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SEISMICITY AND ATTENUATION IN THE CENTRAL VANUATU (NEW HEBRIDES) ISLANDS: A NEW INTERPRETATION OF THE EFFECT OF SUBDUCTION OF THE D'ENTRECASTEAUX FRACTURE ZONE

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Abstract. The spatial distribution of the intermediate-depth earthquakes in the central Vanuatu (New Hebrides) islands includes a remarkable gap in seismic activity located between depths of 100 and 200 km and having a lateral extent of about 150 km. No well-located earthquakes determined from teleseismic data during a 16-year period nor any microearthquakes located by a local seismograph network during a 5-year period have occurred in the gap. A zone of attenuation of high-frequency shear waves overlaps the seismicity gap. No contortion of the Benioff zone in the region of the gap indicative of major disruption of the subducted plate is apparent. However, the gap is close to the extrapolated location of the subducted part of the D'Entrecasteaux Fracture Zone (DFZ). The DFZ is a ridgelike bathymetric feature on the oceanic plate being subducted beneath the island arc. A positive thermal anomaly associated with the DFZ may cause the gap of intermediate-depth seismicity and produce anomalous absorption of high-frequency shear waves. Alternatively, a zone of strong scattering associated with the subducted part of the DFZ may also account for the anomalous attenuation.

Introduction

Despite the regularity in the overall geometry of subducting plates [e.g., Isacks and Barazangi, 1977; Bevis, 1982], mantle earthquakes are characterized by a strong tendency to cluster in nests of activity that are separated by zones of low activity or even gaps of activity [e.g., Santo, 1970]. In the Vanuatu (New Hebrides) islands, both small and large intermediate-depth earthquakes show the same spatial pattern of gaps and nests [Coudert et al., 1981]. This pattern is stationary in time during at least the period from 1961 to 1981 for teleseismically located events (J.-M. Marthelot and B. L. Isacks, preprint, 1982). The determination of the structural and/or stress heterogeneities responsible for the inhomogeneous distribution of intermediate-depth earthquakes may provide an important constraint on the origin of mantle events.

In this paper we use two different approaches to examine the relationship of a gap of intermediate-depth activity to properties of the subducting lithosphere in the central Vanuatu islands of the New Hebrides island arc. One approach is to determine the spatial relationship of the seismicity gaps with possible anomalies in the attenuation of high-frequency shear waves that propagate within the descending plate. The presumed capacity of the subducting lithosphere to propagate efficientlyhigh-frequency shear waves [Oliver and Isacks, 1967] has been used to infer the continuity or discontinuity of the descending slabs from observations of efficient or inefficient propagation paths [Barazangi et al., 1972, 1973; Isacks and Barazangi, 1973].

Another approach is to extrapolate the position of a structural feature seen on the surface portion of the oceanic plate to the subducted part of the plate. The D'Entrecasteaux Fracture Zone (DFZ) is an aseismic ridge that is located on the subducting oceanic plate and abuts the central part of the Vanuatu islands. Chung and Kanamori [1978a] and Pascal et al. [1978] examined the spatial correlation between the subducted part of the DFZ and extrapolated the subducted part of the DFZ to a transverse alignment of intermediate-depth hypocenters. In this paper we show that a different and more geometrically consistent extrapolation of the ridge at depths can be made which connects the subducted DFZ with the gap of intermediate-depth seismicity and with the corresponding zone of anomalous attenuation of high-frequency shear waves in the subducted lithosphere.

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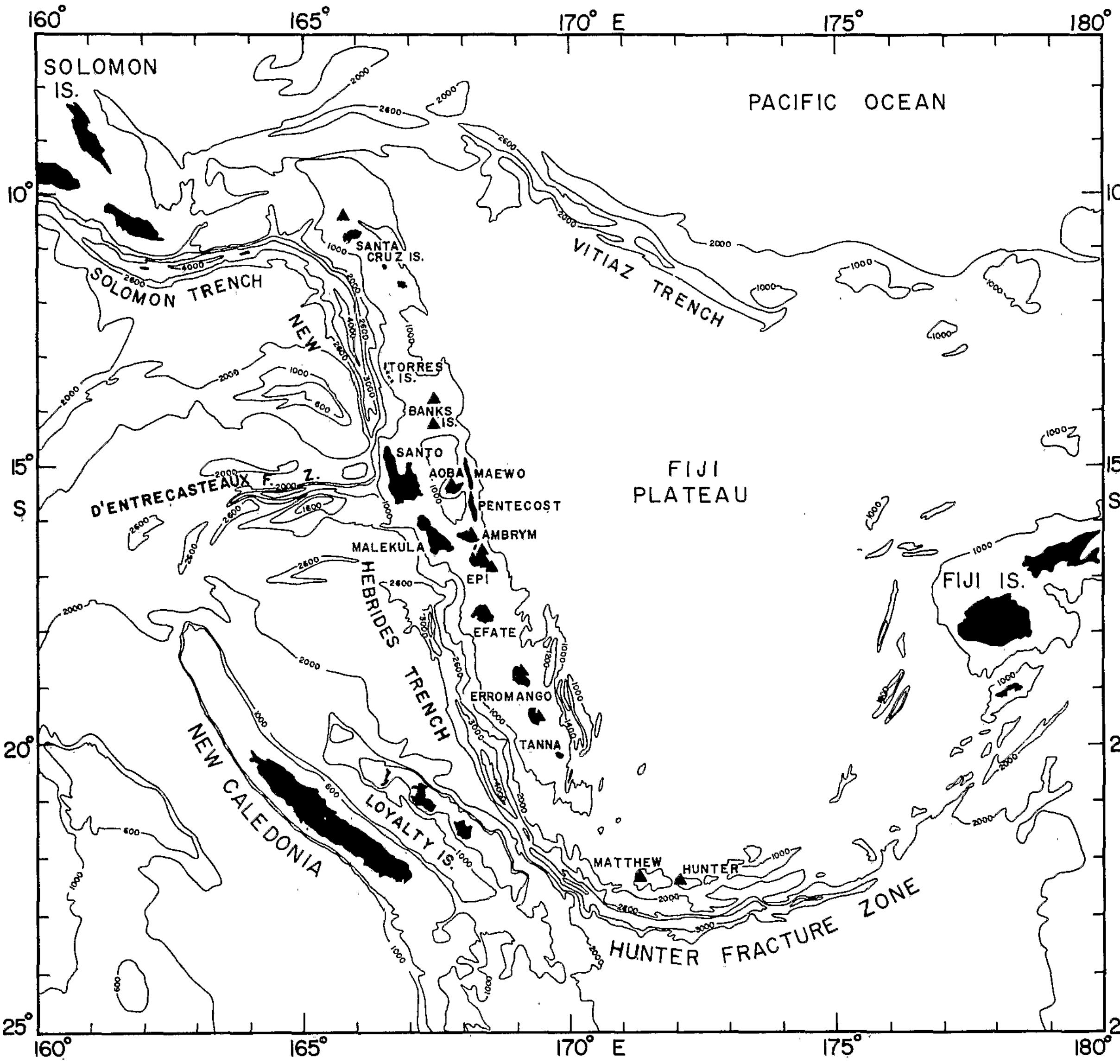

