shallow events there.

Indonesian Arc

Along the Indonesian arc, the lithosphere of the Indo-Australian plate subducts. This is a long and smooth arc except near its eastern end, the Banda Sea region, where the trench axis curves with a small radius of curvature. In the Banda Sea region the Australian continental lithosphere is thought to collide with the trench [Bowin et al., 1980].

The deep seismic zone along the arc can be divided into three parts according to its characteristic configuration. The westernmost part, to the east of the Sunda Channel at about 106°E, is characterized by a short length of the deep seismic zone, which extends downward to depths of not greater than 200 km. In the central part, the deep seismic zone is long along its dip, extending to depths of 600 km. The dip angle is almost constant, about 30°, at depths above 200 km, whereas it becomes as large as 70° at greater depths. The lithospheric slab apparently bends sharply at a depth of about 200 km.

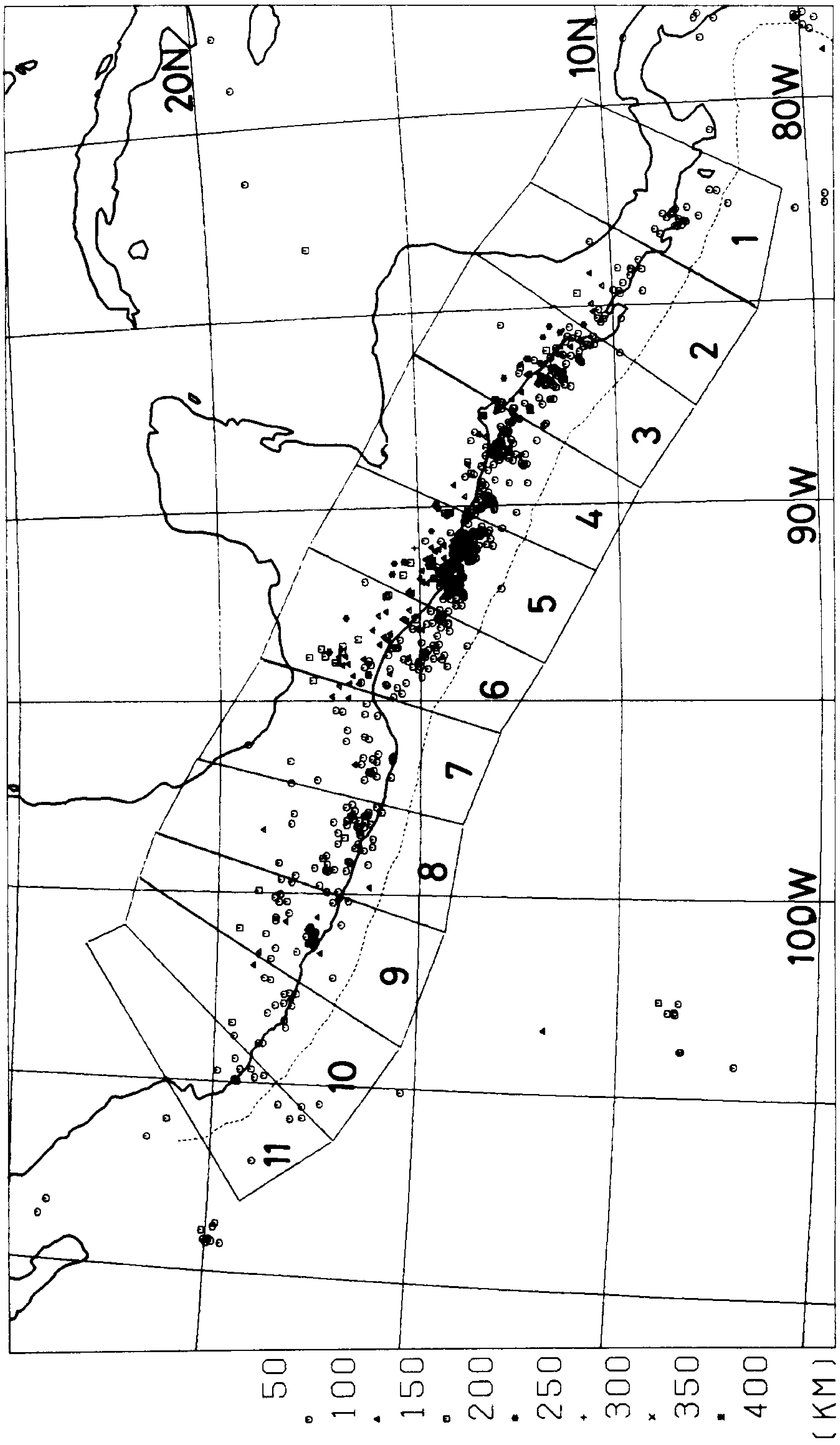

Fig. 2h. Middle American arc.

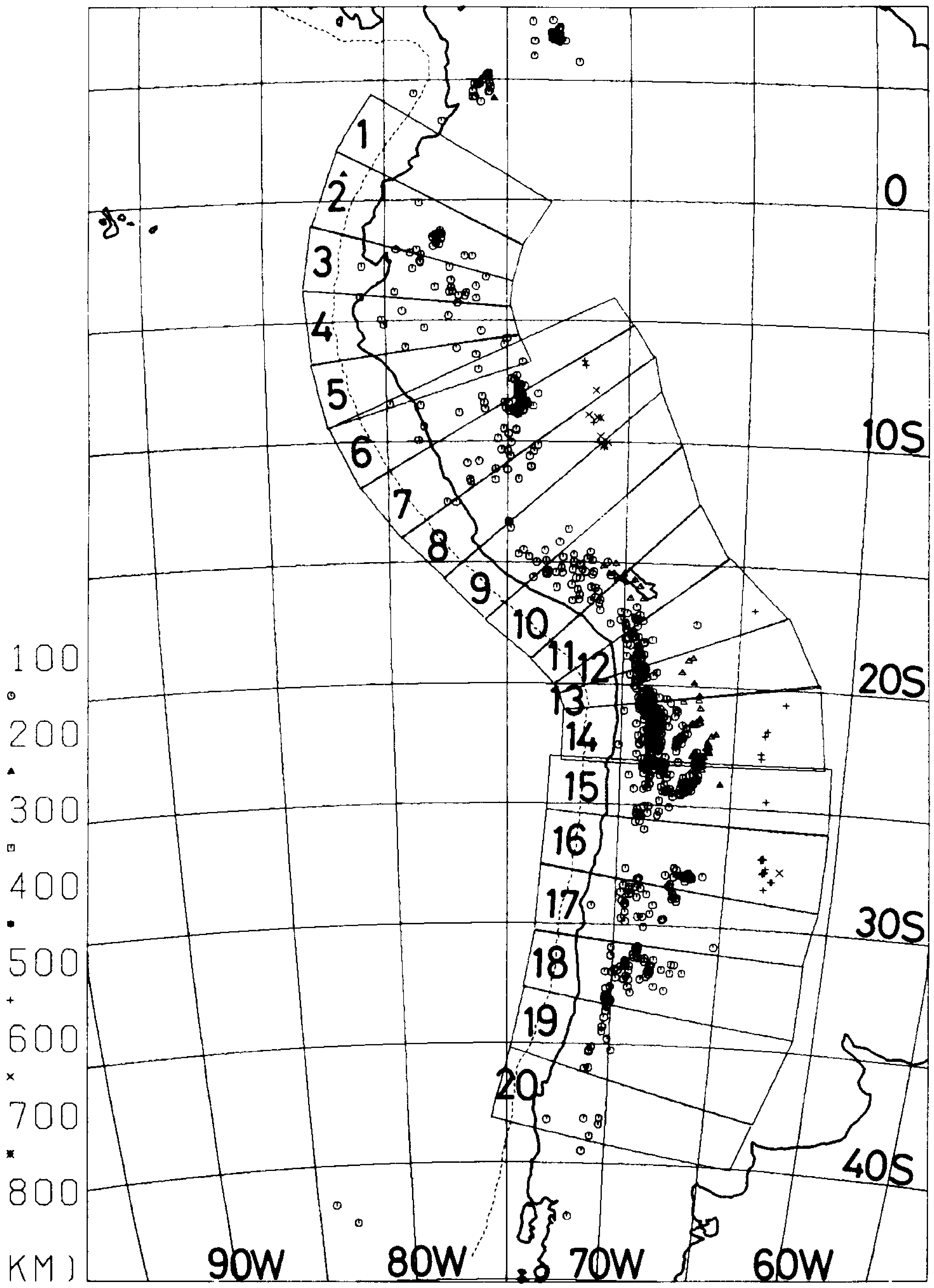

Fig. 2i. Peru and Chile arcs.

In the easternmost part, the Banda Sea region, the trench axis curves sharply northward to further westward. The deep seismic zone is also strongly contorted. For this peculiar configuration, either a 180° bend of the lithospheric slab [Hatherton and Dickinson, 1969; Hamilton, 1974] or a 90° bend [Cardwell and Isacks, 1978; Papp, 1980] has been proposed. Cardwell and Isacks [1978] proposed that the Seram trough subduction zone is not a continuation of the Banda arc subduction zone.

Figures 3c and 4c show the result of the shell fitting. The fit is excellent along the entire arc. This good fit is, however, the result of introduction of a tear; the shell is torn before bending along the 6°S latitudinal line at the easternmost part. Without this tearing it is impossible to reproduce the characteristic shape of the deep seismic zone in the central part of the Indonesian arc (Figure 4c), demonstrating a long-range mechanical interaction of the subducting slab along its strike. A tear is made for the resultant opening of the shell to coincide with the observed gap in seismicity. As shown in Figure 5, this seismic gap is semicircular at greatest depths in the Banda region and has been interpreted in various ways by Cardwell and Isacks [1978], Papp [1980] and Hatherton and Dickinson [1978]. We suggest that this semicircular aseismic area is a consequence of lithospheric tearing and is closely related to the slab shape in the central part of the Indo-

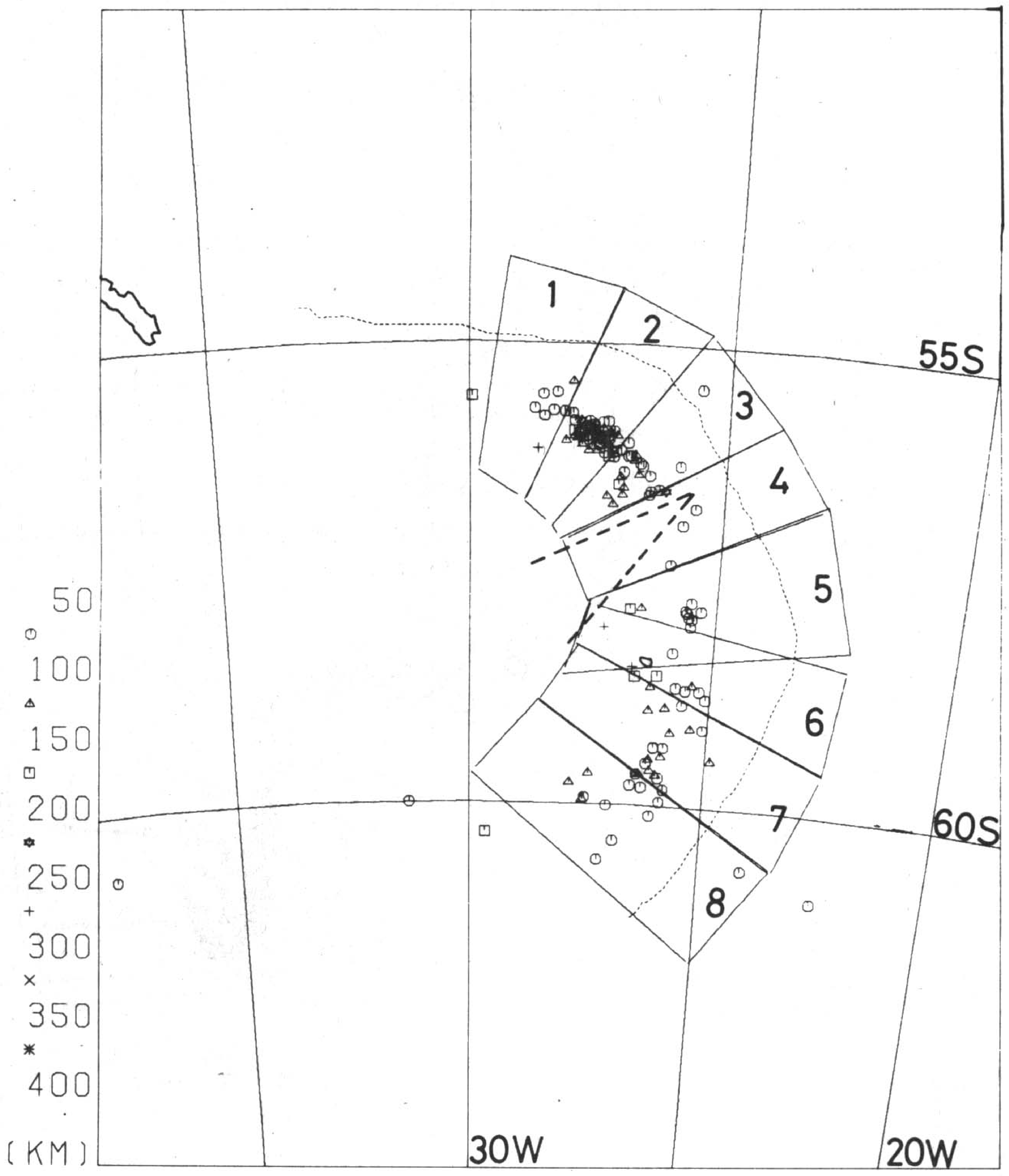

Fig. 2j. South Sandwich arc.

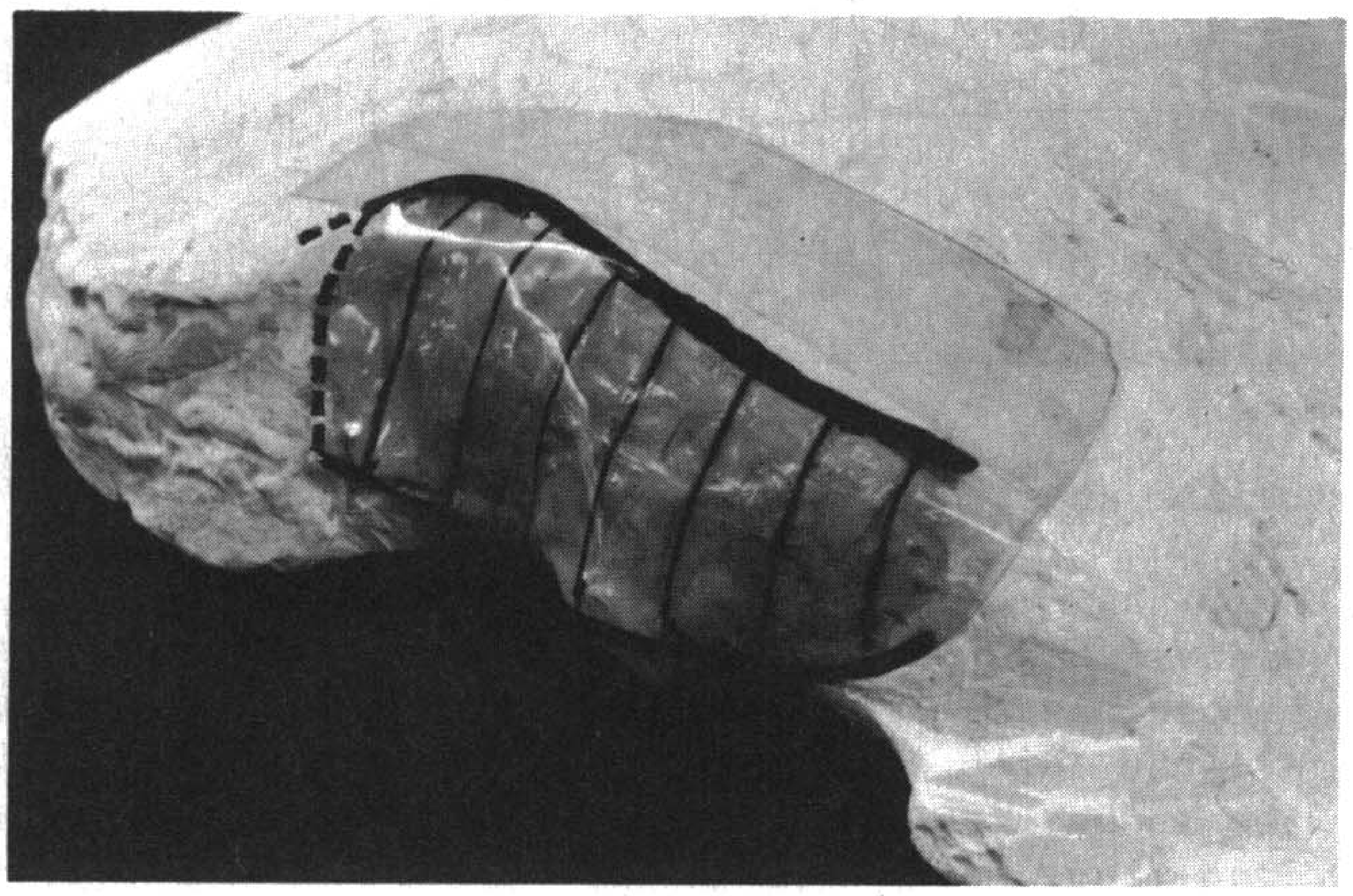

Fig. 3a. Tonga-Kermadec arc.

