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SHALLOW AND INTERMEDIATE-DEPTH SEISMICITY IN THE NEW HEBRIDES ARC: CONSTRAINTS ON THE SUBDUCTION PROCESS

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ABSTRACT

Teleseismically located earthquakes in the New Hebrides Arc are unevenly distributed along the length of the subduction zone. Shallow seismicity near the plate boundary fits a static model of plate interaction along an interface with varying degrees of coupling between overriding and subducting plates. This interpretation is supported by striking differences in source radiation from earthquakes occurring in different parts of the plate boundary, and by systematic along-strike variations in forearc morphology.

The irregular distribution of intermediate-depth seismicity can be considered from two opposing points of view: one assuming a continuous or relatively uniform subducted slab; the other invoking an irregular, possibly discontinuous slab. At the northern and southern ends of the New Hebrides Arc, abrupt changes in the length of the inclined seismic zone coincide with structural and geophysical discontinuities in the subduction zone; a recent elongation of a previously shorter island arc northward and southward could explain many of these observations. In cross section, the intermediate-depth events define a spoon-shaped profile, with a nearly vertical plunge from 100 to 200 km depth and a gentler 60° dip below that.

The disrupted morphology and seismicity of the central New Hebrides Arc is also considered using both the uniform and non-uniform lithosphere models. Although the tectonic complexity at depth may imply disruption of the subducted lithosphere, the present subduction of the D'Entrecasteaux fracture zone plays a dominant role in the shallow deformation of this portion of the island arc.

INTRODUCTION

This paper summarizes a series of seismologic observations made along the active convergent plate boundary of the New Hebrides Arc (Figure 1). The Vanuatu and Santa Cruz Islands regions are among the world's most active source areas for shallow and intermediate-depth earthquakes. On a global scale,

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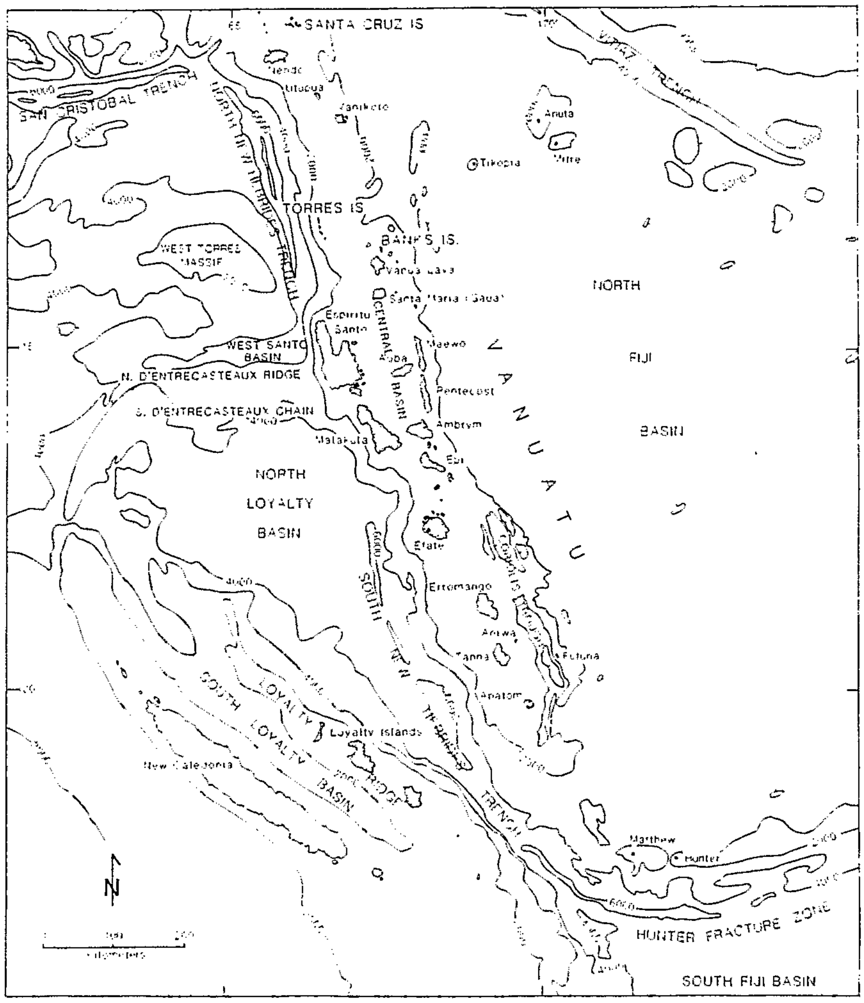
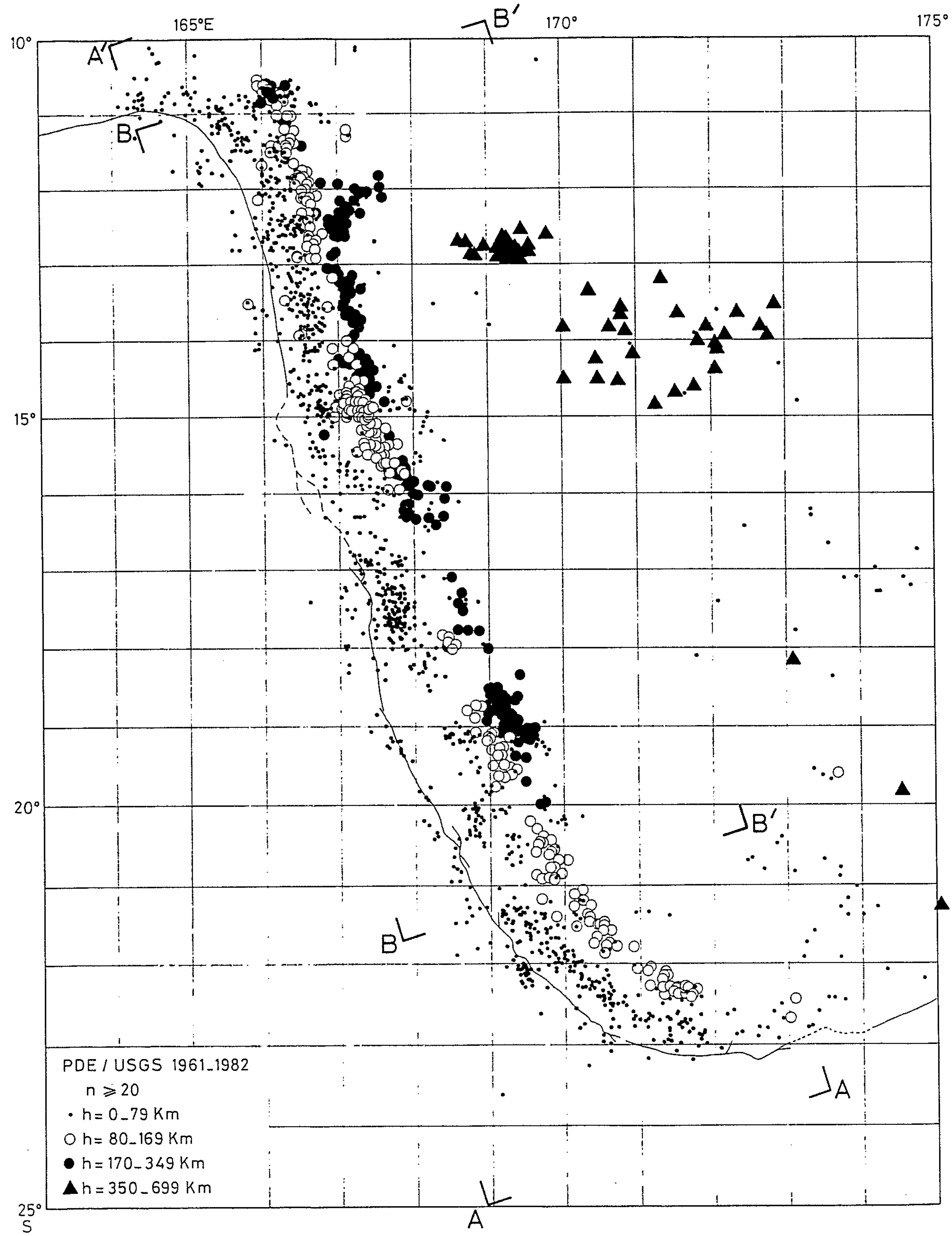


Figure 1. General bathymetry of New Hebrides Arc region after Kroenke, Jouannic, and Woodward (1983).

this plate boundary appears as a continuous belt, densely populated with earthquakes; on a local scale, however, the seismicity of the New Hebrides Arc appears to be far from homogeneous. We will focus on this heterogeneity of shallow and intermediate-depth activity. Examination of well-located teleseismically and locally recorded events reveals clear non-random patterns of seismicity that may provide a key to understanding the process of lithospheric subduction in a structurally complex zone.

Heterogeneity in the distribution of shallow seismic activity may reflect long-term differences in coupling along the plate interface (Lay and Kanamori, 1981). Such mechanical variations have been linked with the distribution of large interplate thrust events, the long-term seismic regime of

Figure 2 (facing page). Spatial distribution of earthquakes along the New Hebrides plate margin (PDE, 1961-83). All mapped earthquakes located by 20 or more seismic stations ($m_b > 4.8$). Note the gap in shallow activity between 18°S and 20°S; the discontinuity in the line of intermediate-depth foci in the area 16°-18°S; the restricted longitudinal extent of deeper events (filled circles) relative to the shallower events (open circles); and the sharp decrease of shallow and intermediate-depth seismic activity in the southern part of the arc east of 171.8°E longitude. The deepest foci earthquakes (filled triangles) are part of a continuous nest of deep activity beneath the North Fiji Basin. Brackets show locations of cross section AA′ (Figure 11) and BB′ (Figure 15). The continuous or dashed line marks the possible boundary between the converging Australia-India and Pacific plates (from Monzier, Collot, and Daniel, 1984).


165°E
170°
175°
10°
15°
20°
25° S
A'
B'
B
B'
B
A
A
PDE / USGS 1961-1982
n ≥ 20
• h = 0-79 Km
○ h = 80-169 Km
● h = 170-349 Km
▲ h = 350-699 Km

different segments of the arc, as well as patterns of inter-event coupling, migration, or precursory seismic activity (Isacks et al, 1981; Marthelot and Isacks, 1984). These along-strike variations are probably related to topographic irregularities on both the descending and overriding plates, and they appear to correlate with changes in the downward extent of the Benioff zone. The variations have to be interpreted in terms of the particular tectonic setting of this unusual plate boundary. Like Wyss, Habermann, and Heiniger (1983) and Habermann (1984), we offer a possible interpretation of the distribution of shallow earthquakes at the New Hebrides plate boundary that includes the asperity model of Lay and Kanamori (1981) and the detachment model of Seeber and Armbruster (1981).

The New Hebrides Arc intermediate-depth earthquakes are assumed to occur within the descending plate (Isacks, Oliver, and Sykes, 1968; Isacks and Molnar, 1971) and provide evidence, not of plate interaction, but of deformation within the descending plate itself. The striking differences in the distribution of intermediate-depth activity, in the maximum depth of these earthquakes, and in the morphology of the inclined seismic (Benioff) zone points to along-strike changes in the distribution of subducted lithosphere. We examine these observations, first in terms of a model of regular, continuous lithosphere distribution, and then in terms of a model of a discontinuous lithosphere.

REGIONAL SEISMOTECTONIC SETTING

Plate Convergence at the New Hebrides Arc

The New Hebrides subduction zone constitutes part of the plate boundary accommodating subduction of the Australia-India plate beneath the Pacific plate and the microplates created by backarc spreading in the North Fiji Basin (Figure 1). The underthrusting and subduction of the Australia-India plate result in intense shallow and intermediate-depth seismicity (Figure 2) that has been extensively studied since 1960. Overall seismic properties have been described by Pascal et al (1978); Lay, Kanamori, and Ruff (1982), Louat, Daniel, and Isacks (1982); and Marthelot and Isacks (1984). More detailed studies, including analysis of local network data from the central and southern part of the arc, have been reported by Isacks et al (1981), Coudert et al (1981), and Marthelot et al (1984).

The direction of relative plate convergence, determined from shallow thrust-type focal mechanisms occurring between 11°S and 21°S, is N76°E ±11° (Isacks et al, 1981) and that determined from mechanisms occurring between 19°S and 21°S is N70°E ±5° (Coudert et al, 1981). Significantly, the orientation of the transform faults in the northern and southern ends of the arc parallel this computed plate convergence; the northern New Hebrides-Solomon transform fault is oriented N75°E and the southern New Hebrides-Hunter fracture zone is oriented N70°E (Monzier, Collot, and Daniel, 1984). Hence, independent of relative movements on the upper plate, the azimuth of relative plate convergence along the entire New Hebrides plate boundary is consistently in the range N70°-75°E. The rate of convergence is on the order of 10 cm/yr (Dubois et al, 1977). A well-defined Benioff zone dips steeply to the east, extending to 300 km downdip along much of the arc.

Shallow Seismicity

In contrast to other subduction zones, such as the Alaska-Aleutian or Chile convergent margins (e.g., Kelleher, Sykes, and Oliver, 1973), the shallow seismicity in the New Hebrides Arc cannot be described in terms of precisely bounded segments ruptured regularly by events of large magnitude (e.g., Marthelot and Isacks, 1984). The extreme structural complexity of both the subducted and overlying plates described may be responsible for the observation above. Progressing from north to south along the length of the arc, the following bathymetric irregularities (Mammerickx et al, 1971; Monzier, Collot, and Daniel, 1984) occur on the subducted plate near the plate boundary (Figure 1): the West Torres Massif, the D'Entrecasteaux fracture zone (DFZ), and the Loyalty Island Ridge. On the upper plate there are four major and unusual topographic features: (1) the west Santo-Malakula protuberance, behind which a major intra-arc central basin is developed (Carney and Macfarlane, 1980; North and South Aoba basins of Katz, this volume); (2) a poorly developed backarc basin (the Coriolis Trough) between 17°S and 21°S (Karig and Mammerickx, 1972); (3) an abrupt truncation of the arc between 21.5°S and 22.5°S; and (4) an abrupt change to an east-west-trending structure including Matthew and Hunter active volcanoes at the southern end of the arc. The first of these features coincides with the position of the DFZ, the subduction of which creates strong coupling between converging plates and major Quaternary uplift of an Oligocene-Miocene volcanic chain (Chung and Kanamori, 1978a,b; Taylor et al, 1980; Jouannic, Taylor, and Bloom, 1982). The interruption of the arc between 21.5°S and 22.2°S coincides with a shortening of the Benioff zone, and has been interpreted by Louat (1982) as a former southern termination of the arc at the latitude of Anatom Island. The presently active termination is near Matthew and Hunter Islands, and may be the result of a recent southward jump (Monzier et al, 1984).