Fig. 1. Bathymetric map of the New Hebrides island arc and surrounding region, taken from Mammerickx et al. [1971]. The solid triangles denote Quaternary volcanoes. Contours are in fathoms. Note the east-west trend of the D'Entrecasteaux Fracture Zone (DFZ) over a length of about 300 km west of Santo and Malekula islands. An arcuate transition zone connects the DFZ to the New Caledonia Ridge [Daniel et al., 1977].

Downdip Extrapolation of the D'Entrecasteaux Fracture Zone

The DFZ is a broad zone with an average depth of 3.5 km (compared with 4.5 km for the adjacent oceanic areas) limited by two narrow ridges that intersect the arc in the southern and northern parts, respectively, of Santo and Malekula islands. The average trend of the DFZ is nearly east-west over a length of more than 300 km west of the Vanuatu islands. Daniel et al. [1977] and Maillet et al. [1982] show that the DFZ is connected to the New Caledonia-Loyalty island ridges through an arcuate transition zone. They emphasize the structural unity of the complex that may represent an Eocene analogue to the present southern New Hebrides-Hunter Fracture Zone system (Figure 1).

Figure 2 shows the interaction of the DFZ with the central Vanuatu islands. The morphology of the area is anomalous. The islands of Santo and Malekula are located at the expected position of the inner trench slope. The islands of Maewo and Pentecost are located at the same position as the back arc rifts present in the northern and southern parts of the arc. A deep sedimentary basin (the Aoba basin) lies between these two groups of islands.

Ravenne et al. [1977] and Chung and Kanamori [1978b] propose that the subduction of the DFZ is responsible for this anomalous morphology. However, most workers (e.g., see Isacks et al. [1981]) conclude that the morphology results mainly from a complex structure of the upper plate inherited from a Miocene episode of intra-arc rifting. The rifting formed the Aoba basin and produced a westward protrusion of the upper plate in the Santo-Malekula area. What does appear to be controlled by the subduction of the DFZ is the Quaternary uplift and tilting of Santo and Malekula [Taylor et al., 1980; Gilpin, 1982] and the compressional features observed within