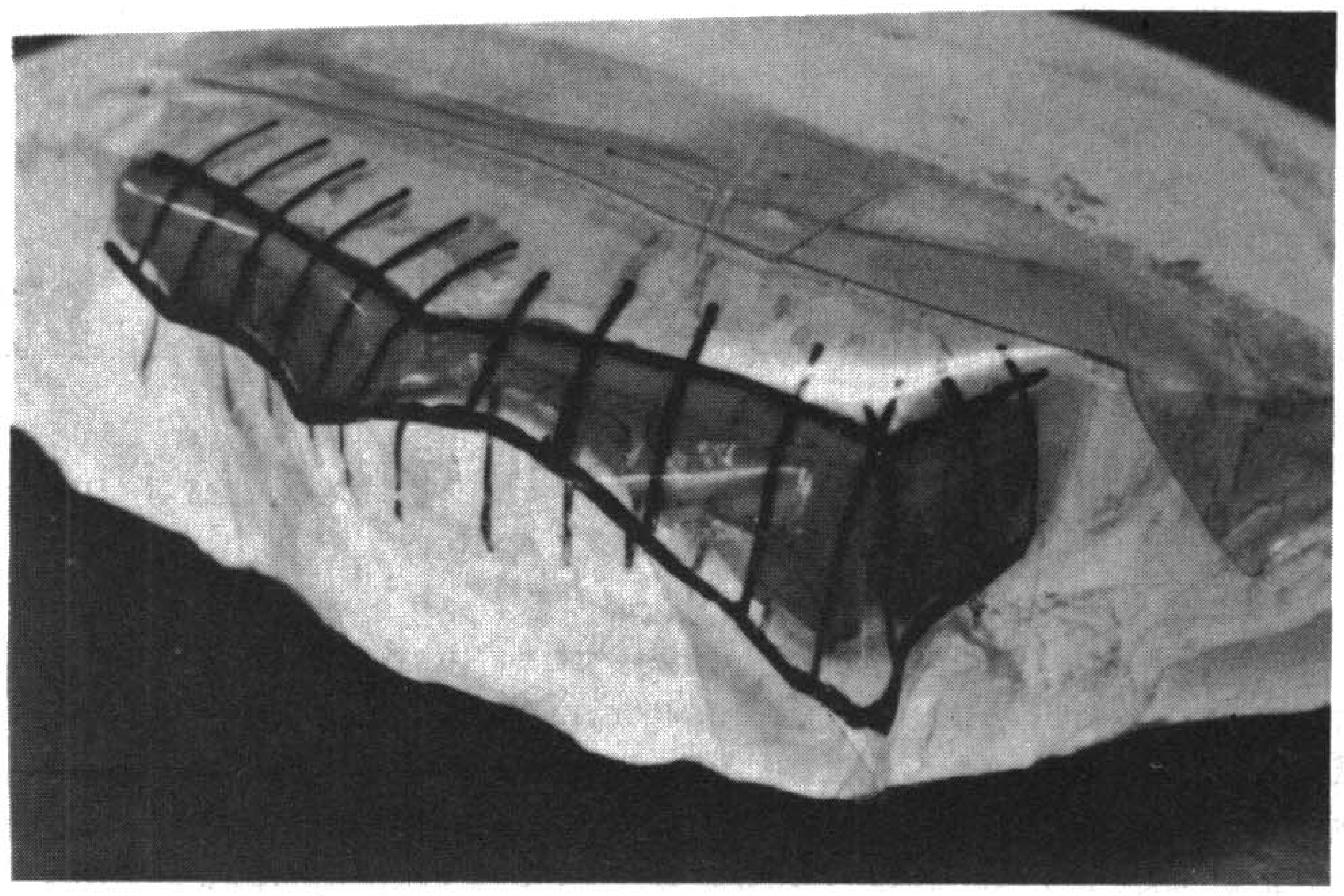

Fig. 3b. New Britain-Solomon-New Hebrides arcs.

Fig. 3. Overview of the result of the shell fitting experiment. The gray portion of the plaster miniature represents the Wadati-Benioff zone. The transparent sheet with bold black lines indicates the bent part of the spherical shell made of polyvinyl chloride resin. (a) Tonga-Kermadec arc (Tonga at the left), (b) New Britain-Solomon-New Hebrides arcs (New Britain at the right), (c) Indonesian arc (Banda Sea at the left), (d) Ryukyu arc (Kyushu at the left), (e) Kamchatka-Kuril-Japan-Izu-Bonin-Mariana arcs (Kamchatka at the left), (f) Aleutian arc (Alaska at the left), (g) West Indies arc (Lesser Antilles at the right), (h) Middle American arc (Panama at the left), (i) Peru and Chile arcs (Peru at the right), (j) South Sandwich arc.

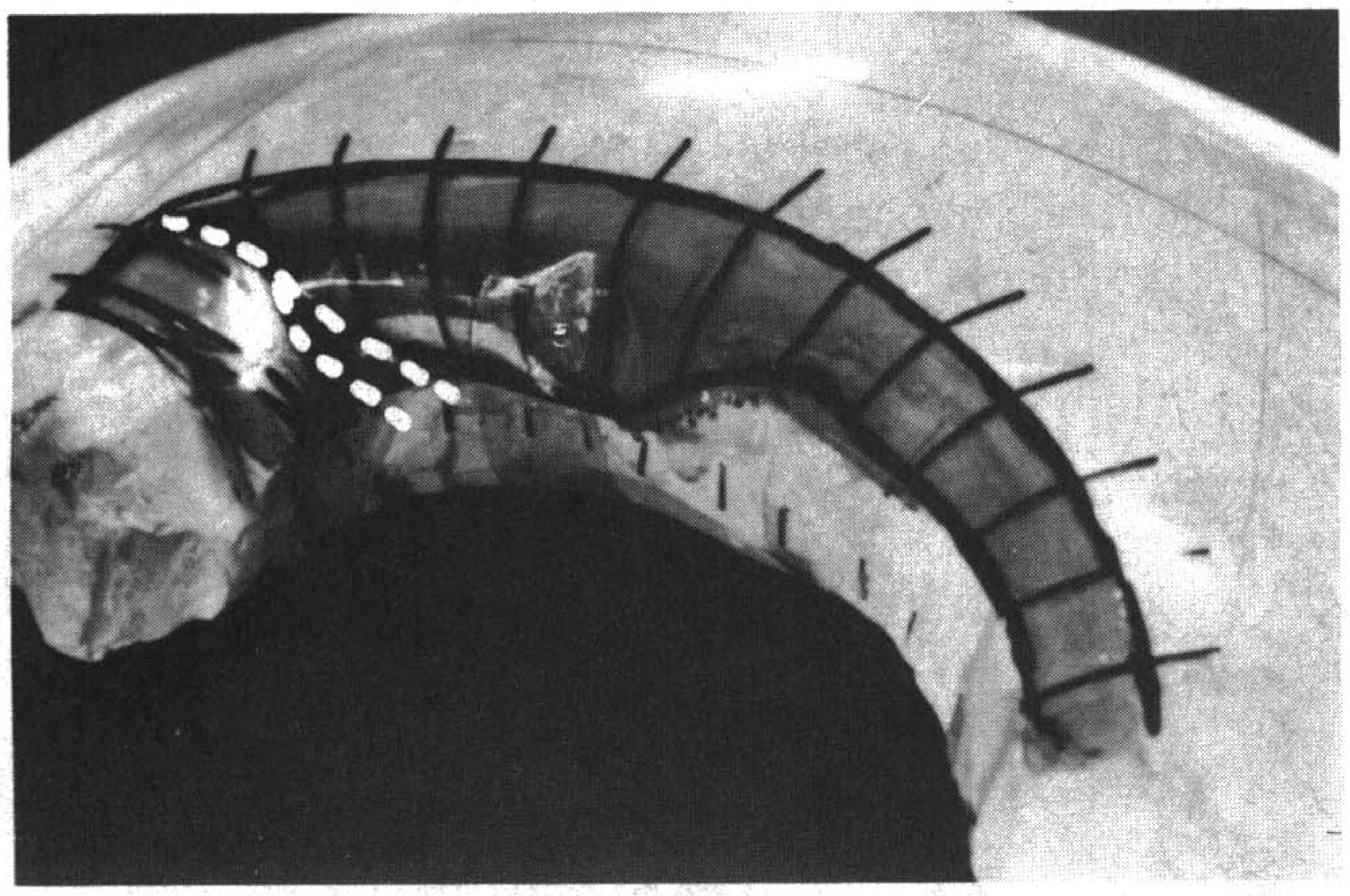

Fig. 3c. Indonesian arc.

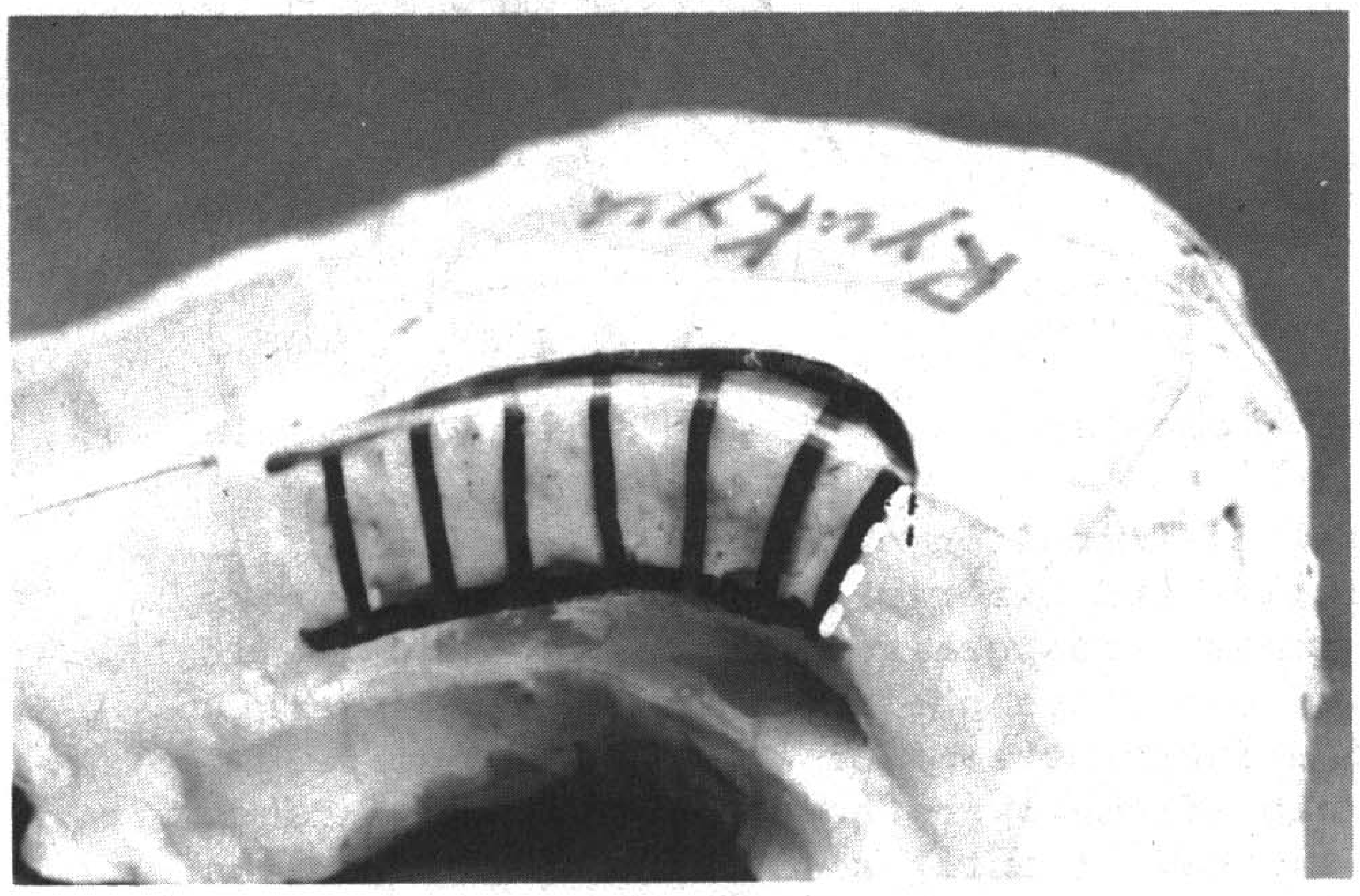

Fig. 3d. Ryukyu arc.

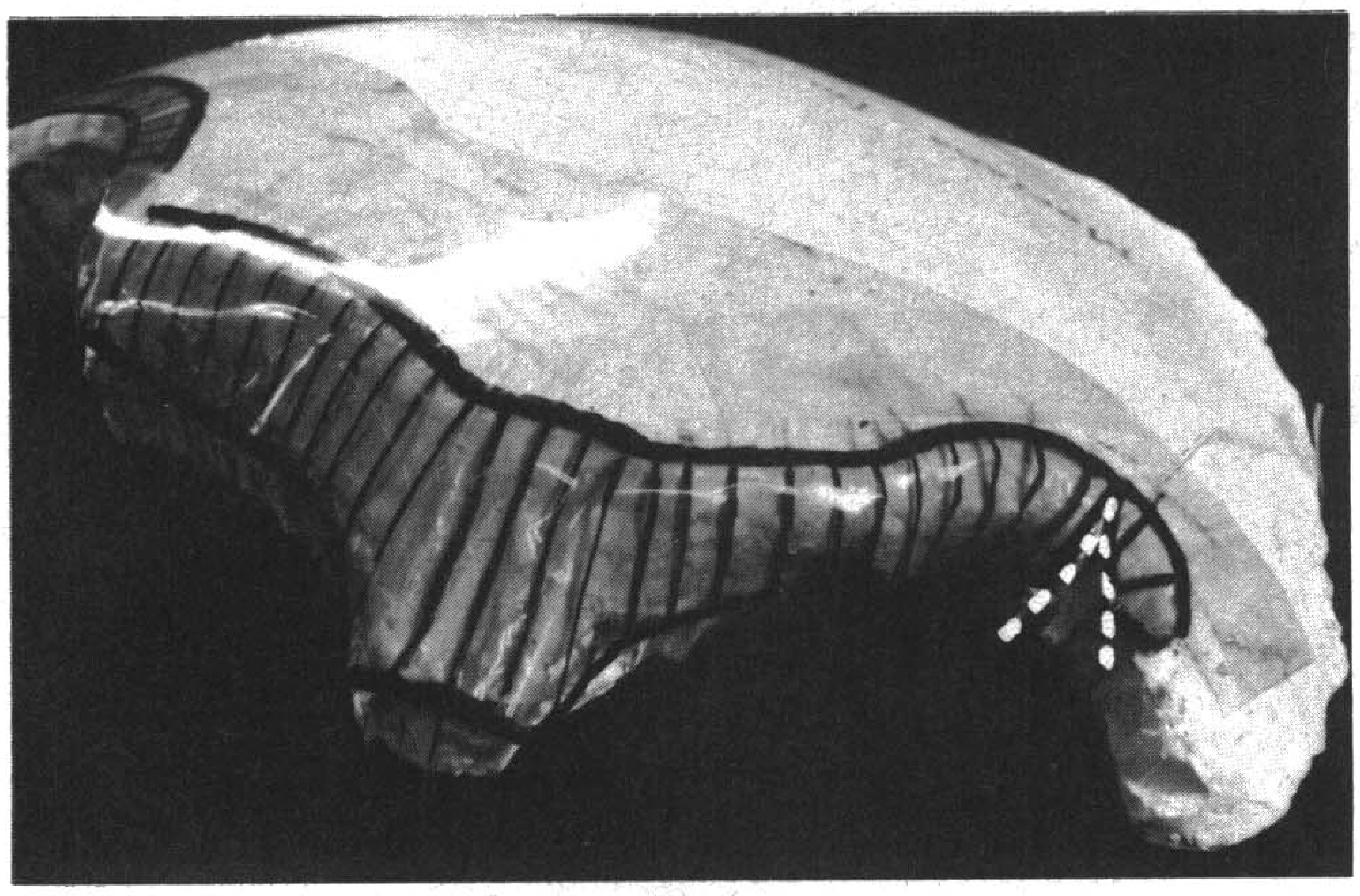

Fig. 3e. Kamchatka-Kuril-Japan-Izu-Bonin-Mariana arcs.

