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Patterns of Seismicity Associated With Asperities in the Central New Hebrides Island Arc

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In the central part of the New Hebrides Island Arc (Efate - Malekula region, 16°S–18.6°S) a sequence of moderate sized earthquakes, their aftershock sequences, and other clusters of small earthquakes together form an intricate but coherent time-space pattern that probably reveals a major asperity complex along the interplate boundary of the subduction zone. This pattern is determined by study of data from a local network. The sequences, including one event with magnitude M_w 7.1, eight events with magnitudes M_w between 5.8 and 6.3, and nearly 13,000 smaller events, occurred during the six year period 1978–1984. The seismicity is very unevenly distributed in space: a sharply defined east-west line near 17.2°S separates the very active Efate region to the south, where nearly 10,500 earthquakes occurred, from the less active Malekula region to the north, where less than 2,500 earthquakes occurred during the six year period. In the Efate region several spatial patterns are highlighted. First, the seismic regimes of the updip and the downdip part of the interplate boundary are different. The updip part is characterized by a low background activity and main shocks with large aftershock zones, while the downdip part is characterized by a very high level of background activity and main shocks with much smaller aftershock zones or no aftershocks. This difference in seismic regimes suggests that asperities are located in the updip part of the interplate boundary, while the downdip part may slip predominantly by creep. A creep episode may have been responsible for the tilt signal observed by periodic relevelings of a 1-km-aperture network of benchmarks on Efate Island. Second, specific locations along the interplate boundary are identified either as sites of very intense and repeatedly activated concentrations of hypocenters or as sharp boundaries limiting the spatial development of aftershock zones. Two areas of concentrated activity particularly stand out; one located in the updip part of the interplate boundary and the other in the downdip part. Most of the clustered activity that occurred during the six years of observation is concentrated in these two areas. Four boundaries limiting the spatial development of aftershock zones are located in the updip part of the interplate boundary. One of these boundaries coincides with one of the areas of intense activity. Epicenters of moderately large events that occurred in the region since 1960 are also concentrated along the boundaries. The zones of concentrated activity and the boundaries limiting the development of aftershock zones can be interpreted either as locations of asperities or as edges of asperities. An alternative interpretation is that a giant asperity is located in the Malekula region, with the different spatial patterns observed in the Efate region being interpreted as the southern edge of that asperity, a transition zone between a locked part to the north and normal subduction to the south. Study of the temporal patterns of the seismicity shows that the main shocks in the downdip part of the interplate boundary are not preceded by obvious long-term (months to year) nor short-term (days to week) precursory activity. In the updip part of the interplate boundary, short-term foreshocks preceded each main shock, but only one of these foreshock sequences is outstanding. Although no clear cyclic pattern related to the main shocks is evident, clustered activity that occurred in the two zones of concentrated activity and two other zones located in the back-arc region are correlated in time with the occurrence of the major sequences located in the updip part of the interplate boundary. Activation of these four zones always follows the sequences in the updip part of the interplate boundary with varying time intervals (days to months). These four zones are also sometimes activated before sequences in the updip part of the interplate boundary. In particular, one of the zones of concentrated activity shows possibly repeated, long–term (few months) precursory activity. This phenomenon could be an indicator of increasing probability of occurrence of main events in the updip part of the interplate boundary.

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INTRODUCTION

The shallow seismicity of the New Hebrides island arc stands out among the world's convergent plate boundaries in several respects. While no great shallow earthquake is known to have occurred there, the region is characterized by frequent moderately large events (M_S < 8) that often form clusters or multiplet-type sequences. Prominent along-strike variations in the seismicity correlate with preexisting structural units of the island arc and with major structures in the subducting oceanic plate [*Pascal et al.*, 1978; *Ebel*, 1980; *Taylor et al.*, 1980; *Isacks et al.*, 1981; *Marthelot*, 1983; *Wyss et al.*, 1983; *Habermann*, 1984]. The New Hebrides provides a particularly good example of how the time-space development and other characteristics of the seismicity are largely controlled by specific structural complexities that produce spatially heterogeneous rheology and stress along and near the interplate boundary.

Models of "barriers" and "asperities" attempt to generalize the effects of heterogeneity to account for aspects of near- and far-field seismic wave radiation [e.g., *Wyss and Brune*, 1967; *Hanks*, 1974; *Aki*, 1979; *Ruff and Kanamori*, 1980], precursory seismicity variations [e.g., *Kanamori*, 1981], and global variations in the seismicity characteristics of major convergent plate boundaries [e.g., *Lay and Kanamori*, 1981; *Lay et al.*, 1982]. Detailed studies of seismicity in California show clear effects of specific structural complexities in the San Andreas system [e.g., *Bakun et al.*, 1980; *Lindh and Boore*, 1981; *Reasenberg and Ellsworth*, 1982]. There are few studies of large events in convergent plate boundaries, however, where the data directly highlight the very complex spatial features of seismicity with which concepts such as "asperities" attempt to cope. Such a high-resolution study essentially requires that one or more large earthquakes occur within or near a modern local network [e.g., *Mizoue et al.*, 1983].

The central New Hebrides arc is affected by the interaction of the subduction of the D'Entrecasteaux fracture zone with a westward protruding part of the upper plate. As a result, the western parts of Santo and Malekula islands are located where the inner trench slope is normally positioned. In spite of these anomalies the Benioff zone appears to be relatively uniform in its regional scale configuration [*Pascal et al.*, 1978; *Isacks et al.*, 1981]. The subducted plate has an unusually sharply downbent cross-sectional profile and a steep dip (70°) at intermediate depths, all producing an interplate boundary with the unusually narrow downdip width of about 50 km. The convergence direction is nearly perpendicular to the N20°W trend of the arc [*Pascal et al.*, 1978; *Isacks et al.*, 1981] with a convergence rate estimated to be 11 cm/y [*Dubois et al.*, 1977].

The central part of the arc can be divided into at least four segments (northern Santo, southern Santo–northern Malekula, southern Malekula, Efate) based on the pattern of uplift and tilting of coral terraces and on the bathymetry of the island arc. These segments also delimit rupture zones of large earthquakes and areas of coseismic uplift, regions with different rates and patterns of small- and moderate-sized earthquake activity, and regions with different histories of large earthquakes [*Taylor et al.*, 1980; *Isacks et al.*, 1981; *Marthelot*, 1983]. The focus of this paper is the region of southern Malekula and Efate islands, shown in Figure 1. Near this region the most notable recent episode of interplate rupture occurred in August 1965 in a sequence of earthquakes accumulating a total seismic moment equivalent to a magnitude $M_W = 7.7$ event [*Ebel*, 1980; *Isacks et al.*, 1981]. That sequence mainly affected a part of the plate boundary just north of the region of interest in this paper. The southern end of the 1965 rupture zone shown in Figure 1 is based on the pattern of coseismic uplift [*Taylor et al.*, 1980]. Prior to 1965, events with magnitudes near 7 occurred southwest of Efate in 1944 ($M_S = 7.3$), 1950 ($M_S = 7.2$), and 1961 ($M_S = 7.2$). Uncertainties in the locations and magnitudes of pre-1963 events, and particularly the sequence of large earthquakes that occurred between 1944 and 1946 ($M_S = 7.0$-7.3), make assessment of even the recent history of rupture of the area shown in Figure 1 difficult, but the record of instrumental observation suggests that much of the plate boundary located in the region of Efate and Malekula islands may not have ruptured seismically during the past 75 years [*Isacks et al.*, 1981].

Nevertheless, the activity of small to moderate events ($M_S < 8$) is extremely high in an area just northwest of Efate Island. It is substantially higher than that found for any other part of the arc during the past 25 years for which the detection level is adequate [*Isacks et al.*, 1981; *Marthelot*, 1983; *Habermann*, 1984]. From 1978 to 1984 this area experienced a major episode of seismicity that included eight earthquakes with magnitudes M_W between 5.8 and 6.3, and the July 15, 1981, earthquake, the largest ($M_W = 7.1$) event to have occurred in the region between Malekula and Efate islands during the past 25 years (and possibly the largest event during the past 75 years of teleseismic earthquake location). The 4 years preceding 1978 were notably quiet. The joint tilt measurement program of the Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) and Cornell University commenced in 1975, while the local seismograph network began operating just 2 weeks after the first large earthquake of the sequence in 1978. Thus the local network caught nearly the entire episode.

In this paper we present a detailed study of the episode that included these 9 main events and over 13,000 smaller events ($M_L > 1.9$) that occurred during the period from 1978 to 1984 in the Efate–Malekula region. We focus on the outstanding features of the spatial and temporal distributions of earthquakes. These distributions are characterized by a strong degree of clustering on several time and spatial scales. Most of the seismicity is concentrated in the region of Efate and forms an intricately interrelated episode of main shocks, aftershock sequences, and other time-space clusters. In addition, we find a remarkable spatial variation in seismicity in a direction perpendicular to the strike of the arc, i.e., in a direction parallel to the dip of the interplate boundary. Much of the strongly clustered activity and the large aftershock zones occur in the updip part of the boundary, while a downdip zone is characterized by a more continuous level of background activity. The view of interplate boundary slippage as one controlled by the interaction of stick-slip failures of strong patches or asperities in the updip part of the boundary with a zone more dominated by creep in the downdip part of the boundary explains many features of our results.

SEISMOGRAPH NETWORK LOCATIONS

A network of 19 seismograph stations was established in the New Hebrides islands in 1978–1979 as a joint project between ORSTOM and Cornell University. Eleven of these stations are installed in the Efate–Malekula region (see Figure 1) and all but one of them (AMK) have been operating since September 14, 1978. In addition, the ORSTOM station PVC has operated in Port Vila, Efate Island, since the early 1960s. All stations of the network

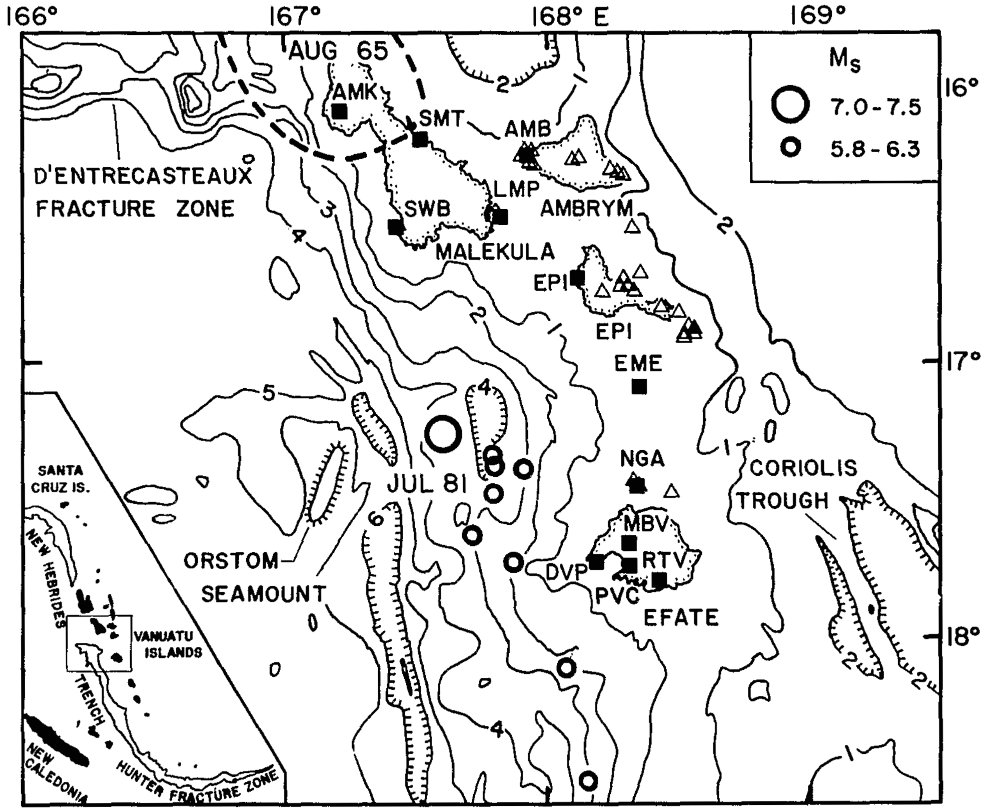

Fig. 1. Map showing the location of the stations of the ORSTOM-Cornell seismograph network (solid squares), and the locations of main shocks of the 1978–1984 episode (open circles). The dashed line is the southern part of the zone inferred to have ruptured during the 1965 sequence by *Isacks et al.* [1981]. Open triangles represent Quaternary and active volcanoes [Ministry of Overseas Development, 1975]. Bathymetric contours (in kilometers) are from *Monzier et al.*, [1984] . The inset shows the entire New Hebrides island arc, with the trench outlined by the 2600-fathom bathymetric contour [*Mammerickx et al.*, 1971].

have a vertical component seismometer. Three of the stations shown in Figure 1 (DVP, SWB, and PVC) have, in addition, a horizontal component seismometer. All signals are transmitted by a radio telemetry system to a base station located at the site of the ORSTOM seismograph station at PVC. The signals are recorded on a triggered, event-detecting, multichannel oscillograph system. The system records a complete sample of events with magnitudes larger than about $M_L = 2.7$. M_L is a local scale based on coda duration. It is tied to the teleseismic m_b scale, using *Tsumura*'s [1967] method, for those events large enough to have m_b values reported in the monthly bulletins of the Preliminary Determination of Epicenters (PDE).

