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Plate Convergence, Transcurrent Faults and Internal Deformation Adjacent to Southeast Asia and the Western Pacific[1]

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ABSTRACT

A model for oblique convergence between plates of lithosphere is proposed in which at least a fraction of slip parallel to the plate margin results in transcurrent movements on a nearly vertical fault which is located on the continental side of a zone of plate consumption. In an extreme case of complete decoupling only the component of slip normal to the plate margin can be inferred from underthrusting. Recent movements in the western Sunda region provide the most convincing evidence for decoupling of slip, which in this region is thought to be oblique to the plate margin. A speculative model for convergence along the margins of the Philippine Sea is constructed from an inferred direction of oblique slip in the Philippine region. This model requires that the triple point formed by the junction of the Japanese and Izu-Bonin trenches and the Nankai trough migrate along the Sagami trough. Absence

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of an offset between the trenches can be explained by rifting within the Izu-Bonin arc. Transcurrent movements in southwest Japan and the Taiwan region suggest that similar movements within well-developed island arcs are initiated during a nascent stage in the development of such plate margins and are often imposed on a pre-existing zone of weakness.

The bulge-like configuration of the western margin of the Andaman basin is explained as a result of inter-arc extension within the western part of this basin. In the Indian Ocean plate south and west of this basin, strike-slip movements inferred from four mechanism solutions, two of which are reported in this work, are suggestive of a distribution of stress in which both axes of compression are nearly horizontal with the stress maximum trending east of north. The largest of recent earthquakes in the eastern Sunda region have resulted in deformation within the arc rather than shallow underthrusting at the plate margins. A zone of shortening in nearly an east - west direction coincides with an intense gravity minimum along the eastern margin of the Celebes basin from the Talaud islands to the Molucca basin. Internal deformation is known or suspected in the Sunda strait, western New Guinea and the Celebes. Recent movements near the east coast of Luzon reveal a zone of underthrusting along the inner wall of a trough marginal to this coast. There is an apparent hiatus in underthrusting between this zone and the one that follows the inner wall of the Philippine trench.

INTRODUCTION

Several of the earth's most extensive zones of transcurrent faulting are located within the strike parallel to active island arcs and arc-like structures. Allen [1965] discussed evidence for movements on three such faults: The Atacama in Chile, the Longitudinal in Taiwan, and the Philippine. To this list can be added the Semangko fault in Sumatra [e. g. Katili, 1970], possibly the Median Tectonic Line in western Japan [Kaneko, 1966 and Okada, 1971], and possibly the Nicaragua trough [Molnar and Sykes, 1969]. One mechanism solution shows evidence for strike-slip movement [Molnar and Sykes, 1969] along this trough, a volcanic graben that is nearly parallel to an adjacent section of the Middle America trench. Such movements may be analogous to those along the Semangko fault, a zone of transcurrent movements that follows a chain of active volcanoes in Sumatra. With the exception of the Atacama [Arabasz and Allen, 1970], the other fault zones show evidence of recent activity that is contemporary with plate consumption in the same region. In the work presented here such a system of contrasting movements is explained by a model of convergence in which slip that is oblique to the plate margin is at least partially decoupled between parallel zones of transcurrent faulting and underthrusting.

A schematic cross section of such a plate margin is shown in Figure 1. The transcurrent fault is near the axis of active volcanism as are the Philippine and the Semangko faults (Figure 2). Coexistence of a chain of active volcanoes and a zone of transcurrent faulting is understandable in that a zone of relative weakness in extension can also be a zone of weakness in horizontal shear and vice versa. However, numerous examples of transcurrent faults within non-volcanic parts of island arcs and within arc-like structures that have no volcanism clearly demonstrate that active volcanism is not a necessary condition for the development of such faults. What is implied by the decoupling hypothesis proposed here is that horizontal shear applied to a plate margin by oblique convergence can, in some situations, be more easily released by transcurrent movements on an interior vertical fault than by oblique slip on an adjacent zone of underthrusting.

Models based on the assumption of rigid plates [e.g. LePichon, 1968] reveal at least four regions of oblique convergence, one of which serves as a type example of a plate margin such as that illustrated in Figure 1. That region is the western Sunda, where horizontal shear and underthrusting occur concurrently on the Semangko fault and along the inner wall of the Java trench respectively. Directions and rates of convergence in this region are computed from a simplified model that does not include slip between the China and Eurasian plates (Figure 2). In the absence of a quantitative measure of this slip, large corrections to slip vectors in the Sunda region are possible; however, such corrections are unlikely because computed centers of rotation for the Indian Ocean and Eurasian (including China) plates are nearly 90° distant from this arc.

The other regions of oblique convergence are the western Aleutians [e.g. McKenzie and Parker, 1967], northern New Guinea [e.g. LePichon, 1968 and Morgan 1971] and that part of the Caribbean margin adjacent to Puerto Rico, [Molnar and Sykes, 1969]. The plate margin in each of these regions does not fit the model proposed here for the western Sunda arc without major modifications. Seismic evidence shows that at least part of the western Aleutian arc is bounded by active zones of faulting,underthrusting seaward of the volcanic islands, and right-lateral shear on the continental side of these islands [Gumper, 1971].

However, unlike most shallow underthrusting [Isacks et al., 1968], these movements are in a direction that nearly parallels the island arc [Gumper, 1971]. Similarly underthrusting north of Puerto Rico parallels the plate margin in this region that is marked by the Puerto Rico trench. Near New Guinea slip between the major plates is obscured by movements between small intervening plates [Johnson and Molnar, 1972] and by possible internal deformation in western parts of this region.

The argument for oblique convergence along the western margin of the Philippine Sea is more tenuous. Plate models based on the spreading history of the mid-ocean system of active ridges cannot be used because no part of this system passes through the Philippine Sea. Therefore, evidence must come directly from the plate margin. Two active zones of shallow underthrusting follow the east side of the Philippine arc (Figure 3). Movements along these zones are nearly normal to the Philippine trench and the east coast of Luzon. Inland from the zones of underthrusting is the Philippine fault, which has Quaternary to Recent offsets consistent with horizontal shear in the left-lateral sense [Allen, 1962]; however, the comparatively low level of recorded seismicity along this fault is puzzling since geomorphic evidence for recent movements is substantial. By applying a model for decoupled slip similar to that proposed for the western Sunda arc, it is possible to infer a direction of oblique convergence for this region.

This direction of slip and selected directions of slip from other parts of the western margin of the Philippine Sea are used to compute a center of rotation for the Eurasian and Philippine Sea plates. In order to compute a model for plate convergence in the northwest Pacific that is reasonably consistent with the configuration of the inclined seismic zones beneath the eastern margin of the Philippine Sea, the center of rotation is constrained to the North Pacific. The center of rotation for the Eurasian and Philippine Sea plates that gives the best fit to the data and satisfies the above mentioned constraint is located near southwest Alaska. The resulting directions of slip along the western margin of the Philippine Sea are consistent with the sense of recent movements on interior faults that parallel major parts of this plate margin. The preferred center of rotation for the Philippine Sea and Pacific plates is in east-central Australia, which implies a direction of convergence that is nearly normal in the Mariana and Izu-Bonin arcs and a rate of convergence that increases northward.

Models such as the one outlined above account for relative motion, in this case convergence, between major plates. Narrow regions between zones of horizontal shear and underthrusting are modeled as small plates. Sufficient data are not available to check model computations against known rates and directions of slip at several locations along these plate margins. Therefore unavoidable errors, perhaps large errors, are contained in the quantitative results.

No attempt is made to include special regions such as inter-arc basins [Karig, 1970] in these models. Active extension within several of these basins marginal to the Philippine Sea and southeast Asia probably influence the rate and direction of convergence along adjacent frontal arcs. The western part of the Andaman basin (Figure 3) contains one or more centers of spreading that became active sometime after late Miocene [Rodolfo, 1969]. New sea floor is forming in the basin west of the Mariana ridge and within the Izu-Bonin arc [Karig, 1971a]. The Okinawa trough, west of the Ryukyu ridge, is considered only marginally active [Karig, 1971a] even though normal faults offset sediments within the trough [Wageman et al., 1970] and heat flow through the floor of the trough is abnormally high [Watanabe et al., 1970]. A mechanism solution for normal faulting near the northeast corner of this trough (solution 28 in Figures 11 and 12) suggest that active extension is still in progress.

In addition to interarc extension, regions of internal deformation that are often difficult or impossible to distinguish from a plate margin composed of a number of small plates are identified. For example, Fitch [1970a], Johnson and Molnar [1972], and this work show that directions of slip in western New Guinea inferred from solutions to shallow underthrusts differ by more than 60° from those computed from rigid plate models. In the Celebes region (Figure 3) a complex pattern of internal deformation results from convergence between pieces of lithosphere overlain by continental crust. Deviations from simple tectonic models are expected in this region as a result of interactions between four major plates of lithosphere (Figure 2).

The arguments presented in this work rely strongly on recorded as well as historic seismic evidence. Forty-six new mechanism solutions for shallow earthquakes are an essential part of this evidence. In addition to the new solutions those published by Katsumata and Sykes [1969] for Ryukyu, Izu-Bonin and Mariana regions and Fitch [1970 a, b] for the Indonesian-Philippine region are used. Each of the new soltuions is based on a distribution of P-wave first motions and S-wave polorization shown in the appendix. A tablulation of parameters for the new solutions, as well as those from Fitch [1970a], is also in the appendix. Detailed seismicity maps based on epicenters computed by the United States Coast and Geodetic Survey (USCGS) are provided for some of the more complex seismic zones within this region. Following the presentation of data, a model is constructed for plate convergence in the northwest Pacific.

Plate Convergence and Internal Deformation

Western Sunda Arc

By analogy with other island arcs, a line of andesitic volcanism in Sumatra and an adjacent deep-sea trench result from consumption of oceanic lithosphere. The Andaman-Nicobar ridge, although not part of a well-developed island arc, does have stratigraphic and structural evidence for a tectonic history in the Cenozoic that is similar to that of the non-volcanic arc between Sumatra and the Java trench [Rodolfo, 1969]. At shallow depths between Sumatra and the non-volcanic arc there are four earthquakes with mechanisms consistent with shallow underthrusting of the oceanic lithosphere beneath the island arc (solutions 7, 8, 9, 10 in Figure 4). A great earthquake on June 26, 1941, the largest of recorded earthquakes in the western Sunda region, may have been a megathrust. It was located west of the Andaman Islands and appeared to have a sub-crustal focus of about 50 to 60 km [Richter, 1958]. Solutions to events at intermediate depths (solution 1 in Figure 4 and solutions 2 and 3 in Fitch and Molnar [1970])are consistent with a descending slab of lithosphere beneath Sumatra within which the axis of least compressive stress is oriented in a down-dip direction. Earthquakes at intermediate depths extend to approximately 200 km beneath Sumatra, and a few epicenters are located at depths of about 100 km beneath the Andaman-Nicobar ridge [e.g. Gutenberg and Richter, 1954; Fitch and Molnar, 1970].

Paralleling this zone of underthrusting is the Semangko fault in Sumatra (Figure 2) and its submarine continuation along the eastern side of the Andaman-Nicobar ridge [Rodlofo, 1969]. This fault zone is seismically one of the more active zones of transcurrent movements within active island arcs. Right-lateral shear along this zone was observed in focal regions of the larger earthquakes recorded from Sumatra [Katili, 1970]. These events included the 1892 Tapanuli, the 1926 Padang-pandjang (listed by Gutenberg and Richter [1954] as two shock of M_s 6 1/2 and 6 3/4), the 1933 Liwa (given a M_s of 7 1/2 by Gutenberg and Richter [1954]),the 1952 Tes (not listed in Gutenberg and Richter [1954]; therefore probably less than M_s 6 1/2) and the 1964 Atjeh (m_b of 6.7 computed by USCGS) earthquakes. For the first of these events, which was probably the largest one, horizontal offset at the fault, inferred from geodetic evidence, was as large as 4 meters (Richter,[1958] from earlier work by H. F. Reid). In addition,other right-lateral offsets of recent origin are known from numerous locations throughout the fault zone [Katili, 1970]. A comparison with seismicity in other parts of this region from lists of recorded earthquakes of large magnitude [Gutenberg and Richter, 1954; Rothe, 1969], as well as recent seismicity [e.g. Barazangi and Dorman, 1969], shows that most shallow activity is seaward of the island, whereas in the Andaman region earthquakes are concentrated along a submarine continuation of the Semangko fault. Qualitatively this migration in activity toward the concave side of the arc is consistent with an increase in the ratio of parallel to normal slip toward the northwest (Figure 3), provided these components of slip are decoupled in a manner similar to that proposed here.

Figure 4 shows mechanism solutions (numbers 2, 3, 4, and 80) for four shallow earthquakes, three of which are located near narrow troughs (Figure 5) that mark a continuation of this fault zone for a distance of approximately 500 km along the east side of the Andaman-Nicobar ridge. Fitch [1970 a, b] interpreted solution 2 as a shallow underthrust; however, right-lateral shear in this region, seismic evidence for which comes from solutions 3, 4 and 80, suggests that the nodal plane with a northwest strike and nearly vertical dip is more likely to represent the fault plane. Motion on this plane was right-lateral with a large component of thrusting in the sense of the Andaman-Nicobar ridge overriding the Andaman basin. Field evidence shows that the interpretation of solution 3 given in Figure 4 is the correct one. This solution is for the Atjeh earthquake in April 1964 after which right-lateral offsets as large as 0.5 meter were observed along a section of the Semangko fault in extreme northern Sumatra [Katili, 1970].

Stress within Lithosphere adjacent to the Western Sunda Arc

Contrasting distributions of stress are inferred from mechanism solutions for shallow earthquakes on opposite sides of the western Sunda Arc. A pair of thrust movements along the northern coast of Sumatra near the northern tip of the island (solutions 5 and 6, Figure 4) are similar to solutions reported in recent years from the continental sides of other island arcs [e.g. Isacks et al., 1968]. These movements show that behind at least some arcs compression is large enough to cause crustal shortening nearly normal to the adjacent plate margin. Although the origin of such stress is unknown, it is probably associated with consumption of oceanic lithosphere along the frontal arc.

A tentative distribution of stress for the oceanic side of the Sunda Arc is such that both axes of compression are nearly horizontal with the minimum stress in a northeast to east-northeast direction. This distribution is inferred from nearly identical solutions to four widely separated earthquakes in the Indian Ocean plate. This unusual seismic zone is seen as a broad band of scattered activity that extends from Australia to India [Sykes, 1970]. Of the events that yielded mechanism solutions one is located seaward of the northern end of the Java trench (solution 65 in Figure 4); another was located on the Ninty-east ridge [Sykes, 1970]; and a third is the Konya earthquake in western India [Sykes, 1970]. The remaining solution (Figure 6) is for an event located west of the Ninty-east ridge in an area covered by sediments that mark the southern limit of the Ganges Cone [Heezen and Tharp, 1967].

If the distribution of stress inferred from these four earthquakes is representative of stress in parts of the Indian Ocean plate outside the broad region of shallow earthquakes,then, for example, the axis of least compression is nearly normal to the Andaman-Nicobar ridge. Extension behind this ridge in the western Andaman basin is shown by widespread extrusions of basaltic magma [Rodolfo, 1969] and normal faulting near the central Andaman trough and north of the Andaman islands (solutions 9, 11 and 12 in Figure 4). Therefore compression within the western basin is less than the fluid pressure of upwelling magma. Active extension began here in late Miocene [Rodolfo, 1969] and has continued to the present as judged by mechanism solutions; however, the rate of extension was probably greater in late Miocene and in late Pliocene to Recent as inferred from a history of late Tertiary to Recent volcanism in this and adjacent regions [Rodolfo, 1969].

An understanding of such a tectonic province is sought by analogy with inter-arc basins that have evolved in special regions within which there is a mechanism for the release of compressive stress [Scholz, 1971]. In the western Sunda region horizontal compression associated with plate convergence approaches a minimum in the Andaman region provided this stress is proportional to the rate of plate convergence that is thought to decrease from south to north along this plate margin.

To gain additional insight into the tectonic evolution of the Andaman basin, consider the following analogy with the evelution of the Basin and Range province of the western United States. Scholz et al., [1971] proposed that the Basin and Range province evolved as a latent inter-arc basin in which the strength of a semi-continental crust prevented basaltic magma from forming new oceanic lithosphere as is occurring in the Lau basin west of Tonga [Karig, 1970]. This province and the western Andaman basin are similar in overall morphology and, to an uncertain extent similar stratigraphically, as are the eastern Andaman basin and the Colorado plateau. The eastern margin of the Andaman basin is a terraced continental slope underlain by a thick sequence of "Mesozoic and Paleozoic sediments, volcanoes and silic intrusions" [Rodolfo, 1969]. Similarly the Colorado plateau is a series of monclines descending toward the Basin and Range Province. The stratigraphic makeup of the Plateau is basically a thick sequence of Paleozoic and Mesozoic rocks intruded by younger volcanics. The western Andaman basin contains several elongated platforms from which rocks of basaltic composition have been dredged [Rodolfo, 1969]. These platforms are separated by flat basins; thus giving this sea floor a basin and range morphology. In addition the size of the western Andaman basin, approximately 800 km long and 300 km wide, is approximately the same as that of the Basin and Range province.

Establishing a similarity in tectonic evolution is more difficult because so little is known about the Andaman basin in comparison with the Basin and Range province. Scholz et al., [1971] suggest that extension within the Basin and Range province was triggered by the formation of the San Andreas fault in the late Tertiary and the progressive disappearance of a pre-existing island arc off the coast of California [e.g. Atwater, 1970]. If this interpretation is applied to the western Andaman basin, then the submarine continuation of the Semangko fault may be the counterpart of the San Andreas fault. However, there is no geologic or geophysical evidence of a post-Cretaceous island arc between Burma and Sumatra. Thus extension in the Andaman basin may not result from upwelling above the inclined slab of lithosphere as was suggested for the driving mechanism of inter-arc extension in other regions [e.g. Scholz et al., 1971]. Possibly upwelling and ensuing volcanism can occur wherever horizontal compression reaches a critical minimum value.

Eastern Sunda Arc

Figure 3 shows the Sunda Strait as a tectonic as well as a physiographic break in the arc. West of the strait the southern end of the Semangko fault (Figure 7) shows eivdence of recent movement in the right-lateral sense. In contrast, recent movements along a fault in western Java are in the left-lateral sense [Katili, 1970]. Unlike the Semangko fault, this fault is not part of an extensive zone of transcurrent movements.