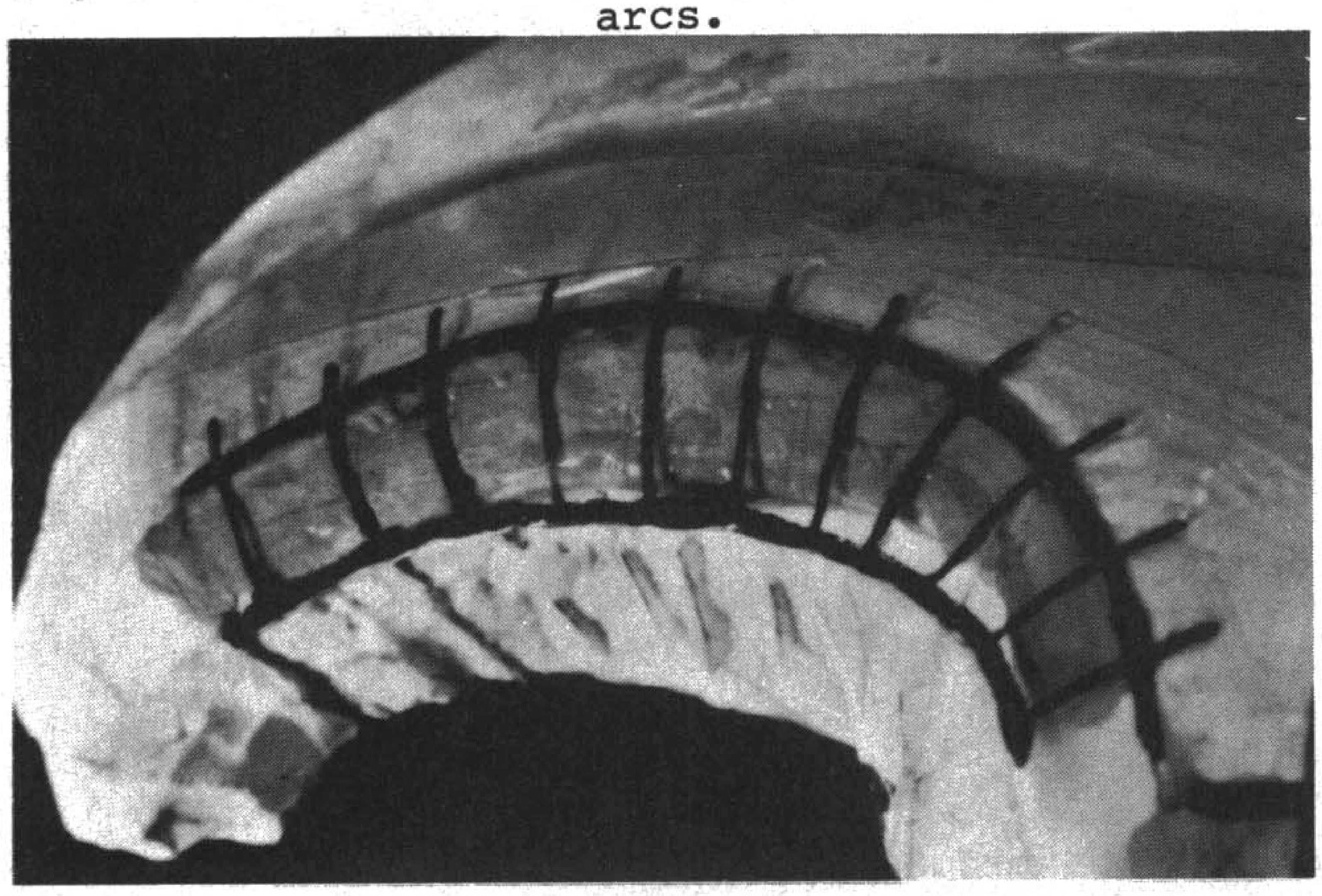

Fig. 3f. Aleutian arc.

Fig. 3g. West Indies arc.

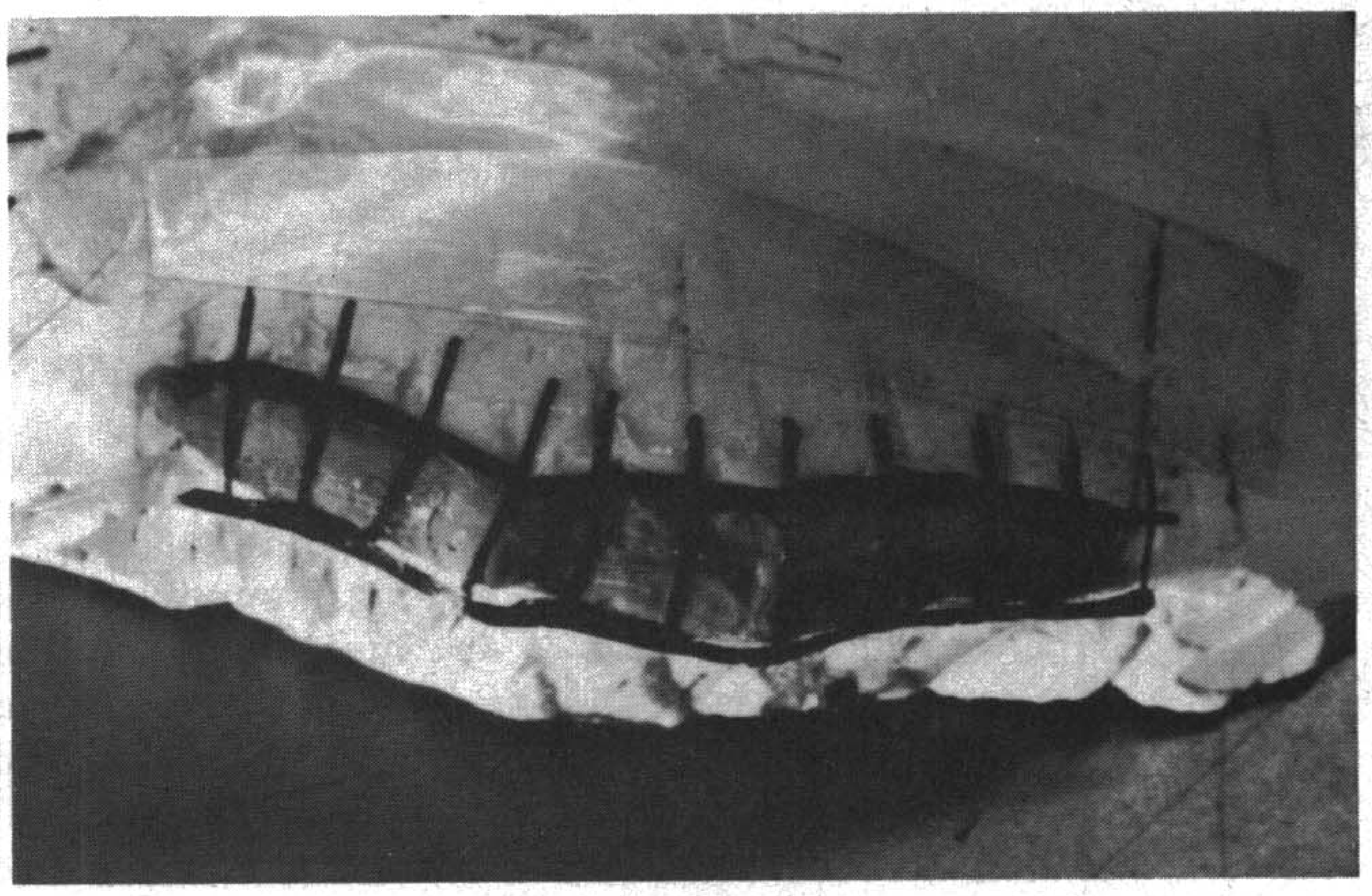

Fig. 3h. Middle American arc.

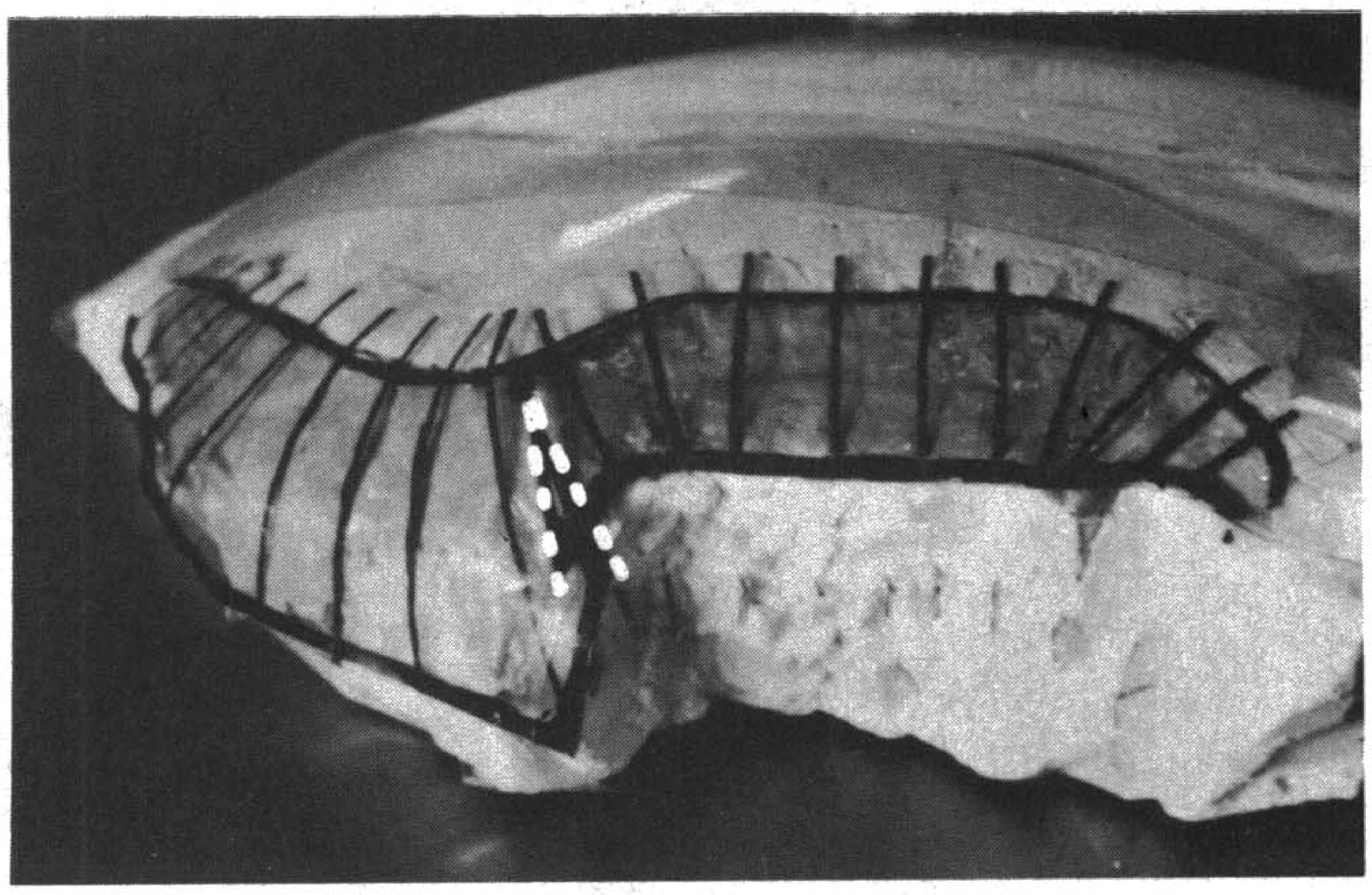

Fig. 3i. Peru and Chile arcs.

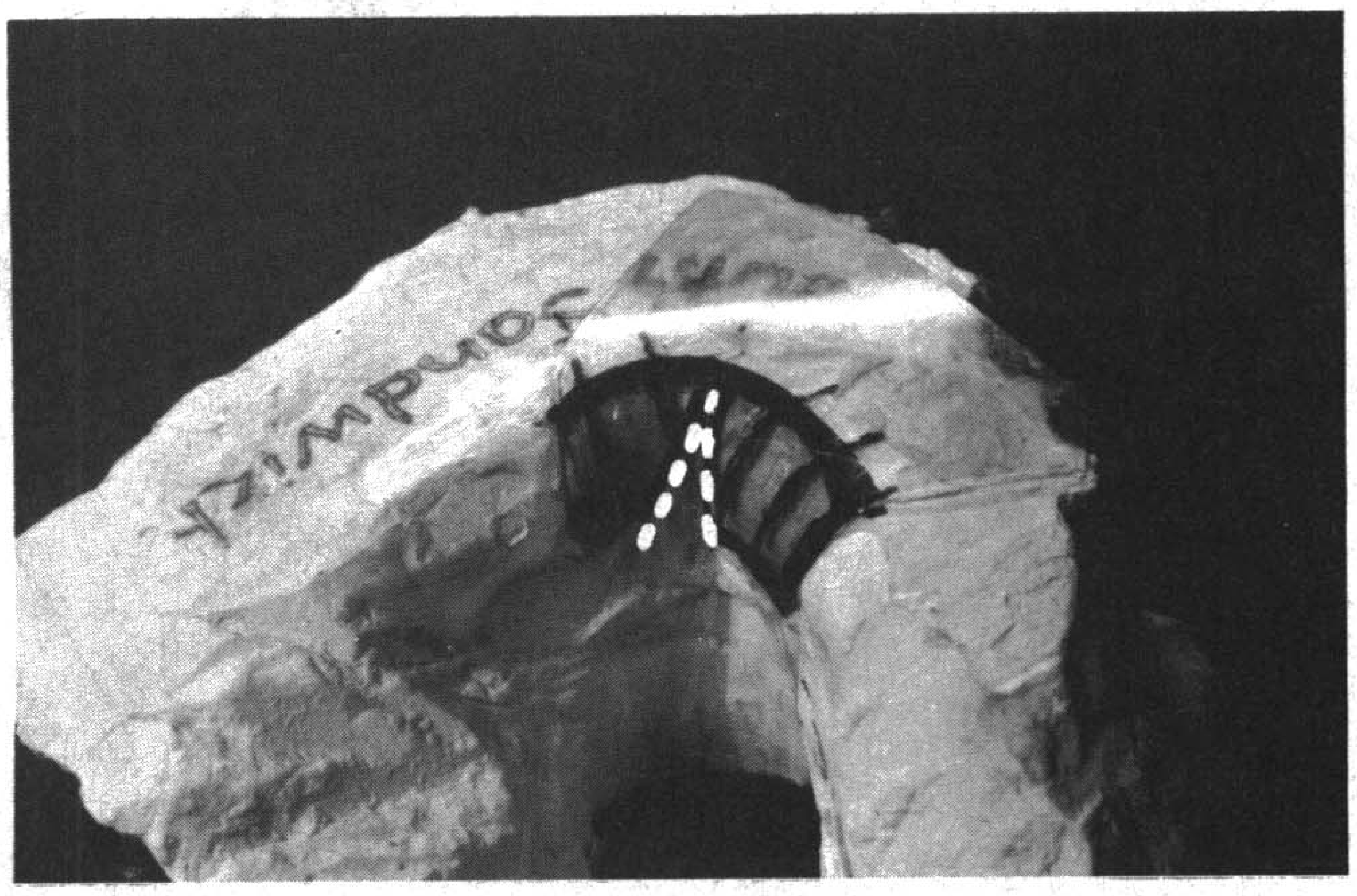

Fig. 3j. South Sandwich arc.