The various shallow seismic regimes reported from the New Hebrides Arc range from quiescence to permanent activity. Isacks et al (1981) and Lay, Kanamori and Ruff (1982) have interpreted the different regimes as a function of topographic irregularities on the Australia-India plate. The contact zone between the two plates appears to be heterogeneous, so the style of interplate motion may change rapidly along the arc. Aseismic creep may predominate in some segments because of thick sediment cover on the underthrust plate, while in other places, continuous seismic activity may result from bathymetric irregularities that introduce zones of increased coupling and tectonic loading. These zones are referred to as "asperities" and appear to accumulate stresses. They also may act as barriers when a neighboring area is ruptured and hence are called rupture barriers.

The model of a thrust contact where the asperities are surrounded locally by weakly coupled zones, and at a greater distance by rupture barriers, can explain the shallow seismicity observed at plate boundaries (Lay and Kanamori, 1981; Isacks et al, 1981; Ruff and Kanamori, 1983; Wyss, Habermann, and Heiniger, 1983; Habermann, 1984). We will describe the New Hebrides shallow seismicity in relation to the present state of coupling between the arc and the Australia-India plate in terms of this model.

Intermediate-Depth Seismicity

The distribution of intermediate-depth earthquakes (Figure 2) suggests tectonic complexity at depth in addition to that in shallower regions. These earthquakes provide information on the geometry, physical properties, and state of stress of the subducted Australia-India lithosphere. Further, intermediate-depth seismicity may help constrain models of plate interaction prior to—and contrasting with—the present-day tectonic setting. The spatial distribution of the intermediate-depth events is used to infer the geometry and the extent of the subducted Australia-India lithosphere. Together with regional stratigraphy and structure (e.g., Carney and Macfarlane, 1982), paleomagnetism (Falvey, 1978), and backarc spreading (e.g., Chase, 1971; Malahoff, Feden, and Fleming, 1982), the geometry of the subducted lithosphere can constrain reconstructions of former arc geometry and processes of arc initiation (e.g., Dubois, Dupont, and Recy, 1982; Karig, 1982).

Deep earthquakes east of the arc (black triangles, Figure 2) appear to occur in a slab detached from a relict subduction zone dipping southwest from the Vitiaz Trench (Barazangi et al, 1973; Isacks and Barazangi, 1977). These foci are apparently not linked with the present subduction at the New Hebrides Arc, but are fundamental in tectonic reconstructions of the Southwest Pacific before the beginning of the present New Hebrides subduction episode. As our subject concerns active seismotectonics of the modern New Hebrides Arc, we will not discuss these deep events further.

SHALLOW SEISMICITY FROM THE INTERPLATE THRUST ZONE

A comparison between teleseismically located epicenters for the past 22 years (Figure 2) and those determined using local networks in this area has shown that the geographical accuracy is not greatly influenced by lateral velocity heterogeneities, such as those associated with the downgoing lithosphere or the backarc spreading zone (Coudert et al, 1981), and that the uneven distribution of epicenters in active and quiet zones is observed in local as well as worldwide network data. Gaps and clusters of shallow seismic events located by worldwide seismic stations may be due in part to long-term variations along strike in the coupling between the downgoing plate and the arc.

The temporal distribution of moderate- to large-magnitude shallow earthquakes (depth <80 km, $m_b>5$) along the arc is shown in Figure 3. Only the earthquakes located between the trench and the 80-km depth contours are projected onto this figure. Thus, backarc shallow activity is excluded and only the earthquake activity near the thrust contact is displayed. South of 20°S, the distance along the trench (the abscissa in Figure 3) is measured along the arc of a circle approximating the strike of the trench in this area.

Two patterns emerge from Figure 3: the earthquakes fall into horizontal and vertical lines which represent temporal and spatial coincidence of events, respectively. Horizontal (temporal) trends predominate between 11°S and 18°S and around 22°S. Those two parts of the arc contain earthquake

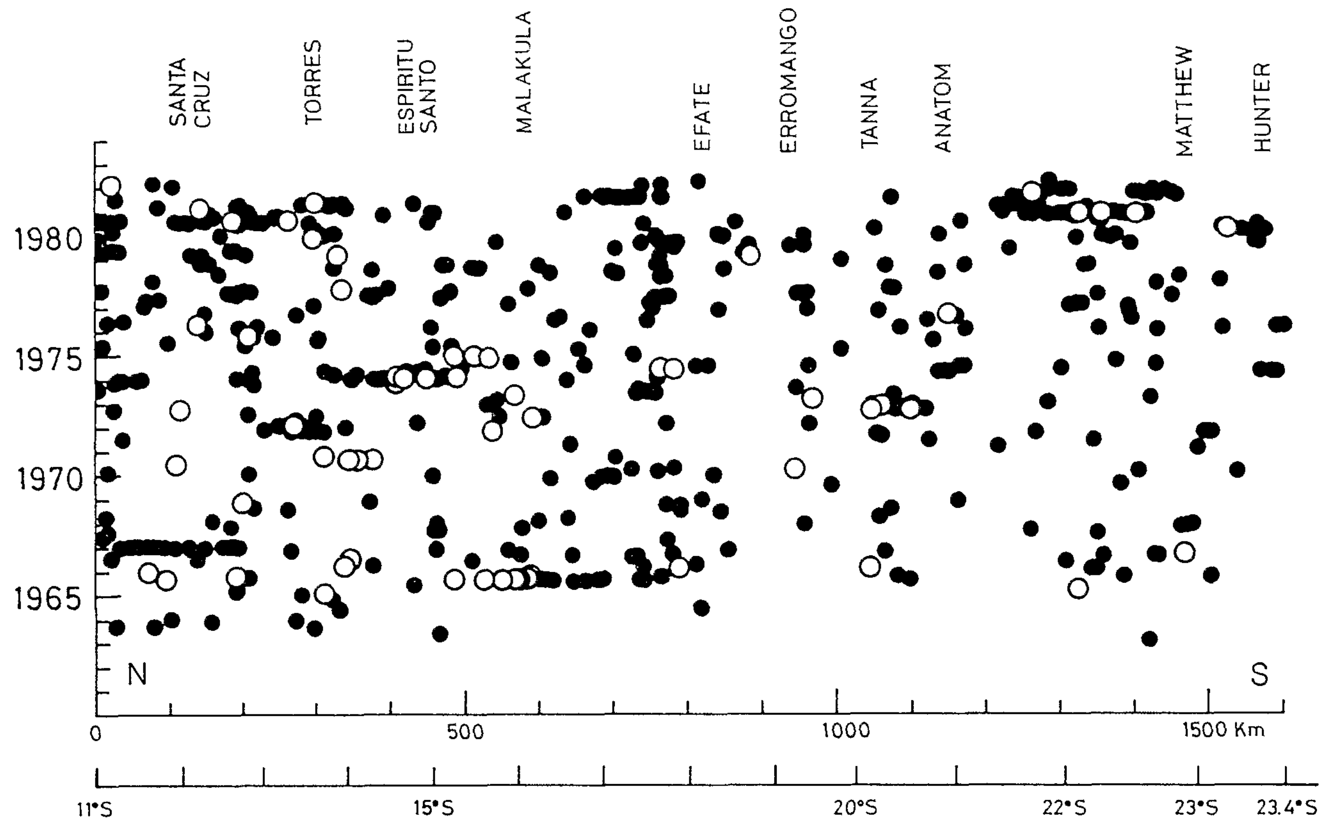


Figure 3. Space-time diagram of shallow earthquakes located between the New Hebrides Trench and the Benioff zone, plotted as a function of distance along the trench, which is assumed to be linear from 11°S to 20°S, and to follow an arc of a circle (centered at 18.1°S, 173.8°E), south of 20°S. Filled circles represent earthquakes with PDE magnitudes (m_b) from 5.0-5.7, open circles are events with magnitudes greater than 5.7. Locations of islands are indicated along the top of the figure. The absence of events prior to 1964 results from the limited number of earthquake magnitudes available in the PDE file from 1960 to 1964.

sequences which fit the model defined by Lay and Kanamori (1981), that is, thrust contact surfaces with moderate and strong "subfault interactions" reflecting a strong spatial correlation of events. A more scattered distribution of events marks seismic activity in the area facing southern Efate, Erromango, and Tanna Islands (18°-21°S). As no major earthquake swarm has occurred since 1961, it is difficult to distinguish between a subduction regime involving continuous slip (creep) or one which involves rupture after a long period of stress accumulation.

Vertical (spatial) trends in the diagram occur at distances along the plate boundary (x-axis) of 200, 460, 780, and 950 km (latitudes 12.8°, 15°, 17.8°, 19.5°, and 20°S), which are subject to continuous seismic activity. These vertical trends appear to bound horizontal segments of spatial earthquake clusters. We interpret these vertical zones to represent, in the model of Lay and Kanamori (1981), asperities acting as rupture barriers.

A Shallow Earthquake Distribution Model

Figure 4 and Table 1 summarize the working model we use to interpret the spatial distribution of shallow earthquakes generated by subduction of the Australia-India plate. The concept of an asperity/rupture barrier framework follows Lay and Kanamori (1981), and that of the detachment zone and associated seismicity follows Seeber and Armbruster (1981).

In the New Hebrides Arc, we present a static seismicity model that considers the asperity zones only as rupture barriers which bound detachment zones or slippage surfaces. The dynamic process of stress loading, or the nature of failure of asperities, is

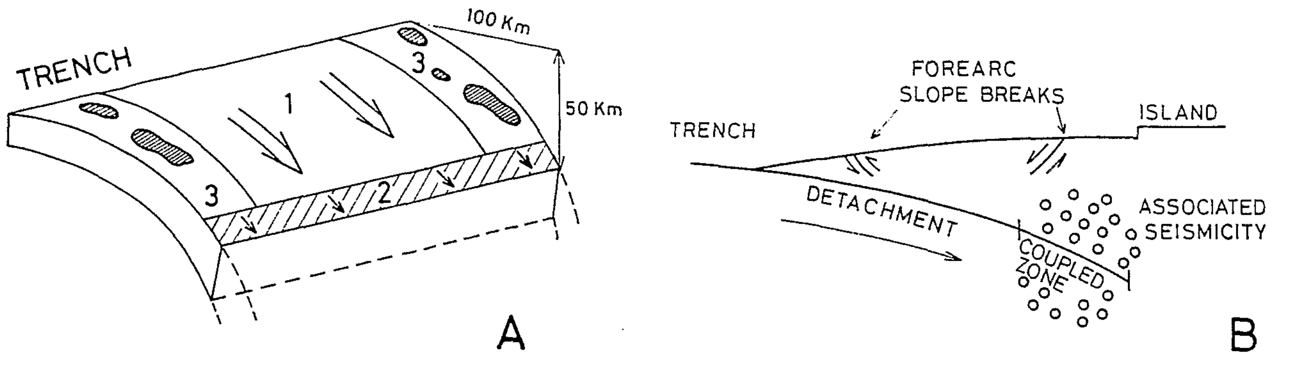


Figure 4. **A)** Schematic representation of thrust contact zone of the New Hebrides plate margin divided into three zones characterized by different physical properties. (1) The *detachment zone* is seismically inactive, except during the process of major plate ruptures. (2) The *coupled zone,* which is generally located along the deeper portion of the plate interface, is characterized by higher stress loading than the detachment zones. (3) The *asperity/rupture barrier zone,* which laterally bounds the detachment zone, is characterized by areas of greater strength (irregularities in plate interface) which stop the slippage due to high localized coupling. This model is adapted from Lay and Kanamori (1981) and from Seeber and Armbruster (1981). **B)** Cross section of the island arc below a detachment zone. In this model, the slope breaks near the crest of the arc are located above a change in the nature of the coupling between the converging plates. Note the associated seismicity within the plates adjacent to the coupled zone, which may be responsible for the diffuse seismicity observed from microearthquake studies of the plate boundary (Wray et al, 1983). This model is adapted from seismicity studies of the Himalayan arc by Seeber and Armbruster (1981).

Table 1. Characteristics of detachment, asperities, and coupled zones in the New Hebrides Arc.

	Detachment Zones	Asperity Zones/ Rupture Barriers	Coupled Zones
Stress loading/ coupling	low	high	moderate-high
Density of asperities	low	high	moderate-high
Seismicity	low	high	high
Geographic extent	moderate	small	continuous
Earthquake stress drop	low	high	moderate-high
P-wave frequency	low	high	high
Trench profiles			

considered using microearthquake data from the central part of the New Hebrides Arc, or foreshock and aftershock sequences (Isacks et al, 1981; Chatelain, Cardwell, and Isacks, 1983; Wyss, Habermann, and Heiniger, 1983; and Habermann, 1984). Our regional-scale model is based mainly on the spatial distribution of shallow events with magnitudes greater than 4.8.