A concentration of shallow earthquakes in the vicinity of the strait (Figure 7) is further evidence for a tectonic break in this region. This activity is exceptional in that adjacent parts of the arc have not experienced high levels of activity in recent years. Possibly this activity results from extension on the seaward side and convergence on the landward side of the strait as suggested by the opposite sense of motion on faults adjacent to the strait (Figure 3).

A step-like increase in the depth to the deepest earthquakes from 200 km west of the strait to greater than 600 km east of it suggests that the rate of underthrusting in this region has a similar step-like increase [Fitch and Molnar, 1970]. Fitch [1970b] pointed out that an abrupt change in orientation of the arc near the Sunda Strait (Figure 3) can account for such a change in the rate of underthrusting and thus can account in general for the configuration of the inclined seismic zone beneath this part of the arc.

Computed slip between the Indian Ocean and Eurasian plates in the entire Sunda region (Figure 3) is nearly constant in magnitude and direction because equators for computed centers of rotation for these plates pass through this region. However, a change in orientation of the arc near the Sunda Strait imposes a large change in the ratio of parallel to normal slip. Along the western arc this ratio progressively increases toward the Andaman region, whereas along the eastern arc it remains nearly constant at a low value. If the decoupling hypothesis is correct, then the absence of an extensive zone of transcurrent faulting along the eastern arc is explained by the absence of a large component of parallel slip.

West of Sumba (Figure 3) the plate margin follows the Java trench along the inner wall of which a zone of shallow earthquakes marks the frictional contact between the plates [e.g. Fitch, 1970a]. East of Sumba this margin follows a narrow trough that makes a loop around the Banda basin [e.g. Hydrographic office chart HO 5590]. It passes north of Ceram (Figure 3) and disappears approximately 200 km farther west [Chase and Menard, 1969]. Along the concave side of this trough only scattered concentrations of shallow earthquakes have been recorded. By comparison with deep-sea trenches this trough is not a striking feature; only locally does it reach depths greater than 3000 m. However, like active trenches a strong gravity minimum parallels this trough [Gutenberg and Richter, 1954; and unpublished gravity profiles from Vema and Conrad cruises, 1971].

The most striking bathemetric feature east of the Java trench is the Weber deep (Figure 3). The inner wall of this deep is seismically one of the more active regions within this arc. E.g. the only shallow earthquakes of large magnitude recorded from the eastern Sunda region are two events located near the inner wall of this deep: one occurred on February 1, 1938 and the other occurred on November 2, 1950 [Richter, 1958].

In fact the larger of recent movements in this region, judging from recorded seismicity, have occurred within the arc (e.g. Figure 4); not along the frictional contact between the convergent plates. The low level of shallow underthrusting at the plate margins may be temporary if computed rates of convergence of 5 and

6 cm/yr [e.g. LePichon, 1968] are consistent with a long recurrence time for major earthquakes; e.g. several hundred years. These rates are approximately half the rates of convergence computed for arcs of the northwestern and the southwestern Pacific. An alternative explanation for the absence of underthrusting is that the close approach of the Australian continent has slowed or stopped plate consumption in this region. Such a disruption is suggested by an apparent reorientation of islands of the outer arc in the vicinity of Timor and by a break in the Java trench in this region. However, it is impossible at present to decide which, if either, of these explanations is more correct.

Junction Between Four Plates

Figure 3 illustrates a complex array of known and suspected fault zones near the junction of four large plates of lithosphere in the region between the Philippine and Sunda arcs. Plate margins in this region are hard to define with certainty from seismic evidence alone and probably are not stable over the time intervals longer than a few million years. McKenzie and Morgan, [1969] point out that junctions between four or more plates are inherently unstable. The metamorphic history of the Celebes and other portions of this complex region shows that several zones of plate convergence within this region have flourished and become extinct in the late Tertiary [Hamilton, 1970].

Recent movements in the Celebes region (Figure 4) include extension near the south coast of the gulf that separates the two northern peninsulas (solutions 27, 28 and 29) and thrust movements in a limited region along the west coast of this island (solution 61). A few foci at intermediate depths beneath the western part of the island [e.g. Barazangi and Dorman, 1969] suggest that the upper mantle is anomalous in this region. A mechanism solution for one of these earthquakes has a nearly vertical axis of minimum compression [Fitch and Molnar, 1970].

A zone of left-lateral shear separates the eastern and western parts of the island and the northern peninsula is traversed by a zone of right-lateral shear [Katili, 1970]. Solution 60 is consistent with left-lateral shear within the former fault zone. Strike-slip (solution 57) and normal faulting (solution 56) in the Makassar strait between Borneo and Celebes (Figure 3) is interpreted as evidence for a hinge for extension in the northern gulf.

Judging from recent distributions of shallow earthquakes (e.g. Figure 8) a fault zone crosses a spur of continental lithosphere (the Sulu spur) east of Celebes (Figure 3). This hypotheorized fault zone joins an active zone of left-lateral shear (solutions 21 and 22 in Figure 4) that in Figure 3 is with great caution drawn as a submarine continuation of a left-lateral fault in extreme western New Guinea [Visser and Hermes, 1966]. The latter fault is probably active judging from the epicenters of recent earthquakes shown in Figure 8. For solutions 21 and 22 the question of which nodal plane represents the fault surface was resolved by an east-west trend in epicenters from events that occurred within a couple of months after the main shock. These are assumed to be aftershocks.

Figure 9 shows scattered concentrations of recent activity along the margins of Geelvink bay and in the vicinity of the Aroe islands south of New Guinea. This activity reveals a major break in an east - west zone of shallow underthrusting that is concentrated inland from the northern coast of New Guinea (Figure 9). Directions of underthrusting inferred from three mechanism solutions (numbers 2, 3 and 23 in Figure 4) are nearly normal to the coast, whereas directions of slip computed from rigid plate models are strongly oblique by this coast (Figure 3). This disparity is difficult to resolve within the mechanics of rigid plates unless other plate margins, as yet unidentified, exist near this region.

Between northernmost Celebes and Halmahera (Figure 3) is a double-arc structure separated by a zone of east-west shortening. Figure 8 shows two lines of active volcanism belonging to separate island arcs. Beneath the western arc and the Celebes basin is an inclined zone of earthquakes that extends to depths greater than 600 km. In contrast a diffuse zone of activity is found at intermediate depths beneath the eastern arc [Fitch and Molnar, 1970]. Between the two arcs is a northern continuation of the Molucca basin, a shallow basin covered with strongly deformed sediments but no recognizable trench-like feature (unpublished profiler records from Vema and Conrad cruises, 1971]. Thrust faulting in the basement associated with a closure of this basin appears to be consistent with a morphology of these sediments. An extreme gravity minimum in the Molucca basin is additional evidence for an anomalous upper mantle in this region (unpublished gravity profiles from Vema and Conrad cruises, 1971).

The best-developed trench-like feature in this region is the southern end of the Philippine trench that can be followed east of Halmahera to approximately 0.5°N [Chase and Menard, 1969]. An almost complete absence of shallow activity on this side of Halmahera suggests that oceanic lithosphere is no longer being consumed along this part of the trench.

North of the double arc the zone of shortening splits into an eastern and western branch (Figure 8). The western branch follows the western margin of the Talaud ridge marked by the island of that name shown in Figure 10. The eastern zone lies between the eastern margin of the Snellius ridge and the southern end of the Philippine trench. Much of the scatter in the distribution of these epicenters may result from an absence of data from local stations and near-source errors caused by propagation through inclined slabs of high-velocity lithosphere. At least in recent years, the Talaud trough dividing these two ridges has been seismically quiet. Every solution to earthquakes in both branches are consistent with some type of thrust movement. Thus the Talaud and Snellius ridges are active horst-like structures as was previously suggested by Krause [1966] from bathymetric data. East of Mindanao the thrust zones that parallel the sides of these horst-like structures join to form a zone of shallow thrusting that continues along the inner wall of the Philippine trench (Figure 8).

Convergence along the Margins of the Philippine Sea

Convergence in the Philippine region has evloved one of the earth's more complex island arcs. Active volcanism extends from southern Mindanao to northern Luzon (Figure 8); however, activity is not confined to a central rift as is the case in some well-developed island arcs such as the Sunda arc. Seismic activity extends to depths of about 200 km beneath the lesser Philippine islands adjacent to the northern end of the Philippine trench [Fitch and Molnar, 1970; Fitch 1970a]. Farther south, adjacent to Mindanao and the eastern margin of the Celebes Sea, this inclined seismic zone reaches depths greater than 600 km. Inland from and parallel to the Philippine trench is a zone of transcurrent faulting showing evidence of Quaternary to Recent movements [Allen, 1962]. At a latitude of approximately 12°N, where the trench ends, the fault zone bends gently westward and finally ends in central Luzon as a broad zone containing several distinct branches.

Figure 8 shows epicenters of recent earthquakes of shallow focus, a few of which are located on or near mapped traces of this fault. Only one of these events was large enough to yield a reliable mechanism solution (number 41, Figure 11), and that solution is consistent with geologic evidence of recent transcurrent movements in the left-lateral sense [Allen, 1962].

Of recorded earthquakes only one of large magnitude was located near the central part of the fault trace. That event occurred in 1901 and was given a magnitude of 7.8 by Richter [1958]. The only other recorded earthquake of large magnitude near this fault occurred in 1924 [Allen, 1962] and was located near a submarine continuation of the fault that appears from bathymetric evidence as a narrow trough in the sea floor [Krause, 1966] south of Mindanao.

Tectonic movements marginal to Luzon include possible underthrusting along the west coast of the island. Consumption of oceanic lithosphere beneath this coast can explain earthquakes at intermediate depth, of which one yielded a mechanism solution consistent with a nearly vertical axis of minimum compression [Fitch and Molnar, 1970]. Also suggestive of underthrusting is the west Luzon Trench [Hayes et al., 1967] that parallels part of this coast.

Shallow underthrusting along the east coast of the island is well documented by a series of movements that began in August of 1968 (Figures 9 and 11). A mean azimuth of underthrusting of 283° inferred from three mechanism solutions (numbers 44, 47 and 51 in Figure 11) is nearly normal to the coast and an adjacent deep-sea trough [Allen, 1965; Chase and Menard, 1969]. That part of the Philippine fault nearest this activity strikes approximately 322°. Along the inner wall of the Philippine trench an average azimuth of underthrusting inferred from five solutions (numbers 40, 39, 45, 35, and 36 in Figure 11) is 264°. A comparison with underthrusting farther north reveals a rotation of approximately 19° in the direction of underthrusting within a distance of a few hundred kms. This apparent rotation is larger than the uncertainty in the determination of the average direction of slip and takes place in too short a distance to be consistent with simple convergence between two plates, unless the center of rotation for these plates lies within this region. Such a rapid change in direction can be explained by the addition of a small plate that includes most of the lesser Philippine islands. This plate was proposed by Katsumata and Sykes [1969] and Fitch [1970a] to explain a large change in the direction of underthrusting between the Philippine and Ryukyu arcs. Some of the largest earthquakes recorded from the Philippine region have foci near one of the lesser Philippine islands [e.g. Allen, 1962], and recent shallow seismicity in this region [e.g. Barazangi and Dorman, 1969] is concentrated in a narrow zone suggestive of a plate boundary. However, this evidence may be misleading. In parts of western New Guinea and elsewhere, narrow zones of shallow earthquakes may mark zones of internal deformation rather than plate margins.

In the lesser Philippine region mechanism solutions to three shallow earthquakes (number 43, 42, and 54 in Figure 11) reveal strike-slip movements that are difficult to incorporate into a model of slip along a simple plate margin. Such movements can be explained as internal deformation caused by stress resulting from plate convergence. For example, in western Japan mechanism solutions for shallow earthquakes [Ichikawa, 1965, 1966] and recent offsets on mapped faults [Allen et al., 1970] show a preferred orientation of compressive stress that is nearly normal to the Japanese trench. With a similar explanation in mind for earthquakes in the lesser Philippine region, solutions 43 and 54 in Figure 11 are drawn as conjugate movements suggestive of compression along a northeast-southwest trend.

A Speculative Model for Plate Convergence in the Western Pacific

The decoupling hypothesis offers another explanation for the change in the direction of underthrusting north of the Philippine trench and the apparent hiatus in underthrusting in this part of the arc. By this hypothesis, the bend in the Philippine fault corresponds to a change in the ratio of parallel to normal slip that is observed as a change in the direction of underthrusting. In the extreme case of complete decoupling a direction of oblique convergence for this region is given by the strike of that section of the Philippine fault between the two zones of underthrusting. With this greatly simplified model for slip in the Philippine region and an additional assumption of rigid plates, a model is constructed for convergence along both sides of the Philippine Sea plate. Some of the gross seismic and geological observations for this plate margin are explained, such as the sense of horizontal shear on interior faults of major proportions (Figure 2). However, no attempt is made to account for localized complications such as inter-arc spreading within the West Mariana basin [Karig, 1971].

The next step in constructing this model is to select directions of slip from other parts of the western margin of this plate that, in addition to the inferred direction of slip in the Philippine region, give directions of total slip between the plates. Plate movements in the Taiwan region (Figure 11) are excluded from the model computations because of obvious tectonic complexity in this region. This complexity is revealed by a superposition of shallow activity that is dominated in recent years by transcurrent movements and a nearly vertical zone of intermediate earthquakes concentrated at depths less than 100 km [Katsumata and Sykes, 1969; Wu, 1970]. The only remaining directions of slip are those from shallow earthquakes along the Ryukyu arc and southwest Japan including the Kanto region (Figure 11). Except for that in the Kanto region, these directions are inferred from mechanism solutions previously reported by Katsumata and Sykes [1969] and from new solutions for the years 1968 to 1970 shown in Figure 12.

In this paper the Sagami trough (Figure 11) is taken to be the northern boundary between Eurasia and the Philippine Sea plates. A direction of slip along this trough (Figure 11) was inferred from the mechanism of the Great Kanto Earthquake of 1923, determined from seismic [Kanamori, 1971] and geodetic evidence (work of Ando reported by Kanamori [1971]). The mechanism was right-lateral shear with a strong component of thrusting. Figure 11 shows that the direction of slip for the Kanto earthquake is nearly identical to that inferred from underthrusting near the coast of southwest Japan. To this evidence can be added directions of slip inferred from mechanism solutions for two historic megathrusts in this region, the Nankaido and Tonankai earthquakes of 1946 and 1944 respectively [Kanamori, 1972]. Furthermore, the rate of movements along that part of the Sagami trough in the Kanto district is approximately 6 cm/yr (estimated from slip during the Kanto earthquake and average recurrence time for similar events in this region), which is in close agreement with a rate of 8 ± 4 cm/yr computed from similar data in the Nankaido region of southwest Japan [Fitch and Scholz, 1971]. This evidence strongly suggests that the slip vector is , at most, only partially decoupled in this region.

Inland from the zone of underthrusting is the Median Tectonic Line along which earliest movements predate the current episode of plate tectonics that in Japan began during the Miocene [Kaneko, 1966; Matsuda et al., 1967]. Geomorphic evidence of Quaternary movements in the right-lateral sense [Kaneko, 1966; Okada, 1971] shows that at least part of the rejuvenated activity along this fault zone is contemporary with underthrusting along the Nankai trough. Seismic ev dence for the onset of underthrusting one to two million years ago[Fitch and Scholz, 1971; Kanamori, 1972] coincides with geologic evidence for post-Pliocene to Recent "upwarping and block movements" in this part of Japan [Matsuda et al., 1967].

The most active section of the median tectonic line judging from geomorphic evidence is the middle section where recent movements yield an average rate of right-lateral slip of about 5 mm/yr [Okada, 1971]. This rate is lower than that of underthrusting along the Nankai trough by more than one order of magnitude. A record of large-magnitude earthquakes in western Japan that is thought to be complete for about the last 600 years [e.g. Imamura, 1928] reveals no major events along this fault zone. Thus large movements have not occurred on this fault in recent years unless these movements occurred aseismically.

Minor movements in the right-lateral sense along a fault zone of this strike can also be explained as internal deformation resulting from east-west compression inferred from recent movements on other faults in western Japan [e.g. Ichikawa, 1965, 1966]. In any case, the assumption that slip is coupled in southwest Japan is probably as good as the assumption of completely decoupled slip in the Philippine region.

Having selected directions of slip that are thought to approximate directions of total slip between the plates, centers of rotation are fit these data. Two solutions that give nearly equal fits are given in Table 1 (solutions 1 and 4). The center of rotation near Alaska is preferred, because an anticipated center of rotation for the eastern margin of the Philippine plate requires a center of rotation for the western margin of this plate in northeast Pacific. A large distance between this center of rotation and southwest Japan is satisfying, because this distance is sufficient to keep computed rates of slip in the Philippine region no larger than the largest spreading rates at crests of active ridges, about 10 cm/yr. [e.g. LePichon, 1968]. Rates that are much larger would not violate plate theory [e.g. McKenzie and Parker, 1967] but would, considering the speculative nature of this model, require additional justification.

The configuration of inclined seismic zones beneath the Izu-Bonin and Mariana arcs (Figure 2) and a relative absence of activity at all depths in the region of the Palau and Yap trenches and along other parts of the southern margin of this plate restrict centers of rotation for the Pacific and Philippine sea plates to a region south to west-southwest of the Mariana arc [Katsumata and Sykes, 1969]. Because instantaneous vectors of rotation can be summed, such a vector for the Eurasian and Philippine sea plates and another for the Pacific and Eurasian plates, when summed, yield a rotation vector for the Pacific and Philippine Sea plates. In computing this sum there is an additional assumption that slip between the

Eurasian and China plates can be neglected in comparison with the other relative plate motions in the summation. Given instantaneous rotations for the Pacific and Eurasian plates computed by others (solutions 5 and 6 in Table 1), it is apparent that if the summed vectors are to yield a center of rotation for the Pacific and Philippine Sea plates that satisfies constraints imposed by recent seismicity along this plate margin, the center of rotation for the Eurasian and Philippine Sea plates must be in the northeast Pacific.

Of the two centers of rotation for the Pacific and Philippine Sea plates, the preferred location is the one in east-central Australia (solution 7 in Table 1). This preference cannot be judged with certainty from available mechanism solutions (Figure 11) because of either large uncertainty in the determinations of the nodal planes (e.g. solutions 20 and 14 in Katsumata and Sykes, [1969]) or possible complications resulting from interarc spreading in the western Mariana trough (solutions 18 and 19 in same), or both. Implied directions of convergence (Figure 13) that are normal in the Izu-Bonin and Mariana arcs are consistent with a large component of horizontal shear along latitudinal fracture zones that separate the Palau and Yap, and the Yap and Mariana trenches (Figure 11).

