SEISMICITY, FOCAL MECHANISMS AND MORPHOLOGY OF SUBDUCTED LITHOSPHERE IN THE PAPUA NEW GUINEA-SOLOMON ISLANDS REGION

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By

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We certify that we have read this dissertation and that in our opinion it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Geology and Geophysics.

DISSERTATION COMMITTEE

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Chairman

Brian Taylor

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I. INTRODUCTION

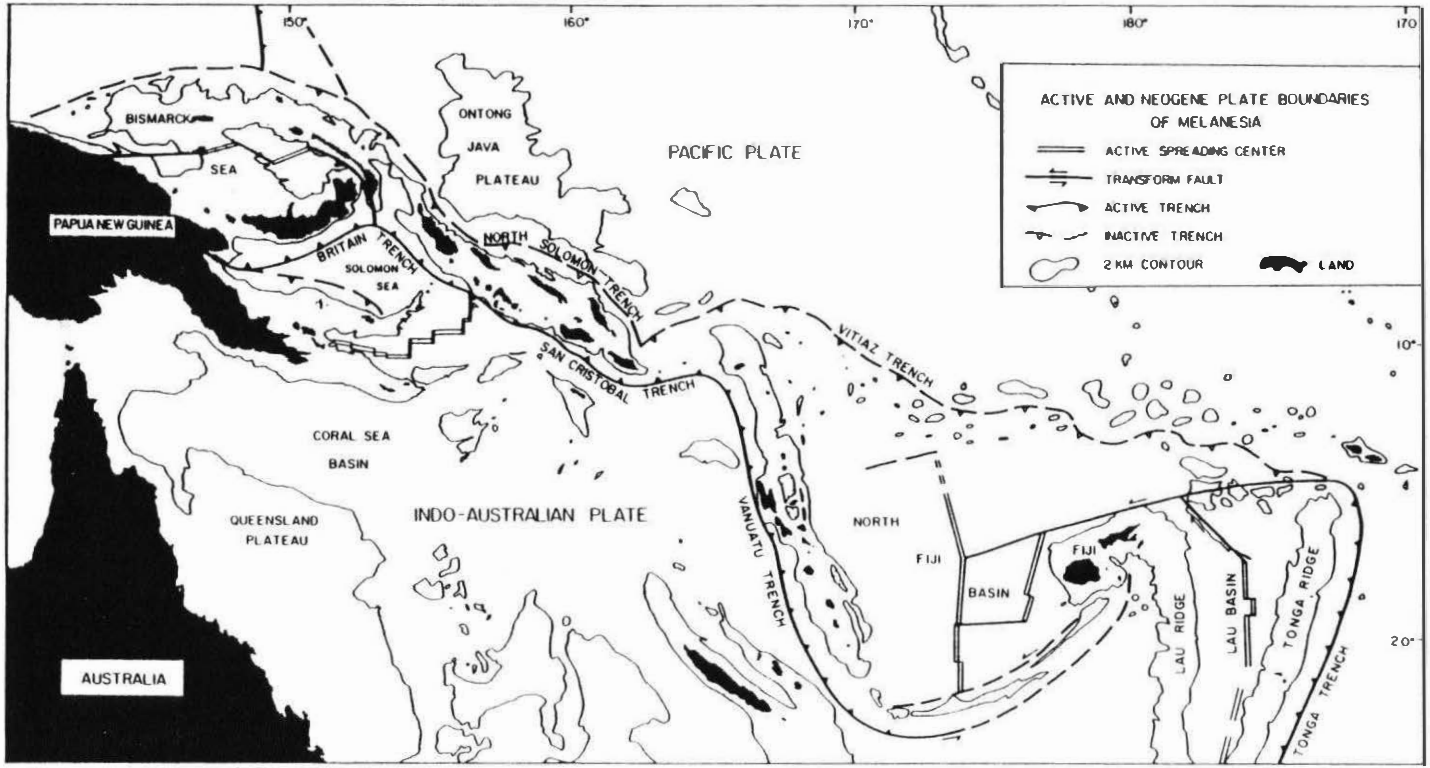
The Papua New Guinea-Solomon Islands region is a major component of the Western Melanesian Borderlands, the convergent boundary between the northward-moving Indo-Australian Plate and the westward-moving Pacific Plate (Figure 1.1). The region represents a wide zone of deformation and includes several smaller plates and both presently active and completed collision events. Collisions between island arcs, continental margins, continental fragments and spreading ridges have played a central role in shaping the present configuration of plate margins. The Wadati-Benioff zones investigated herein are associated with the past and present day convergence of two major plates and the spreading systems and the marginal basins sandwiched between them.

The study area is quite extensive, and for practical purposes the region is divided into the subregions of Papua New Guinea (Chapter II), the New Britain corner (Chapter III) and the Solomon Islands (Chapter IV). The overlap between the individual study units is intentional and necessary, since the divisions are entirely arbitrary. The areal extent of each subregion is defined within the appropriate chapter and an introduction is provided to familiarize the reader with the tectonic framework within which the data are interpreted.

Many studies of the seismicity and focal mechanisms of the Papua New Guinea-Solomon Islands region, integrated with extensive petrological, structural, gravity and magnetic surveys, are paving the way to an understanding of both the relative motions across, and the

Figure 1.1

Summary of active and Neogene plate boundaries of Melanesia (after Taylor and Karner, 1983).



ACTIVE AND NEOGENE PLATE BOUNDARIES OF MELANESIA
ACTIVE SPREADING CENTER
TRANSFORM FAULT
ACTIVE TRENCH
INACTIVE TRENCH
2 KM CONTOUR
LAND
150°
160°
170°
180°
170
10°
20°
PACIFIC PLATE
INDO-AUSTRALIAN PLATE
BISMARCK SEA
PAPUA NEW GUINEA
ONTONG JAVA PLATEAU
NORTH SOLOMON TRENCH
BRITAIN TRENCH
SOLOMON SEA
SAN CRISTOBAL TRENCH
VITIAZ TRENCH
CORAL SEA BASIN
QUEENSLAND PLATEAU
AUSTRALIA
VANUATU TRENCH
NORTH FIJI BASIN
FIJI
LAU RIDGE
LAU BASIN
TONGA RIDGE
TONGA TRENCH

evolution of, the plate boundaries. World-wide Seismograph Station Network montitoring of seismicity in general and the installation of WWSSN stations in Papua New Guinea (PNG), New Britain (RAB), and Solomon Islands (HNR) in particular have provided data for many studies contributing to the understanding of the regional tectonics. These local stations were installed and operating by 1964, therefore many early seismicity studies include poorly located hypocenters and a general lack of events in some of the less seismically active areas. This study uses an accumulated 20 years of seismicity data which is a significant improvement in data density over previous studies. In addition, 128 additional focal mechanism solutions are presented, updating the available data to 1981.

Besides the general relationship between seismicity, earthquake focal mechanisms and slab configuration, this study addresses the following problems. First, the polarity of some of the now inactive subduction zones is difficult to determine based on any one discipline. In fact, ambiguity in arc polarity has been a major limiting factor in determining microplate rotations in the southwest Pacific. Seismicity can provide direct evidence of the polarity of a Wadati-Benioff zone, but only with sufficient data density. I believe there is now enough data to adequately define the polarity of at least two of these proposed inactive Wadati-Benioff zones-the North Solomon Trench and the Trobriand Trough. Second, the presence of so-called "diffuse" plate boundaries (e.g. northern New Guinea and the Papuan Peninsula) makes the definition of minor plates (at least on a seismic basis) and estimation of their relative motions difficult. Most of the diffuse plate boundaries result from seismicity originating in multiple tectonic elements interacting at or near the plate boundary. Third, in the Papuan region a decision must be made regarding what physical characteristics define an "active" subduction zone - seismicity, volcanism, the nature of the deformation front? Fourth, collisions between buoyant lithospheric elements and arc-trench systems are typically short-lived events, yet produce widespread zones of deformation and shifts in the configuration of convergent plate boundaries. The study of such collisions is important because they probably play a primary role in the orogenic process (Dewey and Bird, 1970). Specifically, we wish to know how suturing occurs between the lithospheric units involved; what is the mechanism of emplacement of ophiolites within the suture zone and whether the emplacement of ophiolite is typical of all sutures? What is the mechanism of uplift for the coast ranges; is there more than one type of mechanism of uplift within a single suture zone; does the mechanism change with time as the collision progresses? How is the subduction process affected by arc-continent collision? Also, what is the origin of the paired basins (Huon Gulf and Finsch Deep) near Huon Peninsula and the associated gravity anomalies? Finally, how does the lithosphere deform at corners and what parameters constrain the type and degree of deformation? This study addresses these problems using primarily teleseismic data.

II. SEISMICITY, FOCAL MECHANISMS AND MORPHOLOGY OF SUBDUCTED LITHOSPHERE IN PAPUA NEW GUINEA

Introduction

Although Papua New Guinea includes Bougainville, Buka and the islands of the Admiralty and Bismarck arcs, this chapter will deal primarily with mainland Papua New Guinea, introducing relevant evidence from nearby, related arcs as appropriate. Much of the geology of Papua New Guinea is summarized in maps prepared by the Australian Bureau of Mineral Resources and Papua New Guinea Geological Survey (Bain et al., 1972; D'Addario et al., 1976). Syntheses of the geology of Papua New Guinea have been presented by Thompson and Fisher (1965), Bain (1973), Dow (1975,1977), Hamilton (1979), Johnson (1979) and Brown et al. (1979/80). Detailed petrological studies have been done by Jakes and White (1969), Davies and Smith (1971), Jakes and Smith (1970), Johnson (1976a,b), Mackenzie (1976), Jaques and Robinson (1977) and Page and Ryburn (1977). Briefly, an Eocene island arc sequence in the North Coast Ranges (Finisterre and Adelbert ranges) is separated from the central Mobile Belt by the Ramu-Markham Fault, which we later show to be a suture zone. The Mobile Belt (also Orogenic Belt) is composed of folded and faulted geosynclinal sediments. The northern flank is metamorphosed to greenschist facies and an ophiolite belt defines the northeastern terminus of this tectonic province. Southwestern Papua New Guinea is the northeastern corner of the Australian continent; metamorphic and granitic rocks are overlain by Mesozoic-Cenozoic marine carbonate and clastic sediments. Metamorphosed sediments and metabasalts of Cretaceous age form the main body of the Papuan Peninsula. These are overthrust from the north by the Papuan Ultramafic Belt, the consequence of an Eocene continent-arc collision. The youngest lithologic unit of the peninsula is the Oligocene-Holocene island arc sequence which is largely medium-to-high-K andesites (Smith, 1982). The geology of New Britain is similar to that of the Huon Peninsula. On New Britain, the oldest dated volcanics and intrusives are Eocene, overlain by less prevalent Oligocene volcanics (Page and Ryburn, 1977). The Huon Peninsula is made up of predominantly argillaceous Eocene rocks which grade upwards to younger (Oligocene-Miocene) volcanics (Jaques and Robinson, 1977).

Reconstructions of the Cenozoic history of the region (Dewey and Bird, 1970; Johnson and Molnar, 1972; Curtis, 1973b; Hamilton, 1979; Johnson, 1979; Kroenke, 1984; and Davies et al., 1984) have somewhat clarified the complex deformational processes which have resulted in New Guinea's unusually complex geology. Hamilton (1979) presents the first interpretation of the Mesozoic and Cenozoic evolution of New Guinea in terms of plate tectonics theory. Johnson (1979) summarizes Cenozoic volcanic events throughout this region. Davies et al. (1984) investigates the structure and evolution of the southern Solomon Sea region. The study of Brown et al. (1979/80) concentrates on the Mesozoic stratigraphy and paleogeography of New Guinea. In the Cenozoic alone, the New Guinea region has been the locus of at least four separate episodes of subduction (Figure 1.1; Kroenke, 1984) and compressional tectonism has dominated (and continues to dominate) its history. In addition to four separate episodes of subduction of varying polarity, the evolution of Papua New Guinea throughout the Cenozoic may include as many as three arc-continent collisions and the formation and subsequent subduction of as many as three marginal basins. All of these tectonic events are discussed in the references cited, however, only in Kroenke (1984) is the New Guinea tectonism thoroughly integrated with tectonism throughout the entire Melanesian region. For this reason, and because seismicity is still observed originating in three of the four Cenozoic subduction zones, we present a very brief summary of subduction in the Papua New Guinea-Solomon Islands region based on Kroenke (1984; see Figure 2.1):

(1) Eocene northward subduction along the Aure-Moresby-Pocklington subduction zone.

(2) Oligocene southward subduction along the Manus-North Solomon-Vitiaz subduction zone.

(3) Miocene southward subduction along the Trobriand subduction zone.

(4) Plio/Pleistocene-Holocene northward subduction along the New Britain-San Cristobal subduction zone.

The locations of tectonic provinces and structural elements to which the text refers are shown in Figures 2.1 and 2.2. Previous studies of the regional tectonics include those of Dow (1977) and Davies et al. (1984). The tectonics as deduced from regional seismicity and focal mechanisms havebeen discussed previously by Denham (1969, 1973, 1975), Isacks and Molnar (1971), Ripper (1975,

Figure 2.1

Cenozoic subduction zones of the Papua New Guinea-Solomon Islands region (after Kroenke, 1984). Subduction is in the direction of the triangular hatchures; filled triangles indicate active subduction zones; open triangles indicate inactive subduction zones.

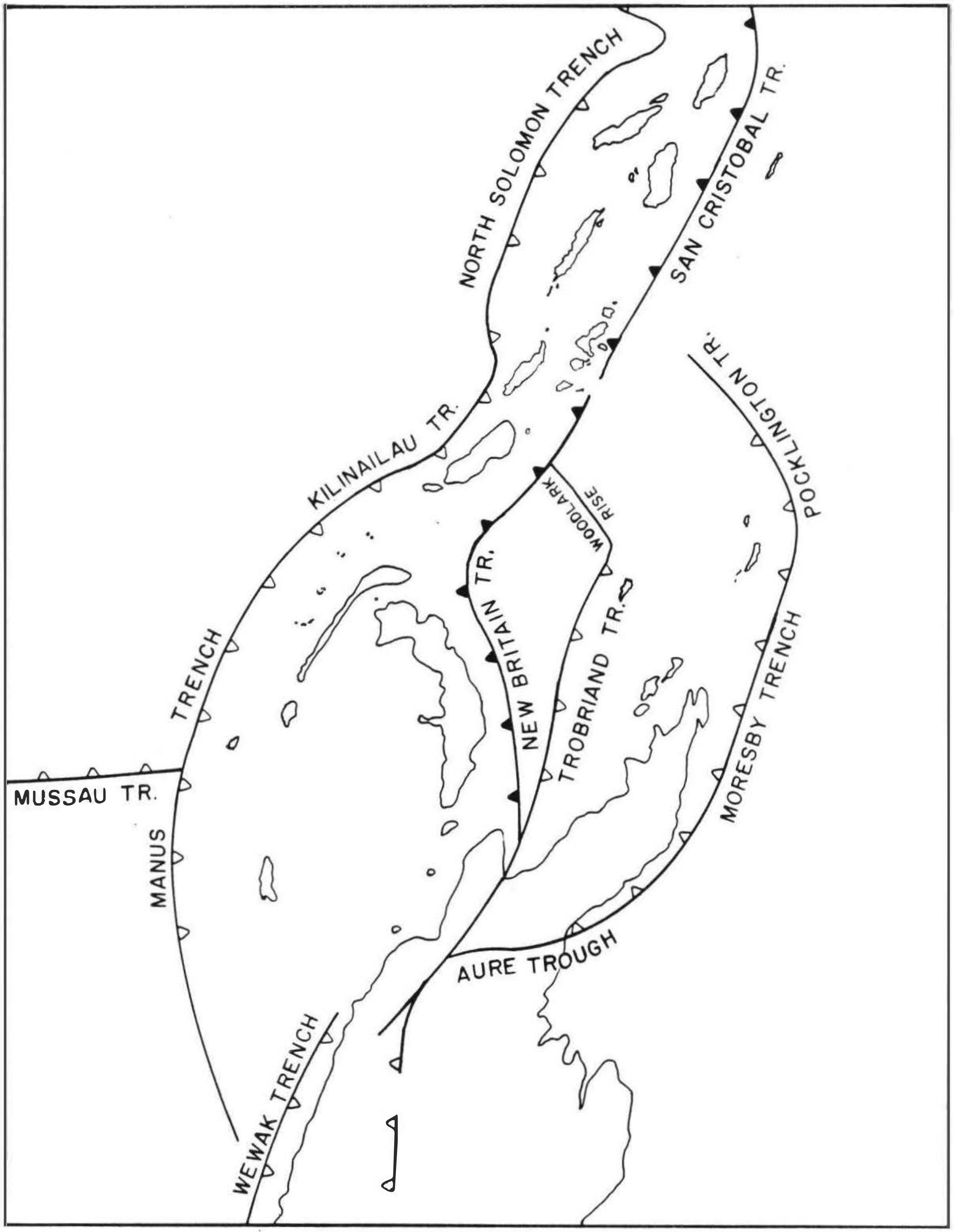
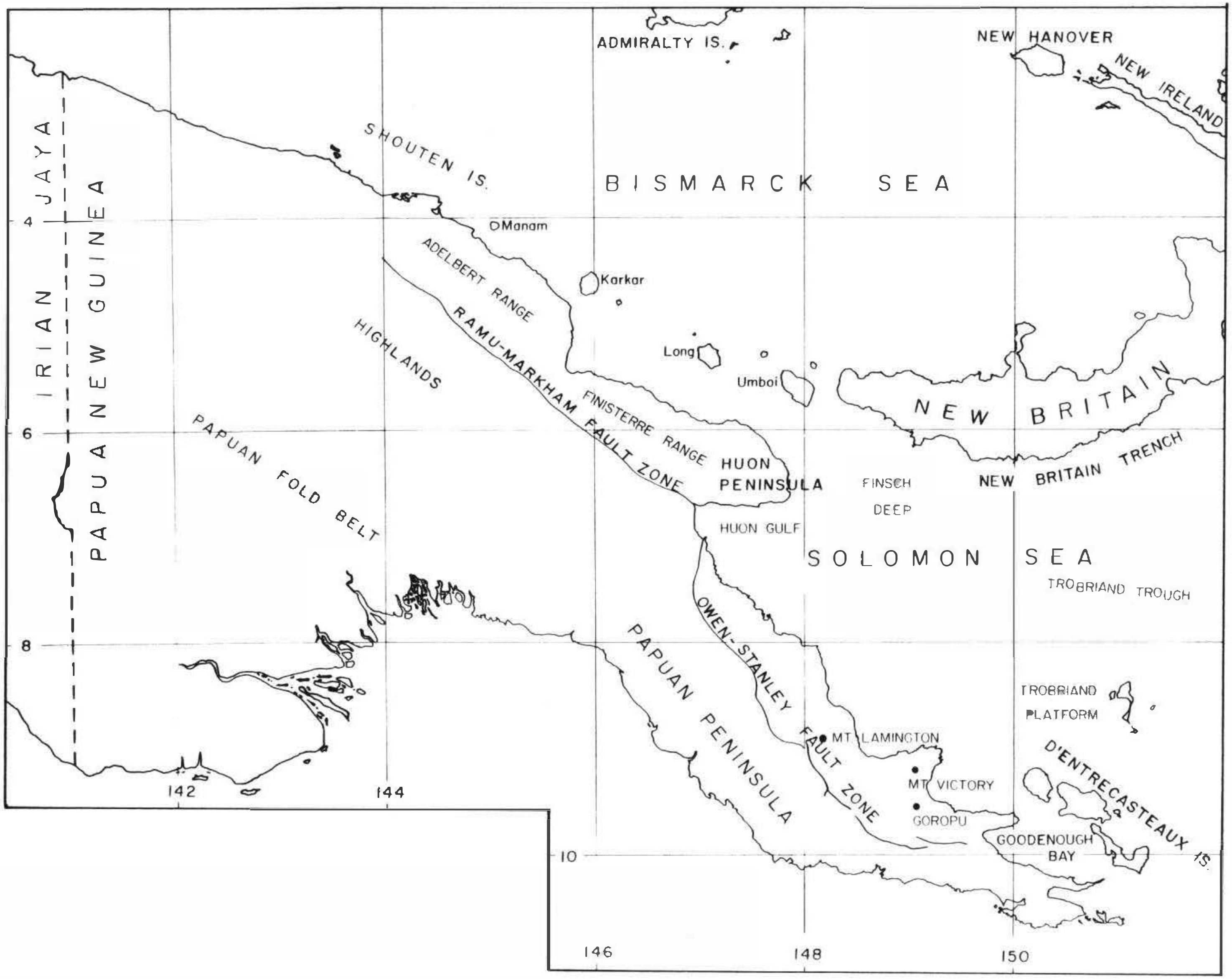

NORTH SOLOMON TRENCH
SAN CRISTOBAL TR.
KILINAILAU TR.
POCKLINGTON TR.
WOODLARK RISE
NEW BRITAIN TR.
TROBRIAND TR.
TRENCH
MORESBY TRENCH
MUSSAU TR.
MANUS
AURE TROUGH
WEWAK TRENCH

Figure 2.2

Place names, locations of tectonic provinces, structural elements and volcanoes in the Papua New Guinea-New Britain region.



ADMIRALTY IS.
NEW HANOVER
NEW IRELAND
SHOUTEN IS.
BISMARCK SEA
IRIAN JAYA
PAPUA NEW GUINEA
Manam
Karkar
Long
Umboi
ADELBERT RANGE
RAMU-MARKHAM FAULT ZONE
HIGHLANDS
FINISTERRE RANGE
HUON PENINSULA
NEW BRITAIN
NEW BRITAIN TRENCH
FINSCH DEEP
HUON GULF
SOLOMON SEA
TROBRIAND TROUGH
PAPUAN FOLD BELT
PAPUAN PENINSULA
OWEN-STANLEY FAULT ZONE
TROBRIAND PLATFORM
MT LAMINGTON
MT VICTORY
GOROPU
D'ENTRECASTEAUX IS.
GOODENOUGH BAY
4
6
8
10
142
144
146
148
150

1980, 1982), Johnson and Molnar (1972), Curtis (1973a,b), Krause (1973), Luyendyk et al. (1973), and Pascal (1979). Johnson and Molnar (1972), Curtis (1973a,b) and Krause (1973) define the geometry and relative motions based on observations of seismicity and earthquake first motions. Dewey and Bird (1970), Johnson and Molnar (1972) and Curtis (1973b) also made some effort to interpret their plate tectonics models in terms of the continent/arc collision in northern New Guinea. Milsom (1970), Luyendyk et al. (1973) and Connelly (1974, 1975) focus their efforts on marine geophysical investigations of the Woodlark and Bismarck Sea basins.

Despite numerous attempts to interpret the seismicity in terms of known structural relationships, some authors have neglected to include in their interpretations temporal relationships between regional tectonic events. In addition, much of the age, geology and seismicity data were unavailable for the early studies. Whereas recent tectonic syntheses which attempt to account for the full range of available geologic and geophysical data of the area are few, this study retains that goal. This study includes much new seismicity data and is different from previous studies in that the observed seismicity is interpreted in terms of both past and ongoing tectonic events. Luyendyk et al. (1973) suggests that further work in deducing the plate kinematics in this area be directed at defining the nature of the plate (or plates) north of New Britain. We define the interaction of the Indo-Australian, Bismarck and Solomon Sea plates along the north coast of New Guinea and present a model of the evolution of collisional tectonics in that area. The active andesite volcanoes of the Papuan Peninsula (Mts. Lamington, Victory and Goropu) do not appear to be associated with a W-B zone (Ripper, 1980) and several authors agree that the relationship of volcanism in the New Guinea Highlands to subduction is not clear. Therefore, particular attention is given to the nature of the boundaries of the Solomon Sea Plate and especially its interaction with the Indo-Australian Plate along the Trobriand Trough.

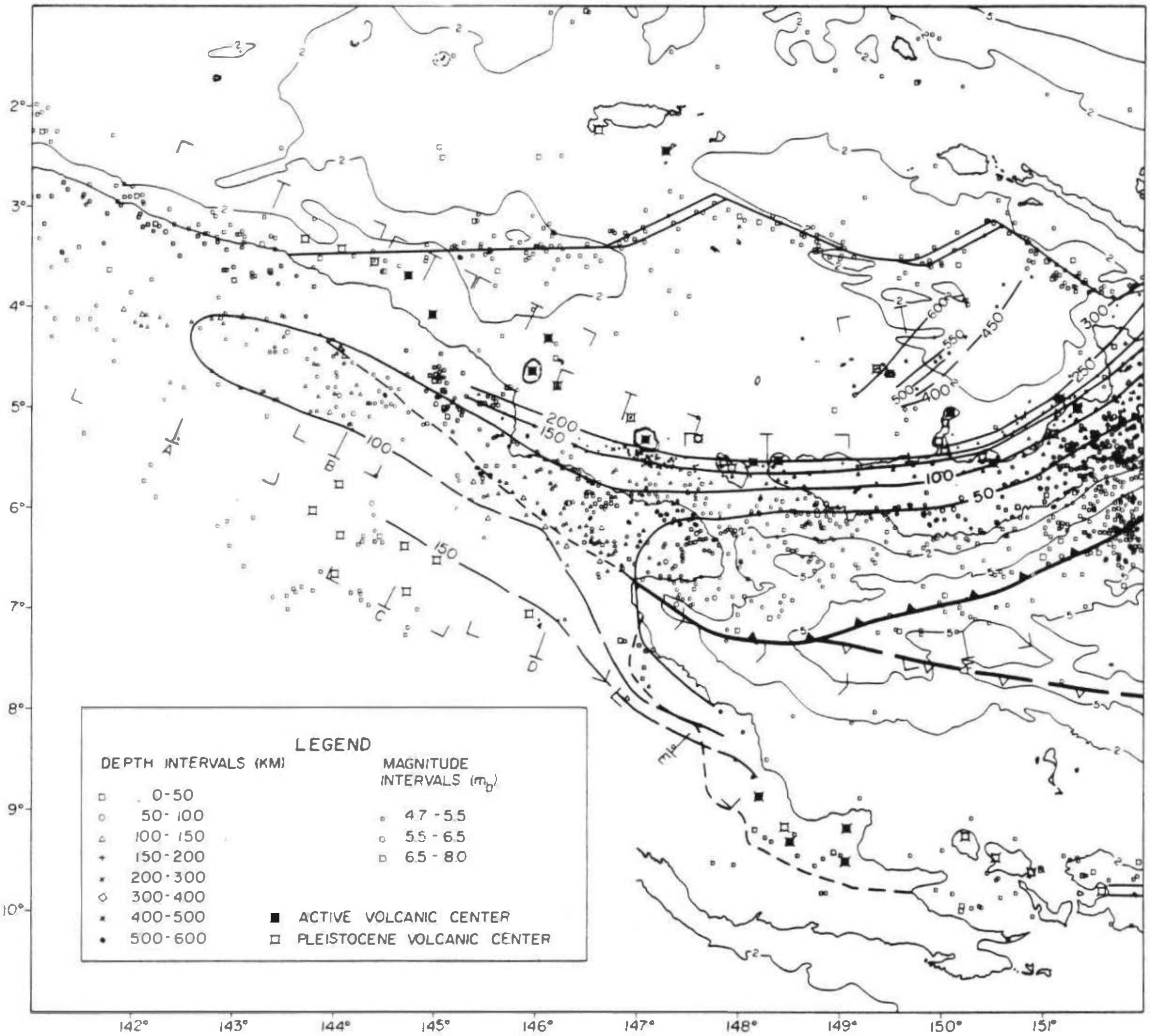
Seismicity

Earthquake activity in the Papua New Guinea region is shown in Figure 2.3. Major volcanic centers are indicated, as are bathymetry and Wadati-Benioff (W-B) zone contours. Earthquake hypocenters are taken from International Seismological Centre (ISC) data files and cover the period from 01/01/64 (following installation of all local World Wide Seismograph Station Network (WWSSN) stations) to 06/30/84. Only earthquakes with body wave magnitudes (M_b) greater than 4.7 and recorded by 15 or more stations are used. The lower magnitude cutoff was determined by the paucity of events in southeast Papua.

Foci for the 33 new focal mechanism solutions were relocated using a combination of joint hypocentral determination (Dewey, 1971) and a single event location scheme. The fifteen largest and best-recorded earthquakes were relocated using the joint hypocentral determination program (JHD77) written by James W. Dewey (1977). The station corrections computed for these earthquakes were used in a

Figure 2.3

Regional seismicity and Wadati-Benioff Zone contours for Papua New Guinea. Seismicity includes all ISC hypocenters with body wave magnitudes greater than 4.7 and recorded by more than 15 stations for the period 01/01/64 to 06/30/84. Wadati-Benioff zone contours are indicated by a heavy solid line at 50 km intervals; dashed contours indicate poor data density. Land areas are shaded and the 2 and 5 km bathymetric depth contours are drawn. Spreading systems are indicated by the usual combination of double line (ridge segments) and single line (transform faults). Large ´tailed´ squares locate Plio-Pleistocene volcanic centers; filled squares are active volcanoes. The locations and widths of profiles A-F (Figures 2.4-2.9) are indicated by brackets.



LEGEND
DEPTH INTERVALS (KM)
0-50
50-100
100-150
150-200
200-300
300-400
400-500
500-600
MAGNITUDE INTERVALS (m_b)
4.7-5.5
5.5-6.5
6.5-8.0
ACTIVE VOLCANIC CENTER
PLEISTOCENE VOLCANIC CENTER
142°
143°
144°
145°
146°
147°
148°
149°
150°
151°
2°
3°
4°
5°
6°
7°
8°
9°
10°

single event hypocenter determination program (SE77; also written by James W. Dewey, 1977) to locate the remaining earthquakes. In this way we avoid introducing extraneous offsets into the existing pattern of seismicity; i.e. all of the earthquakes are mislocated in the same manner with the overall effect being an offset of the entire earthquake subset. The relocated positions serve mainly as a check on the accuracy of the ISC positions. In most cases earthquakes with magnitudes greater than 5.9 were relocated to within 0.1 degree of their ISC positions; earthquakes with magnitudes between 5.6 to 5.9 were typically relocated within 0.2 degree of their ISC positions. ISC depth determinations for earthquakes in the 100-600 km depth range were very close to the relocated depths largely because of abundant depth phases. The accuracy of ISC depth determinations for earthquakes in the 50-100 km depth range are highly dependent on magnitude; the higher the magnitude the better the accuracy of the depth determination. Relocated depths in this depth range are generally shallower by 10-20 km. Hypocenters have the poorest depth accuracy in the 0-50 km range and in most cases accuracy could be improved significantly by use of a local land array, ocean bottom seismometer (OBS) array or state-of-the-art modelling techniques (e.g, Wang et al., 1979). This type of spatial accuracy is probably typical and therefore, for our purposes (definition of seismic features on a regional scale) we feel justified in using the ISC positions for both areal and depth representations of seismicity.

The seismicity has four main trends:

(1) A band of shallow seismicity extends across the Bismarck Sea along the Bismarck Sea seismic lineation (Denham, 1969) westwards to the north coast of New Guinea. The lineation is a system of northwest oriented transforms with east-northeast oriented speading segments (Taylor, 1979).

(2) West of New Britain, the belt of seismicity associated with the New Britain Trench bends west by northwest through the Huon Peninsula and along the Coast Ranges of northern Papua New Guinea. Deep earthquakes are observed north of central and eastern New Britain and are believed to occur in lithosphere subducted at the New Britain Trench. The relationship of this deep seismicity to the shallow seismicity is fully discussed in Chapter III. West of New Britain, no earthquakes occur at depths greater that 300 km. Maximum hypocentral depth decreases westwards to about 150 km near 142^{o}E. Shallow earthquakes beneath northern New Guinea are much less common than intermediate earthquakes. The shallow earthquakes are occasionally associated with obvious surface features such as the inter-section of the Bismarck Sea seismic lineation with the north coast, however, the intense shallow seismicity of the Coast Ranges is more commonly diffuse. Nearing the Huon Peninsula, almost all shallow activity is subcrustal (deeper than 40 km). Much of the shallow and intermediate Huon Peninsula seismicity is due to thrusting of the allochthonous Finisterre block onto the continental crust of Papua New Guinea along a low-angle, ramp-like thrust surface. In northern Papua New Guinea there is continued convergence of the Indo-Australian and Bismarck Sea

plates along a northeast azimuth, but no subduction. The Ramu-Markham suture zone overrides the doubly-subducted Solomon Sea Plate.

(3) Shallow seismicity occurs in a diffuse band through the central New Guinea Highlands. Many volcanic centers are located in the Highlands of New Guinea; some sparse shallow earthquakes appear to be located near the volcanoes. Shallow activity in this aptly-named Mobile Belt is probably the result of compression due to continued convergence without subduction (Ripper, 1980), producing foreland folding and thrusting.

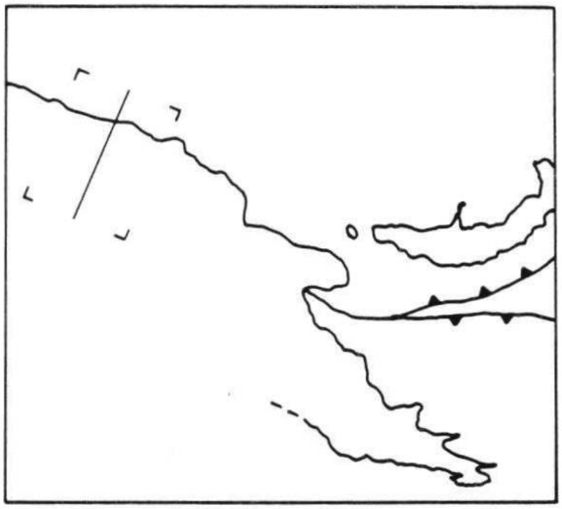
(4) Diffuse shallow and intermediate seismicity is observed along and east of the Papuan Peninsula. Most of the shallow hypocenters are associated with the Owen-Stanley Fault Zone, with active volcanism, and with propagation of the Woodlark spreading center into the Papuan Peninsula. Sparse shallow and intermediate events are seen to dip south-southwest from the Trobriand Trough beneath the peninsula.

The Wadati-Benioff (W-B) zone contours in Figure 2.3 are based on observed seismicity; many depth profiles were constructed perpendicular to known or proposed structures at varying intervals. The six profiles illustrated in Figures 2.4-2.9 are considered representative. Many more profiles were constructed than are shown. The top of the slab was drawn along the upper limit of observed seismicity such that it intersects the trench axis (whenever a trench axis is present). It is understood that at intermediate levels the seismicity may be confined to the interior of the slab (Isacks and Molnar, 1971). Trench axes or surface fault traces are given as reference points. Focal mechanism solutions included in the vertical cross-sections are presented as the back hemisphere of a view of the focal sphere perpendicular to the cross-section.

The locations and widths of profiles A-F are included in each figure and are also shown in Figure 2.3. From west to east, the dip of the W-B zone changes, but not in a simple way. The depth extent of the steeply north-dipping W-B zone remains fairly constant at 200-250 km from the Adelbert Range to New Britain; from 142°E to the Adelbert Range, the maximum depth of events is about 150 km (Fig. 2.3). The gently southwest-dipping W-B zone reaches a maximum depth of about 150 km. Profile A (Figure 2.4) shows intense shallow seismicity at the intersection of the Bismarck Sea seismic lineation with the north coast of New Guinea (upper right). Motion is predominantly left-lateral with a small component of thrust. There is very little shallow seismicity present on the New Guinea mainland, and only scattered intermediate events. In profile B (Figure 2.5) some shallow seismicity from the Bismarck Sea seismic lineation is still present. An intermediate zone of hypocenters extends from about 70-150 km; the upper limit of the zone may be interpreted as convex. Shallow seismicity from the Ramu-Markham Fault (upper left) and from internal deformation of the Adelbert Range (upper right) dominates profile C (Figure 2.6). The beginning of a fold in the intermediate and deep seismic zone is present. Detailed interpretations of the focal mechanisms shown in Figures 2.6-2.8 are given in a following section concerning the structure and evolution of the northern New Guinea

Figure 2.4

Seismic section A. The following is true for Figures 2.4-2.9. Projection onto vertical plane of ISC seismicity. Locations and widhths of profiles are indicated to the left of the projection. Major land and bathymetric features are identified by a letter code: RMF=Ramu-Markham Fault zone, NBT=New Britain Trench, and OSF=Owen-Stanley Fault zone. Triangles mark the positions of active and Neogene volcanoes. A solid line outlines the inferred location of the top of the Wadati-Benioff zones. Focal mechanisms shown are back hemispheres; numbering corresponds to the numbering system of Appendix I. All profiles are from south (left) to north (right).



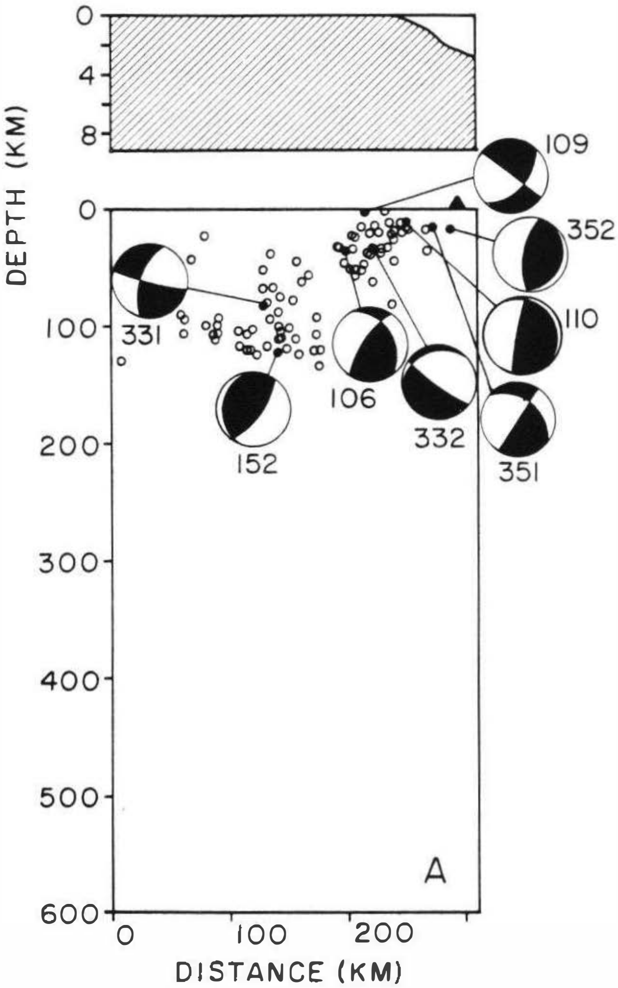

0
4
8
DEPTH (KM)
0
100
200
300
400
500
600
109
352
110
351
332
106
152
331
A
0
100
200
DISTANCE (KM)

Figure 2.5

Seismic section B.

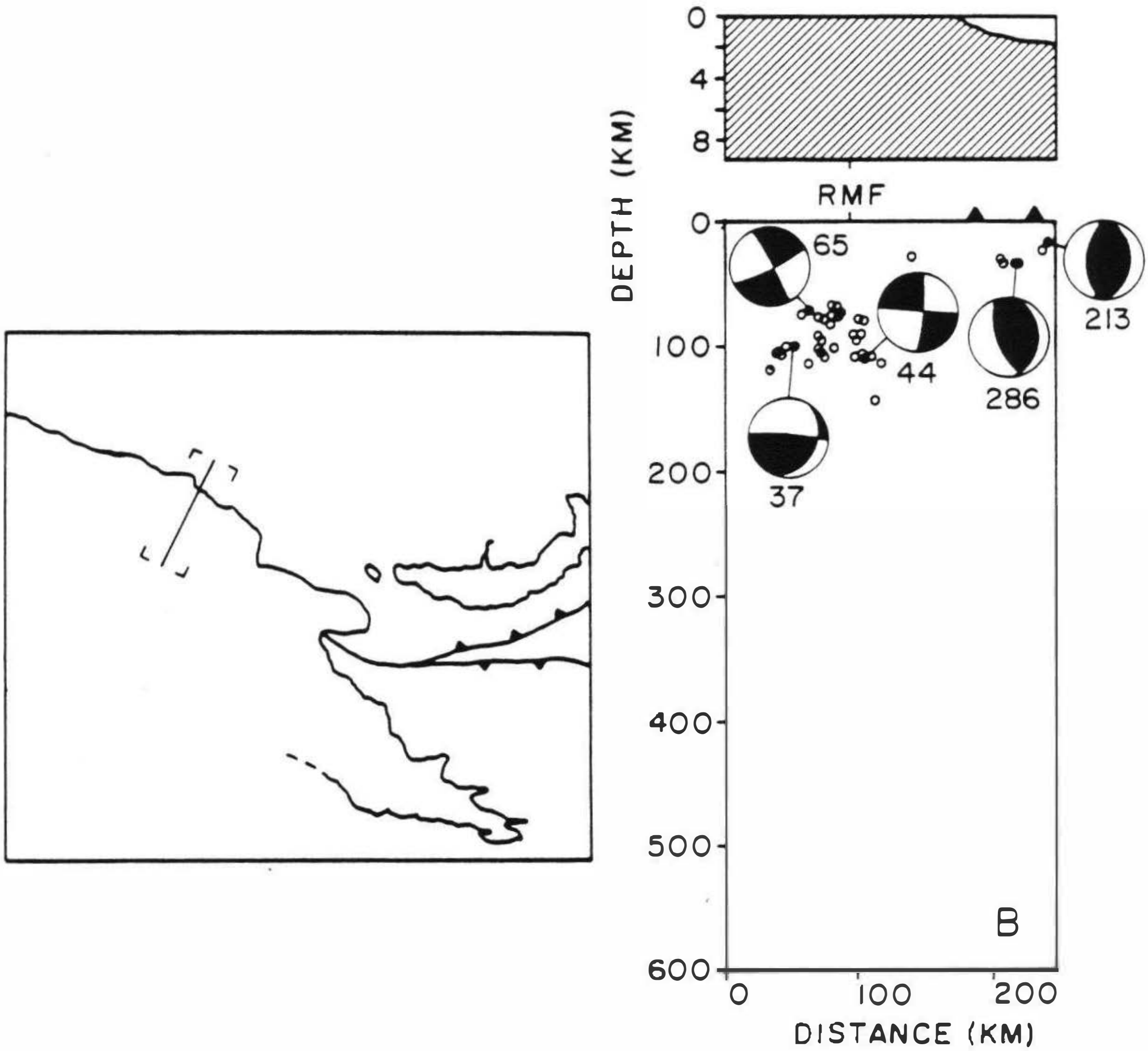
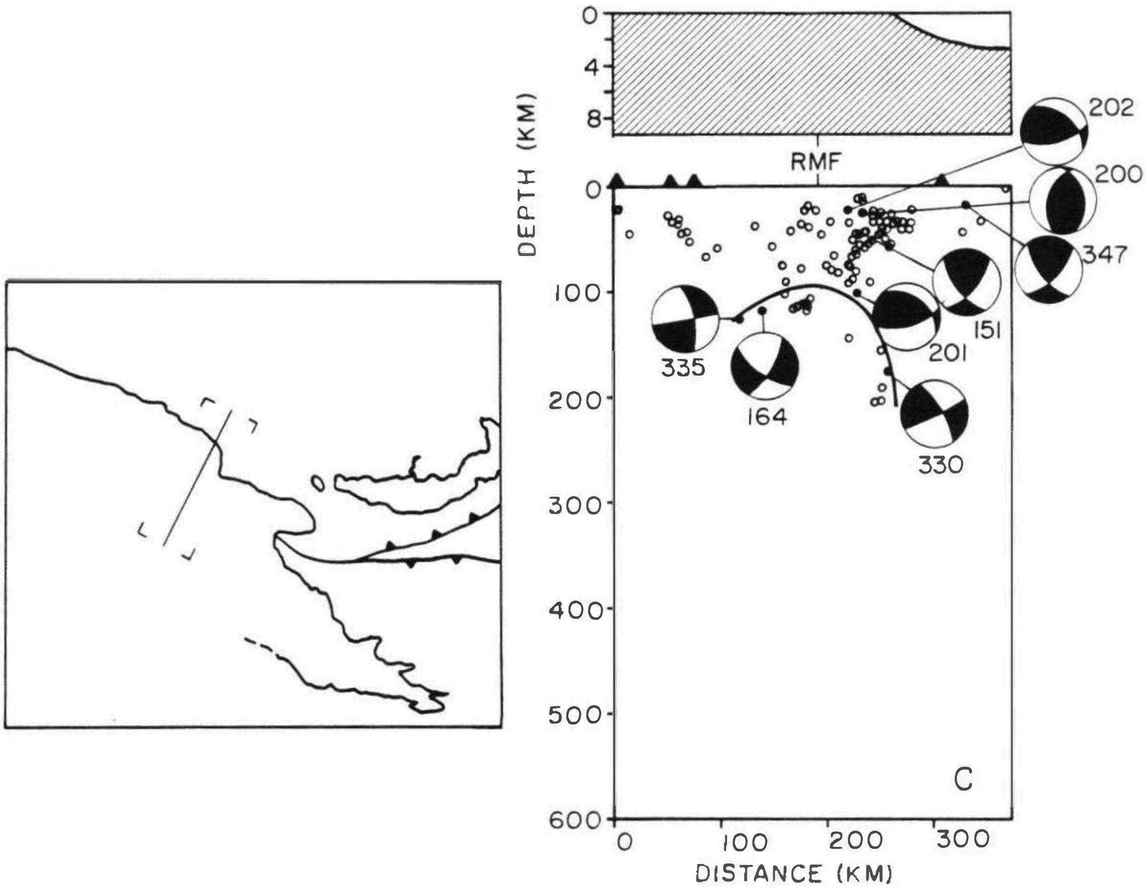

DEPTH (KM)
0
4
8
RMF
0
65
44
286
213
37
100
200
300
400
500
600
B
0
100
200
DISTANCE (KM)

Figure 2.6

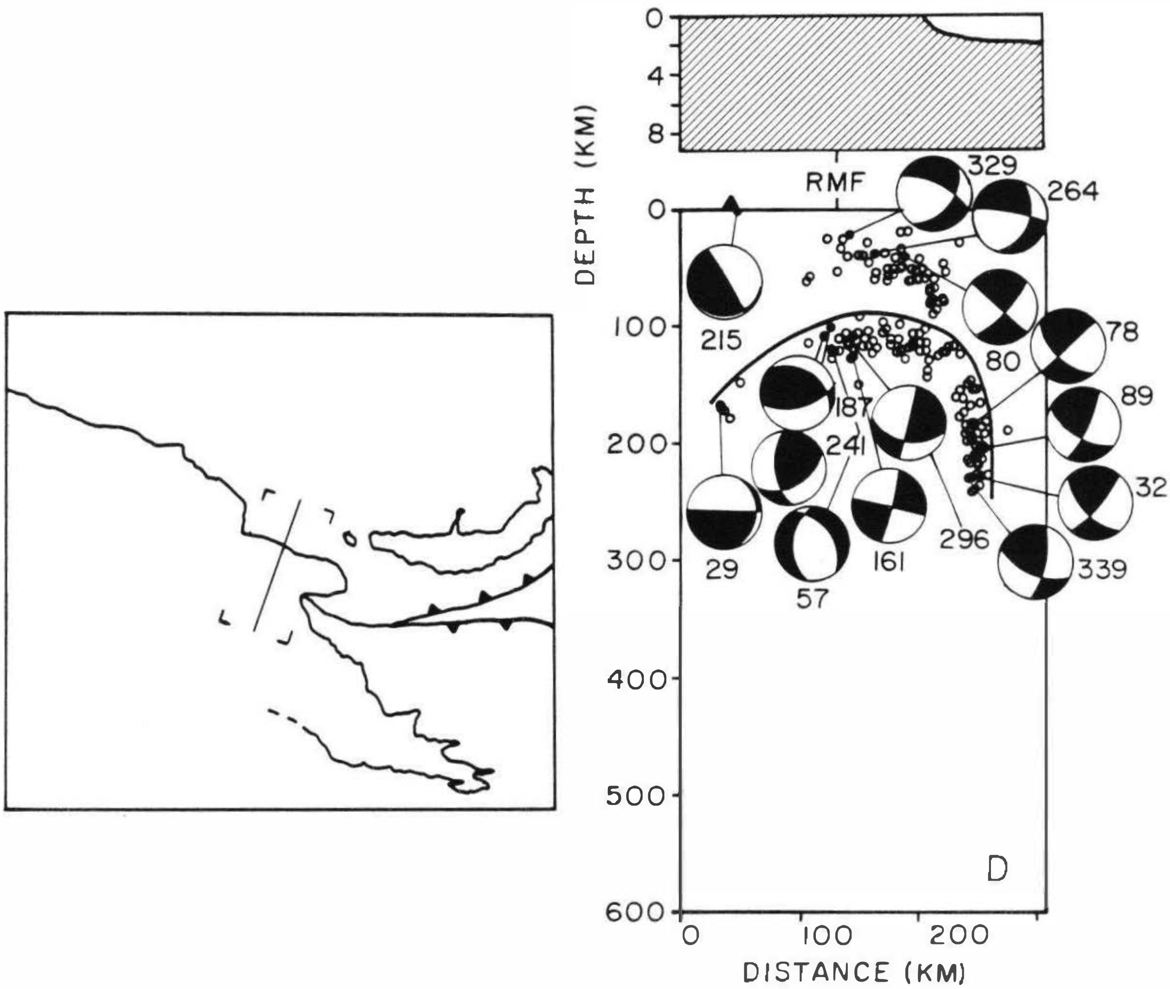
Seismic section C.