An important feature of the oscillograph recording system

TABLE 1. Parameters of Main Shocks ($M_w \geq 5.8$)

Date	Origin Time, UT	Latitude[a] °S	Longitude[a] °E	M_s[b]	Mo[c] x10 ^{25} dyne cm	M_w[d]
Sept. 1, 1978	0416	17.38	167.88	5.9	1.1	6.0
Jan. 27, 1979	1815	18.52	168.15	6.3	2.1	6.2
Aug. 17, 1979	1259	17.73	167.87	6.1	3.1	6.3
Aug. 26, 1979	1147	17.63	167.71	6.0	2.5	6.2
July 15, 1981	0759	17.26	167.60	7.1	58.	7.1
Jan. 18, 1982	0423	17.33	167.80	5.6	0.63	5.8
March 12, 1983	0849	18.15	168.16	5.8	1.7	6.1
Aug. 3, 1983	1817	17.47	167.81	5.6	0.68	5.8
Aug. 5, 1983	0525	17.36	167.81	5.7	0.96	5.9

[a]Relocations with all available teleseismic and local data for 1978–1981 events, except January 27, 1979 [Bulletin of the International Seismological Centre (ISC) location]; remaining locations based on local data only.

[b]M_s, surface wave magnitude taken from monthly bulletins of the Preliminary Determination of Epicenters (PDE).

[c]Mo, seismic moments reported by *Chinn and Isacks* [1983] or in Monthly Bulletins of the PDE (1981-1983 events).

[d]M_w is calculated from Mo by $M_w = (1/1.5) \times (\log(Mo)-16.1)$.

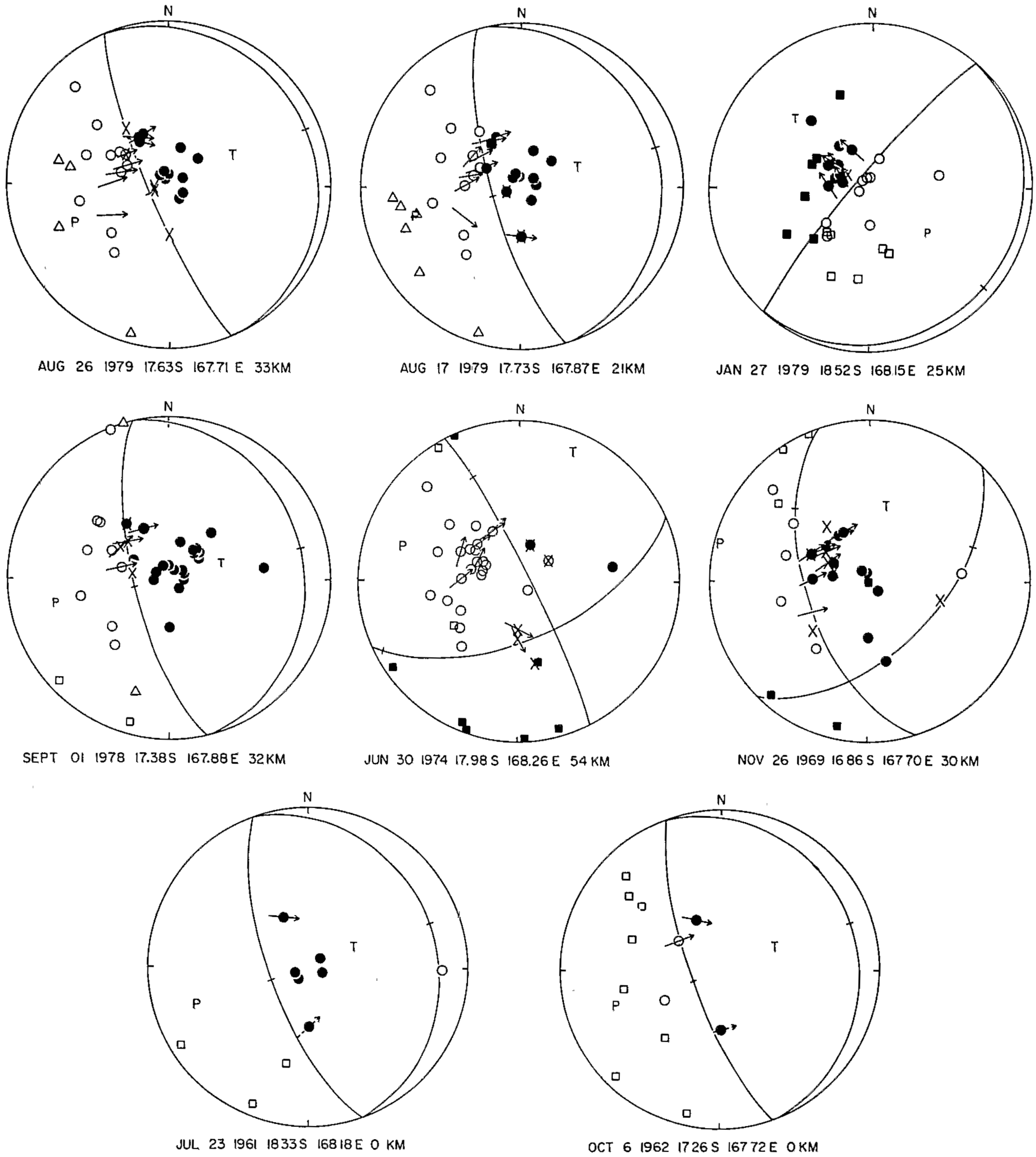

Fig. 2. New focal mechanism solutions for the Efate-Malekula region using data from the International Geophysical year (IGY) network for the 1961–1962 events and from the Worldwide Network of Standardized Seismograph (WWSSN) stations for the 1969–1979 events. All solutions are shown on equal-area projections of the lower hemisphere of the focal sphere. Open and solid circles represent dilatational and compressional first motions, respectively. Crosses indicate compressional wave data that are judged to be near a nodal plane. Open and solid triangles represent dilatational and compressional first motions, respectively, from the ORSTOM-Cornell seismograph network. First motions that are reported in seismological bulletins are shown as open and solid boxes for dilatational and compressional readings, respectively. Arrows indicate S wave polarization directions (dashed where uncertain). Tick marks on the nodal planes indicate the poles to the plane. The P and T axes are located at the base of the letters. The date, latitude, longitude, and depth of the event are shown below the focal sphere.

(in contrast to a rotating drum recorder) is that during active periods, no earthquakes are lost by traces being overwritten. All station traces are displayed on a single record with a common time base and a recording speed of 1 cm/s, and arrival times are read on a digitizing table. The uncertainties in arrival times are less than 0.05 s. Earthquake locations were determined using the U.S. Geological Survey computer program HYPOINVERSE [*Klein*, 1978]. The P wave velocity structure and the value of the ratio of P wave velocity to S wave velocity (V_P/V_S) were taken from model 1 of *Coudert et al.* [1981].

The quality and number of arrival time readings, the network geometry, and the position of the hypocenter relative to the network all affect the accuracy of the location. For earthquakes located west of the line connecting the stations DVP and SWB the hypocentral depths were poorly determined except for events occurring near stations DVP and SWB. An ocean bottom seismograph

TABLE 2. Parameters of Focal Mechanism Solutions

Event[a]	Date	Origin Time, UT	Latitude[b] °S	Longitude[b] °E	Depth[b] km	Pole 1		Pole 2		P Axis	
						TR[c]	PL[c]	TR[c]	PL[c]	TR[c]	PL[c]
85	Sept. 1, 1978	0416	17.38	167.88	20	077	18	257	72	257	27
86	Jan. 27, 1979	1815	18.52	168.15	23	310	83	130	07	130	52
87	Aug. 17, 1979	1259	17.73	167.87	25	074	15	254	75	254	30
88	Aug. 26, 1979	1147	17.63	167.71	22	067	10	247	80	247	35
97	July 23, 1961	2151	18.33	168.18	0	070	20	250	70	250	25
98	Oct. 6, 1962	0423	17.26	167.72	0	070	15	250	75	250	30
99	Nov. 26, 1969	1244	16.86	167.70	30	072	33	314	36	283	03
100	June 30, 1974	0833	17.98	168.26	54	336	30	243	06	284	25

[a]Event numbers are a continuation of the numbering system of *Pascal et al.* [1978], *Isacks et al.* [1981], and *Coudert et al.* [1981].
[b]Locations for pre-1978 events from the bulletins of the International Seismological Centre (ISC); otherwise same as Table 1.
[c]Trend (TR) is measured clockwise from the north in degrees; plunge (PL) is measured from the horizontal in degrees.

(OBS) experiment was also conducted in the region in September 1978 as a joint project by ORSTOM, Cornell University, and the Marine Science Institute of the University of Texas. The OBS seismograph stations were located in the forearc region south of Malekula and northwest of Efate islands. Comparison of the two sets of locations obtained with the OBS readings included and excluded indicated good agreement between the two sets of epicenters and shows no bias in epicenters determined by the land network alone. Because the depths are not so well determined, the emphasis of this study is on the distribution of epicenters.

In this paper we analyze the seismicity of the Efate–Malekula region for the period from September 1978, when the network started operating, to August 1984, nearly a 6-year interval. Among the 13,100 earthquakes located during this period, we selected 12,228 events with depths less than 80 km and an rms error less than 1.

SOURCE PARAMETERS OF THE MAIN SHOCKS

The nine major earthquakes of the 1978–1984 episode, having a magnitude M_w greater than or equal to 5.8, are listed in Table 1 and their locations are shown in Figure 1. The 1978–1981 events were relocated using both teleseismic data and all available local data. The locations were obtained using the *Jeffreys and Bullen* [1940] and the *Herrin et al.* [1968] travel time tables, once without any depth constraint and a second time with depths held fixed at the depths determined by *Chinn and Isacks* [1983] by analysis of long-period P waveforms. A fifth set of locations was obtained by using only the local stations. For each event the resulting five locations differed by less than 10 km. This result confirms the conclusion of *Coudert et al.*, [1981] that there is little relative bias in the locations of New Hebrides earthquakes based on teleseismic data versus those based on local data. The lateral velocity variations associated with the subduction zone here do not have the large effect on locations that is found in some other areas.

All events of the 1978–1984 episode, except the January 27, 1979, earthquake, have typical interplate thrust-type solutions. The slip vectors for these events match the average convergence direction of previously determined mechanisms located along the interplate boundary [see *Isacks et al.*, 1981]. The focal mechanism of the January 27, 1979, event is quite different from that of the typical interplate thrust (see Figure 2). The depth determined by *Chinn and Isacks* [1983] places the event close to the interplate boundary, so that it is difficult to determine in which plate it is located and makes its focal mechanism difficult to interpret. Focal mechanism solutions for the 1978 and 1979 events are shown in Figure 2 along with otherwise unpublished solutions for events in the region of the 1978–1984 episode that occurred prior to the episode (see Table 2). For the July 1981 event and succeeding shocks, we list in Table 2 the Harvard moment tensor solutions published in the monthly bulletin of the Preliminary Determination of Epicenters (PDE) (see also *Dziewonski et al.* [1981]).

The seismic moments listed in Table 1 are those calculated by *Chinn and Isacks* [1983] for the 1978–1979 events and the Harvard determinations for the best fitting double-couple for the other events. These seismic moments are close to those predicted by standard moment–magnitude relationships using M_s [e.g., *Pucaru and Berckhemer*, 1978; *Hanks and Kanamori*, 1979]. The M_w values are calculated from these seismic moments, as indicated in Table 1.

OVERALL CHARACTERISTICS OF THE EPISODE

The seismicity in the Efate–Malekula region which was recorded by the local network from September 1978 up to August 1984 is summarized in Plate 1*a*. Because of the very large number of events, we plot the number of earthquakes per unit area rather than plot each event. This better summarizes and highlights the main spatial patterns of the seismicity. The number of earthquakes in square windows each 0.05° by 0.05° in dimension is determined for overlapping windows spaced 0.01° apart (degrees of latitude and longitude). Note the range covered by the red and white colors (Plate 1*b*) selected to emphasize high concentrations of activity.