From arguments in favor of the center of rotation in Australia it would be hazardous to conclude that the center of rotation for the Eurasian and Pacific plates computed by LePichon [1968] is less accurate than that computed using the center of rotation for the American and Pacific plate from McKenzie and Parker [1967]. The latter is somewhat more satisfying because it is a fit not only to the strike of transform faults within and marginal to the Pacific Ocean, but also to slip vectors from mechanism solutions for underthrusts along the convex side of the Aleutian arc. In any case, the least well-determined rotation vector in the sum is the one for the Eurasian and Philippine Sea plates.

The remaining two solutions (numbers 2 and 3) given in Table 1 contradict the decoupling hypothesis by assuming that the directions of underthrusting along the east side of the Philippine Islands give the direction of total slip in this region. Solution 2 is a poor fit to the data. A standard deviation of 18° is larger than the uncertainty in many of the inferred directions of underthrusting. Solution 3 is completely unacceptable because it implies opening along either the Ryukyu arc or the Philippine arc. These negative results can be interpreted as additional support for the decoupling hypothesis.

CONCLUSION

The sense of parallel slip along the western margin of the Philippine Sea inferred from the preferred center of rotation for the Eurasian and Philippine Sea plates agrees with the sense of recent offsets on the Median Tectonic Line, the Longitudinal fault, and the Philippine fault (Figure 2). However, computed ratios of parallel to normal slip in southwest Japan, Taiwan, and, to a lesser extent, in the Philippines (Table 2) conflict with seismic evidence from these regions. The largest estimates of right-lateral shear along the Median Tectonic Line (about 5 mm/yr.) [Okada, 1971] are about

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an order of magnitude less than that required for complete decoupling. If continued development of an island arc in southwest Japan results in complete decoupling, then the ratio of parallel to normal slip inferred from solution 1 (Table 1) will be approximately 1 to 2. This speculation assumes that the preferred center of rotation will remain in its present position near southwest Alaska. Such an assumption is difficult to defend for a plate margin such as this one, parts of which are in early stages of development. For example, imagine within a plate of lithosphere a nascent island arc that is extending itself in only one direction. As such a convergent plate boundary continues to grow it will cause migration of an initial center of rotation in a direction that in a simple case is given by the direction in which the arc is extending itself.

In contrast to southwest Japan, a well-defined zone of underthrusting has yet to develop in the region between the southern end of the Ryukyu arc and Luzon. Recorded shallow activity in this region strongly suggests that the Longitudinal fault is at least as active and probably more active than other faults in the region with the possible exception of the zone of underthrusting along the southern end of the Ryukyu arc [Katsumata and Sykes, 1969]. Thus a ratio of parallel to normal slip of less than one third computed from the inferred direction of oblique slip for this region is inconsistent with recent seismicity of the region.

Earthquakes at depths as great as 150 km that are found beneath eastern Taiwan and in decreasing concentrations south of the island are suggestive of plate consumption; however, the manner in which this activity manifests itself at the surface is still a puzzle. The spatial configuration of the seismic zone can be explained by a curled edge on the part of the plate adjacent to Taiwan.

The assumption of complete decoupling in the Philippine region results in ratios of parallel to normal slip that are 1 to 1 for the part of the arc adjacent to the Philippine trench and 10 to 1 in the region of the hiatus in underthrusting north of the trench. Although a weak argument can be made for a concentration of recorded seismicity on the part of the fault adjacent to this hiatus, the level of activity is much less than that in the zones of underthrusting. Thus it is difficult to justify the assumption of complete decoupling without appealing to geomorphic evidence that at least quantitatively appears to be more substantial than the seismic evidence for slip [Allen, 1962].

As shown in Figure 13 angles formed by the western margin of the Philippine Sea and inferred directions of oblique slip vary by as much as 60°. In the Tiawan region, where decoupled slip is hypothesized, this angle is greater than 70°. Large angles of oblique slip such as this seemingly require a zone of horizontal shear that has little strength relative to that of the zone of plate consumption. However, a simple model for oblique convergence suggests that decoupling can occur at angles as large as 45° even when all fault zones have equal strength.

Consider the plate margin in Figure 14 in which a uniform horizontal force per unit area (F) in the direction of the slip vector is applied to the region. Simple conditions for horizontal shear on either the vertical or the inclined faults are obtained by equating horizontal shear stress to the product of normal stress and the coefficient of friction (μ):

(1) $F\ (\cos\alpha - \mu\sin\alpha) = \mu N_H$ for the vertical fault

and (2) $F\ (\cos\alpha - \mu\sin\alpha\sin\delta)\sin\delta = \mu N_H$ for the inclined fault where N_H is the contribution to normal stress from the hydrostatic load. When (1) > (2) horizontal shear occurs on the vertical fault in preference to the inclined fault. Assuming a dip of 30° for the latter the inequality simplifies to $\cos\alpha > \frac{3\mu\sin\alpha}{2}$. In which case angles of oblique slip as large as 45° satisfies the inequality (assuming μ is about 0.7). This argument is only slightly weakened by using an expression for oblique shear rather than horizontal shear in equation (2) This simple model suggest that decoupling of oblique convergence is only weakly dependent on the angle of oblique slip in regions where the strength of a vertical fault is equal or less than that of the zone of shallow underthrusting.

One of the more interesting results of the preferred plate model for the northest Pacific is that the Sagami trough marks the path of an unstable triple point formed by the junction of three major plates near Japan (Figure 2). Computations, illustrated in Figure 15 with diagrams proposed by McKenzie and Morgan (1969] reveal a large component of right-lateral shear along the Sagami trough at a rate of about 70 km per million years. Absence of an offset between the Izu-Bonin and Japanese trenches requires extension between the Philippine Sea and Pacific plates in the vicinity of the triple junction. Normal faulting is known in this region from a mechansim solution to the Boso-Oki earthquake of November 26, 1953 (Kanamori, personal communication, 1971]. Karig [1971b] speculated that elongated troughs within the Izu-

Bonin arc result from a nascent stage in the development of an inter-arc basin. Extension within this arc is supported by a mechanism solution (number 13, Figure 11) for normal faulting [Katsumata and Sykes, 1969] and high values of heat flow [Watanabe,et al., 1970]. If the Izu-Bonin trench has remained stationary, then the argument for extension near the triple junction can be applied to the remainder of the Izu-Bonin arc. By this argument, extension within this arc is a consequence of the mechanics of rigid plates, and thus only passive upwelling of magma is required to form new sea floor. However, this speculation is hazardous because the bulge-like configuration of the Mariana ridge (Figure 2) strongly suggests that inter-arc extension can generate enough pressure to push the frontal arc into an adjacent ocean basin [Karig, 1971a].

Recorded seismicity along the Izu-Bonin arc is conspicuously lacking in shallow earthquakes of large magnitude [e.g. Kanamori, 1972]. A cessation of plate consumption along this plate margin was proposed by Kanamori [1972] to account for this absence. Inter-arc extension provides an alternate explanation by which compressive stress normal to the margin of the Pacific plate is reduced to a sufficiently low value that consumption of the Pacific plate can take place without large-magnitude earthquakes. Such a mechanism for stress reduction again implies passive upwelling of magma unlike that within the West Mariana basin. Wu [1971] interprets the low level of shallow seismicity along the entire eastern margin of the Philippine Sea as evidence for plate separation.

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Within tectonically active margins of southeast Asia and the western Pacific, the Philippine fault and the western Andaman basin are of special interest because each appears to have an analgue in another part of the world. The former is in some ways similar to the Alpine fault in New Zealand, and the latter is similar to the Basin and Range province of the United States. The western Andaman basin and the Basin and Range province are tectonically similar in that each region is bounded on one side of an extensive zone of transcurrent faulting and on the other side by semi-stable continental margin, and within each region there is active extension accompanied by outpouring of basaltic magma. Scholz et al., [1971] interpreted the Basin and Range province as a latent inter-arc basin. Similarly the western Andaman basin can be interpreted as an interarc basin: however, unlike most interarc basins, this one has not formed above a descending slab of lithosphere.

Previous interpretations of this basin as a "rhombochasm" [Carey, 1958; Rodolfo, 1969] requires lateral movements of adjacent parts of south-east Asia and the Sunda arc, whereas the interpretation proposed in this work requires only outward movement of the Andaman-Nicobar ridge to form a bulge that is apparent from physiographic maps of the region (e.g. Figure 4 in Rodolfo, [1969]). This interpretation implies that the total amount of extension within the western basin is much less than its area.

Some close comparisons can be made between the physiographic expression and tectonic setting of the Alpine fault and those of the Philippine fault. For example, the Alpine fault is confined to a narrow zone in the southern part of the South Island and broadens northward into a series of subparallel branches. Although active volcanism is absent in the South Island, seismic evidence suggests that a zone of convergence follows a greater part of the west coast of this island. Two submarine earthquakes north of Milford Sound yielded mechanism solutions consistent with thrust faulting [Johnson and Molnar, 1972]. A possible submarine continuation of this fault south of Milford Sound parallels a zone of earthquakes at intermediate depths [Smith, 1971] and a deep-sea trench [Hayes et al., 1971]. From this evidence it seems probable that the plate margin in this region is not a zone of pure horizontal shear. Consquently, computed centers of rotation for the Indian Ocean and Pacific plates that are constrained to give plate motion in New Zealand that is pure horizontal shear along the Alpine fault will be in error proportional to the rate of convergence in this region.

In this work concurrent horizontal shear and plate consumption in the same region is explained by decoupling of oblique slip. In some regions such as in the western Sunda arc and eastern parts of the Philippine arc, decoupled slip occurs along parallel zones of horizontal shear and shallow underthrusting. The lithosphere between these fault zones is a long narrow plate that in an ideal situation will move in such a way as to cause extension at one end of the plate and compression at the other. In general, these simple end effects are obscurred by complications such as a changing ratio of parallel to normal slip along the arc and internal deformation resulting from volcanism. In addition, the narrowness of such a plate may result in earthquake sequences on one side of the plate influencing those on the other side. If this were the case a rigid plate approximation would be of doubtful validity. Zones of convergence in continental regions, such as the one that extends from eastern Turkey to Central Asia, southwest of Lake Baikal, may be extreme cases of decoupled slip in which the boundary between the major plates is composed of numerous plates so small that their motion is dependent on the motion of the surrounding plates even on a time scale as short as a few years. The width of the contact zone between the major plates, that in places exceeds 100 km judging from the width of the seismic zones in the region [e. g. Nowroozi, 1971], can be considered support for such a plate model.

In regions of plate convergence without a well-developed island arc such as southwest Japan and Taiwan, transcurrent movements appear to be part of an initial stage in the lateral growth of an adjacent zone of convergence. Thus transcurrent faults within active island arcs may predate the formation of the arc in that region. Furthermore, such faults not only can inherit their trace but also can inherit their sense of movement from a pre-existing fault.

These ideas can be applied to Cenozoic faulting on the San Andreas system in California. There is evidence for slip on the San Andreas that predates the time when this fault became part of the boundary between the American and Pacific plates [e.g. Atwater, 1970]. Some of these early movements may have occurred within an active island arc associated with a mid-Cenozoic trench that existed off the coast of western North America [Atwater, 1970]. As the plate margin was transformed progressively from a convergent margin between the Pacific and Farallon plates [e.g. McKenzie and Morgan, 1969], that pre-existing transcurrent fault inherited the present plate margin in the region. This speculation explains why the location of the pre-existing zone of underthrusting was not transformed into the present plate margin.

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TABLE I

INSTANTANEOUS VECTORS OF ROTATION *

SOLUTION	CENTER OF ROTATION LATITUDE	CENTER OF ROTATION LONGITUDE	SLIP AZIMUTHS	STANDARD DEVIATIONS	RATE $\times 10^{-7}$ deg/yr	REMARKS
1. Eurasia wrt Philippine Sea	56°N	154°W	**Philippine fault, Kanto Eq. and underthrusts along Ryukyu arc and southwest Japan	7°	9	Least squares fit constrained to North Pacific with rate computed from rate of underthrusting adjacent to southwest Japan of 8±4 cm/yr (Fitch and Scholz, 1971)
2. Eurasia wrt Philippine Sea	45°N	145°E	***Kanto Eq. and underthrusts along Ryukyu and Philippine arcs	18°	28	Same as in Solution (1)
3. Eurasia wrt Philippine Sea	23°N	124°E	Same as in Solution (2)	8°	—	Least squares fit implying plate separation along either the Ryukyu or Philippine arc
4. Eurasia wrt Philippine Sea	6°N	111°E	Same as in Solution (1)	6°	—	Least squares fit implying a northward increase in rate of convergence along western margin of the Philippine Sea
5. Eurasia wrt Pacific	60.5°N	85.7°W			12	Center of rotation for America and Pacific plates computed by McKenzie and Parker (1967) with rate computed from spreading rate of 6cm/yr at the mouth of the Gulf of California (e.g. Atwater, 1970)
6. Eurasia wrt Pacific	67.5°N	41.5°W			8	Le Pichon (1968)
7. Pacific wrt Philippine Sea	26°S	143°E			7	Sum of Solutions 1 and 5
8. Pacific wrt Philippine Sea	1°N	179°W			7	Sum of Solutions 1 and 6

* All vectors are right handed when looking outward from the center of the earth.

** Slip azimuths from underthrusts 15, 23, 26, 27, 30, 31, 22 in Figure 11.

*** Slip azimuths from underthrusts 44, 47, 51, 39, 40, 49, 35, 36 in Figure 11 as well as those listed above for Ryukyu arc and southwest Japan.

TABLE II

RATES OF SLIP

FAULT	AZIMUTH OF FAULT	AZIMUTH OF SLIP**	DECOUPLED SLIP RATES* PARALLEL (STRIKE SLIP)	NORMAL (DIP SLIP)
Median Tectonic Line (Southwest Japan)	249°	310°	4	7
Longitudinal Fault (Tiawan)	22°	307°	2	9
*** Philippine Fault Adjacent to Hiatus in Underthrusting	321°	305°	10	1
Philippine Fault Adjacent to Philippine Trench	346°	304°	7	7

* Rates are considered no better than first order approximations because of uncertainty in the rotation vectors.

** Computed from Solution (1) in TABLE I.

*** Large ratio of oblique to normal slip in this region is a consequence of constraints placed on solution (1) (see text for detailed argument).

FIGURE CAPTIONS

Figure 1 Vertical section of a well-developed island arc in a region of oblique convergence. Decoupling hypothesis is illustrated by transcurrent movement on a vertical fault adjacent to the center of active volcanism.

Figure 2 Plate boundaries and major transcurrent faults in the Far East. Solid boundaries are those that are well-defined by recent shallow earthquakes [e.g. Barazangi and Dorman, 1969]. Dashed curves extrapolate between well-defined boundaries. Dotted curves represent traces of known transcurrent faults of great length: M.T.L., L.F., P.F. and S.F. stand for Median Tectonic Line, Longitudinal fault, Philippine faults, and Semangko fault, respectively. S.T. stands for Sagami trough. Plate margins east of New Guinea are from Johnson and Molnar [1972].

Figure 3 Major fault zones adjacent to southeast Asia. Shaded and stripped regions are those of known or suspected extension and shortening respectively. Subareal traces of major transcurrent faults and the sense of recent movements on these faults are from a review paper by Katili [1970]. Saw-tooth curves mark zones of shallow underthrusting that are seismically active judging from recent distributions of shallow earthquakes. Smooth continuations of these curves represent zones of underthrusting along which, at most, only scattered concentrations of shallow earthquakes were recorded in recent years. Thin curves (dashed where there is little supporting evidence) mark fault zones that may or may not be part of a plate margin. Directions of relative motion between the major plates computed from rigid plate models are given by solid lines [Morgan, 1972] and dashed lines [LePichon, 1968].

Figure 4 Mechanism solutions for recent shallow earthquakes in the Indonesian - Philippine-region adapted from Figure 10 in Fitch, [1970a]. Open circle with oppositely directed arrows gives epicenter and horizontal projection of axis of minimum compression (the T axis) for recent normal faulting. A direction of slip ~~(in this case shallow underthrusting)~~ is inferred from those solutions of the thrust type in which one nodal plane is nearly vertical. This plane is assumed to be the auxillary plane [e.g., McKenzie and Parker, 1967]. If both nodal planes have nearly the same dip angle, the axis of maximum compression is plotted. Closed circle and arrow gives epicenter and horizontal projection of direction of slip. The sense of movement is such that oceanic lithosphere moves in the direction of the arrow relative to an observer fitted to an adjacent island arc. Closed circle with opposing arrows gives epicenter and horizontal projection of axis of maximum compressive stress (the P axis) for recent thrust faulting. Strike-slip movements are illustrated by shear symbols. Central Andaman trough and rift valley [Rodolfo, 1969] are represented by parallel solid and dashed curves. Regions enclosed by a solid curve are prominent bathymetric depressions, either deep-sea trenches or troughs.

Solutions 1 through 4 are from Fitch [1970a], solutions 45 through 80 (for which details are given in the Appendix) are new solutions mainly from the years 1968 to mid-1970. Solutions 9, 11, and 12 in the Andaman region are from Fitch [1970b]. Solutions 1 through 5 in western New Guinea and solution 20 near the north end of the Yap trench are from Johnson and Molnar [1972] and Katsumata and Sykes [1969] respectively. Solutions 5 and 6 in northern Sumatra and 31, 37, 39, 40 and 44 in the Philippine region were improved by using additional S-wave polarization angles and additional P-wave polarities. These improved solutions are also given in detail in the appendix. Solutions 1 and 11 (solid squares) are for earthquakes at depths that are transitional from shallow and intermeditate activity. With reference to the earth's surface, these solutions show normal faulting with one nodal plane having a steep dip. Such solutions are consistent with down-dip orientation of the axis of minimum stress within the descending lithosphere in this region [Fitch and Molnar, 1970].

Figure 5 Recent shallow seismicity and bathymetry of the Andaman region. Open and closed circles are epicenters computed by the USCGS from arrival times at more than 20 and 10 to 20 stations, respectively, for in the years from 1961 to 1970. Bathymetry (in meters) is from Plate 1 of Rodolfo, [1969]. Solid lines in northern Sumatra represent mapped fault traces within the Semangko fault zone [Katili, 1970].

Figure 6 Mechanism solution for shallow earthquakes in the Indian Ocean. Nodal planes are given by the heavy curves. Polarity of P-wave first motion is given by: open circle for clear dilatation, closed circle for clear compression, open triangle for weak dilatation, closed triangle for weak compression, and x for weak arrival of uncertain polarity. Arrows give S-wave polarization. X's enclosed in circles are poles to the nodal planes. T and P stand for axis of minimum and maximum compression respectively. Within each set of parentheses is an azimuth and plunge in that order. Data are plotted on an equal-area projection of the lower hemisphere of the focal sphere.