DEPTH (KM)
0
4
8
RMF
0
100
200
300
400
500
600
202
200
347
151
201
335
164
330
C
0
100
200
300
DISTANCE (KM)

collision zone. In Figure 2.7 the folded configuration of the intermediate and deep hypocenters is well-developed. This seismicity clearly reveals a westward-plunging flexural fold in the lithosphere (Hamilton, 1979; Ripper and McCue, 1983) of the Solomon Sea Plate. Shallow seismicity is confined to the Finisterre Range; focal mechanisms show ramping of the Finisterre block onto the New Guinea Mobile Belt. Profile E (Figure 2.8) also shows the broad fold in the Solomon Sea lithosphere, but now the fold is much broader and its crest is shallower (about 30 km). A few shallow hypocenters are located in the vicinity of the Owen-Stanley Fault Zone. The bathymetry shows a double trench feature; the New Britain Trench on the south is separated from the Finsch Deep by a narrow ridge - the "Vitiaz Slice" of Johnson (1977). Finlayson et al. (1977) report anomalously thick crust in this region. It is important to note that this is a basement ridge, the seaward continuation of the Huon Peninsula, and not simply a melange wedge. The flanking basins seem to have formed in response to continued uplift of the Huon Peninsula. Markham Canyon is the seaward continuation of the Ramu-Markham fault zone. Wrench faulting associated with sinistral movement on the Ramu-Markham fault zone is postulated as the structural control of the Huon Basin ("Huon Chasm") by Davies et al. (1984). However, within 50 km of the surface there are very few earthquakes associated with the Ramu-Markham Fault Zone and no left-lateral focal mechanism solutions. Teleseismic data are not very helpful in determining the structure of either the Huon Basin or the Finsch Deep. Profile F (Figure 2.9) shows the well-developed W-B zone of the New Britain Trench. The

Figure 2.7

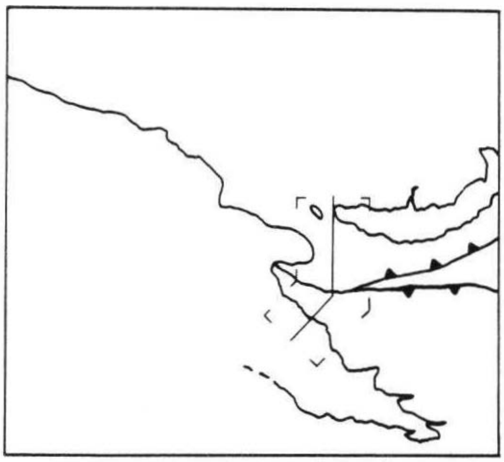
Seismic section D.



DEPTH (KM)
0
4
8
RMF
0
100
200
300
400
500
600
0
100
200
DISTANCE (KM)
D
329
264
215
80
78
187
89
241
32
29
57
161
296
339

Figure 2.8

Seismic section E.



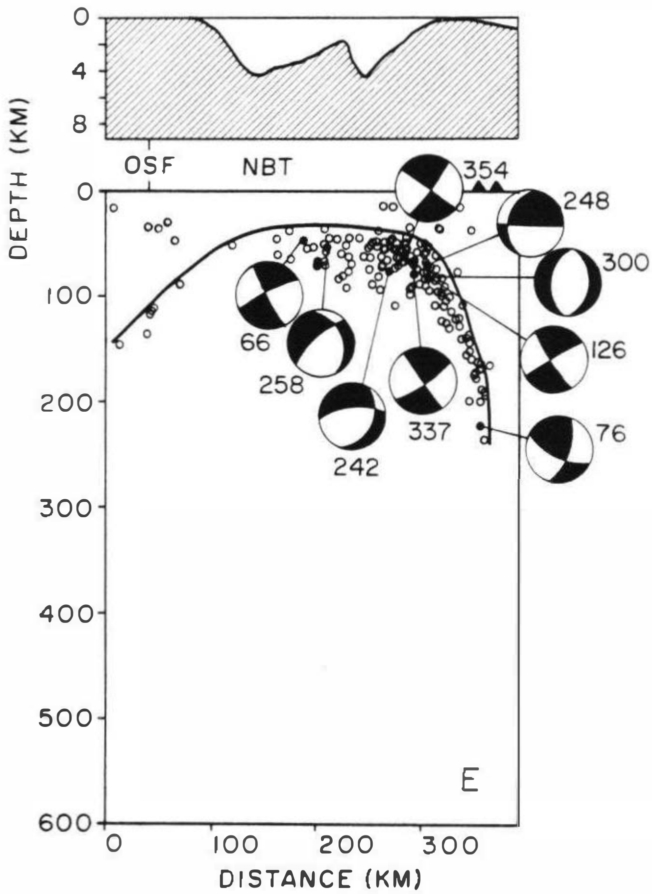
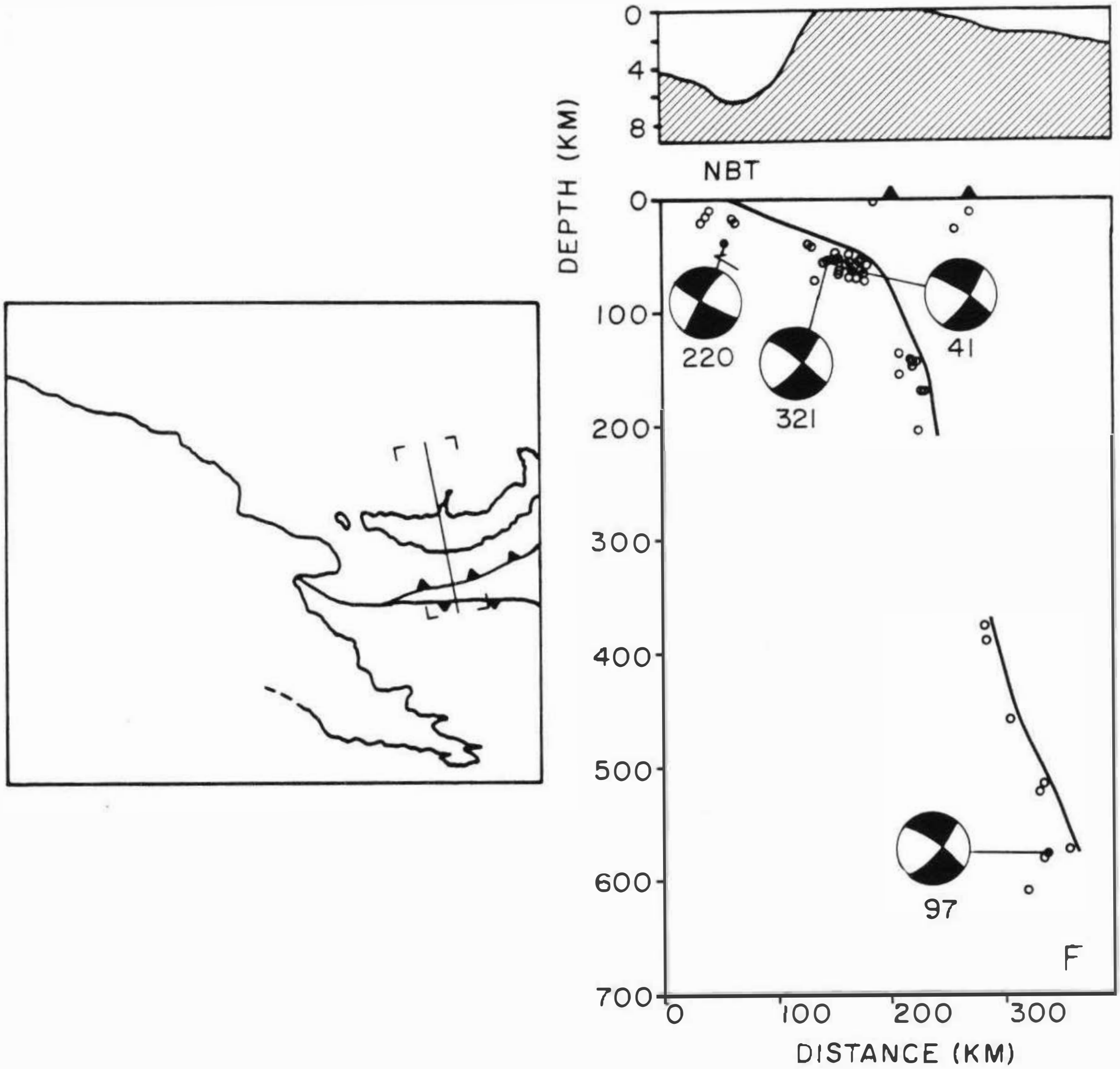

DEPTH (KM)
OSF
NBT
354
248
300
126
76
66
258
242
337
E
DISTANCE (KM)
0
4
8
100
200
300
400
500
600

Figure 2.9

Seismic section F.


DEPTH (KM)
0
4
8
NBT
0
100
200
300
400
500
600
700
220
321
41
97
F
0
100
200
300
DISTANCE (KM)

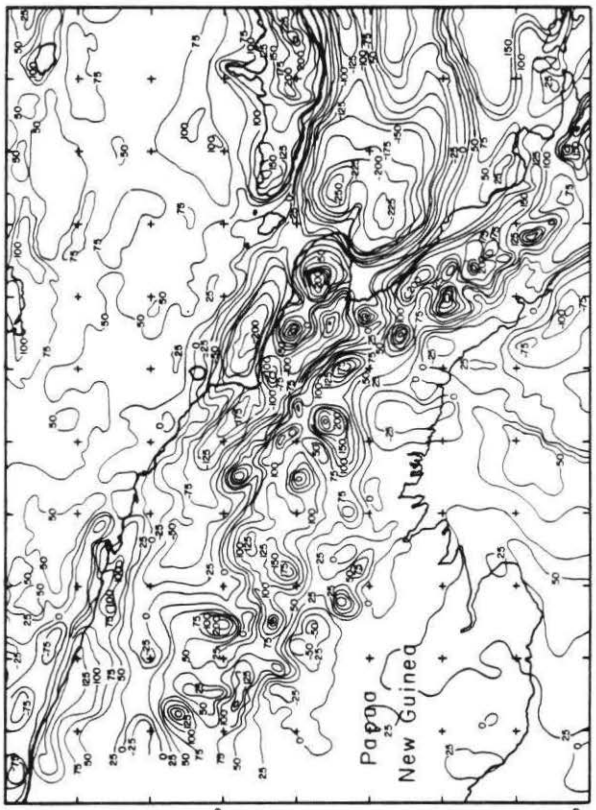
seismic zone dips north at an initially shallow angle; the dip then steepens abruptly to about 70-75°. Deep earthquakes (400-630 km) are believed to originate in a piece of lithosphere subducted at the New Britain Trench, but discontinuous with the intermediate seismicity.

Beneath the Coast Ranges of northern New Guinea the Solomon Sea Plate forms a flexural fold with an axis that is subparallel to the strike of the Ramu-Markham Fault and that plunges westward at an angle of about 5° beneath the mainland. The southern limb of the fold dips southwest beneath southeast and central Papua and the northern limb dips north beneath the volcanic arc of New Guinea (west of New Britain to Shouten Islands). Quaternary volcanism off the north coast of New Guinea is related to subduction of the Solomon Sea Plate beneath the Bismarck Sea Plate. Mt. Lamington, Mt. Victory and Mt. Goropu are andesite volcanoes related to subduction of the Solomon Sea Plate beneath the Indo-Australian Plate along the Trobriand Trough.

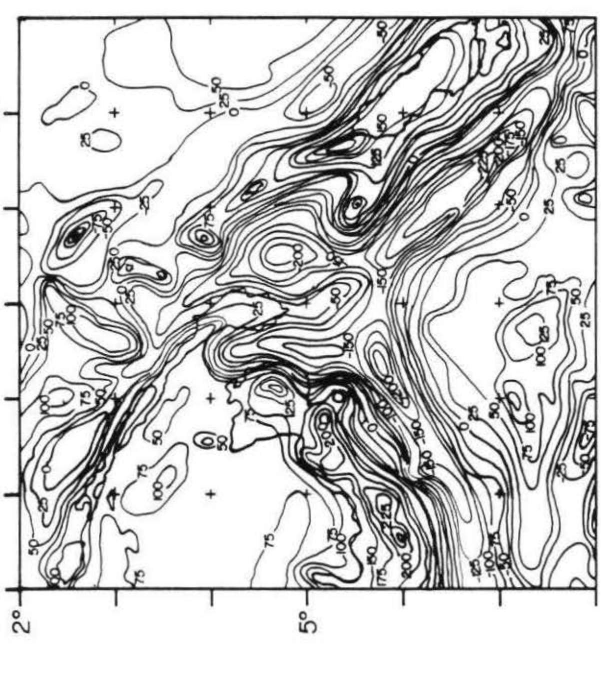
The double trench seen in Profile E (Figure 2.8) consists of the Finsch Deep to the north and the Huon Basin to the south. The Finsch Deep and Huon Basin bordering the Huon Peninsula and the Feni Deep and St. George's Channel bordering New Ireland are analogous structures. While there is no apparent relationship between the two sets of structures with respect to surface features, the two sets are in identical positions with respect to subsurface structures. St. George's Channel and Huon Basin are probably strike-slip sutures, and Feni Deep and Finsch Deep may be pull-apart basins. Both sets of structures are characterized by strike-slip faulting and/or normal

Figure 2.10

Free-air gravity map of the Papua New Guinea (top) and New Britain regions (bottom; after Watts et al., 1981).



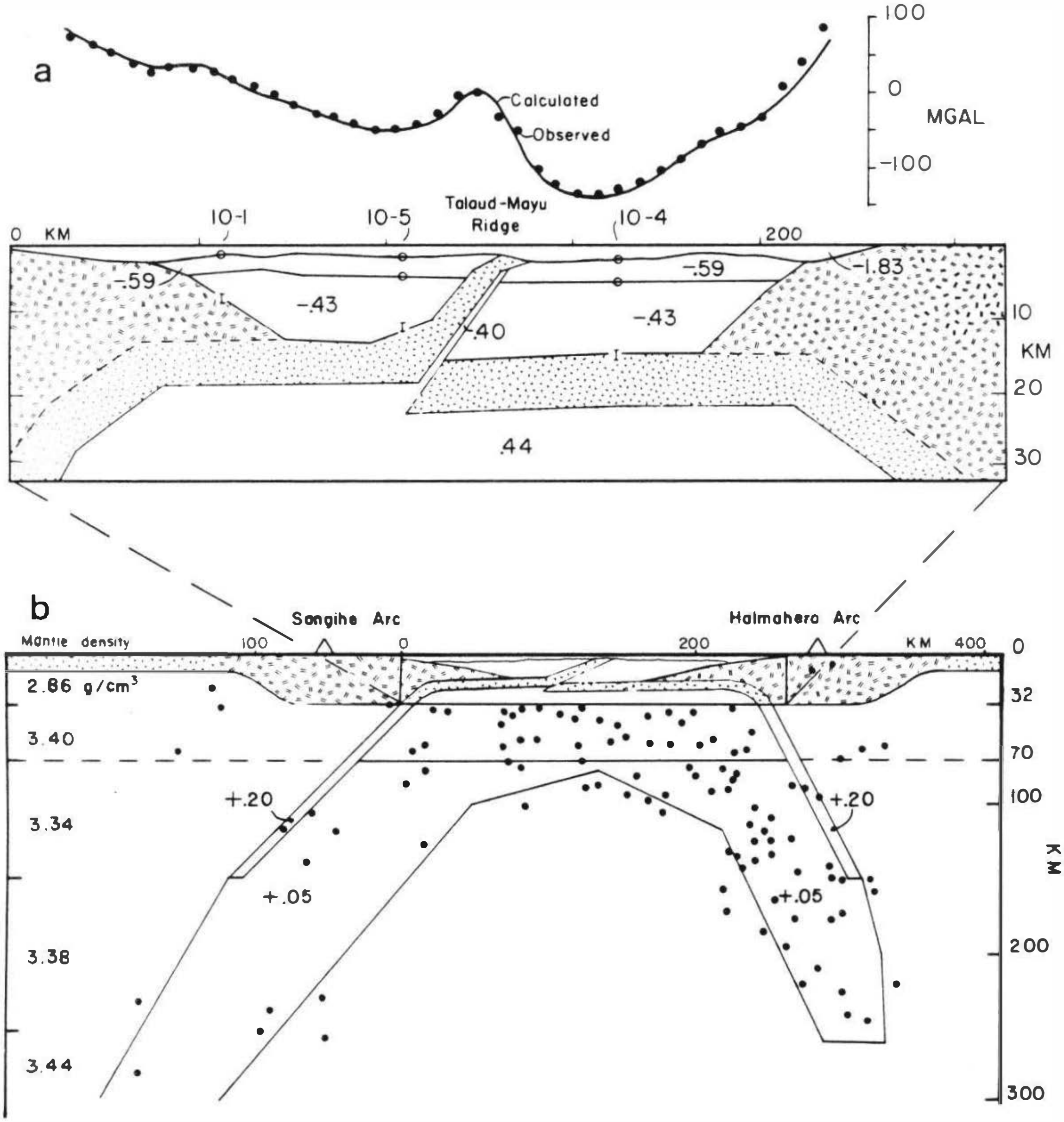
(a)



(b)

Figure 2.11

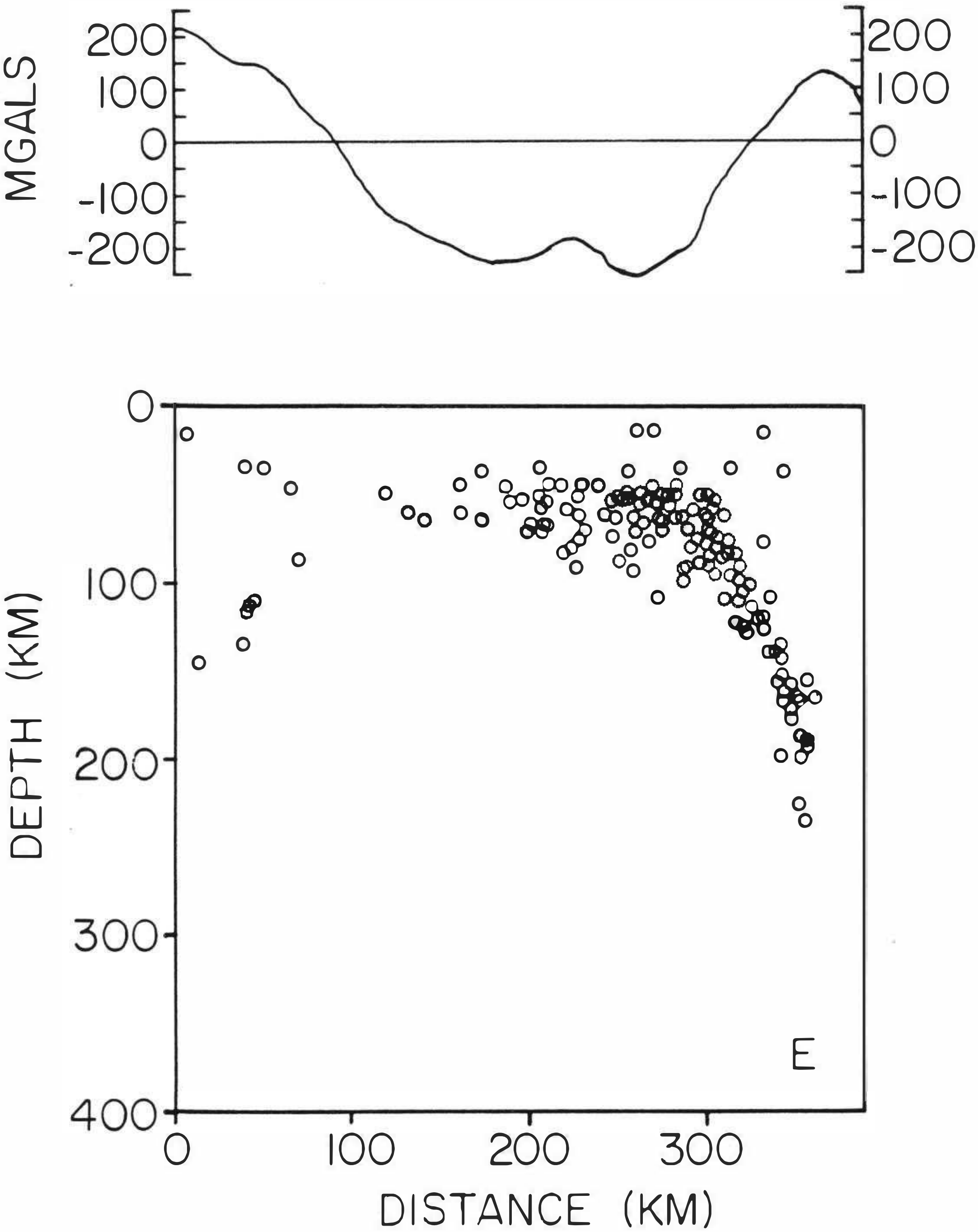
Gravity model for the central Molucca Sea (after McCaffrey et al., 1980).



a
100
0
MGAL
-100
Calculated
Observed
Talaud-Mayu Ridge
0 KM
10-1
10-5
10-4
200
-.59
-.43
.40
-.59
-.43
-1.83
.44
10
KM
20
30
b
Sangihe Arc
Halmahera Arc
Mantle density
100
0
200
KM 400
2.86 g/cm³
3.40
3.34
3.38
3.44
+.20
+.05
+.20
+.05
0
32
70
100
KM
200
300

Figure 2.12

Free-air gravity along seismic section E (Figure 2.3).


MGALS
200
100
0
-100
-200
DEPTH (KM)
0
100
200
300
400
E
DISTANCE (KM)

faulting and have similar gravity signatures (compare Figure 10 a and b); distinct gravity lows. Technically, the New Britain Trench proper ceases to exist at about 149°E where the fold begins to plunge beneath the Huon Peninsula. The very large gravity negative seen in Figure 2.9 near the Huon Peninsula is generated by the interaction of three lithospheric plates. The Indo-Australian and the Bismarck plates are in collisional contact along the Ramu-Markham Fault and form an arc-continent collision overriding the Solomon Sea Plate. A similar development is seen within the Moluccan collision zone (Figure 2.11), and there a large gravity negative is also generated (Silver and Moore, 1978; McCaffrey et al., 1980; McCaffrey, 1982). The observed gravity and seismicity along Profile E (just east of Huon Peninsula) is very similar to that of the central Moluccan Sea (compare Figures 2.11 and 2.12).

Focal Mechanisms

Many focal mechanisms have been published for the Papua New Guinea-Solomon Islands region. A list of all available earthquakes in and near Papua New Guinea with fault plane solutions is given in Appendix 1. The source codes for the data are as follows:

WH	Wickens and Hodgeson (1967)
IM	Isacks and Molnar (1971)
JM	Johnson and Molnar (1972)
C	Curtis (1973b)
R1	Ripper (1975)
R2	Ripper (1977)
P	Pascal (1979)

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R1	Ripper (1975)
R2	Ripper (1977)
P	Pascal (1979)

R3 Ripper (1980)
LK Lay and Kanamori (1980)
WT Weissel et al. (1982)
DW Dziewonski and Woodhouse (1983)
PC this dissertation

An asterisk denotes earthquakes which have solutions that are poor in the opinions of the original authors. The solutions are given as azimuth and plunge of the poles to the X and Y (nodal) planes assuming a Type II source.

Thirty-two additional focal mechanism solutions have been obtained for moderate to large earthquakes covering the period 1970-1981. The positions of the new focal mechanisms are relocated as described in the SEISMICITY section; the original ISC depth is listed for events with fewer than 3 reliable pP readings. In all cases P-wave polarities were read directly from long-period recordings of the WWSSN stations. The original data, projections of the P-wave polarities and inferred fault and auxilliary planes onto the lower hemisphere of the homogeneous focal sphere, are included in Appendix II.

New and previously published solutions are plotted in Figures 2.13-2.15 for the depth ranges specified. The quadrants defined by the nodal planes are black for compressional and white for dilatational first motions of P. The numbers correspond to the event numbers in Appendix 1. Shallow strike-slip focal mechanisms along the Bismarck Sea seismic lineation extend from the north coast of New Guinea, across the Bismarck Sea, into New Ireland and New Britain (Figure 2.13). The solutions occur in three main groupings, each

Figure 2.13

Focal mechanisms for earthquakes located in the Papua New Guinea-New Britain region for the depth range 0-50 km. The following information is true for Figures 2.13-2.15. Where possible the focal mechanism is centered over the epicenter; in some cases the epicenter is indicated by a triangle and a line is drawn to the corresponding solution. Compressional quadrants are shaded and dilatational quadrants are unshaded. Tension axes are shown as white circles against the shaded conpressional quadrant. Numbers correspond to the numbers in Appendix I.

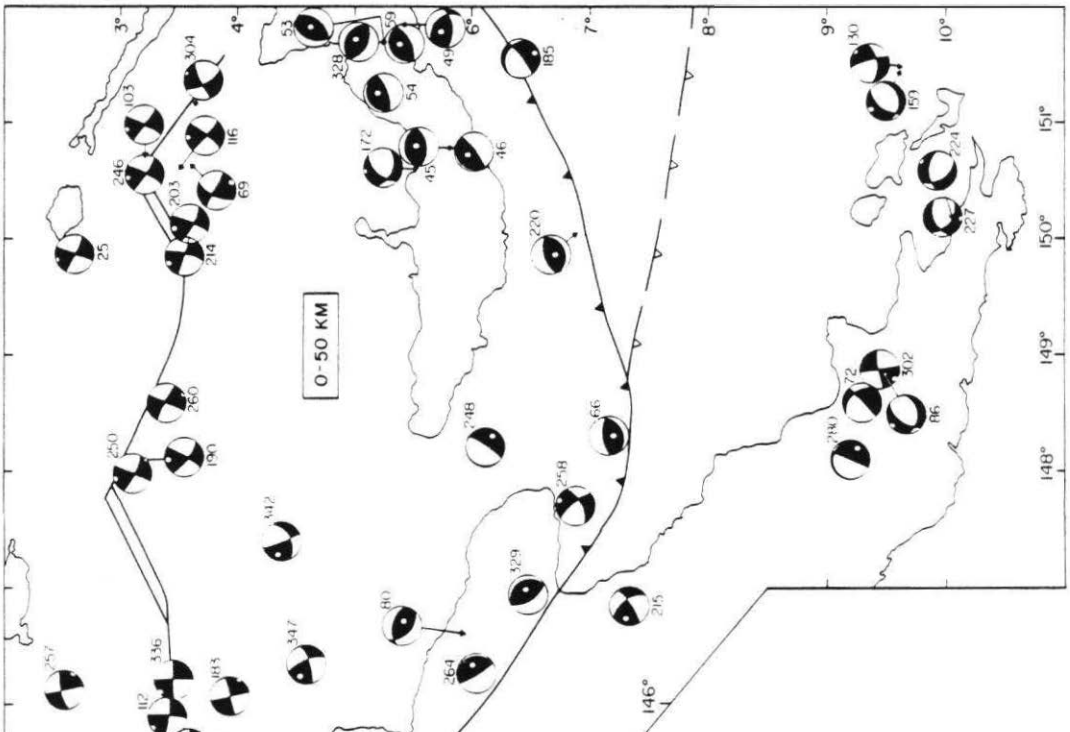
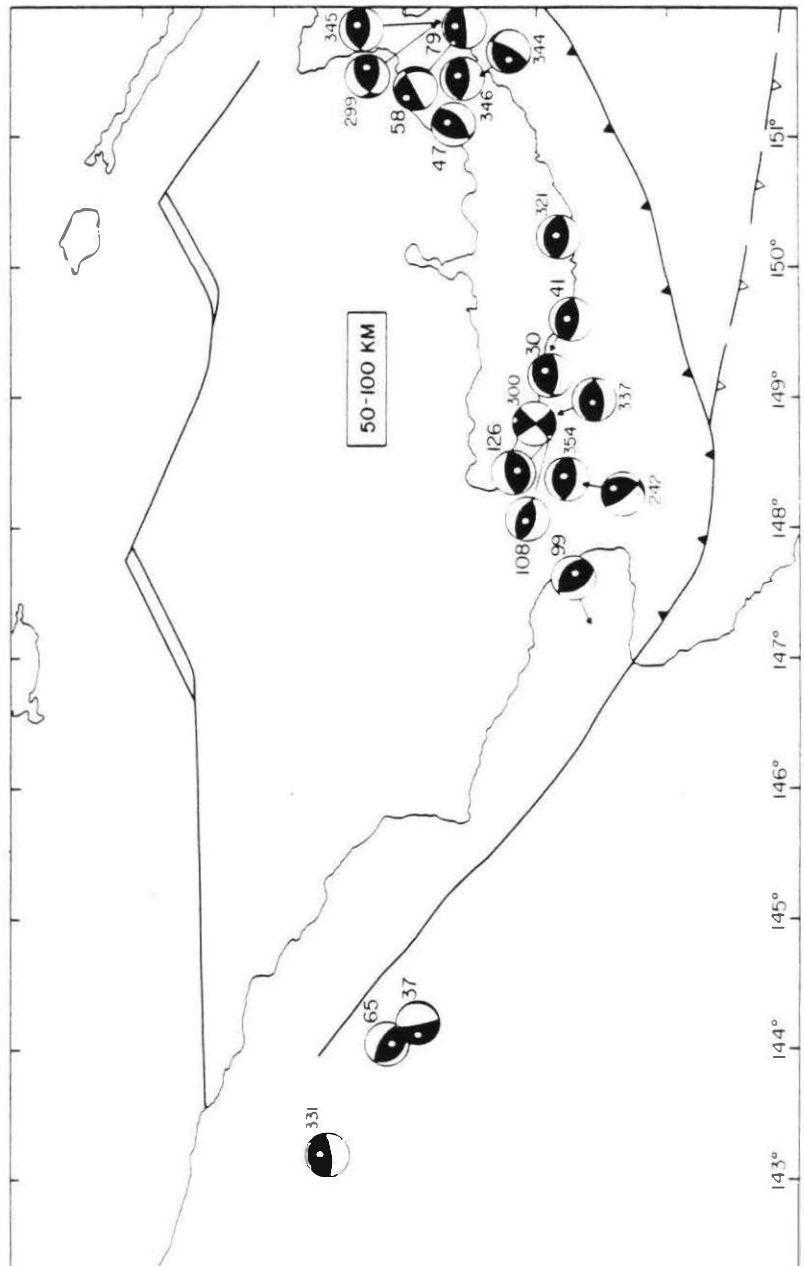

0-50 KM
3°
4°
6°
7°
8°
9°
10°
142°
143°
144°
145°
146°
148°
149°
150°
151°

Figure 2.14

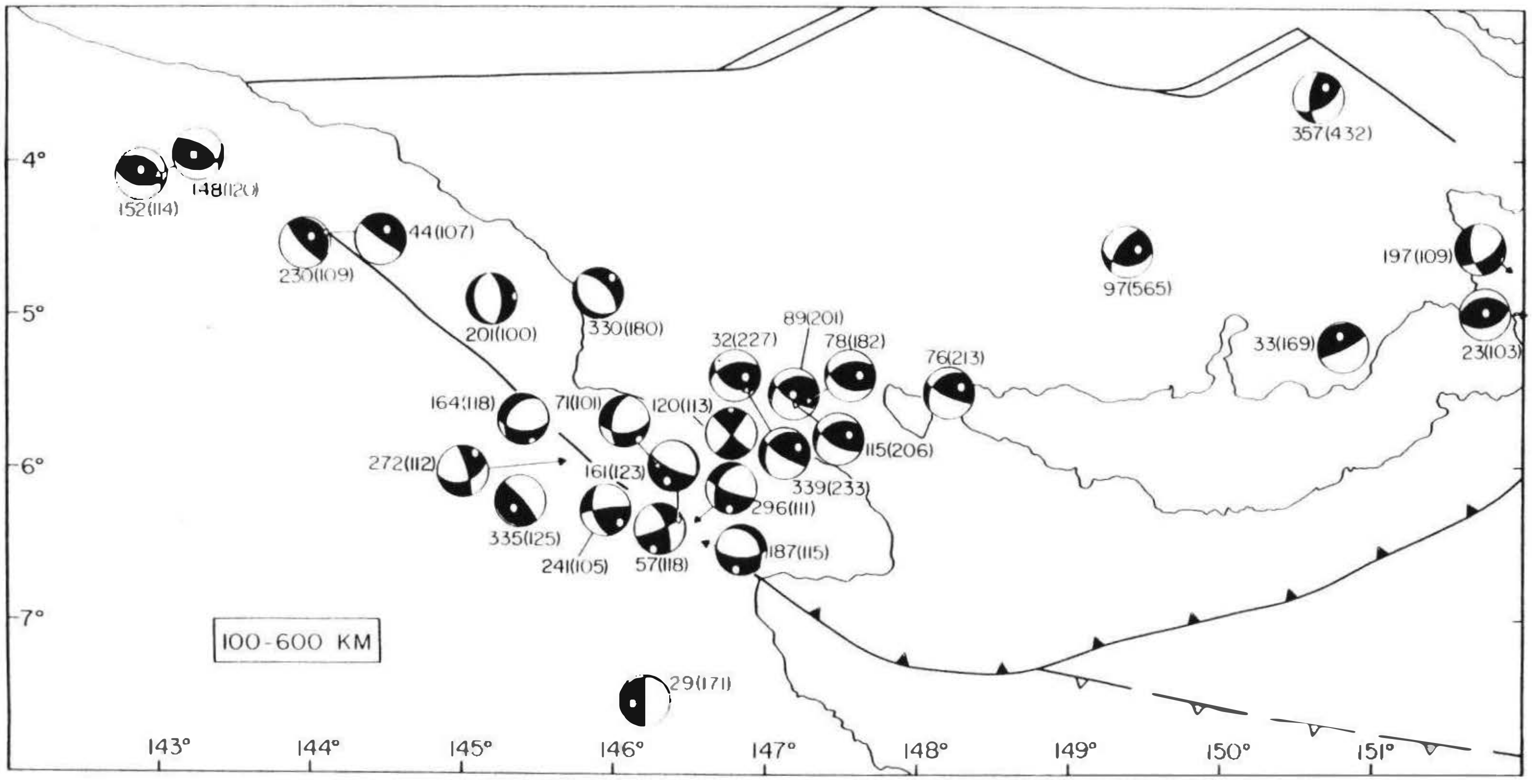
Focal mechanisms for earthquakes located in the Papua New Guinea-New Britain region for the depth range 50-100 km.



50-100 KM
3°
4°
5°
6°
7°
142°
143°
144°
145°
146°
147°
148°
149°
150°
151°
238
331
65
37
99
108
126
354
242
300
337
30
41
321
47
58
299
345
79
346
344

Figure 2.15

Focal mechanisms for earthquakes located in the Papua New Guinea-New Britain region for depths greater than 100 km. Depth of focus is in parentheses next to the event number.


357(432)
152(114)
148(120)
230(109)
44(107)
97(565)
197(109)
201(100)
330(180)
89(201)
32(227)
78(182)
76(213)
33(169)
23(103)
164(118)
71(101)
120(113)
115(206)
272(112)
161(123)
339(233)
296(111)
335(125)
241(105)
57(118)
187(115)
100-600 KM
29(171)
-4°
-5°
-6°
-7°
143°
144°
145°
146°
147°
148°
149°
150°
151°

associated with a separate transform segment; all of the solutions have one nodal plane subparallel to the trend of the appropriate transform segment. Motion on these transforms has long been recognised as sinistral. On the western most section, fault planes are oriented E-W. Mechanisms of the central section (curving into the ridge segment) have inferred fault planes which are oriented more NW-SE. The curved section of this transform has been interpreted as a series of extremely short en echelon ridge and transform sections (Eguchi et al., 1985), hence 203 and 214 are included in this central grouping. Events 69, 103, 116, 246 and 304 have inferred fault planes parallel to the NW-SE easternmost transform, south of New Ireland.

Two strike-slip solutions occur north of the Bismarck Sea seismic lineation groupings, 25 and 257. Event 25, west of New Hanover, has been interpreted by Johnson and Molnar (1972) as related to faulting along the southwest coast of New Ireland. The orientation of the inferred fault plane is certainly consistent with the interpreted left-lateral motion. Event 257 is more problematical; this event, together with events 342 and 347, which also have large strike-slip components, may be interpreted as NW-SE extension/NE-SW compression, consistent with the regional stress regime, yet far removed from any known tectonic feature. Events 215 and 302 may be related to the Owen Stanley fault system. However, the fault system is composed of many short, differently oriented segments, and assigning a fault and a sense of motion based solely on ISC location is pointless. Event 200 is internal to the Adelbert block (see Fig. 2.6). Note that, with the possible exception of event 258, no earthquakes in the region of the

Ramu-Markham Fault Zone (often presumed to be left-lateral) have strike-slip focal mechanism solutions.

Shallow normal faulting is scattered throughout the New Guinea-New Britain area. Events 151, 200 and 202, while very different in character, are all within the Adelbert block and, as such, may represent complex internal deformation within the block. The thrust event 151 is the deepest of the three. Both 248 (Finsch Deep) and 258 (Huon Gulf) are located in the upper 30 km of the severely folded Solomon Sea Plate (see Figure 2.8) and may be the results of bending stresses within the upper portion of the slab. Normal-type solutions typify the D'Entrecasteaux Islands (130 and 159) and southeast Papua (72, 86, 224, 227, 280). These events usually indicate horizontal N-S oriented extension, although the orientation of the fault planes of some of the events on the Papuan Peninsula may be influenced by preexisting fault segments of the Owen-Stanley fault zone. The Woodlark Spreading System is believed to be rifting through Dawson Strait, into Goodenough Bay, Papua (Weissel et al., 1982). Petrological evidence of this is provided by peralkaline rhyolites erupted in the eastern D'Entrecasteaux Islands (Smith, 1976; Johnson et al, 1978). These lavas are believed to be representative of the initial stages of rifting (Smith, 1975). Event 172 is probably related to active volcanism on New Britain. 185 is located beneath the New Britain Trench and shows horizontal extension orthogonal to the trench; this event may result from bending of the lithosphere prior to subduction (Chappell and Forsyth, 1979).

Many shallow thrusting events occur beneath eastern New Britain where the seismic zone dips NNW at 45^{o}. The events as a group are characterised by downdip extension; tension-axes subparallel to the dip of the W-B zone and B-axes subparallel to the strike. This shallow thrusting along the New Britain Trench appears to cease west of about 150^{o}E. Events 220 and 66 could indicate very high angle thrusting to the north, but event 66 most likely represents shallow underthrusting to the south (see Figure 2.8). Events 80, 264 and 329 occur within a shallow-to-intermediate grouping of earthquakes (see Figure 2.7) and may be related to ramping of the Finisterre block south onto the New Guinea Mobile Belt.

Except for a small gap east of Willaumez Peninsula, thrust events in the 50-100 km depth range are fairly consistent and evenly distributed along New Britain (Figure 2.14). Events 47, 58, 79, 299, 344, 345, and 346 in eastern New Britain reveal underthrusting of Solomon Sea Plate lithosphere beneath the Bismarck Sea in a NNW direction. Events 30, 41, 108, 126, 300, 321, 337, and 354 show thrusting in a due-northerly direction. Event 242 is located deep within the subducted lithosphere and shows an almost E-W direction of maximum compression; this event may be a deep, compressional bending event. Event 99 is within the Ramu-Markham thrust surface. Events 65 and 331 are best interpreted as indicating regional N-S compression; although 65 could be interpreted as low angle thrusting to the southwest. Events 37, 238 and the unusually deep (79 km) strike-slip event, number 300, are difficult to interpret in terms of either relative motion or regional stress regime.

Intermediate events over 100 km (Figure 2.15) in depth appear to indicate a mixed stress regime. Most of these are clustered beneath the Finisterre Range-Huon Peninsula. The deeper events to the north of Huon Peninsula (32, 76, 78, 89, 115 and 339), ranging in depth from 182-233 km, are extremely consistent and indicate downdip extension within the near-vertical subducted slab. Events located well within the Huon Peninsula (57, 71, 161, 164, 187, 272 and 296) are for the most part normal events originating in the upper part of the anticlinal fold in the Solomon Sea lithosphere. The events indicate extension in a predominantly N-S or NE-SW direction, and are therefore interpreted as arising from the extreme bending of the plate in this region (see Figure 2.7). The two deep events, 97 and 357, have nodal planes oriented subparallel to the strike of the deep lithosphere (see W-B zone contours in Figure 2.3). Despite the diffence in depths, 565 and 432 km, respectively, both solutions are very similar and show downdip extension.