The most noticeable feature in Plate 1*a* is the "hot spot", i.e., a small area of very concentrated seismicity, centered northwest of Efate Island near 17.5°S and 167.9°E. This is the most remarkable and persistent feature of the seismicity in the region. The hot spot is connected at its southern end to another very active zone with an east-west trend and located west of the hot spot (Plate 1*a*). In the Malekula region there is only a very small concentration of activity beneath the southern coast of Malekula (Plate 1*a*).

Plate 1*a* also shows that the seismicity has an extreme degree of spatial heterogeneity. The much lower level of seismicity in the Malekula region (north of 17.2°S) than in the Efate region (south of 17.2°S) clearly stands out, and near 17.2°S the highly concentrated activity northwest of Efate Island ends abruptly. The seismicity in the Malekula region is much more diffuse than in the Efate region; earthquakes are widespread throughout the region and no clear pattern of spatial organization is apparent. No main event occurred in the Malekula region during the 6 years of observation (see Figure 1). The most prominent activity in the Malekula region, besides aftershocks of the July 15, 1981, earthquake, consists of a group of four clusters (8 earthquakes with $M_L \leq 3.4$ in 1 day, 7 earthquakes with $M_L \leq 2.9$ in 2 days, 42 earthquakes with $M_L \leq 3.4$ in 7 days, and 33 earthquakes with $M_L \leq 3.4$ in 2 days, respectively) which occurred in September–October 1982 south of Malekula Island.

The temporal and spatial development of the seismicity is highlighted by the aftershock sequences of major shocks of the 1978–1984 episode and by several very obvious time–space clusters of events. We focus attention on these obvious clustering phenomena that are clearly recognized without detailed statistical analyses. The duration of each aftershock sequence or cluster is selected by first computing the daily average number of earthquakes, over the 6-year period of observation, and its standard deviation in a 0.1° by 0.1° grid system and then finding days when the activity in a box of the grid system is larger than the daily average plus twice the standard deviation. For the periods so selected, however, we then plot all events located throughout the region. The method is only used as an objective, reproducible guide to know when and where to begin or end the clustering of activity.

We can divide the total time monitored into two types of intervals: (1) those during which the prominent aftershock sequences and clusters occur, and (2) those remaining. We call the activity during the remaining times "background" activity, but this is only a relative characterization and is not meant to imply that this activity is a homogeneous Poissonian process, for example.

There is a striking difference between the sizes of the areas affected by the aftershock zones of the main shocks, ranging from anomalously large areas to cases with no aftershock sequences at all. On the basis of the areas of the aftershock zones, we can classify the main shocks into three categories. The first category includes events which, given their magnitude, are followed by anomalously large aftershock zones. In this category are the two August 1979 events, which were followed by aftershock zones that were larger by a factor of 2 or 3 than expected [*Isacks et al.*, 1981], and the July 1981 event which was followed by an aftershock zone larger by a factor of 10 than expected [*Chatelain et al.*, 1983]. The second category includes events which are followed by normal to small-sized aftershock zones (September 1, 1978; March 12, 1983; August 3 and 5, 1983), while the third category includes events which are not associated with any aftershock sequence at all (January 27, 1979, and January 18, 1982). Therefore we can divide the times during which clustering is prominent into two parts. The first includes all normal- to small-sized aftershock sequences and other clusters (we refer to this as "clustered activity"), while the second includes all the large or oversized aftershock sequences (we refer to this as "large aftershock sequences").

Clustered activity, shown in Plate 1*b*, thus includes aftershocks of main events listed in Table 1 which affected small to normal areas given the magnitude of the main shock (March 12, 1983, and August 3 and 5, 1983), foreshock sequences for the August 1979 and July 1981 main events, and all other clusters which occurred during the 1978–1984 period of observation. These other clusters had frequency-time distributions intermediate between an aftershock sequence and a swarm [*Mogi*, 1963]. The large aftershock sequences, shown in Plate 1*c*, includes the two August 1979 aftershock sequences, the July 1981 aftershock sequence, and a large area affected by a cluster that formed the aftershock sequence of a magnitude (M_s) 5.1 event in June 1983. The remaining background activity is shown in Plate 1*d*. Main events without aftershocks (January 27, 1979, and January 18, 1982) are included in the background activity.

Most of the background activity (Plate 1*d*) occurs in a clearly defined southeast-northwest trending zone subparallel to the trench and about 30 km wide. This zone is located near the inferred position of the downdip part of the interplate seismic zone in the Efate region. The seismicity is not evenly distributed in this zone but is markedly concentrated near 17.5°S near the northern end of the zone, i.e., at the position of the hot spot shown in Plate 1*a*. Farther north no clear band of background activity is apparent, but a small outstanding concentration appears beneath the southern coast of Malekula coinciding with the small nest of Plate 1*a*. There is also a marked interruption in the band of background activity in the Efate region, near 18.1°S (Plate 1*d*).

In contrast to the background activity, the large aftershock sequences (Plate 1*c*) occur mostly seaward of the zone of background seismicity (compare Plates 1*c* and 1*d*). They are located in the updip part of the interplate boundary and within the oceanic plate beneath the trench. These aftershock zones are mainly contiguous with the background zone but overlap somewhat in the region of concentrated seismicity. The most active part of the large aftershock sequences is contiguous to the hot spot and west of it (compare Plates 1*c* and 1*a*).

The two main shocks without aftershock sequences are located in the background zone, as are the events with normal- to small-sized aftershock zones. Thus a characteristic of the background zone may be a tendency for normal to small or no aftershock sequences. Further evidence for this behavior is shown in Figure 3. Shown are the locations of all events reported by the PDE, for the period 1978–1984, for which the network recorded no associated aftershock sequence or cluster. These events are notably concentrated in the background zone of the Efate region.

Clustered activity (Plate 1*b*) does not occur in random places throughout the region but in several well-defined small areas, which are repeatedly activated. Almost all clustered activity is located in the Efate region. Only one very active small spot is located in the Malekula region beneath the southern coast of the island, coinciding with the position of the most active of the small nests of background activity shown in Plate 1*d*. In the Efate region, clusters affect mostly the forearc region. The most outstanding cluster area is the same as the hot spot located northwest of Efate Island shown in Plates 1*a* and 1*d*. This shows that the hot spot, in overall activity, includes both clusters and background activity. A second prominent area

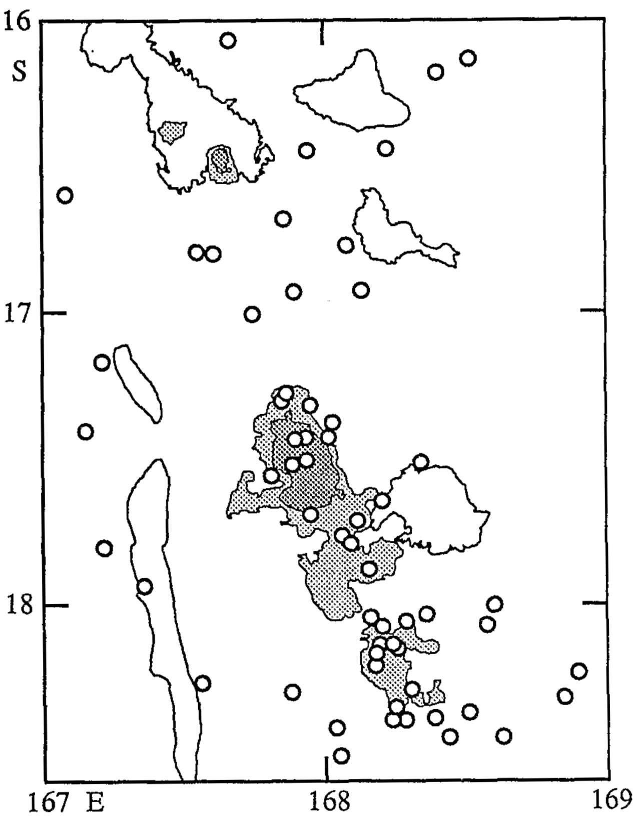

Fig. 3. Map showing the distribution of earthquakes occurring between September 1978 and August 1984 and large enough to be listed in the Preliminary Determination of Epicenters (PDE) of the U.S. Geological Survey for which no aftershocks nor obvious associated clusters were detected by the ORSTOM-Cornell network. The locations are those obtained with the local network. Note the concentration of these epicenters in the "background" seismicity zone. For reference in this and other figures the lighter shaded area is within the contour of the spatial density of epicenters for the "background" activity (see Plate 1*d*) for 15 or more events per cell. The darker area is within the contour for 30 or more events per cell, and highlights the "hot spot" (see Plate 1*a*). Also shown are the island outlines and the 6-km bathymetric contour, as in Plate 1.

is located west of Efate Island and has an oblique trend with respect to the background seismicity trend. The foreshock sequence of the August 17, 1979, event forms a separate zone just south of this area. The back arc region is affected by two cluster areas, much smaller and less intense than those of the forearc region.

In the following section we study the seismicity of the Efate region in more detail. We first focus on the zones which localize much of the activity in the region. We distinguish two of these zones in particular, which we call for convenience zones A and B. Zone A is simply the hot spot referred to already, while zone B is the prominent concentration of clustered activity apparent in Plate 1*b* located in the updip part of the interplate boundary west of the hot spot.

We then show the very intimate spatial and temporal relationships of the main events, clusters, and aftershock sequences. These relationships (1) highlight very specific spatial features which act as very sharp boundaries limiting the spatial development of the aftershock sequences, and (2) demonstrate a coherent evolution in the seismicity of the 6-year period sampled, related to the occurrence of the magnitude 7 earthquake in 1981.

SPATIAL FEATURES OF THE SEISMICITY IN THE EFATE REGION

Zones A and B

The hot spot of zone A shows the highest and most continuous level of background seismicity in the entire Efate-Malekula region and is also repeatedly activated by clusters. Almost 18% of the total activity of the 1978–1984 period occurred in a small zone centered on 17.5°S–167.9°E, with a dimension of about 0.2° and 0.4° in longitude and latitude, respectively. Including the after-shocks sequence of the August 1983 events, four of the five prominent clusters which occurred in the downdip part of the plate boundary were located in zone A. The clusters occurred in September 1978 (41 earthquakes with $m_b \leq$ 5.0 in 5 days), December 1979 (168 earthquakes with $m_b \leq$ 5.2 in 10 days), August 1983 (192 aftershocks in 7 days associated with two M_w = 5.8, 5.9 events), and April 1984 (113 earthquakes with $m_b \leq$ 5.5 in 16 days) (Figure 4). Only very few earthquakes composing these clusters occurred outside the hot spot, i.e., for example, in the updip part of the interplate boundary. Two smaller clusters occurred in March (20 earthquakes with $M_L \leq$ 4.3 in 2 days) and June 1980 (11 earthquakes with $M_L \leq$ 4.6 in 4 days). The first one is located in the hot spot, while the second is located just north of the hot spot, near the epicenter of the July 15, 1981, main event (Figures 4*c* and 4*d*). Four of the main shocks of the 1978–1984 episode (September 1, 1978, January 18, 1982, August 3 and 5, 1983) which occurred in the downdip part of the interplate boundary are located on the northern edge of zone A (Figure 4, see also Table 1).

The only downdip prominent activity that occurred outside zone A includes the January 1979 event (without after-shocks; see Figure 4*a*) and the small aftershock sequence following the March 12, 1983, event (47 earthquakes in 3 days) (Figures 4*d* and 4*e*). This activity occurred in the southern part of the background seismicity zone, south of its interruption near 18.1°S.

The updip part of the interplate boundary was affected by four clusters in December 1978 (22 earthquakes with $m_b \leq$ 4.8 in 6 days), March 1979 (123 earthquakes with $m_b \leq$ 4.6 in 4 days), April 1979 (23 earthquakes with $m_b \leq$ 4.5 in 2 days), and February 1981 (51 earthquakes with $M_L \leq$4.6 in 9 days) (Figure 5). They all occurred close to each other and define what we term zone B. Besides the immediate foreshocks of the August 1979 and July 1981 main shocks, no other cluster was recorded outside zone B in the updip part of the interplate boundary. Zone B is a narrow band with a southwest-northeast orientation and bounded on either end by the trench and the hot spot in background activity, respectively (Figure 5*d;* see also Plate 1*b*). Zone B is also located in between the epicenters of the two main events of August 1979 (Figure 5*d*). In the next section, zone B will be shown to be one of the most important features in the spatial development of the large aftershock sequences.