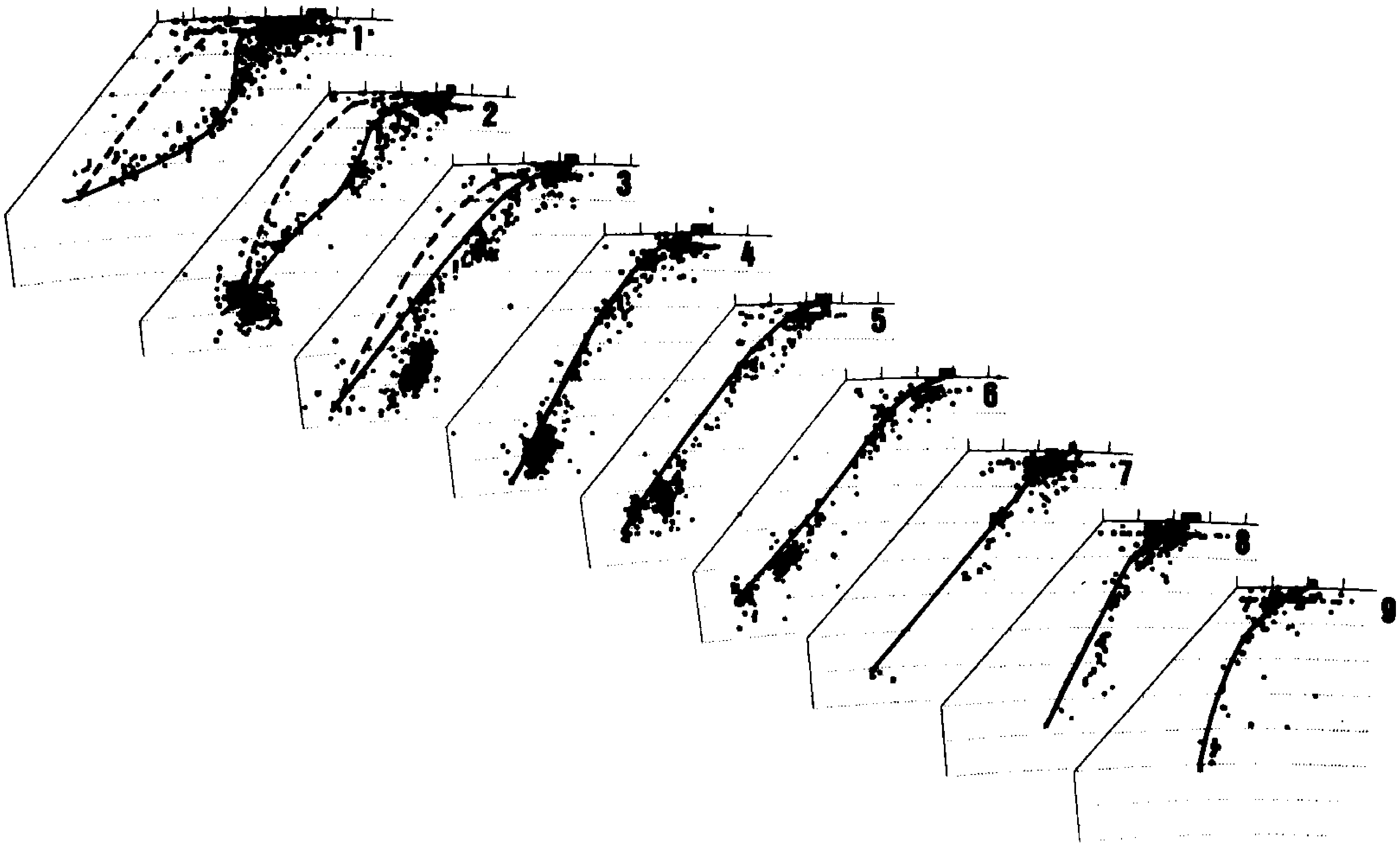

Fig. 4a. Tonga-Kermadec arc.

Fig. 4. Vertical cross sections of hypocentral distribution on which the figures of the bent spherical shell are superposed. Circles and asterisks denote the hypocenters determined by P and S arrival times and pP-P times, respectively. Dashed and solid lines indicate the cross-sectional figures of the vinyl shell fitted to the miniature of the Wadati-Benioff zone before and after the introduction of tear, respectively. Note that tearing in one place makes the fit significantly better over a great distance along the arc. Larger symbols denote larger events. A thick solid line indicates the cross sectional figure of the bent spherical shell. Regions and localities specified by letters and numbers are referred to Fig.2.

Fig. 4b. New Britain-Solomon-New Hebrides arcs.

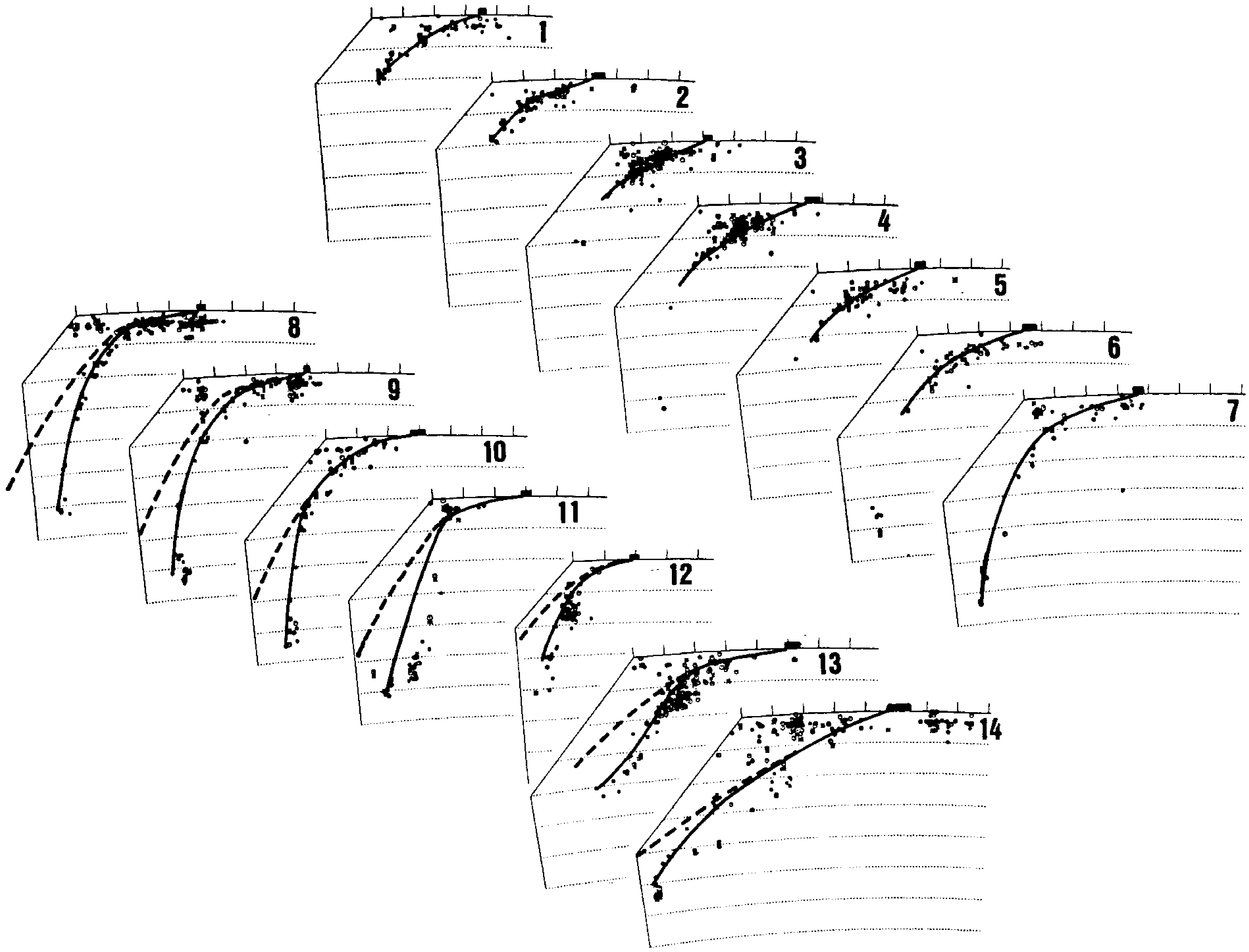

Fig. 4c. Indonesian arc.

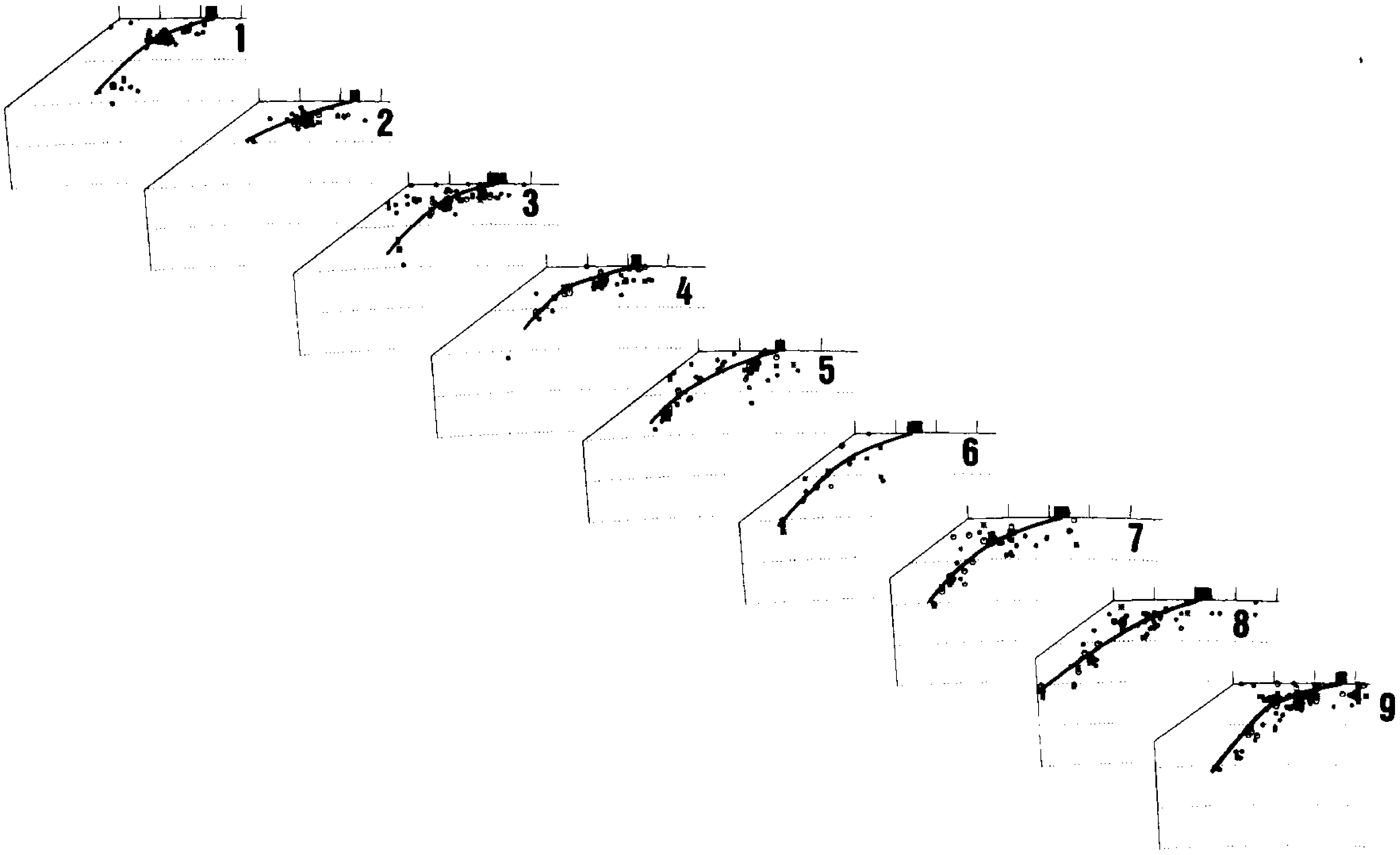

Fig. 4d. Ryukyu arc.

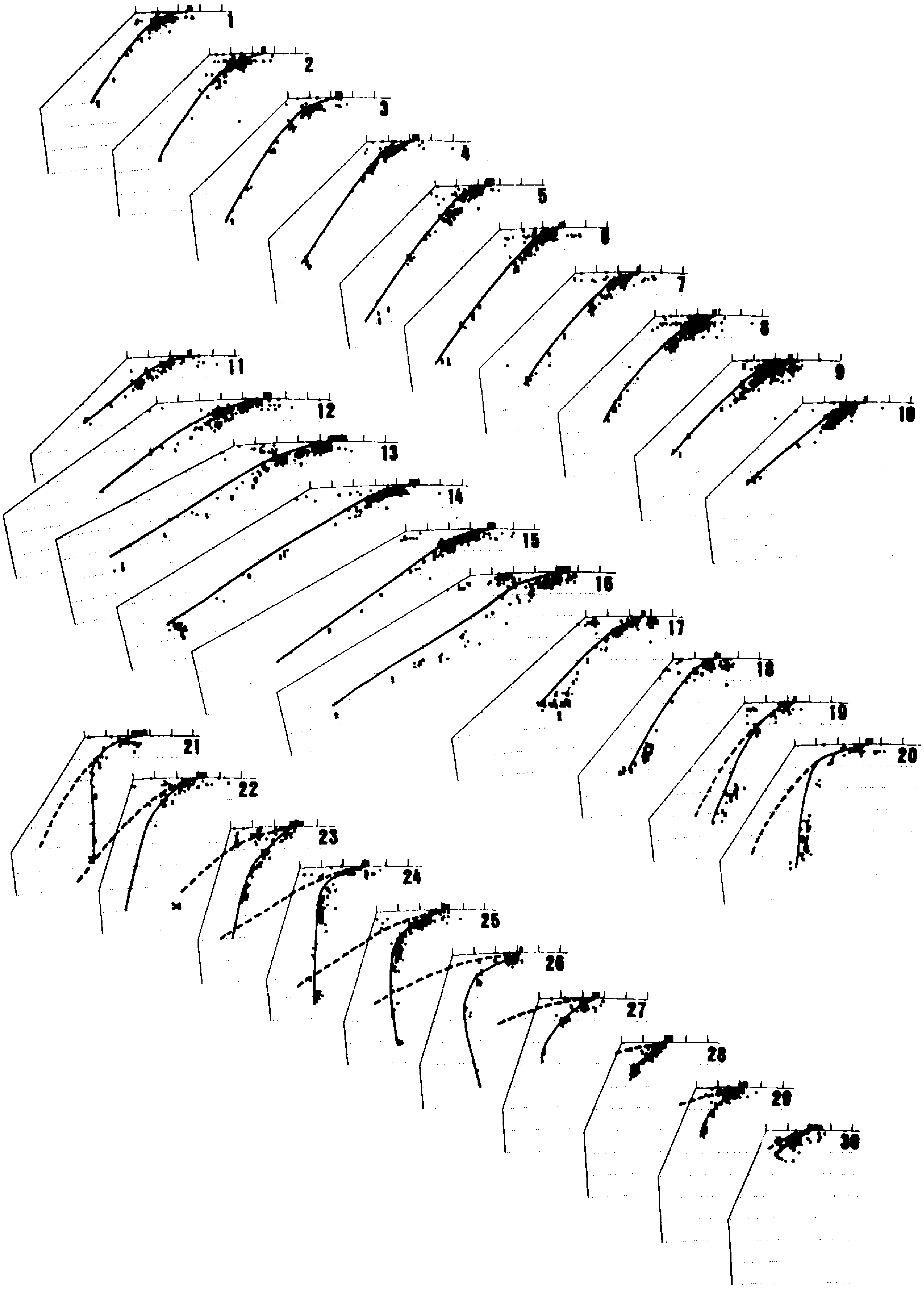

Fig. 4e. Kamchatka-Kuril-Japan-Izu-Bonin-Mariana arcs.

nesian arc. In our interpretation the slab edge just to the north of the semicircular gap had been attached to the slab edge just to the south of it before lithospheric tearing. The focal mechanisms of events 20 and 30 of Cardwell and Isacks [1978] may be interpreted as hinge faulting associated with this tearing.