The Structure and Evolution of the Northern New Guinea Collision Zone

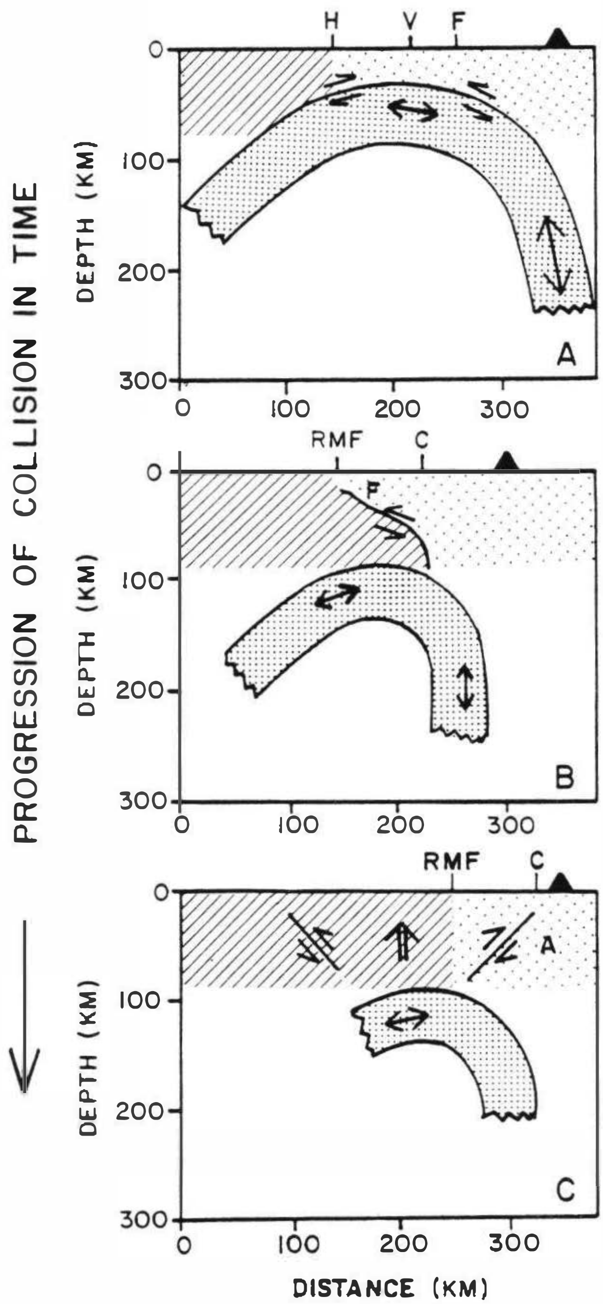
Subduction polarity reversal for northern New Guinea (from southwest- to northwest-dipping) was suggested as early as 1970 by Dewey and Bird and later by Johnson and Molnar (1972) and Hamilton (1979). Past studies (Jakes and White, 1969; Johnson and Molnar, 1972; Karig, 1972) have indicated the presence of a SW-dipping W-B zone as well as a NW-dipping W-B zone in northern Papua New Guinea. However, Johnson et al. (1971) and Johnson and Jaques (1980) claim that the seismicity does not clearly define a southwest dip. Both the southwest dip and the overall character of the double-sided W-B zone has been demonstrated in the above text and agree quite well with tectonic reconstructions of the area (see for example, Falvey and Pritchard, 1984; Kroenke, 1984). There is no southwest subduction of the Bismarck Sea Plate beneath the Indo-Australian Plate as proposed by Denham (1975) and Johnson and Molnar (1972), however the two plates are in collisional contact. This continent-arc collision overrides the anticlinal fold in the Solomon Sea Plate formed by the New Britain Trench/Trobriand Trough collision.

Despite superposition of the effects of diverse tectonic events, late Cenozoic evolution of the northern New Guinea region primarily reflects the collision of the Adelbert-Finisterre-Huon-New Britain Arc with what was once the north coast of mainland New Guinea. In Miocene times, before collision, the island of New Britain and what is now the Coast Ranges of New Guinea may have been more-or-less in line with the trend of New Ireland (Falvey and Pritchard, 1984; Taylor, 1979). The collision has proceeded by rotation of the leading edge of the south-facing New Britain Arc over the north-facing Trobriand Trough, eventually bringing the Adelbert-Finisterre-Huon-New Britain Arc into contact with the then northern New Guinea coast. The collision probably began in northwestern New Guinea/West Irian in late Miocene (Kroenke, 1984) and suturing bas migrated southeast. Suturing is completed between the arc and northern New Guinea near and northwest of the Adelbert Range, suturing is at an advanced stage in the Finisterre Range, and it is proceding today south of the Huon Peninsula. In terms of its seismicity, the Ramu-Markham Fault Zone changes its characteristics in response to its changing role as a suture. Near and northwest of the Adelbert region, the Ramu-Markham has very little shallow seismicity and intermediate seismicity is displaced to the south of the surface fault trace. Near the Finisterre region, the Ramu-Markham is a north-dipping, ramp-like surface and appears to be the surface along which the Finisterre block overrides the New Guinea mainland. Farther east the collision between the New Britain Trench and the Trobriand Trough may be proceding; the eastern terminus of the Ramu-Markham Fault Zone, the Markham Canyon, probably propagates east with the point of suturing. Seismicity and rapid uplift of the north coast, particularly the Huon Peninsula (Chappell, 1974), are clear indications that the collision is not yet complete.

Figure 2.16 is based on vertical cross-sections of seismicity (Figures 2.6-2.8) and illustrates the progression of the collision with time, i.e. from northwest to southeast along the north coast of West Irian-Papua New Guinea. Of all proposed models of this collision zone, this most closely resembles model "b" of Johnson and Molnar (1972). The configuration of the lithosphere in Figure 2.16a is very similar to a model of the Moluccan Sea collision zone proposed by McCaffrey (1982). Directly above the folded Solomon Sea lithosphere there are few earthquakes in the 0-30 km range and no focal mechanism

Figure 2.16

Cartoon depicting the evolution of the northern Papua New Guinea collision zone. Arrows summarize information provided in Figures 2.6-2.8. The Indo-Australian Plate is shaded; Bismarck Sea Plate is lightly stippled; Solomon Sea Plate is darkly stippled. The collision has progressed from northwest (2.16C) to southeast (2.16A) along the north coast of New Guinea. RMF=Ramu-Markham Fault zone; C=coast line; H=Huon Gulf; V=basement ridge; A=Adelbert block; in 2.16A F=Finsch Deep; in 2.16B F=Finisterre block.


PROGRESSION OF COLLISION IN TIME
H
V
F
0
100
200
300
DEPTH (KM)
A
RMF
C
F
B
RMF
C
A
C
DISTANCE (KM)

solutions, therefore the teleseismic data cannot determine the presence of a central pressure ridge (corresponding to the Talaud-Mayu Ridge) and thrust faulting at the apex of the folded lithosphere. Sediments in the Huon Gulf (H) portion of the New Britain Trench are about 1500 m thick and gently folded (Davies et al., 1984). The Finsch Deep (F) is largely sediment free and separated from the New Britain Trench by a narrow basement ridge (V), the seaward continuation of the Huon Peninsula. The top of the Solomon Sea lithosphere is inferred to be at about 30 km depth compared to 6 km only 60 km further east. In Figure 2.16b, shallow and intermediate seismicity (30-100 km) outlines the sinuous form of the Ramu-Markham suture. Focal mechanism solutions imply ramping of the Finisterre block (F) up onto the New Guinea Mobile Belt. In support of this interpretation we note the northward tilt of the Finisterre block (Jaques, 1975) and the rapid recent uplift of Huon Peninsula (Chappell, 1974). Figure 2.16c depicts a more mature stage of the collision in the vicinity of the Adelbert Range (Figure 2.6). Intermediate seismicity is offset to the south of the surface trace of the Ramu-Markham fault zone (RMF). Suturing may be complete in this region but continued compression from the northeast appears to be accomodated by two conjugate surfaces facilitating uplift of the Adelbert block (A) by wedging under of the Indo-Australian and Bismarck Sea plates. Northwest of 144^{o}E seismicity is diffuse, and suturing is assumed to be complete in this area.

There are no ophiolites and/or melange sediments emplaced along the western Ramu-Markham fault zone to indicate that the initial stages of the arc-continent collision in northern Papua New Guinea proceeded in a manner similar to that of the Moluccan arc-arc ccllision. The differences observed between the Moluccan arc-arc collision and the New Guinea arc-continent collision may represent basic differences between arc-arc and arc-continent collisions. In northern New Guinea, the collision begins with thrusting of the arc onto the continental crust along a low-angle, ramp-like thrust surface. The colliding arc experiences rapid uplift. As the collision continues, the thrust surface may steepen and/or suturing may progress too far, resulting in formation of two separate conjugate thrust surfaces. Part of the sutured arc then wedges under itself along the northern conjugate surface, causing further uplift. This conjugate thrust surface eventually may evolve into a true subduction zone. This model provides a mechanism for the reversal of subduction direction following arc-continent collision.

Subduction Beneath the Papuan Peninsula?

Kroenke (1984) proposed that southward subduction along the Trobriand Trough apparently overlaps the cessation of subduction along the Manus-North Solomon-Vitiaz subduction zone and the establishment of subduction along the New Britain-San Cristobal-New Hebrides subduction zone. However, the Trobriand Platform is the site of extensive imbricate faulting (Davies et al., 1984), a characteristic of very slow convergence, and several bits of evidence suggest that the trough may still be active. Namely, the deformation front is not buried by trench sediments, and the trough has a poorly developed southward-dipping Wadati-Benioff zone with active andesite volcanism at the surface. Subduction along the Trobriand Trough is either slow or stopped because of the collision of the Adelbert-Finisterre-Huon Arc with northern New Guinea. The Trobriand Trough and the Woodlark Rise were therefore late Miocene-Pleistocene plate boundaries of the Solomon Sea Plate. The new boundary of the Solomon Sea Plate is the Woodlark Spreading System which is propagating into the Papuan Peninsula; this boundary is as yet incomplete. Smith (1975) has suggested that the calc-alkaline (shoshonitic) Quaternary volcanics may represent volcanism migrating along an arc-trench system which was disrupted about the same time as spreading was initiated in the Woodlark Basin. Indeed, the calk-alkaline volcanism is roughly 150-200 km above the probable location of lithosphere subducted at the Trobriand Trough (Figure 2.3).

Strictly speaking, therefore, the Papuan Peninsula-Trobriand Platform straddles both a paleo-plate boundary and a newly formed plate boundary between the Solomon Sea and Indo-Australian plates. The weak zone of earthquakes which dips to the south is associated with lithosphere subducted at the Trobriand Trough. Lithosphere subducted at this trough extends beneath the New Guinea mainland, where it forms the southward-dipping limb of a broad flexural fold in the Solomon Sea Plate lithosphere. The Woodlark Rise is a trench-trencb transform between the Trobriand Trough and New Britain Trench.

Observed motion along this feature is right lateral (based on the only good focal mechanism solution available) accomodating differential motion between the western portion of the Solomon Sea Plate and the much younger Woodlark Basin (Weissel et al., 1982). If there is active subduction on the Trobriand Trough, one would expect to see left-lateral motion on the Woodlark Rise. Therefore, there may be active subduction at the Trobriand Trough, but its absolute magnitude must be much less than the observed right-lateral differential movement. Davies et al. (1984) concluded that subduction is active or has only recently ceased; alternatively, subduction may have ceased long ago and recently been reactivated by propagation of the Woodlark Spreading System into the Papuan Peninsula.

Conclusions

A zone of earthquakes associated with subduction of Solomon Sea Plate lithosphere at the New Britain Trench continues along the north coast of Papua New Guinea to West Irian. Maximum hypocentral depth decreases from 300 km near Huon Peninsula to 150 km near 142^{o}E. Intense subcrustal activity be Huon Peninsula is related to ramping of the Finisterre Arc onto the continental crust of the New Guinea Mobile Belt. Subcrustal seismicity near the Adelbert Range is indicative of wedging of the Indo-Australian and Bismarck Sea lithosphere beneath the Adelbert Range. Two very different mechanisms of uplift operate in close proximity in this region; the mechanism of uplift may initially be quite simple, such as ramping on low-angle thrust surfaces. Later, as suturing occurs, the mechanism of uplift becomes more complex, such as wedging. There is no trench along most of northern Papua New Guinea, although there may be one west of 143^{o}E; the Bismarck and Indo-Australian plates are in collisional contact, the surface expression of the suture is the Ramu-Markham Fault Zone. The arc-continent collision zone overrides and depresses the flexural fold of the Solomon Sea lithosphere formed by merging of the New Britain Trench and the Trobriand Trough. Although there is active volcanism along the northern Papua New Guinea coast to the Shouten Islands, there is probably only slow active subduction of Solomon Sea lithosphere west of Huon Peninsula (148^{o}E). Convergence between the Bismarck Sea and Indo-Australian plates is accomodated both as ramping and wedging in the areas mentioned above and within the New Guinea Mobile Belt. Most of the seismicity and early Pleistocene volcanism within the Mobile Belt is in an area directly opposite the Adelbert and Finisterre blocks. The seismicity is probably the result of continued convergence whereas the Highlands volcanism may represent volcanism from the Trobriand slab.

From 144.5^{o}E to 148^{o}E an arch-like trend in the intermediate seismicity is evident. The seismicity clearly reveals a westward-plunging anticlinal fold in the lithosphere of the Solomon Sea Plate (Hamilton, 1979; Ripper and McCue, 1983). The southern limb of the fold dips southwest beneath southeast and central Papua and the northern limb dips north-northeast beneath the volcanic arc of northern New Guinea. Near Huon Peninsula, the fold is a broad arch with its crest at about 30 km depth; near the Adelbert Range, the fold becomes narrower and the crest reaches a depth of about 100 km. The Bismarck-Indo-Australian collision zone overrides this folded Solomon Sea lithosphere producing a large (-250 mgal) negative in the free air gravity. The gravity negative is centered over Huon Peninsula, the present site of active collision between the New Britain and Trobriand trenches. Bathymetry of the region east of Huon Peninsula shows a double trench; the deeper New Britain Trench to the south is separated from the Finsch Deep to the north by a narrow basement ridge. Markham Canyon (and the Huon "Chasm") are the seaward continuations of the Ramu-Markham Fault suture zone.

Diffuse shallow and intermediate seismicity is observed along and east of the Papuan Peninsula. The intermediate depth hypocenters originate within the southwest-dipping W-B zone of the Trobriand Trough. Although active andesite volcanism is associated (Mts. Lamington, Goropu and Victory) with this poorly defined W-B zone, it is likely that the subduction rate is extremely small. Most of the shallow hypocenters are associated with the Owen-Stanley Fault Zone, with the active volcanoes, and predominantly with rifting of the Papuan Peninsula ahead of the westward propagating Woodlark spreading center.

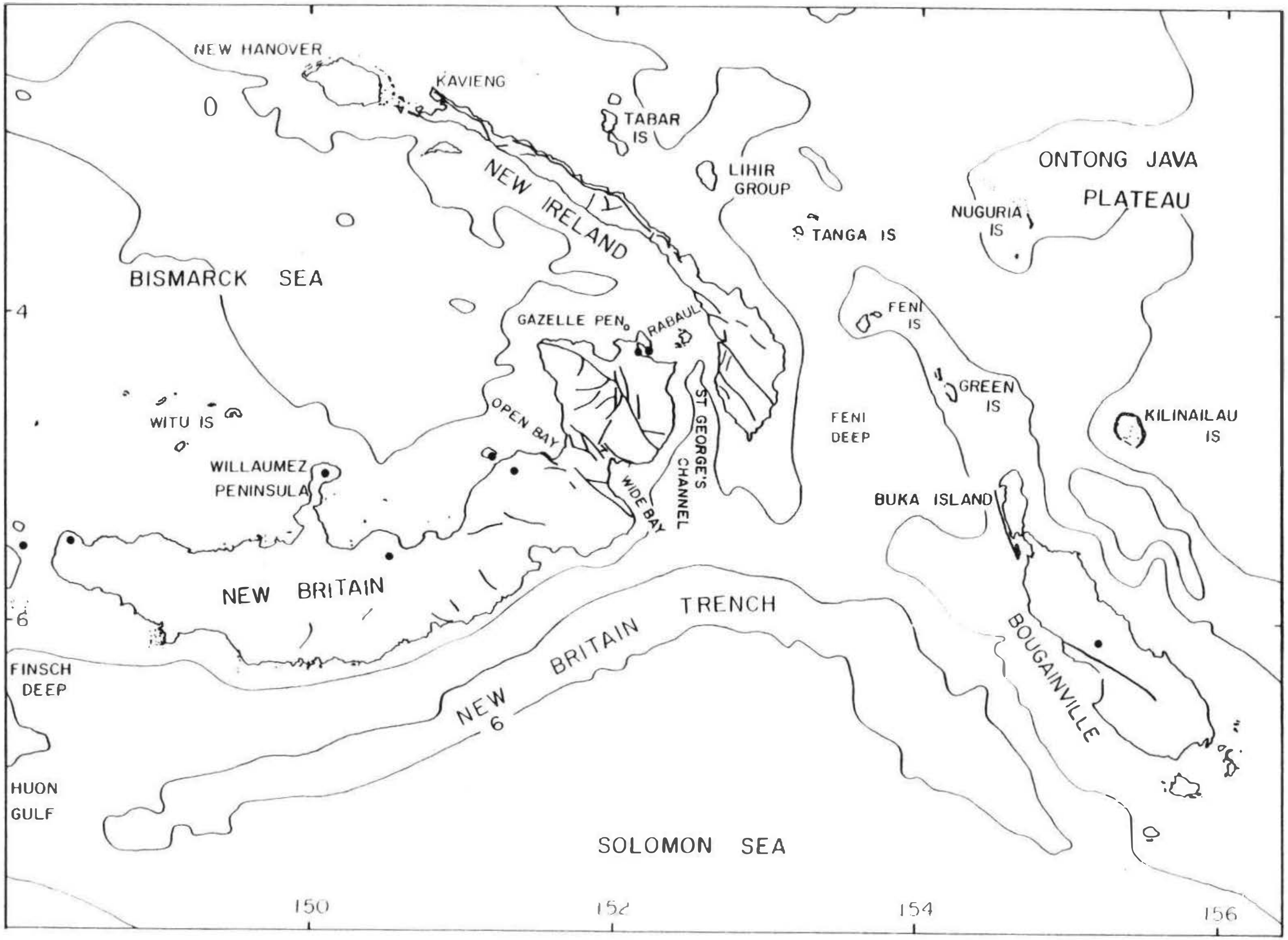
III. SEISMICITY, FOCAL MECHANISMS AND MORPHOLOGY OF SUBDUCTED LITHOSPHERE AT THE NEW BRITAIN TRENCH CORNER

Introduction

The New Britain Trench is an active part of the Melanesian convergent boundary between the Solomon Sea Plate to the south and the Pacific and Bismarck plates to the north. The trench is situated south of New Britain and Buka-Bougainville islands (Figure 3.1) and extends from Huon Gulf on the west to Simbo Ridge (156.5^{o}E) on the southeast. The New Britain Trench strikes N43W near Bougainville, then bends southwards through an angle of 79^{o} south of New Ireland. Figure 3.1 also shows the 2 km contour and the locations (solid circles) of active volcanic centers. Active volcanism is present in central Bougainville to the east and a chain of active volcanoes extends from Rabaul, New Britain, westwards to the Shouten Islands (about 143^{o}E). The geology and structure of New Britain, New Ireland and Bougainville are similar (Brooks, 1970; Finlayson et al., 1972), and these islands are thought to have formed a continuous arc segment prior to the opening of the Manus Basin in the Bismarck Sea (Taylor, 1979). On New Britain, the oldest dated island arc-related volcanics are of Eocene age, overlain by a lesser volume of early Oligocene volcanics (Page and Ryburn, 1977). The oldest dated formations of New Ireland are Oligocene island arc volcanics (Hohnen, 1978). The age of Bougainville's oldest arc-related volcanism is uncertain, but it is

Figure 3.1

Location map for New Britain corner region. Solid circles represent active volcanic centers. 2 and 8 km bathymetric contours are shown.


NEW HANOVER
KAVIENG
0
TABAR IS
LIHIR GROUP
NEW IRELAND
TANGA IS
NUGURIA IS
ONTONG JAVA PLATEAU
BISMARCK SEA
GAZELLE PEN.
RABAUL
FENI IS
GREEN IS
FENI DEEP
KILINAILAU IS
ST GEORGE'S CHANNEL
OPEN BAY
WIDE BAY
WITU IS
WILLAUMEZ PENINSULA
BUKA ISLAND
NEW BRITAIN
TRENCH
NEW BRITAIN
BOUGAINVILLE
6
FINSCH DEEP
HUON GULF
SOLOMON SEA
4
6
150
152
154
156

probably Oligocene (Blake and Miezietis, 1967). All of the early island arc volcanic units are overlain by Miocene carbonates. On New Britain and Bougainville the carbonates are intruded and overlain by Plio-Pleistocene volcanics.

The New Britain Trench marks the northern boundary of the Solomon Sea Plate and the southern boundary of the Bismarck Plate (Denham, 1969; Johnson and Molnar, 1972). An important part of the tectonic framework in this area is the Bismarck Sea seismic lineation, a shear zone defined by a line of shallow earthquakes across the Bismarck Sea (Denham, 1969). It consists of 5 segments of transform and spreading ridge (Taylor, 1979) arranged in a predominantly E-W trend. The Bismarck Sea seismic lineation forms the northern boundary of the Bismarck Plate. The Solomon Sea, Bismarck and Pacific plates meet at a triple junction at or near the New Britain corner.

Seismicity associated with the New Britain Trench is the most intensive in the world. Although the intensity of seismicity associated with the arc-trench system decreases westward, New Britain Trench seismicity extends through the north Coast Ranges of New Guinea (refer to Chapter II). Both the line of active volcanoes and the intermediate seismicity of the western New Britain Arc cease near 143°E. Previous studies of the seismicity and focal mechanisms include those of Denham (1969), Santo (1970), Johnson and Molnar (1972), Curtis (1973a,b), Krause (1973), Ripper (1975, 1980, 1982) and Pascal (1979). The early studies of Denham, Santo and Johnson and Molnar served to establish general trends in the seismicity and, based on these trends, the geometry of the plate boundaries. Analyses of the Solomon Sea-Bismarck Sea-Pacific triple junction by Johnson and Molnar, Curtis and Krause, while largely unsuccessful, highlighted the complex nature of convergent motions in this area. Ripper (1975) and Taylor (1979) drew attention to the segmented nature of the Bismarck Sea seismic lineation and Taylor (1979) presented a much improved triple junction analysis. All of the above mentioned authors interpret their data within the framework of the paradigm of plate tectonics except Pascal (1979). Because of the diffuse nature of several of the proposed plate boundaries, Pascal called upon slip-line field theory as an approach to study of the effects of continent-arc collisions in this region. In addition, Lay and Kanamori (1980) have studied source properties of individual large earthquakes near the New Britain corner.

Beneath the New Britain and Solomon Island arcs there is a Wadati-Benioff zone associated with the descending slab of Solomon Sea lithosphere. Despite the many seismicity studies, the morphology of the W-B zone has not been described in detail. The subducting lithosphere follows the surficial trench configuration around the New Britain corner. Isacks and Molnar (1971) suggested that in such a situation the slab would be either contorted (subjected to observable lateral tension; stretched) or disrupted (subjected to observable wrench-faulting) or both. Both contortion and disruption of the Hokkaido corner - the junction of the Kurile and Hokkaido/Honshu (norther Japan) island arcs -has been observed (Stauder and Mualchin, 1976; Sasatani, 1976). In this corner a zone of east-west vertical hinge faults separates the Hokkaido/Honshu W-B zone (dipping 30 degrees) from the more steeply-dipping (45 degrees) Kurile W-B zone. North-dipping tension axes extending to depths of 450 km imply considerable contortion in the southern part of the Kurile W-B zone. Similarly, there is a sharp bend in the Peru-Chile Trench. Whereas there is general agreement regarding the presence of contortion in the slab (Sacks and Snoke, 1978; Hasegawa and Sacks, 1979), both the disruption or segmentation of the slab near the bend (Stauder, 1973; Barazangi and Isacks, 1978) and the change in dip of the lithosphere to either side of the bend are as yet debated.

It has been suggested (Stauder and Mualchin, 1976) that focal mechanism solutions in the Hokkaido area seem to be related to stresses within one of the slab segments of the Hokkaido corner. Sasatani (1976), however, concluded that the stress distribution as defined by the focal mechanisms is attributable to the presumed contortion or distruption.

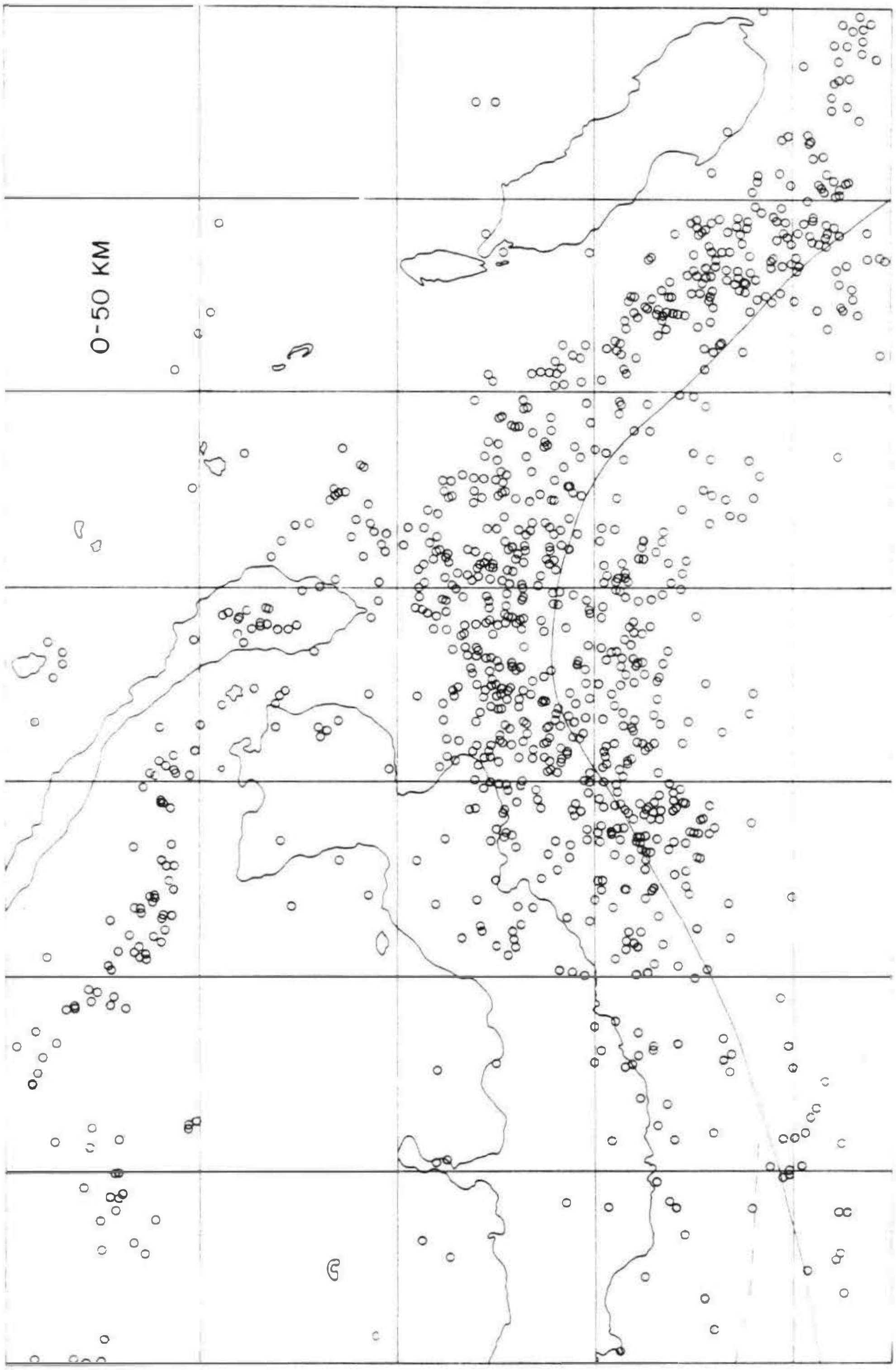
This chapter is mainly concerned with the relationship between slab contortion and earthquake generating stress. The corner seismicity is interpreted in detail and a three-dimensional picture of the morphology of the subducted lithosphere is presented. To further investigate the relationship between slab contortion/segmentation and earthquake slip motions, we present focal mechanism solutions for a large number of earthquakes, 12 of which were prepared for this study. Comparisons are made between the New Britain corner and other similar features such as the Hokkaido and Peru-Chile corners. The possible physical constraints affecting the observed morphology of the slab are discussed and finally, the nature of the triple junction between the New Britain Trench and the Bismarck Sea seismic lineation is considered.

Seismicity

Regional seismicity within sequential depth intervals is presented in Figures 3.2-3.10. Data are taken from compilations of the International Seismological Centre (ISC) for the magnitude range $M_b > 4.7$ over the time period 01/01/64 -06/30/84. Only earthquakes recorded by 15 or more stations are used. Both land outlines and the topographic axis of the New Britain Trench are shown for the purpose of orientation. Intense shallow seismicity (Fig. 3.2) is evenly distributed over the corner area from south of Bougainville to central New Britain. A large number of events occur seaward of the trench, probably because of the severe flexure of the lithosphere.The majority of the large, shallow events (Figures 3.2, 3.3) occur in the main thrust zone at depths of 40-70 km. Seismicity is sparse at depths over 125 km (Figures 3.5-3.7). There is a seismic gap over the depth range 250-380 km beneath Bougainville and over the range 250-440 km between the Willaumez and Gazelle peninsulas of New Britain (Figures 3.8, 3.9). Deep earthquakes occur on both the Bougainville and New Britain sides of the bend, but their distribution is not what would be expected for a simple up-bowing of the lithosphere in response to

Figure 3.2

Regional seismicity for the New Britain corner region in the depth interval 0-50 km. The following information pertains to Figures 3.3-3.10 as well: Seismicity includes all hypocenters with body wave magnitudes greater than 4.7 and recorded by more than 15 stations for the period from 01/01/64 to 06/30/84. Land areas are outlined and the topographic axis of the New Britain Trench is shown.


0-50 KM

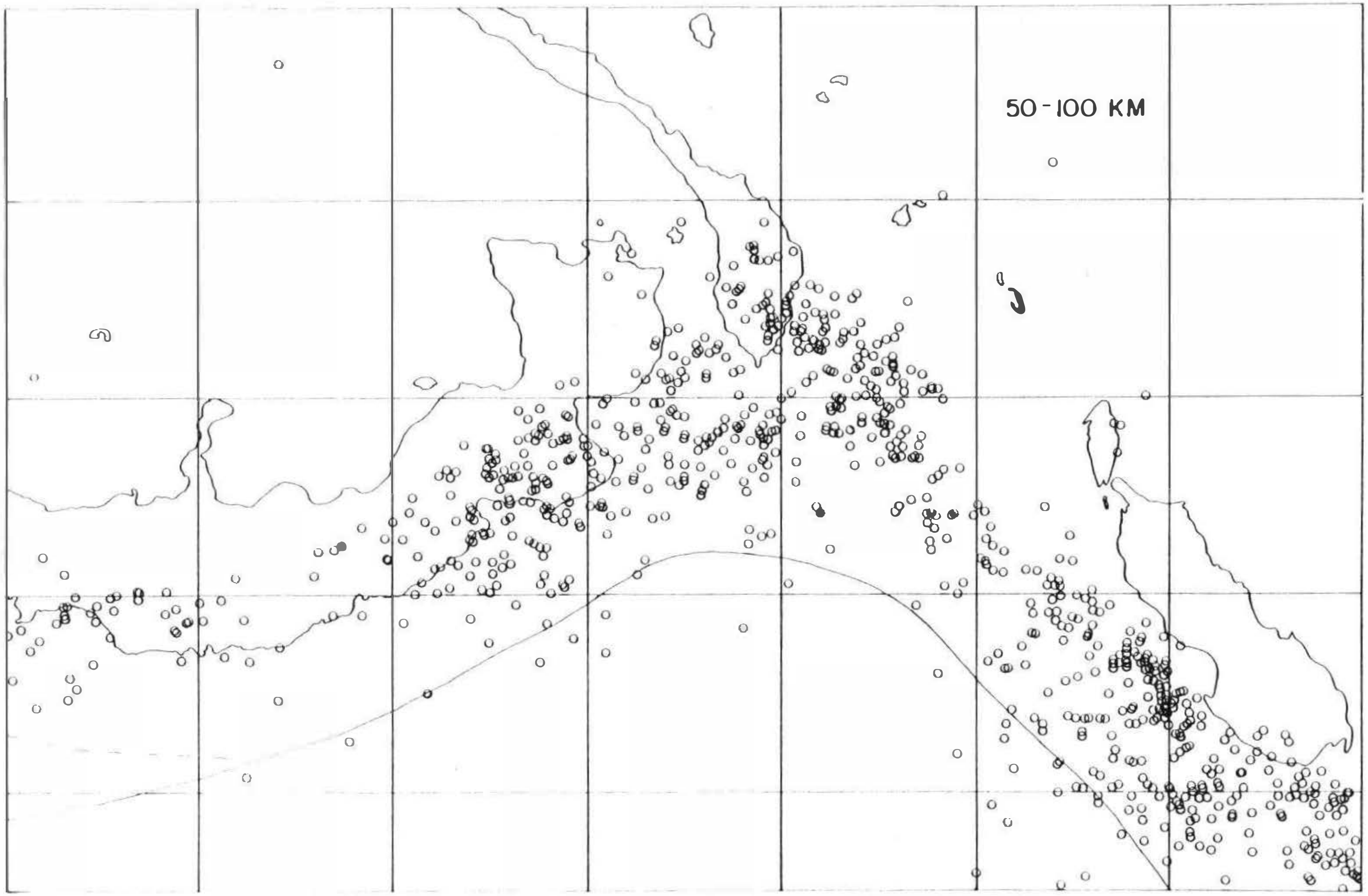


Figure 3.3 New Britain Regional Seismicity, 50-100 km.

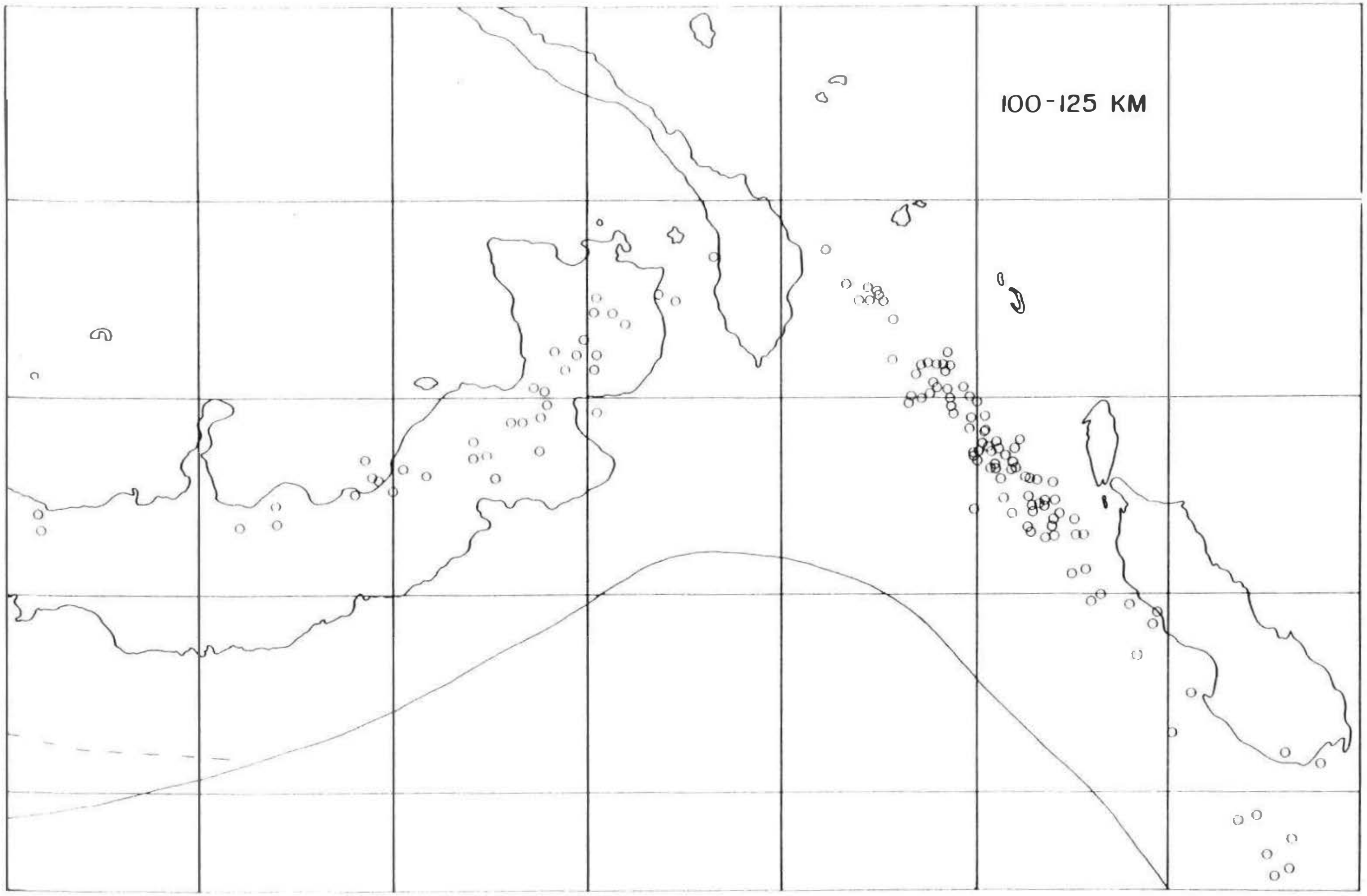


Figure 3.4 New Britain Regional Seismicity, 100-125 km.

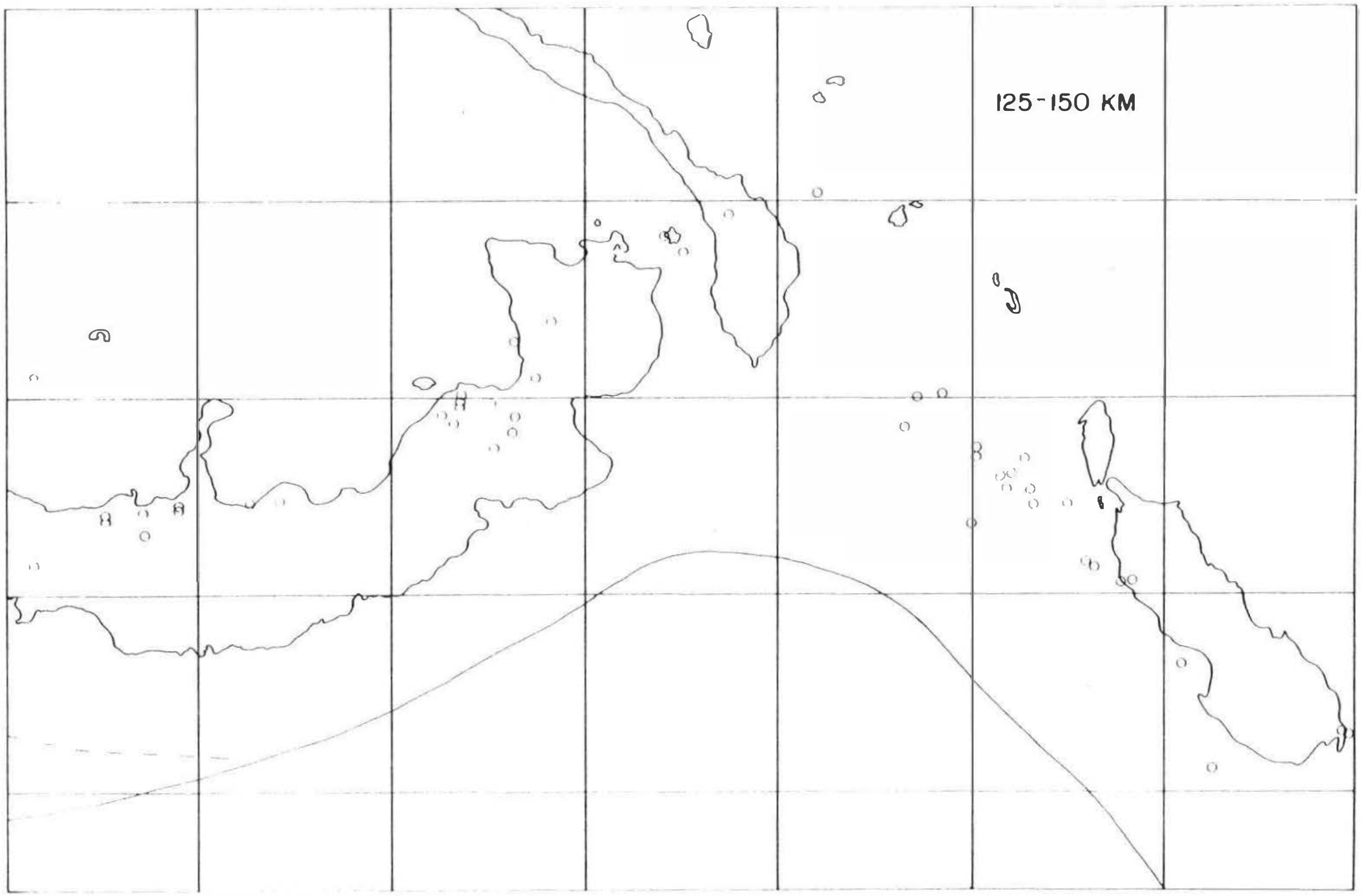


Figure 3.5 New Britain Regional Seismicity, 125-150 km.

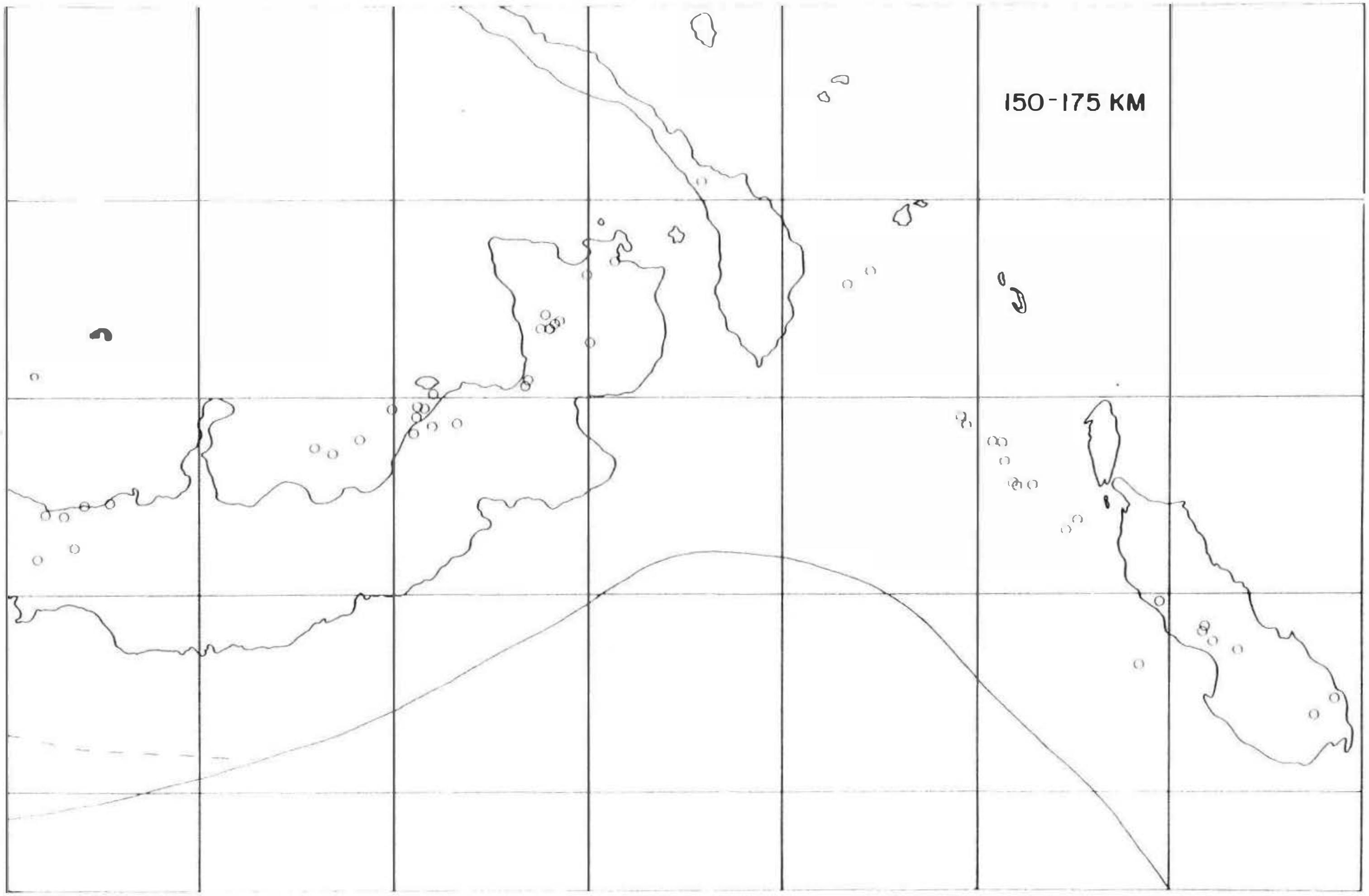


Figure 3.6 New Britain Regional Seismicity, 150-175 km.