Sharp Boundaries in the Development of the Large Aftershock Sequences

Preliminary studies of the 1979 and 1981 sequences reported by *Isacks et al.* [1981] and *Chatelain et al.* [1983] emphasize the abnormally large aftershock areas of those events but do not show the spatial relationships among the

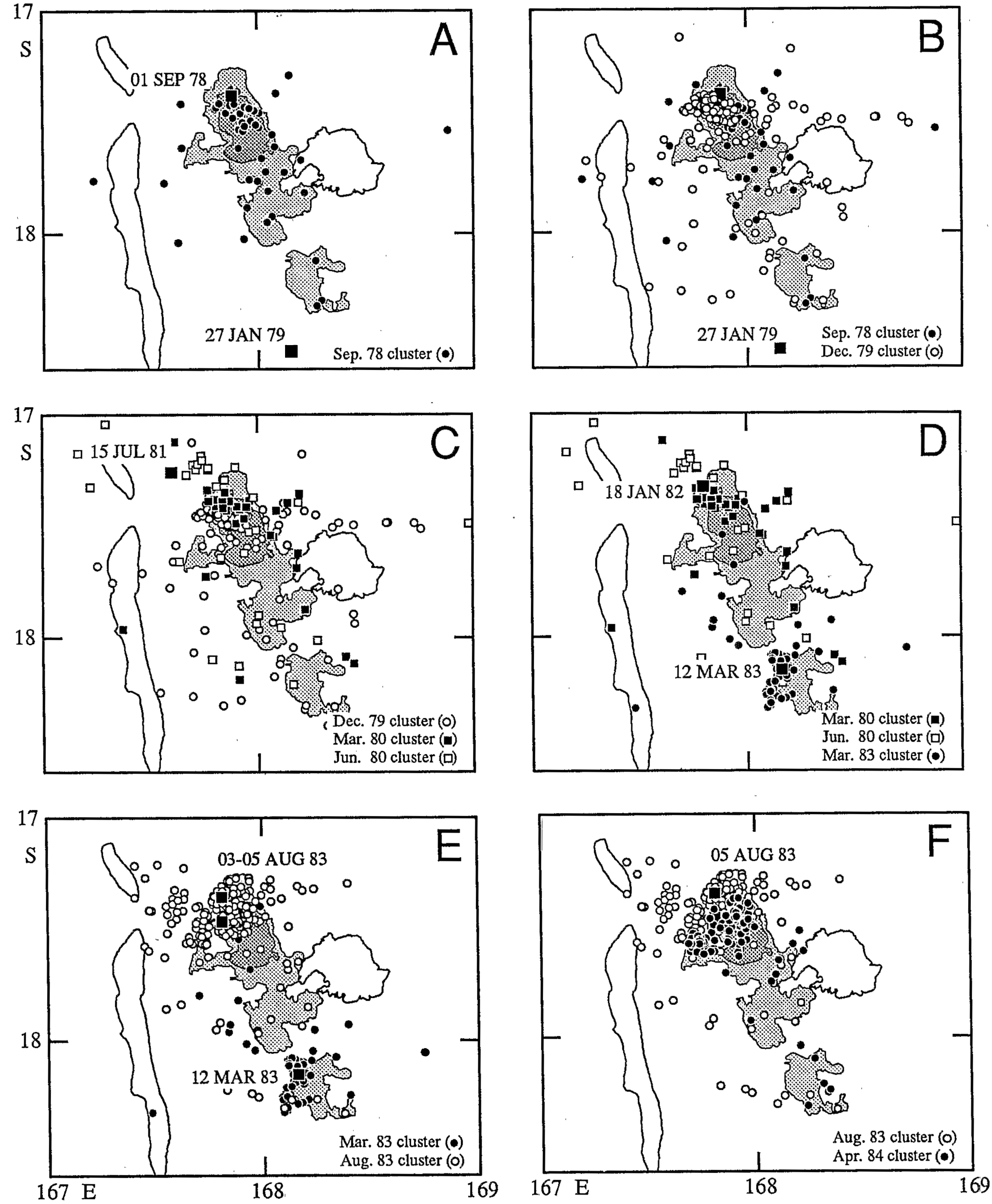

Fig. 4. Maps of epicenters showing the clusters located by the ORSTOM-Cornell network in the downdip part of the interplate boundary in the Efate region, shown sequentially in time. The main shocks of the 1978–1984 episode are shown by large solid squares. In each successive frame the next activity overlies the preceding one for comparison. Only successive clusters are shown in each frame. All the activity from throughout the region recorded for the periods chosen is plotted. Format as in Figure 3. (*a*) September 1 main shock with late September 1978 cluster (solid circles), and January 27, 1979, main shock (no aftershock activity); (*b*) December 1979 cluster (open circles); (*c*) March 1980 cluster (solid squares), June 1980 cluster (open squares), and July 15, 1981, main shock for reference; (*d*) January 18, 1982, main shock (no aftershock activity), March 12, 1983, main shock with aftershock activity (solid circles); (*e*) August 3 and 5, 1983, main shocks and aftershock activity (open circles); (*f*) cluster in April 1984 (solid circles). Note that during the 6 years of observation, almost all the clustered activity in the downdip part of the interplate boundary occurs in the hot spot (zone A, represented by the dark gray area).

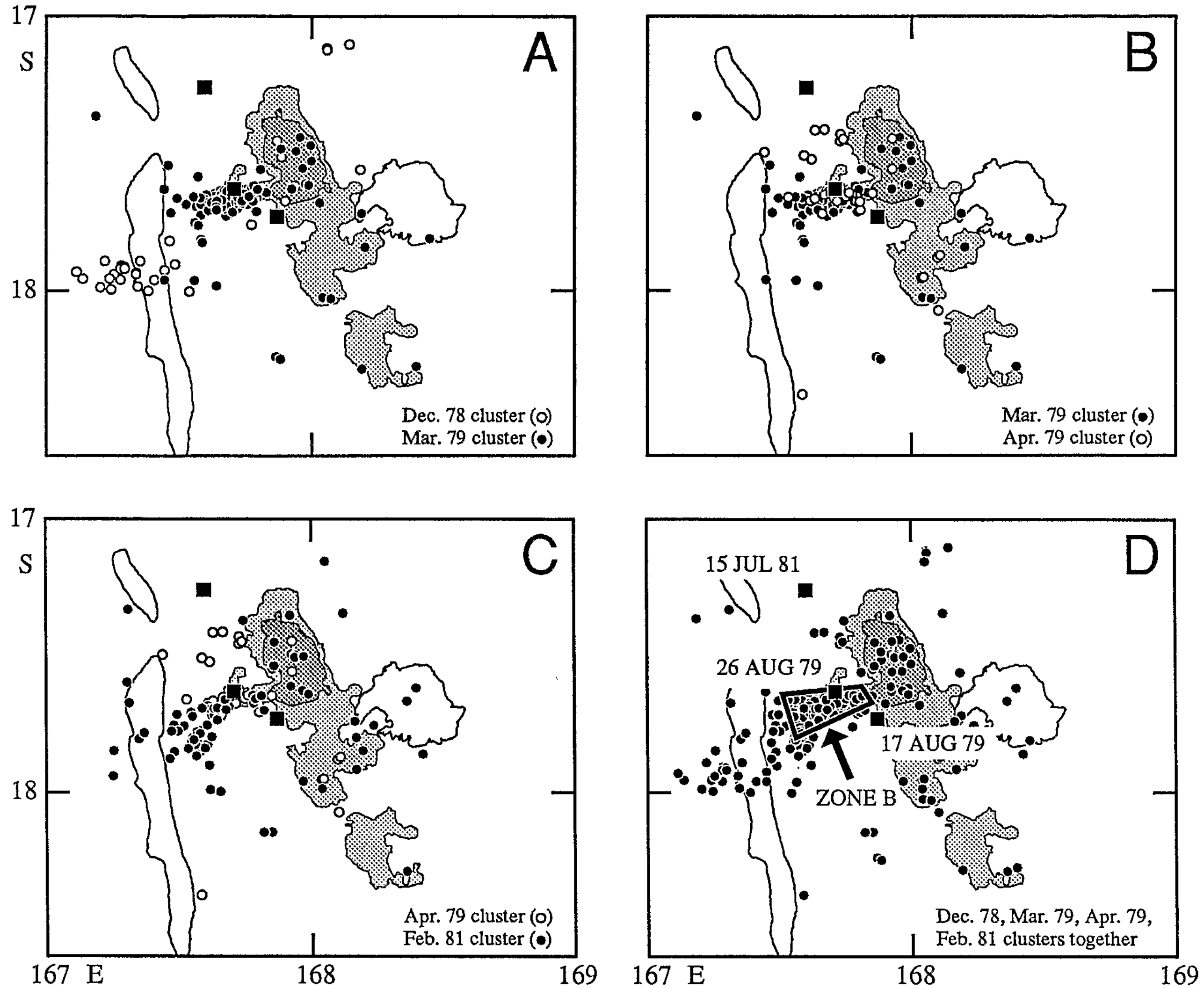

Fig. 5. Maps of epicenters showing the clusters located by the ORSTOM-Cornell network in the updip part of the interplate boundary in the Efate region, other than the 1979, 1981, and 1983 sequences. The clusters are shown sequentially in time. The 1979 and 1981 main shocks are shown by large solid squares. In each successive frame the next activity overlies the preceding one for comparison. Only successive clusters are shown in each frame. All the activity from throughout the region recorded for the periods chosen is plotted. Format as in Figure 3. (*a*) December 1978 cluster (open circles) and March 1979 cluster (solid circles); (*b*) April 1979 cluster (open circles); (*c*) February 1981 cluster (solid circles); (*d*) all events of the four clusters of Figures 5*a*, 5*b*, and 5*c* shown together (solid circles), with the two August 1979 and the July 1981 main events (solid squares). The most active part of the zone where these clusters occur is shown by the box in Figure 5*d*, and outlines zone B.

immediate foreshocks, the main shocks, and the aftershock zones nor the importance of zone B in limiting the spatial development of the sequences. The 1979 and 1981 aftershock sequences, as well as the June 1983 cluster (161 earthquakes in 7 days, following a $M_s = 5.1$ event), are mostly located in the updip part of the interplate boundary in the Efate region. Thus most of the activity is limited by the trench to the west and by the western edge of the background seismicity zone to the east (see Plate 1*c*). The only notable exception is the 1981 aftershock sequence which shows significant activity within the oceanic plate beneath the trench axis and in the hot spot region. The seaward activity is concentrated beneath the ORSTOM seamount [*Chase et al.*, 1983] located near 17.3°S and 167.2°E (Figure 1).

The development of these sequences is highly controlled to the north and to the south by very sharp boundaries. The four sequences are contiguous and activate areas limited by these boundaries. The most outstanding of these boundaries is zone B, which is involved in all of the sequences. Three other boundaries are also apparent, which we call for convenience boundaries 1, 2, and 3.

Zone B as a boundary. The development of the immediate 1979 foreshock sequence is strictly limited to the north by zone B (Figures 6*b* and 7*a*). The August 17, 1979, aftershock zone overlies two well defined areas, zone B and the area affected by the immediate foreshocks (compare Figures 6*b* and 6*c*, see also Figure 7*a*). Only one cluster of aftershocks was recorded outside these two areas, north of zone B, near the epicenter of the August 26 main shock (Figure 6*c*). These earthquakes can be considered as foreshocks to the August 26 main shock. The northern limit of the August 17 sequence thus coincides with the northern edge of zone B.