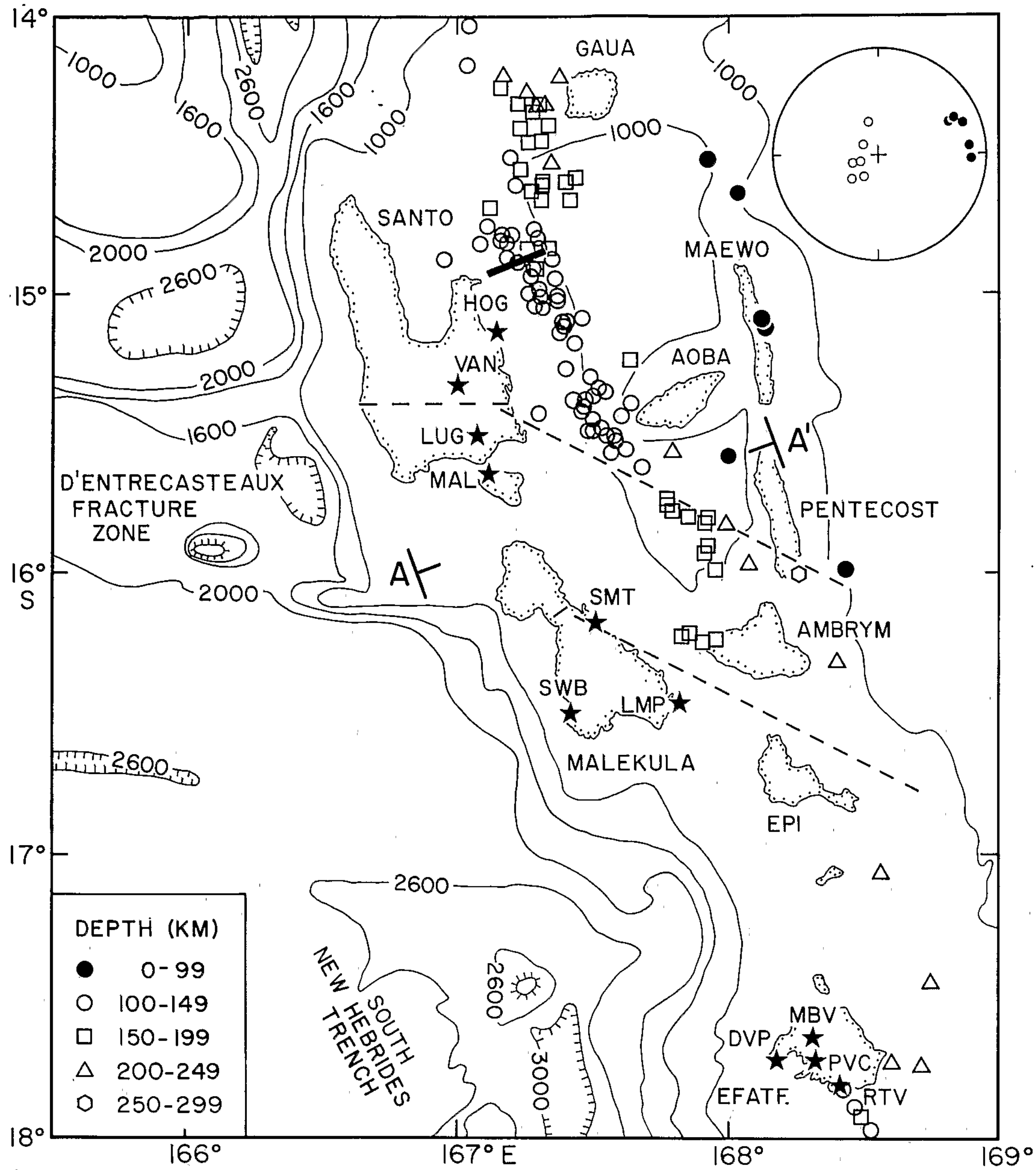

Fig. 2. Map of the central Vanuatu islands showing the distribution of the intermediate-depth earthquakes located by the ISC using more than 30 stations in the period from 1964 through 1979. Note the gap of activity in the Epi region that contrasts with the nest beneath Santo. The stars indicate the location of the stations of the Cornell-ORSTOM seismograph network used in the analysis of high-frequency shear wave propagation. The dashed lines on Santo and Malekula islands indicate tilt discontinuities inferred to represent the position of the ridges limiting the DFZ beneath the islands [Taylor et al., 1980]. The extrapolation of the DFZ to depths of 300 km, assuming that it is a rectilinear feature, is indicated by the oblique dashed lines east of Santo and Malekula. The short line segment northeast of "HOG" indicates the position of a transverse fault located within the subducting plate downdip of northern Santo Island [Pascal et al., 1978]. Focal mechanism solutions of four recent shallow earthquakes located within the upper plate are shown. The nodal plane, T axes (open circles), and P axes (solid circles) are shown together on an equal-area projection of the lower hemisphere of the frontal sphere. The parameters of these events are given in Table 1 and Figure 3.

the upper plate in the central part of the arc [Roca, 1978; Isacks et al., 1981]. Taylor et al. [1980] and Gilpin [1982] also infer that two major east-west tilt discontinuities located in southern Santo and northern Malekula (Figure 2) represent the location beneath these islands of the two ridges that bound the DFZ.

New focal mechanism solutions of six recent shallow earthquakes located along the eastern boundary of the Aoba basin confirm the existence of compressional deformation in this part of the upper plate (see Table 1 and Figures 2 and 3). Geological evidence indicates that Maewo and Pentecost islands have been uplifted substantial-

Table 1. New Focal Mechanism Solutions for Earthquakes in the Back Arc Region of the Central Vanuatu Islands

Event	Date	Latitude °S	Longitude °E	Depth km	Pole 1 Trend	Pole 1 Plunge	Pole 2 Trend	Pole 2 Plunge	P Axis Trend	P Axis Plunge	T Axis Trend	T Axis Plunge
101	May 12, 1980	14.52	167.93	38	070	60	250	30	070	15	250	75
102	April 3, 1982	15.10	168.15	33	083	71	240	18	066	27	229	62
103	April 5, 1982	15.12	168.13	33	072	56	272	32	084	12	303	75
104	Oct. 5, 1982	15.59	168.00	18	113	53	259	32	093	11	215	70
105	Nov. 16, 1982	14.61	168.03	27	060	66	247	24	065	21	253	69
106	April 26, 1983	15.99	168.43	33	064	49	295	29	093	11	343	61

The data for event 101 are shown in Figure 9. The parameters for events 102-106 are taken from the Preliminary Determination of Epicenters bulletin listing of the "best double couple" representation of the Harvard moment tensor [see Dziewonski et al., 1981].

ly during the Quaternary. Isacks et al. [1981] suggest that this uplift results from the reactivation by horizontal compression of a preexisting system of horsts and grabens originally similar to those still found in the northern and southern parts of the arc. They also suggest that the compression that causes the uplift is due to the interaction of the DFZ with the arc. The new focal mechanism solutions of the events shown in Figure 2 can be interpreted as indicating uplift along the steeply dipping nodal planes striking west-northwest subparallel to the narrow linear ridge upon which the island of Maewo and Pentecost are located. These are the focal mechanisms expected if a horst and graben system of high-angle, originally normal faults were reactivated by horizontal compression as reverse faults.

Figure 4 is a cross section of the intermediate depth earthquakes shown in Figure 2. It indicates the extreme regularity and steepness of the Benioff zone in this 500-km-long section of the arc, as found by Pascal et al. [1978] for the entire arc. The dip of the zone is 70°. In order to extrapolate the DFZ into the subducting

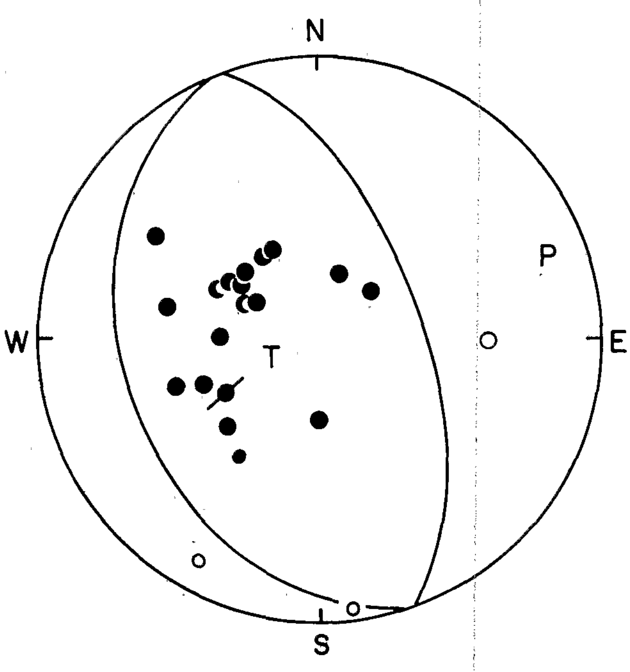

Fig. 3. Lower hemisphere focal mechanism solution for event 101. Compressions are solid circles, and dilatations are open circles. The line shows the first motion for an S wave. Also shown are the positions of the P and T axes.