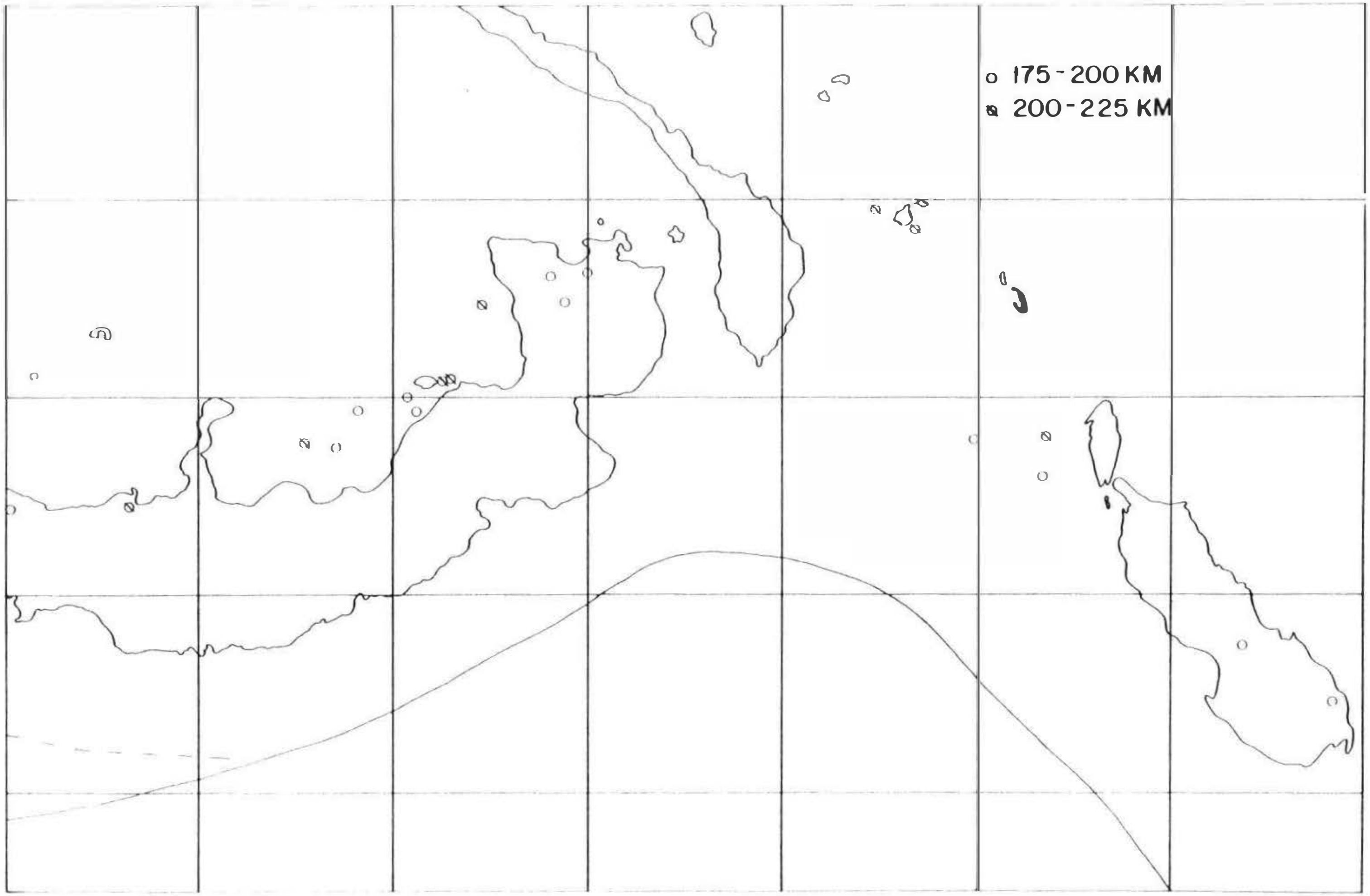


Figure 3.7 New Britain Regional Seismicity, 175-225 km.

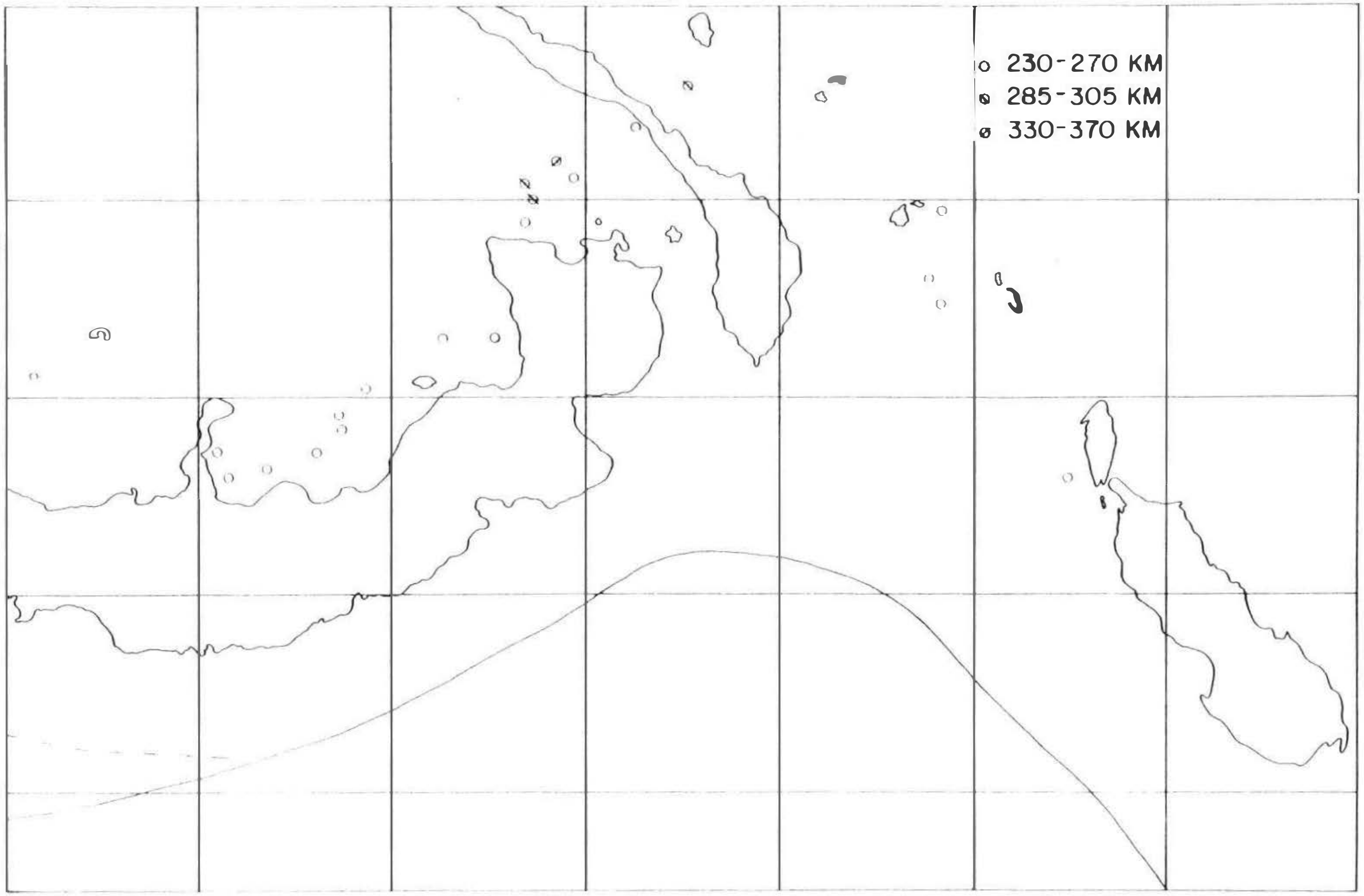


Figure 3.8 New Britain Regional Seismicity, 230-270, 285-305, 330-370 km.

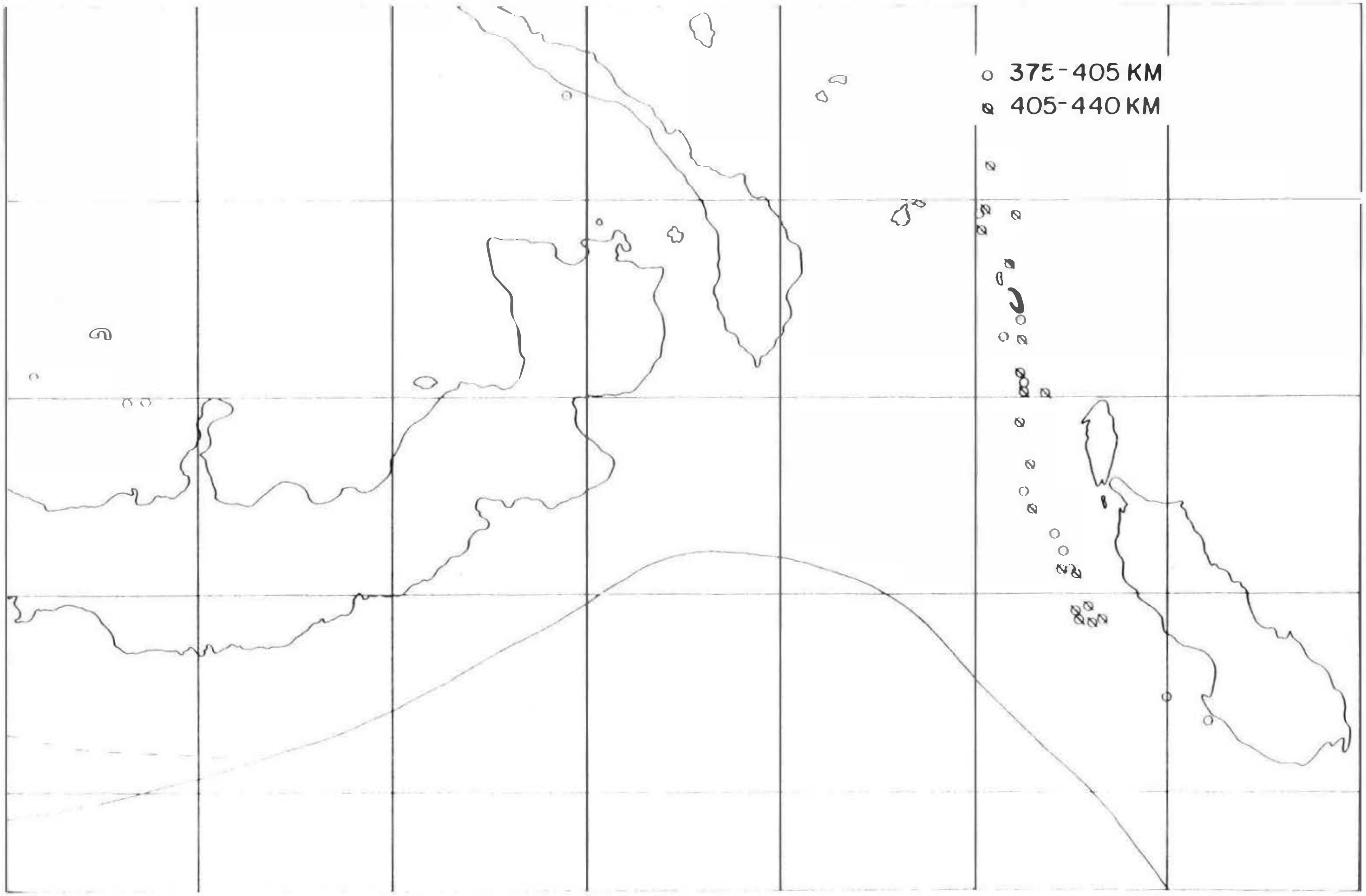


Figure 3.9 New Britain Regional Seismicity, 375-440 km.

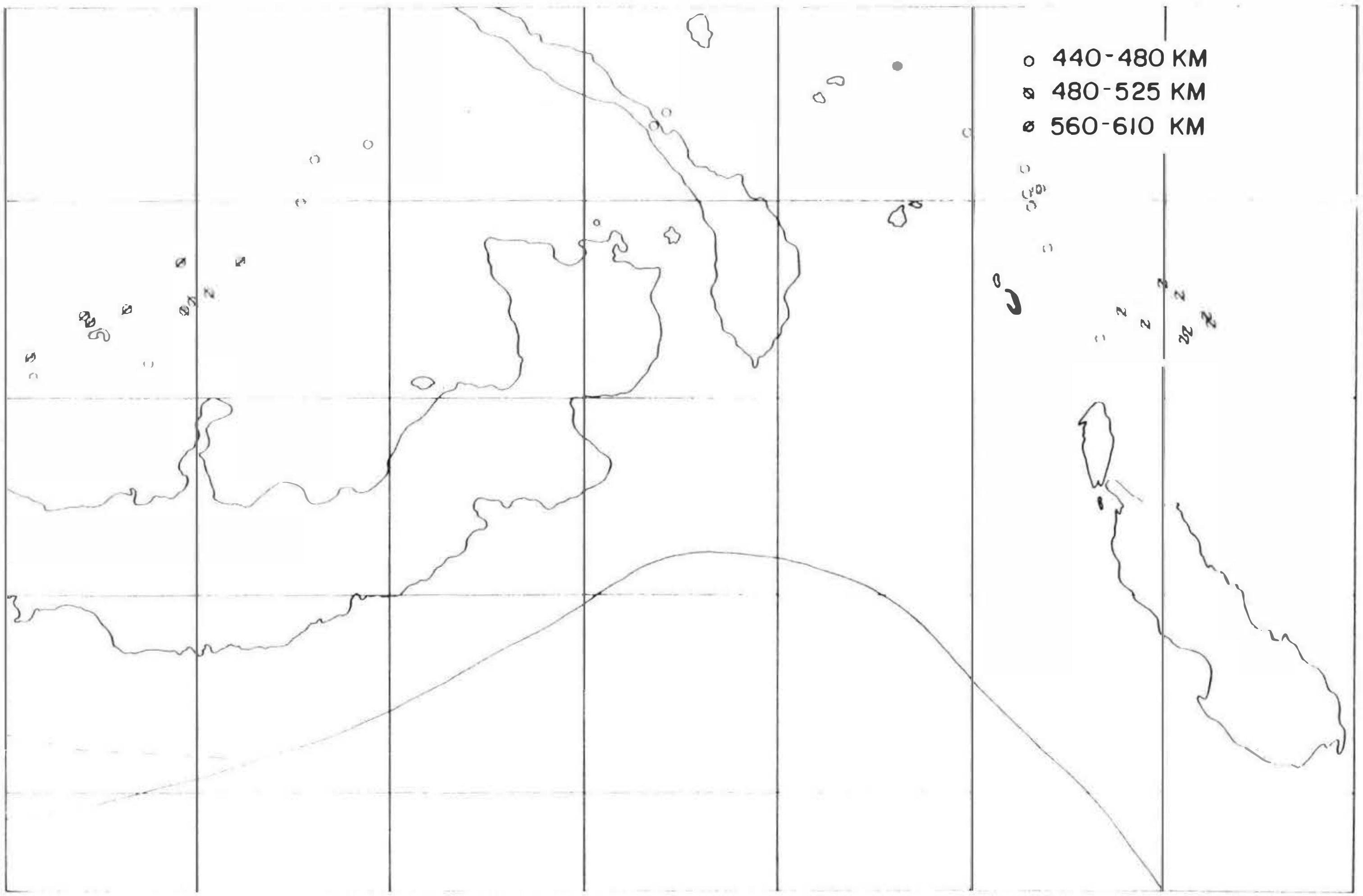


Figure 3.10 New Britain Regional Seismicity, 440-525, 560-610 km.

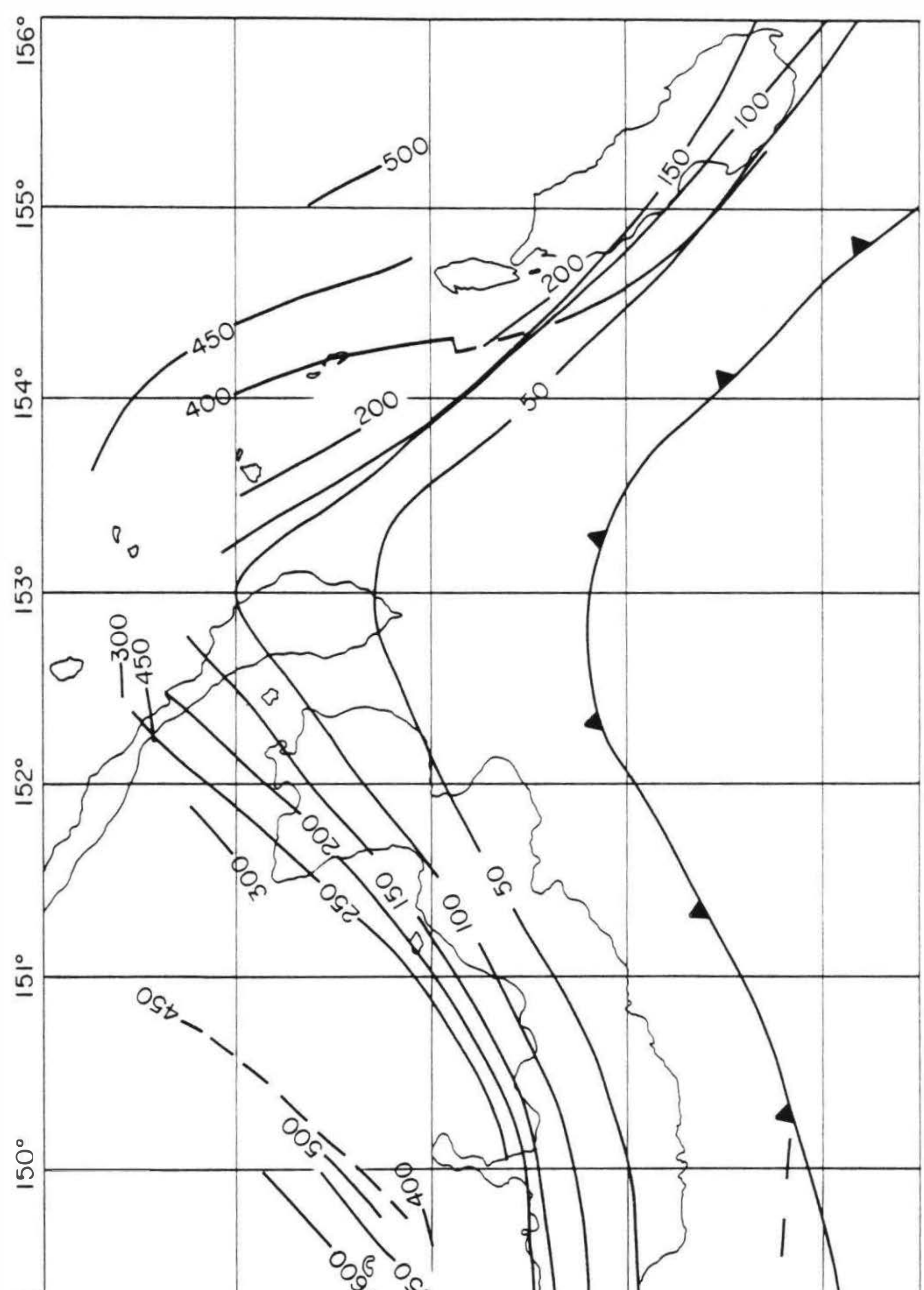
the curvature of the trench.

The 50 and 100 km isodepth contours (Figure 3.11) are roughly parallel to the New Britain Trench; this parallelism is disrupted at the corner. On the Bougainville side, the W-B zone flattens somewhat at 100 km for a considerable distance. The 150 km contour reflects the almost vertical aspect of the seismic zone near Buka; nearer the crest of the bend there are only 5 (>200 km) events determining the position of the 200 km contour; the 150 km contour is inferred. The 400 km contour is well-determined, substantiated by many events (see Figure 3.9); the 450 and 500 km contours are less well-determined. With only 5 events in the depth interval 175-370 km, no attempt was made to include W-B zone contours for 250-350 km. On the New Britain side, the W-B zone contours are continuous to 250 km. Deeper contours can be drawn only near the corner and north of Willaumez Peninsula. The 450 km contour near the corner is based on only two events (see Figure 3.10), however, those two events indicate the presence of some subducted lithosphere and cannot be ignored. The deep seismic zone north of Willaumez Peninsula dips very steeply to 550 km and then flattens, extending deeper into the mantle and having a very different shape compared to the seismic zone north of Bougainville. The deep (350-450 km) seismicity curves under the near-vertical 0-350 km seismicity on the Bougainville side, perhaps in response to collisional contact with the Ontong Java Plateau.

For a simple up-bowing of the lithosphere, comparable to bending a piece of paper over the corner of a desk, the shallow and intermediate contours should extend much farther to the north;

Figure 3.11

Wadati-Benioff zone contours in 50 km intervals for the New Britain corner based on observed seismicity (Figures 3.2-3.10). Land areas are outlined; the topographic axis of the New Britain Trench is indicated by a heavy hatchured line. The 450 km contour near New Britain is dashed because there is some uncertainty in its location. The 400 km contour near Bougainville curves under the shallow and intermediate seismicity.

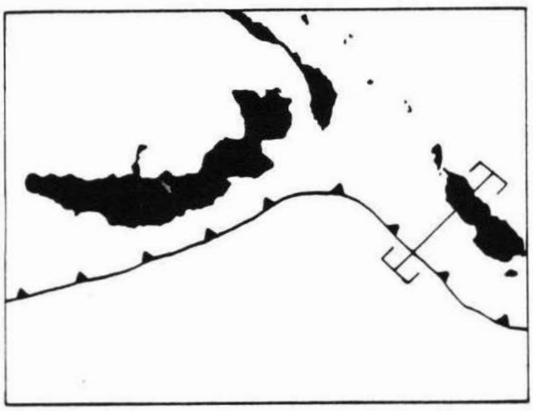

156°
155°
154°
153°
152°
151°
150°
149°E
3°S
4°
5°
6°
7°
500
450
400
200
200
150
100
50
300
450
300
250
200
150
100
50
450
500
400
600
550

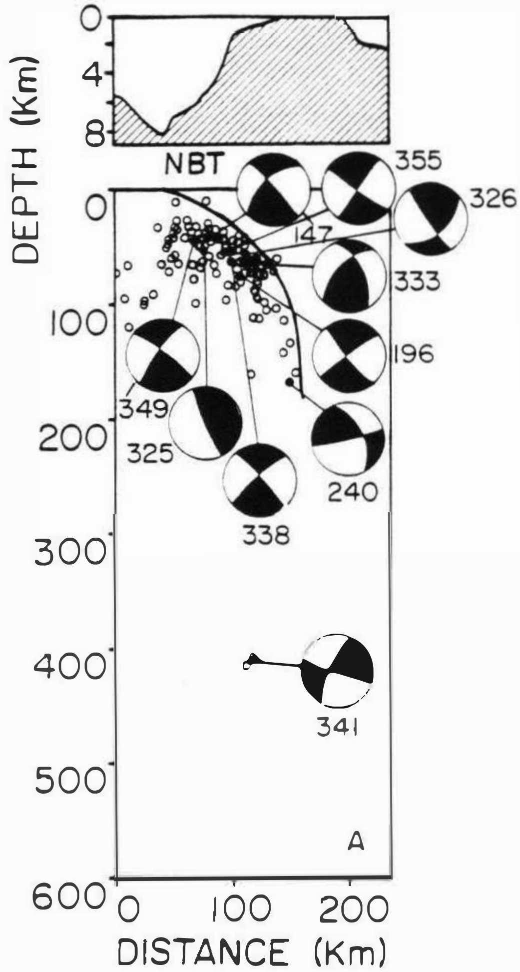
obviously this is not the situation observed. There appears to be too little subducted slab for the known duration of subduction (at least 5 my) and a conservative estimate of the rate of subduction (12 cm/yr). The contours reveal that the shallow and intermediate seismic zone of the New Britain corner is contorted (bowed) upwards at the corner, and that normal dip is restored on both sides of the bend in the trench. If the seismic gap between 250-380 km is interpreted as a gap in the lithosphere, then the contours may be interpreted as showing a broad, north-plunging, flexural fold over the depth range 0-250 km, with large sections of lithosphere detached from the flanks of the fold.

A set of vertical cross-sections (Figures 3.12-3.17) orthogonal to the local strike of the New Britain Trench shows considerable contortion both at the corner and along adjacent sections of the trench. The locations and widths of these profiles are shown with the individual profiles. Focal mechanism solutions shown on the vertical profiles are back hemispheres of a view of the focal sphere perpendicular to the cross-section. Near Bougainville (Figure 3.12) the W-B zone dips northeast at an initially shallow angle, then steepens rapidly until it is almost vertical below 100 km. There is very little teleseismic activity in the overriding plate. Deep events are displaced to the southwest, under the intermediate seismicity. Focal mechanisms indicate underthrusting of the Pacific Plate by the Solomon Sea Plate. The deep event (341) shows downdip compression. In Figure 3.13 the depth extent of the W-B zone is slightly greater than that of Figure 3.12, however, the dip is less steep at shallow levels and the deep seismicity is not displaced under the shallow and

Figure 3.12

Seismic section A. The following information is true for Figures 3.12 and 3.13. Projection onto vertical plane of ISC seismicity. Locations and widths of profiles are indicated to the left of the projection. Major bathymetric features are identified with a letter code: NBT=New Britain Trench. A solid line outlines the inferred position of the top of the Wadati-Benioff zone. Focal mechanisms are shown as back hemispheres; numbering corresponds to the numbering system of Appendix I.




DEPTH (Km)
0
4
8
NBT
0
100
200
300
400
500
600
355
326
147
333
196
349
325
240
338
341
A
0
100
200
DISTANCE (Km)

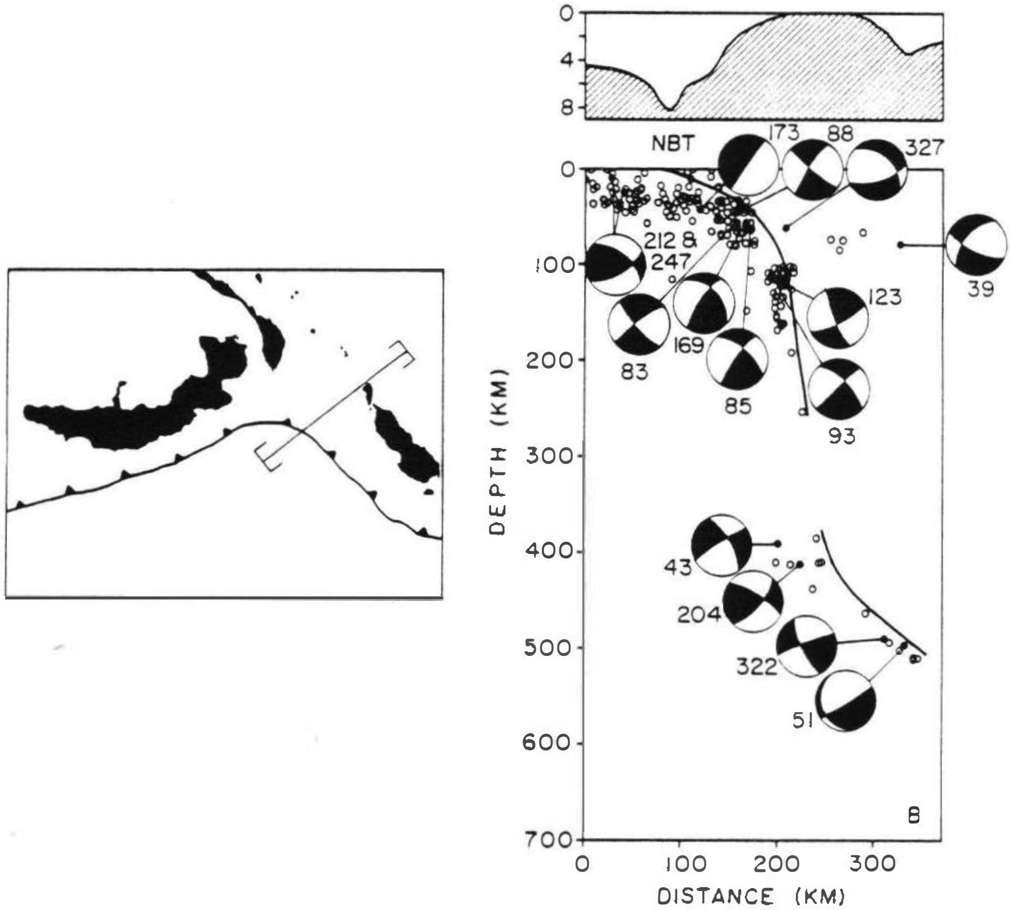


Figure 3.13 Seismic Section B, New Britain.

intermediate seismicity. Focal mechanisms reveal active thrusting at shallow levels, downdip extension in the 100-200 km range and near-vertical compression at great depth. Viewed in sections orthogonal to the trend of the deep seismicity (Fig. 3.14), the relationship between the intermediate and deep seismicity is obvious. These profiles show a deep seismic zone (380-530 km) clearly separated by a gap (250-380 km) from the seismic zone shallower than 250 km. The lower part of the deep seismic zone dips in the same direction as the upper 250 km. Judging from the curve of the 400 and 450 km contours in Fig. 3.12, the deeper lithosphere appears to have broken from the flank of the folded Solomon Sea slab some time after the formation of the bend in the New Britain Trench . The deep lithosphere on the New Britain side is similarly situated. A speculative scenario for the distortion of the W-B zone includes the following: In response to the southward migration of the western New Britain Trench, the lithosphere at the pivot point (south of New Ireland) bulged upwards, conserving surface area. The intermediate and deep lithosphere of the trench was pushed into a vertical dip or slightly under the top part. Instead of hinge-faulting along the axis of the fold, excess lithosphere was sheared from the flanks of the arch.

Figure 3.15, at the corner, shows the very gentle plunge of the lithosphere; this is the area of shallowest dip - the dip increases on either side of this section. Figures 3.16, 3.17 and 3.18 are vertical sections through New Britain showing a W-B zone which is not as steep at shallow levels, but of similar dip at intermediate levels to the Bougainville section. The location of the gap in seismicity

Figure 3.14

Two seismicity profiles orthogonal to the trend of the deep seismicity near and north of Bougainville. Profile G is from 4.7°S, 153.0°E to 3.9°S, 154.6°E and Profile H is from 5.5°S, 153°E to 4.4°S, 155.4°E. Both are 75 km wide.

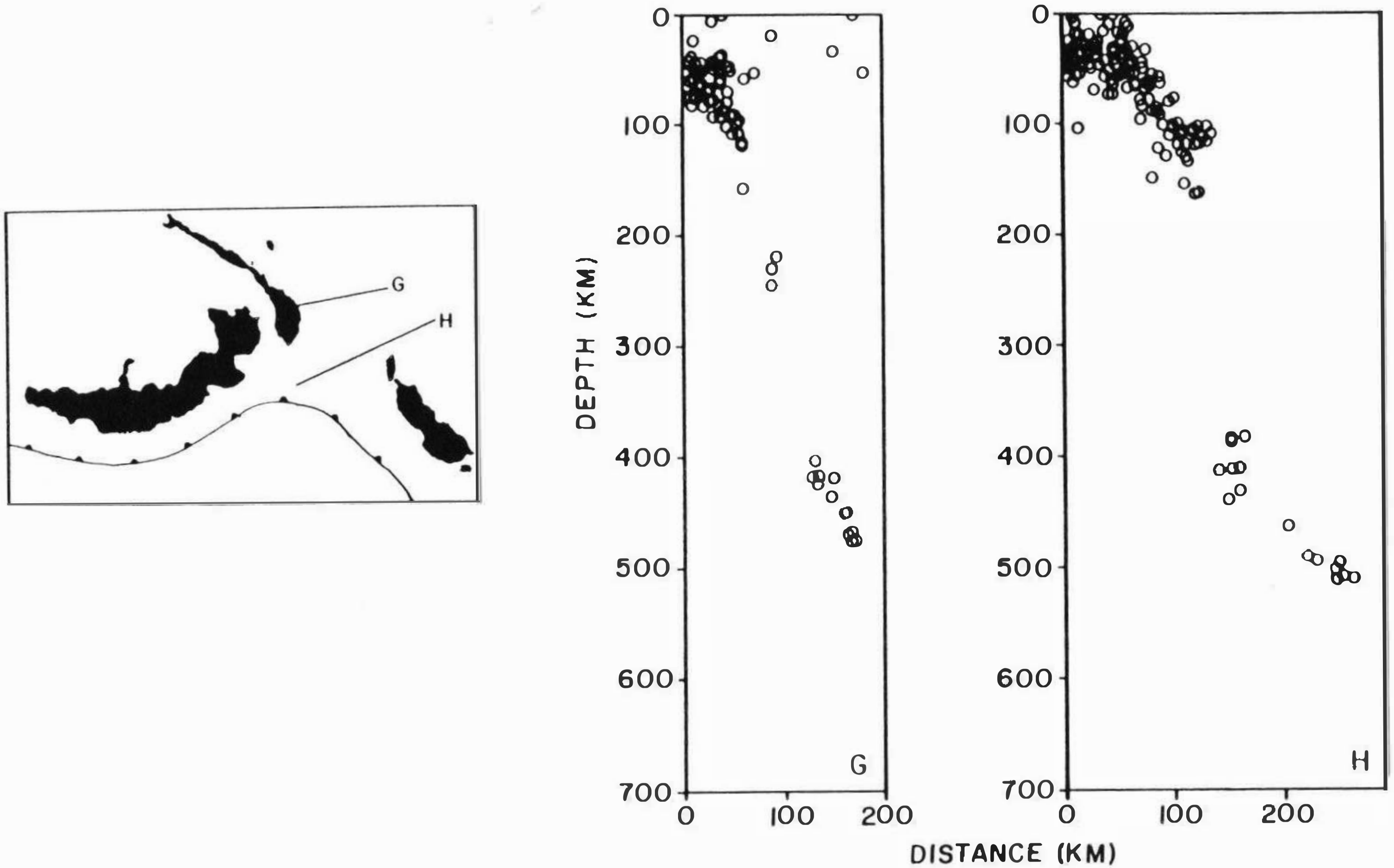
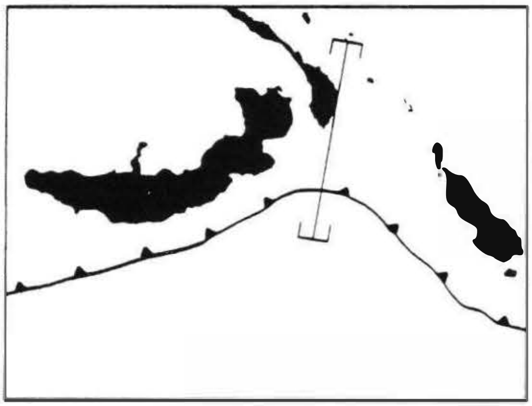
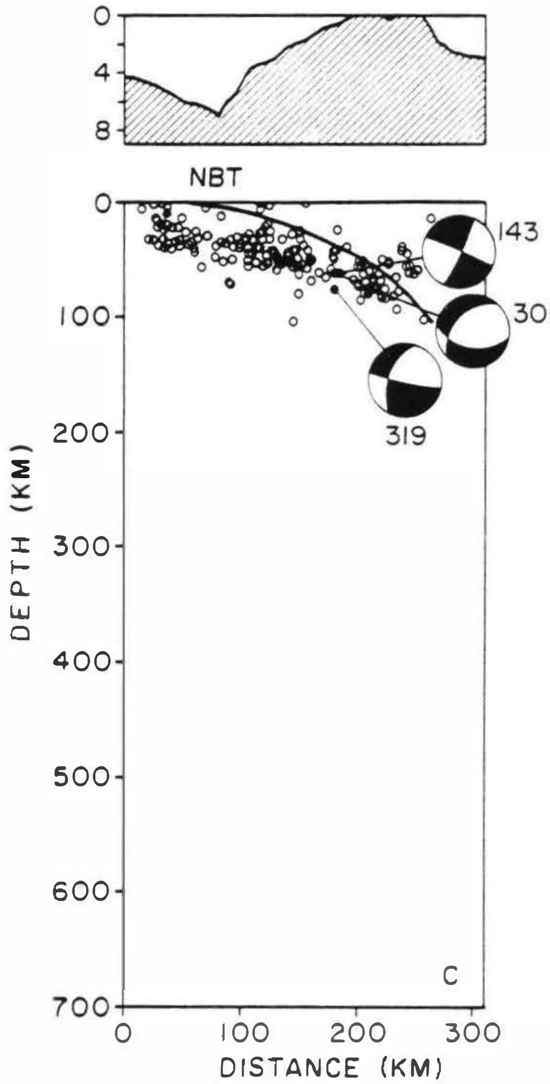

G
H
DEPTH (KM)
0
100
200
300
400
500
600
700
DISTANCE (KM)
0
100
200

Figure 3.15

Seismic section C. The following information also pertains to Figure 3.16-3.18. Projection onto vertical planes of ISC seismicity. Locations and widths of profiles are indicate to the left of the projection. The major bathymetric feature is identified by a letter code: NBT=New Britain Trench. A solid line outlines the inferred location of the top of the Wadati-Benioff zone. Focal mechanisms shown are back-hemispheres; numbering corresponds to the numbering system of Appendix I.

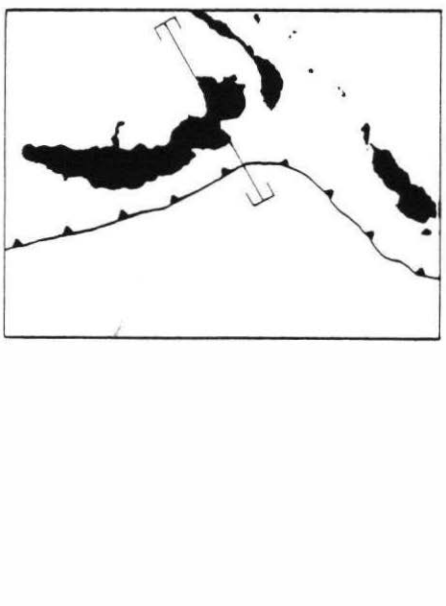




0
4
8
NBT
0
100
200
300
400
500
600
700
DEPTH (KM)
143
301
319
C
0
100
200
300
DISTANCE (KM)

Figure 3.16

Seismic section D.



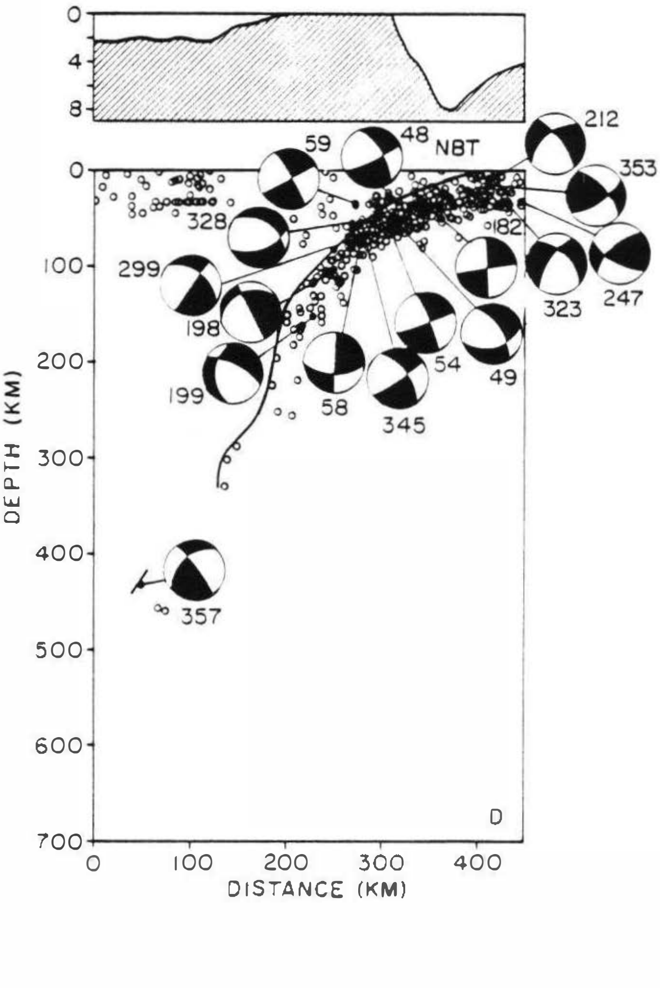
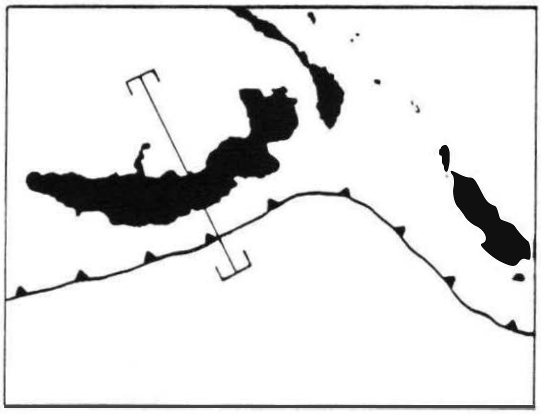

NBT
DEPTH (KM)
DISTANCE (KM)
D

Figure 3.17

Seismic Section E.



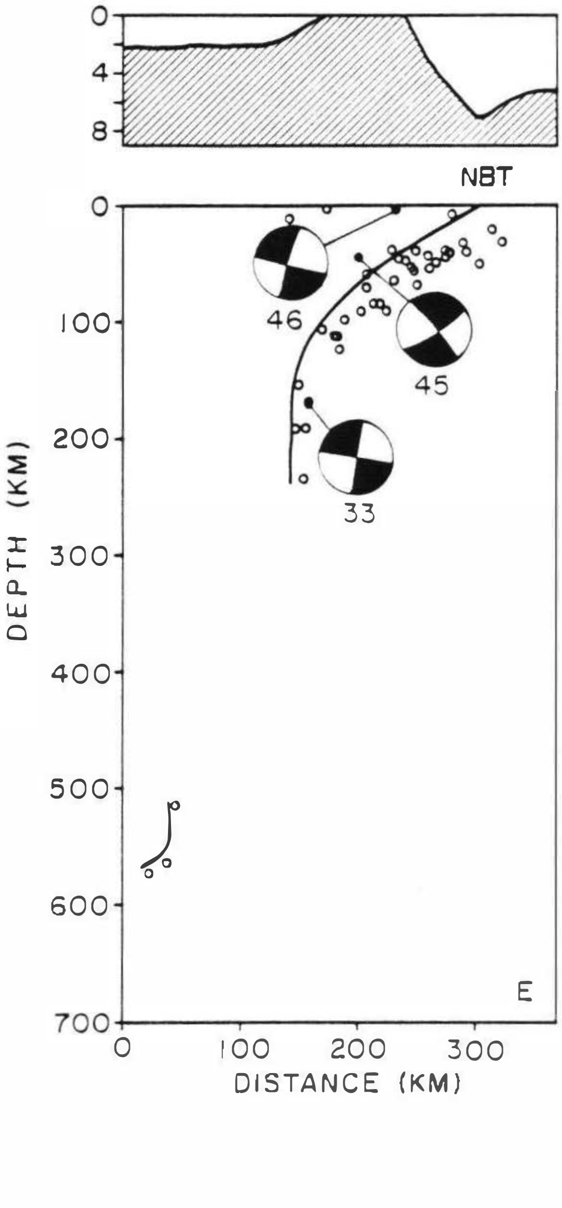
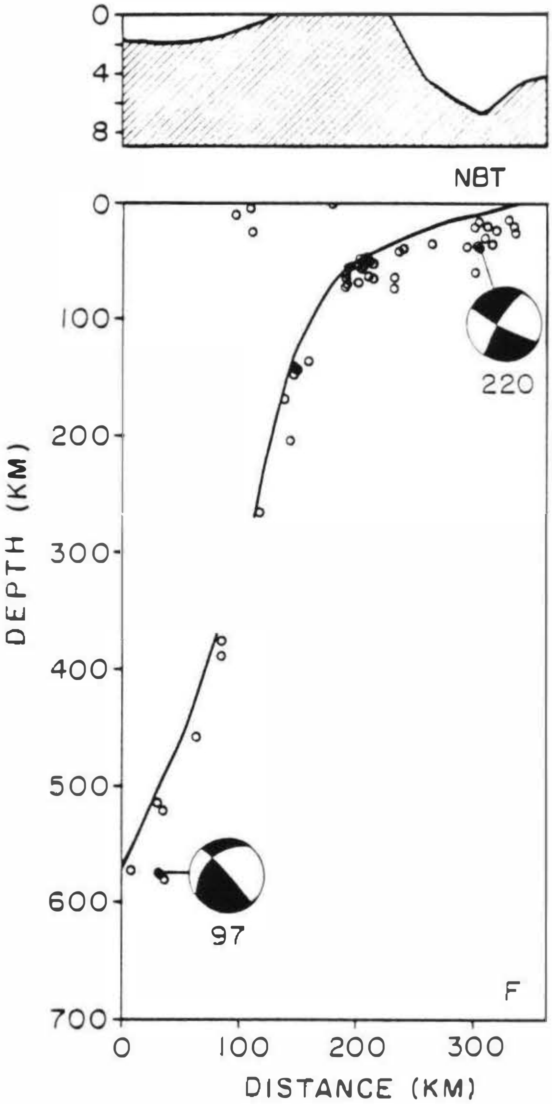

NBT
46
45
33
DEPTH (KM)
DISTANCE (KM)
E
0
4
8
0
100
200
300
400
500
600
700
0
100
200
300

Figure 3.18

Seismic Section F.


NBT
DEPTH (KM)
DISTANCE (KM)
220
97
F

(250-400 km) and the total depth extent are also similar. In all three profiles focal mechanism solutions show underthrusting of the Bismarck Sea Plate by the Solomon Sea Plate in a northwest direction. The depth range 100-250 km is a mixed stress regime (which may be indicative of the fractured nature of the subducted lithosphere) with mechanisms indicating both downdip extension and compression in close proximity. Deep (>400 km) events consistently show downdip extension.

The folding of the slab can best be seen in the set of vertical sections (Figure 3.19) cross-cutting the folded lithosphere. The fold begins as a broad, shallow arch (Profile I), steeper on the Bougainville side, then tightens somewhat (Profile J) and plunges to about 100 km in depth before it finally pinches out (Profile K). There is evidence in the seismicity for both large-scale contortion and segmentation of the slab. A series of three-dimesional cartoons of the apparent morphology of the slab based on observed seismicity are shown in Figures 3.20-3.22. Figure 3.20 is a due-west view of the eastern (Bougainville) side of the fold; Figure 3.21 is a due-east view of the western (New Britain) side of the fold. Figure 3.22 is an end-on view, looking due-south at the fold; the seismicity is also plotted for comparative purposes (shallow seismicity from the Bismarck Sea seimic lineation is not shown on the cartoon). The gap in seismicity is shown as a gap in the lithosphere, although this is not necessarily the case - hence the question marks.

Figure 3.19

Projection of ISC seismicity onto planes orthogonal to the direction of plunge of the folded Solomon Sea lithosphere at the New Britain corner. The sequence of the profiles is from south (I) to north (K). 3.19I extends from 5.22°S, 150.3°E to 6.0°S, 155.3°E; 3.19J extends from 4.4°S, 149.5°E to 5.3°S, 154.9°E; and 3.19K extends from 3.8°S, 150.0°E to 4.7°S, 155.4°E. 3.19I, J are 50 km wide; 3.19K is 75 km wide.