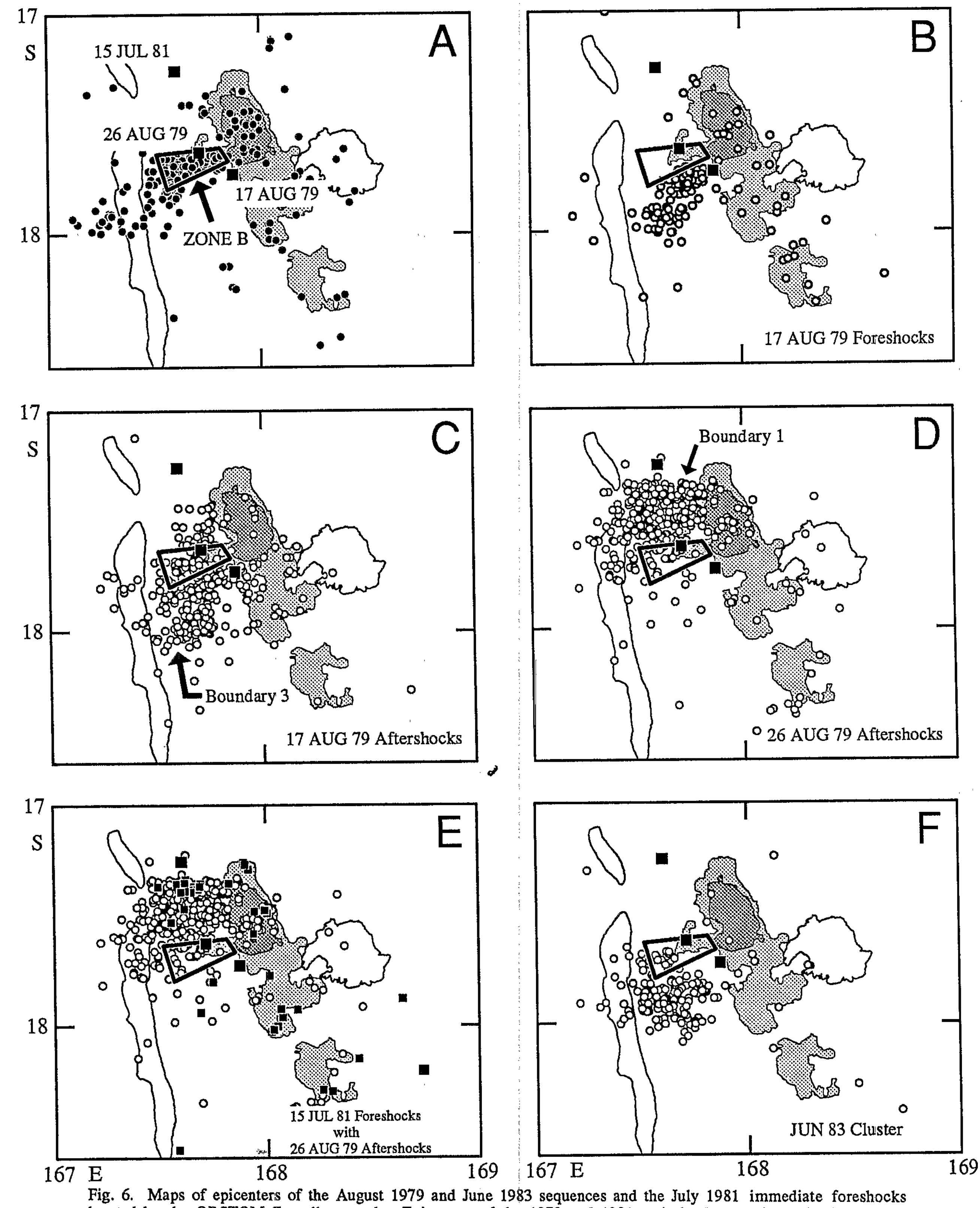

Fig. 6. Maps of epicenters of the August 1979 and June 1983 sequences and the July 1981 immediate foreshocks located by the ORSTOM-Cornell network. Epicenters of the 1979 and 1981 mainshocks are shown by large solid squares. Ten days of aftershock activity are shown for the August 1979 earthquakes. All the activity recorded throughout the region for the periods chosen is plotted. Format as in Figure 3. (*a*) Zone B (box) and the 1979 and 1981 main events (solid squares), as in Figure 5*d*; (*b*) zone B and the foreshock sequence of the August 17, 1979, earthquake (open circles); (*c*) zone B and aftershocks of the August 17, 1979, earthquake (open circles); (*d*) zone B and aftershocks of the August 26, 1979, earthquake (open circles); (*e*) zone B, aftershocks of the August 26, 1979, earthquake (open circles) and the foreshocks of the July 15, 1981, earthquake (solid squares); (*f*) zone B and the cluster in June 1983 (open circles). Zone B acts as a very sharp boundary in each of the sequences. The very sharp east-west trending northern boundary of the August 26, 1979, aftershock sequence (Figure 6*d*) is called boundary 1; the July 15, 1981, foreshocks occurred along this boundary (Figure 6*e*). All the sequences occurring south of zone B also stop along 18.1°S (boundary 3; Figure 6*c*).

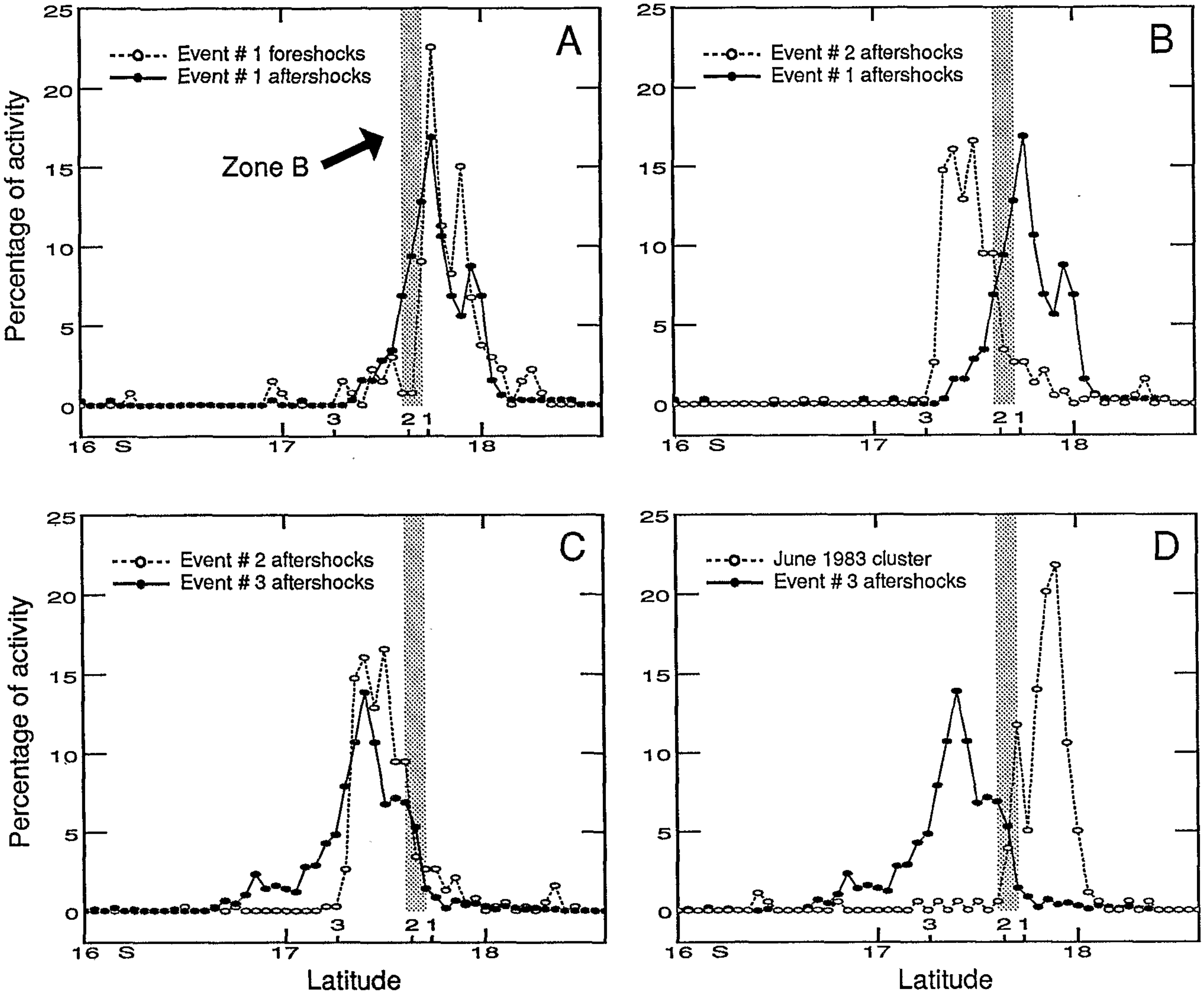

Fig. 7. Histograms showing the latitudinal dependence of the seismicity for the August 1979, July 1981 and June 1983 sequences. Latitude is taken as a convenient measure of a spatial dimension parallel to the strike of the plate boundary. The curve for each sequence gives the percentage of activity taken as the ratio of the number of events occurring in bands of 0.05° of latitude over the total number of earthquakes of the sequence. Each band includes all the activity between 167°E and 169°E. In each successive frame the activity of the preceding sequence is shown for comparison. The shaded area in each histogram represents the spatial extension in latitude of the most active part of zone B (as shown in Plate 1*b*). Note that zone B acts as a very sharp boundary for each of the sequences. For the 1979 and 1981 aftershock sequences, 10 days of activity are shown. The numbers at the bottom of each histogram indicate the latitude of the August 17, 1979, (1) the August 26, 1979, (2) and the July 15, 1981, (3) main shocks. (*a*) The August 17, 1979, immediate foreshock sequence (open circles and dashed line) and the August 17, 1979, aftershock sequence (solid circles and solid line); (*b*) the August 26, 1979, aftershock sequence (open circles and dashed line) ; (*c*) the July 15, 1981, aftershock sequence (solid circles and solid line); (*d*) the June 1983 sequence (open circles and dashed line).

The August 26, 1979, aftershock sequence occurred north of the area affected by the August 17, 1979, sequence. The two August 1979 sequences are contiguous and overlap in zone B, while the area affected by the August 17 aftershocks was nearly inactive (Figures 6*d* and 7*b*). Zone B acts as the southern boundary of the August 26, 1979, aftershock sequence (Figures 6*d* and 7*b*).

Chatelain et al. [1983], using preliminary data, claimed that the July 15, 1981, aftershock zone extends as far south as the southern limit of the August 17, 1979, aftershock zone. Figures 7*c* and 8 show that only few earthquakes occurred south of zone B. The level of activity south of zone B is comparable to the background level of activity. Even though Chatelain et al. may have overestimated the size of the July 1981 aftershock zone, the area clearly affected by the aftershocks is still larger by a factor of at least 7 or 8 than that expected for an earthquake of magnitude (M_S) 7.1. As can be seen in Figures 7*c* and 8, zone B acts as a very strong boundary limiting the spatial development of the July 15, 1981, aftershock zone to the south.

Finally, zone B plays also a key role in the development of the June 1983 cluster. The cluster, shown in Figure 6*f*, followed a "main shock" with a magnitude M_S = 5.1 (not shown on the figures), on June 26, 1983. The main shock occurred on the southern edge of zone B. This cluster represents a very large aftershock zone for an earthquake of such magnitude (compare, for instance, with the area affected by the aftershocks of the March 23, 1983, event (M_S = 5.8)

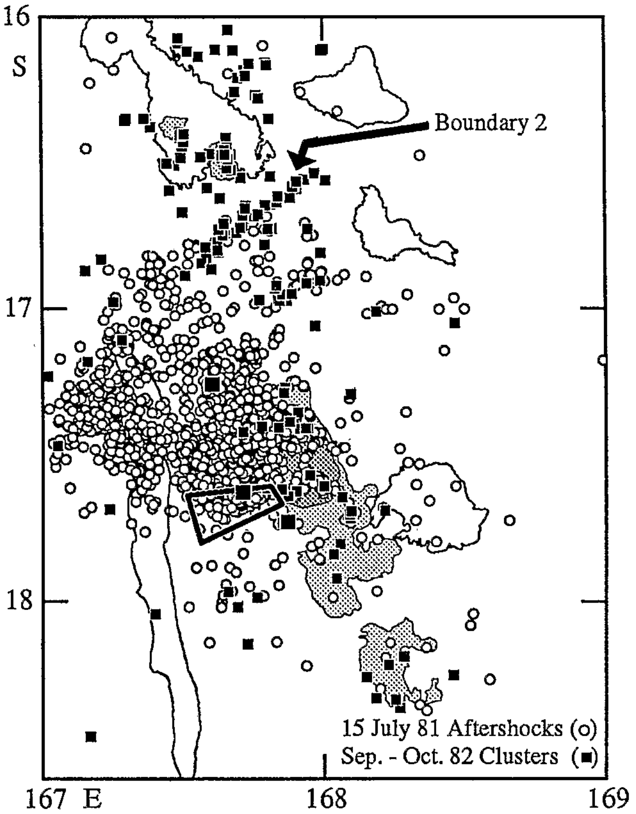

Fig. 8. Maps of epicenters showing zone B (box), the July 15, 1981, aftershocks (open circles), and the September–October 1982 clusters which occurred south of Malekula Island (solid squares). Epicenters of 1979 and 1981 main shocks are shown by large solid squares. Ten days of aftershock activity are shown for the July 1981 earthquake. All the activity recorded throughout the region for the periods chosen is plotted. Format as in Figure 3. Note the sharp southern end of the July 15, 1981, aftershock zone, coinciding with the southern edge of zone B. Note also the linear cluster of September 1982 located on the northern edge of the July 15, 1981, aftershock zone (boundary 2).

shown in Figure 4*e*). The most striking characteristic of the June 1983 sequence is that it occupied the same zone affected by the aftershocks of the August 17, 1979, event (compare Figures 6*f* and 6*c*). As in the August 17, 1979, case, zone B is the northern limit of the June 1983 cluster (Figures 6*f* and 7*d*).