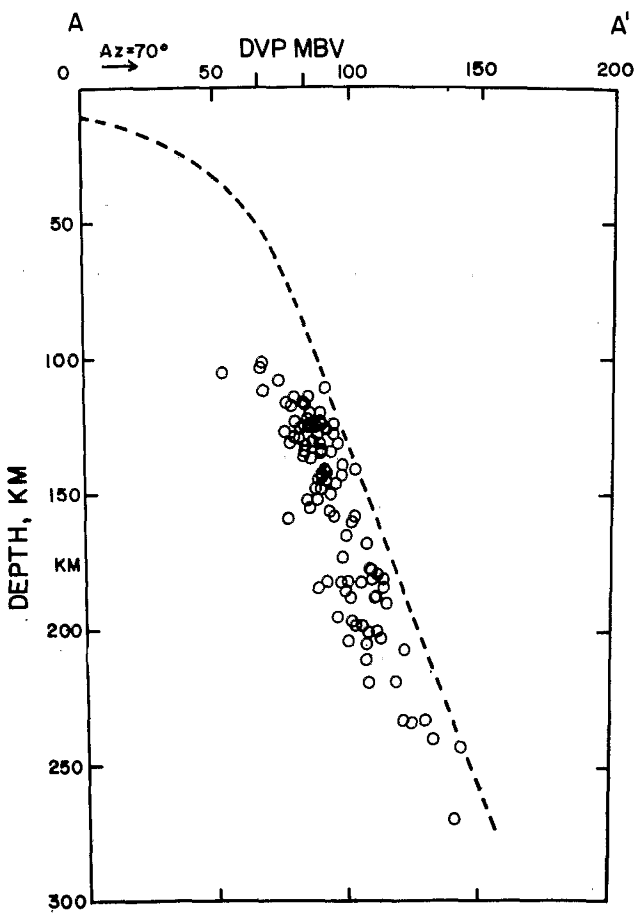

Fig. 4. Cross section of all the earthquakes shown in Figure 2. The horizontal and vertical scales are equal. The dashed line represents the assumed upper surface of the subducting plate. The position of the shallow interplate boundary is taken from Isacks et al. [1981]. The positions of the seismograph stations DVP and MBV located on Efate Island with respect to the subducting plate are indicated. Note that although the distribution of intermediate-depth earthquakes along the arc is very irregular, the geometry of the Benioff zone is extremely regular.