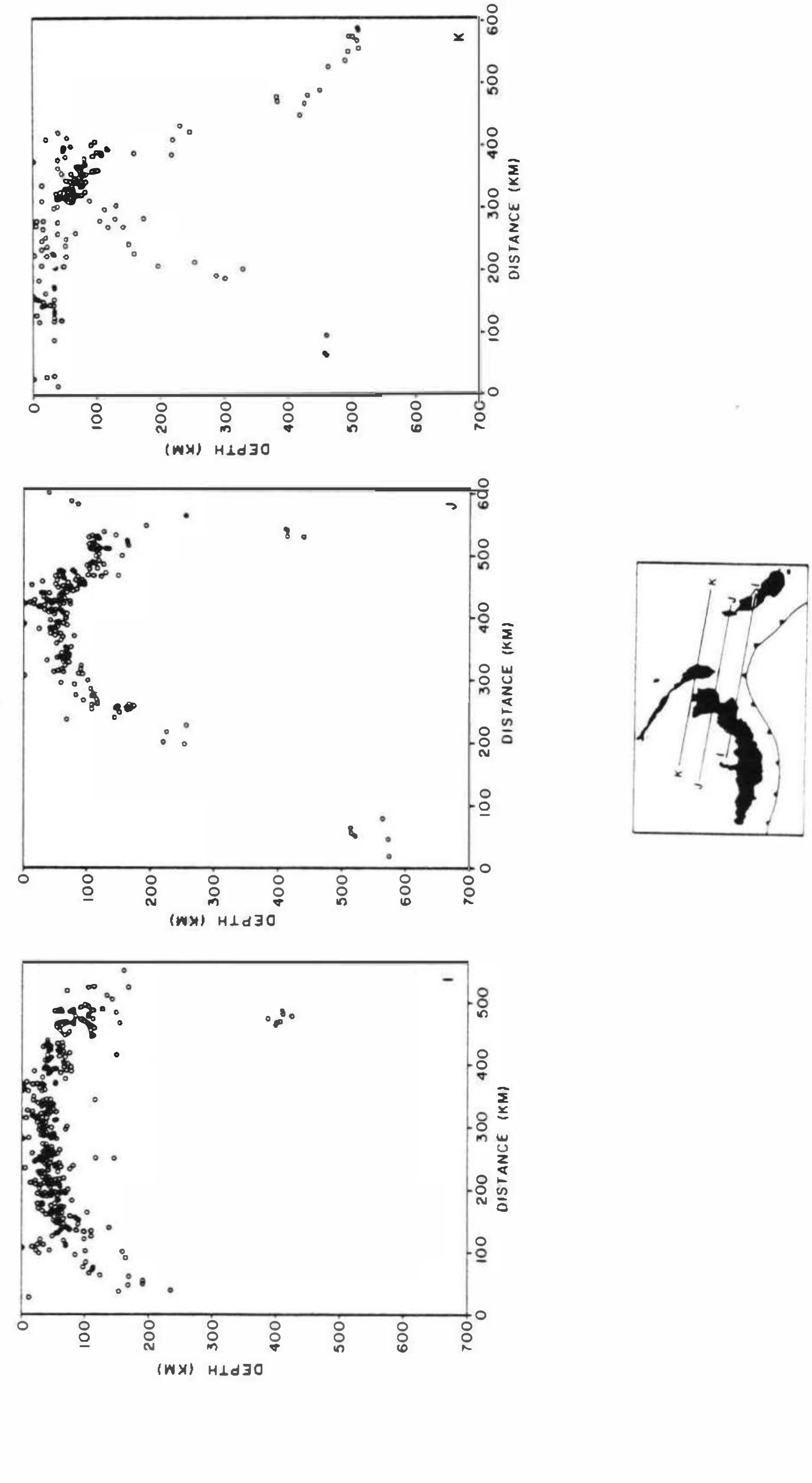
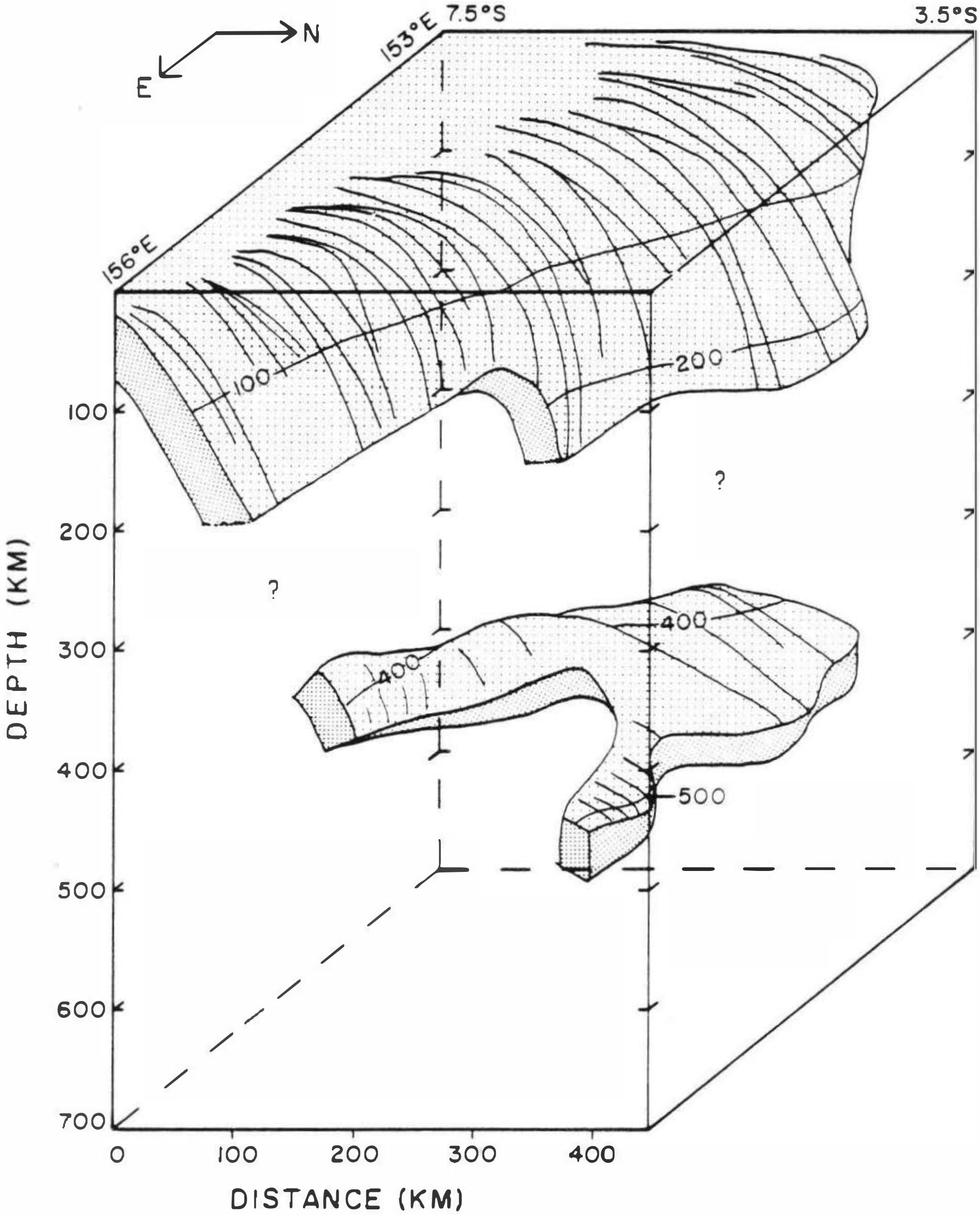

DEPTH (KM)
DISTANCE (KM)
K
J
I

Figure 3.20

Cartoon based on observed seismicity depicting the morphology of subducted lithosphere at the New Britain corner. This is a view from the Bougainville side, looking due West.



N
E
153°E
7.5°S
3.5°S
156°E
100
200
?
?
400
400
500
DEPTH (KM)
100
200
300
400
500
600
700
0
100
200
300
400
DISTANCE (KM)

Figure 3.21

Cartoon based on observed seismicity depicting the morphology of subducted lithosphere at the New Britain corner. This is a view from the New Britain side, looking due East.

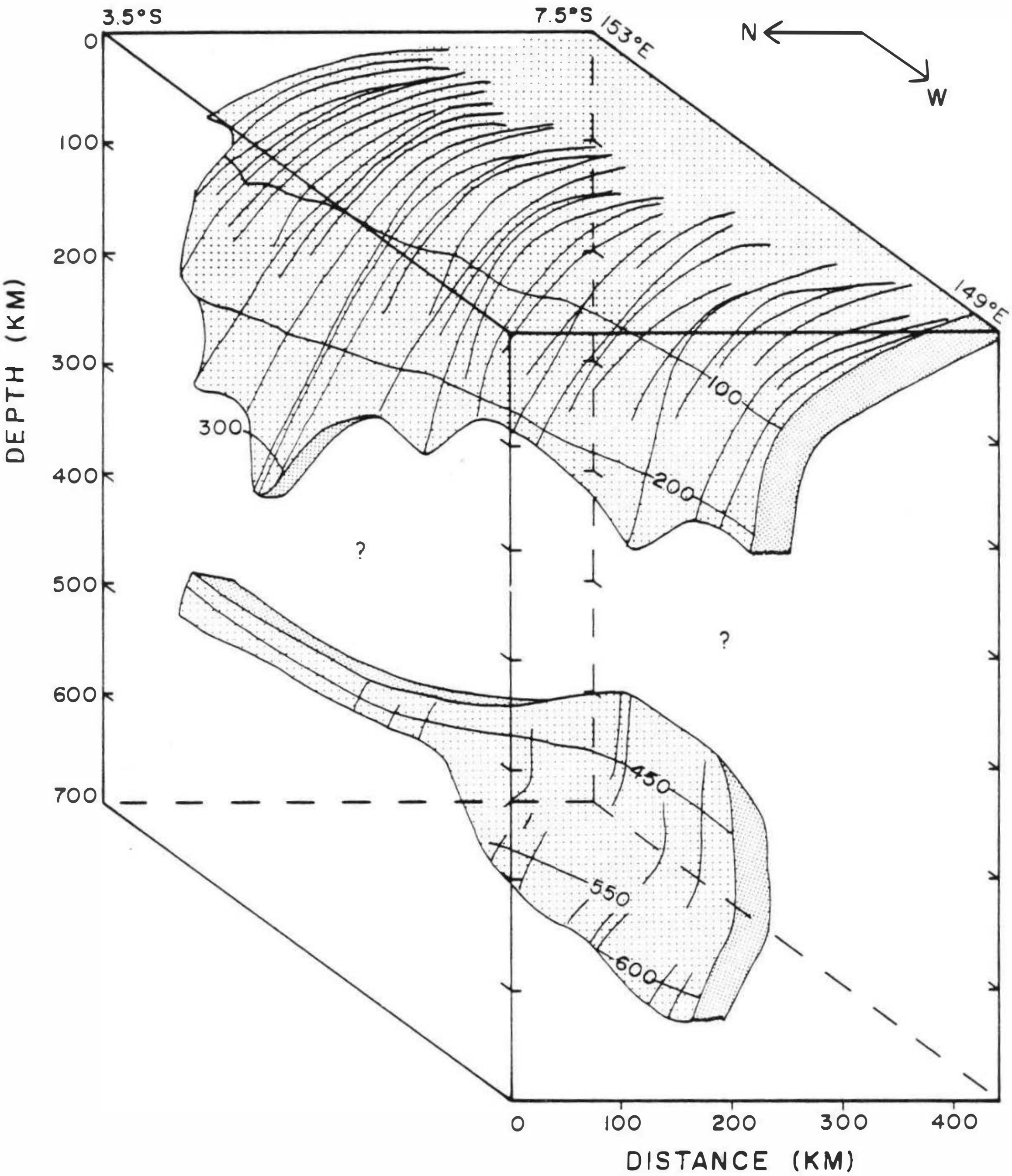
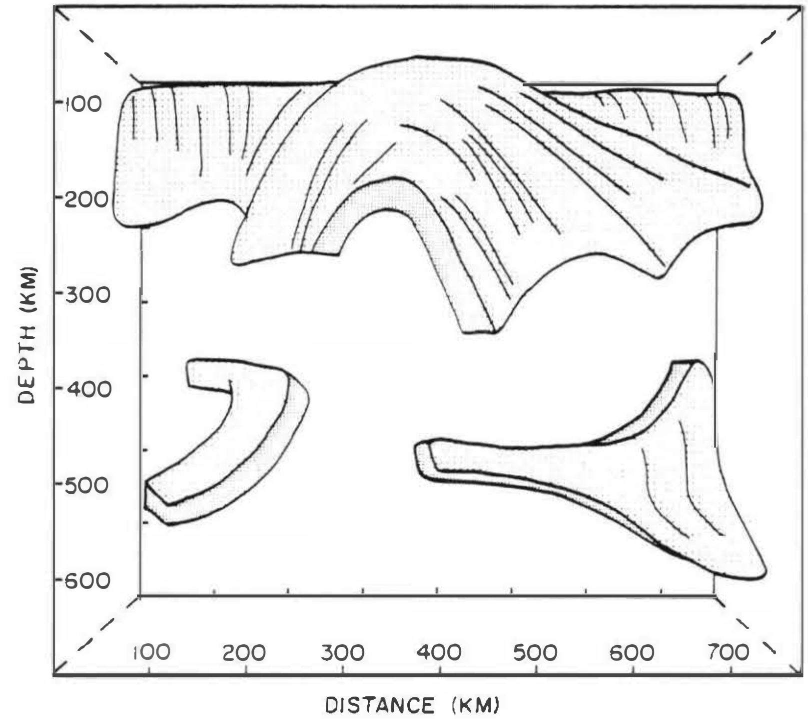
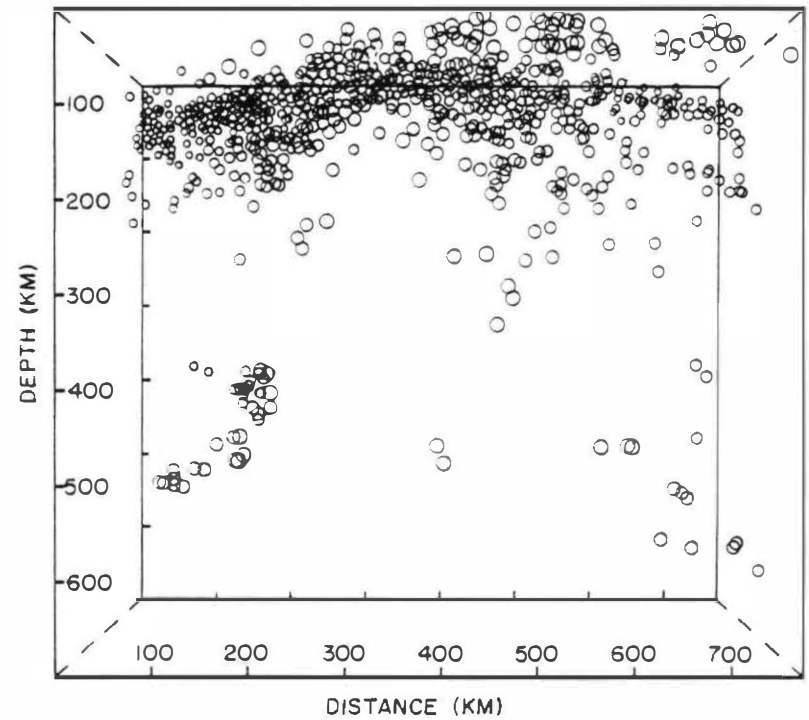

3.5°S
7.5°S
153°E
149°E
N
W
DEPTH (KM)
0
100
200
300
400
500
600
700
300
100
200
450
550
600
?
?
DISTANCE (KM)
0
100
200
300
400

Figure 3.22

Cartoon (above) based on observed seismicity (below) depicting the morphology of subducted lithosphere at the New Britain corner. This is a view from New Ireland, looking due South. Shallow seismicity from the Bismarck Sea seismic lineation, which is obvious in the seismicity diagram, is not shown in the cartoon.


DEPTH (KM)
100
200
300
400
500
600
100
200
300
400
500
600
700
DISTANCE (KM)


DEPTH (KM)
100
200
300
400
500
600
100
200
300
400
500
600
700
DISTANCE (KM)

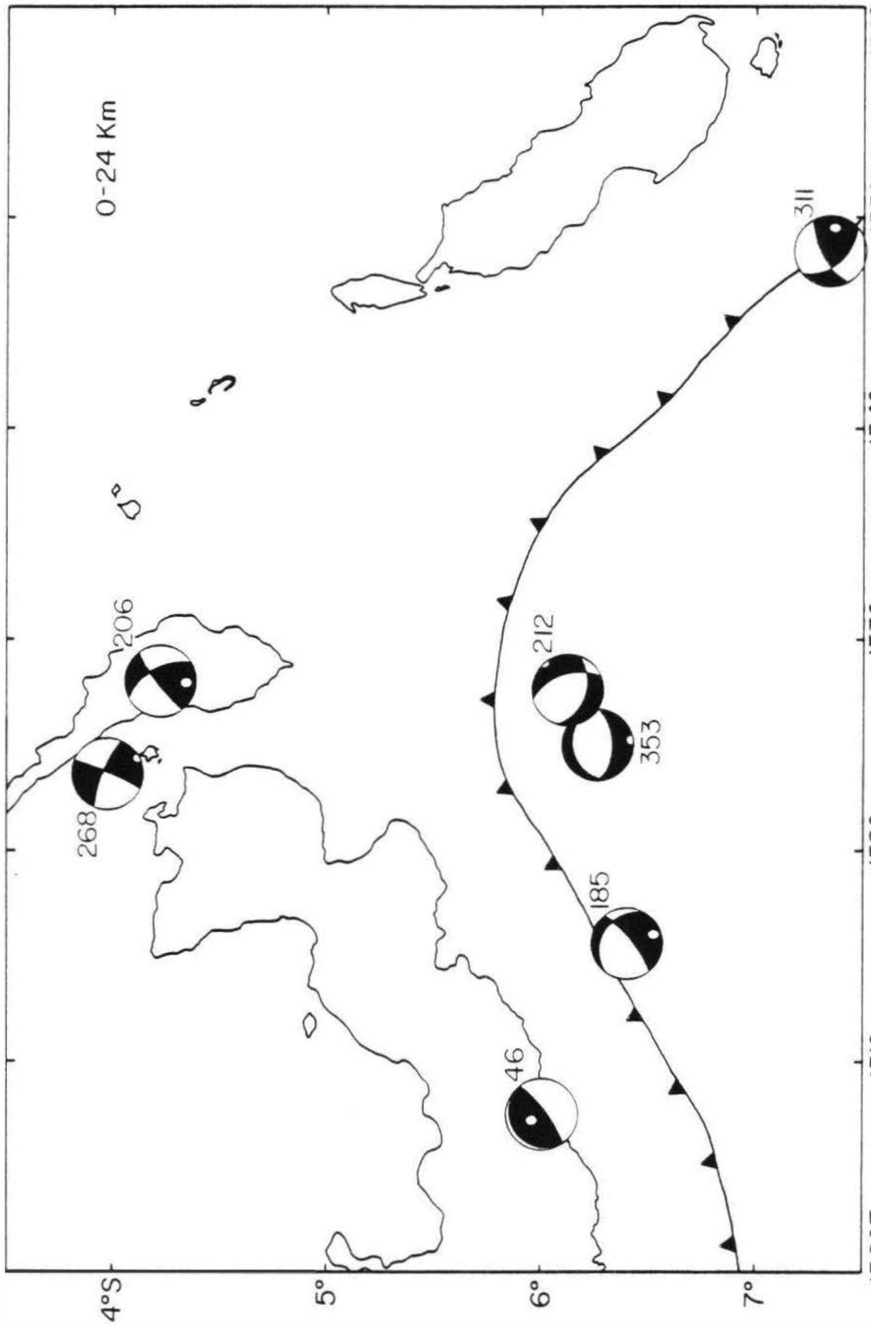
Focal Mechanisms

The focal mechanism solutions of shallow, intermediate and deep earthquakes in the New Britain corner region are included in Appendix I. Twelve additional focal mechanism solutions have been obtained for moderate to large earthquakes covering the period 1970-1981. The positions of the new focal mechanisms were relocated as descibed in Chapter II (SEISMICITY); the original ISC depth is listed for events with fewer than 3 reliable pP readings. In all cases P-wave polarities were read directly from long-period recordings of the WWSSN stations. Equal-area projections of the data for these new solutions are given in Appendix II. Both new and previously published solutions are shown in Figures 3.23-3.26 for the depth ranges specified. The quadrants defined by the nodal planes are black for compressional and white for dilatational first motions. The numbers correspond to the event numbering scheme in Appendix I.

Normal faulting occurs at shallow depths, however, most of these events are located beneath or seaward of the New Britain Trench (numbers 81, 185, 212, 247, 282, 323 and 353). These events show horizontal extension orthogonal to the trench and may therefore be associated with the tensional regime generated by bending of the lithosphere prior to subduction. One other shallow normal event with a large component of strike-slip (262) is located within the Feni Deep, a large basin to the east of New Ireland. The normal event east of Willaumez Peninsula (172) may be associated with active volcanism

Figure 3.23

Focal mechanisms for earthquakes located in the New Britain corner region for the depth range 0-24 km. The following information pertains to Figure 3.23-3.27. Where possible, the focal mechanism is centered over the epicenter; in some cases the epicenter is indicated by a triangle and a line is drawn to the corresponding solution. In areas where crowding of the solutions became a problem, a few solutions were omitted. Compressional quadrants are shaded and dilatational quadrants are unshaded. Tension axes are shown as white circles against the shaded compressional quadrant. Numbers correspond to the numbering system of Appendix I.



0-24 Km
4°S
5°
6°
7°
150°E
151°
152°
153°
154°
155°
156°
46
185
212
353
268
206
311

Figure 3.24

Focal mechanisms for earthquakes located in the New Britain corner region for the depth range 25-49 km.

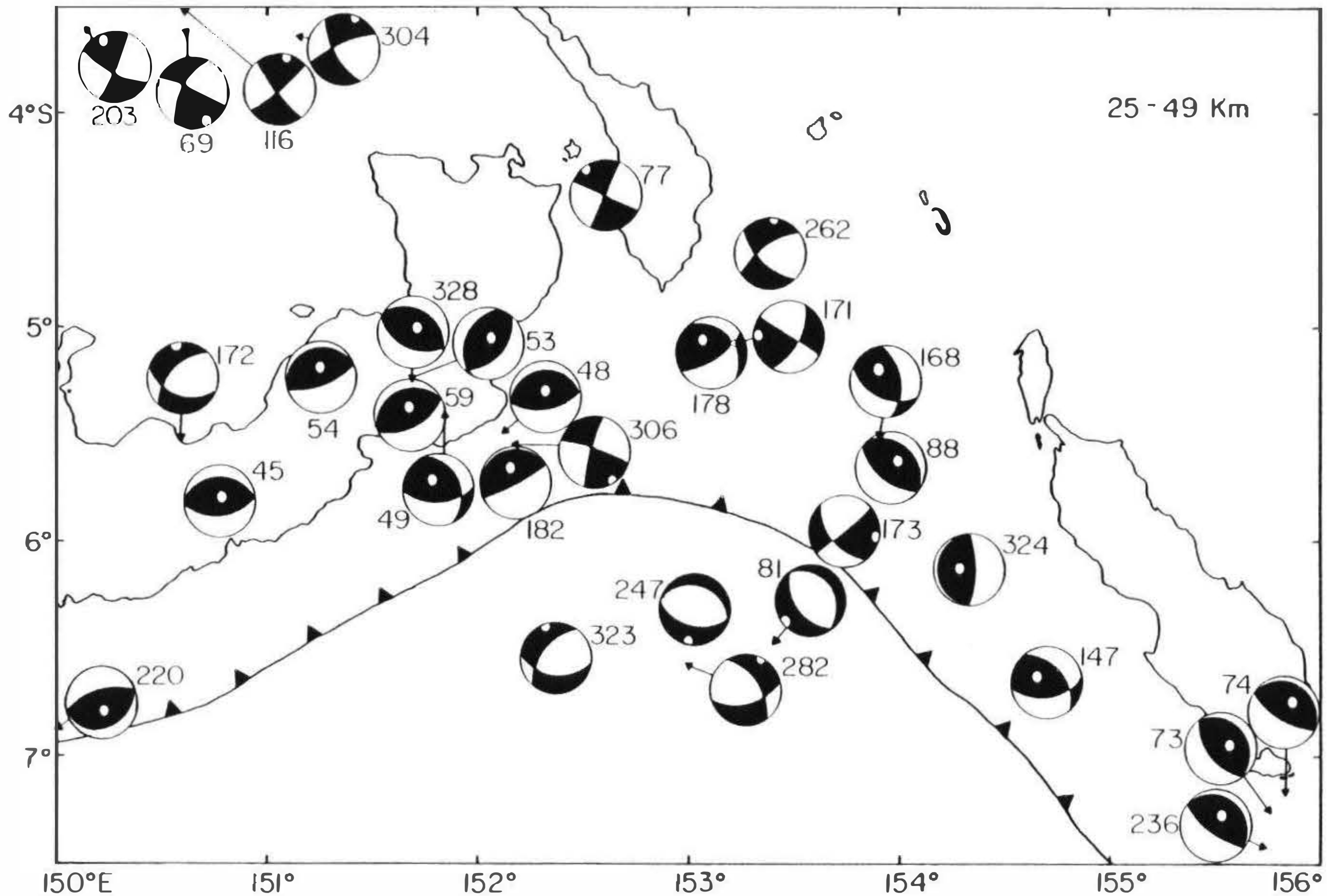
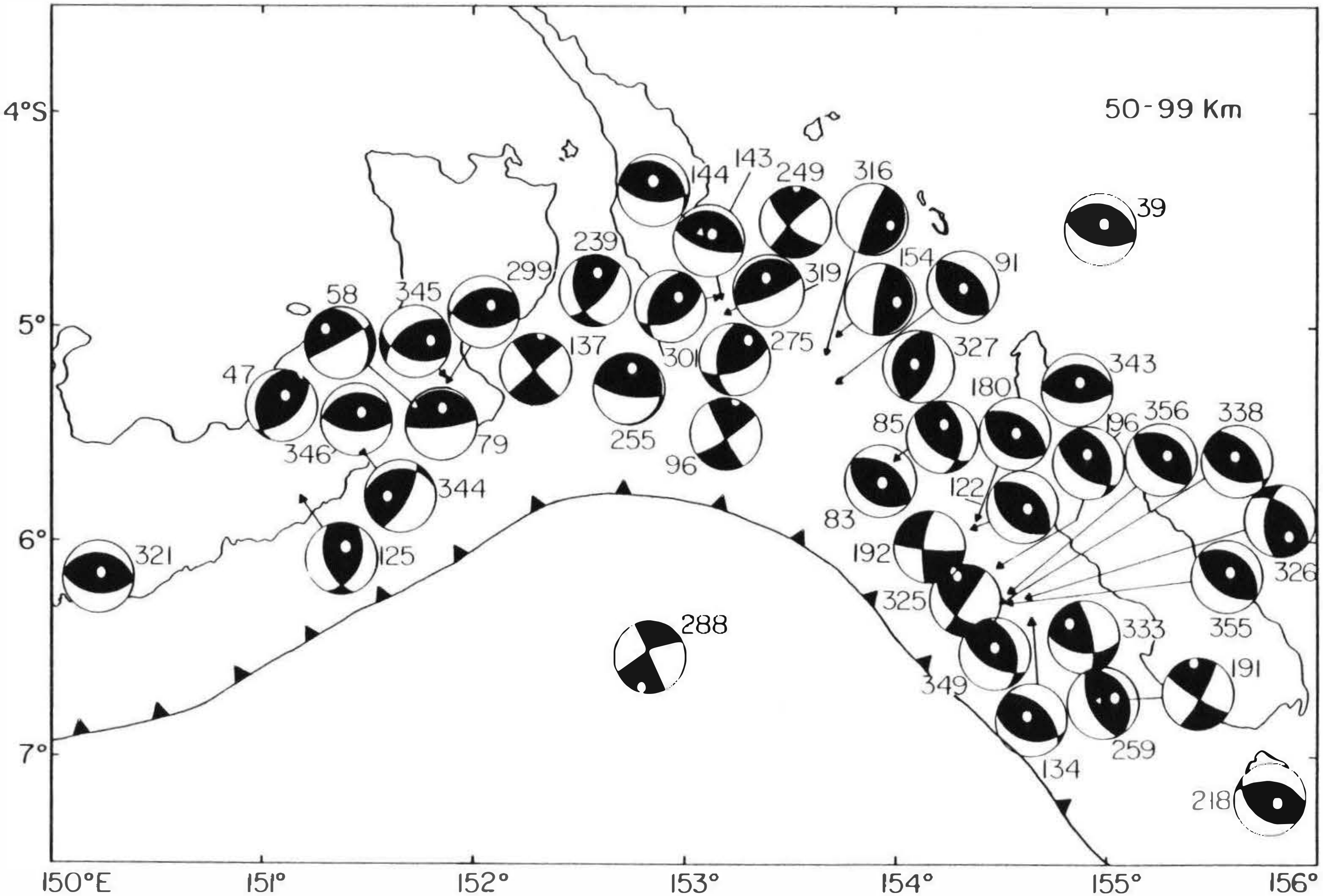

25 - 49 Km
4°S
5°
6°
7°
150°E
151°
152°
153°
154°
155°
156°
203
69
116
304
77
262
328
53
172
54
59
48
306
45
49
182
178
171
168
88
173
324
247
81
323
282
220
147
74
73
236

Figure 3.25

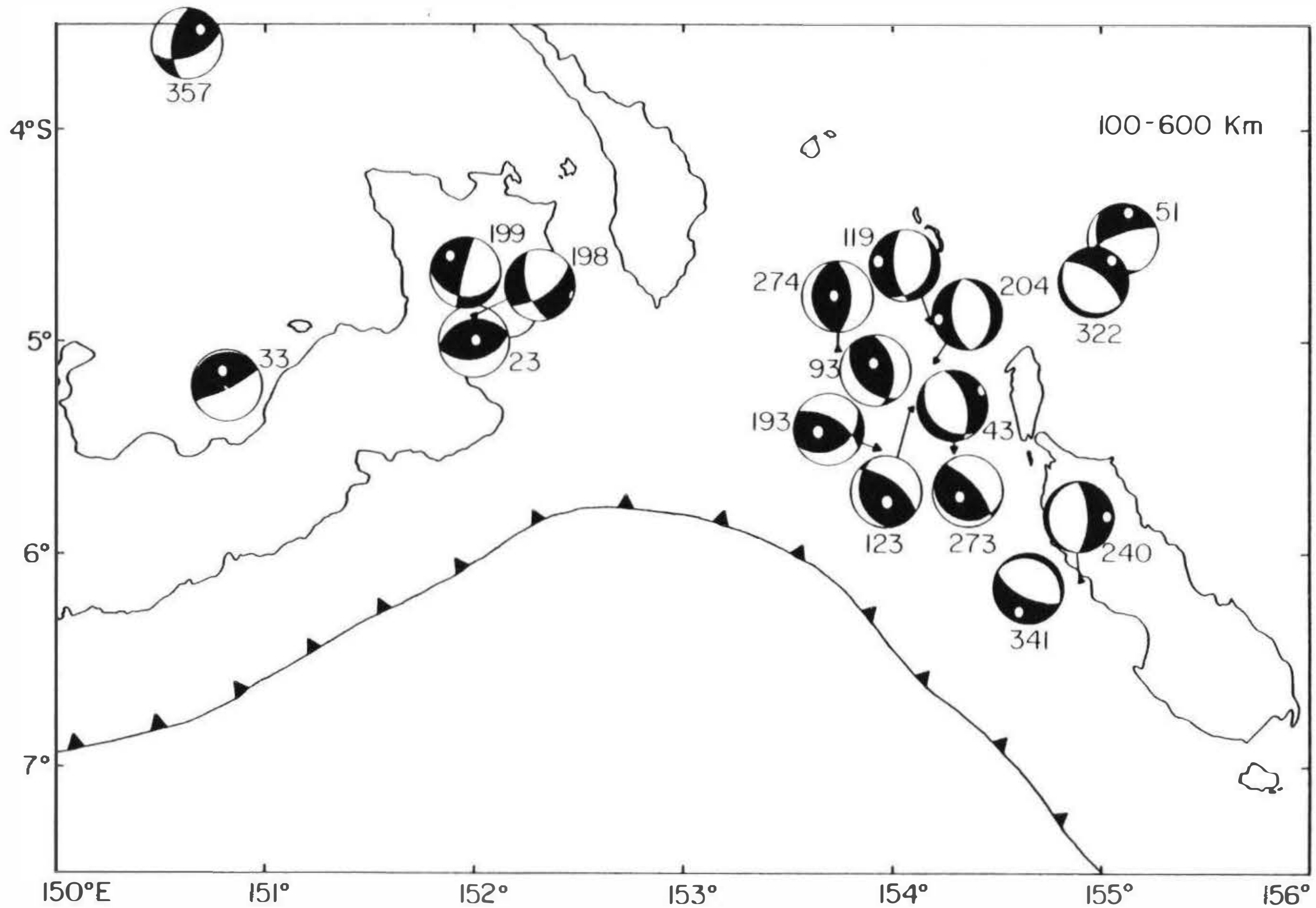
Focal mechanisms for earthquakes located in the New Britain corner region for the depth range 50-99 km.



50-99 Km
4°S
5°
6°
7°
150°E
151°
152°
153°
154°
155°
156°
321
58
345
299
239
144
143
249
316
39
47
346
79
344
125
137
255
301
96
275
319
154
91
327
343
180
196
356
338
85
83
122
192
325
326
355
333
349
191
259
134
218
288

Figure 3.26

Focal mechanisms for earthquakes located in the New Britain corner region depths of 100 km and greater.



357
4°S
5°
6°
7°
100-600 Km
199
198
33
23
119
274
204
51
322
93
193
43
123
273
240
341
150°E
151°
152°
153°
154°
155°
156°

on New Britain.

There are many shallow strike-slip events associated with segments of the Bismarck Sea seismic lineation, which come down through New Britain and New Ireland in one main segment and two, possibly more, minor segments (see Fig. 3.1) to form a triple junction zone at the bend. If nodal planes parallel to the apparent strike of the main transform segments are taken as the fault planes, then events 69, 77, 116, 203, 206, 268, 304 and 306 all show left-lateral motion, consistent with relative motion of the Pacific and Bismarck plates.

The bulk of the thrust events are in the 50-99 km range with thrusting on the Bougainville side extending to 90 km, deeper than usual. The focal mechanisms of these events follow a consistent pattern; one nodal plane dips steeply to the south, the other dips gently north. If this latter plane is taken as the fault plane, there is underthrusting of the Pacific Plate by the Solomon Sea Plate in a direction N36^{o}E (based on an average of slip directions listed in Chapter IV (FOCAL MECHANISMS) and of the Bismarck Plate by the Solomon Sea Plate in a direction N17^{o}W (based on an average of slip directions for events 23, 33, 45, 46, 47, 48, 53, 54, 59, 79, 182, 220, 239, 299, 321, 328, 344, 345 and 346). Comparing the stress axes inferred from these solutions with the local trend of the seismic zone, the tension axes of thrust events near New Britain and Bougainville are vertical or subparallel to the plane of the main thrust zone. The orientation of the nodal planes and tension axes appears to reflect primarily the dip direction of the Wadati-Benioff zone. There are no normal events which would indicate extension orthogonal to the fold axis. The transition from events dipping to the northeast to events dipping to the northwest occurs over a very small area. The small transition area may be the result of the relatively young age of the Solomon Sea lithosphere, 40-60 my (Davies, et al., 1984), i.e. low flexural rigidity. Also, because this lithosphere is severely flexed on three sides, the stress field may vary significantly from any predicted model.

The intermediate depth range (70-200 km) seems to be a mixed stress regime. Most intermediate events (Figure 3.26) show downdip extension (23,33, 93, 123, 273, 274), however, three events (198, 199 and 240) show down-dip compression. All of the deep events on the Bougainville side (43, 51, 204, 322 and 341) show near-vertical compression; deep events on the New Britain side (97 and 357) show downdip extension. In all cases at least one nodal plane is subparallel to the local trend of the slab (not the local trend of the trench).

Conclusions and Discussion

One of the most interesting features of the New Britain Trench is the sharp bend at the junction of the New Britain and Solomon Island arcs. The morphology of the trench appears continuous around the corner. Similarly, we have shown that levels of shallow and intermediate seismic activity, W-B zone contours and depth extents of seismic zones are similar and continuous around the corner. Deep seismicity probably originates in segments of lithosphere detached from the main slab; however, it is possible that the large gap (250-380 km) is merely a seismically quiet zone. The bend in the trench at the New Britain corner results in the formation of a flexural fold in the subducted lithosphere, plunging very gently to the north. Because the dip of the W-B zone is slightly steeper on the Bougainville side, the fold is offset to the east of New Ireland. Having established that the lithosphere is both contorted and disrupted, we must examine the contraints on the morhpology of the slab. The main constraints are clearly not geometrical. In this situation, the age of the underthrusting lithosphere and the nature of the overriding lithosphere are of primary importance. The thickness and, more importantly, the flexural rigidity increases with age for oceanic lithosphere (Watts, 1978). There is roughly an order of magnitude increase in flexural rigidity from 0-90 my (Detrick and Watts, 1978). Lithosphere in the vicinity of the Hokkaido corner is about 100 my old (Molnar et al., 1979). The age of the Solomon Sea lithosphere is unknown and estimates range from 33 to 70 my old. This is within the same age range as lithosphere at the Peru-Chile corner (Molnar et al., 1979). However, the dip of the Peru-Chile seismic zone is quite gentle (10-30^{o}) and it is unlikely that extensive upwarping would develop. The presence of continental crust on the overriding lithosphere together with the advanced age of the Hokkaido slab may be the controlling factors regarding disruption of the slab. The presumably thicker continental lithosphere forces the subducted slab into a steeper attitude than can be accomodated resulting in tearing or wrench-faulting. There is no continental lithosphere on the overriding plate at the New Britain bend, thus the slab is free to bow upwards without extensive wrench-faulting at shallow and intermediate levels. Large sections of lithosphere have, instead, separated from the subducted slab at about the 300 km level along the flanks of the fold. Thus, the deep focus earthquakes northeast of Bougainville are not from an earlier episode of subduction of the Pacific Plate as postulated by Ripper (1975). It is also important to note that the slab near New Britain is continuous only to about 250 km. Excess lithosphere at a sharp bend in a trench may be accomodated either by wrench-faulting near the axis of the fold or by shearing large sections of deep lithosphere from the flanks of the fold. It is possible that the fabric of the subducted lithosphere determines which process occurs.

Focal mechanism solutions appear to be related to the slab contortions. Slip-directions are suborthogonal to the trench axis except for a few at the axis of the fold; there the slip directions reflect the dip-direction of the subducted lithospere and could be described as having a degree of ′overprinting′ from the stresses generated by folding. In agreement with Sasatani (1976), the sense of earthquake slip motion is consistent with the sense of slab contortion and this close relationship between slip motion and the sense of slab contortion may indicate that plastic deformation results from the earthquake slip motions.

Although the precise nature and geometry of the transform and spreading ridge segments of the easternmost terminus of the Bismarck Sea seismic lineation is poorly known, it is clear from the bathymetry, distribution and NNW orientation of land faults on New Britain and New Ireland, and focal mechanism solutions that the lineation is a complex, left-lateral shear zone. The splintering of the main transform as it approaches the New Britain Trench may be the result of fracturing of the overriding plates in the area of regional uplift over the anticlinal fold in the subducted Solomon Sea lithosphere. The triple junction between the lineation and the New Britain Trench has been located at various points by several authors, but the information indicating the complexity of the Bismarck Sea seismic lineation also indicates the complexity of tbe triple junction. This study using seismicity and focal mechanism solutions has been of little help in defining the precise nature of the triple junction; extensive use of both land and ocean bottom seismometer arrays would probably be more fruitful. Caution must therefore be exercised in attempting triple junction analyses in this region, as the triple junction is actually a zone in which several en echelon segments of transform on the overriding plates encounter the trench. The relative importance of each segment is unknown.

IV. SEISMICITY, FOCAL MECHANISMS AND SUBDUCTED LITHOSPHERE IN THE SOLOMON ISLANDS

Introduction

The Solomon Islands form a linear double chain of islands northeast of the New Britain and San Cristobal trenches (Figure 1.1). They are part of the Melanesian convergent boundary between the westward-moving Pacific Plate and the northward-moving Indo-Australian Plate. The interaction between these major plates is buffered by a mosaic of small plates in the areas of the Bismarck Sea, Solomon Sea and North Fiji Basin. The Solomon Sea Plate is bounded on the north by the New Britain Trench, on the west by a zone of continental rifting and diffuse seismicity in the Papuan Peninsula, and on the south by the Woodlark Basin spreading system (Weissel et al., 1982). Initiation of the westward-propagating Woodlark spreading system began prior to 5 ma, the age of the oldest identifiable magnetic anomaly (Taylor, in press). The eastern Woodlark Basin is opening at a rate of 7 cm/yr and at the same time is being subducted beneath the Solomon Islands, the spreading system forming a triple junction with the New Britain and San Cristobal trenches. Southeast of the triple junction the convergence rate is about 11 cm/yr along an azimuth of N73^{o}E (Molnar et al., 1975) and northwest of the junction it is about 14 cm/yr along an azimuth of N45^{o}E (Taylor, in press). Summaries of the regional geology are provided in Coleman (1965, 1970), Coleman and

Packham (1976) and Hackman (1973, 1980). Arc volcanics provide evidence of convergence between the Pacific and Indo-Australian plates in this region since the early Eocene. However, the polarity of the subduction has varied and a number of different models of the tectonic evolution have been proposed (Coleman and Packham, 1976; Weissel et al., 1982; Falvey and Pritchard, 1984; Kroenke, 1984). Bathymetric and seismic reflection data indicate a relict subduction zone dipping south from the North Solomon and Vitiaz trenches (Kroenke, 1972; Brocher, in press). It is generally accepted that the abnormally thick lithosphere of the Ontong Java Plateau collided with the North Solomon Trench sometime during the Miocene, although the exact timing remains controversial (Coleman and Packham, 1976; Kroenke, 1972, 1984). Following this collision the arc polarity reversed and the present regime of northeast subduction at the New Britain, San Cristobal and New Hebrides trenches began by 10 ma. An hiatus in island arc volcanism lasting from late-early to early-late Miocene observed throughout the Solomon Islands (Coleman, 1970; Kroenke, 1984) may be taken as evidence of a temporary cessation of subduction during the reversal; thus double subduction as suggested by Curtis (1973b) is unlikely. Relative motion between the major plates during this interval may have been accomodated elsewhere in the Melanesian convergent boundary, possibly along the Trobriand subduction zone (Kroenke, 1984).

There have been several studies of the seismicity and tectonics of the Solomon Islands region (Curtis, 1973a,b; Denham, 1969; Johnson and Molnar, 1972; Kraus, 1973; Pascal, 1979; Ripper, 1975, 1977, 1980;

Taylor, 1979; Weissel et al., 1982). These studies outline the general geometry of the active plate boundaries and subduction zones, but remain inconsonant in their interpretation of the diffuse seismicity south of the northern relict subduction zone. Although early investigators recognized the lower levels of seismicity in the central Solomons, it was only recently that this was attributed to the subduction of a spreading center (Coleman, 1975a; Weissel et al., 1982).

In this chapter the seismicity is updated and reinterpreted using hypocenters selected from the International Seismological Center (ISC) data file. The earthquake hypocenters are displayed in map view and as depth profiles; this information is then used to construct a contour map of the (inferred) morphology of the subducted lithosphere. Eighty-four additional focal mechanism solutions are presented and their relationship to predicted Pacific-Indo-Australian plate motionsis discussed. The data are located within a 1200 km-long segment of the Solomons arc between 152-163^{o}E. Some of the most interesting aspects of this study are: (1) the nature of the gap in seismicity along the entire length of the New Georgia Group; (2) the origin of the diffuse, shallow and intermediate depth seismicity near Santa Isabel and (3) the source of the deep earthquakes which are located 380-550 km beneath the Solomons.