Ryukyu Arc

The Ryukyu trench is relatively short, about 1000 km, along its strike from Kyushu to Taiwan. The lithosphere of the Philippine Sea plate subducts into this trench northwestward. Although this trench is connected eastward to the Nankai

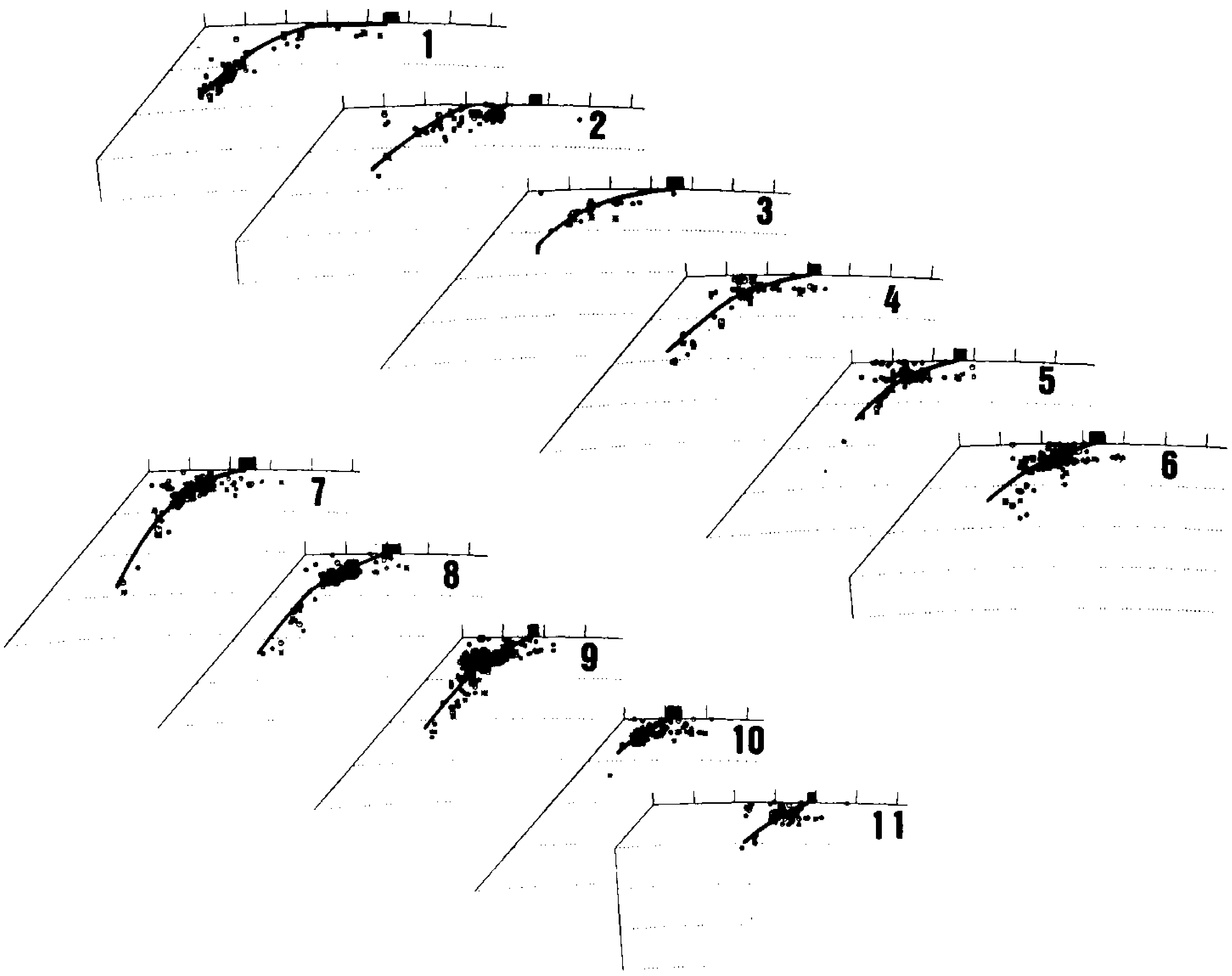

Fig. 4f. Aleutian arc.

trough, the latter is ignored in the present analysis as the Wadati-Benioff zone of the Nankai trough is very short, reaching a depth of only 70 km [Shiono et al., 1980; Ukawa, 1982; Inoue and Yamaoka, 1985].

The configuration of the deep seismic zone in this region has been studied by Katsumata and Sykes [1969] and Shiono et al. [1980]. Figure 2d shows a seismicity map based on the ISC data. The Wadati-Benioff zone to the south of Kyushu reaches a depth of about 300 km with an almost uniform dip angle. Beneath Kyushu, the dip angle is somewhat greater. The trench axis bends sharply westward at its southern end.

Figures 3d and 4d show the result of the shell fitting. A good fit is achieved solely by bending except near the southern end of the arc, where some difficulty is encountered in fitting. Figure 6 shows the hypocentral distribution viewed from a different angle, which exhibits more clearly the westward bend of the seismic zone at its southern end. The intermediate-depth activity terminates abruptly to the end of the westward bend where the subducting slab is suggested to be detached from the surface lithosphere further westward. The western end of the slab is presumed to be free from lateral constraint. The hinge fault mechanisms of nearby

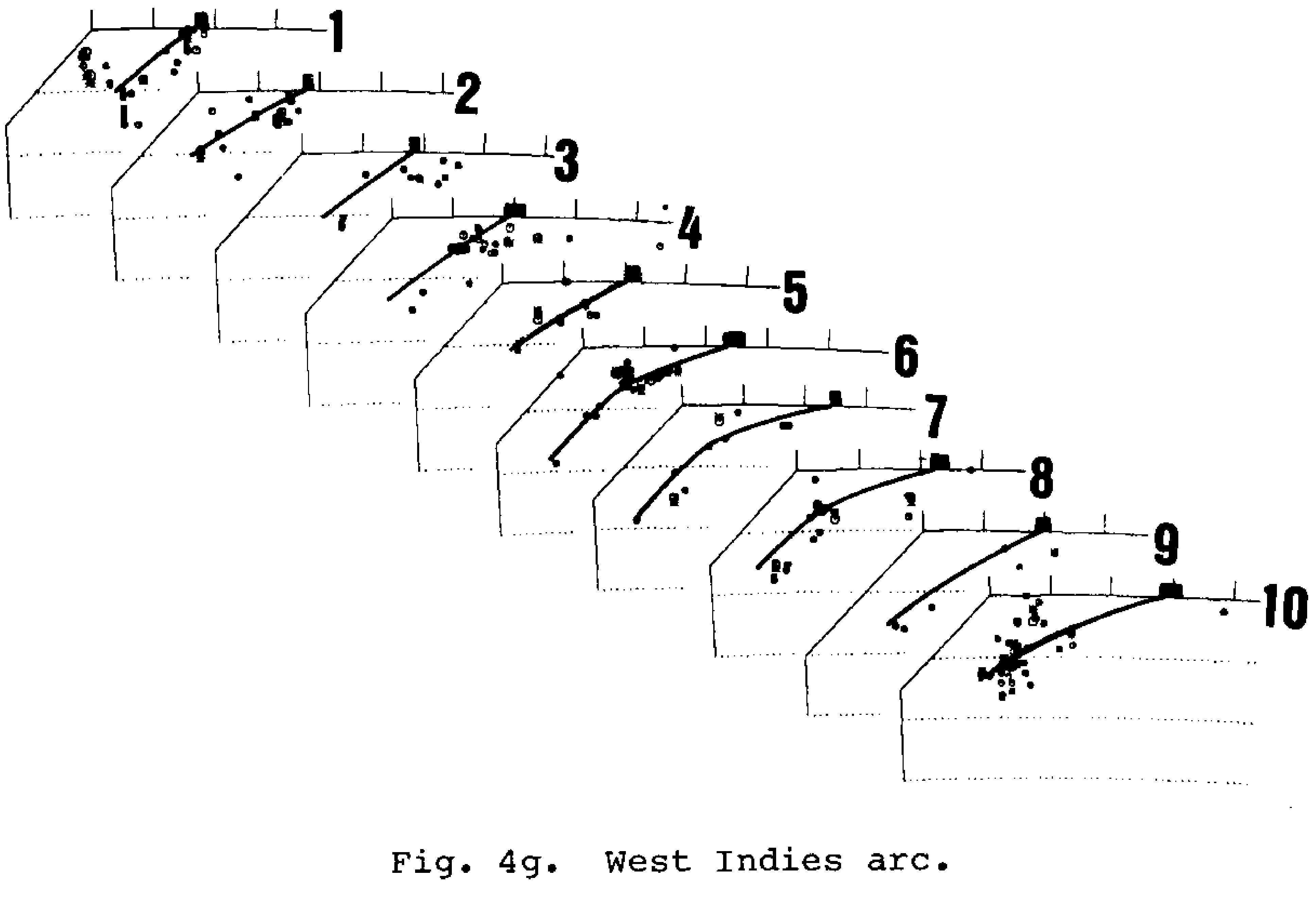

Fig. 4g. West Indies arc.

Fig. 4h. Middle American arc.

earthquakes at depths around 100 km are consistent with this idea [Katsumata and Sykes, 1969; Wu, 1978b]. After the shell is torn so that the western end of the bent portion of the shell is free from lateral constraint, an excellent fit is achieved along the entire arc.

Kamchatka-Kurile-Japan-Izu-Mariana Arcs

The Pacific plate in the western Pacific subducts along the long trench system from Kamchatka to Mariana. Figure 2e shows the hypocentral distribution of intermediate- to deep-focus earthquakes along this trench system. The events plotted are selected from the ISC bulletins so that their magnitudes are greater than 4.5 and their hypocenters are determined by more than 10 first arrivals. This hypocentral distribution is consistent with the results of previous workers [Tarakanov, 1979; Annaka, 1977; Horiuchi, 1977; Yoshii, 1979; Katsumata and Sykes, 1969; Isacks and Barazangi, 1977].

The shape of the trench axis is generally convex oceanward (Kurile-Kamchatka, Honshu, and Mariana), but the Izu-Bonin trench is almost straight. The Wadati-Benioff zone dips at about 60° beneath the Kurile-Kamchatka region and reaches about 600 km depth in the middle portion of the arc. The dip angle becomes progressively shallower southwestward along the Kurile arc and is only about 30° at the Northern Honshu arc. The downgoing slab of the Northern Honshu arc extends over 1300 km along its dip beneath the Japan Sea. No such straight and long subducting slab exists in other subduction zones of the world. From the Honshu to the Izu-Bonin arcs the dip of the descending slab becomes progressively steeper southward. To this end, in the Mariana arc, the dip angle becomes as steep as about 90°. The Wadati-Benioff zone extends down to depths of more than 600 km. At the southern part of the Mariana arc, however, the leading edge reaches only a depth of 200 km.

This long trench system is an extreme example for demonstrating the close connection between the lithospheric inextensibility and the slab shape. Figures 3e and 4e show the result of the shell fitting. The Northern Honshu arc is short along its strike and dips gently as compared to the Kurile-Kamchatka arc to the north and the Izu-Bonin arc to the south. For these neighboring three arcs, reasonably good fit is achieved only by bending at a variety of dip angles and widths of the slab.

The marked contrast in dip angle of the deep seismic zone between the Northern Honshu arc and the adjacent two arcs can be interpreted as a direct consequence of the lateral continuity of the inextensible lithosphere. In general, the slab near the arc-arc junction tends to dip at a shallower angle than the slab far from it because of the lateral constraint of the slab across the junction [Aoki, 1974b]. This tendency can be compared to the shallow dip nature of the Honshu slab, which is short along its strike. The adjacent two large slabs with large dip angles prevent the Honshu slab from bending more steeply than at the present shallow angle.

A good fit is not possible to achieve for the very steeply dipping Wadati-Benioff zone in the Mariana arc when fitting is attempted only by bending (Figure 4e). The poorness of fit is extreme, extending northward to the middle portion of the Izu-Bonin arc. There is, however, a

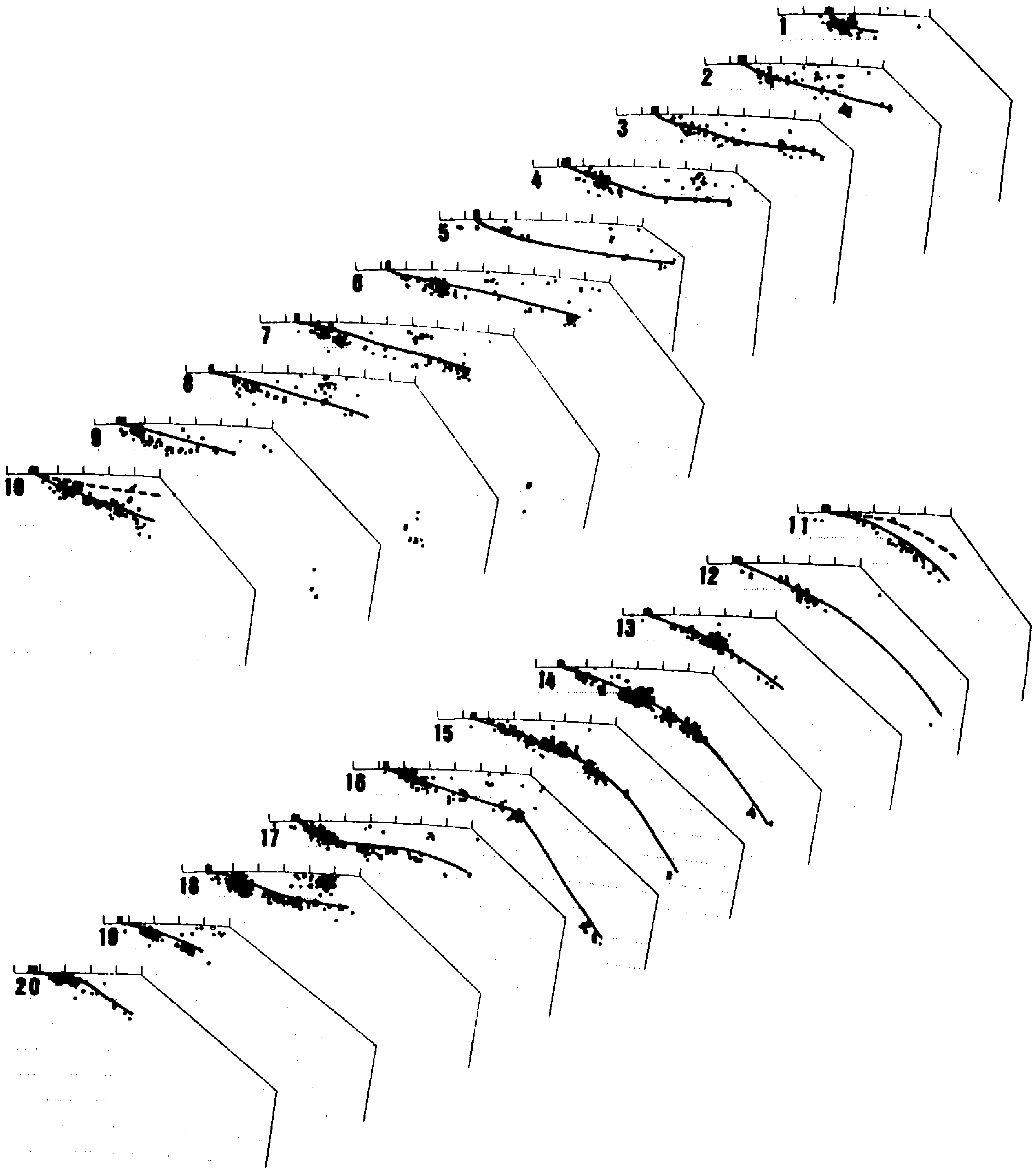

Fig. 4i. Peru and Chile arcs.

distinctive seismic feature suggesting a tearing of the lithospheric slab in this region. The leading edge of the Wadati-Benioff zone lies at depths of more than 600 km in the northern and middle parts of the Mariana arc, but at depths of only about 250 km in the southern part. The discontinuous change occurs across the latitudinal line at about 13°N. When the model slab of shell is cut roughly along this latitudinal line, an excellent fit follows. The bent shell after tearing reproduced the observed distinctive change in seismicity across 13°N. The model suggests that the leading edge of the southern slab had been attached to the southern edge of the northern slab before the lithosphere was torn.