Figure 7 Recent shallow seismicity near Sunda Strait. Epicenters are mapped as closed or open circles as in Figure 5. Heavy curves represent traces of major faults identified in Katili [1970].

Figure 8 Recent shallow seismicity, volcanism, and major faults in the Philippine and adjacent regions. Solid circles are epicenters of shallow earthquakes located by the USCGS from 20 or more arrival times for P-waves. This activity is from the years 1961 to 1971. Triangles give locations of active volcanoes reported (in the Catalogue of Active Volcanoes of the World including Solfatara Fields) by Neuman Van Padang, [1953]. Heavy curves represent traces of major transcurrent faults [Katili, 1970]. Dashed parts of these curves represent submarine continuations for which there is seismic and bathymetric evidence that is referenced in the text. Deep-sea trenches and troughs outlined with bathymetric contours are from the charts of Chase and Menard [1969].

Figure 9 Recent shallow earthquakes in western New Guinea and adjacent regions. Epicenters are mapped as closed or open circles as in Figure 5. The heavy solid and dashed lines represent subareal and inferred submarine trace of the Sorong fault. [Visser and Hermes, 1962].

Figure 10 Recent shallow earthquakes and bathymetry near the Talaud Islands. Epicenters are mapped as closed and open circles as in Figure 5. Bathymetry (in fathoms) is from Plate 1 of Krause [1966].

Figure 11 Mechanism solutions for recent shallow earthquakes along margins of the Philippine Sea (adapted from Katsumata and Sykes, [1969]). Mechanism solutions represented by the same symbols used in Figure 4. Symbols shown in key represent: (1) trench axis, (2) island chains and submarine ridges, (3) major fault zones. Solutions with numbers less than 27 are from Katsumata and Sykes [1969]. Solution 52 and those in the Philippine region are the same as those shown in Figure 4.

Solutions 27 through 35 are new solutions for the years 1968 to mid-1970, details of which are shown in Figure 12. The slip vector for the Kanto earthquake was determined uniquely from seismic and geodetic evidence reported by Kanamori [1971].

Figure 12 Additional mechanism solutions for shallow earthquakes in Ryukyu, southwest Japan, and Mariana regions. Locations were computed by the USCGS. Nodal planes are given by heavy curves. Polarity of P-wave first motion given by: open circle for clear dilatation, open triangle for weak dilatation, closed circle for clear compression, closed triangle for weak compression and x for weak arrival of inderterminate polarity. Arrows give S-wave polarization. X enclosed in a circle gives the location of a pole to one of the nodal planes. Locations of P (axis of maximum compression) and T (axis of minimum compression) axes are given by small closed circles.

Figure 13 Convergence along the margin of the Philippine Sea plate. Plate margin is in several regions greatly simplified (for details see text). Large arrows are inferred relative motion between plates. M.T.L., L.F. and P.F. stand for Median Tectonic Line, Longitudinal fault and Philippine fault respectively.

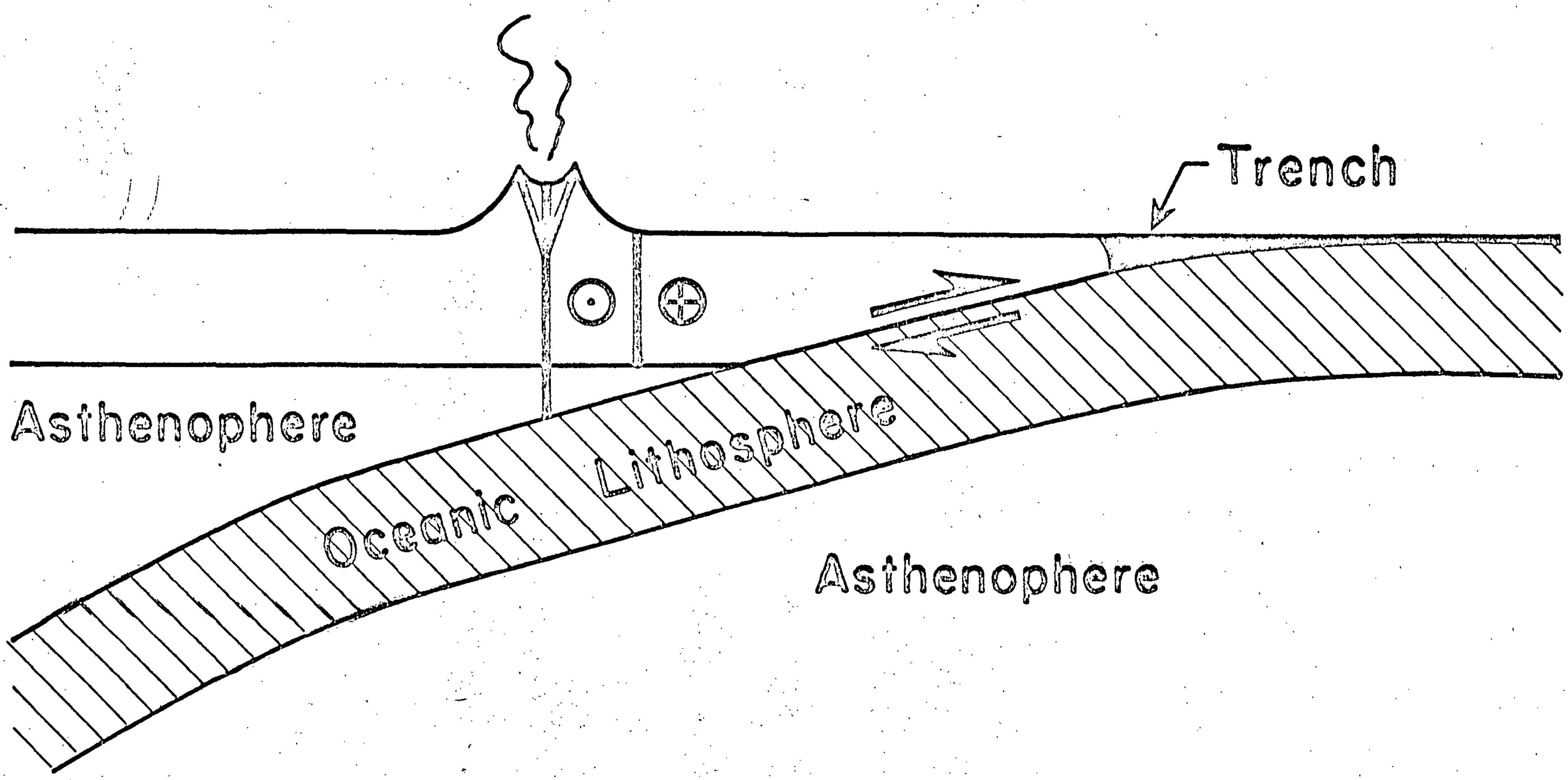
Figure 14 Schematic diagram of a zone of oblique convergence. (A) map view, (B) vertical cross section. Large arrows are slip vectors.

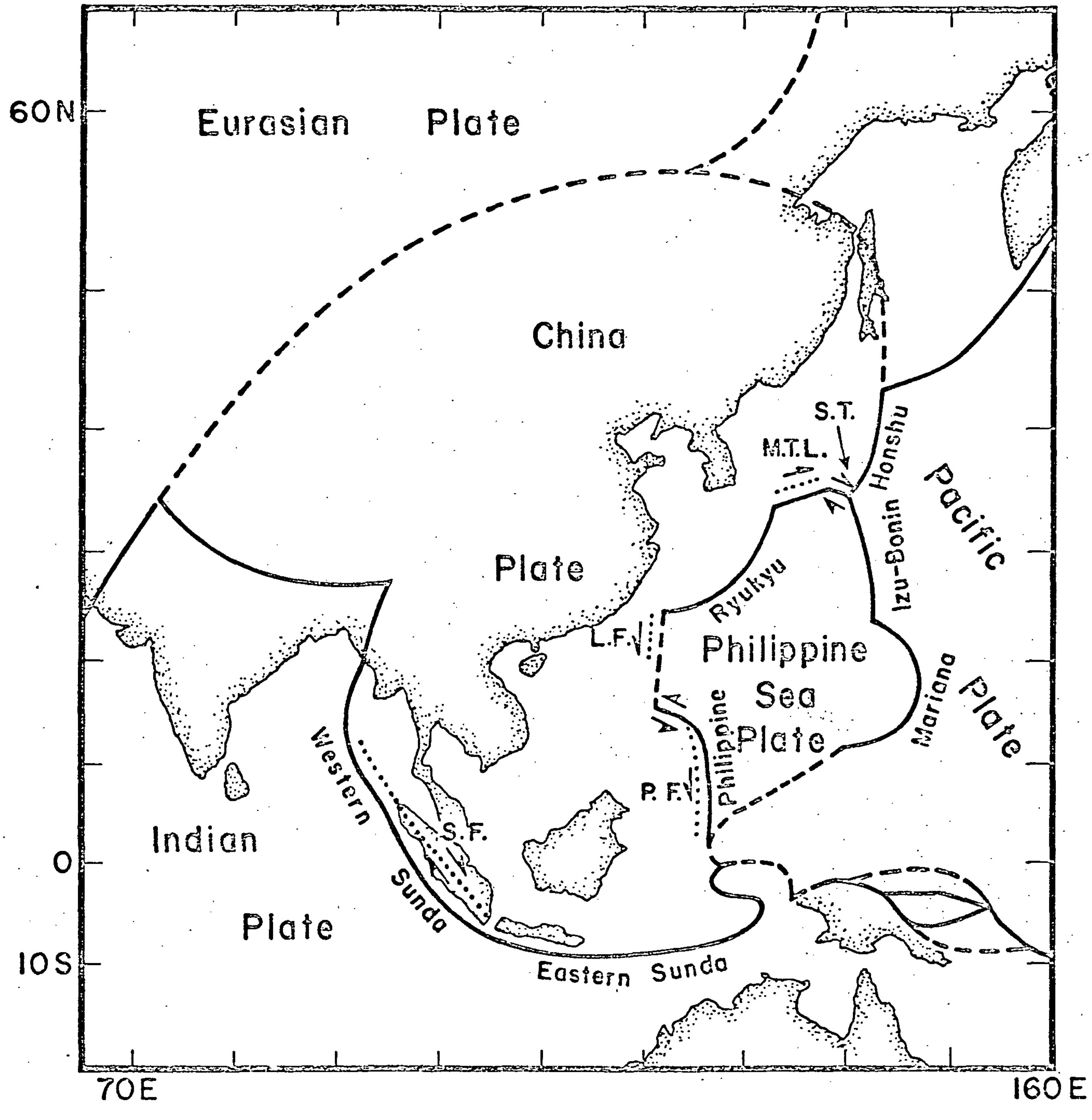
Figure 15 Migration of a triple point along the Sagami trough. Regions A, B and C on the left side of the figure represent pieces of Eurasian, Pacific, and Philippine Sea plates near Japan. The lines that join at the triple point represent a possible configuration for boundaries between these plates at the onset of underthrusting adjacent to southwest Japan; the lines between A and B, C and B, and A and C represent the Japanese trench, Izu-Bonin trench and the Nankai trough, respectively. The approximate time lapse since onset of underthrusting along the Nankai trough is one million years [Fitch and Scholz, 1971]. Using this time interval and rates of plate convergence computed from solutions 1 and 7 in Table I, it is possible to estimate the configuration of consumed lithosphere (dashed lines) and new positions for plate margins that move in response to migration of the triple point. The triple point migrates in the direction of the arrow which nearly coincides with the strike of the oceanic part of the Sagami trough. The rate is about 70 km per million years. The shaded region represents the amount of new oceanic lithosphere resulting from plate separation along the Izu-Bonin arc. This rifting is inferred from the absence of an offset between the Japanese and Izu-Bonin trenches.

APPENDIX

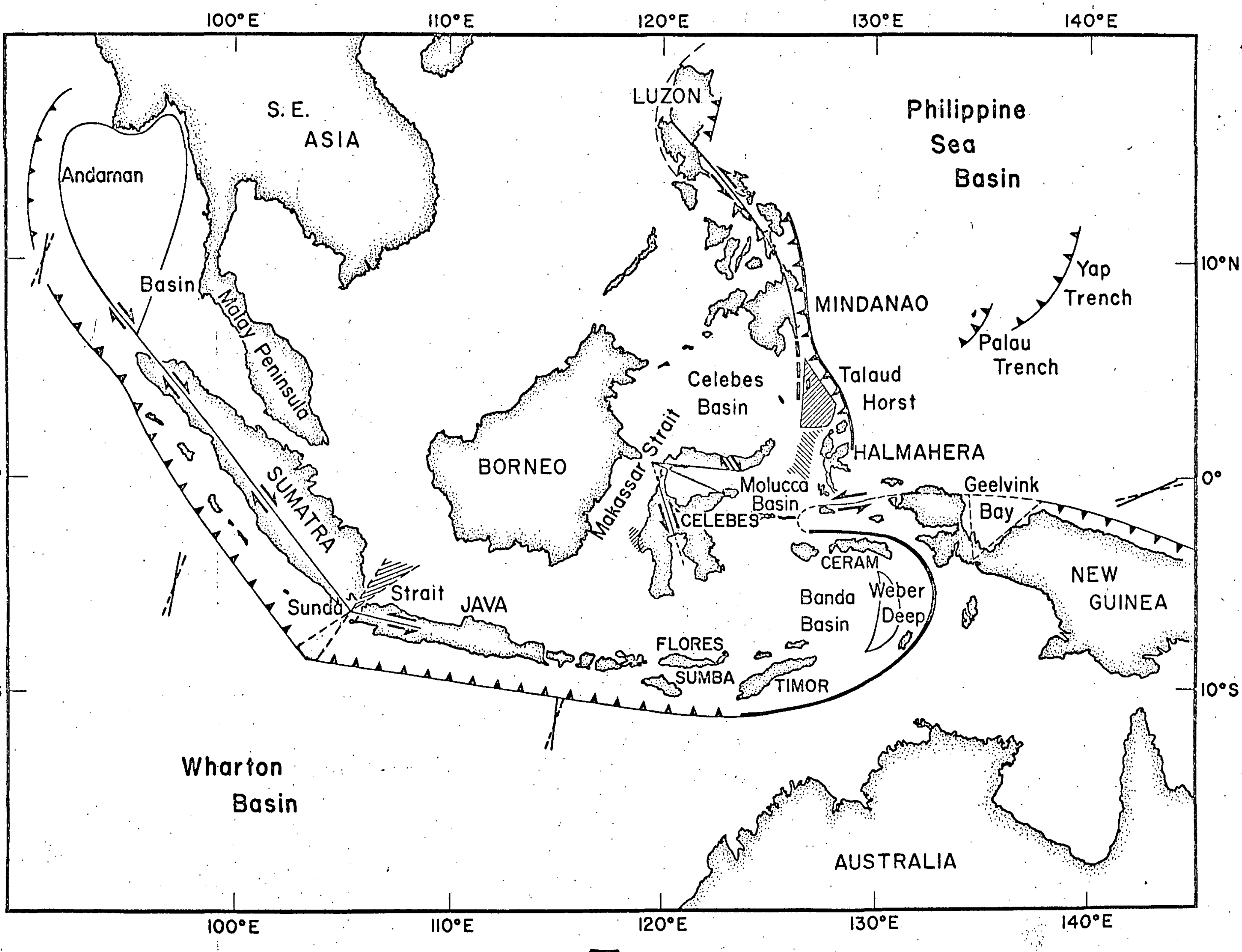
Caption A-1

Additional mechanism solutions plus improved solutions for shallow earthquakes in the Indonesia - Philippine region. Symbols and projects are the same as for Figure 12. Locations were computed by USCGS.