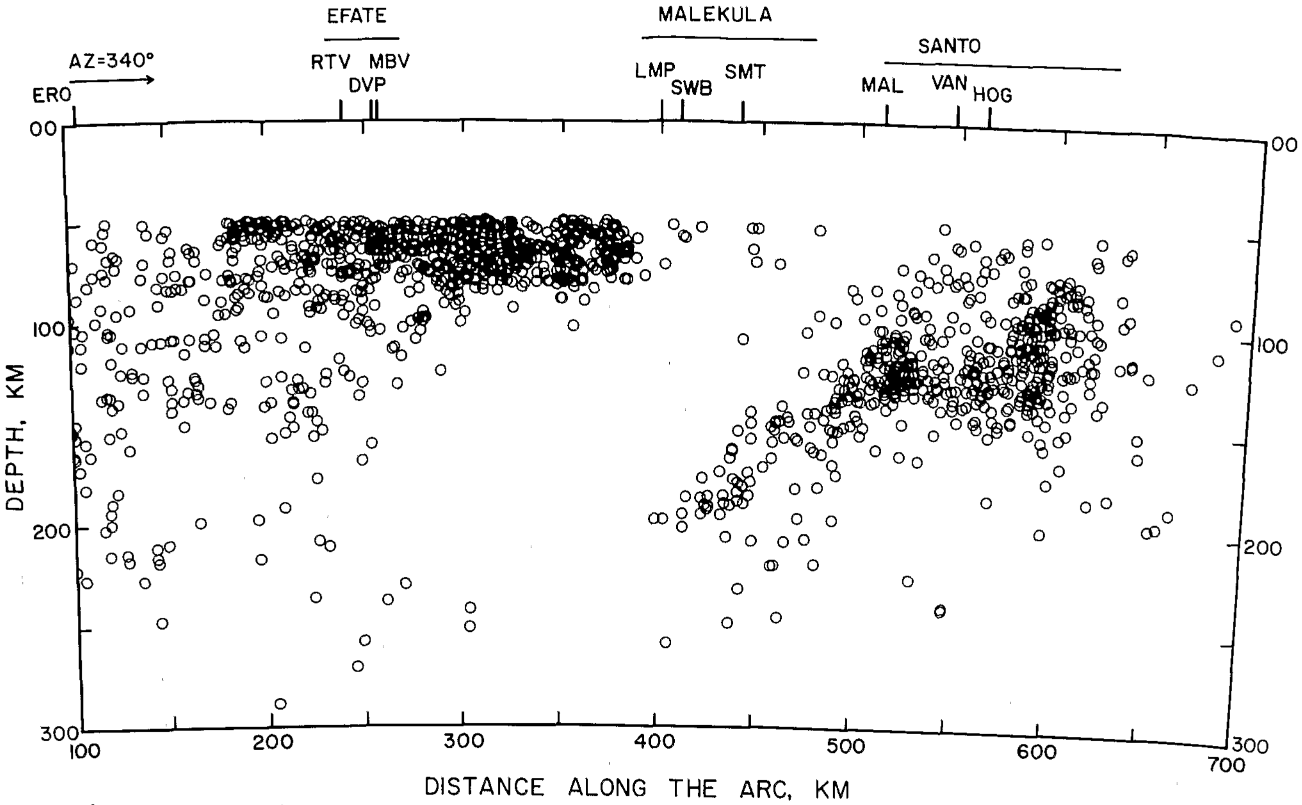

Fig. 5. Front view of the earthquakes having depths larger than 50 km located in the central Vanuatu islands by the local Cornell-ORSTOM seismograph network from August 1979 through December 1981. The positions of the stations are indicated by short vertical lines. PVC is located close to DVP and MBV in this section. The positions of the main islands are indicated by horizontal lines. Only grossly mislocated or unconstrained locations (Rms $\geq$ 1 s and/or number of readings < 5) have been rejected. Note the striking gap of intermediate-depth activity in the center of the figure.

plate, we make the following assumptions: (1) the constant trend of the DFZ apparent over a length of more than 300 km to the west of the arc also characterizes the subducted portion of the DFZ, (2) the tilt discontinuities observed on Santo and Malekula islands mark the position of the DFZ under the islands, and (3) the dashed line in Figure 4 represents the upper surface of the subducted lithosphere in the region. With these assumptions the downdip projection of the DFZ to depths of 300 km is indicated by the oblique dashed lines shown in Figure 2. For simplicity, the curvature of the subducted lithosphere at shallow depths is ignored and the 70° dip at intermediate depths extrapolated to the surface.

As shown in Figure 2, this extrapolation of the DFZ completely misses the transverse faultlike features described by Isacks and Barazangi [1977], Pascal et al. [1978] and Chung and Kanamori [1978a]. In those studies the approximate spatial coincidence was the only basis for associating the faultlike features with the subducted part of the DFZ. In the next section we examine the possible relationship between the subducted DFZ and features of the intermediate-depth seismicity in the area, especially the pattern of gaps and nests of activity apparent in Figure 2.

Gap in Intermediate-Depth Seismicity

Figure 5 shows a front view (looking N250°E) of the earthquakes having depths greater than 50 km located in the central Vanuatu islands by a local network of seismograph stations during a 2.5-year period starting in August 1979. More recent data, covering the 5-year period from mid-1978 to April 1983, show essentially the same patterns. The magnitude range of the earthquakes detected by the network has a lower limit around magnitude 3. The network of 19 stations has been jointly operated by Cornell University and the Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) since September 1978. The position of the stations is indicated by short vertical lines (see also Figure 2). The purpose of the section is not to resolve fine structures of the Benioff Zone but to highlight the gap in seismicity. Thus, to retain as large a sample as possible, only grossly mislocated or unconstrained locations have been rejected.

It is remarkable, however, that no microearthquake has been located during the 5-year period in a zone extending between depths of 100 and 200 km over a distance of about 150 km along the arc. Examination of more recent data for the period 1983-1984 shows the same patterns. This gap of activity also characterizes the distribution of well-located intermediate-depth events located by the International Seismological Centre (ISC) during a 16-year period (Figures 2 and 9). Similarly, the nest of activity located beneath Santo Island is apparent in both data sets.

Anomalous Attenuation

The magnification response of a component of the network is determined mainly by the natural