For the part of the Northern Honshu arc the bent shell tends to dip somewhat shallower than

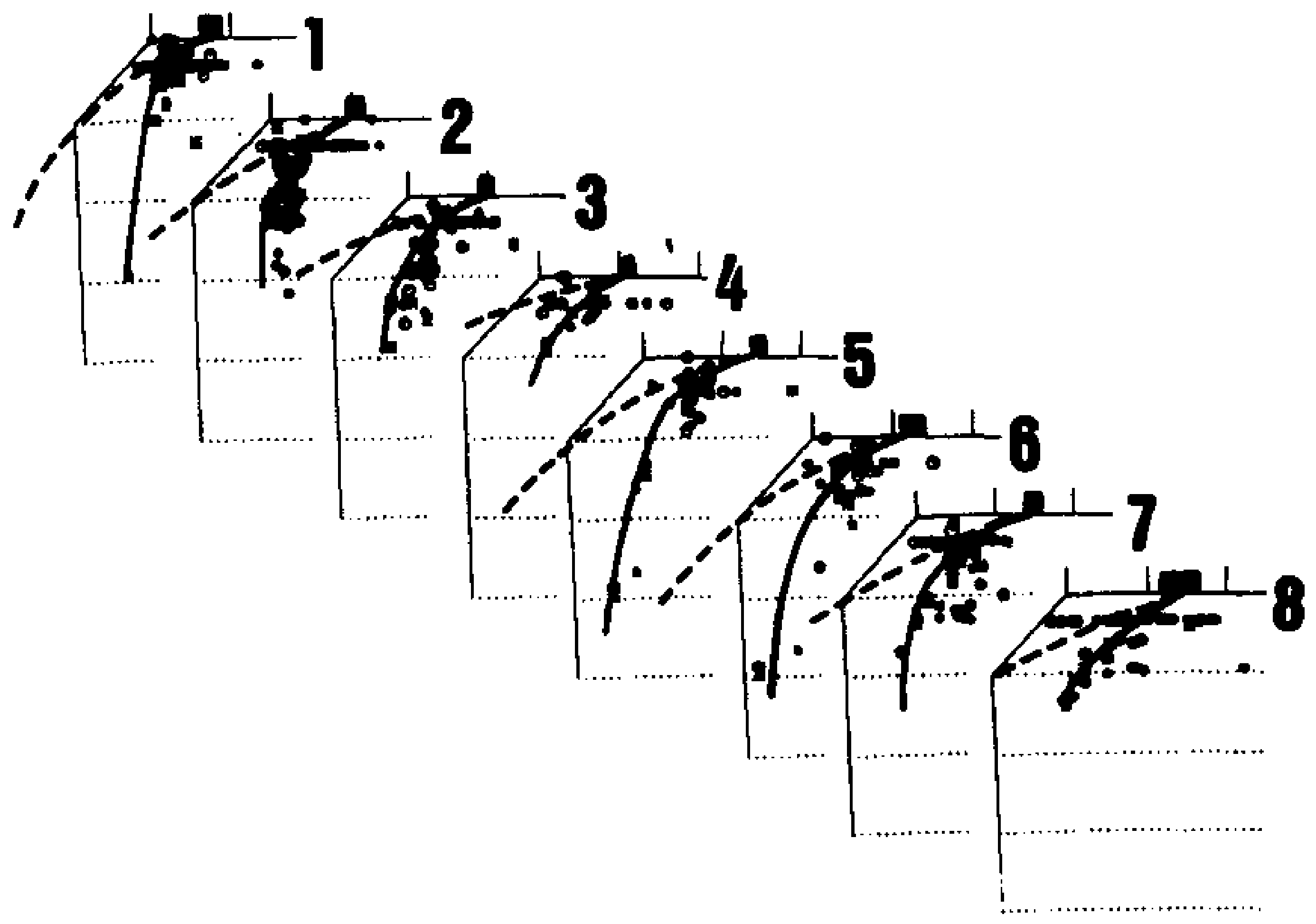

Fig. 4j. South Sandwich arc.

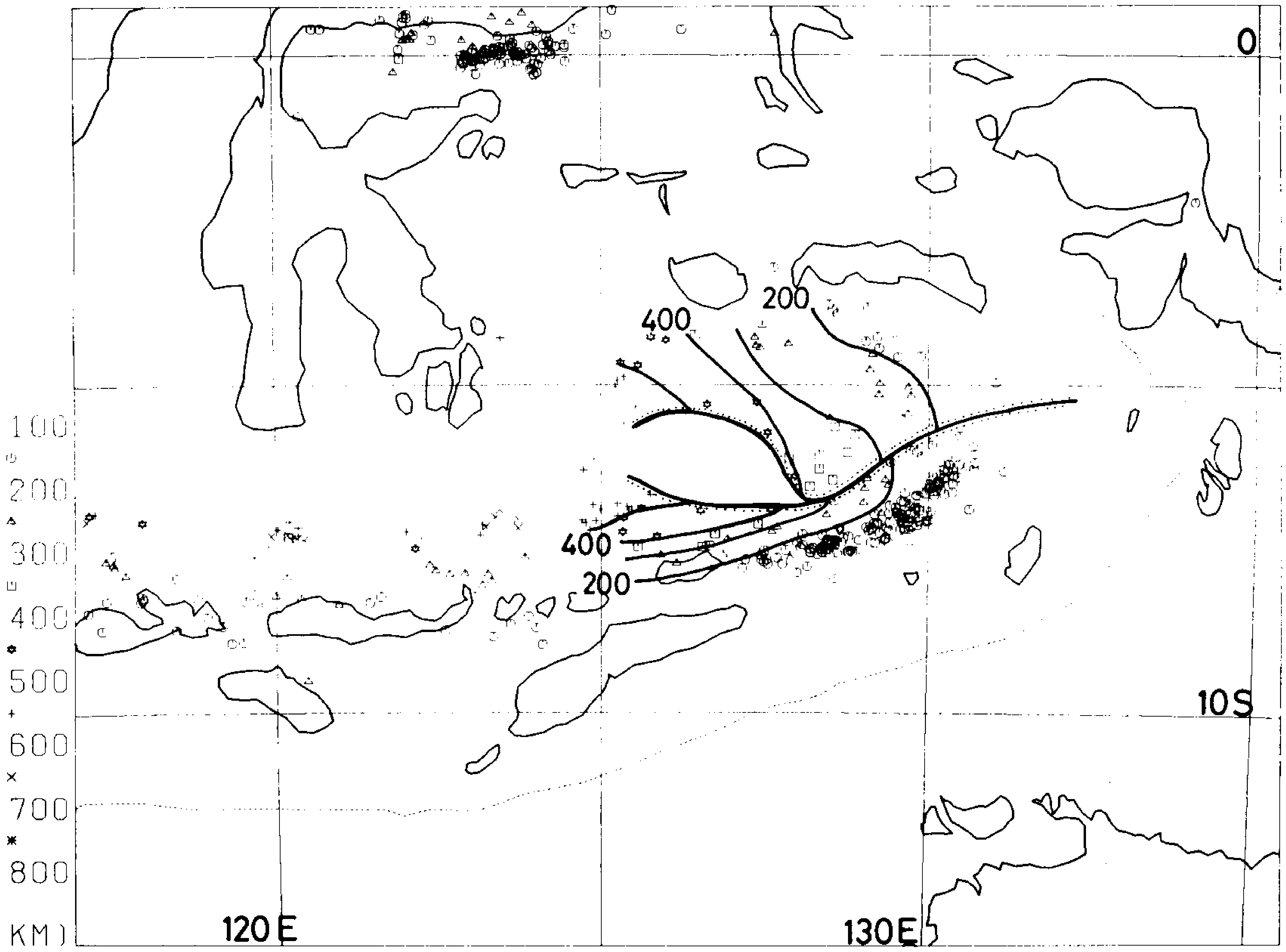

Fig. 5. Focal depth contours in the Banda Sea region drawn on the basis of our fitting experiment. The solid lines with dots indicate the torn portions of the shell which were attached to each other before tearing.

the real deep seismic zone. This tendency is particularly apparent in section 13 near the junction of the Kurile and the Northern Honshu arcs and in section 16 near the junction of the Northern Honshu and the Izu-Bonin arcs. Recently, a careful study has been made of the hypocentral distribution of intermediate-depth earthquakes near the Kurile-Northern Honshu junction [Hasegawa et al., 1985], according to which the deep seismic zone at depths greater than 200 km changes its dip abruptly across the Kurile to the Northern Honshu arc. Such an abrupt change in dip may suggest a tearing of the descending slab. Sasatani [1976] reported several intermediate-depth earthquakes having mechanisms of vertical hinge fault type consistent with the idea of lithospheric tearing in the relevant region. Intermediate-depth earthquakes of similar mechanisms have also been reported at the junction of the Northern Honshu and the Izu-Bonin arcs by Isacks and Molnar [1971] and Aoki [1974b], who suggested a slab tearing there. Lithospheric tearing suggested at the above two junctions is not so extensive as to cause an apparent gap in seismicity, but it provides a reasonably good explanation for the observed small misfit of the bent shell to the miniature of the deep seismic zone.

At the junction between the Izu-Bonin and the Mariana arcs there is an isolated seismic activity near 600 km depth, leaving a marked gap in seismicity at shallower depths. Here the bent shell forms a sharp cusp as seen in section 22 of Figure 4e. If the downgoing slab is continuous from its shallowest to its deepest parts, the misfit is apparently serious. If, on the other hand, the activity at greatest depths is ignored, the situation would be quite similar to the one we have already seen at the junction between the Solomon and the New Britain arcs, where the bent shell forms a sharp cusp in the absence of the corresponding deep seismicity. It is quite likely that the isolated activity at greatest depths is the one within a detached slab of lithosphere. We do not consider that this activity is evidence against the inextensibility of the lithospheric slab.

Aleutian Arc

The Aleutian trench extends over 3000 km along its strike from Alaska to the Kamchatka peninsula. Along this trench there are no marked cusps or junctions. The trench line is smooth, and the curvature is slightly greater in the western portion. Local seismograph networks have recently been established in two areas, one in the vicinity of Amchitka Island ($178^{\circ}-180^{\circ}$)E [Engdahl, 1977] and the other in the vicinity of the Shumagin Islands (160°W) [Reyners and Coles, 1982; Davies and House, 1979]. Comparison of these data with the well-determined ISC data indicates that the results based on teleseismic data show no substantial bias or distortion for the spatial distribution of earthquakes at depths greater than 50 km [Barazangi and Isacks, 1979a].

Earthquakes along this trench are mostly

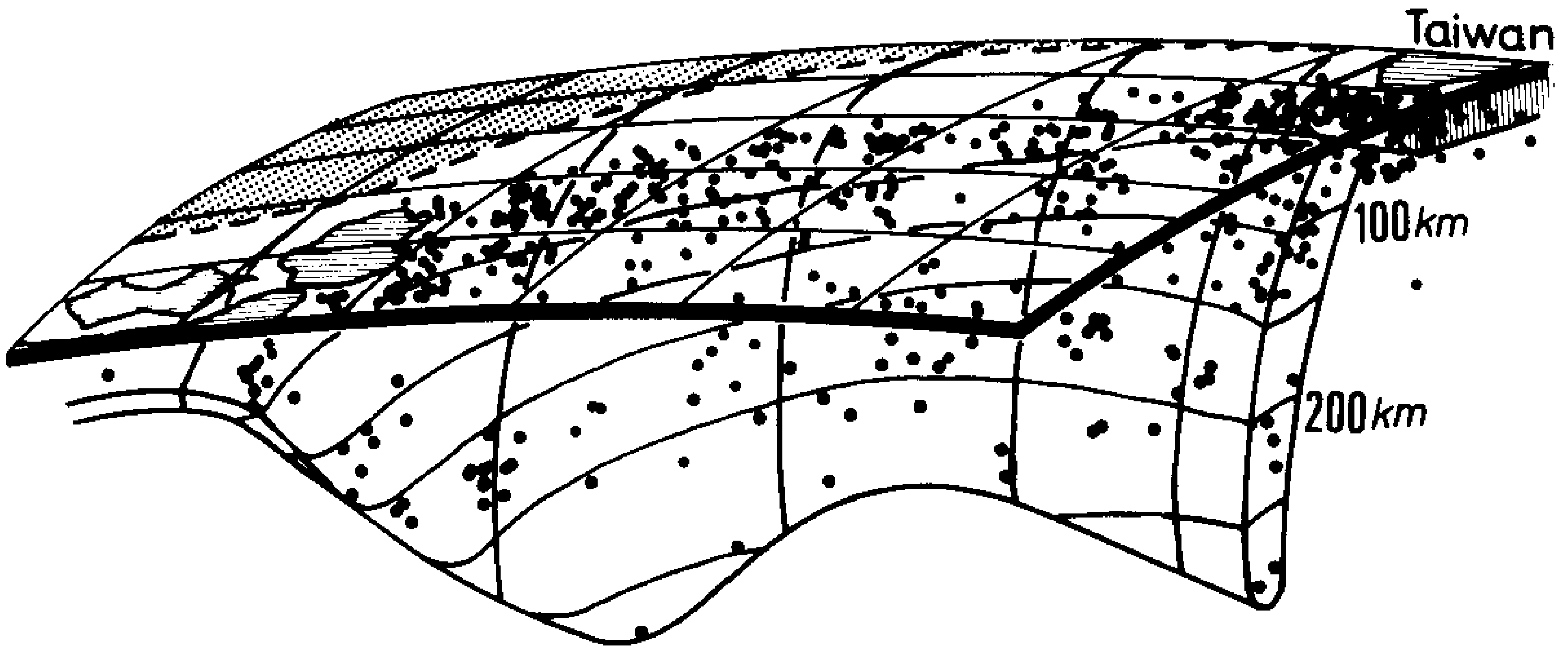

Fig. 6. Oblique view of the hypocentral distribution in the Ryukyu region. The intermediate-depth activity terminates abruptly at its western end near Taiwan as if the subducting slab is detached there from the surface lithosphere further westward.

confined to within 200 km in depth and do not exceed a depth of 300 km (Figure 2f). In the westernmost portion (west of 175°E) the length of the Wadati-Benioff zone is very short, reaching only 100 km in depth. In the eastern portion near the Alaska peninsula, the Wadati-Benioff zone dips at an extremely low angle from the trench to a depth of about 50 km. In general, the whole Wadati-Benioff zone is more gently dipping in the eastern part than in the western part. This trend seems to be inconsistent with the variation of the curvature of the trench, because the dip angle of an inextensible subducting slab is expected to have a negative correlation with the curvature of the arc, according to the Frank's [1968] model. A good fit of the spherical shell to the miniature of the Wadati-Benioff zone, however, can be achieved simply by bending (Figures 3f and 4f). As can be seen in Figure 2f, the distance between the trench axis and the intersection of the upward extension of the trend of the deep seismicity with the earth's surface is greater toward the east. This makes the curvature of the 100-km contour line nearly constant along the arc, although the curvature of the trench axis is smaller in the east. Such a uniformity of the curvature of the 100-km contour line is the reason why a good fit is possible without tearing. Though the possibility of lithospheric tearing has been suggested beneath the Bowers ridge near Amchitka Island [Abe, 1972], there is no indication for it in the observed seismicity and in our shell-fitting experiment.

West Indies Arc

Along the trench in the West Indies region, the Atlantic oceanic basin subducts beneath the Caribbean plate. Two plates, the North American and the South American, subduct in contact with each other at about 14°N. The topographic boundary is, however, uncertain, and the relative motion between them is as small as 0.2-0.3 cm/yr according to the relative motion model of Minster and Jordan [1978]. Because of this smallness we regard the slabs subducting along the trenches as a continuous slab. Although the trench can be traced clockwise from Honduras to Venezuela (the Cayman trough, the Puerto Rico trench, and the Lesser Antilles trench), the events deeper than 50 km occur only to the east of 75°W (Figure 2g). Along the Lesser Antilles arc, although the axis of the trench is uncertain, the Wadati-Benioff zone extends to depths of about 250 km, whereas the deepest events occur at depths around 150 km along the Puerto Rico trench.

The fit of the spherical shell to the miniature of the West Indian deep focal zone can be achieved simply by bending without tearing (Figures 3g and 4g).

Middle American Arc

The Middle American trench extends from the mouth of the Gulf of California to off Panama along the southern coast of Middle America, where the Cocos plate subducts beneath the two plates, the North American and the Caribbean. These two plates are bounded by the Polochic-Motagua left-lateral strike slip fault, just to the south of the Yucatan peninsula. Figure 2h shows the epicentral distribution of earthquakes. The events whose focal depths are less than 50 km are excluded to clarify the depth profile. Selected are the events whose magnitudes are greater than 4 and whose hypocenters are determined using more than 10 arrivals. The Wadati-Benioff zone of this subduction zone reaches a maximum depth of 250 km near Guatemala. The dip angle is greater in the southeastern portion than in the northwestern portion. The variation of this dip angle has been explained by the difference of the absolute motion between the North American and the Caribbean plates [Cross and Pilger, 1982].