Trench
Asthenophere
Oceanic Lithosphere
Asthenophere


60N
0
10S
70E
160E
Eurasian Plate
China
Plate
Indian
Plate
Western
Sunda
S.F.
Eastern Sunda
L.F.
P.F.
Ryukyu
Philippine Sea Plate
Philippine
M.T.L.
S.T.
Honshu
Izu-Bonin
Mariana
Pacific
Plate

2


100°E
110°E
120°E
130°E
140°E
10°N
0°
10°S
S. E.
ASIA
LUZON
Philippine
Sea
Basin
Andaman
Basin
Malay Peninsula
MINDANAO
Yap
Trench
Palau
Trench
Talaud
Horst
Celebes
Basin
HALMAHERA
BORNEO
Makassar Strait
SUMATRA
Molucca
Basin
Geelvink
Bay
CELEBES
CERAM
NEW
GUINEA
Strait
Sunda
JAVA
Banda
Basin
Weber
Deep
FLORES
SUMBA
TIMOR
Wharton
Basin
AUSTRALIA

3

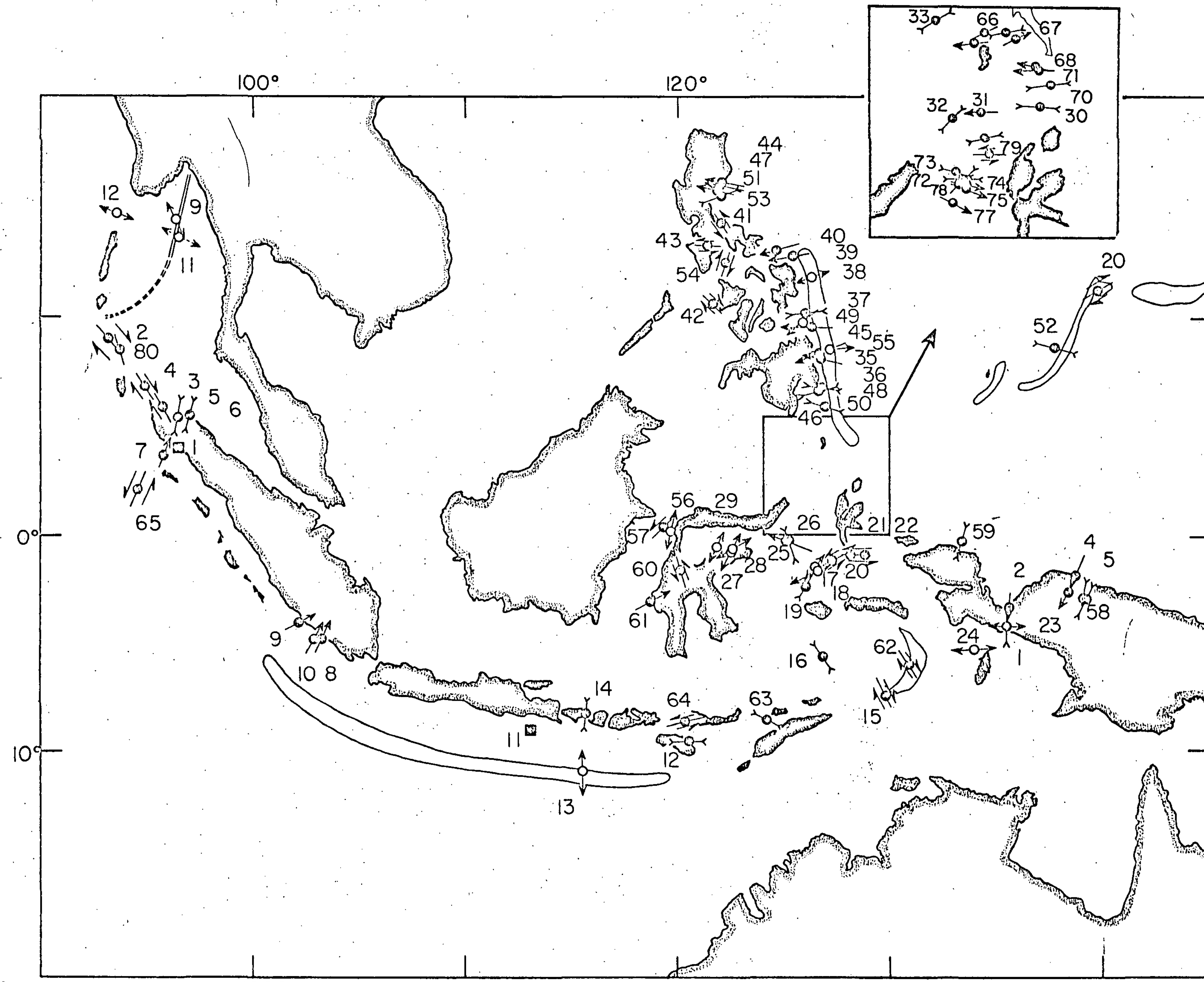
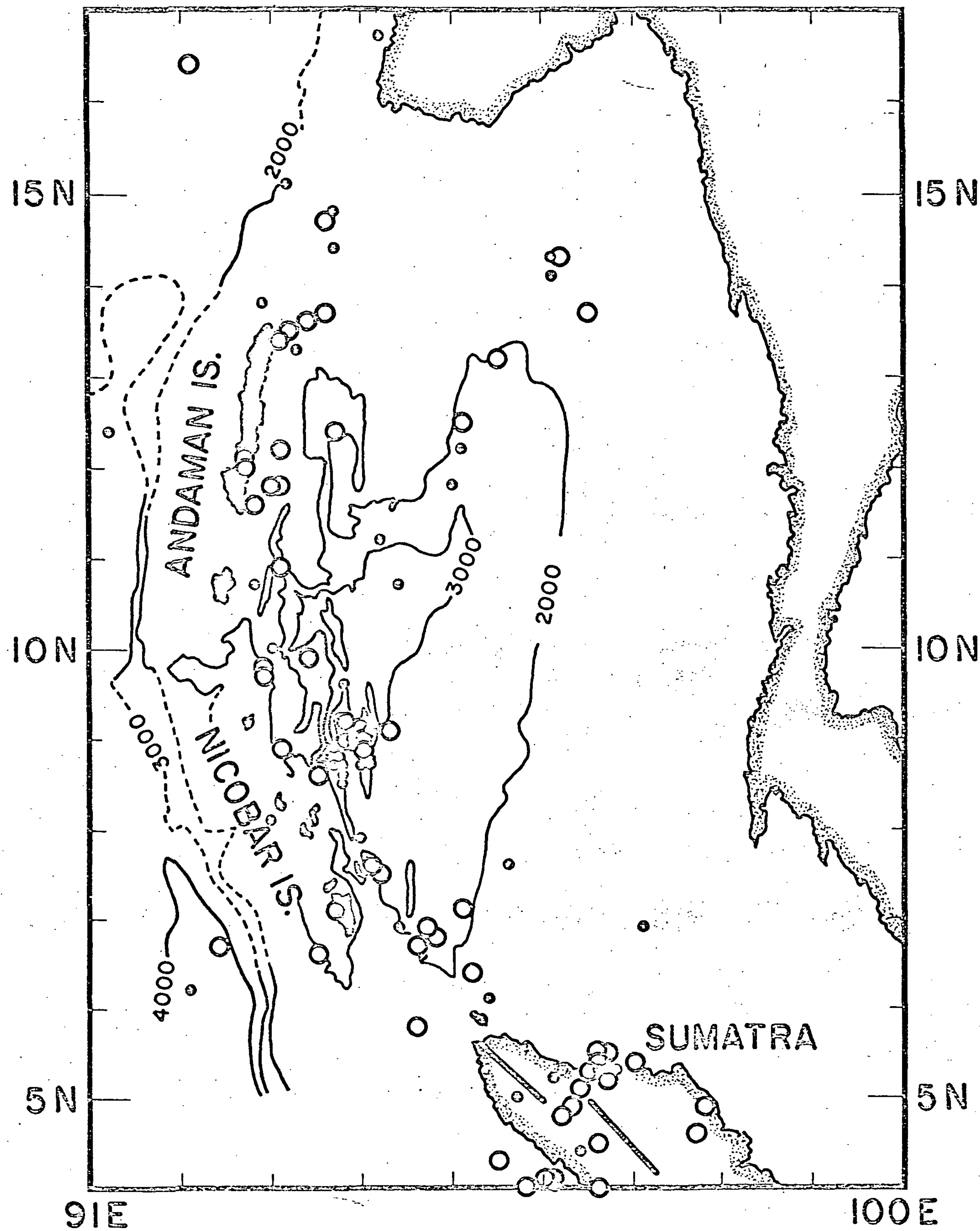
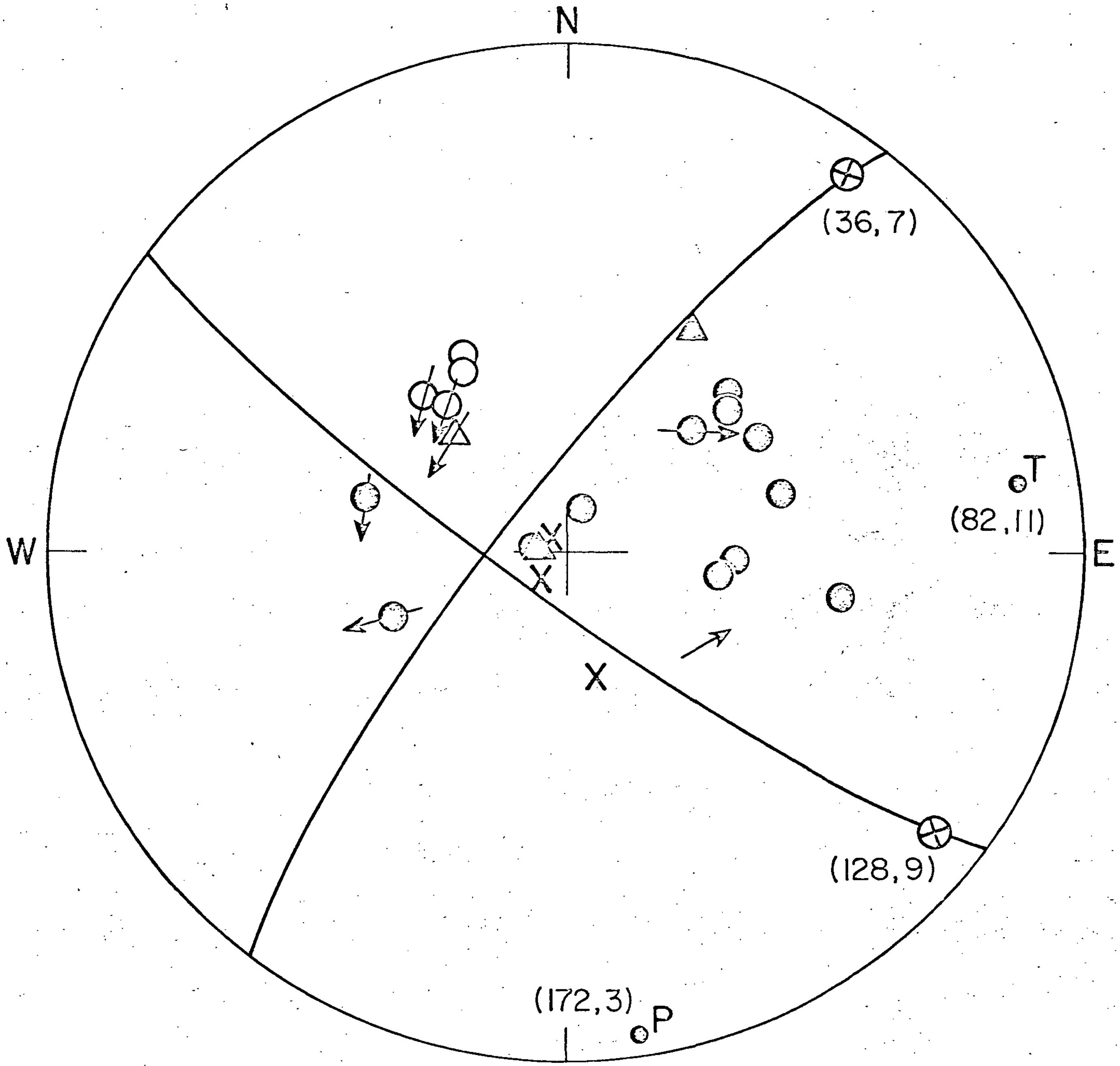


Fig 4


15N
15N
10N
10N
5N
5N
91E
100E
2000
2000
3000
3000
4000
ANDAMAN IS.
NICOBAR IS.
SUMATRA



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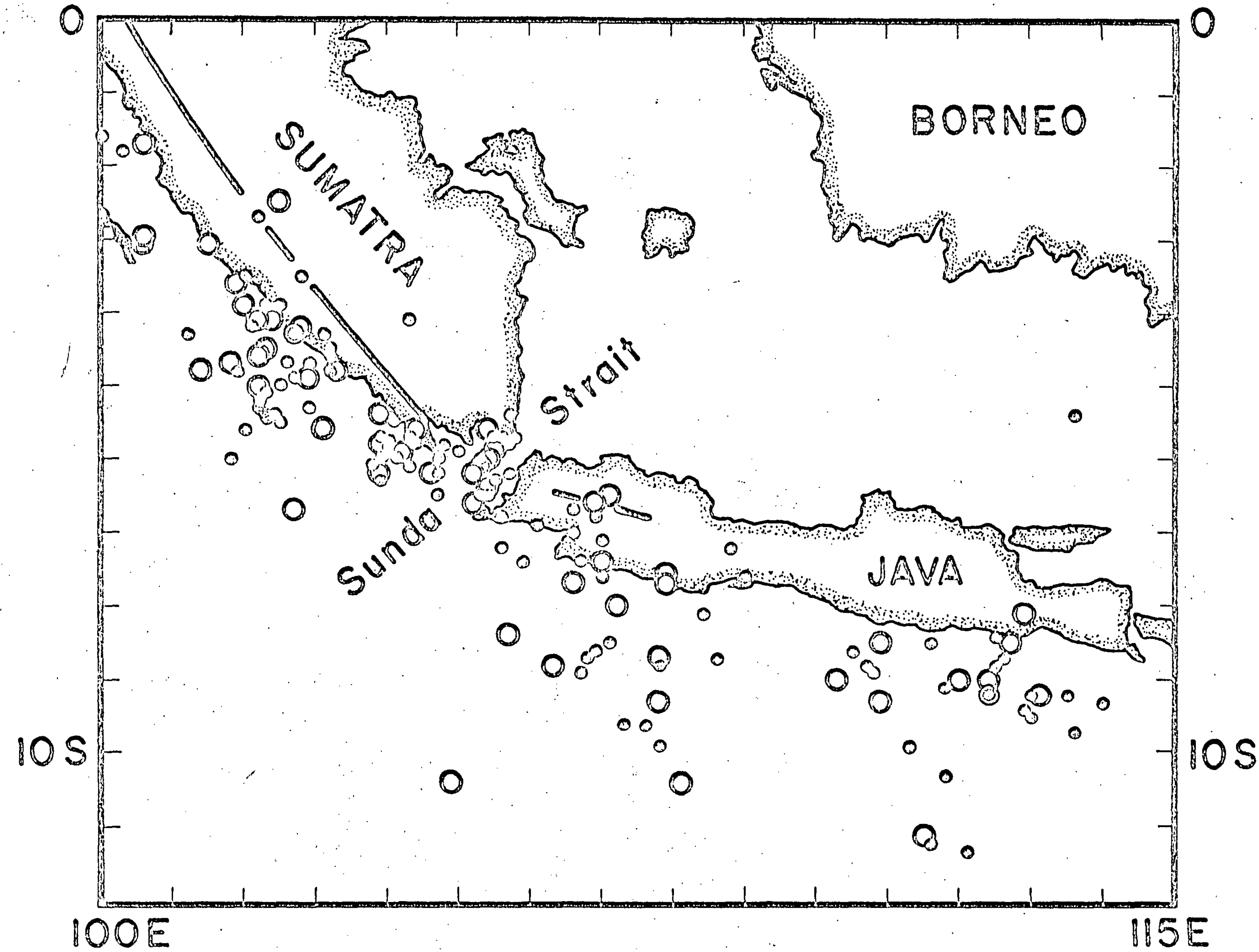
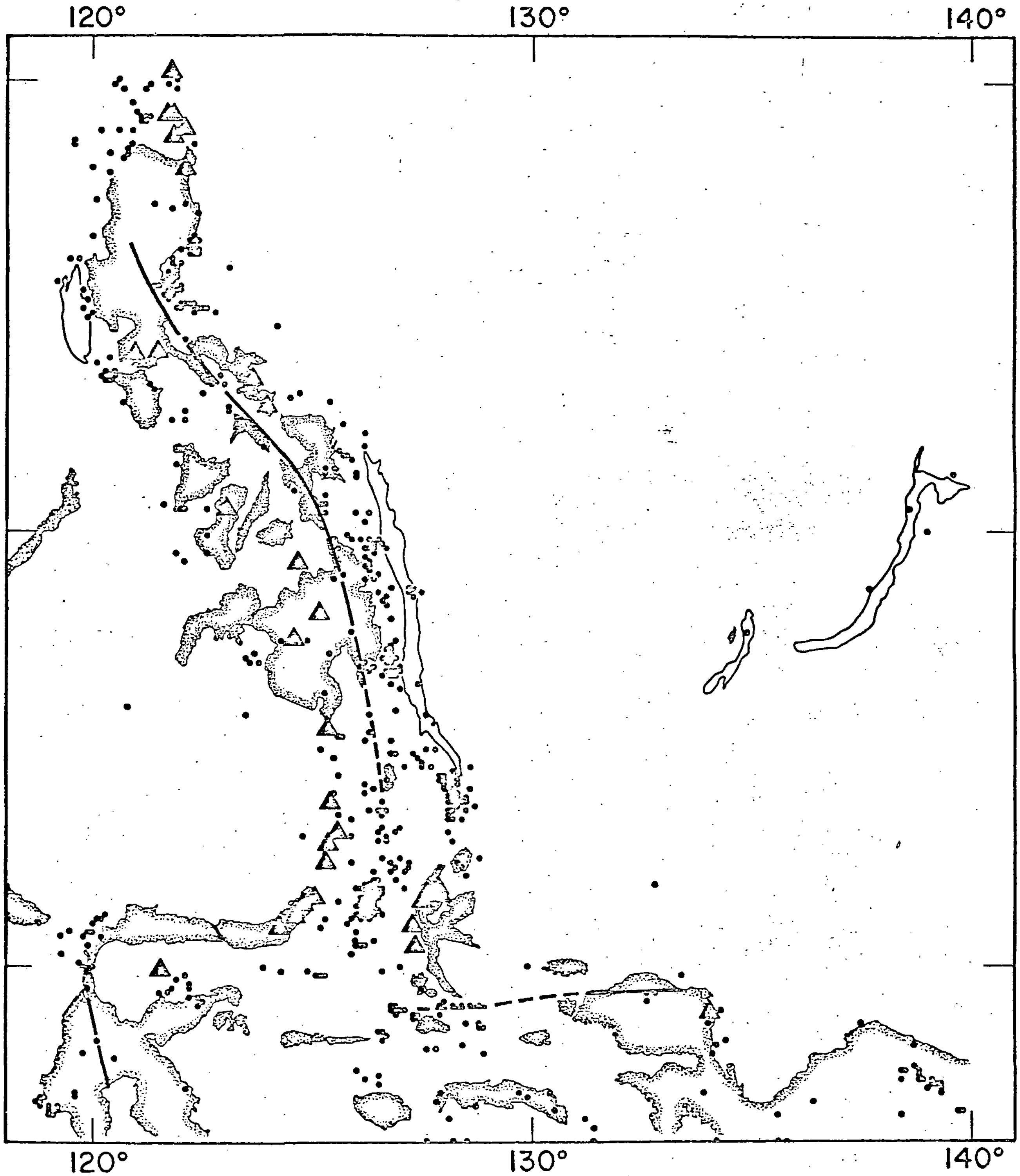
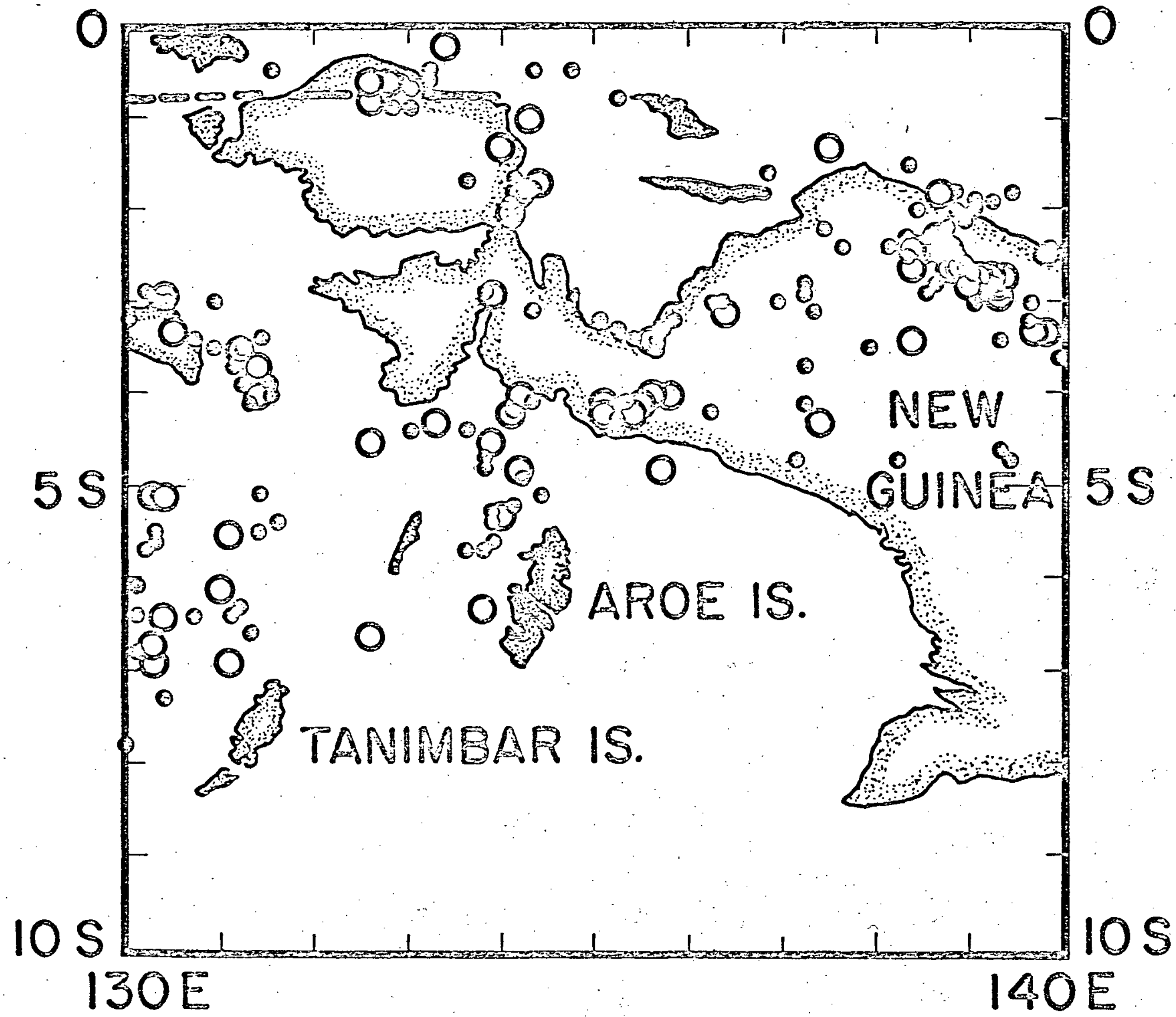
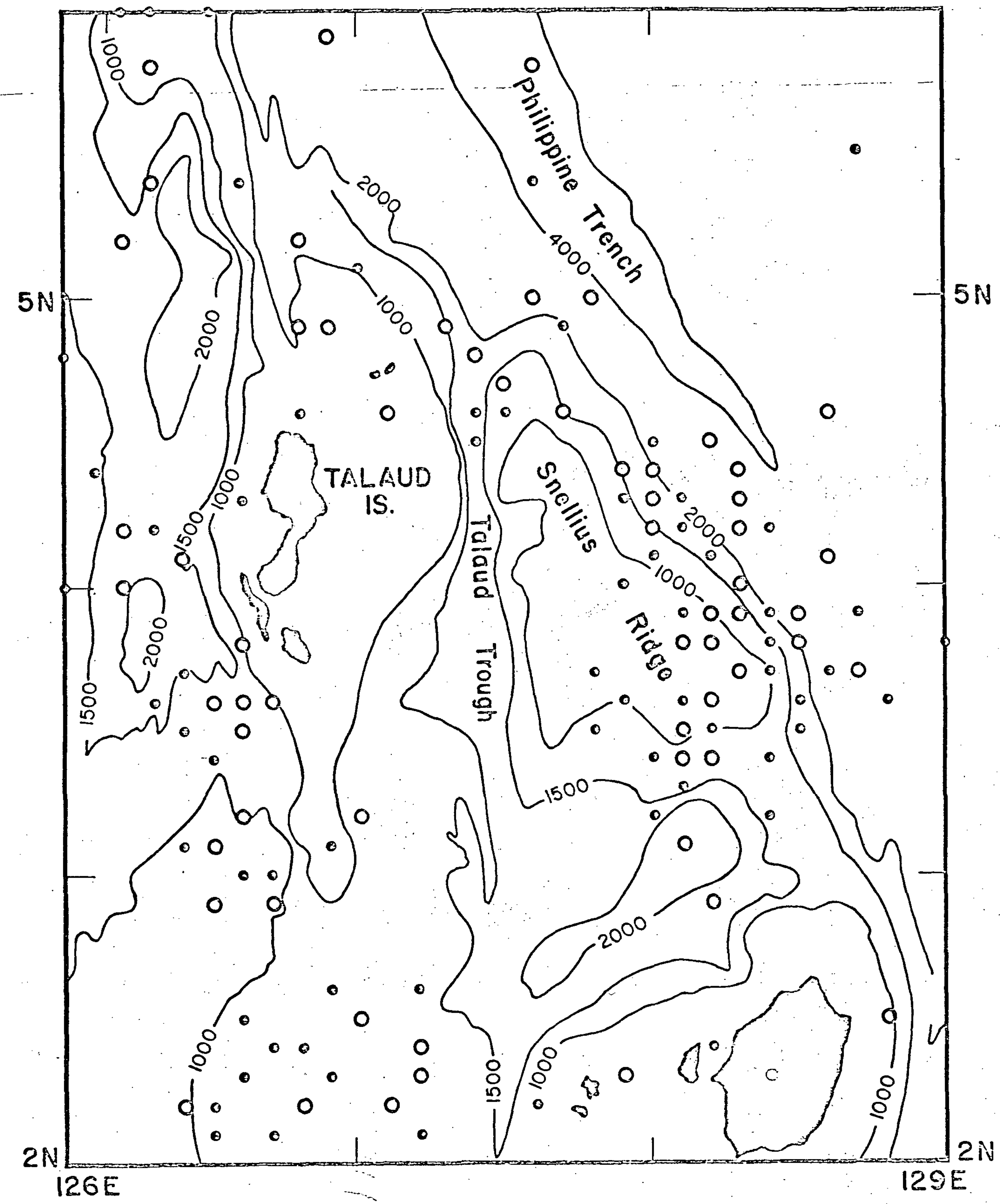