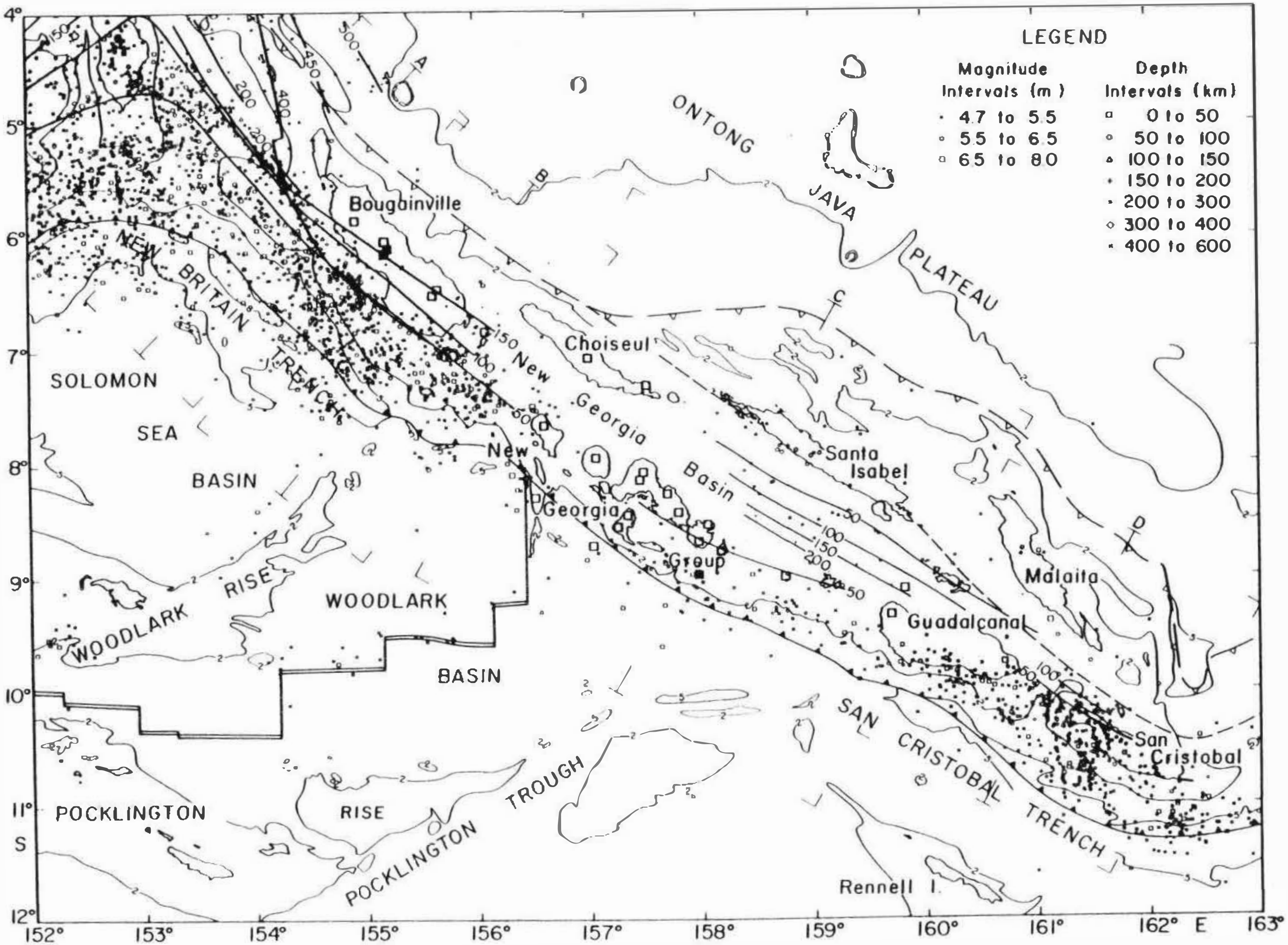
Seismicity

Figure 4.1 shows the distribution of hypocenters, locations of volcanoes and major tectonic features of the Solomon Islands arc-trench region from Buka-Bougainville to San Cristobal. Earthquake hypocenters are taken from the ISC data files and cover the period from 01/01/64 to 06/30/84. Only earthquakes with body wave magnitude (M_b) greater than 4.7 and recorded by 15 or more stations are used. The lower magnitude cutoff was determined by the paucity of events in the central Solomons. Foci for the 84 new focal mechanisms were relocated using the same JHD (Joint Hypocentral Determination) technique described in Chapter II SEISMICITY section.

The seismicity plotted in Figure 4.1 shows three primary features. First, the spacial density of earthquake foci changes along strike; shallow (<70 km) and intermediate (70-300 km) seismicity is concentrated into two zones of greater intensity under the northwestern and southeastern parts of the arc. The very low level of seismicity from 156-159°E coincides with the site of subduction of the young Woodlark Basin lithosphere; slip occurs primarily aseismically. Second, a zone of low-to-moderate shallow activity extends across the Woodlark Basin. Milsom (1970) first suggested this shallow seismicity might be due to active spreading, a proposal later supported by Luyendyk et al. (1973) and confirmed by Weissel et al. (1982) and Taylor (in press). And third, diffuse shallow to intermediate activity is also observed northeast of New Georgia and

Figure 4.1

Regional seismicity and Wadati-Benioff zone contours for the Solomon Islands. Seismicity includes all ISC hypocenters with body wave magnitudes greater than 4.7 and recorded by more than 15 stations for the period 01/01/64 to 06/30/84. Wadati-Benioff zone contours are indicated by a heavy solid line at 50 km intervals. Land areas are shaded, and 2, 5, and 8 km bathymetric contours are drawn. The Woodlark spreading system is indicated by the usual combination of double line (ridge segments) and single line (transform faults). A solid, hatchured line indicates the topographic axis of the New Britain and San Cristobal trenches; the dashed, hatchured line marks the location of the North Solomon Trench, which is also the northern boundary of the Malaita Anticlinorium. The dashed line represents the Kaipito-Korighole Fault. Large open squares mark the locations of Plio-Pleistocene volcanoes; large filled squares are active volcanic centers. The widths and locations of seismic profiles A-D (Figures 4.2-4.5) are indicated by brackets.


LEGEND
Magnitude Intervals (m)
4.7 to 5.5
5.5 to 6.5
6.5 to 8.0
Depth Intervals (km)
0 to 50
50 to 100
100 to 150
150 to 200
200 to 300
300 to 400
400 to 600
ONTONG JAVA PLATEAU
Bougainville
NEW BRITAIN TRENCH
SOLOMON SEA BASIN
Choiseul
New Georgia Basin
Santa Isabel
New Georgia Group
Malaita
Guadalcanal
WOODLARK RISE
WOODLARK BASIN
SAN CRISTOBAL TRENCH
San Cristobal
POCKLINGTON RISE
POCKLINGTON TROUGH
Rennell I.
A
B
C
D
4°
5°
6°
7°
8°
9°
10°
11° S
12°
152°
153°
154°
155°
156°
157°
158°
159°
160°
161°
162° E
163°

Guadalcanal, extending to Santa Isabel and Malaita. This diffuse seismicity provides direct evidence of lithosphere formerly subducted at the North Solomon Trench.

The Wadati-Benioff (W-B) zone contours in Figure 4.1 are based on observed seismicity; many depth profiles were constructed orthogonal to the trench axis at varying intervals. The five depth profiles shown in Figures 4.2-4.6 are considered representative. Many more profiles were constructed than are shown. The top of the slab was drawn along the upper limit of observed seismicity and such that it intersects the topographic trench axis. It is understood that at intermediate levels the seismicity may be confined to the interior of the slab (Isacks and Molnar, 1971). The hypocenters shown as depth profiles in Figures 4.2-4.5 define a zone of seismicity which dips to the northeast. Both the dip and the depth extent of the zone vary significantly along strike. North of Bougainville, Figure 4.2 shows a well-defined zone of seismicity that dips at an initially shallow angle, then steepens until it becomes almost vertical below 100 km. ISC data indicate a seismic zone about 30 km thick. There is a remarkable lack of seismic activity in the overriding plate. Near Bougainville, Figure 4.3, the dip of the seismic zone is slightly shallower and the zone has thickened. The W-B zone in these profiles is continuous to just over 200 km; there is a seismic gap from 250-380 km. Deep seismicity is in two zones at 400 +/- 20 and 500 +/- 20 km. As shown in Chapter 3, the apparent offset is caused by a difference in strike between the trench axis and the deep subducted lithosphere just north of Bougainville and west of Buka. Profile C (Figure 4.4)

Figure 4.2

Seismic section A. The following information pertains to Figures 4.2-4.5. Projection onto vertical planes of ISC seismicity. Locations and widths of profiles A-D are shown in the diagram to the left of the projection. Major bathymetric features are identified by a letter code: NBT=New Britain Trench, SCT=San Cristobal Trench. A solid line outlines the inferred location of the top of the Wadati-Benioff zones.

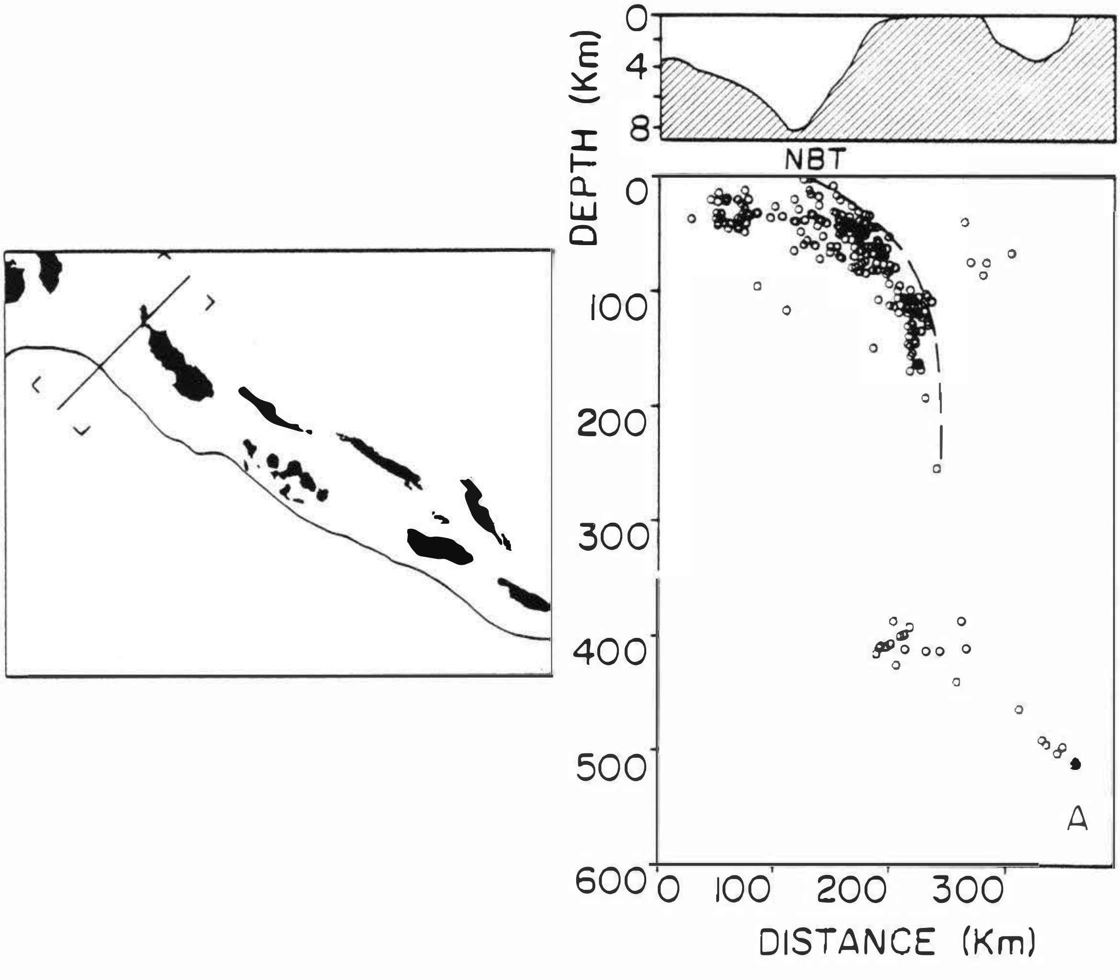

0
4
8
DEPTH (Km)
NBT
0
100
200
300
400
500
600
0 100 200 300
DISTANCE (Km)
A

Figure 4.3

Seismic section B.

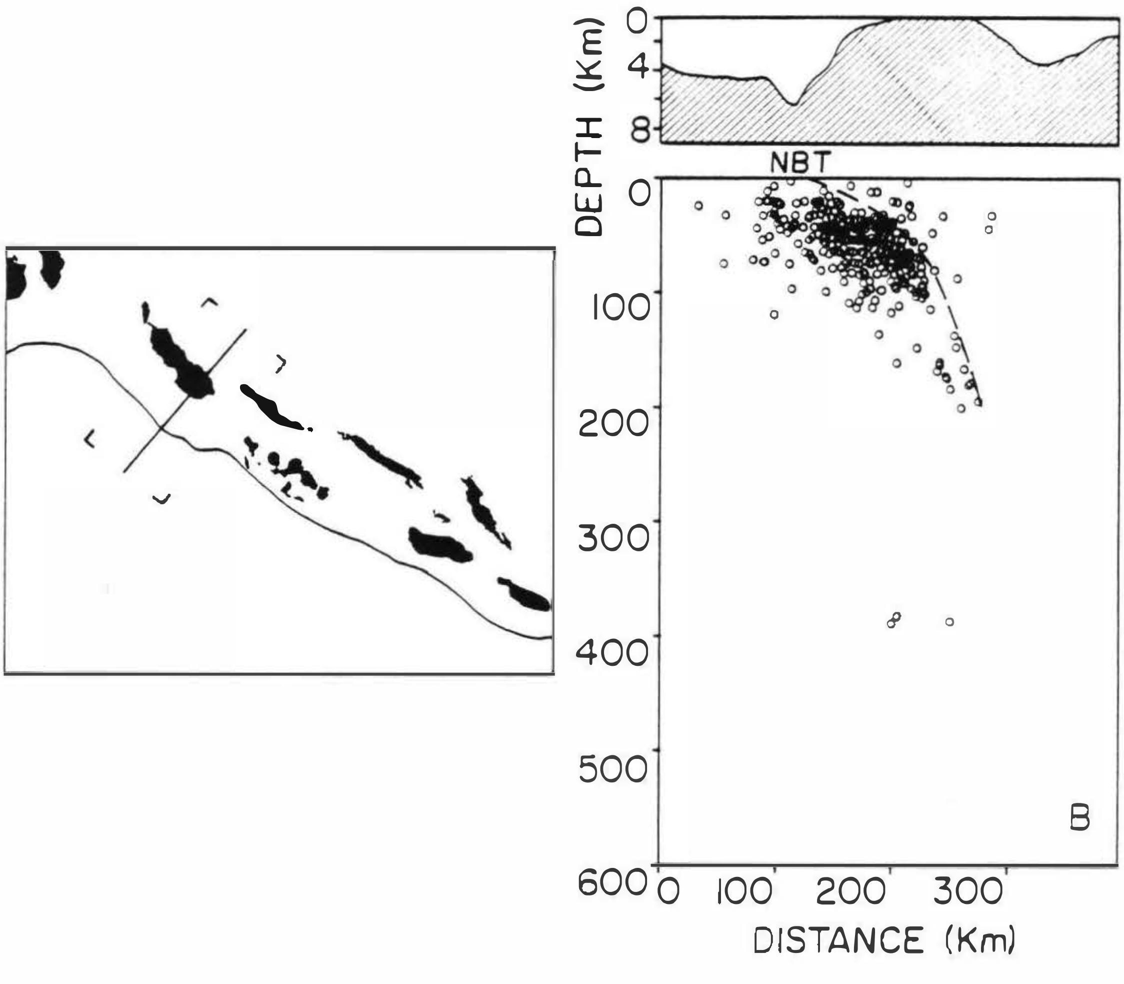
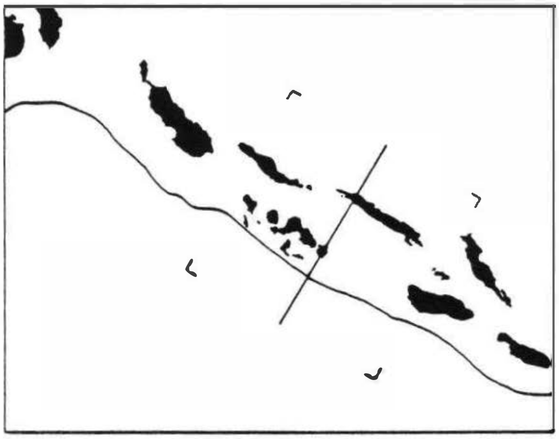

DEPTH (Km)
0
4
8
NBT
0
100
200
300
400
500
600
B
0
100
200
300
DISTANCE (Km)

Figure 4.4.

Seismic section C.



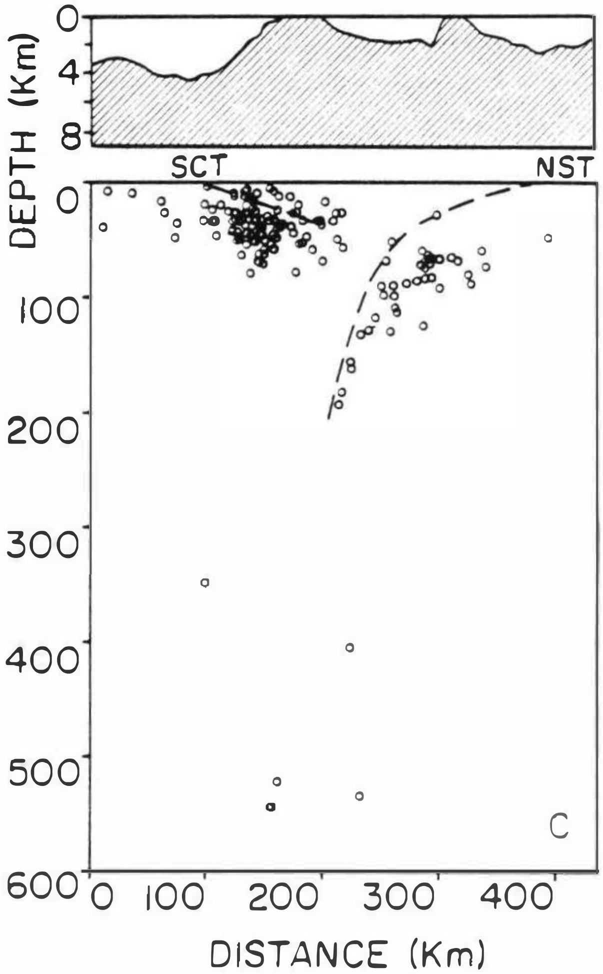
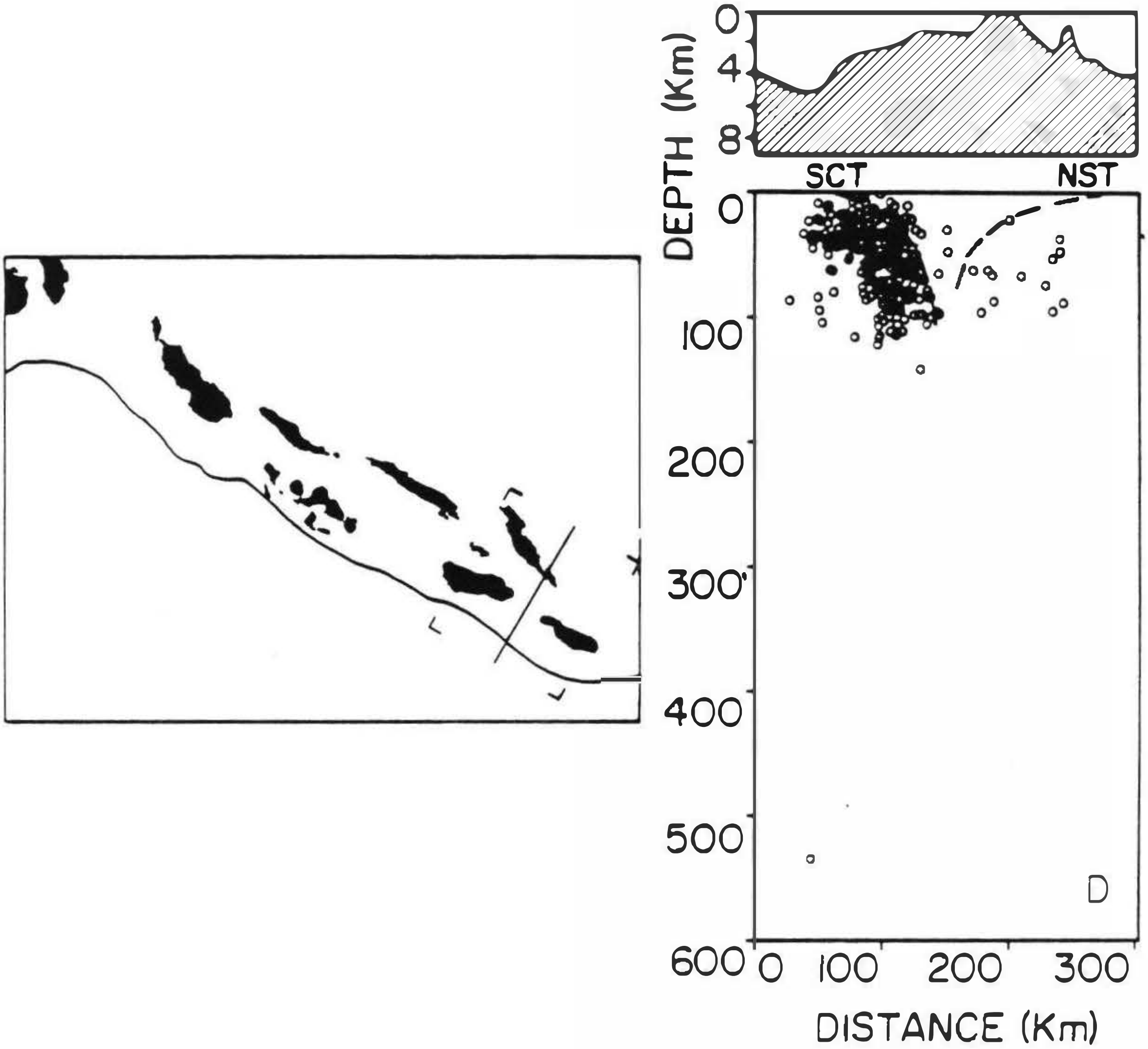

DEPTH (Km)
0
4
8
SCT
NST
0
100
200
300
400
500
600
0
100
200
300
400
C
DISTANCE (Km)

Figure 4.5

Seismic section D.


DEPTH (Km)
0
4
8
SCT
NST
0
100
200
300
400
500
600
D
0
100
200
300
DISTANCE (Km)

traverses the New Georgia Group. The subduction of the young lithosphere of the Woodlark Basin is characterized by shallow, diffuse, low magnitude seismicity. There is no well-defined W-B zone - it apparently extends no deeper than 80 km, yet the Plio-Pleistocene volcanoes of the New Georgia Group occur 30-100 km from the trench axis. Figure 4.5 shows a near-vertical seismic zone continuous to just over 100 km. A few deep events are seen in Figures 4.4 and 4.5, however, their relationship to subduction at the San Cristobal Trench is unclear. The events may originate in lithosphere subducted at either the San Cristobal Trench or at the North Solomon Trench; possibly both.

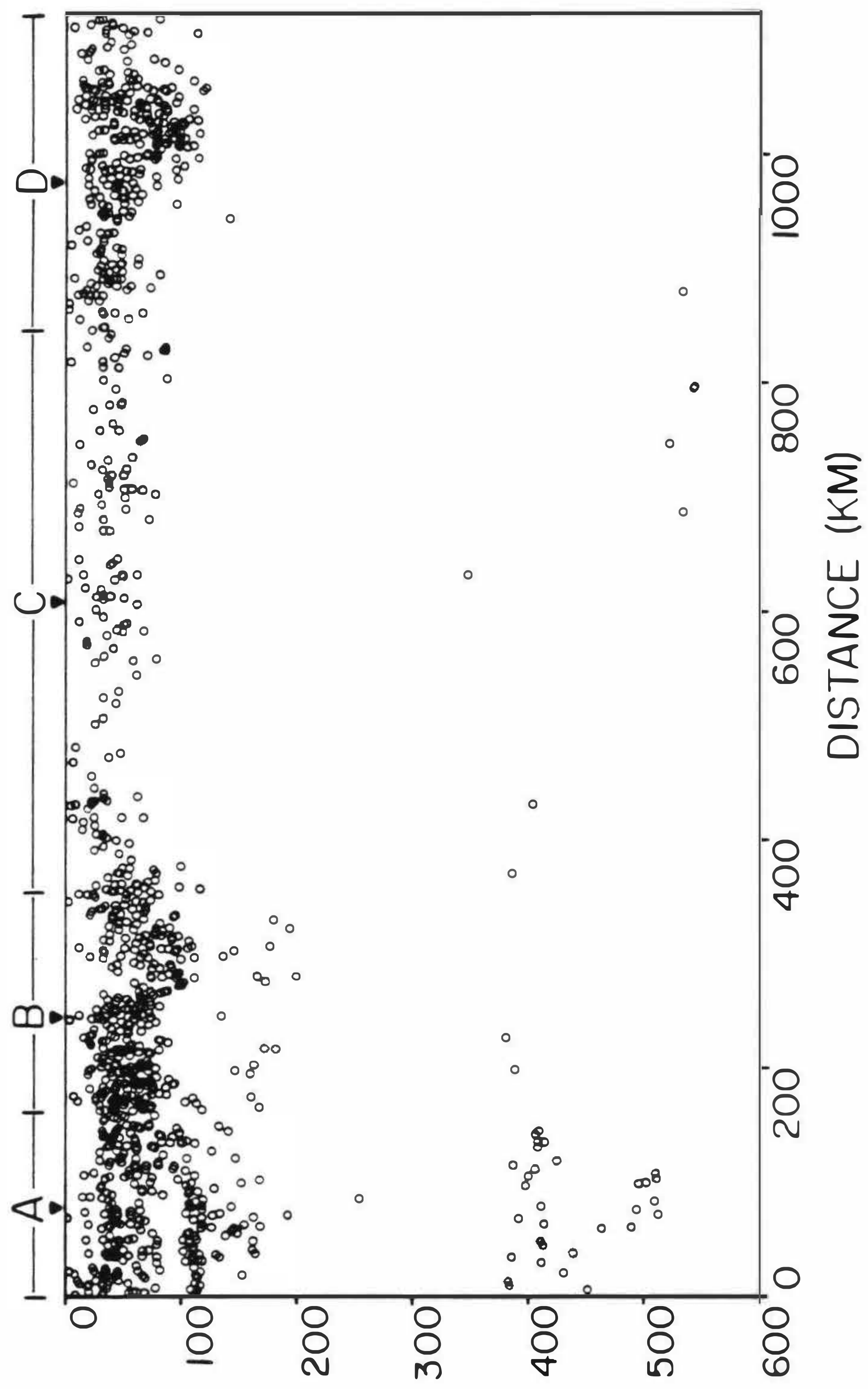
A number of events in Figures 4.4 and 4.5 define a southwest-dipping zone which may be attributed to the relict slab of the North Solomon Trench. The Korighole Fault (also Kaipito-Korighole Thrust) represents the suture between the North Solomon forearc and overthrust crustal sections of the Pacific Plate. Near Guadalcanal the 50 km contour of the relict W-B zone crosses the suture. Hence the top of the slab is drawn to intersect the topographic axis of the North Solomon Trench. Since hypocenters in the shallow part of the zone were relocated at depths much smaller than those reported by ISC, the top of the W-B zone is drawn well above the upper level of ISC seismicity. In support of our decision we note that a similar systematic mislocation of depths has been observed elsewhere. Hirata et al. (1983) compared cross-sections of hypocenters determined by ISC and a local land array to hypocenters determined from data recorded by an offshore OBS array near Honshu, Japan. Scattered activity to depths of 100 km beneath and seaward of the trench was observed for the ISC and network data, but activity was confined to 30 km depth seaward of the trench and 40 km beneath the trench and forearc for the OBS data. Denham (1975) and Neef (1978) suggested that the Pacific Plate may be underthrusting Santa Isabel, however, judging from the lack of great thrust events (only one event in this region, 139 (Figure 4.7), indicated thrusting), absence of cross-arc structures and the overall low level of seismicity, this zone is probably not actively subducting. In addition, single and multichannel seismic reflection profiles across the Ontong Java Plateau and North Solomon Trench (Kroenke, 1972; Kroenke et al., in press) show no evidence of active underthrusting of the Solomon Islands by the Ontong Java Plateau. Either the seismicity is entirely relict (Toksoz, 1975) or the presently subducting lithosphere-almost horizontal in this area-may be pushing the old slab deeper into the aesthenosphere, forcing reequilibration. The relict seismic zone is well-defined by the seismicity only in profiles taken orthogonal to Santa Isabel. There are scattered hypocenters to the north and south which follow the general trend of the North Solomon Trench, but not enough to define a southwest-dipping W-B zone as well as that observed near Santa Isabel. It is interesting to note the earthquake, 39 (Figure 4.8), north of Buka with its thrust-type mechanism. We speculate that the old slab may be present along the entire length of the Solomon Islands, forcing the presently active slab into its near-vertical dip.

The recognition that this relict slab is present and somewhat active seismically has significant implications for current petrological studies. The Holocene volcano, Savo, is located 100-150 km above the relict W-B zone, as are the Plio-Pleistocene volcanoes of Choiseul, Mt. Matambe and Kamboro Peak.

A seismicity section from 5.5°S, 153°E to 11.0°S, 162°E, parallel to the general trend of the arc is shown in Figure 4.6. Inverted triangles indicate intersections with cross-profiles A-D (Figures 4.2-4.5). Background seismicity due to the North Solomon remnant slab has been removed to enhance illustration of the gap in seismicity generated by subduction of the spreading axis and young lithosphere of the Woodlark Basin. According to Marshak and Karig (1977), separation of the Solomon Sea and Indo-Australian plates by the Woodlark spreading system should continue for some depth beneath the Pacific Plate, resulting in an inverted V-shaped gap in the subducted lithosphere. Seismicity from the segmented subducted lithosphere of the Solomon Sea Plate extends to over 500 km (Figure 4.6). The lithosphere suducted beneath Guadalcanal and San Cristobal is apparently equilibrated at a much shallower level, 100-150 km. Nowhere in the central Solomons does the seismicity associated with subducted Woodlark Basin lithosphere extend to over 80 km. There is indeed a gap in the seismicity, however, based on available data we are unable to prove that the gap in seismicity represents a gap in the lithosphere. Gaps in intermediate depth seismicity, or an absence of intermediate and deep seismicity are observed along strike in this and other W-B zones (e.g., Eguchi et al., 1984). The causes are not well understood. The subducted lithosphere in this area is certainly hot

Figure 4.6

Projection of seismicity onto a plane subparallel to the strike of the Solomon Islands. This profile extends from $5.5^{\circ}S$, $153.5^{\circ}E$ (left) to $11.0^{\circ}S$, $162.0^{\circ}E$ (right) and has a width of 425 km.


A
B
C
D
0
200
400
600
800
1000
DISTANCE (KM)
0
100
200
300
400
500
600
DEPTH (KM)

and thin and may deform plastically (Forsyth, 1975). It will be difficult to determine with certainty the existence of a gap in the lithosphere using propagation studies because of the presence of the relict northern slab to appreciable depth.

Deep earthquakes occur in pod-shaped clusters confined to two depth levels, 400 +/- 20 and 500 +/- 20 km near Bougainville and are (or were) part of the Solomon Sea Plate W-B zone. The W-B zone of central New Britain has many of the same characteristics as that near Bougainville. Southeast of the triple junction, deep earthquakes near Guadalcanal and San Cristobal occur at a slightly deeper level, 535 +/- 10 km. There is very little indication that the presently active W-B zone includes these deep events. The deep earthquake seen in Figure 4.5 is actually located seaward of the San Cristobal Trench. Similar deep seismicity has been observed along strike beneath the Vitiaz Trench and has been interpreted as originating in lithosphere subducted by the Vitiaz Trench and/or in lithosphere subducted by the New Hebrides Trench in the past. The deep events in the southeast Solomon Islands may originate in lithosphere subducted at the San Cristobal Trench which has been deformed by proximity to the North Solomon Trench, or they may originate in lithosphere subducted at the North Solomon Trench. It is impossible to assign them a source at this point.

Focal Mechanisms

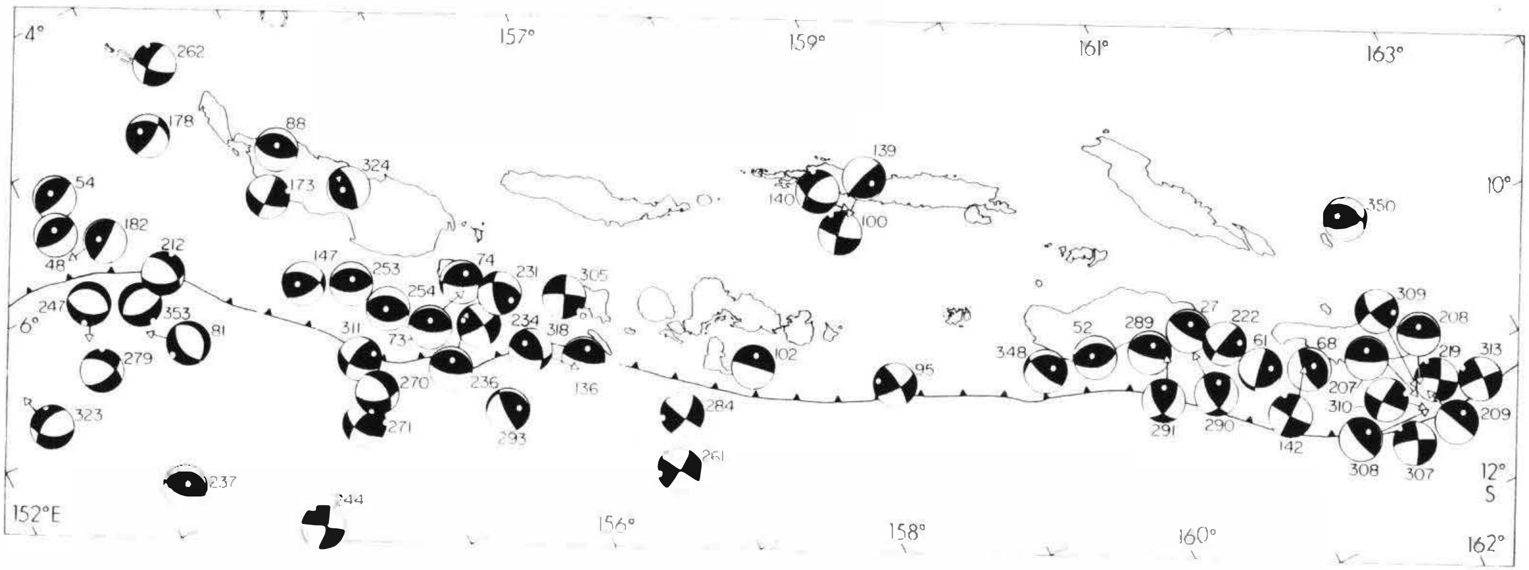
Many focal mechanisms have been published for the Solomon Islands area. A list of all available earthquakes with fault plane solutions is provided in Appendix I. Eighty-four new focal mechanism solutions have been obtained for moderate to large earthquakes covering the period 1970-1981. These solutions are presented in Table 4.1. The positions of the new focal mechanisms were recomputed as described in Chapter II, SEISMICITY; the original ISC depth is listed for events with fewer than 3 reliable pP readings. In all cases P-wave polarities were read directly from long-period recordings of the WWSSN stations. The original data, projections of the P-wave polarities together with inferred fault and auxiliary planes onto the lower hemisphere of the homogeneous focal sphere, are included in Appendix II.

New and previously published solutions are plotted in Figures 4.7-4.9for the depth ranges 0-50 km (Figure 4.7), 50-100 km (Figure 4.8) and over 100 km (Figure 4.9). The quadrants defined by the nodal planes are black for compressional and white for dilatational first motions. The numbers correspond to the event numbers in Appendix I.

In the northwest and southeast Solomon Islands the moderate-to-large, shallow hypocenters between the island arc and the trench axis consist mainly of thrust-type earthquakes which occur at or near the contact between the overriding and underthrusting plates. This part of the W-B zone is usually referred to as the ´main thrust zone´ and

Figure 4.7

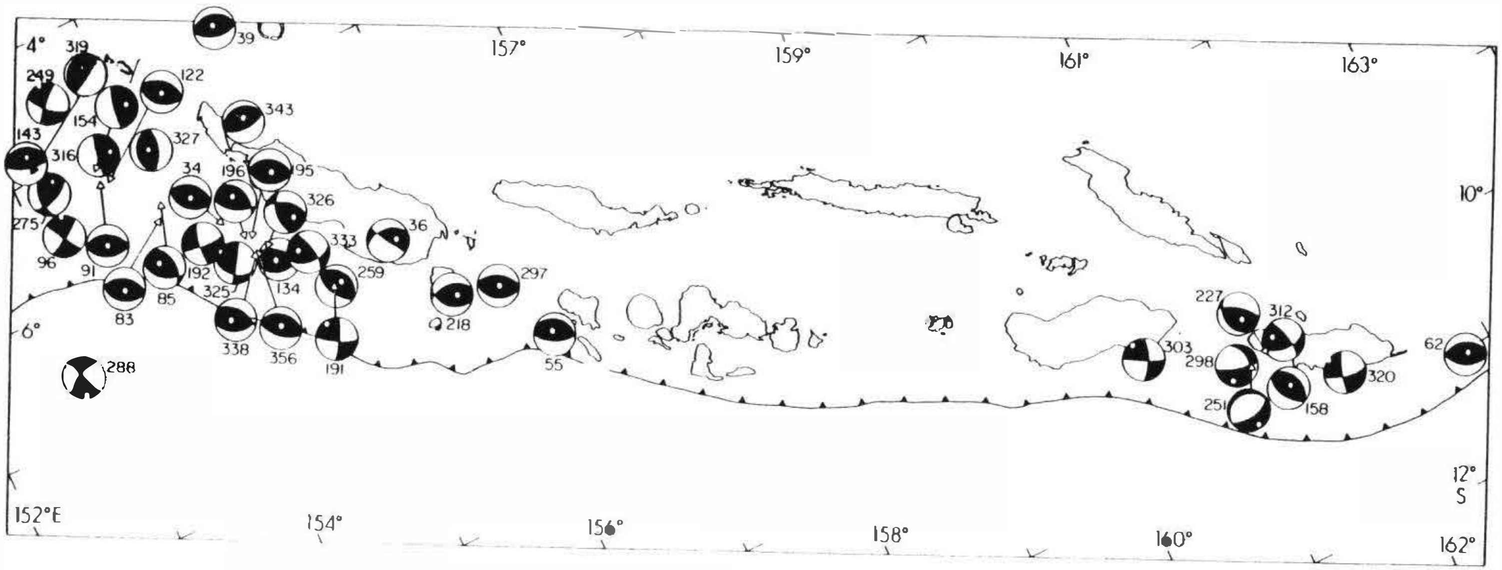
Focal mechanisms for earthquakes located in the Solomon Islands region in the depth range 0-50 km. The following information pertains to Figures 4.7-4.9. Where possible, the focal mechanism solution is centered on the epicenter; in some cases the epicenter is indicated by a triangle and a line is drawn connecting it to the corresponding solution. In some areas where crowding of focal mechanism solutions became a problem, some identical or similar solutions were omitted. Compressional quadrants are shaded and dilatational quadrants are unshaded. Tension axes are shown as white circles against the shaded compressional quadrant. Numbers correspond to the numbering system of Appendix I.



4°
157°
159°
161°
163°
10°
6°
12°
S
152°E
156°
158°
160°
162°
262
178
88
324
173
54
182
48
212
247
353
81
279
323
237
244
147
253
254
74
231
305
311
73
234
318
270
236
136
271
293
139
140
100
102
284
261
95
350
348
52
289
27
222
61
68
309
208
219
313
207
310
209
291
290
142
308
307

Figure 4.8

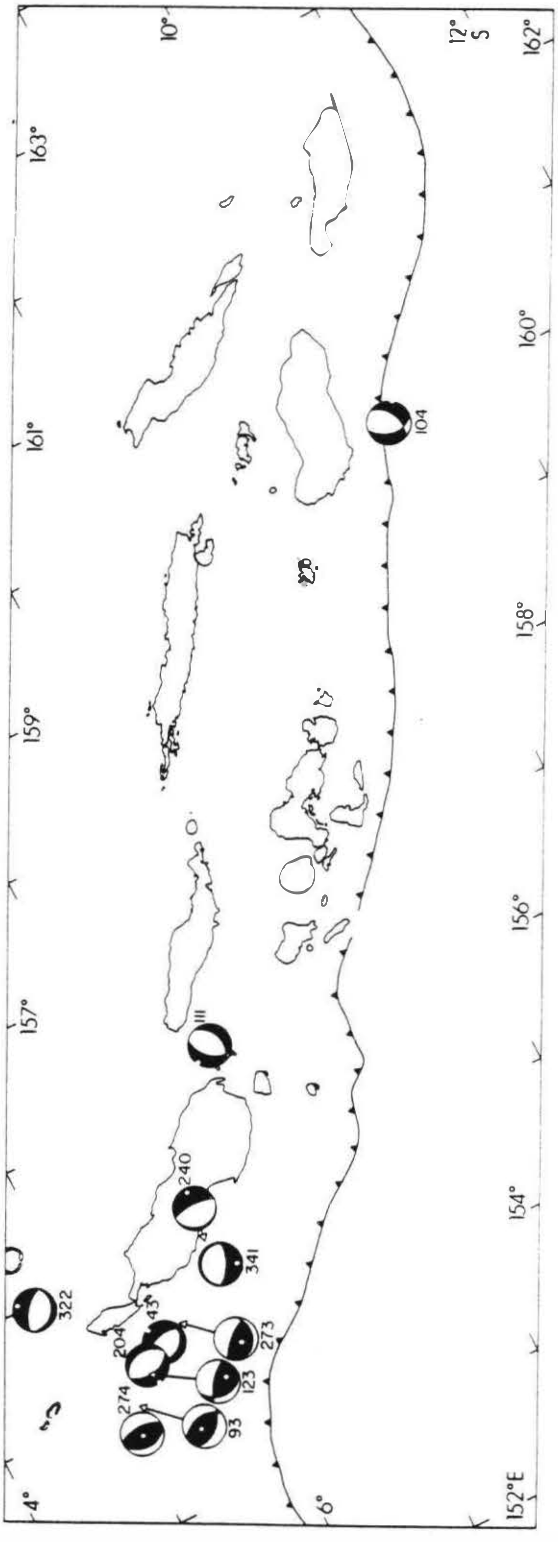
Focal mechanisms for earthquakes located in the Solomon Islands region in the depth range 50-100 km.



4°
6°
10°
12°
S
152°E
154°
156°
157°
158°
159°
160°
161°
162°
163°
39
319
249
122
343
154
327
143
316
34
196
95
326
275
36
96
91
192
333
259
297
85
325
134
83
218
227
312
338
356
191
55
303
62
298
320
288
251
158

Figure 4.9

Focal mechanisms for earthquakes located in the Solomon Islands region at depths equal to or greater than 100 km.


4°
6°
10°
12° S
152°E
154°
156°
158°
160°
162°
157°
159°
161°
163°
274
93
123
204
43
273
322
341
240
111
104

is characterized by great thrust events, gentle dip and an extent of 40-70 km in depth. Below this depth range earthquakes are thought to occur as a result of accumulated intraplate stress. North of Bougainville, thrust events occur as deep as 122 km; three earthquakes with depths listed by ISC as 99, 115 and 122 km were relocated to depths of 95, 90 and 95 km, respectively. Unfortunately, except for the event at 99 km, the relocations were made with fewer than 3 pP-P times. The maximum depth of thrusting in this area is therefore probably around 95 km, these unusually deep thrusting events being considered a downward continuation of the thrust faulting characteristic of the main thrust zone. The unusual depth may be the result of a combination of the rapid rate of convergence (14-15 cm/yr) and the very steep dip. The inferred fault planes of thrust events show no consistent change in dip from the trenchward to the arcward end of the main thrust zone. However, the inferred fault planes of thrust events in the southeast Solomon Islands are consistently shallower (near horizontal) than those to the northwest.

The sharp bend in the subduction zone as the trench curves to the west south of New Britain suggests that laterally directed stresses may make a large contribution to the overall state of stress in the down-going slab. As discussed in the previous chapter, geometrical constraints on the descending lithosphere are the most likely mechanism for generating such stresses and thermoelastic properties of the lithosphere constrain their magnitude. The transition from events dipping to the northwest to events dipping to the northeast occurs over a very small area; the T-axes of thrust events near New Britain and Bougainville are vertical or subparallel to the plane of the main thrust zone. The orientation of the nodal planes and tension axes appears to reflect primarily the dip direction of the Wadati-Benioff zone. There are no normal events which would indicate extension orthogonal to the fold axis. The small transition area at the crest of the bend and the apparent absence of (normal) transition events indicate that the lithosphere being subducted in the vicinity of the New Britain corner is relatively young and flexible.

The solutions clearly indicate that the Solomon Sea Plate is under-thrusting the Pacific Plate along Bougainville. Slip directions for 20 thrust events in the northwest Solomon Islands (events 34, 55, 73, 74, 83, 87, 122, 134, 136, 195, 196, 218, 236, 237, 253, 254, 259, 297, 356 and 338) were chosen for nodal planes subparallel to the local strike of the trench axis; the average direction of slip is computed to be N36^{o}E (S.D. 11.4), very close to the N34^{o}E value computed by Johnson and Molnar (1972). South of New Georgia, thrust mechanisms indicate that the Indo-Australian Plate is underthrusting the Pacific Plate. The average direction of slip determined from 14 events (numbers 27, 52, 56(not shown), 62, 68, 158, 207, 209, 229, 289, 290, 291, 308 and 348) is N63^{o}E (S.D. 23.6). These directions of slip are each about 10 degrees less than the directions of relative motion derived from the Pacific-Indo-Australian pole of rotation and the opening of the Woodlark Basin (N45^{o}E and N73^{o}E; Molnar et al., 1975; Taylor, in press), though the angular difference between each pair of directions is the same (27-28^{o}).

In the vicinity of New Ireland, the Bismarck Sea seismic lineation has been characterized as a broad band of left-lateral faults, rather than a single transform (Ripper, 1980; Taylor, 1979). Events 96, 249 and 262 are interpreted as left-lateral strike-slip motion along the easternmost sections of the lineation. Strike-slip events 191 and 192 (Figure 4.8) are deeper than most strike-slip events in the northwest and are not associated with any particular feature; these events are part of a lengthy series of earthquakes and aftershocks spanning several months and may represent minor adjustments. Minor strike-slip faulting is observed on Bougainville (173). Left-lateral strike-slip faulting associated with the Korighole Fault is observed near Santa Isabel (100 and 140). The strike-slip component of shallow thrust mechanisms of the San Cristobal Trench, and the proportion of strike-slip (to thrust) events increase sharply near San Cristobal. South of San Cristobal, the motion is almost entirely strike-slip. This suggests that the San Cristobal Trench and the northern New Hebrides (Torres) Trench are contiguous, but not continuous, connected by a transform or by a section of trench along which there is very little actual subduction.