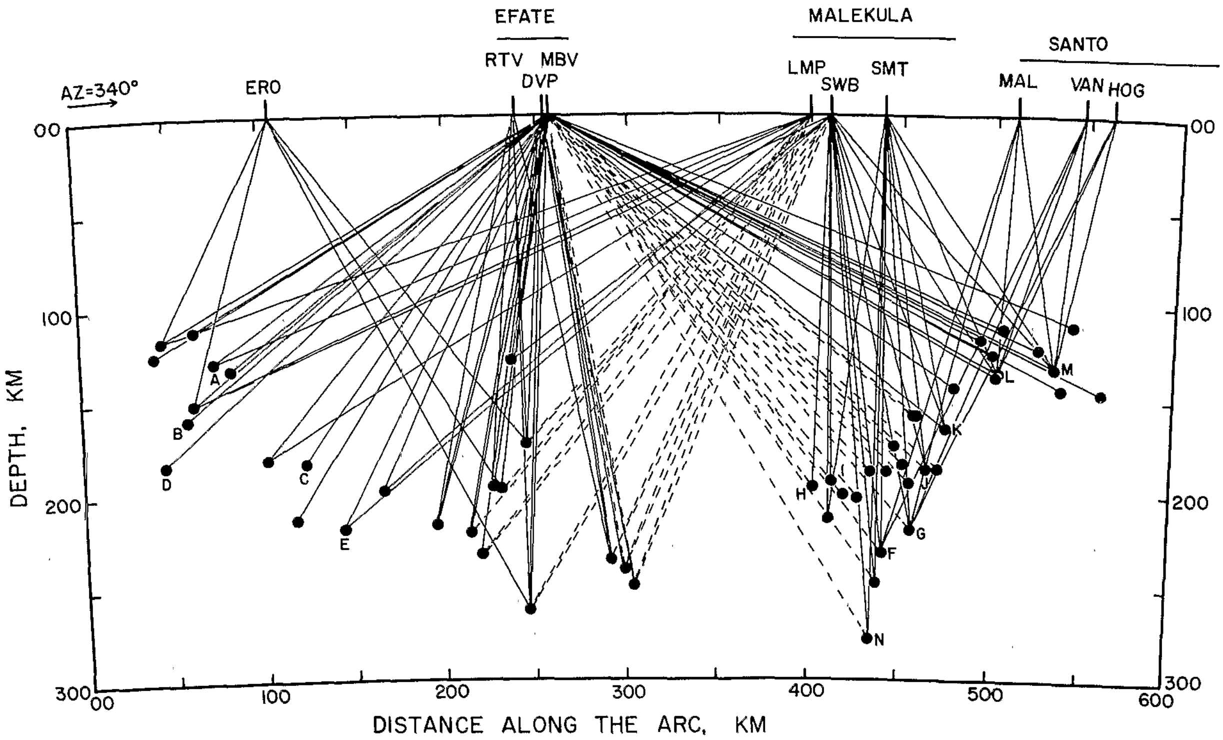

Fig. 6. Front view of the pattern of propagation of high-frequency S waves from the intermediate-depth earthquakes located in the central Vanuatu island arc to the seismograph stations of the Cornell-ORSTOM network. Earthquakes are shown by circles. Solid lines indicate efficient propagation of high-frequency S waves. Dashed lines indicate strong attenuation of high-frequency S waves.

frequency of the geophone, 4.5 Hz, and the filter response of the amplifier. The magnification response has a broad peak centered near 10 Hz. The S wave signals, however, have predominant frequencies in the range of 4-7 Hz that results from a corner in the spectra of the ground displacement signals near 4-7 Hz. In this study, variations in attenuation along the path are inferred mainly from the presence or the absence of the 4-7 Hz signals. The variations are summarized in Figure 6 and examples of seismograms are shown in Figures 7 and 8. Propagation paths are shown as straight lines. These lines are reasonable approximations to the actual ray paths owing to a typically large ratio of vertical to horizontal distance between source and receiver.

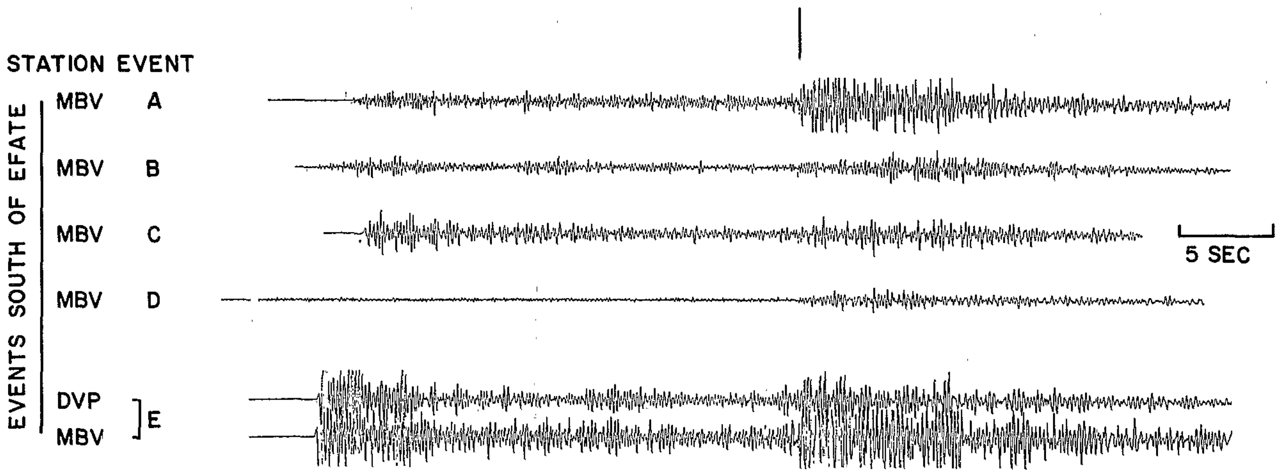

Fig. 7. Examples of seismograms recorded on Efate for events located to the south of Efate. The name of the station and the letters used to identify the events in Figure 6 are indicated. The events are aligned with respect to the expected arrival time of S waves at MBV that is indicated by the heavy line. Note the striking variations observed in the characteristics of the propagation of high-frequency shear waves for the events located north of Efate Island.

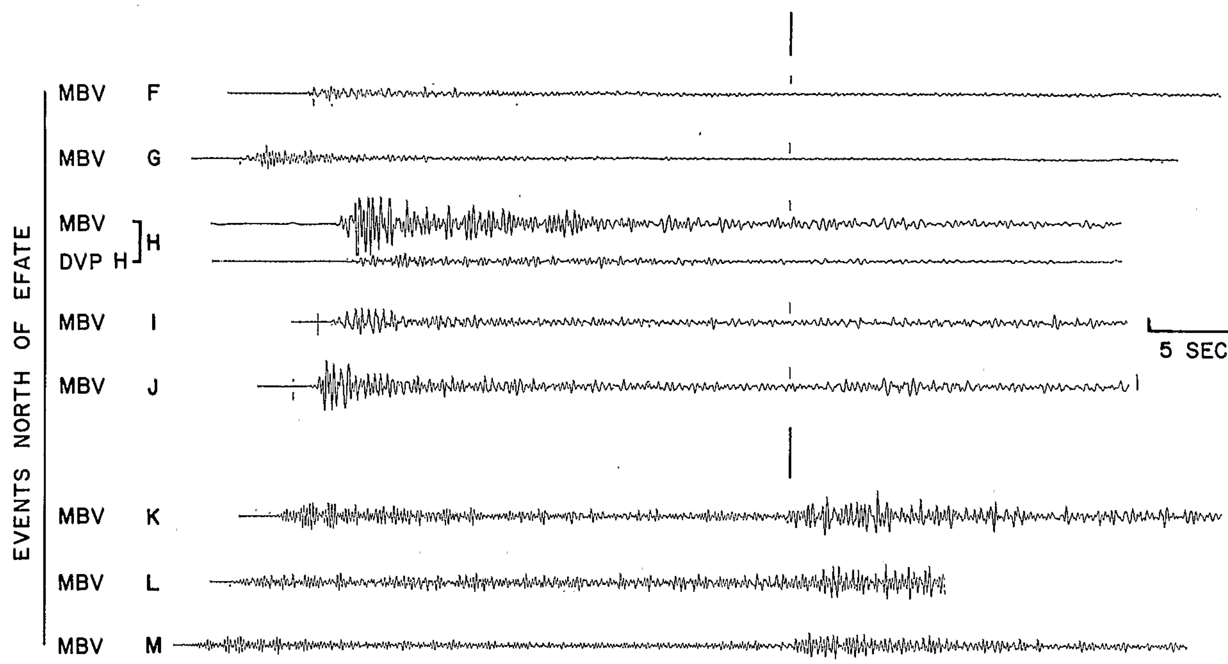

Fig. 8. Examples of seismograms recorded on Efate for events located to the north of Efate (see Figure 7).