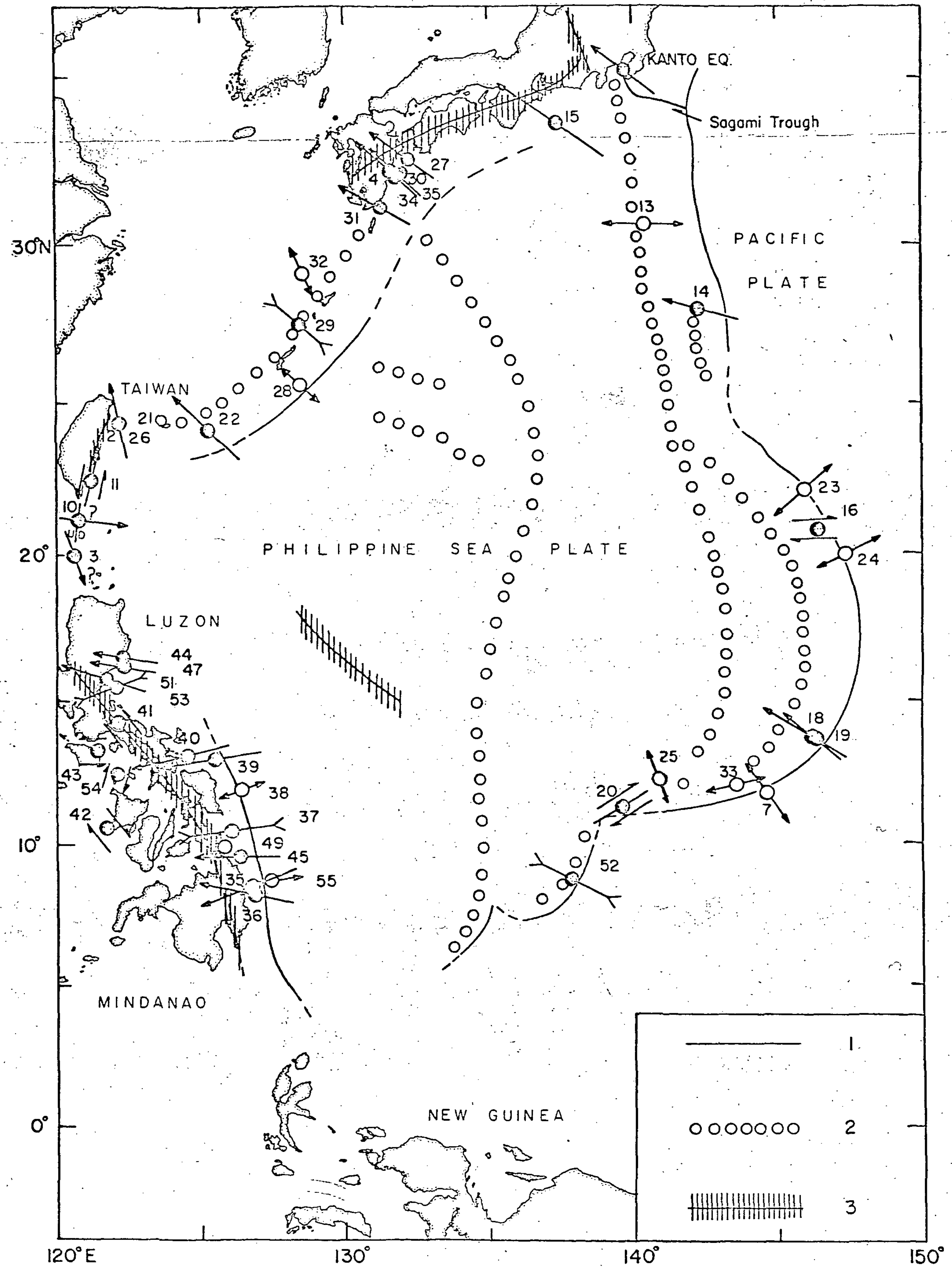
7



120°
130°
140°
20°
10°
0°
20°
10°
0°
120°
130°
140°

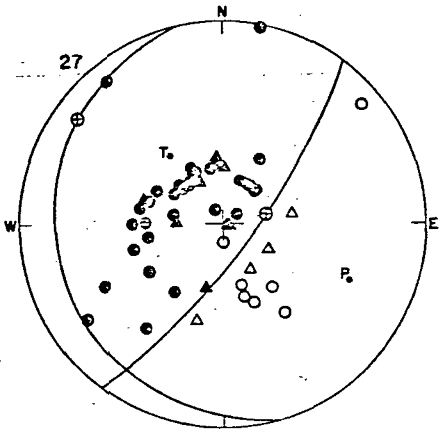

0
0
5 S
5 S
10 S
10 S
130E
140E
NEW
GUINEA
AROE IS.
TANIMBAR IS.


Philippine Trench
TALAUD
IS.
Talaud Trough
Snellius Ridge
5N
5N
2N
2N
126E
129E
1000
2000
4000
1500



KANTO EQ.
Sagami Trough
PACIFIC PLATE
PHILIPPINE SEA PLATE
TAIWAN
LUZON
MINDANAO
NEW GUINEA
30°N
20°
10°
0°
120°E
130°
140°
150°
1
2
3

11



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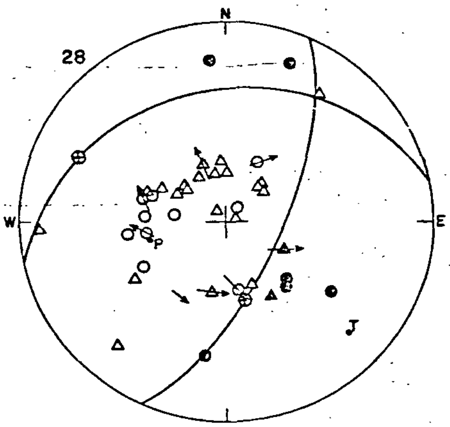
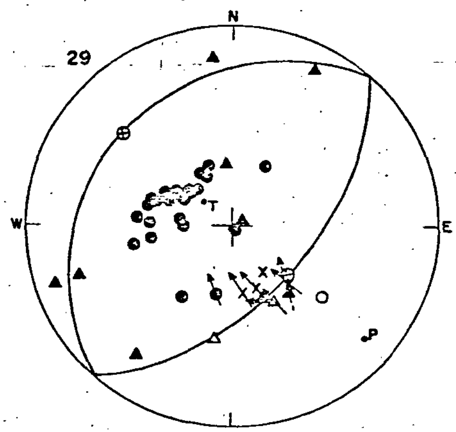
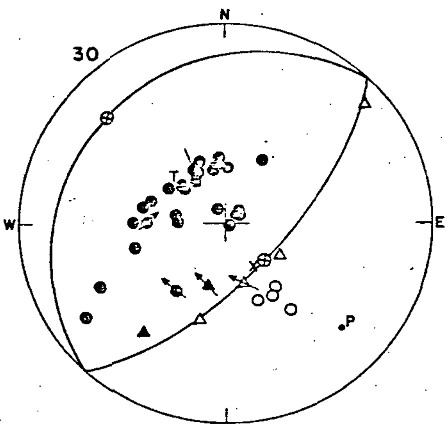


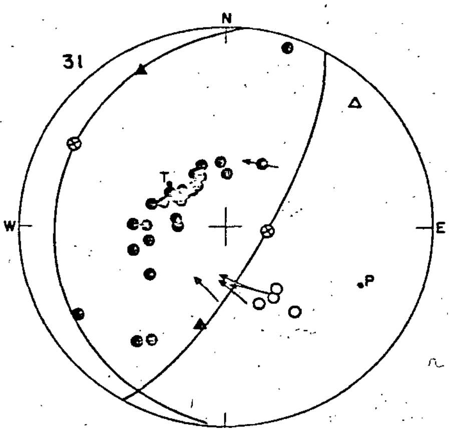
AUG 3 1968 25.6N 128.4E 19KM



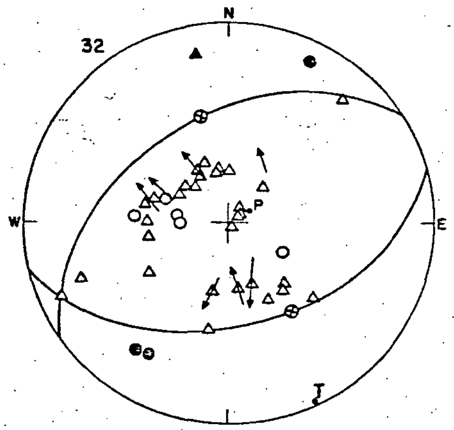
NOV 12 1968 27.5N 128.4E 30KM



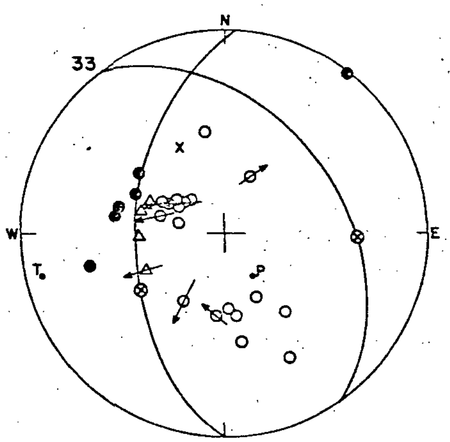
APR 21 1969 32.1N 131.8E 30KM



SEP 17 1969 31.1N 131.3E 8KM



DEC. 31 1969 28.5N 129.1E 30KM



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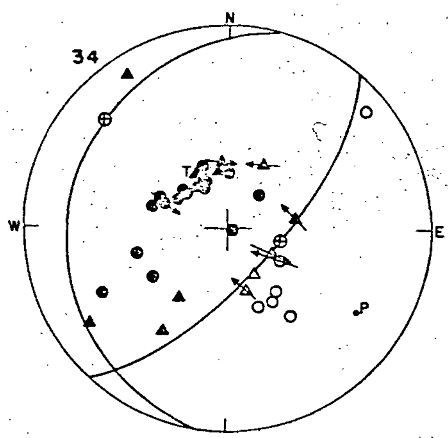