A nearly continuous zone of shallow seismicity parallels the trench along its entire length (Figure 2). This is interpreted as a coupled zone, an area of plate interaction which may vary in size, but which exists, independent of structural heterogeneities, all along the plate boundary (Table 1). The seismicity near this coupled zone may be associated with stress accumulation in both the downgoing and overlying plates, as well as along the boundary itself. In contrast, there is a more heterogeneous distribution of earthquakes along the interplate zone closest to the trench. We interpret these seismic and aseismic zones to represent areas of greater or lesser coupling produced by asperities and detachment zones. Figure 4 shows the model covering both the continuous and heterogeneous seismicity zones. The interplate contact surface can be divided into three parts: (1) closest to the trench, several separate detachment zones associated with areas of low seismicity; (2) asperity zones related to the clusters of foci which bound the detachment zones; and (3) further downdip, a coupled zone associated with a nearly continuous distribution of earthquakes along the arc (Table 1). The sizes of the three zones depicted on Figure 4 vary along the arc. The difference between the coupled zones and the asperity zones is only a geometric one, and may not imply different physical properties.

Detachment zones in the New Hebrides Arc (Table 1) are well defined by the seismically quiet zones between 18°S and 21°S. Except beneath Espiritu Santo Island, the detachment zones are bounded on the west by the trench. These detachment zones are modeled as portions of the plate interface where the stress loading is low. These also may be the slip surfaces for large earthquakes with surface-wave magnitudes of 7 or more, but the paucity of historical data prevents any direct mapping of these slip surfaces. Paleoseismological studies of prehistoric earthquakes, using data from uplifted coral terraces (e.g., Taylor, Bloom, and Lecolle, 1982) may be successfully applied to this problem.

Asperity zones or rupture barriers in the New Hebrides Arc (Table 1) are transverse clusters of epicenters bounding quiet zones (Figure 2) and exhibit continuous seismic activity (Figure 3). The best example is the area around 20°S (Figures 2 and 3).

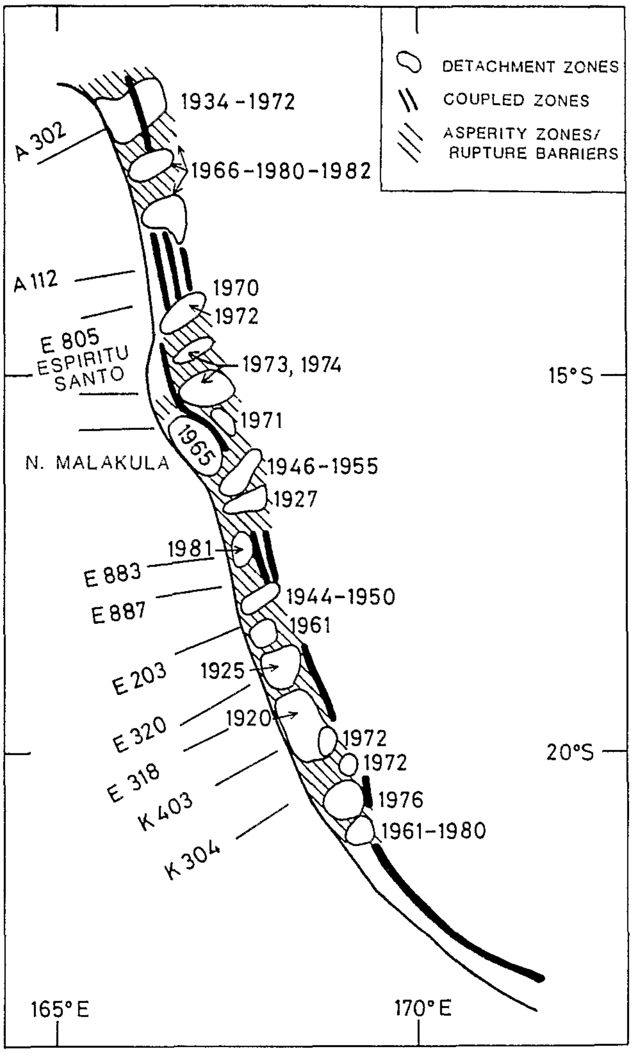


Figure 5. Distribution of the plate-interface types defined in Figure 4, along the New Hebrides plate boundary. The detachment zones are inferred by gaps in shallow activity. The coupled zones are defined by continuous belts of seismicity parallel to the trench. The asperity zones or rupture barriers on the edges of the detachment zones are defined by areas of high seismicity between the trench and the coupled zone. Earthquakes which may have partially or totally ruptured a detachment zone have been marked by the years of occurrence. Sometimes a swarm may involve several detachment zones. Only the teleseismic data (Figure 2) have been used for this interpretation. A 302 through K 304 indicate the trend of corresponding bathymetric profiles illustrated in Figure 10.

We see these clusters as zones where the stress-accumulation stress-release cycle controls the occurrence of earthquakes and the slip extension in nearby detachment zones. These asperities may be associated with topographic irregularities or with specific material properties of the contact surface.

The largest earthquakes occur where there is slip on a large surface such as the detachment zones. The exact boundaries of the detachment zones cannot, in general, be very accurately delineated. In the Espiritu Santo area, however, a temporary network, established 1.5 years after the December 1973 to January 1974 swarm (noted hereafter as the 1974 swarm), has recorded the distribution of long-term aftershocks. According to our working hypothesis, these aftershocks might be used to trace the distribution of asperity zones/rupture barriers (or of the coupled zone) around the main slippage zones involved in the 1974 swarm (Figure 6). In a second case, at latitude 20°S, the limits of the large 1925 and 1920 rupture areas (detachment zones) might also be assigned using the locations of small earthquakes recorded by a 1977 land-ocean bottom seismograph experiment. This pattern of activity is remarkably similar to that observed using the 20-year PDE (Preliminary Determination of Epicenters) catalog (compare Figures 2 and 7).

From the trend shown in Figure 5, and the historical record of shallow earthquakes, two zones stand out as possible areas for major events in the near future: the southern Malakula detachment zone, which has been aseismic since 1927, and the southern part of Vanuatu, which covers the 1925 and 1920 detachment zones. Great earthquakes in that area were felt in 1875 in southern Vanuatu (O'Reilly, 1956) and on Loyalty Island (local records of April 1875). A major tsunami was reported following that earthquake inferring that the March 28, 1875 focus involved a large near-surface rupture. The time separation between the 1875 and the 1920 events may imply a 50-year rupture cycle in the area. Thus, an increasing possibility may exist for a M_s 7.5-8.0 shallow earthquake between latitudes 18.5°S and 20°S. Furthermore, the proximity of the large 1920 and 1925 rupture zones and the narrowness of the barrier separating them (Figure 6) presents the possibility that, of the entire New Hebrides Arc, this area may be the most susceptible to a very large multiple rupture extending over 300 km along the strike of the arc.

Seismic Observations

Based on the patterns of shallow seismicity alone, our classification of the interplate surface may seem to be somewhat limited. However, several additional pieces of evidence point out major along-strike changes in the nature of the plate boundary. First, we discuss observations of P-wave frequencies that radiated from interplate earthquakes requiring fundamentally different source mechanisms from those of neighboring portions of the plate boundary. In a later section, we discuss bathymetric irregularities of the trench inner wall that appear to be associated with portions of the plate boundary classified as detachment zones.

A low-magnification vertical seismic station in southern New Caledonia (16 km north of NOU, Figure 9) with a bandwith of 1-10 Hz has enabled us to record unsaturated P-waves from moderate-sized New Hebrides earthquakes. On Figure 8, seismic traces from this station, all at the same magnification, demonstrate the variation in source mechanism for nearby events occurring along the New Hebrides Arc. Epicenters of these events are denoted on Figure 9 by letters A through H and their

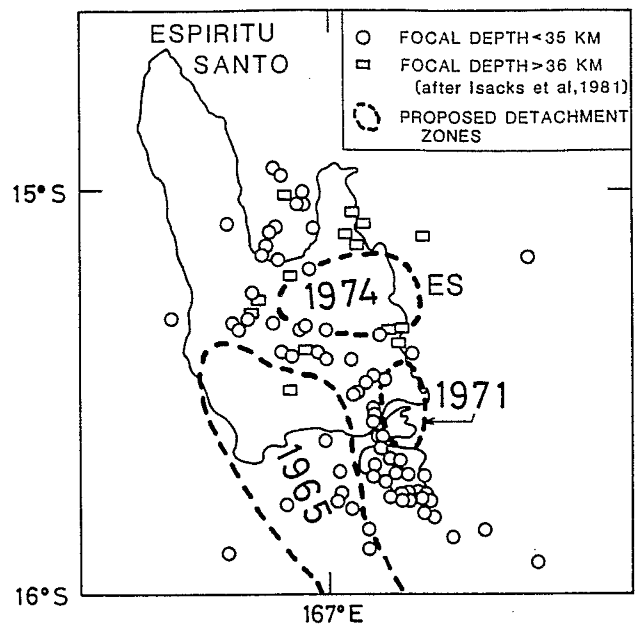


Figure 6. Shallow microearthquake epicenters from a July-August 1975 temporary seismic network on Espiritu Santo Island. These microearthquakes are assumed to mark the boundaries of detachment zones which ruptured during the large- or moderate-sized events in 1965, 1971, and 1974. The year indicates the major events that are tentatively assigned to rupture of these detachment zones. Note that the eastern Espiritu Santo detachment zone (ES) coincides exactly with an easterly protuberance of the coastline, that could be a result of long-term localized uplift of this portion of the island.

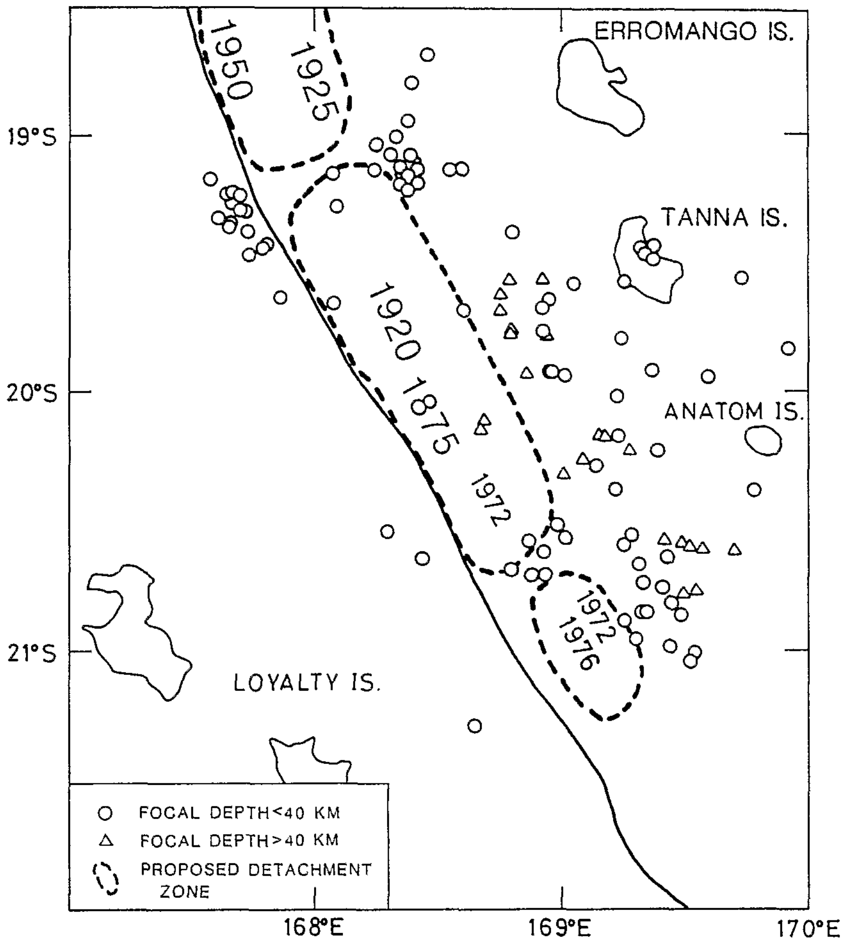


Figure 7. Shallow microearthquake epicenters from an August-September 1977 land ocean-bottom seismograph experiment (Coudert et al, 1981). Note the similarity of this pattern of microearthquakes with that defined by moderate-sized events shown in Figure 2. Years indicate occurrence of earthquakes which have possibly ruptured the detachment zones delimited by the microearthquake epicenters. Large numbers indicate major events with $M_s > 7.0$. Data are from Isacks et al (1981) and the location of the 1875 event is inferred from O'Reilly (1956) and local news accounts of April 1875.

Table 2. Hypocentral parameters for earthquakes used in frequency analysis (Figures 7 and 8). Data are from PDE.

Event	Date	Latitude (S)	Longitude (E)	Depth (km)	m_b
A	22 Jul 1981	21.64°	169.52°	36	4.8
B	12 Nov 1980	21.71°	169.52°	47	4.8
C	17 Feb 1981	21.74°	169.38°	30	5.6
D	30 Oct 1980	21.41°	169.15°	33	5.2
E	19 Feb 1981	21.54°	169.46°	33	5.7
F	25 Nov 1981	21.41°	170.44°	33	4.9
G	18 Aug 1979	22.40°	170.97°	57	5.3
H	24 Nov 1981	22.50°	170.63°	30	5.6
I	17 Jul 1980	17.17°	167.63°	34	5.1
J	12 Jun 1980	17.31°	167.81°	32	5.1
K	30 Oct 1980	17.84°	167.98°	33	4.7
L	27 Jul 1976	16.97°	167.19°	13	4.8

parameters are given in Table 2.