Because of this geometry and because the sources are located within the subducted plate, the seismic waves must travel a substantial part of the path within the subducted plate.

Efficient propagation of high-frequency S waves is observed for the events located to the south of Efate Island, independent of the depths of the events. No observations for these events are available at the stations located north of SWB. No high-frequency S waves are observed at the stations located on Efate Island for events located north of the island and deeper than 175 km, while from events shallower than 150 km, high-frequency S waves are clearly observed. The classification of events having depths between 150 and 175 km was not always clearcut and was based on the relative amplitude of the P and S wave arrivals at MBV. For these events, S wave arrivals smaller than P wave arrivals were classified as attenuated, and S wave arrivals as large as P wave arrivals were classified as efficient.

All the events located beneath Malekula and Santo islands show efficient propagation of high-frequency S waves at the northern stations SWB, SMT, MAL, VAN, and HOG. The pattern of attenuation at the station LMP appears to be complex. Closely located events show opposite characteristics of high-frequency S wave propagation at LMP.

Records obtained at the broadband station PVC located on Efate Island (Figure 2) provide additional evidence for anomalous attenuation of shear waves. For example, event N (Figure 6) produces a clear S wave on the horizontal component of the broadband instrument at PVC. The arrival, however, has an anomalously low predominant frequency of 1 Hz as a result of the attenuation along the path. The observation of low-frequency S waves at PVC for the events showing attenuation of high-frequency (4-7 Hz) S waves indicates that the absence of high-frequency S waves is not due to a special orientation of the source mechanism. This point is further strengthened by the consistency of the data for numerous earthquakes.

The pattern of attenuation shown in Figure 6 must be due either to anomalous properties of the mantle along the path or to anomalies located close to the station. Two types of observations indicate that the attenuation takes place at depths. An example of the first type is that a shallow event located close to Pentecost Island produces clear high-frequency S waves at MBV. The azimuth of this event relative to MBV is within the range of azimuths of the intermediate-depth events showing attenuation at MBV. As the ray path from this shallow event to MBV is refracted through the mantle, the path within the crust beneath the station is close to the path for an intermediate-depth event having the same azimuth. A localized attenuating body located within the crust to the north of Efate Island would therefore have to be restricted to a very narrow cone beneath the island. The second class of observations includes events located beneath Efate which give high-frequency S phases at Efate stations but show attenuation at the Malekula stations (see Figure 6).

We thus conclude that spatial variations in the mantle are most likely responsible for the pattern of high-frequency S wave attenuation. It is difficult, however, to distinguish between the two possibilities that (1) a single zone of attenuation is located in the subducted slab at the intersection of the south-to-north and north-to-south dashed ray paths in Figure 6 or (2) two zones of attenuation are located north of Efate and south of Malekula and are each located near the upper slab interface or mantle wedge above the slab near where the rays leave the slab. The first possibility is the simplest