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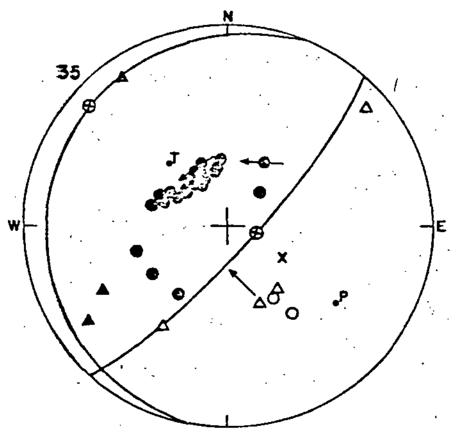
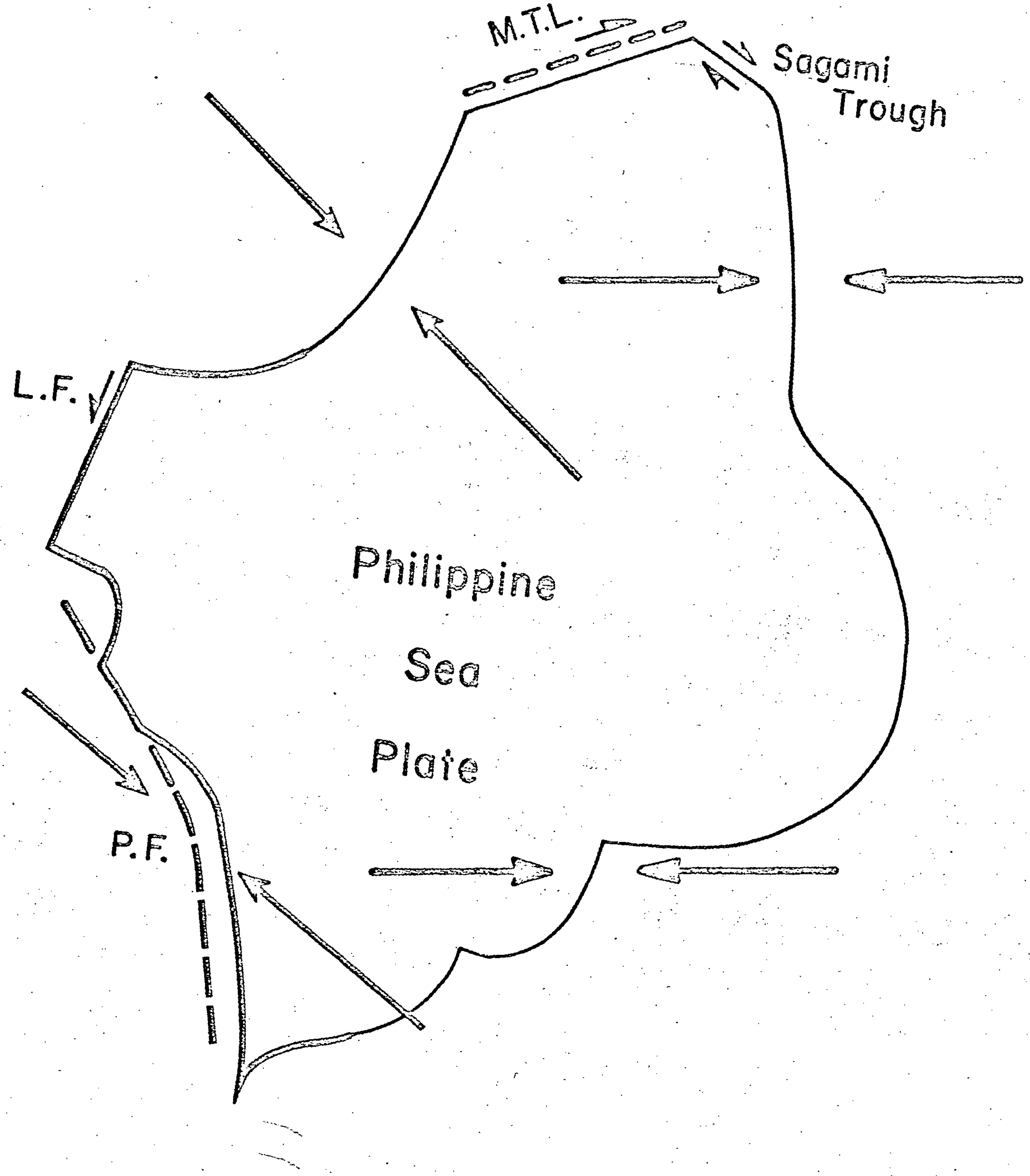
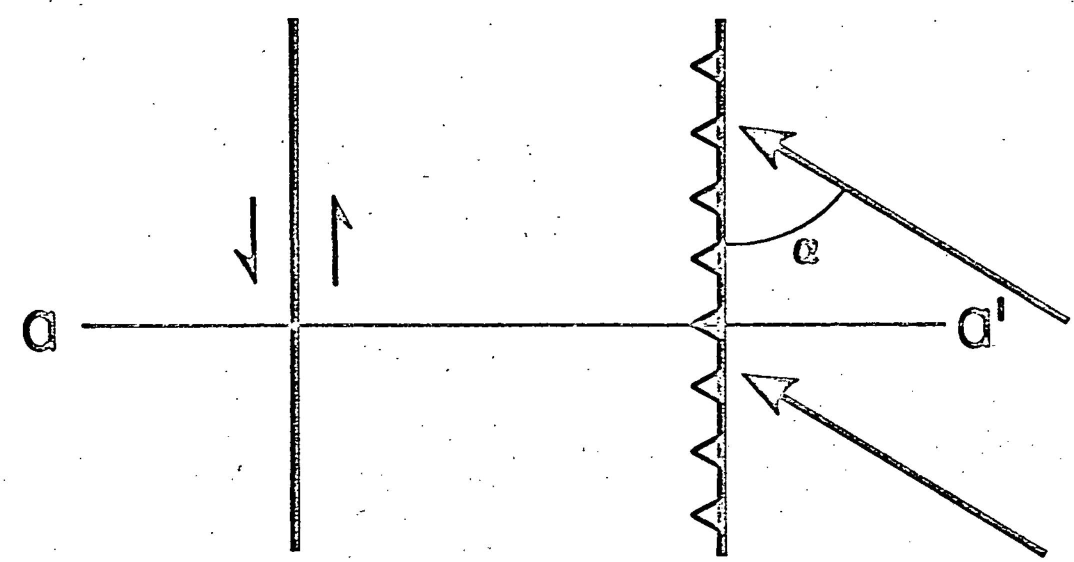


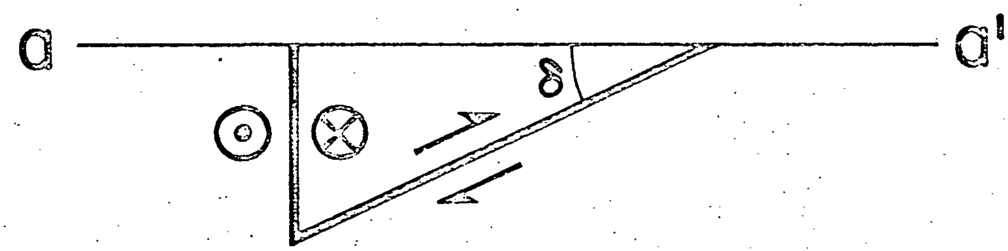
JUL 26 1970 32.1N 131.8E 30KM

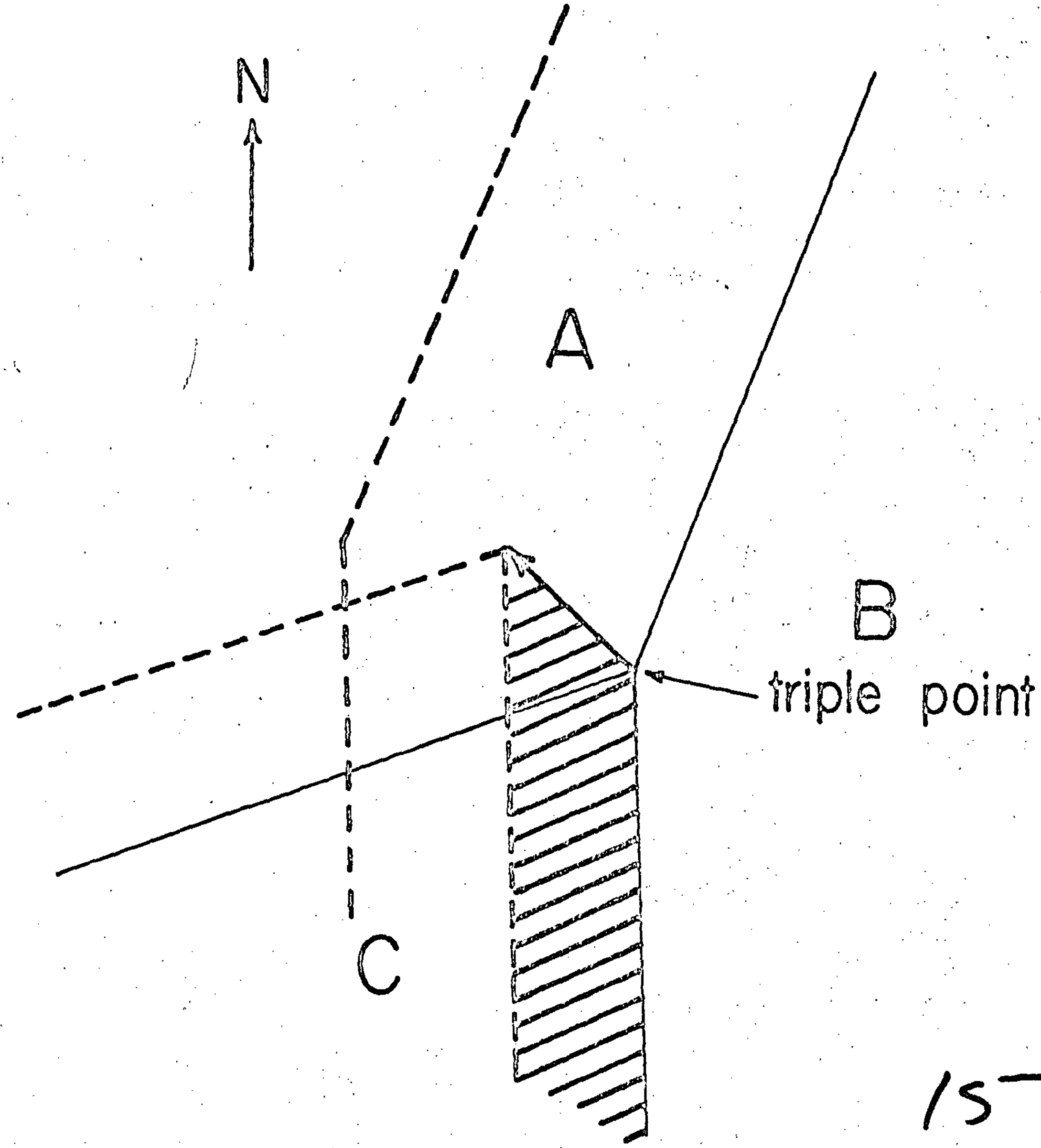

M.T.L.
Sagami
Trough
L.F.
Philippine
Sea
Plate
P.F.

A



B





SLIP	RATE cm/yr	STRIKE AZ
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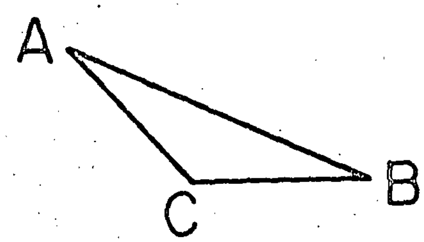
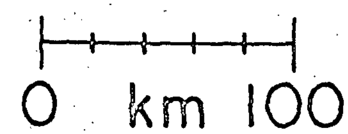
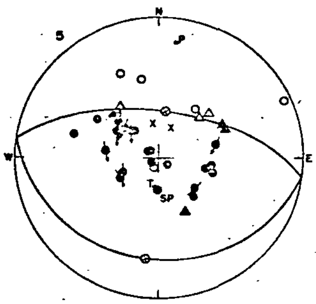
AC	7	312
BC	7	268







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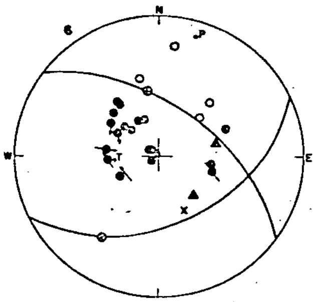

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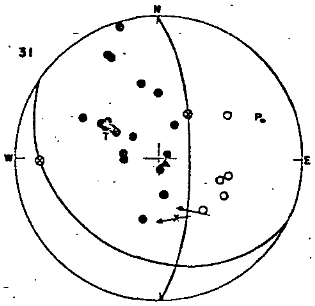

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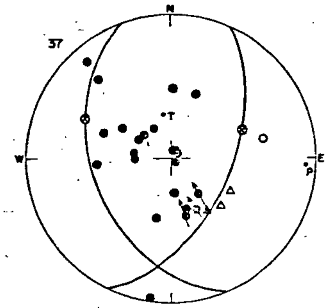

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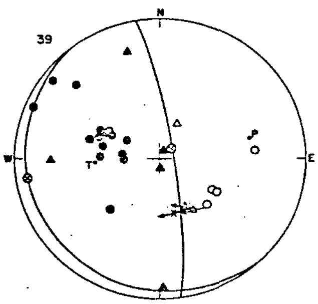

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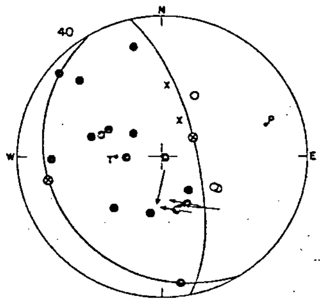

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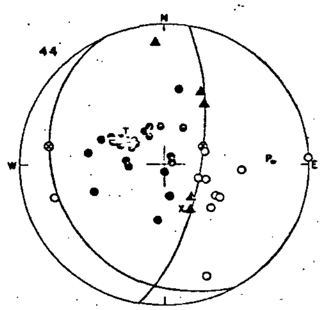

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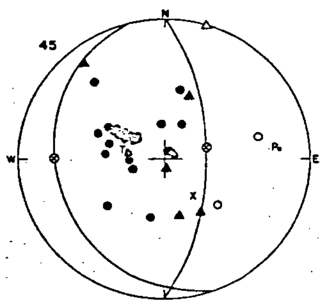

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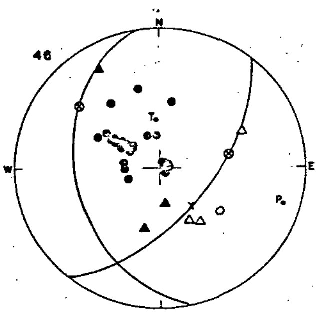

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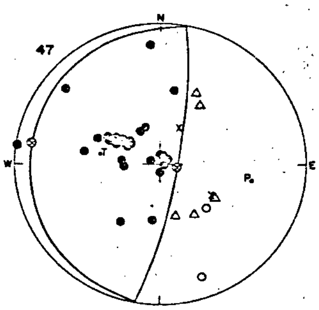

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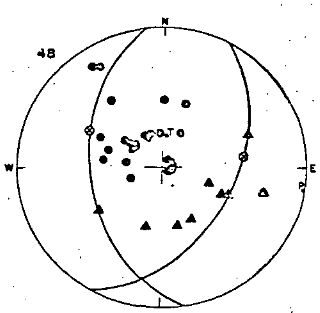

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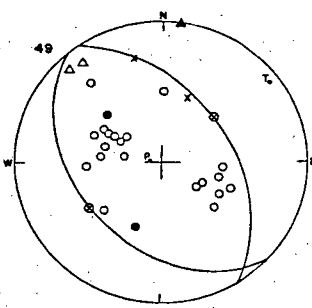

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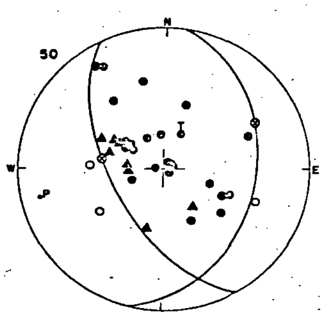
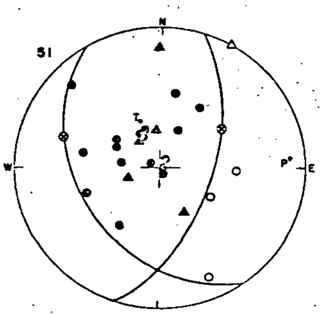
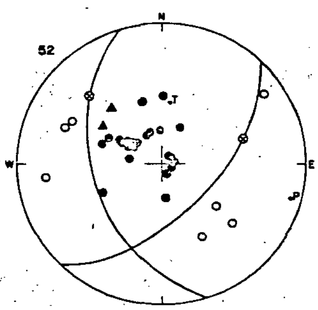


MAR 30 1970 6.7N 126.6E 76 KM



AFR 7 1970 15.8N 121.7E 30 KM



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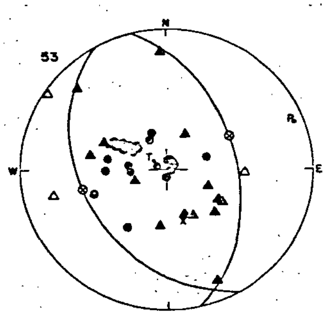

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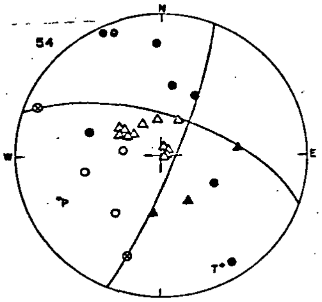
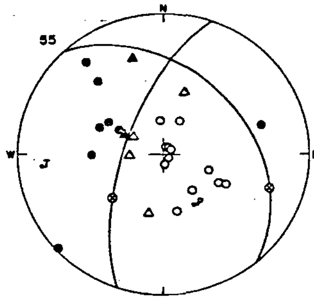
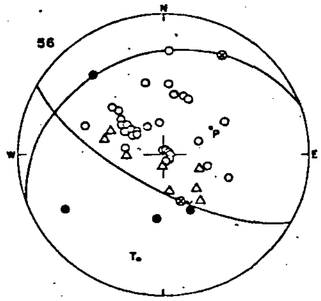