LePichon et al. [1973] cited the Middle American trench as a unique case where the trench axis is convex landward, so that the shape of the Wadati-Benioff zone cannot be explained using the concept of lithospheric inextensibility. Detailed examination of the morphology and the seismicity based on the recent ISC data (Figure 2h), however, shows that the arc structure is segmented into three parts each of which is convex oceanward. Two arc-arc junctions can be recognized near the gulf of Tehuantepec and near Managua, where the Wadati-Benioff zone forms cusps as in other arc-arc junctions (see Figures 2h and 3h).

In our experiment the shell is able to fit the miniature of the Wadati-Benioff zone simply by bending (Figures 3h and 4h). Such a good fit, however, would not be possible if the cusps of the Wadati-Benioff zone at the arc-arc junctions were ignored. This result indicates the importance of high resolution in hypocentral determination for clarifying the deformational property of a lithospheric slab.

Peru and Chile Arcs

Along the coastline of Peru and Chile, from the Carnegie ridge to the Chile rise, the Nazca plate of lithosphere subducts eastward, forming the Andean mountain system on the continent. There is no back-arc basin related to this subduction zone. The relatively poor accuracy of hypocentral determination and the associated difficulty in distinguishing earthquakes in the downgoing slab from crustal events permit various interpretations about the configuration of the subducting slab. In our experiment, in general, we adopt the interpretation of Barazangi and Isacks [1979b].

The dip angle and the length of the slab vary along the Peru-Chile trench, as seen in Figure 2i. Along the coastline from Ecuador to Peru (north of 15°S), the Wadati-Benioff zone has a shallow dip (15°-20°) and reaches a depth of only 200 km. Its curvature is convex downward. Beneath the northern Peru-western Brazil region, there is an isolated deep activity, which is confined to a linear belt in a depth range 500-650 km trending about N10°W. This linear belt has been considered as a detached part of the descending slab [Isacks and Molnar, 1971; Fukao, 1972]. We therefore exclude this activity from our fitting experiment. Along the middle portion of the Peru-Chile trench (15°S-30°S) the Wadati-Benioff zone extends to depths of about 600 km at a relatively large dip angle of 30°. The curvature of the zone is generally convex upward. There is a seismic gap between depths of 300 and 500 km, but the continuation is evident from the analysis of seismograms of the deepest events [Isacks and Barazangi, 1973]. Moreover, the general trend of the Wadati-Benioff zone of the shallower portion is consistent with that of the deeper portion (Figure 4i). For this reason, we consider that the lithospheric slab in this region reaches the 600-km depth without a break. To the south of 30°S, the Wadati-Benioff zone is convex downward and reaches a depth of only 200 km with a small dip angle of 15°-20°. Thus for the Peru-Chile arc, the middle portion is characterized by the slab convex upward and dipping relatively steeply, while the north and south portions are characterized by the slabs convex downward and dipping very shallowly.

A plaster miniature is constructed according to the configuration of the Wadati-Benioff zone as interpreted above. It is impossible to fit the shell on the miniature along the entire arc by bending only. For example, when the shell is bent to fit the northern portion and the southern portion of the slab simultaneously, the fitness is poor near the bend of the Peru-Chile trench at about 19°S (Figure 4i). The surface area of the bent spherical shell becomes excessive here, and its dip angle tends to be smaller than the actual dip. This phenomenon is perhaps related to an abrupt change of the dip angle of the Wadati-Benioff zone seen in Figure 2i near the boundary between sections 10 and 11. This transition from the relatively flat Wadati-Benioff zone in central Peru to the steeper Wadati-Benioff zone in southern Peru can be interpreted as a tear in the descending slab of the Nazca plate [Barazangi and Isacks, 1979b; Chinn et al., 1980]. If the spherical shell is torn according to this interpretation, a good fit is achieved (Figure 3i). The resultant two pieces of lithospheric slab overlap each other over a maximum width of about 50 km at the greatest depths, although such an overlap is not yet observed in seismicity.

Seismic observations from a local network in this region do not show clear evidence of tearing [Hasegawa and Sacks, 1981; Boyd et al., 1984]. If, however, the downgoing slab is laterally continuous as advocated by Hasegawa and Sacks [1981], the slab must be strongly folded in the relevant region to conserve its surface area. No such evidence for folding has yet been detected. If, moreover, the downgoing slab is continuous without tearing, a strong compression must occur laterally within the slab, a mechanism which is not supported by focal mechanism studies [Stauder, 1975; Hasegawa and Sacks, 1981]. We note that introduction of tearing causes only a slight offset along the torn portion of the lithospheric slab (see cross sections 10 and 11 in Figure 4i) but it makes the fit better along the entire arc.

South Sandwich (Scotia) Arc

The South Sandwich subduction zone provides one of the best examples of lithospheric tearing resulting from the inextensibility of lithospheric slab. Along the South Sandwich trench, the South American plate is subducted westward. The length of the trench is as short as 600 km. Behind the South Sandwich arc, in the east Scotia Sea, there is a spreading center, the spreading rate being 7-9 cm/yr at present [Barker, 1972]. The hypocenters in this region are determined with poor accuracy, partly because of the lack of nearby seismograph stations. The depths determined by pP phase, however, provide us with the shape of Wadati-Benioff zone accurately enough to construct the miniature of the South Sandwich subduction zone. All along the trench, intermediate-depth earthquakes occur down to depths of 300 km, forming a deep seismic zone dipping at an angle of 60°-90° (Figure 2j).

The fit of the spherical shell to the miniature deep seismic zone cannot be achieved without tearing because the curvature of the trench axis is very large in relation to the dip of the seismic zone. More specifically, only the shallower portion can be fit by bending, and the deeper portion, which extends nearly vertically, requires a tear of the downgoing slab of lithosphere (Figure 4j). The hypocentral distribution shows a wedge-like gap of seismicity near 57°S latitude as illustrated by the dashed line, which can be interpreted as a gap of the slab itself. When the spherical shell is torn along the corresponding position, a good fit can be achieved simply by bending, and the seismicity gap is expressed as the opening of the torn portion of the lithospheric slab (Figures 3j and 4j).

Forsyth [1975] proposed a tearing of the subducting slab in the South Sandwich region based on a focal mechanism study. He attributed the events of hinge fault type with relative subsidence of the southern slab to the effects of lithospheric tearing, which are, however, located somehow northward (56°S) from the above position indicated by the hypocentral distribution. This discrepancy may not be serious because the gap in the slab represents the place where seismic activity was high in the past, but it does not necessarily correspond to the place now active in hinge faulting.

Discussion

From the results of our experiment, we conclude that a lithospheric slab has the following deformational properties: (1) The descending lithosphere manifested as the Wadati-Benioff zone is inextensible and conserves its surface shape. (2) When the subducting lithosphere is forced to deform beyond its inextensibility, tearing takes place but only locally. The subducting lithosphere is not torn into as many strips as suggested by Strobach [1973], Carr et al. [1973], and Rodriguez et al. [1976], and it does not bend by numerous vertical faults to have such a stairlike structure as suggested by Lliboutry [1969] and Freund et al. [1980].

The lateral continuity of the lithospheric slab constrains its own geometric configuration. The most striking example of such a geometric constraint is seen in the slab configuration beneath the Northern Honshu arc. The slab is narrow, about 900 km along its strike, but long extending, about 1300 km along its dip, in a straightward fashion at a shallow dip of 30°. For most other arcs the slab is longer along its strike than along its dip. For a few arcs (e.g., the Celebes arc [McCaffrey, 1982]), the slab is longer along its dip, but the dip angle is high in such a case. Long and shallow dipping extension of the lithospheric slab is unique to the Northern Honshu arc. This arc is a part of the long chain from the Kamchatka arc to the Mariana arc and is sandwiched by the Kurile and Izu-Bonin arcs, both of which are quite long not only along their dips but also along their strikes. Apparently, the long and wide slabs of the Izu-Bonin and the Kurile arcs geometrically prevent the Japan slab from dipping steeply. This situation is strikingly similar to the lithospheric cusp, with a shallow dip seen at an arc-arc junction.

The dip angle of the lithospheric slab varies along a trench. The configuration of the trench axis is different among different subduction zones in the world. Our experiment does not consider why a lithospheric slab dips at its present angle and why the trench axis curves in its present form. Our experiment, however, does indicate that the inextensible nature of the lithosphere is one of the most important factors that determine the geometric configurations of the downgoing slab and the trench axis, which constrain one another. The simplest constraint is known as Frank's relation. Though many other factors have been suggested for consideration, (e.g., the age of the lithosphere [Cross and Pilger, 1982], the absolute velocity of the upper plate [Wu, 1978a; Horiuchi, 1977], the role of a lubricant layer between the subducting slab and the surrounding asthenosphere [Jischke, 1975], the existence of sea mountains [Cross and Pilger, 1982], or a large-scale mantle flow driven by the motion of the lithosphere [Hager and O'Connel, 1978]), the inextensibility of the lithosphere and the concentration of strain into a local region are certainly the major factors that control the slab geometry and its evolution.

The deformation of the subducting slab has to accompany some stresses, which are induced internally due to the lateral continuation and the finite thickness of the slab. Stresses may also be generated by some external force in the asthenosphere. The phenomenon of a double-planed seismic zone, most remarkably observed in the Northern Honshu arc [Hasegawa et al., 1978], is intriguing in this respect. Several theories have been proposed to explain the origin of a double seismic zone: unbending of the subducted lithosphere [Engdahl and Scholz, 1977; Isacks and Barazangi, 1977; Tsukahara, 1980], thermal stresses within the lithosphere [Goto and Hamaguchi, 1983; House and Jacob, 1982], and sagging of the slab into the asthenosphere [Sleep, 1979]. All these theories assume that the subducting slab must be concave downward in its stress-free state and therefore that a straight slab such as seen beneath northeastern Japan experiences compressional and extensional stresses in its upper and lower planes. No satisfactory explanation, however, seems to have been given for why the slab has unbent to become straight. The result of our experiment gives a hint to this fundamental question. We have shown that the northern Honshu slab is simply straightened by the lithospheric inextensibility or by its internal stress originating from the lateral constraint. The presence of an external force acting on the deforming portion is not a "necessary condition" to unbend the lithosphere.

We have found in our fitting experiment that there are several arcs where the deep seismic zone is too steeply dipping to achieve a good fit by bending only. The examples are the South Sandwich arc, the south Mariana arc, the northern end of the Tonga arc, the southern end of the Ryukyu arc, and the Banda Sea region of the Sunda arc. In all of these arcs, some seismicity gaps are observed, and tearing of the spherical shell explains both the seismic gap and the shape of the deep seismic zone. Of the five arcs cited above, all but the last have an active spreading center behind the arc: the Scotia basin, the Mariana trough, the Lau basin, and the Okinawa trough, respectively [Uyeda and Kanamori, 1979; Karig, 1971; Taylor and Karner, 1983]. The northern end of the Tonga arc and the southern end of the Ryukyu arc are marked by a sharp bend of the trench axis and an abrupt termination of deep seismicity at that bend. A similar feature is also seen at the southern end of the New Hebrides arc, which has again an active spreading center behind it, the Fiji Plateau [Weissel, 1981]. Although tearing was not required for this arc in our fitting experiment, this is simply because we ignored a sharp bend of the seismicity at depths shallower than 100 km. If the seismicity shallower than 100 km is taken into account, tearing should certainly be necessary, as suggested from focal mechanism studies [Johnson and Molnar, 1972; Pascal et al., 1978].

Thus, with the notable exception of the Banda Sea arc, the back arc opening is apparently

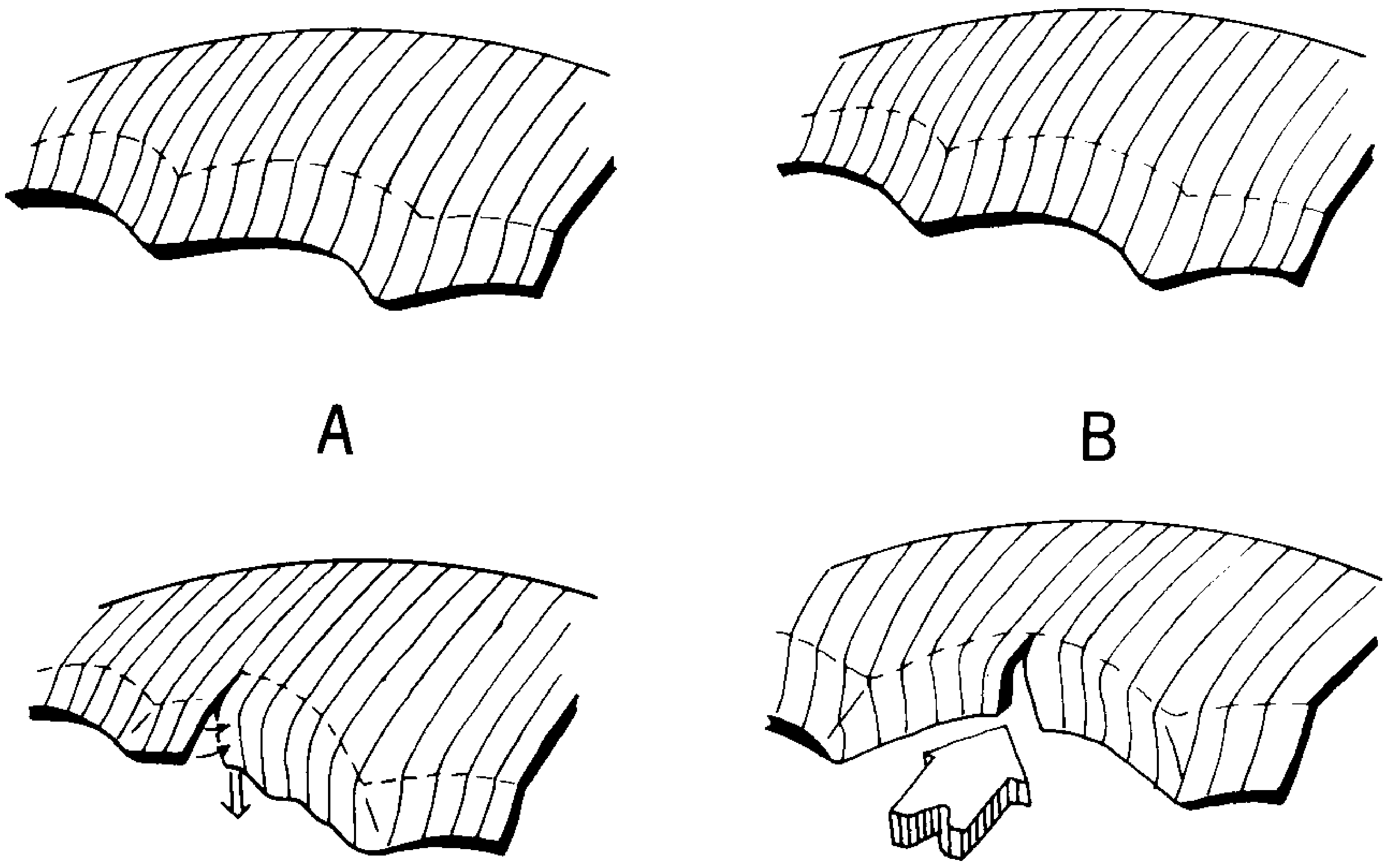

Fig. 7. Schematic illustrations of mechanisms of back-arc opening. (Left) Tearing of the subducting slab causes back-arc opening. (Right) Back-arc opening causes tearing of the subducting slab.

associated with a tearing and the resultant opening and steepening of the subducting slab, implying some causal relationship between them. The causality can be considered in one way or the other. First, we discuss the case in which lithospheric tearing is a result of back-arc opening. The asthenosphere flow associated with the back-arc opening pushes the subducting slab oceanward. The flow can be either the local flow upwelling beneath the back-arc basin, as proposed by Elsasser [1971], or the regional flow, as proposed by Uyeda and Kanamori [1979], Dickinson [1978], and Alvarez [1982]. As schematically illustrated in Figure 7b, the local flow would tend to make the trench axis convex oceanward. The regional flow would tend to steepen the downgoing slab. In either case, tensional stress arises within the slab "along" its strike to cause lithospheric tearing.