Other Boundaries. A well-defined east-west trending boundary passes just south of the July 15, 1981, main shock epicenter. It is sharply defined as the northern limit to the development of the August 26, 1979, aftershocks (Figures 6*d* and 7*b*). To the east it ends near the epicenter of the September 1, 1978, earthquake and close to the northern end of the hot spot. As can be seen from Plate 1*a*, this boundary is also the boundary between the highly active Efate region and the less active Malekula region. We call it boundary 1.

The immediate foreshock activity to the July 15, 1981, earthquake was not very important and includes only two small clusters. Both of these clusters occurred along boundary 1. The first one occurred near the hot spot, while the second occurred near the pending main shock epicenter (Figure 6*e*). Although some of the July 15, 1981, aftershocks occurred north of boundary 1 (Figure 8), the most active area is the same as the area affected by the August 26, 1979, aftershocks located between boundary 1 and zone B (Figure 7*c*). The clusters of March and June 1980 also occurred just north of boundary 1 (compare Figures 4*d* and 6*d*).

Two other boundaries can be recognized but are less sharply defined than boundary 1. The first one is the northern limit of the July 15, 1981, aftershock zone. Aftershocks stop near the southern coast of Malekula along a southwest-northeast trending line (Figure 8, see also Figure 7*c*). This boundary is activated again by a remarkably linear cluster in September 1982 (42 earthquakes with $M_L \leq$ 3.4 in 7 days) (Figure 8). We call it boundary 2.

Boundary 3 is located near 18.1°S. The 1979 foreshock sequence ends near about 18.1°S (Figure 6*b* and 7*a*), as do the August 17, 1979, aftershock sequence (Figure 6*c* and 7*a*) and the June 1983 cluster (Figures 6*f* and 7*d*). Unlike zone B and the two other boundaries though, this boundary did not experience any clustered activity.

TEMPORAL RELATIONSHIPS

The July 1981 Earthquake as the Main Shock of the 1978 -1984 Episode.

The 1978–1984 episode can be considered as a seismic episode related to the occurrence of the July 15, 1981, main shock. The episode started in 1978 after 4 years of quiescence and shows a progressive migration of the activity to the north, toward the July 15, 1981, main shock epicenter. The episode can be divided into four parts.

1. The 1978–1979 sequences form a long-term "foreshock sequence" for the July 1981 event. The August 17, 1979, sequence, the August 26, 1979, event and the September 1, 1978, event as well as clusters during 1978–1979 occurred on the edges and just outside of the aftershock zone of the July 1981 event, a pattern common to long-term foreshock activity of great earthquakes [e.g., *Kelleher and Savino,* 1975].
2. These sequences were followed by a 1.5-year period of quiescence in 1980–1981. Only few small clusters occurred during this period, and the general level of seismicity in the entire region was considerably lower in 1980 than during the other years of observation.
3. The main shock occurred on July 15, 1981, and was followed by a 2–3 month aftershock sequence.
4. A postseismic episode then occurred in 1982–1984 along or near the boundaries of the aftershock zone of the 1981 sequence. The March 1983 and June 1983 sequences occurred south of the aftershock zone, while to the north several clusters occurred in the region of southern Malekula and Epi Islands in September–October 1982. To the east, the hot spot was again activated by the January 1982 event and the August 1983 and April 1984 sequences.

Aside from this overall pattern organized around the July 15, 1981, main shock, several other more specific temporal patterns stand out in relation to the August 1979, July 1981, and June 1983 sequences in the updip part of the interplate boundary, as described below.

Patterns of Immediate Foreshock Activity.

Out of the nine main shocks, only the August 17, 1979, main shock was preceded by outstanding immediate foreshock activity. After activation of a small zone near the August 17, 1979, epicenter during late June/early July (26

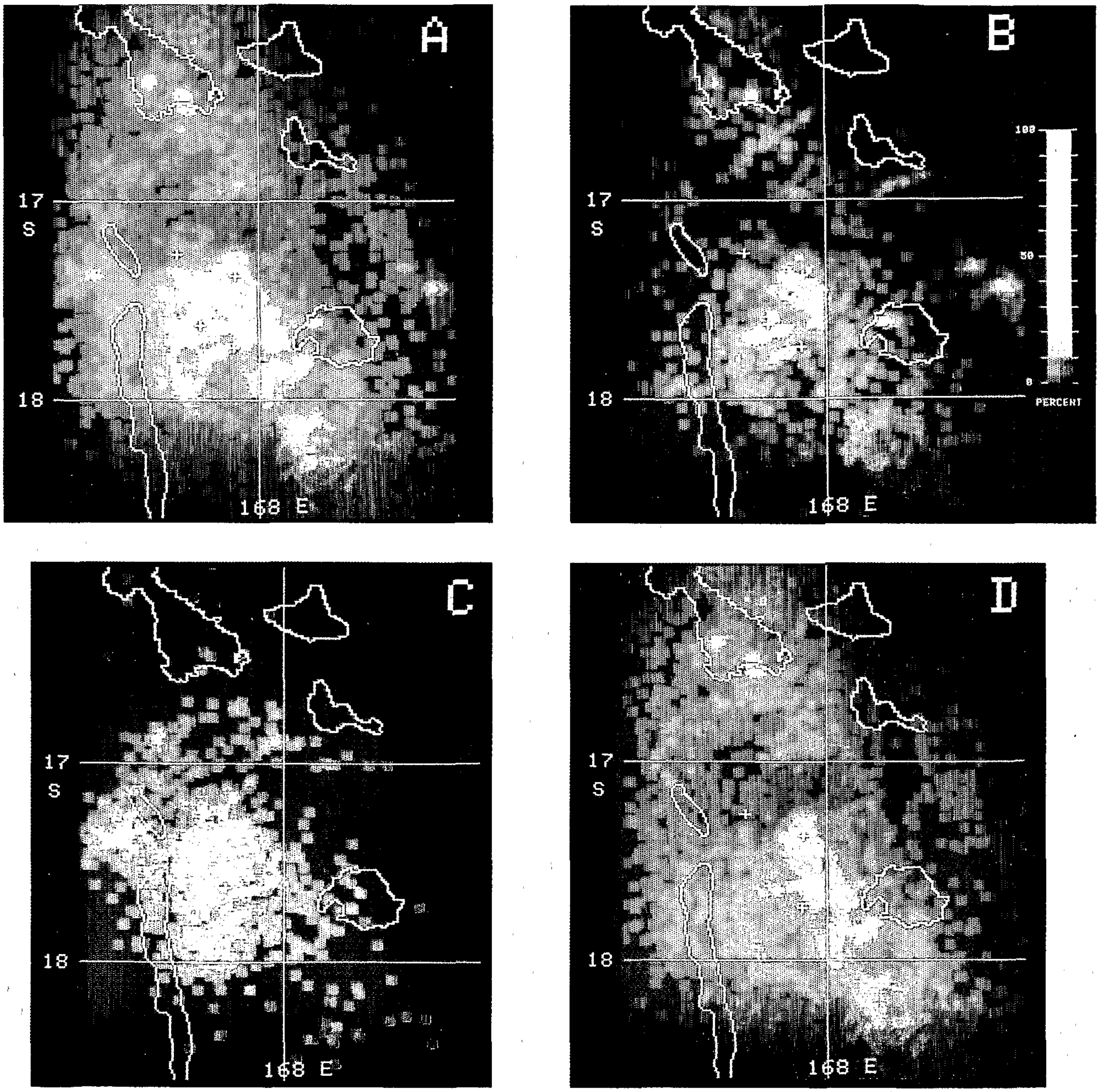

Plate 1. Color image of the spatial density of epicenters. The color scale shown in Plate 1*b* applies to all four frames and shows the number of events per cell, normalized to a percentage of the maximum number for the particular data set, for each data set shown. The cells are overlapping "squares," each 0.05° latitude by 0.05° of longitude, centered on a grid with a spacing of 0.01° of latitude and longitude. The gridded counts are mapped to pixels on the display of an image processor, and the image is then zoomed (bilinear interpolation) by a factor of 2 in order to fill the 512 x 512 pixel screen. (*a*) Total seismic activity, September 1978 through August 1984, maximum number of events per cell, N, is 185. (*b*) Activity during periods when prominent clusters occurred but excluding aftershocks of August 1979 and July 1981 events and June 1983 cluster, total time = 175 days, N = 64. (*c*) Cumulative aftershock activity for the August 1979 and July 1981 aftershock sequences and June 1983 cluster, total time = 40 days (10 days per sequence), N = 36 events. (*d*) "Background" activity obtained by removing activity shown in Plates 1 *b* and 1*c* from the total in Plate 1*a*, N = 152 events. The 6-km bathymetric contour and island outlines are shown by white lines. The white plus marks are the locations of the 1978–1981 main shocks (see Table 1). Comparison of Plates 1*c* and 1*d* shows the different seismic regimes of the updip and the downdip parts of the interplate boundary in the region of Efate Island. The updip part of the interplate boundary is characterized by low background and a high level of aftershock activity, while the downdip part shows opposite characteristics.

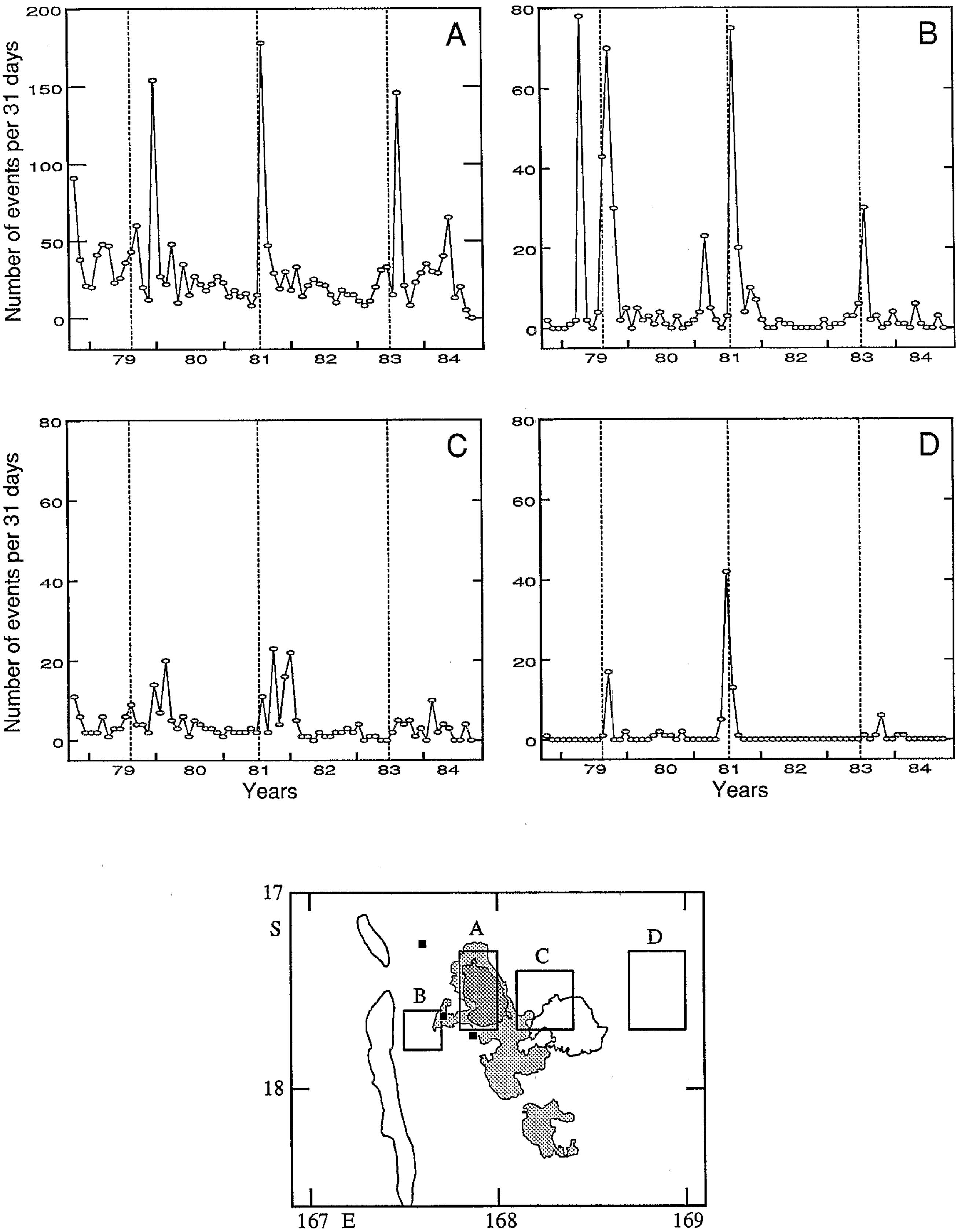

Fig. 9. Histograms showing the number of earthquakes recorded during the 1978–1984 period of observation for 31 day periods, in four zones located in the Efate region. The location of the zones is shown in the map at the bottom of the figure. Format for the map as in Figure 3. The dashed lines in each histogram indicate the occurrence of the August 17, 1979, and July 15, 1981, main shocks and the strongest event of the June 1983 cluster. In each zone the major clusters are correlated with the occurrence of the 1979, 1981, and 1983 events. Note also that activation of zone B precedes both the August 1979 and the July 1981 earthquakes.

earthquakes with $m_b \leq 4.7$ in 5 days; not shown on the figures), the most immediate precursory activity (Figure 6*b*) started 8 days before the main shock and consisted of several clusters (87 earthquakes altogether), each starting with a magnitude (m_b) 4.2–4.9 event, south of zone B. The first of these clusters occurred on August 9 near the trench. The following clusters then migrated from the trench toward the main shock epicenter [*Isacks et al.*, 1981].