Normal faulting occurs at shallow depths (Figure 4.7). Events 81, 212, 247, 270, 282 and 353 are located beneath or seaward of the New Britain Trench. These events show horizontal extension orthogonal to the trench and may therefore be associated with the tensional regime generated by bending of the lithosphere prior to subduction (Chappel and Forsyth, 1979).

Events 261 and 285 are located close to a N-S trending transform, however, the strike-slip motion of these events is inconsistent with motion along the transform. These events, together with event 95, may reflect intraplate deformation. Diffuse, shallow seismicity also extends northeast along the Woodlark Rise, the northern margin of the Woodlark Basin, merging with the main trend Solomon Islands seismicity at 155^{o}E. Focal mechanisms along the Woodlark Rise indicate both right-lateral (244) and left-lateral (271 and 311) movement parallel to the trend of the Woodlark Rise; the right-lateral solution is the best of the three. The significance of the variation in mechanism types is moot, since the right-lateral solution is the better of the three. The Woodlark Rise is a Miocene trench-trench transform fault and is probably responding to differential movement due to partial decoupling of the Solomon and Woodlark basins along the northern margin of the Woodlark Rise (Weissel et al., 1982).

Two events (numbers 39 and 350) are located far north of the main Solomon Islands seismicity and may reflect continued convergence (possibly as obduction of the Pacific Plate onto the North Solomon forearc) along the North Solomon Trench.

The fault planes and axes of deep earthquakes (all showing downdip compression) appear to be oriented obliquely to the New Britain Trench, however, in the vicinity near and north of Bougainville the fault planes are subparallel to the trend of a piece of lithosphere broken from the New Britain slab.

Conclusions

Hypocenters along the Bougainville section of the New Britain Trench define a W-B zone with near-vertical dip to a maximum depth of 200 km. The slab is not continuous to great depth, contrary to Curtis (1973a), Denham (1975) and Pascal (1979). Hypocenters along the San Cristobal Trench define a W-B zone with vertical dip to a depth of just over 100 km. Thrusting in this area has a large strike-slip component which increases from Guadalcanal to San Cristobal, until motion is almost entirely strike-slip south of San Cristobal.

The central Solomon Islands near New Georgia is one of several sites worldwide where subduction of an active spreading system occurs. These sites are characterized by shallow, diffuse, low-magnitude seismicity. No north-dipping W-B zone is defined in the central Solomon Islands, yet within 30-100 km of the topographic trench axis are the great outpourings of Plio-Pleistocene lavas which make up the New Georgia Group. The Woodlark Basin's fortuitous arrangement of ridge sections and transforms results in the spreading ridges being subducted parallel to the direction of convergence (orthogonal to the trench); ridge subduction affects the same location over a prolonged period of time, resulting in high-volume, near-trench volcanism. In contrast, oblique subduction of ridge segments of the Chile Rise has resulted in a zone characterized by low level seismicity and an absence of volcanism (Forsyth, 1975). The fracture zones of the Chile Rise are nearly parallel to the direction of convergence (orthogonal to the trench); subduction of ridge segments affects a location for a brief period of time, whereas subduction of the fracture zones affects the same location over a prolonged period of time. The net effect is similar to the subduction of a fracture zone.

The collision of the Ontong-Java Plateau with the North Solomon Trench and the subsequent polarity reversal of the Solomon arc has been doubted in the past. Evidence for a southwest-dipping subduction zone has been cited as "indirect and ambiguous" by Coleman (1975b), and Turner and Hughes (1982) suggested (based on petrological studies) that if, indeed there were a fossil subduction zone along the North Solomon Trench, it must have dipped to the northeast. Curtis (1973a), using data spanning 1961-1970, noted that diffuse seismicity south of Santa Isabel appeared to form a southwest-dipping zone, but could conceivably be incorportated into a diffuse northeast-dipping zone including the foci near New Georgia. Figure 4.4 clearly shows a southwest-dipping W-B zone. The reader should keep in mind that this is very low level seismicity; in this case a considerable amount of time (20 years) was required to accumulate enough large earthquakes to define the W-B zone adequately. This is the first time that seismic evidence of arc reversal has been reported in the literature.

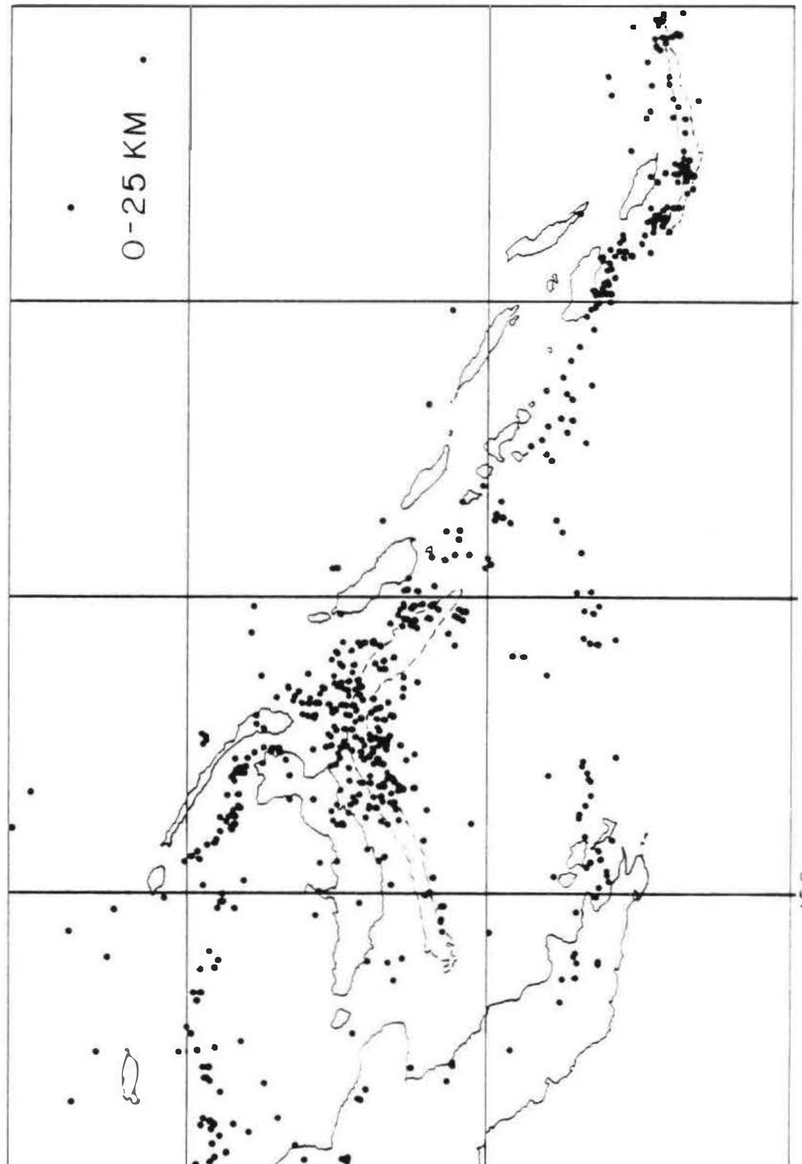
Deep earthquakes in the Solomon Islands cluster in pod-shaped zones at 380-550 km and may be associated with detached lithosphere. As shown in Chapter 3, these earthquakes may originate in a piece of slab broken from the present slab of lithosphere subducted at the New Britain corner. Deep events located in the southern Solomon Islands are rare and appear to be downdip of the North Solomon Trench lithosphere. However, in this area the relative motion of the plates may be displacing the deep part of the lithosphere subducted at the San Cristobal Trench under the shallower part of the slab, in a manner not unlike that north of Bougainville. There are so few deep earthquakes in the southern Solomons region that it is difficult to assign them a source with any degree of certainty.

V. CONCLUSIONS AND SPECULATIONS

Studies of the spatial distribution of earthquakes can help define both present and past plate boundaries. Seismicity throughout the entire Papua New Guinea-Solomon Islands area is shown in Figures 5.1-5.5 for the depth ranges specified. Data are taken from the ISC catalogue and include all hypocenters with body wave magnitudes (Mb)>4.7 and recorded by more than 15 stations for the period 01/01/64 through 06/30/84. At very shallow depths, 0-25 and 25-50 km (Figures 5.1,5.2) the trends of the New Britain and San Cristobal trenches are clear, as are the Bismarck Sea seismic lineation and the Woodlark spreading system. Diffuse shallow seismicity is seen in the Papuan Peninsula region and within the central New Guinea Highlands. There are scattered epicenters along the Manus-North Solomon Trench. In Figure 5.3 the New Britain Trench trend clearly extends into northern Papua New Guinea. In the central Solomon Islands region two separate trends are visible: one trend south of the New Georgia Group and a second trend along Santa Isabel. At the 100-350 km level (Figure 5.4) seismicity of the New Britain Trench is continuous from south of Bougainville, through New Britain, and northern Papua New Guinea. A few events along the Papuan Peninsula are seen to join with the main New Britain Trench seismicity in the vicinity of the Huon Peninsula. In this region the seismic zone becomes much wider, reflecting the broad, arch-like character of the subducted Solomon Sea lithosphere. In the southern Solomon Islands region, a small number of events is clustered south of Santa Isabel, originating in lithosphere subducted

Figure 5.1

Summary of ISC seismicity for the Papua New Guinea-Solomon Islands region for the depth range 0-25 km. The following information pertains to Figures 5.2-5.5 as well: Included are all ISC hypocenters with body wave magnitudes greater than 4.7 and recorded by more than 15 stations for the period 01/01/64 to 06/30/84. The depth interval is indicated in the upper right corner of each figure. Land areas are drawn with a solid line; the 5 km bathymetric contour is dashed.


0-25 KM
160
155
150
145
140
3
8

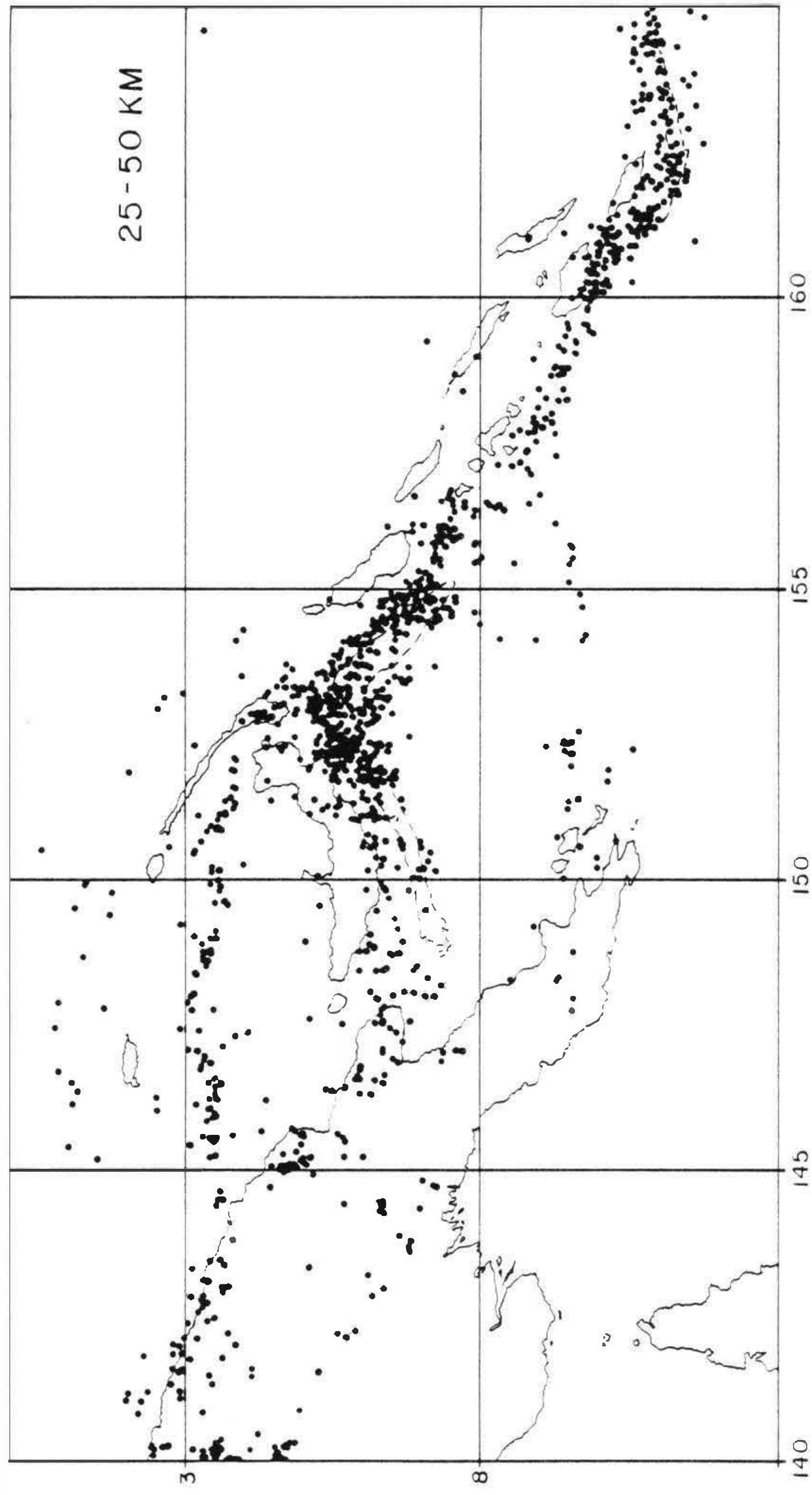


Figure 5.2 Seismicity Summary, 25-50 km.

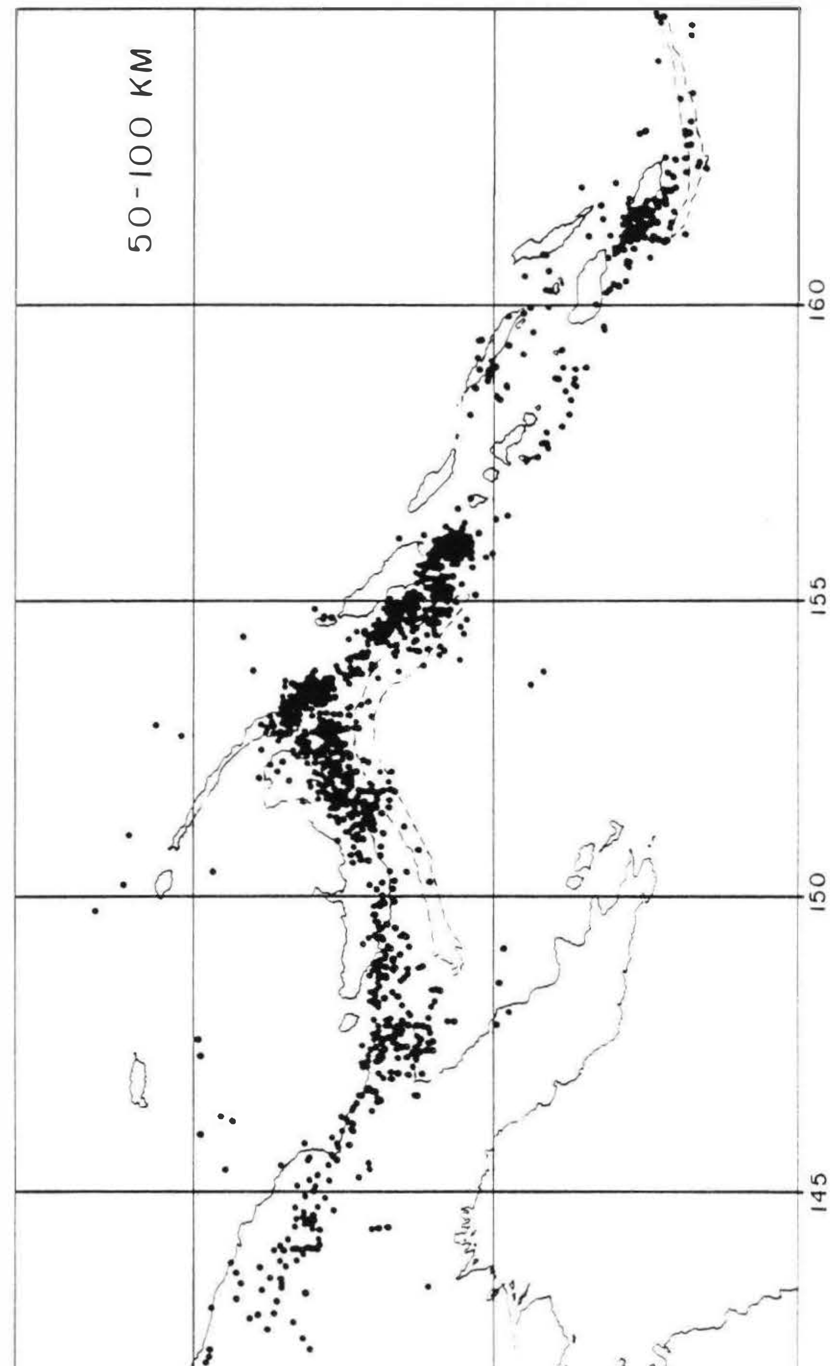


Figure 5.3 Seismicity Summary, 50-100 km.

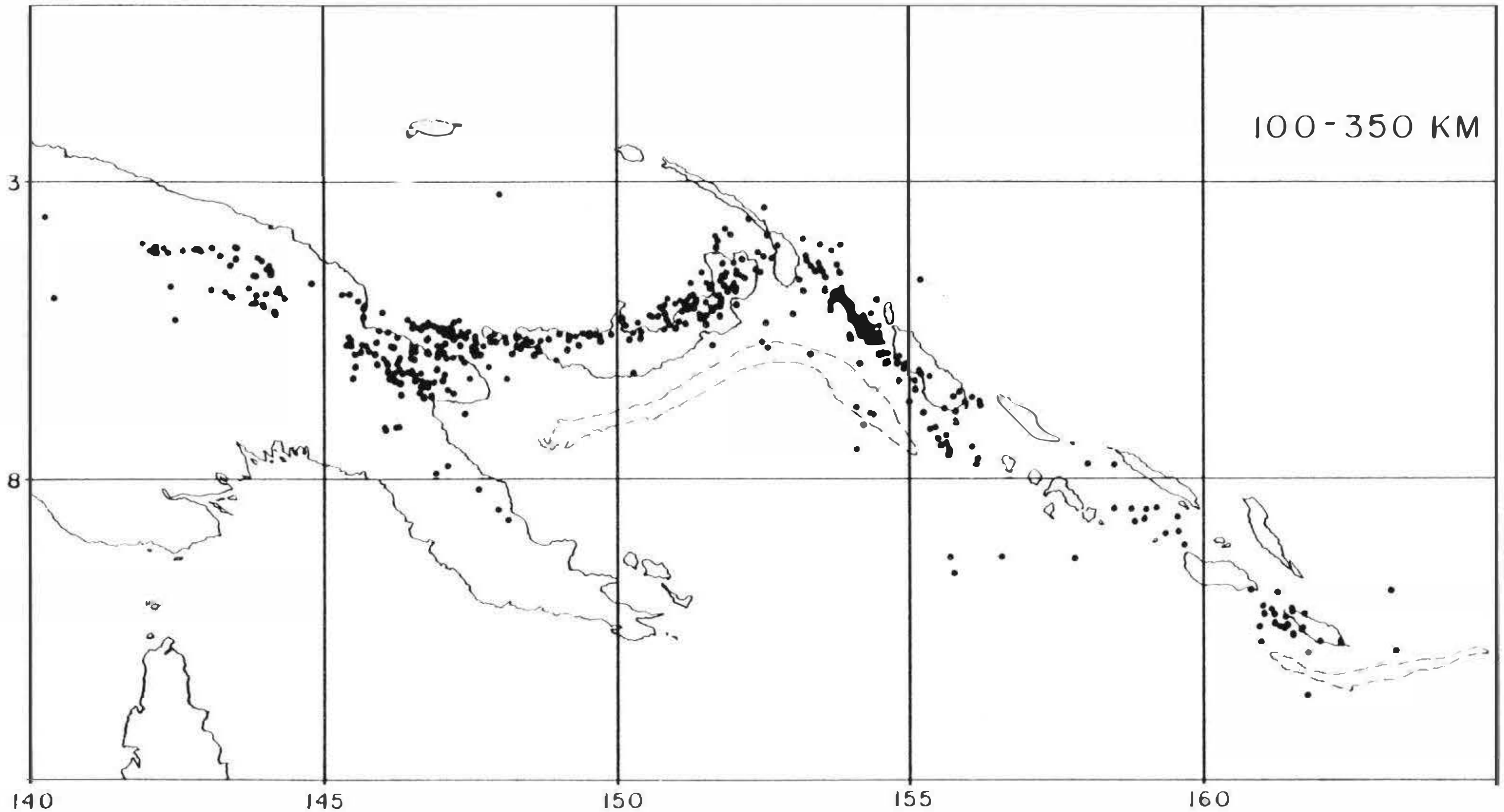


Figure 5.4 Seismicity Summary, 100-350 km.

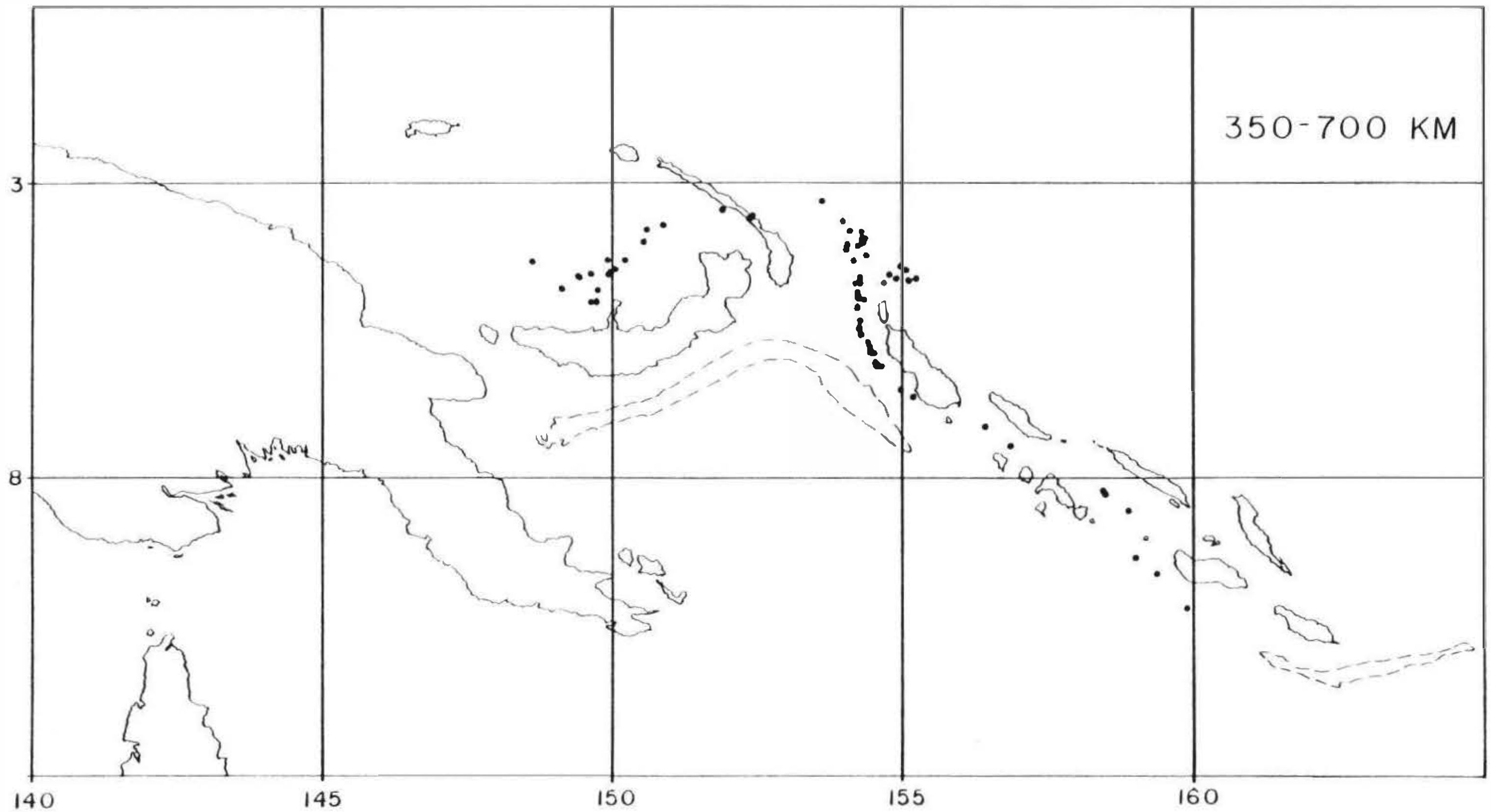


Figure 5.5 Seismicity Summary, 350-700 km.

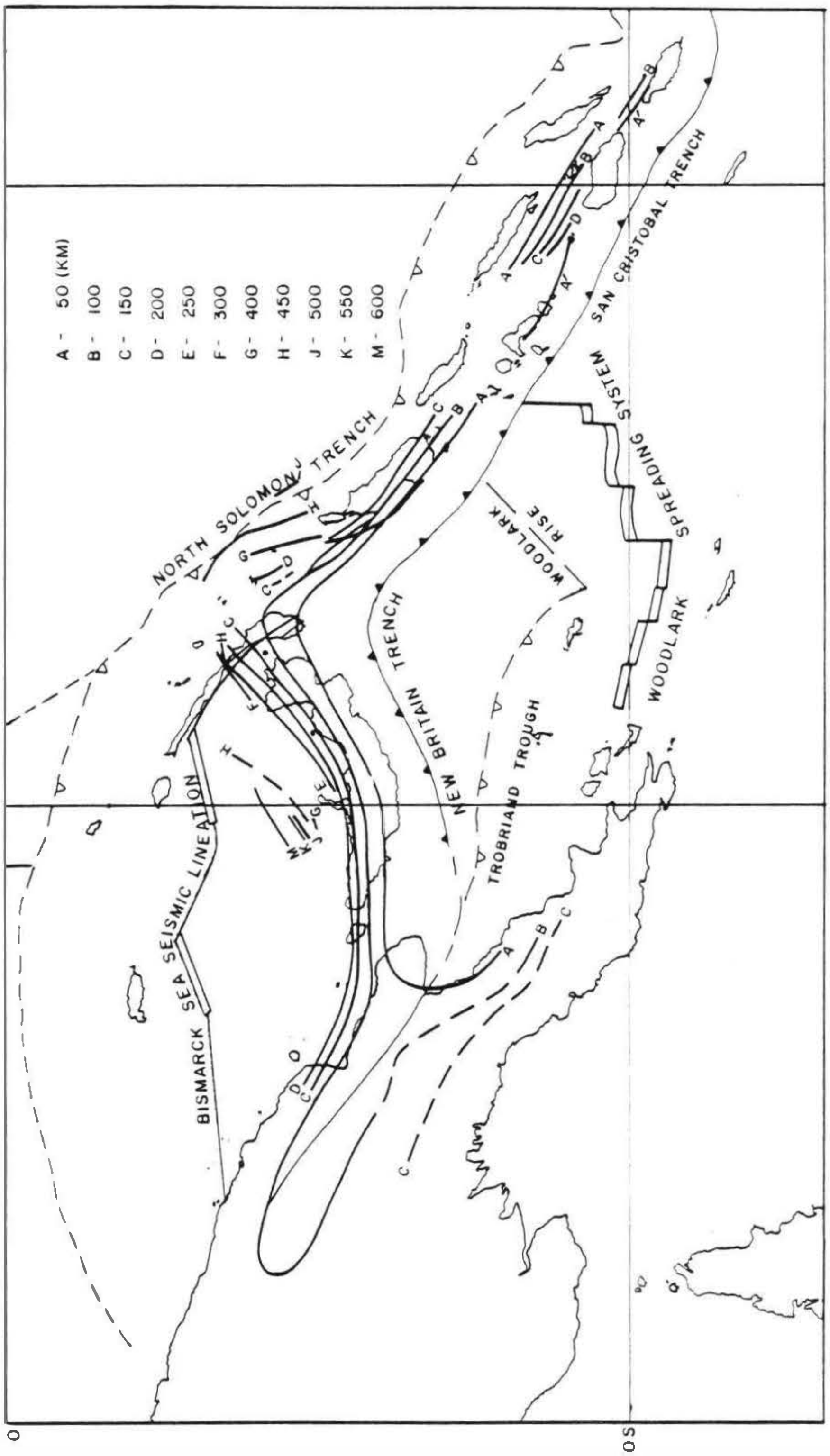
at the North Solomon Trench. A second cluster of hypocenters is located near San Cristobal, however, these events are less than 150 km deep and originate in lithosphere subducted at the San Cristobal Trench. Deep earthquakes (Figure 5.5) of the northern Solomon Islands probably occur in sections of lithosphere which are detached from the New Britain slab at about the 250-300 km level; this is fairly evident from the seismicity. The source of the deep earthquakes in the central and southern Solomon Islands is more problematical, since the North Solomon and San Cristobal slabs are in such close proximity.

A summary of Wadati-Benioff zone contours for the Papua New Guinea-Solomon Islands region based on observed seismicity is presented in Figure 5.6. There is no active volcanism associated with subduction at the San Cristobal Trench; the W-B zone extends to only about 80 km for most of its length. Although the W-B zone extends to over 100 km near San Cristobal, much of the motion in this region may be strike-slip. Collision with the Louisiade Plateau, located south of the San Cristobal Trench is imminent, if not already in progress. Active (Savo) and Plio-Pleistocene (Choiseul) volcanism is associated with a reactivation of seismicity in lithosphere subducted at the North Solomon Trench. This seismicity provides direct evidence of a southwest-dipping subduction zone at the North Solomon Trench, firmly establishing the collision of the Ontong-Java Plateau with the North Solomon Trench and the subsequent polarity reversal of the Solomon Arc

The central Solomon Islands near New Georgia is one of several sites worldwide where subduction of an active spreading system occurs. These sites are characterised by shallow, diffuse, low-magnitude

Figure 5.6

Summary of Wadati-Benioff zone contours for the Papua New Guinea-Solomon Islands region. Also shown are the axes of the New Britain, San Cristobal and North Solomon trenches, the Woodlark Rise, and the ridge and transform configurations of the Bismarck Sea seismic lineation and the Woodlark spreading system.



A - 50 (KM)
B - 100
C - 150
D - 200
E - 250
F - 300
G - 400
H - 450
J - 500
K - 550
M - 600
NORTH SOLOMON TRENCH
SAN CRISTOBAL TRENCH
WOODLARK SPREADING SYSTEM
WOODLARK RISE
NEW BRITAIN TRENCH
TROBRIAND TROUGH
BISMARCK SEA SEISMIC LINEATION
160E
150E
140E
0
10S

seismicity. No north-dipping W-B zone is defined in the central Solomon Islands, yet within 30-100 km of the topographic trench axis are the great outpourings of Plio-Pleistocene lavas which make up the New Georgia Group. Apparently, the angle formed between the ridge sections and the direction of convergence determines the presence or absence of volcanism; in the Woodlark Basin, ridge sections are subducted orthogonal to the trench axis. In contrast, subduction of ridge sections parallel or oblique to the trench axis (e.g Chile Rise) results in an absence of volcanism.

Wadati-Benioff zone contours are severely distorted around the New Britain corner. There is some active volcanism in central Bougainville, but none to the northwest, around and near the corner; active volcanism associated with the New Britain Trench resumes at Rabaul. This may be an indication of the fractured nature of the slab at the intermediate (as well as deep) level (100-300 km) on the Bougainville side of the corner. Volcanism of the Tabar-Feni Islands may be related to uplift of the southern New Ireland in the corner region. Active volcanism is seen throughout the entire New Britain Arc, as far west as the Shouten Islands. Volcanism in the western New Britain Arc (Long Island to Shouten Islands) is more highly differentiated, chemically distinct from that of New Britain Island, and may result from elevation of preexisting partial melts of the subducted Solomon Sea lithosphere within the Bismarck Sea-Indo-Australian continent-arc collision zone. Both Tabar-Feni and Shouten islands are in similar positions with respect to flexural folds in the subducted lithosphere.

Seismicity of the Papuan Peninsula is sparse, yet the nature of the westward-plunging fold in the Solomon Sea Plate lithosphere is clear. Active andesitic volcanism on the peninsula may result from continuous, extremely slow subduction along the Trobriand Trough.

Considerable controversy surrounds the existence of the Trobriand Trough W-B zone both regarding the direction of subduction and the present level of relative motion at the zone. Whereas the level of teleseismicity is quite low and focal mechanisms do not indicate tectonic activity related to motions on the cross-arc transform (Woodlark Ridge), yet the deformation front is clear of sediment and there is an inclined seismic zone associated with presently active andesitic volcanism. Island arc-type volcanism, while indicating the presence of subducted lithosphere, may not be a good indicator of active subduction; within this study region there is active subduction without island arc volcanic activity (central and southeast Solomon Islands) and island arc volcanic activity without apparent active subduction (Tabar-Feni Islands, possibly Shouten Islands). Trobriand subduction was to the south. Two anticlinal folds in the subducted lithosphere of the Solomon Sea Plate are clearly illustrated.

In a very general sense, the principles of plate tectonics can be applied to this area with good results. Caution must be exercised, however, because these small plates do not entirely control their own relative motions; their motion is controlled by the larger Pacific and Indo-Australian plates. Tectonic events occur at a much accelerated rate in buffer zones such as this. Plate motions are typically fast-subduction averaging 10-17 cm/yr and spreading rates averaging 7-10 cm/yr. The existence of seismically diffuse plate boundaries and internal deformation of theoretically "rigid" plates may be difficult concepts to accept, but considering the complexity of petrologic, stratigraphic and structural relationships within collision zones, the seismic signature should be no less complex. In this region, wherever there is collision-related tectonism, we see diffuse seismicity. At least one of the smaller plates contains paleo-plate boundaries which may be active.

It is clear that, as suggested by Johnson and Jaques (1980), reversals in subduction polarity ("flips") do not usually occur according to the classic model proposed by Mackenzie (1969)-at least not in the Papua New Guinea-Solomon Islands region. The actual change in the site of subduction must happen almost instantaneously on a geologic time scale, since the time elapsed while one trench shuts down completely (no further introduction of new material into the upper mantle, hence no further volcanism) until another trench is established and generating island arc volcanics is only about 1-2 my. The old slab does not break off as a rule, because the new site of subduction is typically 100-300 km away. The inactive slab remains intact and is usually seismically quiet within 10-15 my unless it is affected by later episodes of subduction, i.e. unless the inactive slab collides with some other deep structure (e.g. another slab).

The Melanesian convergent boundary is made up of several subduction zones and their associated marginal basins. Back arc spreading in this region appears to be a response to short term changes in the relative motions of the smaller plates buffering the motion between the large Pacific and Indo-Australian plates. An indication of this is the similar life-span for both active back-arc spreading systems and subduction zones - typically 5-10 my.

This region has been a convergent zone between the Pacific and Indo-Australian plates for over 50 my and will continue as such until the next major reorganization of plate motions. Subduction zones within the Melanesian convergent zone have been migrating northwards, away from the Australian continent. Subduction along the New Britain-San Cristobal-New Hebrides arc-trench system is now a complex, almost futile, process and may be nearing an end. The San Critobal Trench already shows several signs of inactivity - (1) Seismicity extends to only 100 km, (2) There is no active volcanism, and (3) Motion along this section of trench is largely strike-slip (southeast of San Cristobal Island, motion is entirely strike slip). Immediately to the south of the San Cristobal Trench is the Louisiade Plateau. The areal extent and crustal thickness of the plateau is unknown, but it may already be entering the trench. To the east, the D'Entrecasteaux Ridge enters and bisects the New Hebrides Trench and to the West, the Woodlark spreading system enters the New Britain Trench. It is possible that within the next 1-2 my, this arc-trench system will become inactive. There is no site within the convergent zone suitable for establishing another subduction zone (for a significant length of time). Obduction of the Pacific Plate onto Malaita and extensive uplift of the central Solomons is an ongoing process (Cooper et al., in press; Kroenke et al., in press; Resig et al., in press). One may speculate that further uplift, deformation and obduction onto existing island arcs is in store as the New Britain-San Cristobal-New Hebrides subduction system fails. Subduction may be reestablished at a site north of Ontong-Java Plateau, outside the present Melanesian convergent zone. Earthquakes have been reported for the area north of OJP by Walker and McCreery (1985); low amplitude sea floor features indicate recent deformation and resemble classic trench-forearc morphology (Kroenke and Walker, 1985). Finally, the continued formation, deformation and uplift of successive generations of island arcs, together with interactions with large oceanic plateaus (such as Louisiade and Ontong-Java) may play a significant role in the formation of continental land masses.

APPENDIX I

New and previously published focal mechanism solutions for earthquakes in the Papua New Guinea-Solomon Islands region. Tension axes and poles to the nodal planes are given in terms of azimuth and plunge. The data source code is explained in the text. Solutions by Wickens and Hodgeson (1967) are included for completeness but were not used in the analysis of relative motions. Blanks indicate data which were unavailable during compilation of this table.

APPENDIX I

#	DATE (d/m/y)	LAT. (^{o}S)	LONG. (^{o}E)	DEPTH (km)	AZ/PLUNGE OF POLES TO NODAL PLANES		T- AXIS	SOURCE
1	06/10/36	5.50	147.00	160	203/25	102/22	152/35	WH
2	08/31/38	4.00	151.50	350	220/22	127/08	171/21	WH
3	09/04/41	4.50	154.00	100	193/18	093/26	145/32	WH
4	12/01/43	4.50	144.00	100	085/00	175/08	220/05	WH
5	01/17/46	6.20	147.70	100	262/17	007/41	050/14	WH
6	11/08/50	9.70	159.50	33	139/30	240/19	097/17	*WH
7	12/04/50	5.00	153.50	100	195/03	286/13	331/07	WH
8	02/17/51	7.00	146.00	225	090/06	182/17	227/07	*WH
9	11/06/52	5.00	145.50	33	322/14	227/18	275/23	WH
10	11/28/52	6.50	155.50	100	192/16	337/71	003/29	WH
11	12/24/52	5.50	152.00	33	064/01	154/03	199/02	*WH
12	04/23/53	4.00	154.00	33	163/08	073/05	118/09	WH
13	12/02/53	2.70	141.50	33	273/14	179/17	227/22	*WH
14	03/03/54	5.50	142.50	33	185/14	177/08	141/04	WH
15	06/07/54	3.50	152.50	475	101/75	346/07	001/50	*WH
16	08/16/55	6.00	155.00	220	250/08	158/12	204/14	WH
17	10/13/55	9.50	161.00	33	251/48	072/42	084/87	WH
18	01/31/56	4.00	152.00	400	272/44	182/45	087/01	WH
19	05/22/56	4.00	152.50	540	329/22	188/62	302/63	WH
20	10/22/60	10.30	161.20	93	228/33	318/00	178/22	WH
21	01/05/61	4.10	143.00	108	356/23	264/03	308/19	*WH
22	06/18/62	4.80	151.80	47	048/25	316/04	359/20	WH
23	06/18/62	5.00	152.00	103	349/40	169/50	349/85	IM
24	07/30/62	3.60	143.70	33	004/10	276/40	326/32	JM
25	01/28/63	2.60	149.90	32	112/00	024/06	338/04	JM
26	01/28/63	2.80	149.80	33	292/01	022/21	335/15	*R1
27	02/13/63	9.90	160.70	30	056/16	236/74	056/61	JM
28	02/26/63	7.60	146.20	182	085/00	175/70	249/41	IM
29	02/26/63	7.50	146.20	171	270/02	168/78	260/45	R1
30	02/27/63	6.10	149.20	57	003/30	146/64	033/68	JM
31	02/27/63	6.00	149.40	52	342/32	223/36	285/53	*R1
32	01/12/64	5.40	146.80	227	163/38	034/39	099/62	R1
33	01/14/64	5.20	150.80	169	334/10	154/80	334/55	IM
34	03/06/64	6.10	154.40	74	042/45	222/45	122/81	JM
35	04/17/64	6.60	154.90	85	037/40	217/50	037/85	JM
36	04/17/64	6.60	155.00	74	190/44	059/34	113/64	R1
37	04/24/64	5.10	144.20	98	093/10	269/80	264/35	IM
38	04/24/64	5.10	144.20	99	079/06	319/77	271/38	R1
39	04/30/64	4.60	153.20	78	015/34	195/56	015/79	JM
40	06/28/64	1.80	149.70	7	139/10	230/05	094/03	R1
41	07/31/64	6.10	149.40	63	006/34	194/56	350/78	JM
42	08/13/64	5.50	154.30	392	044/54	244/34	056/10	IM
43	08/13/64	5.50	154.30	392	041/58	255/28	061/15	R1
44	09/12/64	4.46	144.08	107	035/02	215/88	035/47	IM

45	11/17/64	5.70	150.70	45	356/34	176/56	356/80	JM
46	11/19/64	6.00	150.80	3	324/14	144/76	324/59	JM
47	12/07/64	5.40	151.30	54	318/36	109/60	009/73	JM
48	02/25/65	5.50	152.00	35	353/30	168/60	000/74	JM
49	03/03/65	5.50	151.90	44	358/30	224/50	312/64	JM
50	07/06/65	4.50	155.00	509	175/21	023/66	004/24	IM
51	07/06/65	4.50	155.10	509	058/56	163/10	008/27	R1
52	07/17/65	9.70	159.80	33	012/38	198/52	349/82	JM
53	08/05/65	5.30	151.70	47	314/40	114/48	014/79	JM
54	08/12/65	5.30	152.20	41	340/22	160/68	340/67	JM
55	10/17/65	8.00	155.90	93	024/30	226/58	356/72	JM
56	11/27/65	9.70	158.70	31	078/10	258/80	078/56	JM
57	12/07/65	6.40	146.30	118	248/23	339/03	202/14	R1
58	12/26/65	5.40	151.60	74	330/00	240/65	308/40	IM
59	02/22/66	5.40	151.50	28	334/30	154/60	334/75	JM
60	02/22/66	5.40	151.60	59	322/41	142/49	322/86	*R1
61	06/15/66	10.40	160.80	31	132/06	025/70	110/47	JM
62	08/05/66	11.10	162.60	52	031/40	198/49	079/82	IM
63	12/10/66	3.60	145.40	33	092/04	002/00	137/02	JM
64	12/14/66	4.86	144.04	80	212/30	032/60	212/75	IM
65	12/14/66	4.80	143.90	74	210/26	046/64	196/69	JM
66	12/23/66	7.10	148.30	43	333/62	174/26	197/70	JM
67	12/23/66	7.10	148.30	46	153/31	333/31	153/80	R1
68	01/13/67	10.60	161.40	32	088/22	268/66	089/68	JM
69	03/17/67	3.60	150.90	33	022/00	112/20	158/14	JM
70	03/17/67	3.60	150.80	33	295/01	025/04	340/04	*R1
71	03/18/67	6.00	146.30	101	103/35	359/21	145/09	*R1
72	03/26/67	9.30	148.60	14	229/50	139/00	172/33	*R3
73	04/10/67	7.40	155.70	30	051/30	217/60	070/74	JM
74	04/10/67	7.30	155.80	30	032/20	200/69	031/65	JM
75	04/10/67	7.30	155.80	47	165/65	029/19	052/60	*R1
76	06/13/67	5.51	148.22	213	024/16	137/55	059/50	IM
77	08/13/67	4.40	152.50	29	114/00	024/02	319/01	JM
78	09/01/67	5.56	147.27	182	018/42	157/40	090/68	IM
79	09/12/67	5.50	151.70	50	355/10	175/80	355/55	JM
80	09/18/67	5.90	146.60	39	196/48	040/40	117/76	JM
81	09/28/67	6.60	153.40	44	220/57	052/32	220/14	JM
82	09/28/67	6.60	153.40	44	181/45	050/33	208/07	*R1
83	10/04/67	5.70	153.90	52	035/50	215/40	215/85	JM
84	10/04/67	5.70	153.90	52	215/30	353/52	251/63	*R1
85	10/08/67	5.60	154.00	70	264/46	040/35	343/66	R1
86	10/08/67	9.49	148.84	17	128/32	358/46	072/61	JM
87	10/08/67	9.50	148.80	17	287/56	058/24	023/61	*R3
88	10/09/67	5.70	154.00	41	040/30	220/60	040/74	JM
89	11/14/67	5.52	147.19	201	033/24	154/50	077/56	IM
90	11/14/67	5.40	147.10	201	151/42	024/34	080/60	R1
91	12/25/67	5.30	153.70	64	022/44	202/46	022/90	JM
92	01/04/68	9.90	148.90	19	319/58	232/84	010/27	*R3
93	01/07/68	5.10	153.90	118	048/45	261/40	328/71	IM
94	01/07/68	5.10	153.90	118	222/25	005/59	253/66	*R1
95	01/19/68	9.40	158.40	33	355/19	262/12	308/24	JM
96	02/12/68	5.50	153.20	74	059/05	329/08	013/10	R1
97	04/24/68	4.60	149.40	565	129/30	004/44	077/59	R1
98	04/25/68	7.10	156.20	419	132/06	232/56	163/41	*R1