Alternatively, lithospheric tearing may be the cause of back-arc opening. Once the lithospheric slab is torn, the resultant two edges of the slab are free from lateral constraint. Those slab segments which have lost their lateral support tend to exert a downward pull on shallower segments owing to their own weight. This pull may cause a retrograde motion of the trench, particularly near the region of lithospheric tearing. This retrograde motion of the trench will open the back-arc basin (Figure 7a). Such a retrograde motion was observed in a paraffin model experiment of plate tectonics by Jacoby [1976]. In his experiment the lithosphere is simulated as a thin skin of paraffin floating on molten paraffin, which is less dense and much less viscous than the solid paraffin. During the subduction of the thin skin of paraffin, the "trench" migrates backward by the negative buoyancy force of the descending skin, as first suggested by Elsasser [1971]. Note that this skin of paraffin is a "plate" rather than a "spherical shell." It simulates only the slab portion near the place of tearing which is free from lateral constraint. The retrograde motion of the free edge of a slab may thus be one of the factors which cause the opening of the back-arc basin, although an exception is observed at the Banda Sea arc. Here the Australian continental crust is colliding with the trench, and its buoyancy may prevent the trench from a retrograde motion.

The arc-arc junction forms a cusp of the Wadati-Benioff zone which can be interpreted as an excessive part of the bent spherical shell. Strangely, such a cusp often lacks deep seismicity. This aseismic nature at depths is observed most typically at the junctions between the Solomon and the New Britain arcs and between the Izu-Bonin and the Mariana arcs, but upon close inspection it can also be found at the junctions between the Kurile and the Northern Honshu arcs and between the Northern Honshu and the Izu-Bonin arcs. A body wave tomographic study may be useful to delineate this aseismic part of the downgoing slab. For the moment the question of why it is aseismic remains unsolved.

The smooth Wadati-Benioff zone associated with the great bend of the Peru-Chile trench is also difficult to interpret, as this is an excessive part of the bent spherical shell. Although folding or tearing and the resultant overlapping are to be expected here, seismic evidence of such a process has not been elucidated. Although we tentatively assumed tearing in our fitting experiment, we must await a further study for the fine structure of the subducting slab in this region.

In this section, we discussed a few examples of the possible tectonic significance of the spherical shell of lithosphere. To conclude this section, we emphasize that the mechanical behavior of the spherical shell itself has the potential to explain a diversity of tectonic phenomena related to subduction.

Conclusion

The deformational property of the subducting lithosphere is examined using an inextensible spherical shell as its analogue. The results of our experiment are summarized as follows: (1) The subducting lithosphere, which is manifested as the Wadati-Benioff zone, is inextensible in the sense that it almost conserves its surface shape and area. (2) The subducting lithosphere undergoes large deformation by tearing as a consequence of strain concentration into a local region. There is some indication that lithospheric tearing is related to the opening of back-arc basins. (3) Lateral constraint of the subducting lithosphere is one of the very important factors that determine the geometrical configuration of descending slabs and of the trench axes.

References

Abe, K., Seismological evidence for a lithospheric tearing beneath the Aleutian arc, Earth Planet. Sci. Lett., 14, 428-432, 1972.

Alvarez, W., Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics, J. Geophys. Res., 87, 6697-6710, 1982.

Annaka, T., Spatial distribution and mechanisms of deep earthquakes in the Izu-Bonin and the northeastern Japan arcs (in Japanese), Jishin, 30, 213-225, 1977.

Aoki, H., Pressure effect on the deformation of slabs descending below island arcs (in Japanese), Jishin, 27, 110-119, 1974a.

Aoki, H., Plate tectonics of arc-junction at central Japan, J. Phys. Earth, 22, 141-161, 1974b.

Barazangi, M., and B. L. Isacks, A comparison of the spatial distribution of mantle earthquakes determined from data produced by local and by teleseismic networks for the Japan and Aleutian arcs, Bull. Seismol. Soc. Am., 69, 1763-1770, 1979a.

Barazangi, M., and B. L. Isacks, Subduction of the Nazca plate beneath Peru: Evidence from spatial distribution of earthquakes, Geophys. J. R. Astron. Soc., 57, 537-555, 1979b.

Barker, P. F., A spreading center in the east Scotia Sea, Earth Planet. Sci. Lett., 15, 123-132, 1972.

Bowin, C., G. M. Purdy, C. Johnston, G. Shor, L. Lawver, H. M. S. Harton, and P. Jezek, Arc-continental collision in Banda Sea region, Am. Assoc. Pet. Geol. Bull., 64, 868-915, 1980.

Boyd, T., J. A. Snoke, I. S. Sacks, and A. Rodriguez B., High-resolution determination of the Benioff zone geometry beneath southern Peru, Bull. Seismol. Soc. Am., 74, 559-568, 1984.

Brotchie, J. F., and R. Silvester, On crustal flexure, J. Geophys. Res., 74, 5240-5252, 1969.

Cardwell, R. K., and B. L. Isacks, Geometry of the subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions, J. Geophys. Res., 83, 2825-2838, 1978.

Carr, M. J., R. E. Stoiber, and C. L. Drake, Discontinuities in the deep seismic zones under the Japanese arcs, Geol. Soc. Am. Bull., 84, 2917-2930, 1973.

Chinn, D. S., B. L. Isacks, and M. Barazangi, High-frequency seismic wave propagation in western South America along the continental margin, in the Nazca plate and across the Altiplano, Geophys. J. R. Astron. Soc., 60, 209-244, 1980.

Cross, T. A., and R. H. Pilger, Jr., Controls of subduction geometry, location of magmatic arcs, and tectonics of arc and back-arc regions, Geol. Soc. Am. Bull., 93, 545-562, 1982.

Davies, J. N., and L. House, Aleutian subduction zone seismicity, volcano trench separation, and their relation to great thrust-type earthquakes, J. Geophys. Res., 84, 4583-4591, 1979.

DeFazio, T. L., Island-arc and underthrust-plate geometry, Tectonophysics, 23, 149-154, 1974.

Dickinson, W. R., Plate tectonic evolution of North Pacific rim, J. Phys. Earth, 26, suppl., S1-S20, 1978.

Dym, C. L., Introduction to the Theroy of Shells, 159pp., Pergamon Press, New York, 1974.

Elsasser, W. M., Seafloor spreading as thermal convection, J. Geophys. Res., 76, 1101-1112, 1971.

Engdahl, E. R., Seismicity and plate subduction in the central Aleutians, in Island Arcs, Deep Sea Trenches, Back-Arc basins, Maurice Ewing Ser., vol. 1, edited by M. Talwani and W. C. Pitman III, pp. 259-271, AGU, Washington D. C., 1977.

Engdahl, E. R., and C. H. Scholz, A double Benioff zone beneath the central Aleutians: An unbending of the lithosphere, Geophys. Res. Lett., 4, 473-476, 1977.

Forsyth, D. W., Fault plane solutions and tectonics of the South Atlantic and Scotia sea, J. Geophys. Res., 80, 1429-1443, 1975.

Frank, F. C., Curvature of island arcs, Nature, 220, 363, 1968.

Freund, R., D. Kosloff, and A. Matthews, A dynamic model of subduction zones, in Mechanisms of Continental Drift and Plate Tectonics, edited by P. A. Davies and S. K. Runcorn, pp. 17-39, Academic, New York, 1980.

Fukao, Y., Source process of a large deep-focus earthquake and its tectonic implications - The western Brazil earthquake of 1963, Phys. Earth Planet. Inter., 5, 61-76, 1972.

Goto, K., and H. Hamaguchi, Characteristics of distributions of thermal stress and stress due to phase change in the descending plate beneath island arc (in Japanese), Jishin, 36, 31-41, 1983.

Hager, B. H., and R. J. O'Connel, Subduction zone dip angles and flow driven by plate motion, Tectonophysics, 50, 111-133, 1978.

Hamilton, W., Earthquake map of the Indonesian region, scale 1:5,000,000, Misc. Invest. Ser., Map I-875-D, U.S. Geol. Surv., Reston, Va., 1974.

Hasegawa, A., and I. S. Sacks, Subduction of the Nazca plate beneath Peru as determined from seismic observations, J. Geophys. Res., 86, 4971-4980, 1981.

Hasegawa, A., N. Umino, and A. Takagi, Double-planed seismic zone and upper-mantle structure in the northeastern Japan arc, Geophys. J. R. Astron. Soc., 54, 281-296, 1978.

Hasegawa, A., N. Umino, and A. Takagi, Seismicity in the northeastern Japan arc and seismicity patterns before large earthquake, Earthquake Prediction Res., in press, 1985.

Hatherton, T., and W. R. Dickinson, The relationship between andesitic volcanism and seismicity in Indonesia, the Lesser Antilles, and other island arcs, J. Geophys. Res., 74, 5301-5310, 1969.

Head, J. W., and S. C. Solomon, Tectonic evolution of the terrestrial planets, Science, 213, 62-76, 1981.

Horiuchi, S., Deformation of sinking slab in consequence of absolute plate motion of island-side, Izu-Bonin-Mariana arc, (in Japanese), Jishin, 30, 435-447, 1977.

House, L. S., and K. H. Jacob, Thermal stresses in subducting lithosphere can explain double seismic zones, Nature, 295, 587-589, 1982.

Inoue, H., and K. Yamaoka, Three-dimensional miniature of earthquake distribution, Tectonophysics, in press, 1985.

Isacks, B. L., and M. Barazangi, High frequency shear wave guided by a continuous lithosphere descending beneath western South America, Geophys. J. R. Astron. Soc., 33, 129-139, 1973.

Isacks, B. L., and M. Barazangi, Geometry of Benioff zones: Lateral segmentation and downward bending of the subducted lithosphere, inIsland Arcs, Deep Sea Trenches, and Back-Arc Basins, Maurice Ewing Ser., vol. 1, edited by M. Talwani and W. C. Pitman III, pp. 99-114, AGU, Washington, D. C., 1977.

Isacks, B., and P. Molnar, Distribution of stresses in the descending lithosphere from a global survey of focal mechanism solutions of mantle earthquakes, Rev. Geophys., 9, 103-174, 1971.

Isacks, B. L., L. R. Sykes, and J. Oliver, Focal mechanisms of deep and shallow earthquakes in the Tonga-Kermadec region and the tectonics of island-arcs, Geol. Soc. Am. Bull., 80, 1443-1470, 1969.

Jacoby, W. R., Paraffin model experiment of plate tectonics, Tectonophysics, 35, 103-113, 1976.

Jischke, M. C., On the dynamics of descending lithospheric plates and slip zones, J. Geophys. Res., 80, 4809-4813, 1975.

Johnson, T., and P. Molnar, Focal mechanisms and plate tectonics of the southwest Pacific, J. Geophys. Res., 77, 5000-5032, 1972.

Karig, D. E., Origin and development of marginal basins in the western Pacific, J. Geophys. Res., 76, 2542-2561, 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.

Lanzano, P., Spherical shell representation of tectonic plate, EOS Trans. AGU, 66(18), 369, 1985.

Laravie, J. A., Geometry and lateral strain of subducted plates in island arcs, Geology, 3, 484-486, 1975.

Lay, T., and H. Kanamori, Earthquake doublets in the Solomon Islands, Phys. Earth Planet. Inter., 21, 283-304, 1980.

LePichon, X., J. Francheteau and J. Bonnin, Plate Tectonics, p.229, Elsevier, New York, 1973.

Liu, H. S., Crustal deformation of the Tibetan Plateau: Constraints from space geodesy, EOS Trans. AGU, 66(18), 246, 1985.

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

Luyendyk, B. P., K. C. MacDonald, and W. B. Bryan, Rifting history of the Woodlark basin in the southwest Pacific, Geol. Soc. Am. Bull., 84, 1125-1134, 1973.

MacDonald, K., B. Luyendyk, and R. P. von Herzen, Heat flow and plate boundaries in Melanesia, J. Geophys. Res., 78, 2537-2546, 1973.

McCaffrey, R., Lithospheric deformation within the Molucca Sea arc-arc collision: Evidence from shallow and intermediate earthquake activity, J. Geophys. Res., 87, 3663-3678, 1982.

Milson, J. S., Woodlark Basin, a minor center of seafloor spreading in Melanesia, J. Geophys. Res., 75, 7335-7339, 1970.

Minster, J. B., and T. H. Jordan, Present-day plate motions, J. Geophys. Res., 83, 5331-5354, 1978.

Papp, Z., A three-dimensional model of the seismicity in the Banda Sea region, Tectonophysics, 69, 63-83, 1980.

Pascal, G., J. Dubois, M. Barazangi, B. L. Isacks, and J. Oliver, Seismic velocity anomalies beneath the New Hebrides island arc: Evidence for a detached slab in the upper mantle, J. Geophys. Res., 78, 6998-7004, 1973.

Pascal, G., B. L. Isacks, M. Barazangi, and J. Dubois, Precise relocations of earthquakes and seismotectoics of New Hebrides island arc, J. Geophys. Res., 83, 4957-4973, 1978.

Reyners, M., and K. S. Coles, Fine structure of the dipping seismic zone and subduction mechanics in the Shumagin Islands, Alaska, J. Geophys. Res., 87, 356-366, 1982.

Rodriguez, R., E. R. Carbe, and A. Mercado, Geometry of Nazca plate and its geodynamic implications, in The Geophysics of the Pacific Ocean Basin and Its Margin, Geophys. Monogr. Ser., vol. 19, edited by G. H. Sutton, M. H. Manghnani, and R. Moberly, pp. 87-103, AGU, Washington, D.C., 1976.

Sasatani, T., Mechanism of mantle earthquakes near the junction of the Kurile and the northern Honshu arcs, J. Phys. Earth, 24, 341-354, 1976.

Shiono, K., T. Mikumo, and Y. Ishikawa, Tectonics of the Kyushu-Ryukyu arc as evidenced from seismicity and focal mechanism of shallow to intermediate-depth earthquakes, J. Phys. Earth, 28, 17-43, 1980.

Sleep, N. H., The double seismic zone in downgoing slabs and the viscosity of the mesosphere, J. Geophys. Res., 84, 4565-4571, 1979.

Solomon, S. C., and J. W. Head, Vertical movement in Mare basins: Relation to Mare emplacement, basin tectonics, and lunar thermal history, J. Geophys. Res., 84, 1167-1682, 1979.

Solomon, S. C., and J. W. Head, Lunar mascon basins: Lava filling, tectonics, and evolution of the lithosphere, Rev. Geophys., 18, 107-141, 1980.

Stauder, W., Subduction of the Nazca plate under Peru as evidenced by focal mechanism and seismicity, J. Geophys. Res., 80, 1053-1064, 1975.

Strobach, K., Curvature of island arcs and plate tectonics, J. Geophys., 39, 819-831, 1973.

Tarakanov, R. Z., A block velocity model of the focal zone and adjacent mantle in the Kurile-Japan region, J. Phys. Earth, 27, suppl., S65-S80, 1979.

Taylor, B., and G. D. Karner, On the evolution of marginal basins Rev. Geophys., 21, 1727-1741, 1983.

Timoshenko, S. P., and S. Woinowsky-Krieger, Theory of Plates and Shells, 580pp., McGraw-Hill, 1959.

Tovish, A., and G. Schubert, Island arc curvature, velocity of convergence and angle of subduction, Geophys. Res. Lett., 5, 329-332, 1978.

Tsukahara, H., Physical conditions for double seismic planes of the deep seismic zone, J. Phys. Earth, 28, 1-15, 1980.

Ukawa, M., Lateral stretching of the Philippine sea plate subducting along the Nankai-Suruga trough, Tectonics, 1, 543-571, 1982.

Uyeda, S., and H. Kanamori, Back-arc opening and the mode of subduction, J. Geophys. Res., 84, 1049-1061, 1979.

Weissel, J. K., Magnetic lineations in marginal basins of the west Pacific, Philos. Trans. R. Soc., London, Ser. A., 300, 223-247, 1981.

Wu, F. T., Benioff zones, absolute motion and interarc basin, J. Phys. Earth, 26, suppl., S39-S54, 1978a.

Wu, F. T., Recent tectonics of Taiwan, J. Phys. Earth., 26, Suppl., S265-S300, 1978b.

Yoshii, T., Compilation of geophysical data around the Japanese island (I) (in Japanese), Bull. Earthquake. Res. Inst. Univ. Tokyo, 54, 75-117, 1979.

Y. Fukao and K. Yamaoka, Department of Earth Sciences, Nagoya University, Chikusa-ku, Nagoya, 464, Japan.

M. Kumazawa, Geophysical Institute, University of Tokyo, Bunkyo-ku, Tokyo, 113, Japan.

(Received May 8, 1985;
accepted September 11, 1985.)