Figure 8 (samples A and B) exhibits seismic traces recorded from two shallow-focus earthquakes in the PDE file with identical magnitudes and locations, and with only slightly different depths. Note the striking difference in the dominant frequency in the coda following the P-waves of these events. This contrast between high- and low-frequency events is a fundamental one, clearly observable on seismic records from neighboring events throughout the arc. Other examples of such contrasting events are shown in Figure 8 (C through L). These differences are not explained by any simple station or propagation effect; neighboring events are recorded on identical instruments and follow nearly identical propagation paths. It is unlikely that they represent different

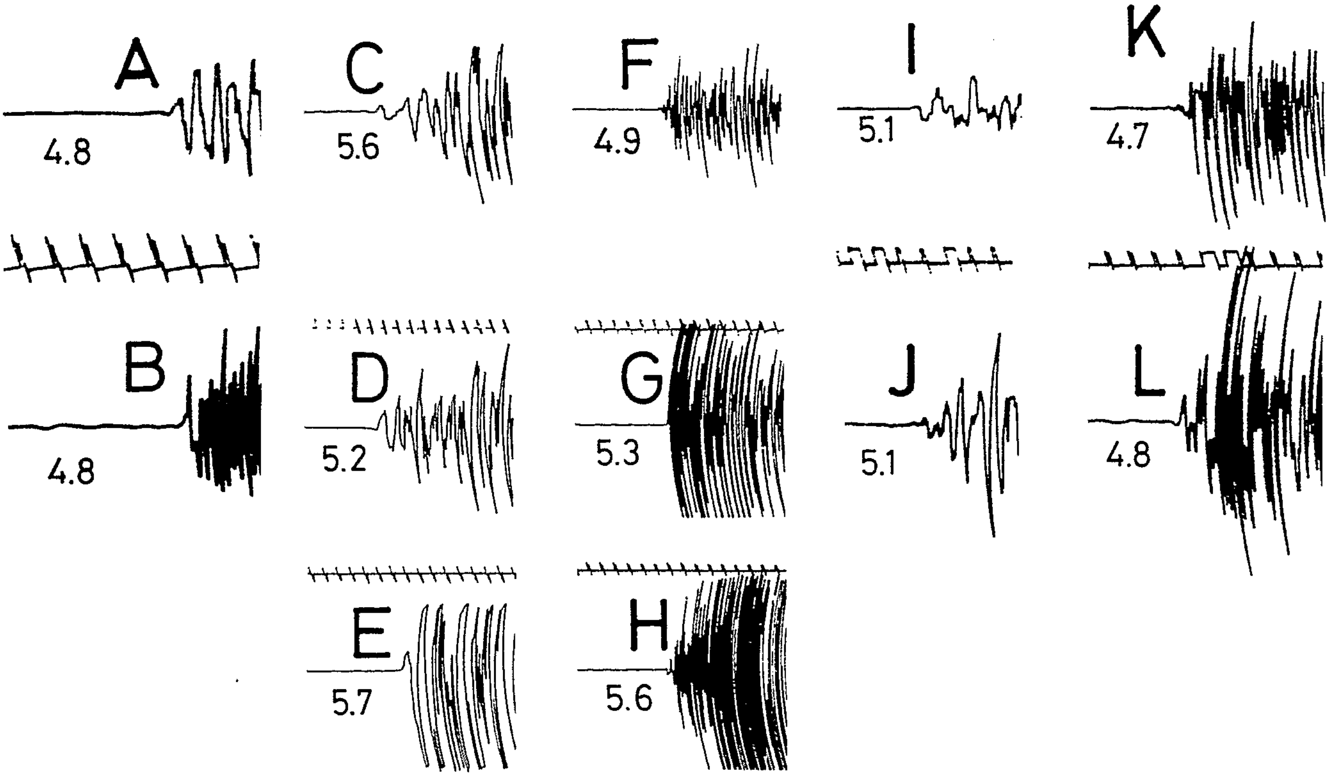


Figure 8. Short-period low-magnification records from the Noumea (NOU) telemetered station for shallow, moderate-sized New Hebrides events. Letters denote earthquakes. Locations of A through H are shown on Figure 9; hypocentral parameters are given in Table 2. The body wave magnitude (m_b) of each event is given beneath the seismogram. Tick marks are separated by one second. Note the striking difference in frequency content of two events (A, B) with almost identical locations; six additional examples from the southern portion of the arc show similar contrasts between low frequency (C, D, E) and high frequency (F, G, H) events. Four examples from the Efate area also display contrasting low frequency (I, J) and high frequency character (K, L).

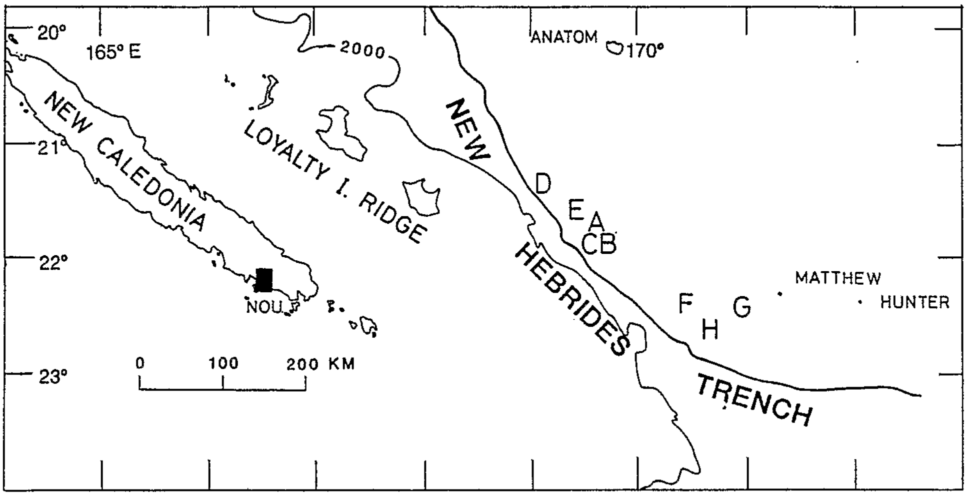


Figure 9. Southern portion of the New Hebrides Arc showing permanent seismic station NOU (New Caledonia). Letters mark the locations of shallow earthquakes A-H recorded in NOU, whose seismograms are shown in Figure 8. Hypocentral information on these events is given in Table 2. Location of trench and selected 2,000-m isobath from Monzier, Collot, and Daniel (1984).

focal mechanisms, because their position and first motion directions are similar. Directivity of the rupture is a second-order effect, not significantly affecting the fundamental P-wave frequency (Madariaga, 1976).

A simple explanation of this phenomenon may be provided by our classification of the interplate boundary into detachment zones with low stress accumulation, and coupled and asperity zones with higher stress accumulation. We might expect systematic differences in the earthquake stress drop in these zones. The observed P-wave spectrum has been related to the source properties by using the simple model of a circular rupture in an elastic medium (Brune, 1970; Hanks and Wyss, 1972). This model implies that, station and propagation effects being identical, the high-frequency content of an earthquake body-wave spectrum requires a higher stress drop than an equivalent low-frequency event. Thus, we might interpret the high-frequency events (B, F, G, H, K and L in Figure 8) as those occurring in the high-stress coupled or asperity zones, while the low-frequency events (A, C, E, I and J in Figure 8) would represent those ruptures which propagate into the low-stress detachment zones. The occurrence of these events in close proximity suggests that the detachment-zone earthquakes may originate near the asperity-type events, but involve rupture extending into the detachment areas.

In addition, strong spatial patterns are observed among these different source types. All of the events located to the south of a distinct line separating events A and B (Figure 8) are characterized by high-frequency first arrivals (events F, G, H, Figure 8). These events appear to occur in the continuous coupled zone extending south from 21°S (Figure 5). The earthquakes just to the north (events A, C, D and E near Figure 8) are all characterized by low-frequency first arrivals and occur near the southernmost detachment zone. The boundary separating these areas coincides with the impingement of the Loyalty Island Ridge on the New Hebrides subduction zone near 21°S (Figure 9). While changes in the topography, flexure, and buoyancy of the downgoing plate might be expected to strongly influence plate interactions in this area, they alone cannot explain the position of strongly and weakly coupled zones in the southern New Hebrides.

Figure 8 (I through L) shows records from the area near Efate Island: events I and J are interpreted as events from a detachment zone; whereas K is related to a higher stress-drop event generated in a coupled zone; and L, also a higher stress-drop event, is located near the trench and is linked with a rupture barrier zone. The close proximity of these contrasting events suggests the juxtaposition of detachment and coupled or barrier zones in this area. Data from local networks with accurate locations of microearthquakes may be useful to define the precise slippage surface of future major earthquakes by the mapping of these detachment areas.

Bathymetric Observations

Figure 10 displays bathymetric profiles to compare seafloor morphology from the outer wall of the trench to the arc in a series of profiles along the strike of the arc. Bathymetric data are taken from Dugas et al (1977), Daniel (1982) and Collot, Daniel, and Burne (1985). Locations of the cross sections are given in Figure 5. Two schematic topographic cross sections of Espiritu Santo and Malakula Islands have been added to produce a complete collection of profiles along the arc. Beneath each profile, we show the classification of the interplate thrust zone into detachment zone (D), coupled zone (C), and asperity zone or rupture barrier (RB).

Three profiles, E 883, E 320 and K 403, stand out where a forearc terrace near the trench is well defined by a sharp trench-slope break and an arcward-tilted slope along the frontal part of the forearc. Each terrace coincides with a detachment zone on the frontal part of the plate boundary, suggesting a genetic relationship (Table 1). The morphology of these terraces may be related to active tectonism along the plate boundary. Uplift and tilting of the forearc wedge may follow slip associated with the major earthquakes rupturing the detachment zone. This uplift also could be responsible for the tsunamis which have been observed in these parts of the arc (e.g., the large 1875 and 1920 events in the southern New Hebrides, O'Reilly, 1956; Iida, Cox, and Pararas-Carayannis, 1967). Profile A 302, across the Santa Cruz portion of the forearc, is an exception to this rule because it is located along a detachment zone without a forearc terrace. The profiles from the coupled or rupture barrier regions (e.g., A 112 or E 203) generally display a steep trench inner wall and a gentle trenchward slope with small breaks (Table 1).

Correlation of forearc terraces with large tsunamigenic earthquakes has been suggested by Nishenko and McCann (1979). They noted, on a global scale, a close relation between the shape and size of forearc terraces and the source areas for major plate-boundary earthquakes. Thus, these forearc terraces indicate the seismic and tsunamigenic potential

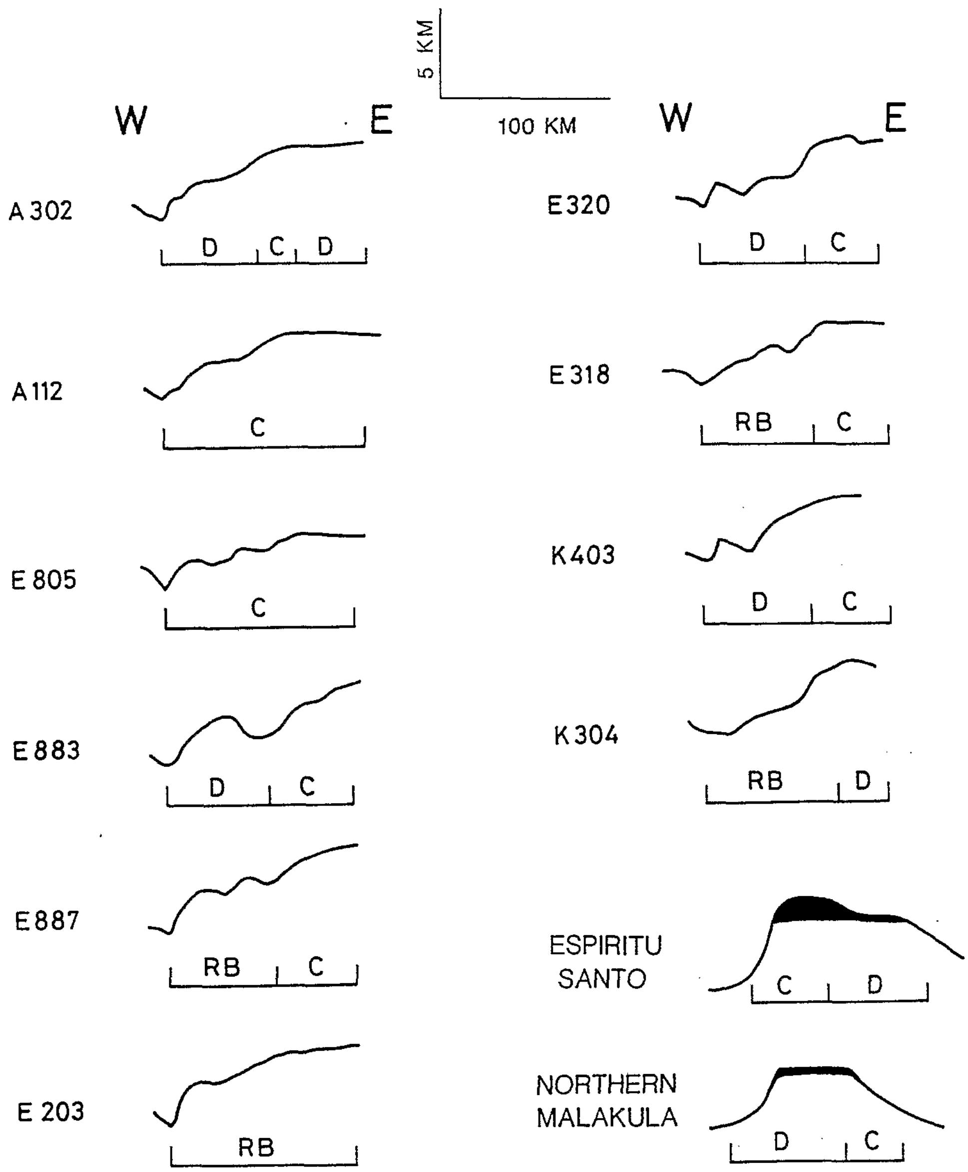


Figure 10. Bathymetric profiles perpendicular to the island arc from the trench to the arc showing the overall shape of the forearc zone. Letters beneath each profile indicate the type of thrust contact as defined in Figure 5: D = detachment zone, C = coupled zone, and RB = rupture barrier. Locations of profiles are shown in Figure 5. Note the striking forearc wedges on profiles E 883, E 320 and K 403 above the detachment zones. Espiritu Santo and northern Malakula sections are simply sketches of the topographic profiles, and have been added to show the inversion of the detachment and coupled zones beneath those islands. Scale is approximate.

of the plate boundaries. In the New Hebrides Arc, where the history of large earthquakes is incomplete, this method may provide a valuable tool for estimating the tsunami and earthquake hazard along various segments of the plate boundary.