The July 15, 1981, event was preceded by two clusters on July 5–6, 1981, and July 12–15, 1981, north of boundary 1 (Figure 6*e*, see also *Chatelain et al.*, [1983]). Although each one started with a magnitude (m_b) 5.0 earthquake, both clusters were quite small (12 and 14 earthquakes, respectively). The first one occurred on the northern edge of the hot spot, while the second occurred near the main shock epicenter. They thus show a migration of the precursory activity from the hot spot toward the main shock. During the weeks preceding the July 15, 1981, event no unusual activity appeared to be located near the trench.

The June 1983 sequence was preceded by a small cluster (12 earthquakes with $M_L \leq 4.6$; not shown on the figures) that started 1 day before the largest event of the sequence and ended 6 hours before it. This cluster occurred near the trench south of zone B and near the largest shock of the sequence, at about the same position of the first cluster preceding the August 17, 1979, event.

Comparison of immediate foreshock activity of the three cases described above shows different patterns of evolution. In August 1979, foreshock activity migrated from the trench toward the main shock epicenter. Note that the foreshock cluster preceding the June 1983 sequence (which affected the same area as the August 1979 sequence) also occurred near the trench. In contrast, the activity preceding the July 1981 sequence migrated from the hot spot toward the main shock epicenter.

Long-Term Precursory and Long-Term Aftershock Activity

Other temporal patterns related to the August 1979, July 1981, and June 1983 sequences include possible long-term precursory and aftershock activity. Four zones were activated before and/or after the three sequences, including zone A (the hot spot), zone B, and two other zones located in the back arc region.

Zone A. Figure 9*a* indicates a possible relationship between activation of the hot spot and the sequences in the updip part of the interplate boundary. The three periods of highest activity are in December 1979, July 1981, and August 1983, thus following with different time delays the August 1979, July 1981, and June 1983 sequences. Two other periods of less intense activity are noticeable in Figure 9*a*, in September 1978 and April 1984. One explanation is that the hot spot is also activated by clusters not related to the activity in the updip part of the interplate boundary. Note, however, that before the network started operating, two earthquakes occurred in the updip part of the interplate boundary in March 1978 ($M_s = 4.8$) near zone B and in May 1978 ($M_s = 5.1$) near boundary 1, which are comparable to the June 1983 earthquake ($M_s = 5.1$). Thus the September 1978 increase of activity in the hot spot may also be related to a sequence in the updip part of the interplate boundary.

The December 1979 cluster was followed by two smaller clusters in March and June 1980 which are located progressively closer to the epicenter of the July 15, 1981, main shock (Figure 4*c*). Both took place just north of boundary 1. The first one occurred on the northern edge of the hot spot and north of the December 1979 cluster, while the second occurred near the July 15, 1981, main shock epicenter (Figure 4*c*). The possible long-term precursory activity preceding the July 15, 1981, event (December 1979, March and June 1980 clusters), as the immediate foreshock activity, shows a migration of the activity from the hot spot toward the main shock epicenter (Figures 4*c* and 6*e*). Even if the December 1979 cluster is not part of the process, the two 1980 clusters still support this pattern.

Zone B. The August 1979 events were preceded by activation of zone B by three clusters occurring in December 1978, March 1979, and April 1979. These clusters moved successively from the trench towards the epicenter of the August 17, 1979, event (Figure 5). The last one, in April 1979, occurred just between the two August 1979 epicenters (Figure 5*c*).

The July 1981 event was also preceded by a cluster on zone B, in February 1981 (Figure 5*c*). As shown by Figure 9*b*, this zone was otherwise only activated by aftershocks of the August 1979, July 1981, and June 1983 events. Since February 1981 no other cluster occurred on zone B (Figure 9*b*). It seems therefore that the clusters which occurred on zone B can be considered as early precursors to the 1979 and 1981 main shocks. Note however that the June 1983 sequence was not preceded by any outstanding activation of zone B (Figure 9*b*).

Back arc. Three clusters occurred very close to each other east of Efate Island (Figure 10) in September 1979 (21 earthquakes with $M_L \leq 5.3$ in 2 days), June 1981 (43 earthquakes with $M_L \leq 4.9$ in 13 days), and July 1981 (12

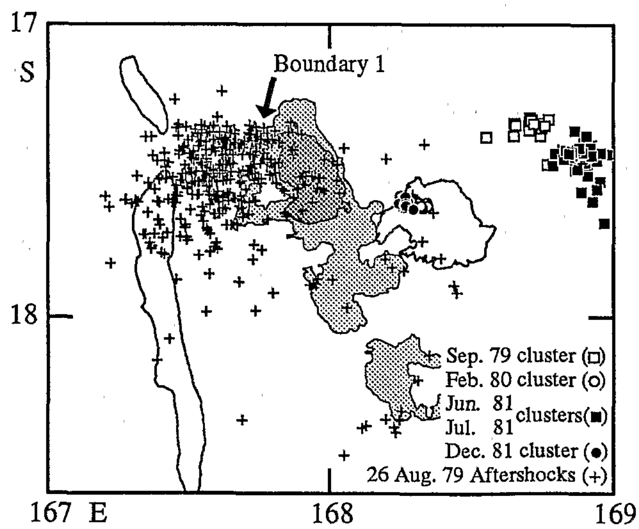

Fig. 10. Map of epicenters showing the back arc activity recorded by the ORSTOM-Cornell network in the Efate region: the September 1979 cluster (open squares), the June and July 1981 clusters (solid squares) east of Efate Island and the February 1980 (open circles) and December 1981 clusters (solid circles) on Efate Island. Only the activity in these clusters is shown. Crosses show the first 10 days of aftershocks for the August 26, 1979, main shock. Format as in Figure 3. Note that the three clusters east of Efate Island are located along the eastern prolongation of the northern limit of the August 26, 1979, aftershock zone (boundary 1).

earthquakes with $M_L \leq 4.7$ in 7 hours), thus preceding and/or following the main events (Figure 9*d*). No other clusters were detected in this zone, although there was also some reactivation of this zone after the June 1983 sequence (Figure 9*d*). As shown by Figure 9*d*, activation of this zone seems therefore to be related to the occurrence of sequences in the updip part of the interplate boundary. Note that these clusters are located on the eastern prolongation of boundary 1 (Figure 10).

The August 1979 and July 1981 events were also followed in February 1980 and December 1981, respectively, by two small clusters (19 earthquakes with $M_L \leq 3.4$ in 3 days, and 12 earthquakes with $M_L \leq 3.4$ in 2 days) which occurred at the same place on Efate Island (Figures 9*c* and 10). No other cluster has been detected at this place since then, but, as in the preceding case, some unusual activity occurred in this zone after the June 1983 sequence (Figure 9*c*).

Other features. Aside from activation of specific zones before and/or after the sequences occurring in the updip part of the interplate boundary, this study highlights one difference of the August 1979 and June 1983 sequences from the July 1981 sequence. The long-term and short-term precursory activity preceding the August 1979 sequence shows a migration from the trench toward the main shock epicenters, i.e., precursory activity migrates from the updip part of the interplate boundary to a main shock located in the downdip part of the interplate boundary. In June 1983 the cluster preceding the sequence was also located near the trench. By contrast, the long-term and short-term precursory activity preceding the July 1981 sequence shows a migration from the hot spot toward the main shock epicenter, i.e., precursory activity migrates from the downdip part of the interplate boundary (or from the upper plate) to a main shock located in the updip part of the interplate boundary.

Note that no obvious long- or short-term precursory phenoma were detected before any of the six main shocks in the downdip part of the interplate boundary (September 1, 1978; January 27, 1979; January 18, 1982; March 17, 1983; August 3 and 5, 1984). Note also that in 6 years of observation, only one of the nine main shocks listed in Table 1, the August 17, 1979, event, was preceded by very outstanding immediate foreshock activity. It is also interesting to notice that the June 1983 sequence, although very similar to the August 1979 foreshock sequence (compare Figures 6*b* and 6*f*), did not lead to a major event. Finally, long- or short-term aftershock activity is much more outstanding than long- or short-term precursory activity.

Aside from immediate foreshocks and aftershocks of the 1979, 1981, and 1983 sequences, only the January 1979 event and the March 1983 sequence occurred outside of the four zones shown in Figure 9, in the Efate region. Figure 9 shows that all the activity in the four zones can be related to activation of the updip part of the interplate boundary. Thus activity in the downdip part of the interplate boundary as well as in the upper plate seems to be dependent on seismic episodes occurring in the updip part of the interplate boundary.

SEARCH FOR TILT SIGNALS FROM THE 1978–1984 EPISODE

Tilt measurements in the central New Hebrides arc include monitoring of a water tube tiltmeter and several Kinemetrics borehole, bubble-level tiltmeters, as well as successive relevelings of two arrays of bench marks, each about 1 km in linear dimension [see *Bevis and Isacks,* 1981].

Water Tube and Borehole Tiltmeter Recordings

The water-tube tiltmeter consists of two orthogonal tubes, 100 m in length, half-filled with water. The water level is independently recorded at both ends of each tube in pots anchored to concrete piers poured on the limestone of the uplifted Holocene age coral terrace. The short-term resolution of the recordings (over minutes to days) is about 0.03 μrad. The instrument has operated discontinuously since 1980. The ground tilt is derived by subtracting the depth at one end of the tube from that of the other and dividing by the length of the tube (100 m). Apparent tilts can be generated by end pier instabilities, in which case only the depth measured at one end of the tube will change substantially. Although the instrument is sensitive to a variety of physical stimuli, the redundancy inherent in the water level measurement, together with additional information such as vault temperature, enable one to distinguish between true ground tilting and other phenomena, the most important of which is end pier instability.

No obvious short-term precursory or postseismic tilt signals were observed for the 1981 event, nor for any of the other main shocks that occurred since the water tube instrument started operating in 1980. A coseismic tilt of about 0.1 μrad was recorded for the 1981 main shock.

Kinemetrics borehole, bubble-level tiltmeters have been operating continuously in the New Hebrides arc since 1975. Three of these tiltmeters are located on Efate Island, and three are located on Malekula Island. The borehole tiltmeters have a noise level which increases with period but are stable in the period range of minutes to hours with a resolution of about 0.2 μrad [*Marthelot et al.,* 1980; *Isacks et al.,* 1978]. Tiltmeters on Efate and Malekula islands recorded all the major events of the 1978–1984 episode. The borehole stations closest to the July 1981 earthquake epicenter show offsets associated with the main shock, while the more distant instruments were not offset at all. Search of the tiltmeter records for preseismic or postseismic tilt change yielded no detectable signals in the period range of minutes to hours before and after the July 1981 event (or for any of the other main shocks).