99	05/11/68	6.40	147.30	76	211/44	061/42	133/75	R1
100	06/02/68	8.10	158.60	35	132/08	041/11	356/02	R1
101	06/03/68	5.40	147.00	190	077/23	174/19	126/30	*R1
102	06/08/68	8.70	157.50	33	042/02	222/88	042/47	JM
103	07/21/68	3.20	150.70	5	036/01	306/05	352/05	R1
104	08/18/68	10.10	159.90	538	096/41	334/32	127/05	R1
105	08/18/68	10.12	159.90	542	112/50	353/20	148/16	P
106	09/08/68	3.70	142.90	29	002/32	258/20	305/38	JM
107	09/08/68	3.70	143.00	29	236/50	070/39	112/81	*R1
108	09/16/68	6.10	148.70	59	194/52	008/38	346/82	R1
109	09/27/68	3.70	143.30	7	208/53	062/32	102/70	R1
110	10/23/68	3.30	143.30	12	282/04	013/10	327/11	R1
111	11/28/68	6.80	156.20	169	132/38	343/48	326/05	R1
112	12/07/68	3.40	145.90	15	275/07	005/06	320/02	R1
113	12/22/68	3.40	148.80	33	116/11	025/04	161/05	*R1
114	01/05/69	8.00	158.90	47	153/62	026/18	189/23	R2
115	03/10/69	5.60	147.20	206	029/22	152/54	066/57	R2
116	04/16/69	3.50	150.90	39	305/05	236/06	350/09	JM
117	04/16/69	3.50	151.00	39	321/04	051/10	006/10	C
118	04/16/69	3.50	151.00	39	039/09	128/05	173/01	R2
119	05/31/69	4.90	154.20	403	083/27	301/58	277/17	R2
120	06/24/69	5.80	146.80	113	310/05	041/06	354/08	R2
121	07/29/69	3.40	144.80	6	188/04	051/10	233/10	*C
122	08/05/69	5.25	153.72	73	042/50	222/40	222/85	P
123	08/07/69	5.30	154.10	116	085/61	216/21	185/60	C
124	08/26/69	5.80	151.20	59	113/30	211/28	158/43	*C
125	08/26/69	5.80	151.20	59	070/36	294/45	011/66	R2
126	11/12/69	6.09	148.74	76	171/30	351/60	171/75	C
127	11/12/69	6.09	148.74	76	170/32	350/58	170/77	P
128	01/06/70	9.60	151.50	8	118/10	226/12	253/02	C
129	01/06/70	9.60	151.50	8	228/37	135/04	174/28	R2
130	01/06/70	9.62	151.50	8	258/15	354/20	037/03	WT
131	03/28/70	6.30	154.60	64	225/39	037/50	264/83	C
132	03/28/70	6.30	154.60	64	037/60	229/28	238/74	R2
133	03/28/70	6.25	154.76	51	040/51	220/39	220/84	P
134	03/28/70	6.40	154.65	64	012/46	224/40	288/73	PC
135	04/28/70	8.10	156.40	5	229/16	325/20	276/26	*C
136	04/28/70	8.10	156.40	5	216/74	040/16	044/59	*R3
137	05/19/70	5.20	152.30	65	319/00	049/06	004/05	C
138	06/25/70	7.88	158.82	66	173/15	353/75	173/30	P
139	06/25/70	8.00	158.73	45	341/81	161/09	161/54	PC
140	08/03/70	7.95	158.72	42	047/34	160/30	012/02	PC
141	08/19/70	10.50	161.50	33	292/64	087/24	068/67	*R2
142	08/19/70	10.54	161.38	35	052/04	321/04	007/06	PC
143	08/27/70	4.85	153.18	61	017/25	197/65	017/70	PC
144	08/28/70	4.60	153.10	88	215/60	007/27	337/69	R2
145	09/23/70	6.60	154.58	54	034/45	214/45	054/90	P
146	09/23/70	6.50	154.60	58	034/45	214/45	054/90	P
147	09/23/70	6.65	154.70	42	352/36	227/38	292/58	PC
148	10/13/70	4.10	143.00	120	211/30	353/54	254/68	R2
149	10/31/70	4.90	145.50	42	204/18	089/52	164/51	R2
150	10/31/70	4.99	145.57	37	066/02	154/06	108/04	P
151	10/31/70	4.95	145.45	45	058/38	178/34	121/56	*PC
152	11/28/70	4.10	142.90	114	215/52	011/36	327/76	R2

153	11/28/70	4.14	142.83	119	051/34	141/02	101/25	*PC
154	12/28/70	5.13	153.67	61	114/10	294/80	114/55	P
155	12/28/70	5.30	153.62	70	022/60	122/06	094/43	PC
156	12/29/70	10.50	161.40	72	236/44	064/46	150/86	R2
157	12/29/70	10.54	161.60	45	073/42	253/48	073/87	P
158	12/29/70	10.66	161.39	60	063/36	243/54	063/81	PC
159	01/25/71	9.60	151.40	38	352/52	129/30	326/12	R2
160	01/25/71	9.80	151.46	31	020/41	122/16	080/41	*PC
161	02/12/71	6.28	146.50	123	025/12	205/12	205/33	PC
162	02/26/71	10.40	161.30	90	342/40	131/46	045/74	*R2
163	02/26/71	10.59	161.39	92	067/66	303/14	314/53	*PC
164	03/13/71	5.70	145.40	118	002/30	132/49	161/08	R2
165	03/13/71	5.78	145.37	111	015/30	230/54	210/12	P
166	03/13/71	5.78	145.32	114	042/30	170/48	200/10	*PC
167	07/14/71	5.60	153.80	43	039/34	181/50	092/69	C
168	07/14/71	5.50	153.90	47	261/36	026/38	322/58	R2
169	07/14/71	5.50	153.79	65	035/38	285/30	340/43	P
170	07/14/71	5.50	153.90	53	255/45	---/--	---/--	LK
171	07/18/71	5.07	153.22	47	030/00	300/24	347/27	PC
172	07/19/71	5.50	150.60	33	021/36	133/28	345/05	R2
173	07/19/71	5.94	153.74	37	051/31	321/04	101/18	PC
174	07/26/71	5.20	153.30	35	228/50	018/36	325/73	C
175	07/26/71	4.90	153.20	48	025/22	152/56	062/58	R2
176	07/26/71	4.87	153.24	53	227/50	347/22	304/54	P
177	07/26/71	4.90	153.20	43	150/50	---/--	---/--	LK
178	07/26/71	5.11	153.11	46	328/20	221/55	314/53	PC
179	07/28/71	5.28	152.80	31	061/04	318/74	254/40	*PC
180	08/09/71	5.88	154.38	60	034/50	214/50	214/85	P
181	08/09/71	6.06	154.30	46	038/49	218/41	218/86	PC
182	08/09/71	5.71	152.18	30	333/09	153/81	333/54	P
183	08/23/71	4.00	146.10	33	256/00	166/00	121/00	R2
184	09/14/71	6.50	151.50	33	191/56	328/26	164/16	R2
185	09/14/71	6.40	151.56	18	212/56	322/12	166/25	P
186	09/14/71	6.51	151.60	22	---/--	---/--	---/--	*PC
187	09/25/71	6.50	146.60	115	228/57	003/24	200/17	R2
188	09/25/71	6.52	146.63	106	018/19	270/41	230/13	P
189	09/25/71	6.54	146.64	126	006/24	186/66	186/21	PC
190	09/27/71	3.20	148.10	33	303/06	034/14	347/15	R2
191	10/03/71	6.73	154.96	58	031/12	300/10	345/16	PC
192	10/04/71	6.02	154.16	52	005/08	096/14	141/04	PC
193	10/28/71	5.50	153.90	120	208/26	333/50	225/59	R2
194	12/04/71	5.98	154.53	79	038/50	218/40	218/85	P
195	12/04/71	6.14	154.54	78	029/54	209/36	209/81	PC
196	12/11/71	6.11	154.49	63	034/35	248/50	340/72	PC
197	12/30/71	4.70	151.90	109	329/24	075/30	112/03	R2
198	12/30/71	4.89	152.00	110	326/24	072/30	110/04	PC
199	01/06/72	4.67	151.86	152	008/56	104/04	312/33	PC
200	01/18/72	4.80	145.12	25	256/08	347/10	312/14	P
201	01/19/72	4.90	145.18	100	264/32	084/58	084/13	PC
202	01/19/72	4.87	144.94	23	267/32	087/58	087/13	PC
203	03/25/72	3.59	150.16	30	294/08	026/16	338/18	WT
204	04/28/72	5.10	154.24	417	079/34	259/56	259/11	P
205	04/28/72	5.31	154.20	417	081/34	261/56	261/11	PC
206	05/05/72	4.21	152.80	17	239/28	143/10	188/28	P

207	08/04/72	11.08	162.08	30	028/16	208/74	028/61	P
208	08/04/72	11.01	162.15	37	028/16	208/74	028/61	P
209	08/06/72	11.14	162.18	24	064/02	244/88	064/47	P
210	08/06/72	11.18	161.96	36	334/28	238/10	019/12	*PC
211	08/17/72	5.88	152.79	22	164/66	344/24	164/12	P
212	08/17/72	6.12	152.76	11	018/40	251/36	045/02	PC
213	08/30/72	3.51	144.92	12	260/90	350/00	305/06	WT
214	09/11/72	3.54	149.88	0	284/12	017/12	332/10	WT
215	10/28/72	7.33	146.83	2	328/11	232/30	284/29	WT
216	10/28/72	7.29	146.73	2	110/07	205/31	252/17	PC
217	10/30/72	6.46	154.78	51	043/40	297/20	343/44	*PC
218	12/16/72	7.20	155.77	97	039/46	190/40	123/75	PC
219	01/10/73	11.06	162.21	4	034/01	304/10	349/08	PC
220	01/18/73	6.86	150.00	47	163/28	339/62	168/18	P
221	01/18/73	7.03	150.07	38	064/54	178/14	140/48	PC
222	02/14/73	10.11	160.91	30	055/46	155/10	115/40	PC
223	05/01/73	10.00	150.00	27	184/44	041/40	024/03	R3
224	05/01/73	10.00	150.20	15	180/32	058/40	028/04	WT
225	05/01/73	10.06	150.28	15	000/38	246/28	036/06	PC
226	05/02/73	10.00	150.20	29	045/38	163/32	011/03	R3
227	05/02/73	9.96	150.21	29	038/35	158/35	188/01	WT
228	05/22/73	10.00	150.30	13	046/46	159.20	007/16	*R3
229	06/09/73	10.34	161.36	79	084/59	217/22	184/60	PC
230	08/13/73	4.54	143.94	109	048/14	228/76	048/59	PC
231	08/24/73	7.37	156.03	34	108/20	214/40	154/42	PC
232	11/26/73	8.60	154.00	15	050/03	164/72	057/97	R3
233	01/31/74	7.50	155.90	16	039/62	---/--	---/--	LK
234	01/31/74	7.52	155.78	15	356/10	263/16	310/20	PC
235	02/01/74	7.80	155.60	16	032/56	---/--	---/--	LK
236	02/01/74	7.42	155.73	37	036/20	216/70	036/65	PC
237	03/09/74	7.66	156.20	35	045/31	212/60	063/29	PC
238	06/24/74	2.29	141.00	51	009/30	125/39	159/04	PC
239	06/27/74	4.83	152.58	50	068/46	314/22	000/50	PC
240	07/19/74	6.11	154.90	165	089/72	269/18	089/27	PC
241	09/20/74	6.28	145.94	105	076/40	172/06	133/33	PC
242	10/16/74	6.36	148.35	70	053/15	283/66	030/55	PC
243	10/23/74	8.40	154.00	48	222/72	080/76	093/57	R3
244	10/23/74	8.40	154.03	18	309/13	216/03	352/04	WT
245	10/23/74	8.60	154.17	11	305/10	215/04	351/04	PC
246	11/19/74	3.20	150.59	18	299/06	031/08	345/10	WT
247	12/02/74	6.31	153.03	32	015/38	195/52	195/07	PC
248	02/27/75	6.11	148.22	40	306/07	126/83	126/38	PC
249	06/06/75	4.50	153.53	61	043/20	135/06	357/10	PC
250	06/16/75	3.10	148.00	39	294/02	025/10	339/08	WT
251	07/11/75	10.40	161.20	72	352/26	172/64	172/19	PC
252	07/20/75	6.60	155.10	16	036/54	---/--	---/--	LK
253	07/20/75	6.80	155.03	43	023/34	203/56	023/79	PC
254	07/20/75	7.10	155.20	33	033/50	---/--	---/--	LK
255	07/31/75	5.29	152.74	51	010/20	269/82	001/46	PC
256	08/06/75	2.51	146.03	35	338/10	068/20	292/05	WT
257	08/06/75	2.51	146.13	33	078/02	168/16	122/13	PC
258	08/14/75	6.88	147.71	53	334/44	228/16	016/15	PC
259	08/21/75	6.75	154.98	54	063/30	243/60	063/70	PC
260	10/11/75	3.39	148.61	33	205/07	115/00	160/05	WT

261	11/25/75	9.16	156.70	33	329/04	059/00	284/03	WT
262	12/07/75	4.64	153.39	29	045/26	144/18	003/05	PC
263	12/17/75	7.17	155.69	41	345/24	108/50	030/56	*PC
264	02/06/76	6.03	146.27	37	058/10	238/80	058/55	PC
265	02/22/76	6.44	156.82	71	064/50	244/40	244/85	*PC
266	03/02/76	6.31	154.80	68	039/44	295/14	336/42	*PC
267	03/06/76	7.27	155.47	45	070/50	250/40	230/85	*PC
268	04/06/76	3.96	152.36	21	294/04	202/12	156/06	PC
269	04/19/76	8.50	148.20	30	306/64	131/26	136/70	R3
270	05/09/76	7.65	154.60	34	262/35	016/30	227/03	R3
271	05/11/76	7.83	154.66	19	057/30	162/24	111/04	PC
272	05/21/76	5.93	145.77	112	348/40	244/18	030/13	PC
273	05/22/76	5.69	154.36	115	018/68	227/20	242/63	PC
274	05/23/76	5.03	153.74	122	088/58	268/32	268/77	PC
275	06/03/76	5.15	153.24	95	340/28	096/40	032/42	PC
276	06/05/76	10.21	161.03	74	032/46	212/44	212/89	*PC
277	06/25/76	4.56	140.07	33	025/37	288/10	330/24	PC
278	06/27/76	4.52	140.18	33	005/61	225/20	253/61	PC
279	07/07/76	9.50	154.30	17	300/58	173/20	333/20	*R3
280	09/16/76	9.20	148.10	15	190/74	295/86	128/39	R3
281	09/16/76	9.31	148.32	33	278/70	206/20	112/65	PC
282	10/05/76	6.58	152.99	33	346/30	236/30	021/00	PC
283	10/12/76	10.50	161.26	111	075/86	255/04	075/41	*PC
284	11/18/76	8.80	156.90	33	235/30	016/44	260/60	R3
285	11/18/76	8.82	156.90	18	062/08	328/20	284/08	PC
286	01/06/77	3.64	144.45	33	000/00	090/00	135/00	WT
287	01/06/77	3.56	144.48	33	088/00	178/16	132/11	PC
288	01/27/77	6.54	152.84	58	154/15	245/02	200/12	PC
289	04/20/77	9.92	160.36	26	040/20	220/70	040/65	PC
290	04/21/77	10.08	160.67	16	084/26	329/40	033/49	PC
291	07/02/77	10.02	160.47	21	082/32	333/28	025/44	PC
292	07/08/77	5.93	154.61	138	346/30	239/30	204/00	*PC
293	07/29/77	8.21	155.70	47	090/10	208/70	110/52	PC
294	08/08/77	10.60	161.19	40	348/40	251/06	037/22	*PC
295	08/12/77	6.60	154.98	62	096/54	276/36	276/81	*PC
296	10/29/77	6.32	146.54	111	022/12	123/42	189/20	PC
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298	11/22/77	10.33	161.10	74	015/12	268/52	222/25	PC
299	12/30/77	5.22	151.86	67	020/40	146/35	088/60	PC
300	01/24/78	5.98	148.83	79	050/06	320/04	005/08	PC
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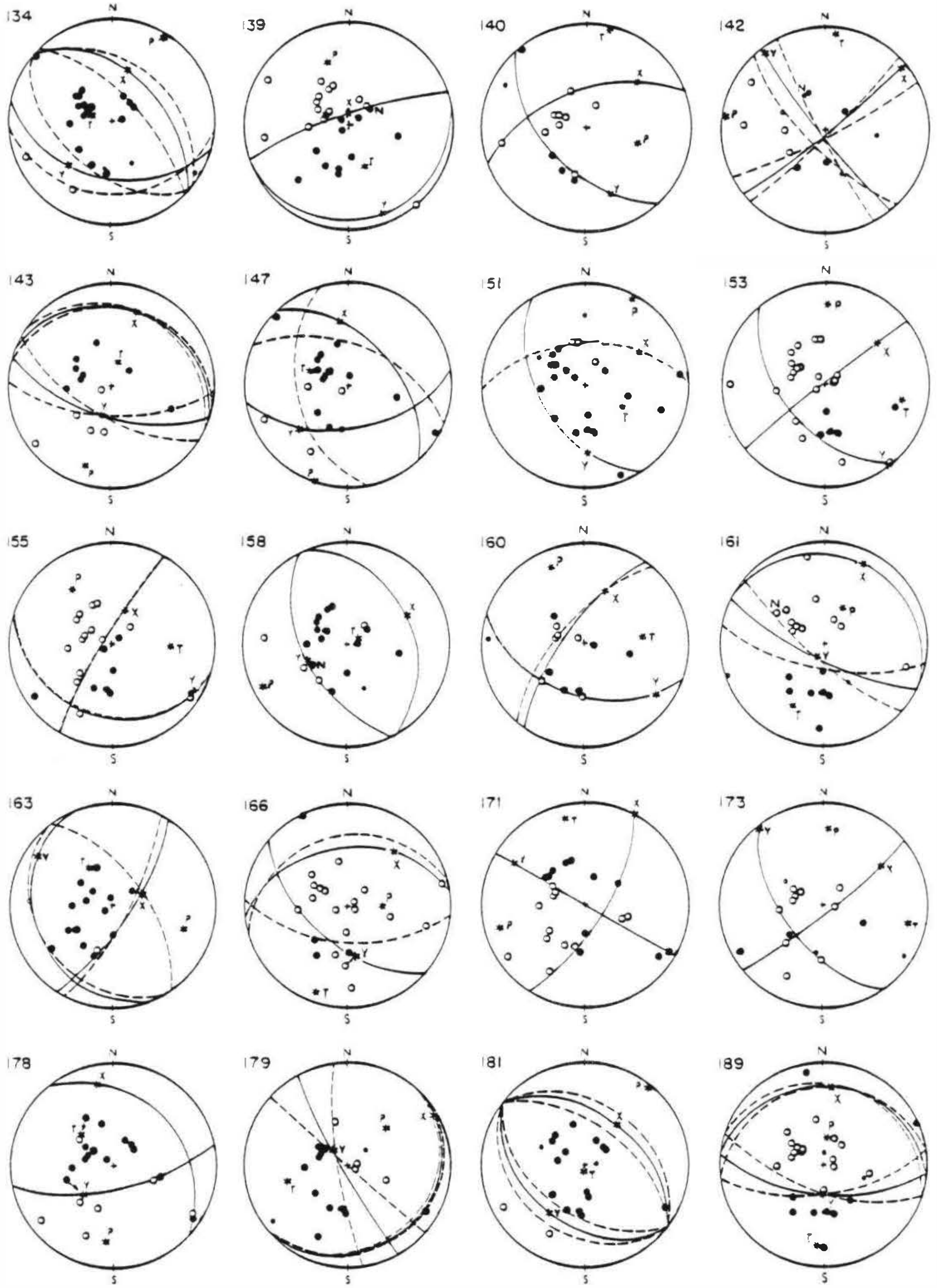
302	04/11/78	9.55	148.94	48	081/02	171/08	216/04	PC
303	04/29/78	9.97	160.46	49	027/06	295/20	342/18	PC
304	08/05/78	3.63	151.17	38	062/18	156/13	018/04	PC
305	09/01/78	7.61	156.47	33	300/02	210/08	165/04	PC
306	10/29/78	5.54	152.19	39	105/06	197/08	151/10	PC
307	11/04/78	11.43	161.91	33	291/14	198/10	335/02	PC
308	11/05/78	11.25	162.09	33	076/12	256/78	076/57	PC
309	11/07/78	11.00	162.11	33	076/26	171/10	127/26	PC
310	11/10/78	11.20	162.08	33	052/14	144/10	098/17	PC
311	11/19/78	7.35	154.84	15	048/34	152/21	104/40	PC
312	12/01/78	10.30	161.52	93	001/36	256/20	302/41	PC
313	12/21/78	11.20	162.58	30	003/00	273/10	318/06	PC
314	03/09/79	9.60	147.90	33	235/34	121/30	176/48	R3

315	06/13/79	6.53	147.25	81	029/22	143/42	180/14	PC
316	08/13/79	5.04	153.73	84	281/80	101/10	101/55	PC
317	11/06/79	9.55	159.73	30	043/36	223/54	043/81	PC
318	02/06/80	8.14	156.30	40	044/36	275/42	344/62	PC
319	02/12/80	4.93	153.21	75	336/15	156/75	336/60	PC
320	02/22/80	10.74	161.84	68	013/18	106/09	329/06	PC
321	02/27/80	6.17	150.23	53	006/38	186/52	006/83	PC
322	03/29/80	4.71	154.96	474	036/68	216/22	036/23	PC
323	04/25/80	6.54	152.37	33	009/40	129/30	337/06	PC
324	05/05/80	6.12	154.33	47	091/74	271/16	271/61	PC
325	05/10/80	6.27	154.33	67	038/40	305/04	344/30	PC
326	05/14/80	6.25	154.63	57	097/36	217/34	159/54	PC
327	06/18/80	5.18	154.11	61	289/30	109/60	289/75	PC
328	06/25/80	5.23	151.69	49	026/36	206/54	026/81	PC
329	06/25/80	6.47	146.95	21	056/28	236/62	056/73	PC
330	06/25/80	4.86	145.89	180	043/62	223/28	043/17	PC
331	07/16/80	4.42	143.18	80	354/18	174/72	354/63	PC
332	09/26/80	3.20	142.41	33	300/14	191.52	261/47	PC
333	09/28/80	6.44	154.89	68	005/36	260/20	306/41	PC
334	08/19/80	3.58	140.04	33	354/02	084/00	310/01	PC
335	10/19/80	6.22	145.37	125	048/80	228/10	228/55	PC
336	01/19/81	3.45	146.22	10	356/24	086/83	313/00	DW
337	02/24/81	6.13	148.91	78	018/53	176/35	317/76	DW
338	03/06/81	6.28	154.51	67	021/44	230/42	303/75	DW
339	03/21/81	5.48	146.88	233	142/55	037/10	070/45	DW
340	04/05/81	6.12	154.34	417	250/55	010/19	212/20	DW
341	04/05/81	6.15	154.65	413	026/20	206/70	206/25	PC
342	04/10/81	4.37	147.41	25	333/38	067/04	284/23	DW
343	05/09/81	5.29	154.86	73	002/30	182/60	002/75	PC
344	05/28/81	5.57	151.48	55	176/59	297/17	264/55	DW
345	08/07/81	5.25	151.89	66	005/34	161/54	045/75	DW
346	08/26/81	5.44	151.45	64	004/30	238/50	339/76	DW
347	10/04/81	4.55	146.37	20	246/20	342/16	295/26	DW
348	10/04/81	9.70	159.57	14	066/17	191/62	095/56	DW
349	10/07/81	6.52	154.47	56	030/36	238/50	339/76	DW
350	10/09/81	9.64	162.16	31	001/31	236/49	321/65	DW
351	10/17/81	2.62	142.22	16	021/33	260/38	324/56	DW
352	11/06/81	3.18	143.72	15	359/06	090/12	135/04	DW
353	12/06/81	6.26	152.50	15	001/35	169/54	176/09	DW
354	12/11/81	6.23	148.40	60	009/33	182/57	021/78	DW
355	12/13/81	6.28	154.54	63	037/37	222/53	022/82	DW
356	12/13/81	6.22	154.55	53	040/34	217/55	046/79	DW
357	12/23/81	3.58	150.63	432	098/32	342/35	041/51	DW
358	12/27/81	2.21	140.34	15	354/14	260/14	307/20	DW

APPENDIX II

Stereographic projections of P-wave first motions to a homogeneous focal sphere. Filled circles represent compression and open cirlces represent dilatation. The smaller circles represent readings that are deemed poor. Nodal arrivals are identified by the adjacent capital letter N. Nodal planes are drawn with solid lines. Rather than assign a letter or number code to each solution based on its quality, dashed lines are drawn to represent maximum variations in strike and dip of the nodal planes. Obviously, all possible variations cannot be illustrated, however, it is immediately clear which solutions are acceptable and which are not. Solutions with unacceptable amounts of variation are not used in slip direction analysis.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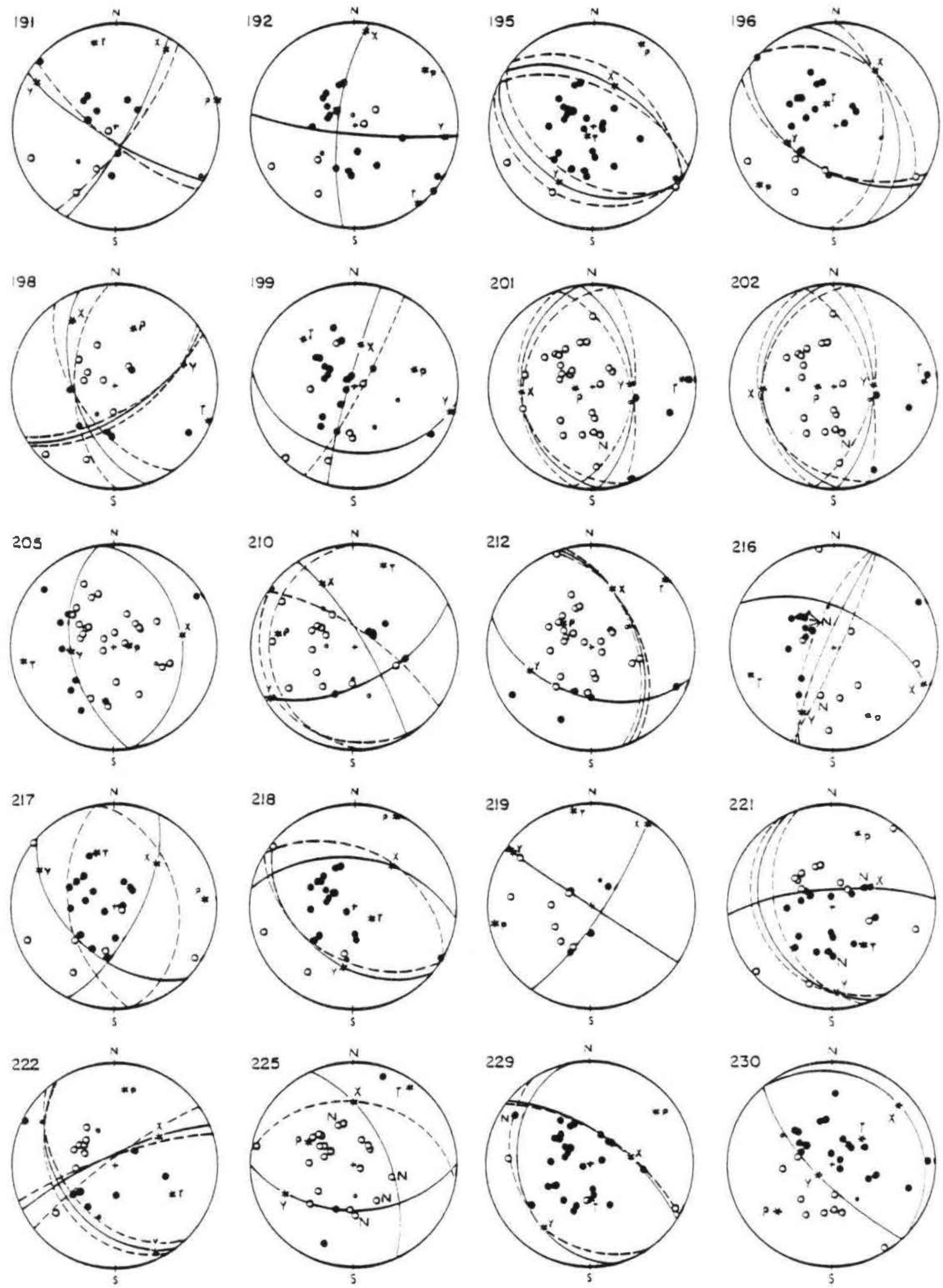
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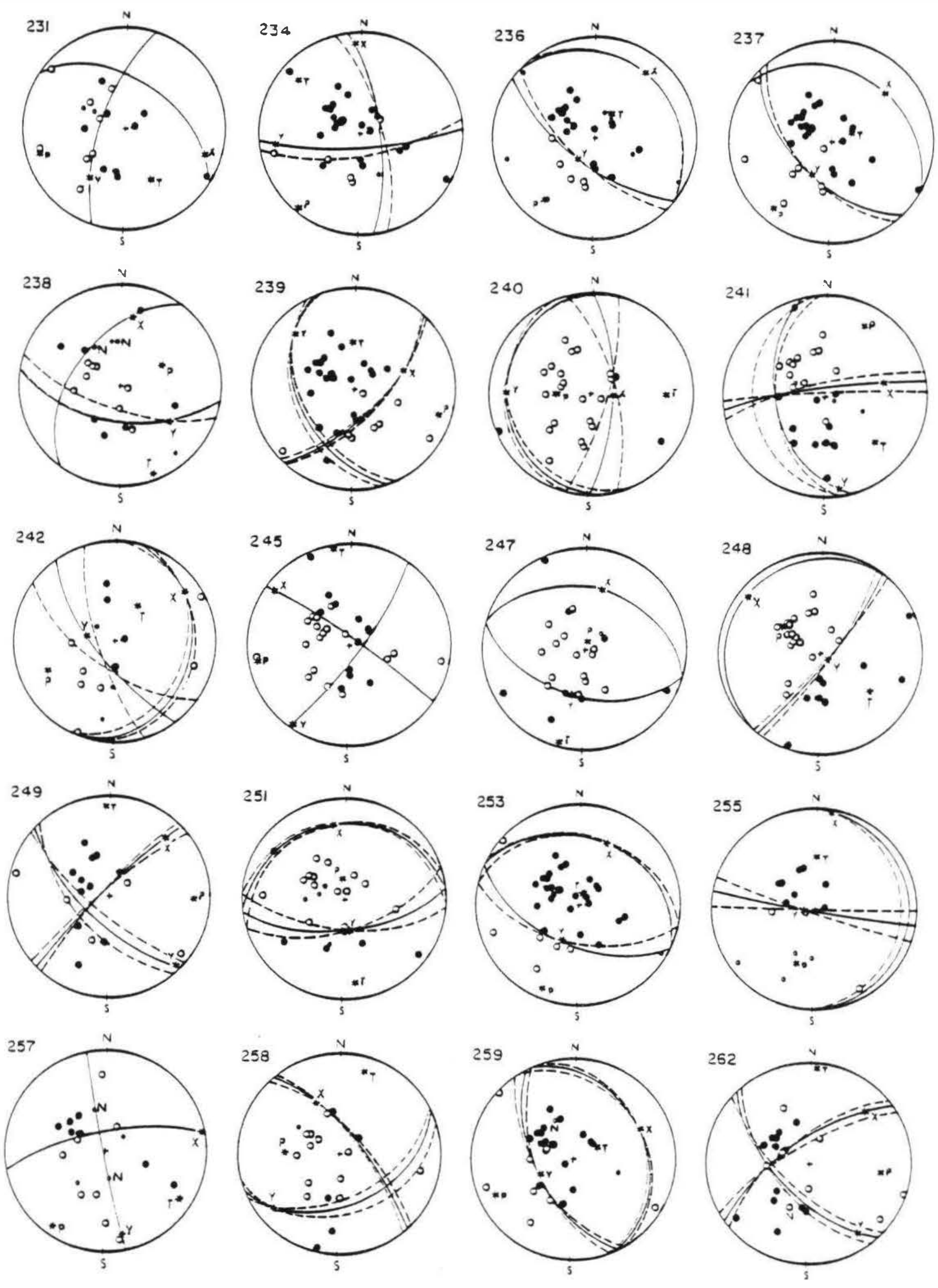
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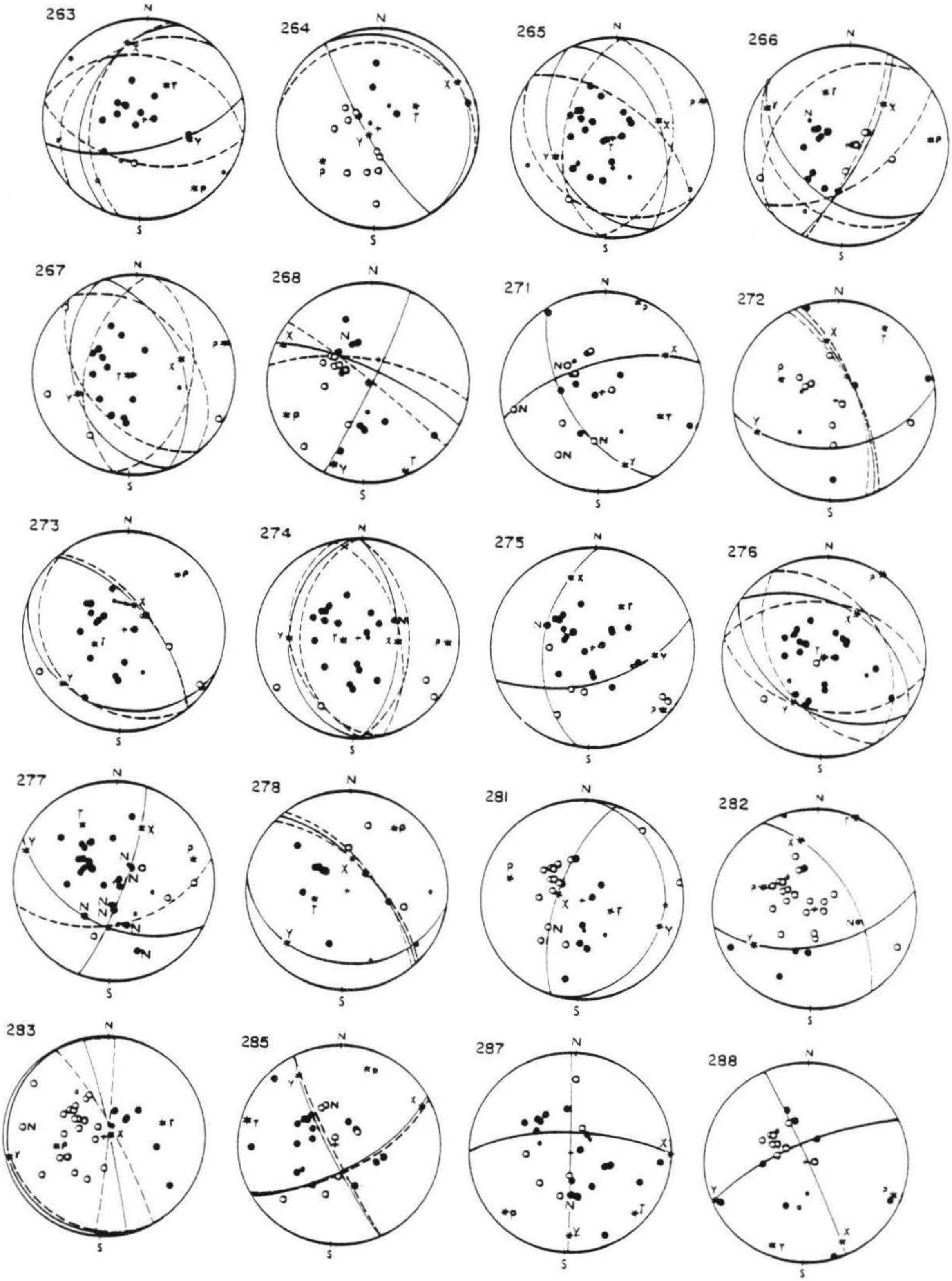
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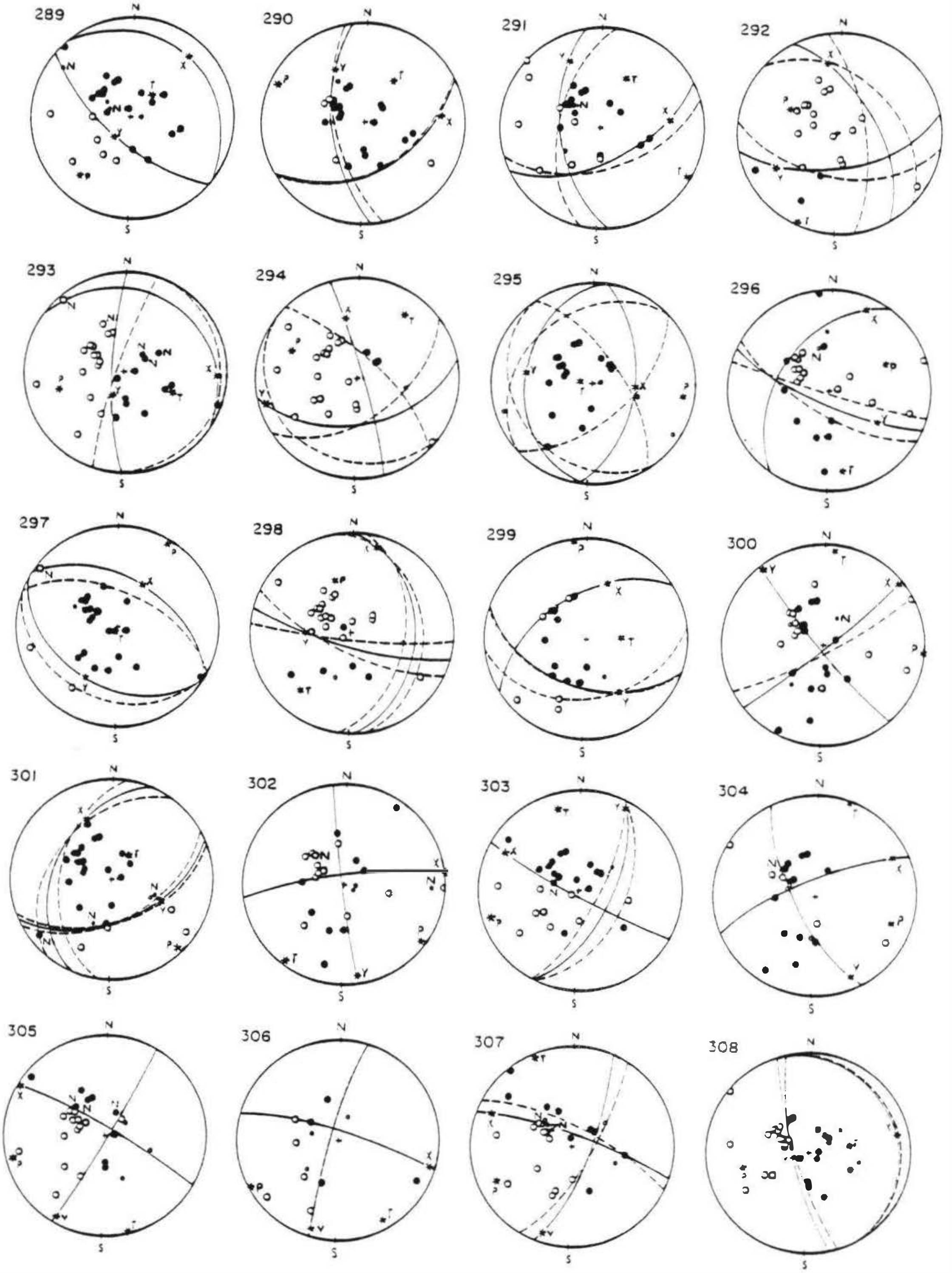
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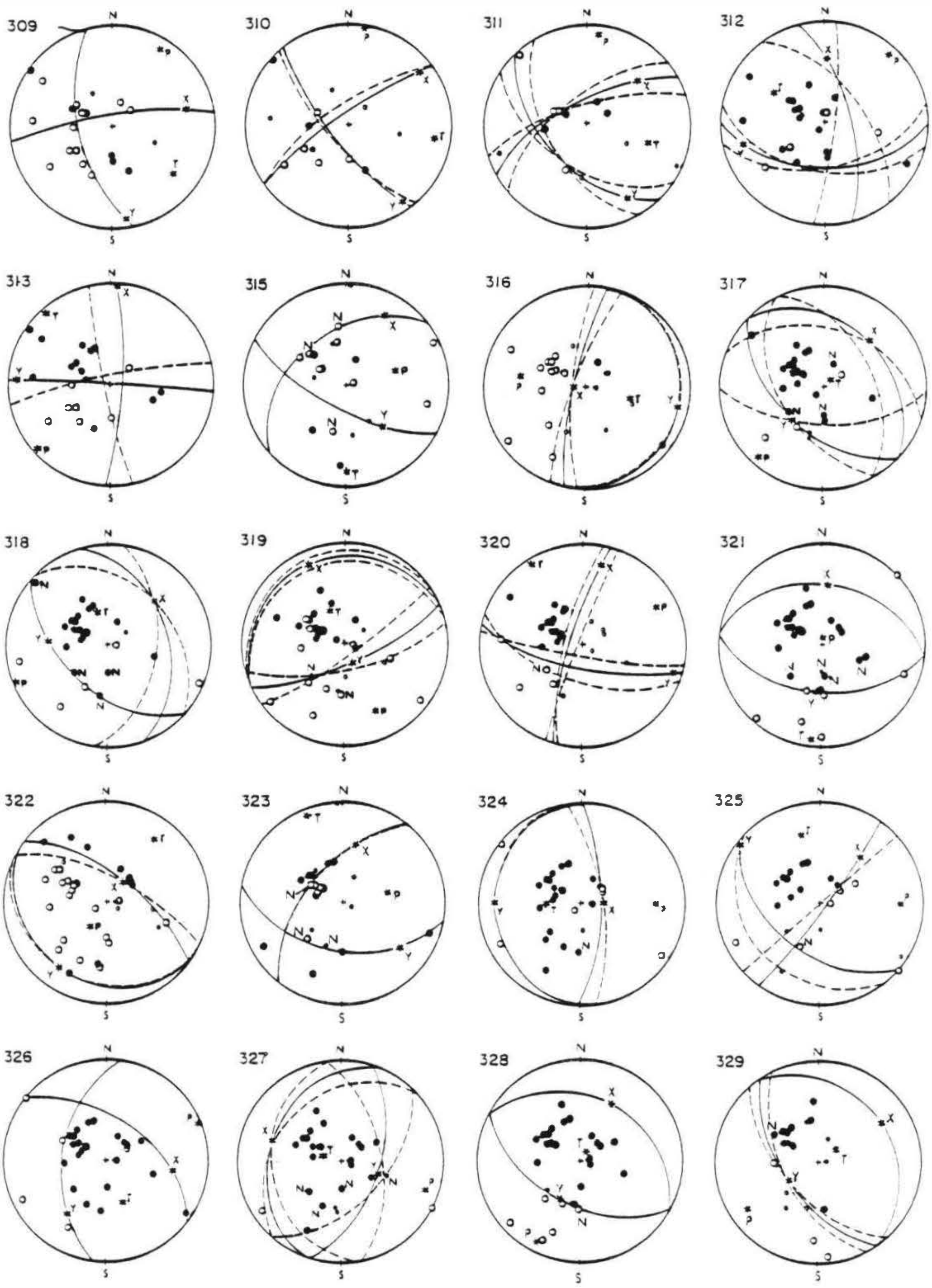
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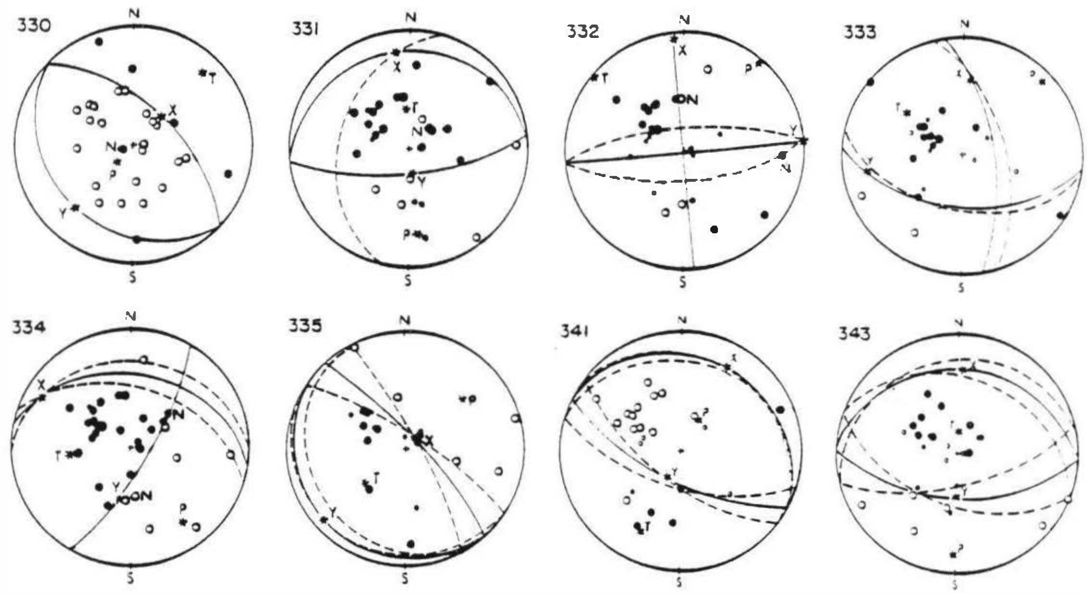
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