The remarkable feature of the seismicity of the Santo-Malakula arc segment is the trenchward shift of the coupled zone from eastern Malakula to the west coast of Espiritu Santo (Figures 4 and 5), where the highest mountains of the arc (to 1,811 m) can be found. The increased coupling of the contact zone resulting from the mass of the western Espiritu Santo mountain range, may be responsible for this shift in the coupled zone. Although the anomaly may be ascribed to the influence of the D'Entrecasteaux fracture zone (DFZ), both the mountain range and the

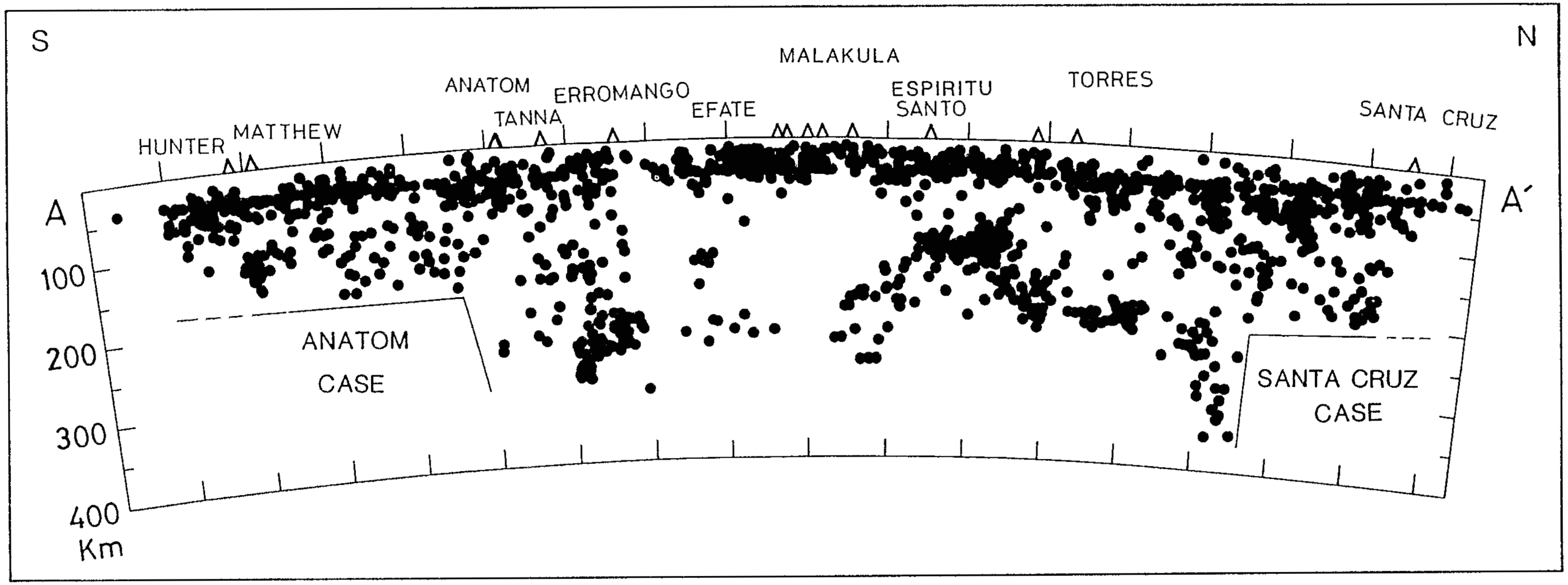


Figure 11. Longitudinal cross section of shallow and intermediate-depth seismicity of the New Hebrides Arc using the same data as in Figure 2. Triangles along top of section indicate the locations of Quaternary volcanoes; location of islands are given along the top. Line of earthquakes at 33-km depth is due to "normal depth" given to poorly constrained PDE hypocenters. Foreshortened areas of descending slab are labeled Anatom and Santa Cruz cases. See text for discussion.

unusual seismicity continue 60 km north of the DFZ to the northernmost extremity of Espiritu Santo (Jouannic, Taylor, and Bloom, 1982). The detachment zone at the latitude of Espiritu Santo apparently is displaced to the eastern side of the mountain range (Figures 5 and 6).

INTERMEDIATE-DEPTH SEISMICITY

Depth Accuracy

In analyzing the three-dimensional distribution of earthquakes, it is important to evaluate the accuracy of hypocentral determinations. In general, for teleseismically located earthquakes, the epicenters can be well constrained from the arrival times at distant seismic stations. However, accurate determinations of focal depth can be obtained only when readings are available from a set of nearby seismic stations. Louat, Daniel, and Isacks (1982) have provided a graphical method of estimating the accuracy of computed hypocentral depths. Within the model used, the accuracy of the computed hypocentral depth is ± 5 km, if the energy radiated from the focus is large enough for a reliable time reading. This is fair accuracy for an oceanic area and comes from the dense network of permanent seismic stations on the islands close to the New Hebrides Arc. Therefore, the hypocentral locations provide a reliable constraint on the presence and morphology of subducted lithosphere in the New Hebrides region.

Distribution of Earthquakes Along Strike

The longitudinal cross section shown in Figure 11 indicates a distribution of intermediate-depth seismicity far less uniform than that of the shallow activity along the top of the cross section and confirms the striking features visible in the map view (Figure 2). The following patterns of intermediate-depth activity are observed: (1) the Benioff zone below 250 km exists only from Tanna to the Santa Cruz Islands, about half the extent of the entire subduction zone; (2) a dense cluster of events at 100-150 km depth appears near Espiritu Santo Island; and (3) a striking, 200-km-wide gap of seismic activity in the 100-200 km depth range stands out in the central part of the arc. The existence of this gap is also confirmed by observations from the local network based in central Vanuatu since 1978 (Marthelot et al, 1985). The complex configuration of foci within the New Hebrides Benioff zone may be interpreted from two opposing viewpoints.

Uniform Lithosphere Model

We may interpret the non-uniform distribution as a short-term peculiarity of focal distribution within a continuous uniform subducted slab. This interpretation (Pascal et al, 1978; Isacks et al, 1981; Louat, Daniel, and Isacks, 1982) assumes the simplest tectonic configuration, since there are no clear data to contradict this assumption. It is highly improbable that either a non-uniform subducted slab, whose length varies along the arc, or that pieces of detached lithosphere could have the uniform dip observed along the entire length of the arc. Furthermore, the direction of plate convergence from focal mechanisms of shallow earthquakes is consistently near N70°E along the entire arc (see above). The trench is smooth at the scale of the arc. The 20-year time window of these observations is small compared to the life of the arc; therefore the peculiarities of focal distribution within the Benioff zone may be only short-term patterns. The irregularities in intermediate-depth activity are therefore a transient effect, and a direct correspondence between Benioff zone heterogeneities and the state of the subducted plate is largely speculative.

Non-uniform Lithosphere Model

The non-uniform distribution of intermediate-depth earthquakes may, in fact, indicate an irregular, discontinuous subducted lithosphere (e.g., Choudhury, Poupinet, and Perrier, 1975). This approach would imply that the short Benioff zones at the northern and southern ends of the arc are the results of a shorter lithospheric slab in those areas and that the partial gap in the central part of Vanuatu may be interpreted in terms of a gap in the subducted lithosphere.

The geologic history of the New Hebrides Arc (Carney and Macfarlane, 1982; Macfarlane et al, this volume) indicates that the present New Hebrides subduction episode is very young; the probability of this subduction beginning simultaneously all over the entire arc is low. Furthermore, the overall complexity of the regional tectonic setting (Chase, 1971; Luyendyk, Bryan, and Jezek, 1974) requires a complex subduction history of the New Hebrides Arc itself. In addition, the irregular gapping and clustering trends shown in Figures 2 and 11 are observed, at lower magnitudes, by microearthquake studies of the arc. We show (below) that a correlation exists in southern Vanuatu between the morphology of the island arc and the irregularities of the Benioff zone.

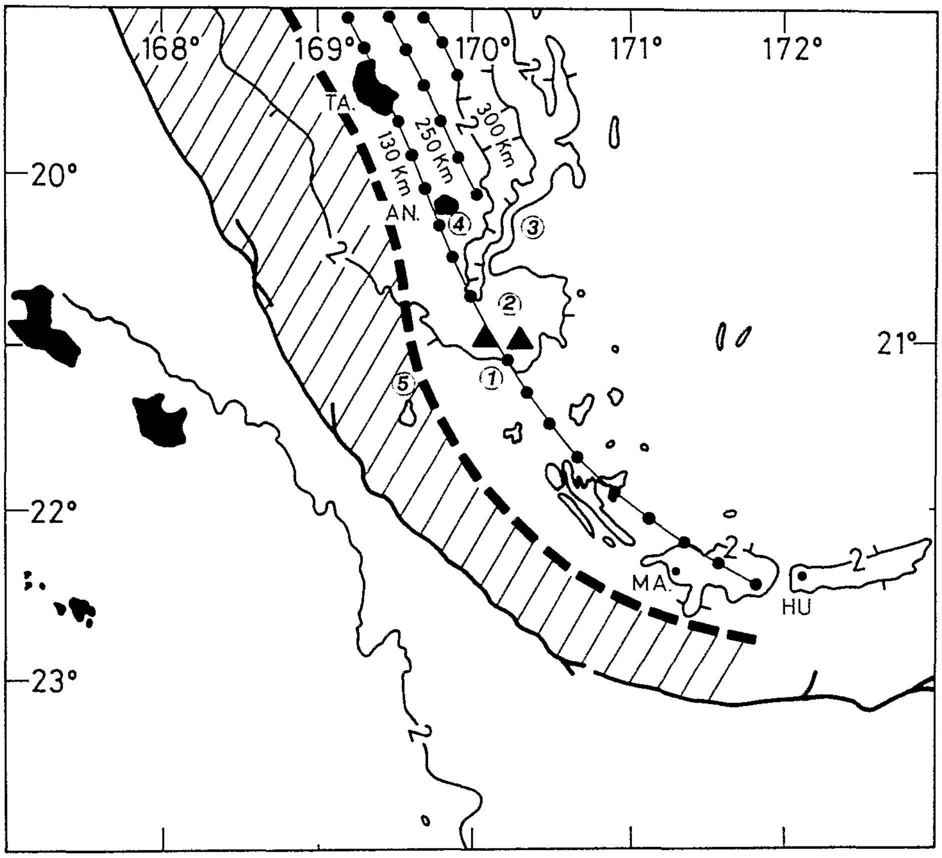


Figure 12. Morphologic and tectonic features of the southern New Hebrides Arc. Trench location and 2 km depth contours are from Monzier, Collot, and Daniel (1984). The trend of arc volcanism is indicated by Quaternary volcanic activity on Tanna (TA), Anatom (AN), Matthew (MA) and Hunter (HU) Islands; submarine volcanoes are shown by filled triangles. Note the abrupt break in arc morphology near 21° S. Zone of shallow seismicity is indicated by shaded area; the breadth of this zone changes abruptly between 21° and 22° S. Approximate Benioff zone contours, taken from maps of PDE locations, are given by black dots. Circled numbers refer to discussion of the Anatom case in text.

The exact correspondence, seen in Figure 2, between the northern edge of the Benioff zone and the northern limit of the subducted slab (from the position of the transform fault terminating the New Hebrides Trench) adds credibility to this approach. The uniformly large dip of the Benioff zone along the arc could be explained by the dominant role gravity and/or aesthenospheric convection has in shaping the subducted slab.

Discussion

These two models represent extreme end-members in a range of interpretations of intermediate-depth seismicity; no doubt the truth lies somewhere between these two. In general, without ancillary geologic or geophysical constraints, there is no empirical way to choose between the interpretations from focal distribution alone. In the case of the southern New Hebrides Arc, however, several additional features may be most easily interpreted by a non-uniform lithosphere model.

The Anatom Case

In the southern part of the arc, we have data that allow us to point out a set of structural and geophysical discontinuities just south of Anatom Island. Figure 12 demonstrates five major structural discontinuities in this portion of the arc:

1. Detailed bathymetric data (Monzier, Collot, and Daniel, 1984) show that the morphologic expression of the volcanic arc narrows and vanishes south of 21° S. The active volcanoes of Matthew and

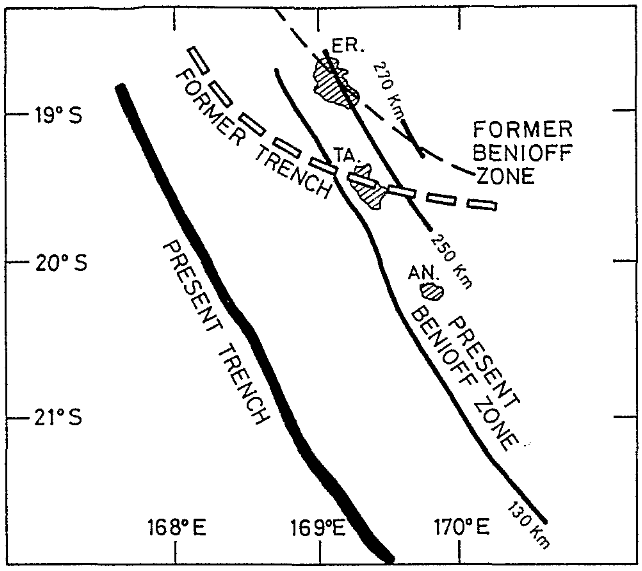


Figure 13. Schematic diagram of possible southern termination of the New Hebrides Arc at the latitude of Anatom Island, ca. 2 Ma. The former trench is not associated with any present morphological feature; its presence is assumed on the basis of the abrupt change in the subducted lithosphere implied by the distribution of intermediate-depth earthquakes in Figure 11, and by bathymetric and geophysical discontinuities summarized in Figure 12. Present Benioff zone contours are the same as in Figure 12. Former Benioff zone is schematic, and intended to show the orientation and possible configuration of the former subduction zone. ER = Erromango, TA = Tanna, AN = Anatom.