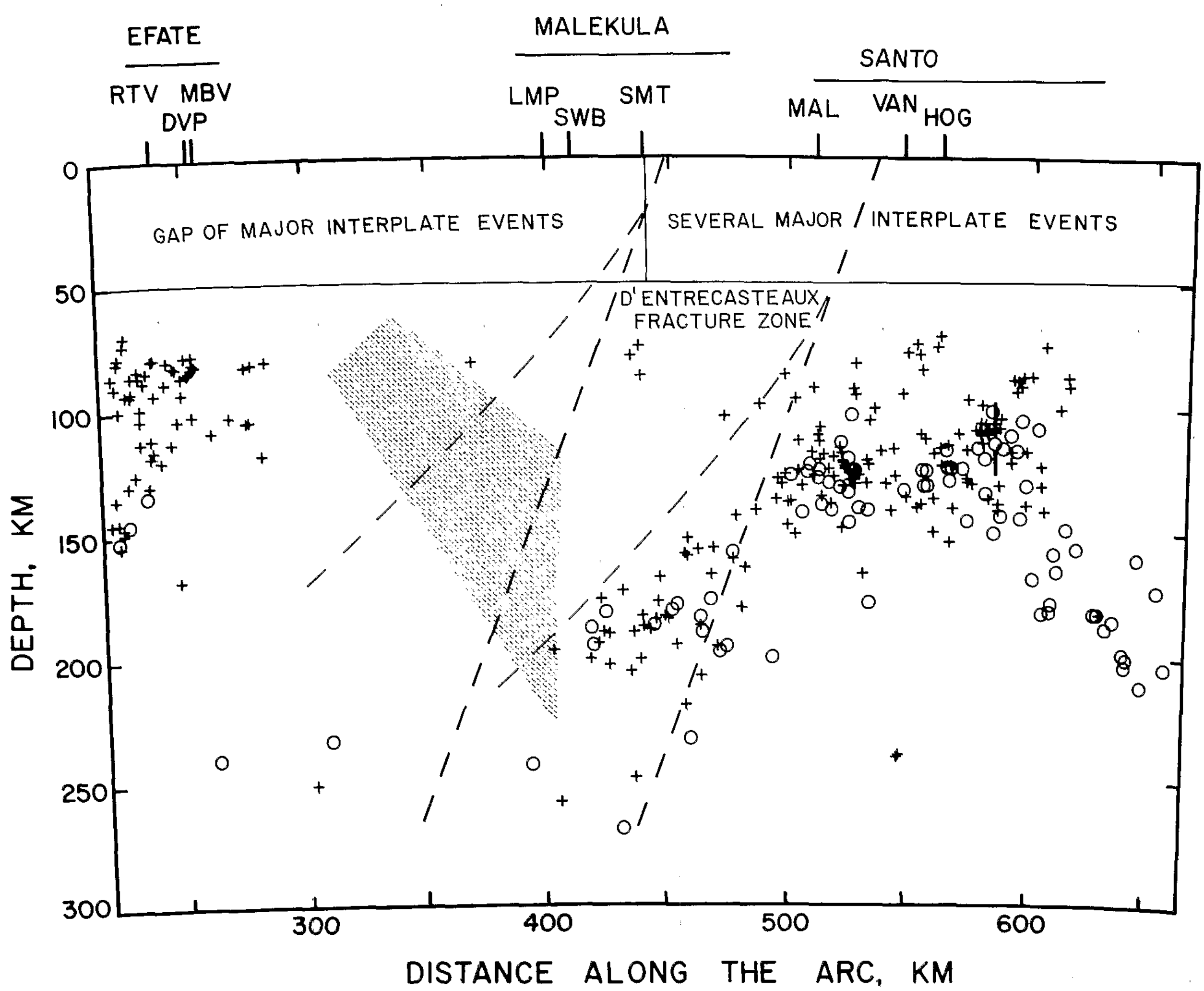

Fig. 9. Front view of the subducting lithosphere in the central Vanuatu island arc summarizing the characteristics of the seismicity in the area and indicating their possible relationships with the subducted D'Entrecasteaux Fracture Zone (DFZ). The circles represent the well-located earthquakes shown in Figure 2. The crosses represent well-located microearthquakes with depths larger than 70 km selected from the events shown in Figure 5. The pattern represents the region of attenuation of high-frequency S waves determined by the observations shown in Figure 7. Two possible projections of the DFZ at depths are indicated by dashed lines. The heavy vertical line within the nest of events located beneath northern Santo Island indicates the position of a transverse fault within the subducting plate. The main characteristics of the shallow seismicity in the area are indicated. The horizontal lines represent the locations of the islands.

interpretation, while the second requires two rather localized areas.

Discussion and Conclusions

Figure 9 summarizes the characteristics of the subducted lithosphere in the central Vanuatu (New Hebrides) islands. A gap of intermediate-depth seismicity exists between Efate and Malekula islands at depths of 100-200 km. This gap is juxtaposed with an active nest of seismicity located beneath Santo Island in which several clusters of events reveal faultlike features in the subducted lithosphere [Isacks and Barazangi, 1977; Pascal et al., 1978]. A zone of strong attenuation of high-frequency S waves overlaps the central part of the gap.

Figure 9 also shows two possible extrapolations of the DFZ at depth. The straight dashed lines correspond to the extrapolation shown in Figure 2. It is based on the assumption that the subducted part of the DFZ, when it was on the surface, had the same east-west trend as the present surface expression of the fracture zone. The curved dashed lines indicate another possible extrapolation based on the assumption that the subducted part of the DFZ had a slightly arcuate shape. This is rather speculative but not inconsistent with the general arcuate structure of the New Caledonia ridge-DFZ system (Figure 1). If the subducted part of the DFZ does curve southward, a close spatial relationship then exists between the subducted part of the fracture zone, the gap of intermediate-depth seismicity, and the possible zone of anomalous attenuation of high-frequency shear waves. The relationship may result from a thermal anomaly associated with the DFZ.

The existence of a thermal anomaly beneath the surface part of the DFZ is suggested by the results of Goula and Pascal [1979], who find a low-velocity zone for S waves under the DFZ seaward of the arc between depths of 100 and 300 km. This low-velocity zone may also account for the observations by Choudhury et al. [1975] of large positive ScS-P residuals from shallow earthquakes located in the central New Hebrides arc to a station located in Antartica. However, Barazangi et al. [1974] find efficient propagation of high-frequency S waves across the DFZ. Thus, while no major anomaly similar to that observed under zones of active back arc spreading is evident beneath the DFZ, a mild anomaly may exist. This anomaly may result in lateral heterogeneities of temperature controlling the distribution of seismicity and the attenuation within the subducted part of the DFZ.

The attenuation of high-frequency S waves inferred to occur at intermediate depth does not require the presence of a thermal anomaly causing absorption of these waves. Aki [1980] proposes that attenuation of high-frequency S waves occurs by scattering. It is possible that the subducted part of the DFZ causes strong scattering of high-frequency S waves within the subducted plate. In particular, the waves may be scattered outside the high-frequency waveguide and absorbed within the adjacent upper mantle.

The hypothesis that the subducted part of the DFZ curves southward may also have implications for the development of the shallow seismicity in the area. Figure 9 indicates the contrast between the distribution of major interplate shallow earthquakes in the northern and central parts of the arc. The curved downdip projection of the DFZ shown in Figure 9 implies that southern Malekula island may be above the western flanks of the already subducted part of the DFZ. That flanking slope on the subduction plate would be in the opposite direction to the slope of the downbending subducting plate and could thus account for the anomalous absence of a pronounced trench west of southern Malekula. Moreover, if the upper plate in the southern Malekula region is subsiding on the flank of the already subducted part of the DFZ, the coupling between the upper plate and the lower plate in the southern Malekula region may be weaker than in the northern Malekula-southern Santo area where the DFZ is lifting the upper plate. This is supported by the determination of stress trajectories within the upper plate that show that in the interplate boundary beneath Santo island the DFZ acts a concentrated source of compressional stress in the upper plate [Roca, 1978; Isacks et al., 1981] (see also Figure 2). A large component of aseismic slippage may thus occur in the southern Malekula area, while in the Santo-northern Malekula area strong interplate coupling results in sequences of major interplate earthquakes.

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