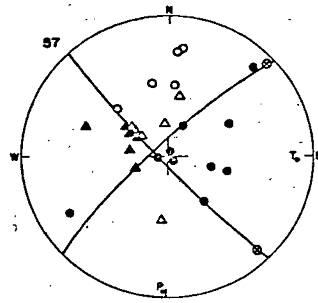
FEB 5 1970 12.5N 122.1E 11 KM



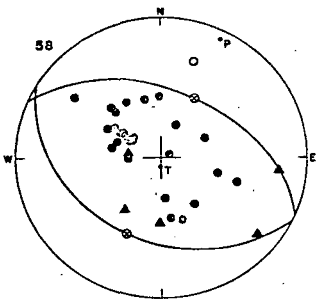
MAR 20 1969 8.6N 127.2E 33 KM



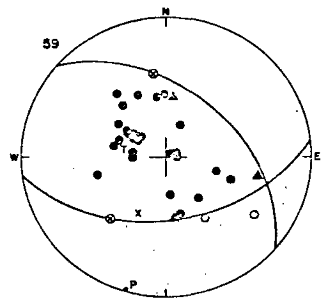
AUG 14 1968 0.1N 119.7E 23 KM



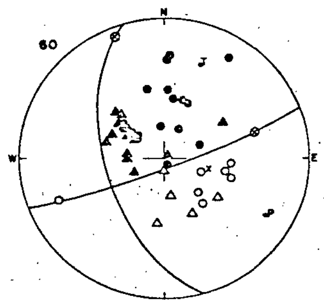
MAR 27 1970 0.3N 119.3E 8 KM



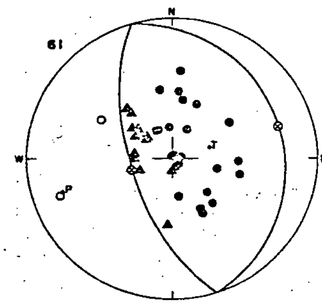
MAY 28 1968 2.9S 139.3E 65 KM



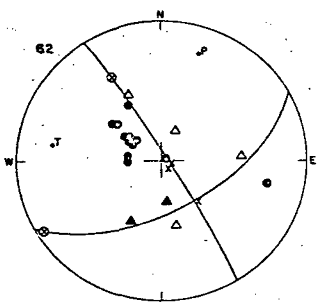
JUL 29 1968 0.2S 133.4E 11 KM



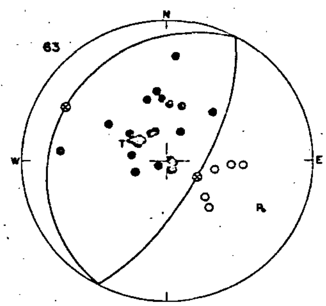
JUN 7 1968 1.7S 120.1E 19 KM



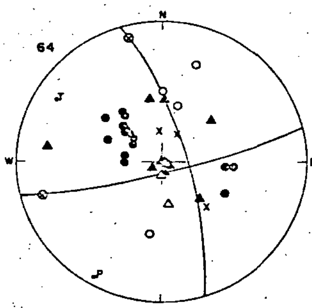
FEB 23 1969 3.1S 118.8E 13 KM



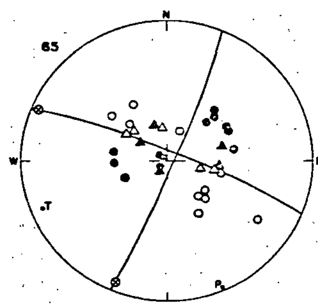
FEB 24 1969 6.1S 131E 38 KM



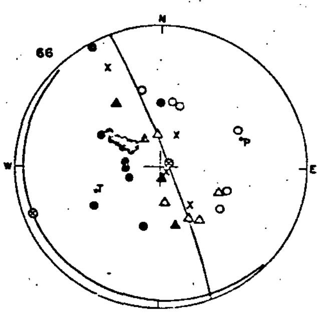
JUN 28 1970 8.7S 124.2E 30 KM



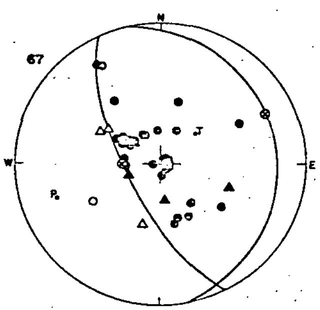
JAN 26 1968 8.8S 120.4E 29 KM



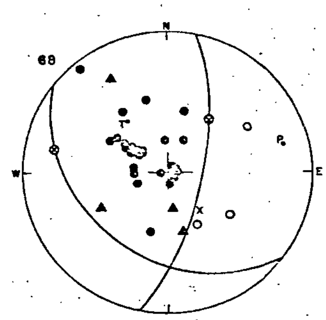
NOV 21 1969 2.0N 94.6E 20 KM



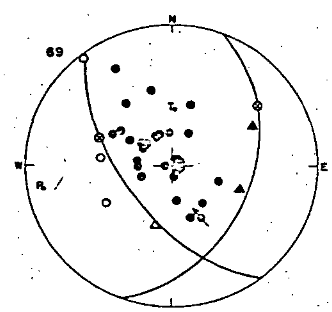
NOV 25 1968 4.9N 126.8E 30 KM



JAN 30 1969 4.8N 127.4E 70 KM

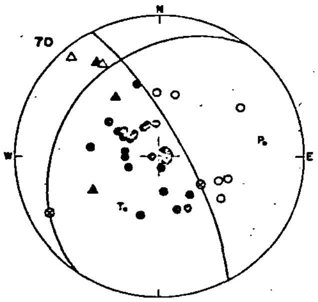


JAN 31 1969 4.1N 128.0E 30 KM



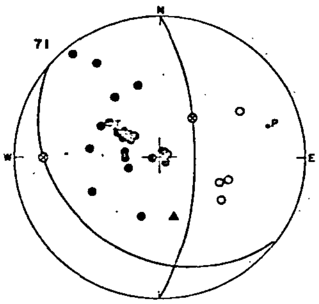
FEB 3 1969 4.9N 127.3E 30 KM

70



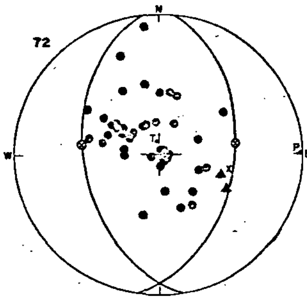
FEB 17 1969 3.8N 128.4E 14 KM

71



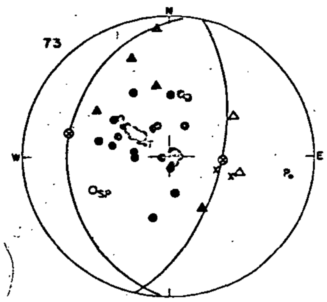
MAR 5 1969 4.0N 128.1E 30 KM

72



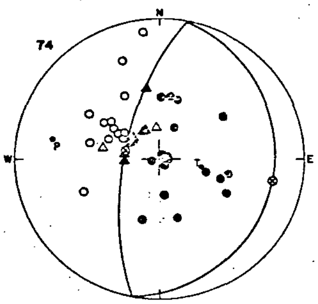
AUG 10 1968 1.4N 126.2E 30 KM

73



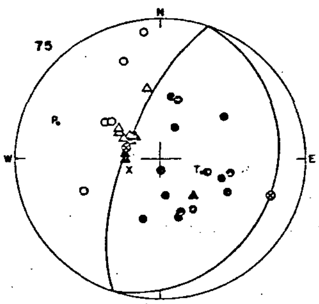
AUG 11 1968 1.5N 126.1E 30 KM

74



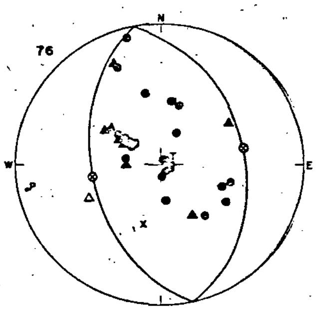
AUG 17 1968 1.3N 126.3E 30 KM

75



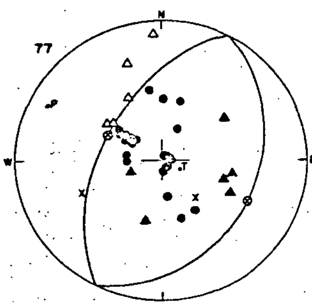
OCT 31 1968 1.2N 126.3E 33 KM

76



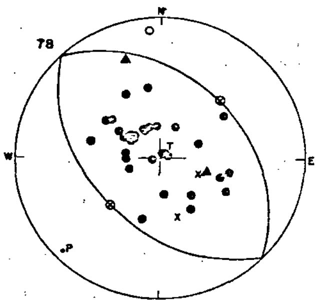
NOV 9 1968 2.4N 126.6E 30 KM

77



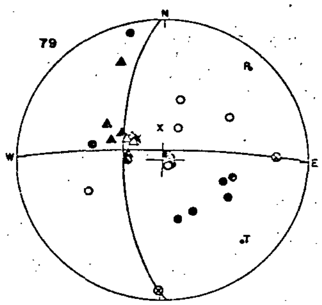
JAN 25 1969 0.8N 126.0E 24KM

78



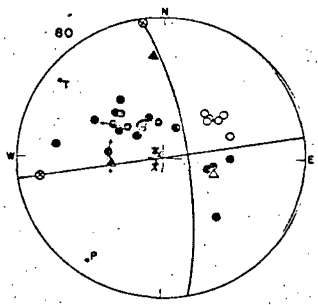
AUG 5 1969 1.2N 126.1E 30 KM

79



DEC 14 1969 2.0N 126.9E 42 KM

80



JUL 2 1967 8.7N 93.8E 30KM

A-3

TABLE 1

Parameters for Additional Mechanism Solutions for Shallow Earthquakes in Ryukyu and Mariana Regions

	DATE	LATI-* TUDE N	LONGI-* TUDE E		POLE 1 AZ	POLE 1 PL	POLE 2 AZ	POLE 2 PL	T AXIS AZ	T AXIS PL	P AXIS AZ	P AXIS PL	B AXIS AZ	B AXIS PL
27	Apr 01 68	32.5	132.2	30	306	12	76	72	322	55	114	32	214	14
28	Aug 03 68	25.6	128.4	19	294	22	167	57	133	20	256	58	34	24
29	Nov 12 68	27.5	128.4	30	311	30	131	60	311	75	131	14	41	0
30	Apr 21 69	32.1	131.8	30	312	22	132	68	312	67	132	23	43	0
31	Sep 17 69	31.1	131.3	8	299	16	96	73	308	61	114	28	207	6
32	Dec 31 69	28.5	129.1	30	346	44	145	44	155	0	58	80	246	10
33	Mar 04 70	12.1	143.7	30	235	48	92	34	256	8	148	69	348	20
34	Jul 25 70	32.1	131.6	30	311	20	104	68	330	66	122	24	218	10
35	Jul 26 70	32.1	131.8	30	312	10	102	78	318	55	126	34	220	4

*preliminary Coast and Geodetic Survey locations

TABLE 2

Parameters for Indonesian - Philippine Shallow Earthquakes 1961-1970

No.	Date	Lat.+	Long.+	Depth	1st Pole PL	1st Pole AZ	2nd Pole PL	2nd Pole AZ	P Axis PL	P Axis AZ	T Axis PL	T Axis AZ	B Axis PL	B Axis AZ
1	* Apr 03 1964	4.0	96.6	70	70	20	20	200	65	200	26	20	0	110
2	Sep 15 1964	8.9	93.1	37	20	51	52	168	17	204	52	88	34	308
3	* Apr 02 1964	5.8	95.5	16	4	240	0	331	3	196	3	285	86	60
4	* Nov 30 1964	6.8	94.8	32	0	236	0	326	0	191	0	281	90	--
5t	Apr 12 1967	5.3	96.5	55	62	8	28	188	17	8	73	188	0	98
6t	* Jun 15 1964	5.3	96.8	67	50	350	30	214	11	16	65	264	36	102
7	Aug 21 1967	3.6	95.8	33	12	23	78	203	33	203	57	23	0	112
8	* Apr 07 1963	-4.9	103.2	46	24	24	66	204	21	204	69	24	0	114
9	Jun 17 1963	-4.1	102.2	69	10	60	80	240	35	240	55	60	0	150
10	* Oct 24 1963	-4.9	102.9	65	16	28	74	208	29	208	61	28	0	118
11	* Feb 19 1967	-9.2	113.1	80	8	229	82	51	53	229	37	51	0	140
12	* Mar 24 1963	-9.7	120.6	0	38	118	37	243	0	90	59	180	31	0
13	* Mar 30 1967	-11.0	115.5	32	54	0	36	180	81	180	9	0	0	90
14	* May 22 1963	-8.2	115.8	76	6	186	84	6	39	6	51	186	0	96
15	Oct 12 1967	-7.1	129.8	45	30	240	36	355	2	29	49	296	41	122

No.	Date	Lat.+	Long.+	Depth	1st Pole PL	1st Pole AZ	2nd Pole PL	2nd Pole AZ	P Axis PL	P Axis AZ	T Axis PL	T Axis AZ	B Axis PL	B Axis AZ
53	Aug 28, 1968	15.5	122.0	15	50	60	40	256	4	69	81	304	7	160
54	Feb 05, 1970	12.5	122.1	11	8	292	24	198	23	247	10	152	64	38
55	Mar 20, 1969	8.6	127.2	33	22	109	51	229	55	150	16	264	31	5
56	Aug 14, 1968	0.1	119.7	23	61	160	18	30	59	60	23	193	20	291
57	Mar 27, 1970	0.3	119.3	8	4	46	8	138	2	182	10	92	81	287
58	May 28, 1968	-2.9	139.3	65	40	204	50	29	6	26	84	180	3	296
59	Jul 29, 1968	-0.2	133.4	11	38	352	40	222	1	196	63	288	27	106
60	Jun 07, 1968	-1.7	120.1	19	5	339	34	74	19	120	28	20	55	240
61	Feb 23, 1969	-3.1	118.8	13	66	253	22	73	22	253	68	73	0	344
62	Feb 24, 1969	-6.1	131.0	38	30	330	4	239	19	18	24	279	59	143
63	Jun 28, 1970	-8.7	124.2	30	70	118	20	298	24	118	66	298	0	210
64	Jan 26, 1968	-8.8	120.4	29	14	254	7	355	5	210	14	301	75	102
65	Nov 21, 1969	2.0	94.6	20	4	293	6	202	1	158	8	248	83	56
66	Nov 25, 1968	4.9	126.8	30	85	68	6	249	40	68	50	249	2	158
67	Jan 30, 1969	4.8	127.4	70	20	64	68	270	25	251	63	48	4	156
68	Jan 31, 1969	4.1	128.0	30	50	38	20	282	17	76	52	323	32	178
69	Feb 03, 1969	4.9	127.3	30	44	291	26	53	10	260	56	3	31	162
70	Feb 17, 1969	3.8	128.4	14	60	125	14	242	26	82	53	212	26	339

No.	Date	Lat.+	Long.+	Depth	1st Pole PL	1st Pole AZ	2nd Pole PL	2nd Pole AZ	P Axis PL	P Axis AZ	T Axis PL	T Axis AZ	B Axis PL	B Axis AZ
16	Apr 22, 1967	-5.6	126.8	32	53	122	30	343	12	146	66	26	21	240
17	* May 21, 1965	-0.2	125.1	51	38	14	41	242	63	310	2	218	28	127
18	* Apr 26, 1965	-1.7	126.6	21	29	68	61	246	75	68	15	246	1	338
19	Jan 24, 1965	-2.4	126.0	6	35	11	45	237	7	213	64	310	25	120
20	* Jun 04, 1963	-1.2	127.3	20	26	77	29	333	39	25	2	294	53	204
21	* Apr 16, 1963	-0.9	128.1	0	5	6	2	96	4	51	2	321	84	204
22	Apr 30, 1963	-0.9	128.8	32	40	15	20	270	13	57	42	315	59	136
23	* Nov 06, 1963	-2.6	138.3	0	16	211	74	31	29	31	61	211	0	120
24	* Apr 23, 1964	-5.4	133.9	0	22	102	60	236	61	134	20	266	19	4
25	* Aug 18, 1966	-0.2	125.1	51	20	291	70	120	24	114	64	286	4	23
26	Oct 26, 1967	-0.2	125.2	42	30	341	60	123	14	130	74	329	40	221
27	* Jun 30, 1964	-0.6	122.6	0	11	60	79	240	55	60	35	240	0	330
28	Apr 23, 1966	-0.9	122.4	45	50	23	40	213	82	256	5	28	3	118
29	* Oct 11, 1964	-0.6	121.8	45	31	53	42	177	56	108	6	206	33	301
30	* Nov 01, 1964	3.1	128.1	89	39	128	26	241	7	94	48	192	40	356
31	Oct 12, 1964	3.0	126.7	59	18	270	60	32	22	70	56	301	24	172
32	* Feb 15, 1965	2.9	126.0	88	12	22	57	276	28	226	46	350	37	120
33	* May 16, 1965	5.2	125.6	53	31	38	48	268	10	240	62	349	26	145
34	* Jun 19, 1963	4.6	126.5	64	10	264	80	84	34	84	54	264	0	354

No.	Date	Lat.+	Long.+	Depth	1st Pole PL	1st Pole AZ	2nd Pole PL	2nd Pole AZ	P Axis PL	P Axis AZ	T Axis PL	T Axis AZ	B Axis PL	B Axis AZ
35	Aug. 21, 1966	8.5	126.7	67	24	248	64	68	19	68	71	248	0	349
36	Sept 18, 1965	8.2	126.8	85	10	282	80	102	35	102	55	282	0	13
37t	Aug 19, 1967	10.4	126.0	58	46	68	34	295	6	93	64	350	25	187
38	* Jan 09, 1965	11.9	126.3	27	37	47	43	274	64	246	4	250	26	160
39t	* Dec 27, 1964	12.9	125.4	0	8	261	81	48	36	76	53	267	4	170
40t	* Nov 24, 1964	13.1	124.5	0	69	57	20	258	25	72	64	270	5	166
41	* Dec 20, 1966	14.3	122.1	37	34	56	2	323	20	104	26	5	60	226
42	* Aug 17, 1962	10.6	121.7	0	6	130	4	222	6	177	2	85	83	347
43	Aug 15, 1966	13.3	121.3	14	30	80	25	182	3	40	38	135	57	307
44	Aug 01, 1968	16.6	122.2	36	20	280	66	65	24	89	63	299	12	185
45	Mar 05, 1968	9.6	126.3	61	65	74	25	270	20	85	68	283	6	178
46	Oct 24, 1968	5.9	126.9	70	50	78	29	309	11	107	61	356	26	204
47	Nov 22, 1968	16.2	122.3	26	80	100	10	280	35	100	55	280	0	10
48	Jan 10, 1970	6.8	126.7	73	42	81	42	298	0	98	81	6	18	190
49	Feb 17, 1970	9.8	125.9	72	50	48	40	237	84	276	5	52	4	144
50	Mar 30, 1970	6.7	126.6	76	30	62	54	280	13	256	66	19	18	162
51	Apr 07, 1970	15.8	121.7	30	47	56	30	288	9	85	60	338	27	180
52	Jan 27, 1969	8.7	137.7	5	40	72	30	314	6	105	53	7	36	200

No.	Date	Lat.+	Long.+	Depth	1st Pole PL	1st Pole AZ	2nd Pole PL	2nd Pole AZ	P Axis PL	P Axis AZ	T Axis PL	T Axis AZ	B Axis PL	B Axis AZ
71	Mar 05, 1969	4.0	128.1	30	60	39	20	270	22	74	60	302	22	171
72	Aug 10, 1968	1.4	126.2	30	44	82	44	278	1	90	82	350	7	180
73	Aug 11, 1968	1.5	126.1	30	30	284	60	94	14	100	74	296	4	191
74	Aug 17, 1968	1.3	126.3	30	20	101	70	281	25	281	65	101	0	11
75	Oct 31, 1968	1.2	126.3	33	20	109	70	289	25	289	65	109	0	19
76	Nov 09, 1968	2.4	126.8	30	50	258	40	78	6	258	86	78	0	349
77	Jan 25, 1969	0.8	126.0	24	34	117	56	297	12	297	78	117	0	27
78	Aug 05, 1969	1.2	126.1	30	50	225	40	45	5	225	85	45	0	315
79	Dec 14, 1969	2.0	126.9	42	22	88	5	182	10	42	20	136	67	284
80	Jul 02, 1967	8.7	93.8	30	0	351	15	261	10	215	10	307	76	81

+ preliminary Coast and Geodetic Survey locations unless otherwise noted (latitude +N, -S)

t improved solution to that found in Fitch (1970b)

* redetermined location