Hunter Islands (at 22.5° S) are located on an anomalous, narrow, east-trending ridge that is clearly separated from the main New Hebrides Arc. This disappearance of the arc is shown by the 2 km isobath in Figure 12. In addition, results from ORSTOM's EVA 12 cruise show a change in the spreading orientation of the central North Fiji Basin spreading center 2 m.y. ago and a probable southward propagation of this axis near 21° S since this change (Maillet et al, 1987). Such a change in the New Hebrides backarc region is consistent with a major break in the subduction history of the arc at the latitude of Anatom Island.

2. Arc volcanism (islands and triangles in Figure 12) is interrupted south of the two possible submarine volcanoes at 21° S.

3. The backarc trough (southern extension of the Coriolis Trough) curves around Anatom Island and disappears (Monzier, Collot, and Daniel, 1984).

4. The maximum depth of the Benioff zone (Figure 11) jumps from 300 km (north of Anatom) to 200 km (south of Anatom).

5. The width of the shallow interplate zone, indicated by the breadth of the shallow earthquake zone (hachured area in Figure 12) narrows rapidly south of Anatom.

These observations indicate a major change in the morphology of both the overriding and descending plates near 21° S. One relatively straightforward interpretation of this discontinuity is that the portion of the New Hebrides Arc south of 21° S represents a southward extension of subduction during the last 2 Ma (Figure 13; Louat, 1982).

Figure 13 presents a possible shape for the old plate boundary: the trench and Benioff zone were curved eastward as is the present southern termination; subsequent southward propagation of this boundary left a tongue of older lithosphere on the subducted plate. Present deformation of this tongue could result in the arcuate patterns of the deepest foci (Figure 11) and focal mechanisms indicative of downdip tension combined with lateral extension (Coudert et al, 1981). We note, in addition, a significant change in the morphology of the backarc (North Fiji Basin) from north-south-trending ridges with gentle slopes (north of 20.5° S) to ridges and scarps with sharp, irregular relief (south of 20.5° S) (Monzier et al, 1984). The rough topography in the south may have been produced by the tectonic complexities of trench migration. An additional consideration is the approach of the Loyalty Island Ridge to the subduction complex, but there is no direct evidence of modification of the trench morphology or the seismicity of the interplate zone due to subduction of the ridge; therefore, we must conclude that its impact on the subduction process is not yet manifest.

The Santa Cruz Case

By analogy with the Anatom case, a similar interpretation of the geometry of the Benioff zone can be made in the northern part of the New Hebrides Arc (Figure 14). Just south of the Santa Cruz Islands, the deepest seismic events of the longitudinal cross section (Figure 11) abruptly shallow from 350 km to 200 km, and the distribution of hypocenters becomes restricted to a narrow tongue. The bathymetric data here are too scarce to show correlation between morphology and length of Benioff zone as in the Anatom case, but the southernmost edge of the Santa Cruz island block does

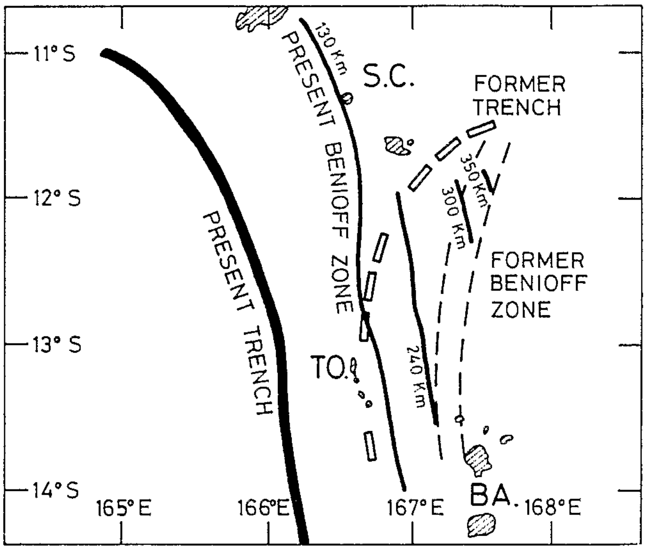


Figure 14. Schematic diagram of a possible former plate boundary of the northern New Hebrides Arc, by analogy with Figure 13, at ca. 2 Ma. This model assumes that the shortening of the Benioff zone from 350 km to 200 km depth results from real changes in the downdip length of the subducted slab. The simplest way to account for the prominent narrow tongue containing the deepest foci (see Figure 11) is to suggest an eastward curve in the former Benioff zone. Present and former Benioff zone contours are the same as in Figure 13. Note that the southernmost island of the Santa Cruz group corresponds to the northern termination of the deep portion of the present Benioff zone and the bend in the 130-km isobath. Island groups: SC = Santa Cruz, TO = Torres, BA = Banks.

coincide with the break in the Benioff zone (Figure 14).

If this northward propagation of the trench is real, it would require the presence of a fracture zone that acted as a plate boundary in the backarc area. The gravitational sinking of a formerly curved lithospheric slab could result in the elongated tongue of intermediate-depth events adjacent to the step (Figure 11). A similar, but slightly shorter tongue of events is also observed in the southern part of the arc beneath Erromango Island.

The hypothesis of a recent northward extension of the subduction zone carries with it an important geological implication: the northernmost portion of the New Hebrides Arc should reflect a shorter subduction history than the remainder of the arc. This is corroborated by recent geologic observations from the volcanic islands located in the northern segment of the arc.

While arc volcanism appears to have occurred continuously throughout the central portion of the New Hebrides Arc, the Santa Cruz Islands in the north experienced a major hiatus in the record of subduction-related volcanism, extending from early Miocene to middle Pliocene (Hughes, 1978). Continuous volcanism in the central part of the New Hebrides Arc is evidenced by upper Miocene to lower Pliocene volcanics and volcaniclastics exposed on Maewo and Pentecost Islands (Carney and Macfarlane, 1982), by lower Pliocene basaltic volcanics exposed in the Banks Islands (Ash, Carney, and Macfarlane, 1980) and by upper Pliocene to Quaternary volcanism in the central volcanic chains (Carney and Macfarlane, 1982).

In contrast, there are virtually no lower Miocene to upper Pliocene volcanic rocks exposed in the northern New Hebrides Arc (Hughes, 1978). The single exception is an anomalous alkali basalt flow from Nendo Island, with a 3.0-Ma date (Hughes, 1978), the geochemical signature of which is interpreted by Dunkley (1983) to represent volcanism related to rifting in the adjacent North Fiji Basin.

The overall notion of temporal changes in the length of the New Hebrides subduction zone is supported by a further geometric consideration. It is now generally accepted that the present tectonic configuration was preceded by a simpler, continuous, northeast-facing Vitiaz Arc (Gill and Gorton, 1973). In this model, subduction of the Pacific plate along this boundary is responsible for the Tertiary arc volcanism observed in the New Hebrides, Fiji, Lau/Tonga, and Kermadec Arcs. Palinspastic reconstructions of the Southwest Pacific generally invoke a continuous Solomon-New Hebrides-Fiji-Lau/Tonga-Kermadec ridge during the early Miocene (e.g., Gill and Gorton, 1973; James and Falvey, 1978; Larue, Collot, and Malahoff, 1980). This continuous arc is thought to have been interrupted by arc-polarity reversal and rotation of the New Hebrides Arc (Falvey, 1978), which resulted in the development of the North Fiji Basin (Chase, 1971).

The present length of the New Hebrides Arc, 1,500 km, is far greater than the reconstructed distance between Fiji and the Solomons Arc; if this arc length were preserved throughout its history, considerable overlap between the Fiji and New Hebrides Arcs would be required during this Vitiaz phase. However, the seismic data presented for the northern and southern ends of the New Hebrides Arc suggests that the late Tertiary arc may have extended only from the Banks Islands to Anatom Island, a distance of 900 km. In this case, a continuous Vitiaz Arc

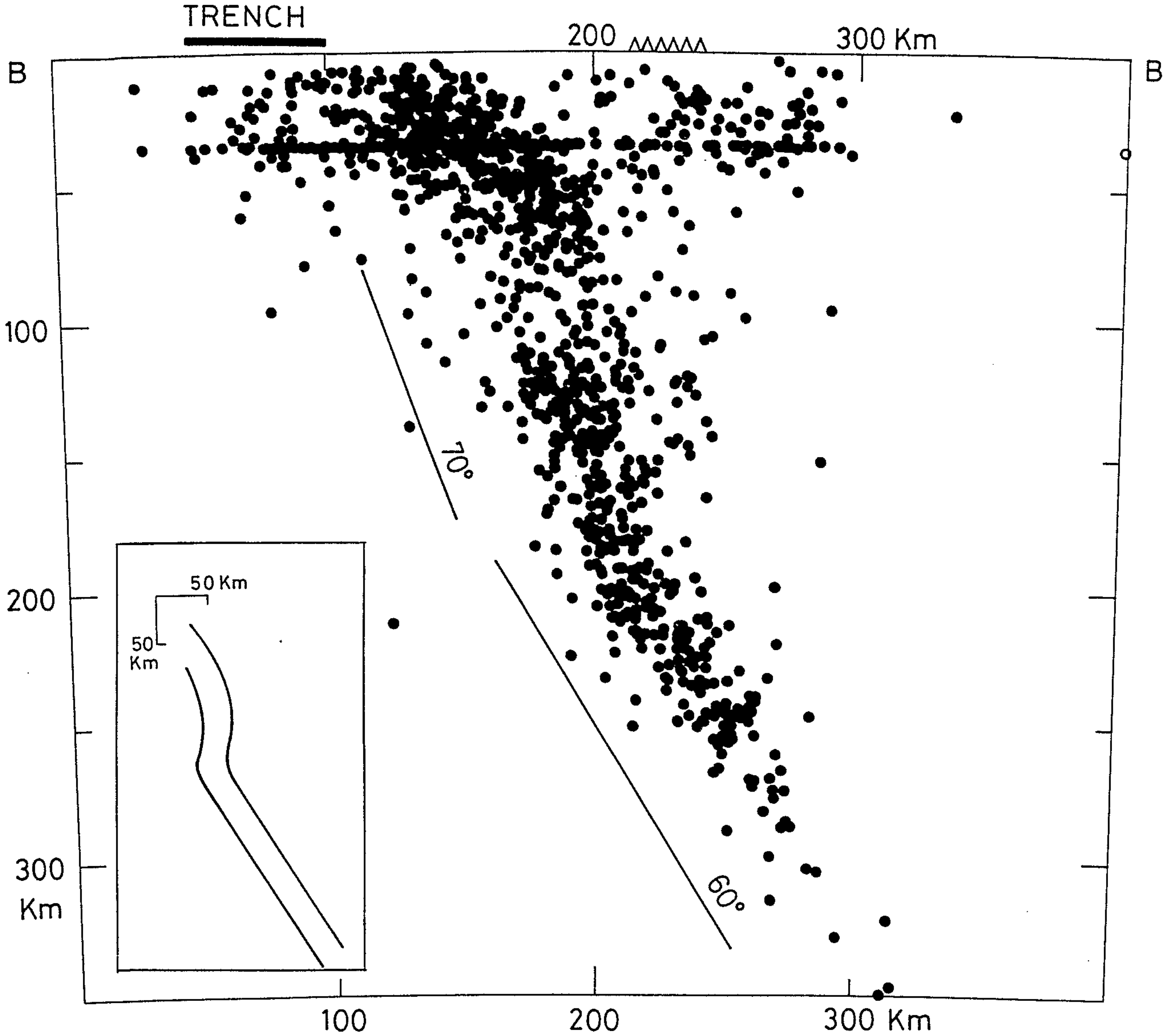


Figure 15. Transverse section across the linear portion of the New Hebrides Arc. Location given in Figure 2 (BB′). Triangles show locations of Quaternary volcanoes. The Benioff zone can be divided into two parts, the upper portion (70-180 km depth) is subvertical, the lower portion (below 200 km) has a dip near 60°. Lines with 70° and 60° dip are shown for reference. Cluster of hypocenters at 33 km depth is the result of locations given "normal depth" in PDE file. Inset shows proposed spoon-shaped cross section of Benioff zone.

could be reconstructed without major overlap between the New Hebrides and Fiji arc segments.

Spoon-Shaped Cross Section

The transverse cross section shown in Figure 15 is projected at an azimuth of N72.5°E, and includes all the shallow and intermediate-depth events from Figure 2 occurring along the linear portion of the arc. This averaged cross section shows a clear break in slope of the Benioff zone at about 200 km depth. Between depths of 100 and 200 km, the Benioff zone is nearly vertical, whereas below 200 km, the dip decreases to 60°. Similar conclusions were reached by Louat, Daniel, and Isacks (1982) after examining narrow cross sections and using the best-located ISC (International Seismological Centre) events. We call this morphology the spoon-shaped cross section.

These observed dips of the New Hebrides

Benioff zone contradict the continuous 70° dip noted previously by Pascal et al (1978) and Coudert et al (1981). Louat, Daniel, and Isacks (1982) show that a systematic bias in the method of joint hypocenter determination (JHD) used by Pascal et al (1978) could be responsible for this discrepancy. In a medium that has a P-wave velocity which varies significantly from that assumed by the model, and which includes both the master event and the earthquakes to be relocated, the master event can produce systematic errors in the hypocentral depths in the relocated events relative to the master event. Given realistic deviations from the simple mantle-velocity model assumed by Pascal et al (1978), the JHD relocations can transform the spoon-shaped cross section seen in Figure 15 into a smooth, steeply dipping Benioff zone.

Coudert et al (1981) also reported a smooth 70° dip in the southern part of Vanuatu, using the same data as Louat, Daniel, and Isacks (1982). In this case the discrepancy may be explained by a simple geometric consideration. Ordinarily, a cross section made perpendicular to the strike will have a greater dip than any section taken at an oblique angle. However, in southern Vanuatu the deepest events located around 20°S display a peculiar arcuate distribution (see Figure 11): on average, a discrete group of 300-km-deep events are located south of one at 275 km, which itself is located south of the 250 km foci. Consequently, contrary to our usual expectation, if the azimuth of the cross section is shifted northward, the apparent dip of the Benioff zone increases. Therefore, in the portion of the New Hebrides Arc near Anatom Island, the maximum-dip cross section is not that perpendicular to the strike of the slab, but one oriented perpendicular to the local trend of the intermediate-depth foci. Thus, a cross section oriented N60°E would have a dip greater than one taken at N70°E (the regional direction of subduction). Coudert et al (1981) have used a cross section perpendicular to the local strike of the trench (N60°E) which is curved eastward in the southern New Hebrides. We have chosen a cross section that takes in the entire island arc and is oriented perpendicular to the average line traced by the intermediate-depth events along its linear portion. Coincidentally, this direction, the present strike of the Benioff zone, is exactly perpendicular to the direction of plate convergence.

A similar kink in the intermediate-depth seismicity has been shown by Engdahl (1977) in the central Aleutian subduction zone at a depth of 110 km. The simplest interpretation without invoking contortion or breaking of the subducted slab, postulates migration of foci from the upper portion of the lithosphere to its center. This shift occurs at depths between 130 and 200 km beneath the volcanic line. If there is a causal connection between the kink in the Benioff zone and the position of the volcanic line, it would imply a change in the physical properties of the subducted lithosphere at about 150 km depth.

SEISMICITY AND TECTONICS OF THE CENTRAL NEW HEBRIDES ARC

We have examined the irregular seismicity in the northern and southern ends of the arc and interpreted it in terms of the opposing uniform and non-uniform lithosphere models. In this section, we present observations of seismicity in the central part of the New Hebrides Arc. Here, the plate boundary is characterized by extraordinarily complex morphology (Karig and Mammerickx, 1972; Luyendyk, Bryan, and Jezek, 1974; Collot, Daniel, and Burne, 1985), with major bathymetric irregularities on the descending plate (Mammerickx et al, 1971; Monzier, Collot, and Daniel, 1984) and structural disruption of the upper plate (Mitchell and Warden, 1971; Carney and Macfarlane, 1982; Taylor et al, 1980). We will show that this area is associated with a highly irregular seismicity distribution, which, once again, may be considered in terms of the opposing uniform and non-uniform lithosphere models.

Structure and Seismicity

We define the central New Hebrides Arc by the area between 14.5°S (Banks Islands) and 18°S (Efate Island), corresponding to the anomalous part of the subduction zone. This area is characterized by six major geologic and geophysical discontinuities on the upper plate (Figure 16):

1. The disappearance of a well-defined bathymetric trench between 14.5°S and 17°S;
2. The trenchward protuberance of the islands of Espiritu Santo and Malakula;
3. The presence of a deep, sediment-filled intra-arc basin (the Aoba basin), bounded by Espiritu Santo and Malakula on the west, and the uplifted blocks of Maewo and Pentecost Islands on the east;
4. The abrupt disappearance of the backarc Coriolis Trough just east of Efate;
5. A sharp change in strike of the volcanic arc at Efate (cross-hatched area in Figure 16); and
6. Extremely rapid Quaternary uplift of the islands in this portion of the arc (Taylor et al, 1980;

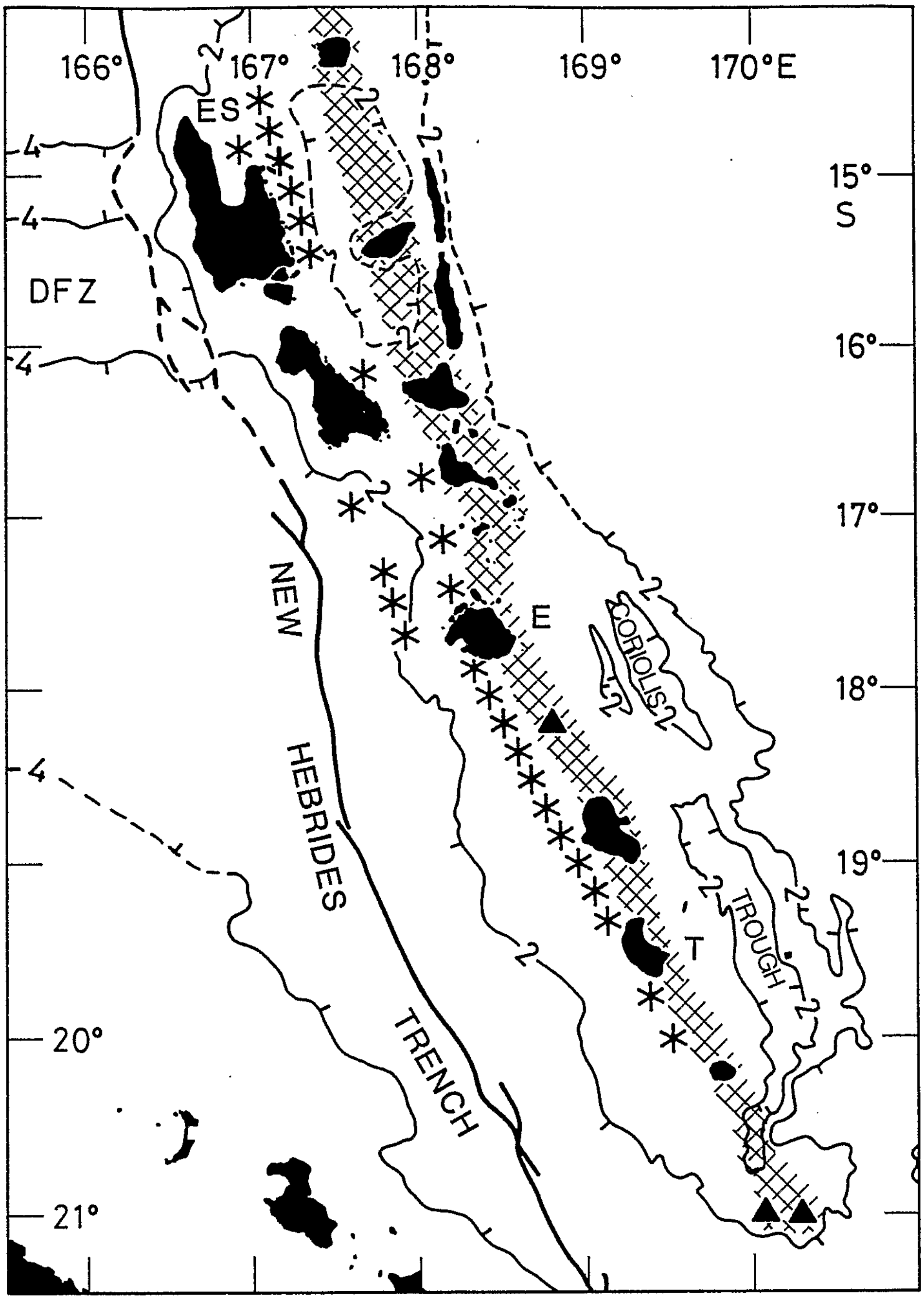


Figure 16. Discontinuities in the central part of the island arc. The cross-hatched area shows the volcanic line which is linear in the south and abruptly changes strike near Efate (E). Black triangles represent probable submarine volcanoes. Asterisks denote the line of 80-km-deep foci located by Prevot and Chatelain (1983) using the local network situated between Espiritu Santo (ES) and Tanna (T) Islands. The line is continuous arcward of Espiritu Santo and south of Efate. Between those two areas, the 80-km-depth foci are scattered over a broad area and a group of these events appears 30 km trenchward of Efate. Note northerly trend of the trench north of Espiritu Santo (Figure 2) and west of Efate; extrapolation of these two lines shows a 50-km shift between them, suggesting a perturbation of the trench by the D'Entrecasteaux fracture zone (DFZ). Note the disappearance of the Coriolis Trough just east of Efate. Bathymetric contours (in km) and trench location Monzier, Collot, and Daniel (1984) are dashed where approximate.

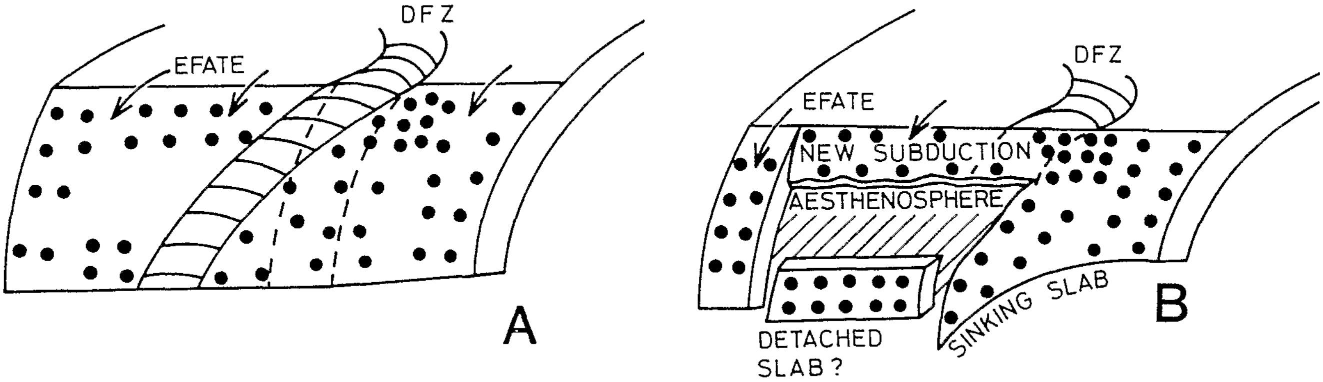


Figure 17. Schematic diagrams of possible interpretations of New Hebrides intermediate-depth seismicity. Figures show oblique views of the subducting (Australia-India) plate in the central Vanuatu area. Approximate locations of Efate Island and the D'Entrecasteaux fracture zone (DFZ) are given along the top of the diagrams, and black dots represent the locations of intermediate-depth earthquakes within the subducted slab. (A) *Uniform lithosphere model:* Continuous lithosphere lies along entire length of subduction zone. Continuity of lithosphere explains the consistent morphology of the subducted lithosphere; subduction of DFZ could explain gap in seismicity and high attenuation. This model requires the southward curvature of a subducted portion of the DFZ (solid lines) rather than linear extrapolation of the trend of the DFZ at the surface (dashed lines). After Marthelot et al (1985). (B) *Non-uniform lithosphere model:* Distribution of intermediate-depth earthquakes indicates distribution of subducted lithosphere. Absence of lithosphere in central Vanuatu would explain gap in intermediate-depth activity, low mantle velocities, high attenuation of shear waves and intense nest of activity near Espiritu Santo Island. Adapted partially from Choudhury, Poupinet, and Perrier (1975).

Jouannic et al, 1980).

These irregularities coincide with a major morphologic anomaly on the descending plate, the D'Entrecasteaux fracture zone (DFZ). The influence of the DFZ on the subduction process has been controversial. Chung and Kanamori (1978b) and Ravenne et al (1977) suggested that subduction of the DFZ is responsible for the physiographic complexities of the central New Hebrides Arc. Isacks et al (1981) and Collot, Daniel, and Burne (1985), however, contend that the interaction is responsible only for the anomalous Quaternary deformation and shallow seismicity of this area, not for the overall physiography. In this section we summarize the seismic characteristics of the area, and consider their implications for the uniform and non-uniform lithosphere models.

Focal mechanisms of shallow earthquakes indicate that seismic slip takes place throughout the central New Hebrides (Isacks et al, 1981). However, the following major seismotectonic peculiarities set this complex region apart from those surrounding it:

1. Both local and worldwide data demonstrate a clear, 250-km-wide gap in intermediate-depth activity (Figure 11; see also Marthelot et al, 1985).

2. A dense cluster of activity occurs at the latitude of Espiritu Santo at 100-150 km depth.

3. A continuous, linear belt of 80 km-deep earthquakes south of Efate abruptly bifurcates and scatters north of Efate (Prevot and Chatelain, 1983).

4. Focal mechanisms indicate hinge faulting within the subducting slab (Pascal et al, 1978; Chung and Kanamori, 1978a).

5. Mantle seismic wave velocity is anomalously low in the central part of the New Hebrides Arc (Choudhury, Poupinet, and Perrier, 1975).

These observations are interpreted below in terms of the uniform and non-uniform lithosphere models, as shown in Figure 17.

Uniform Lithosphere Model

The striking gap in seismicity (Figure 17a) beneath southern Malakula may represent a gap only in the seismic deformation of a continuous lithospheric slab. Gaps and active clusters are common features of intermediate-depth activity throughout the world's subduction zones (e.g., Isacks, Sykes, and Oliver, 1967; Katsumata and Sykes, 1969). The similarity in slab morphology along the entire length of the trench is most simply explained by lithospheric continuity. The continuity of arc volcanism throughout the central New Hebrides Arc also

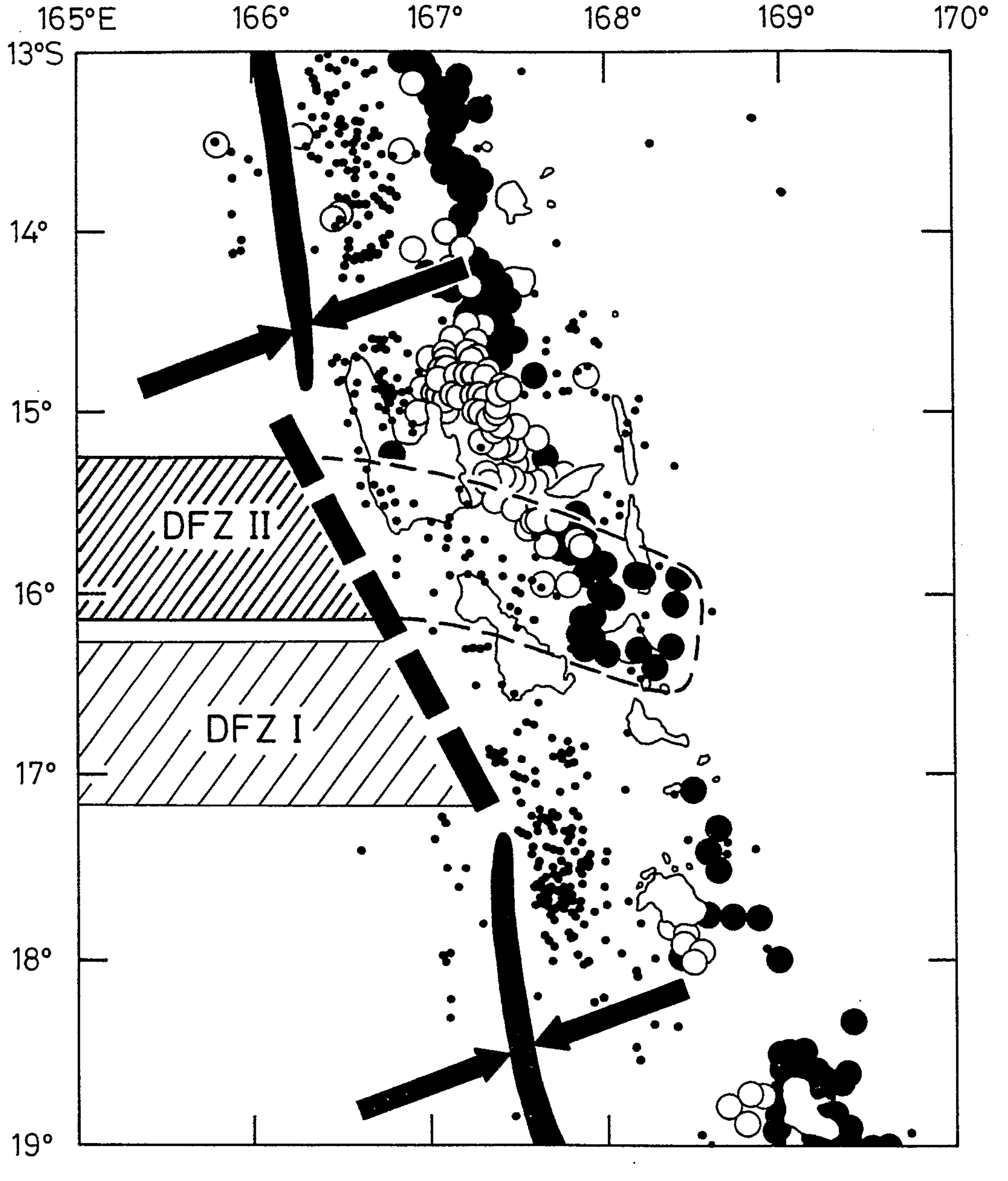


Figure 18. Seismicity of central Vanuatu and the role of the D'Entrecasteaux fracture Zone (DFZ). DFZ I shows the proposed location of the DFZ at ca. 3 Ma. DFZ II shows the present location of the DFZ. Dashed lines east of DFZ II mark the linear extrapolation of the DFZ into the subducted plate, based on the direction of dip. Shallow and intermediate-depth earthquakes are shown by dots and circles as in Figure 2. Note that this linear extrapolation of the DFZ coincides, not with the gap in intermediate-depth activity, but with the active nest of seismicity near Malakula. Arrows indicate the relative motion between the Australia-India plate and the arc. Heavy solid lines show the well-defined trench, and the heavy dashed line is the approximate trend of the plate boundary between these linear segments. Note the marked changes in strike near Espiritu Santo and Efate Islands.

requires the presence of subducted lithosphere.

Marthelot et al (1985) observed a striking pattern of attenuation of high-frequency shear waves that corresponded exactly to the gap in intermediate-depth activity. He suggested that this coincidence might be explained by subduction of the DFZ and its influence on the physical properties of the lithosphere (scattering and/or thermal anomalies). This hypothesis requires curvature of the subducted portion of the DFZ. Subduction of a straight DFZ would not intersect the gap in intermediate-depth activity, but the zone of high activity just north of it (Figure 18). The zone of high activity would thus represent increased deformation on the edge of the DFZ.

Non-uniform Lithosphere Model

The five independent observations listed above might be best explained by the absence of subducted lithosphere beneath southern Malakula and Efate (Figure 17b). The absence of subcrustal earthquakes (Figure 11) and the high attenuation of shear waves (Marthelot et al, 1985) could occur because the rigid lithospheric slab beneath the island arc is absent in this area. Furthermore, the observation by Choudhury, Poupinet, and Perrier (1975) of an anomalous low-velocity mantle in central Vanuatu also could be explained by the absence of high-velocity lithosphere there. The hinge-faulting focal mechanism (for an earthquake at 110 km depth), discussed by Pascal et al (1978) and Chung and Kanamori (1978a), has an east-trending, nearly vertical fault plane. The sense of motion on this fault plane, with the southern wall down dropped, is the reverse of what would be expected as a result of subduction of a buoyant aseismic ridge. Alternatively, it could be explained by the hinge-like deformation near the edge of a sinking piece of lithosphere (Figure 17b). This hypothesis is consistent with the southeastward protuberance of lithosphere suggested by the group of intermediate-depth earthquakes protruding beneath the Malakula-Efate gap in seismicity (Figure 11). The absence of earthquakes in this gap is confirmed by microseismicity records of the local network (Marthelot et al, 1985); this reduces the probability of a "chance" gap in intermediate-depth activity. The non-uniform lithosphere model avoids the *ad hoc* assumption of southward curvature of the DFZ within the subducted lithosphere. In this model, the DFZ plays a role only as a zone of weakness, along which lithospheric tearing may take place.

Discussion

Either of these two opposing models can explain the anomalous distribution of intermediate-depth earthquakes in the central New Hebrides Arc. However, both have serious limitations. The uniform model requires unverifiable assumptions of southward curvature of the DFZ prior to its subduction, and it cannot explain the anomalous activity adjacent to the gap or the hinge-faulting focal mechanism of an intermediate-depth event there. On the other hand, the non-uniform model invokes major along-strike variations in the subduction process—a condition at odds with the usual assumption of the simplest possible tectonic configuration and with the observations of uniformity of lithospheric structure on either side of the area of disruption. The continuity of the arc volcanism above this gap requires some continuity of the subduction process, at least in the recent geological past. The uniformity of slab morphology must then be explained by some more general physical property of the slab or of the subduction zone itself. In general, the choice between these two models is at present a philosophical one—it cannot be placed on a solid empirical basis until further seismological or geophysical data become available.

Influence of the DFZ on the Shallow Subduction Process

Regardless of the interpretation of its role in deformation of the subducted lithosphere at depth, it is clear that the DFZ has had a profound influence on the near-surface subduction process. The rapid Quaternary uplift and tilting of Malakula and Espiritu Santo have been documented in many geomorphic studies (Taylor et al, 1980; Jouannic et al, 1980; Gilpin, 1982) and appear to be spatially closely linked to the subduction of the DFZ. Collot, Daniel, and Burne (1985) apply the rigid indentor model of Molnar and Tapponier (1975) to explain many of the structural complexities of central Vanuatu (Figure 19). This indentor model can explain the localized uplift of Espiritu Santo and Malakula in the forearc, the recent horst-like uplift of Maewo and Pentecost in the backarc, the opening of backarc troughs to the north and south of central Vanuatu, and the sinistral and dextral strike-slip faulting immediately north and south of the DFZ.

The seismicity of this area has been examined by Isacks et al (1981) and Marthelot and Isacks (1984) using both teleseismic and local network data. Present-day subduction is clearly demonstrated by

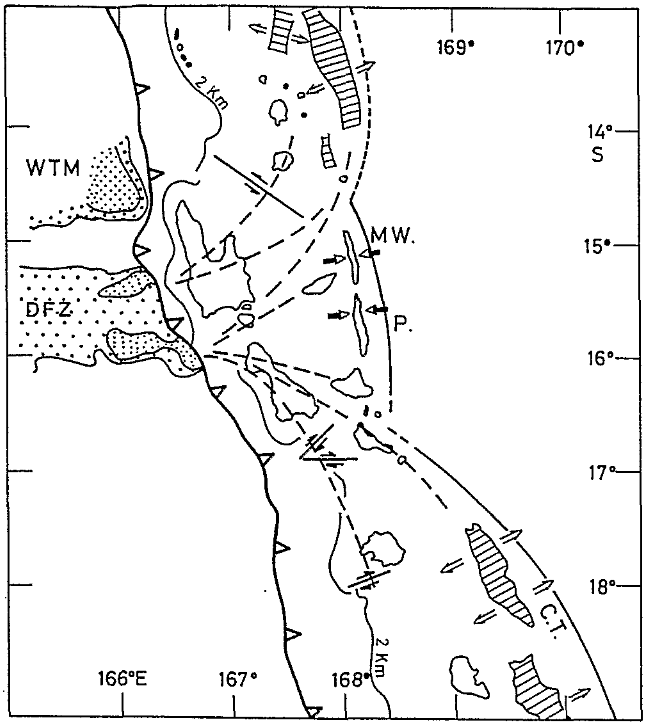


Figure 19. Present stress/strain pattern and surficial effects due to the subduction-collision of the D'Entrecasteaux fracture zone (DFZ), after Collot, Daniel, and Burne (1985). Shaded areas are the backarc troughs (C.T. shows the precisely mapped Coriolis Trough; the backarc troughs in northern Vanuatu are represented schematically). Dashed line indicates the fan-shaped stress trajectories interpreted from the major physiographic features. Strike-slip faulting is from focal mechanisms of shallow earthquakes, with sense of motion indicated by small arrows. Larger arrows display the preferential directions of backarc compression or extension. On the Pacific plate, the 3-4 km depths (sparse stippling) and <3 km depths (dense stippling) are shown for the DFZ and the West Torres Massif (WTM). Central Vanuatu islands: MW = Maewo, P = Pentecost.

thrust-type focal mechanisms of shallow earthquakes along the plate boundary. This portion of the arc, however, is characterized by large thrust earthquakes with strong coupling of neighboring events and well-defined precursory seismicity patterns, including moderate-sized compressional events in the upper plate (Marthelot and Isacks 1984). On the other hand, thrust-type events near Maewo and Pentecost (Burne, Collot and Daniel, this volume) demonstrate that part of the convergent motion between the arc and the Australia-India plate is taken up in the backarc region. Consequently, the actual velocity of plate convergence at Espiritu Santo and northern Malakula may be different than that in adjacent areas. These patterns are a possible result of increased interplate coupling adjacent to the DFZ.

CONCLUSIONS

1. Striking heterogeneity of shallow and intermediate-depth seismicity is observed along the New Hebrides Arc. This heterogeneity can be interpreted by changes in the subduction process along the length of the arc. For shallow seismicity, this implies variations in the degree of coupling at the plate interface, related to structural variations in the upper and lower plates. For intermediate-depth earthquakes, heterogeneous distribution may indicate changes in size, morphology or even the presence of the subducted slab beneath the island arc.

2. The shallow plate interface can be divided into three types, based on the shallow earthquake distribution. These three plate-boundary types are believed to have three distinct physical properties: (1) *the detachment zone* is seismically inactive, except during major interplate ruptures, and in the southern part of the arc may be the source for the large tsunamigenic earthquakes along the plate boundary; (2) *the coupled zone* is defined by a continuous belt of seismicity along the deeper portion of the plate interface and is characterized by a higher average stress loading than the detachment zones; (3) *the rupture barriers* are thought to be zones of high strength that bound the detachment areas and limit the potential size of plate boundary earthquakes. They are defined by zones of high seismicity along the shallow portion of the plate interface closest to the trench.

3. Fundamental differences exist in the frequency content of P-waves radiated from nearby shallow earthquakes. These differences may be ascribed to differences in coupling along the plate interface, with strongly coupled rupture barriers producing high-frequency P-waves, and with weakly coupled detachment zones producing low-frequency P-waves.

4. The portions of the plate boundary assigned to detachment zones are generally associated with anomalous forearc morphology, such as a large, clearly defined terrace that forms the inner wall of the trench. Large coseismic movements of these terraces during rupture of the detachment zones may be responsible for the tsunamis generated in this portion

of the arc.

5. Intermediate-depth seismicity in the New Hebrides Arc is characterized by major gaps and clusters of high activity. This heterogeneity of activity may be interpreted from opposing points of view using either a uniform or a non-uniform lithosphere model. The uniform lithosphere model contends that the subduction zone is best characterized by a continuous, relatively uniform subducted slab; the non-uniform model contends that the irregular distribution of Benioff zone earthquakes implies discontinuity of the subducted lithosphere.

6. In the case of the southern New Hebrides Arc, the coincidence of major structural and geophysical discontinuities coincide with a major shortening of the Benioff zone just south of Anatom Island and can be interpreted in terms of a recent southward extension of the subduction zone since 2 Ma.

7. By analogy with the Anatom case, the intermediate-depth seismicity of the northern New Hebrides Arc may indicate a similar northward migration of a former northern termination of the arc near the Santa Cruz Islands.

8. The best-located intermediate-depth events define a spoon-shaped cross section, the Benioff zone being nearly vertical between 100 and 200 km depth, and dipping eastward at 60° below 200 km depth. The kink in the Benioff zone occurs directly beneath the volcanic line.

9. The central New Hebrides Arc, from the Banks Islands to Efate, is marked by major disruption of the morphological, structural, and seismic continuity of the arc. These irregularities in the plate boundary may be interpreted by using either the uniform or the non-uniform lithosphere models. The limited data available make it difficult to discriminate between these two models. Subduction of the D'Entrecasteaux fracture zone beneath this portion of the island arc plays a dominant role in the geologic and shallow seismic deformation. However, subduction alone cannot explain all the morphologic and tectonic complexity of this port of the arc.

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