Measurements of Tilt by Releveling

The array of bench marks closest to the events of the 1978–1984 episode is located at Devils Point, Efate, near the seismograph station DVP (see Figure 1). The bench mark array was first leveled in 1975 and, subsequently, has been releveled 2–4 times per year. The array is used as a multicomponent tiltmeter with a resolution of about 1 μrad. The north and east components of tilt computed from all the releveling observations at the Devils Point array on Efate Island are shown in Figure 11. The computations are similar to those described by *Bevis and Isacks* [1981]. Figure 11 updates the tilt history at Devils Point through 1984, adding 4 years of measurements for a total of nearly 10 years of observation. No clear tilt signals are seen to be immediately associated with the main shocks, but there does appear to be a large, long-term tilt signal. From 1976 to 1984, nearly 6 μrad of tilt occurred in a mainly north–south

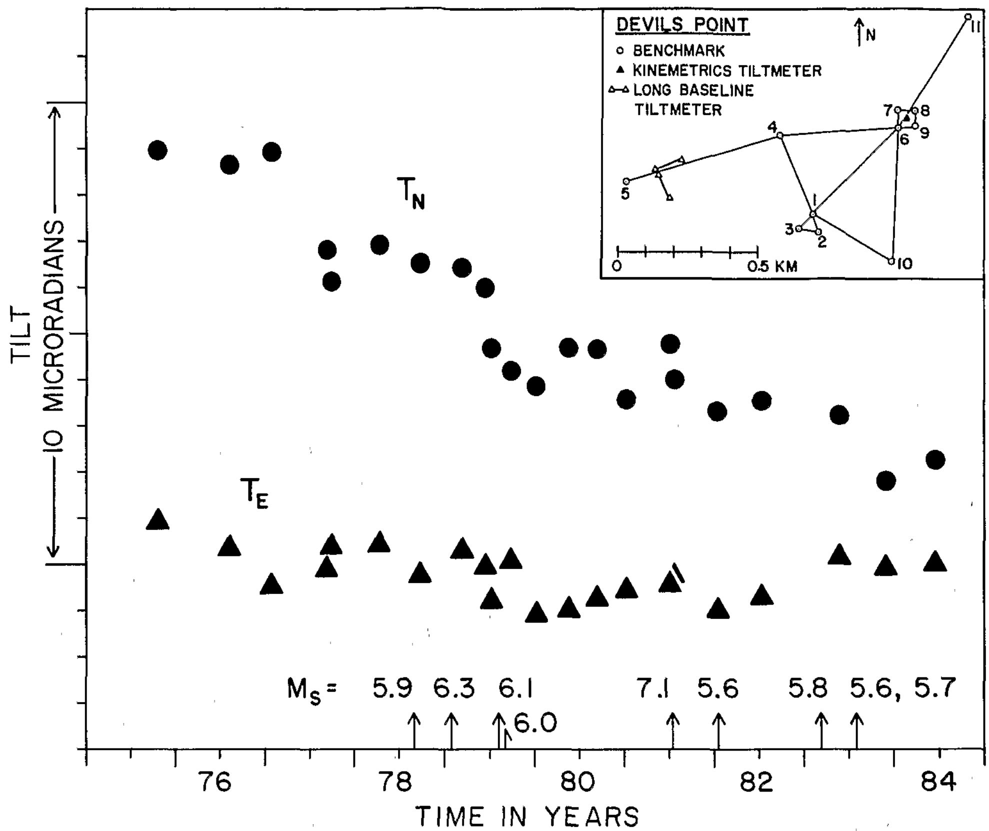

Fig. 11. The north (TN) and east (TE) components of tilt calculated from releveling of the Devils Point, Efate Island, array of bench marks. The array is located near the DVP seismograph station in Figure 1. The tilt components (solid circles TN, solid triangles TE) were calculated using an unweighted, least squares analysis with the July 1981 releveling as a reference [see *Bevis and Isacks*, 1981]. The data have a calculated standard deviation of about 1 µrad [see *Bevis and Isacks*, 1981]. Arrows show the times of the major earthquakes. The inset shows a map of the tilt instrumentation and bench marks (open circles) at the Devils Point site. The water tube tiltmeter is shown by the open triangles and connecting lines. Water level is measured at the four sites shown by the triangles. The solid triangle is the site of a borehole, bubble-level tiltmeter.

direction with the ground moving upward to the north. Note that the tilt after 1980, i.e., after the period covered by Bevis and Isacks, indicates a continuing tilt to the north at Devils Point. The temporal nature of this signal is not well resolved by the data. As discussed by *Bevis and Isacks* [1981], it might indicate a creep episode along the plate boundary which had a role in triggering the 1979 and 1981 events [see also *Beavan et al.*, 1984]. Although departures from an overall linear trend are of marginal significance, given the scatter and errors of measurements, a change in tilt rate does appear to occur in both components around 1979–1980.

Discussion and Conclusion

Difference Between the Malekula and the Efate Seismic Regimes

An outstanding overall feature in the seismicity of the 1978–1984 period, as monitored by the local network, is the contrast in the levels of activity in the Efate region and the Malekula region. These two regions are separated near 17.2°S by a very sharp east-west boundary, where the very high level of activity observed in the Efate region abruptly decreases. The contrast holds for both small and large events. Nine earthquakes with magnitude $M_w \geq 5.8$ occurred in the Efate region between 1978 and 1984, while none occurred in the Malekula region. A comparable pattern is observed from 1960 to 1978: fewer earthquakes with magnitude $M_S \geq 6.0$ occurred in the Malekula region than in the Efate region (Figure 12).

The transition in seismicity is in the region of a major transition in the structure of the island arc, indicated by the bathymetry, between the more "typical" island arc–trench structure associated with the South New Hebrides Trench and the anomalous westward protruding Malekula and Santo blocks of the central New Hebrides (see Figure 1). A marked embayment in the forearc morphology exists between Efate and Epi islands, and the sharp east–west boundary to the locally recorded seismicity is located on the southern part of this embayment.

It is notable that for the moderate to large earthquakes for which reliable focal mechanism solutions can be obtained, no event has occurred in the Malekula region during the past 25 years with a mechanism indicative of interplate slip. This gap in interplate events is located between the rupture zones of the 1965 Santo-northern Malekula sequence and the 1978–1984 episode considered in this paper. The gap remains enigmatic in terms of its potential for a future large earthquake. One alternative is that a large unbroken patch of the interplate boundary remains in the Malekula region, a large asperity which acted as a rupture-stopping barrier to the 1965 and 1981 earthquakes. A second alternative is that

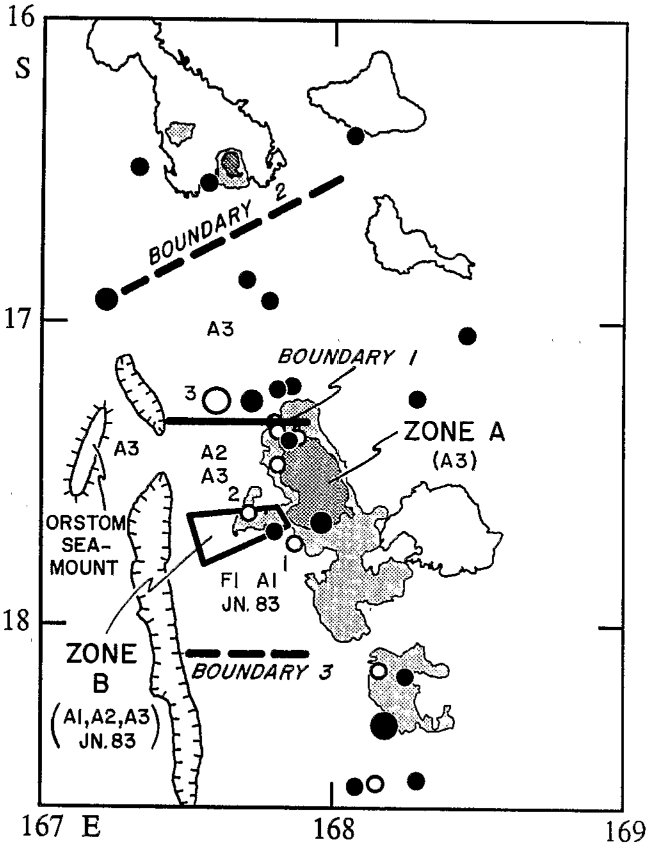

Fig. 12. Summary of the spatial features located in the Efate-Malekula region. Format as in Figure 3, plus a 4-km contour highlighting the ORSTOM seamount. The 1979 and 1981 main shocks are numbered as follows: (1) August 17, 1979, (2) August 26, 1979, (3) July 15, 1981. The regions affected by their aftershocks are labeled A1, A2, and A3, respectively, while F1 indicates the region affected by the foreshocks of the August 17, 1979, event. Also indicated is the region affected by the June 1983 cluster (JN. 83). Zone A is shown by the dark shading as in previous figures. The most active part of zone B (see Plate 1*b*) and boundary 1 are shown by heavy lines. Boundaries 2 and 3 are shown by dashed lines. Also shown are locations of main shocks of the 1978–1984 episode with magnitude (M_w) greater than 5.7 (open circles) and other events (solid circles) since 1960 with magnitude (M_s) greater than 5.9. Magnitude scale as in Figure 1. Note the concentrations of earthquakes along boundary 1, Zone B, and on the northern end of zone A.

the rupture zone of the 1965 earthquake extends south of the southern coast of Malekula Island and abuts with that of the 1981 earthquake (boundary 2 in Figure 12), as implied by *Habermann* [1984]. In this case there may be little area left to be ruptured in a future earthquake. However, the uplift pattern described by *Taylor et al.* [1980] for the 1965 sequence does not support this second alternative. Yet a third possibility that also minimizes a pending "gap" is that the two seismic rupture zones do not join but are separated by an area of predominantly aseismic creep along the plate boundary. Possible evidence for the existence of an unruptured asperity between the 1965 and 1981 rupture zones is the interpretation of the complex distribution of small earthquakes beneath southern Malekula as intraplate deformations near a locked and stressed section of the the interplate boundary [*Isacks et al.*, 1981; *Wray et al.*, 1983].

Updip and Downdip Interplate Seismic Regimes in the Efate Region.

In contrast with the Malekula region the seismicity in the Efate region shows a clear spatial pattern. The zone affected by the August 1979, July 1981, and June 1983 sequences and the zone where the background activity occurs are quite distinct and abut with little overlap. The area affected by these sequences is located between the trench and the back - ground zone. Thus, although the depth of the earthquakes of these sequences are not accurately determined, it is reasonable to infer from the relative location of the epicenters that the earthquakes of the August 1979, July 1981, and June 1983 sequences are located in the shallower, updip part of the plate boundary, while the background activity appears to be located in the deeper, downdip part of the plate boundary (or in adjacent parts of the interacting plates). Another characteristic is that the larger events located in the background zone have smaller aftershock zones than the earthquakes occurring west of the background zone or no aftershocks at all.

These characteristics suggest the possibility that slippage along the plate boundary occurs in two different modes. The downdip part may slip predominantly by creep, accompanied by a continuous level of small events, while the updip part is locked and fails episodically. The boundaries limiting the development of aftershock sequences in the updip part of the interplate boundary may reveal the location of strong patches or asperities, which tend to lock the plate boundary and which accumulate stress during creep along the downdip portion of the boundary.

Another more speculative association is with the tilt signal recorded by relevelings of the array of bench marks on Efate Island. The possible tilt change that occurred near 1980 could be the recording of a creep episode in the downdip zone which increased the load on the locked part of the interplate boundary and thereby led to the 1979–1981 episode of plate slippage. The continuing tilt observed after 1981 may also indicate that the process is not over and that stress continues to accumulate in the updip part of the interplate boundary.

Zones of Concentrated Seismicity, Boundaries, and Asperities

Summary of major spatial features. The most outstanding zone of concentrated activity is the hot spot (zone A), located northwest of Efate Island (Figure 12). This zone has the highest and most persistent level of background activity in the entire Efate-Malekula region. Most of the clustered activity in the downdip part of the interplate boundary is concentrated there, and four of the nine main shocks of the 1978–1984 episode occurred on the northern edge of the zone (Figure 12). The second zone of concentrated activity is zone B, located west of Efate Island (Figure 12). If we exclude the August 1979, July 1981 and June 1983 sequences, almost all the clustered activity of the updip part of the interplate boundary is concentrated in zone B. All the clustered activity of the backarc region is concentrated in two less outstanding zones located near and east of Efate Island (Figure 10). A common characteristic among these four regions is that all their clustered activity can be related in time to the August 1979, July 1981, and June 1983 sequences of the updip part of the interplate boundary.

Zone B acts as a boundary in all the sequences located in the updip part of the interplate boundary (Figure 12). A second sharply defined boundary (boundary 1), located northwest of Efate Island near 17.2°S, limits the northern extent of the August 26, 1979, aftershocks (Figure 12). Boundary 1 also marks the transition between the very active Efate region and the less active Malekula region (Plate 1*a*). Two other boundaries (boundaries 2 and 3) are located south of Malekula Island and near 18.1°S (Figure 12). The three main shocks of 1979 and 1981 located in the updip part of the interplate boundary occurred near zone B and boundary 1, and all the boundaries, except boundary 3, were activated by clusters. These clusters can be related to the occurrence of the August 1979, July 1981, and June 1983 sequences.

Zones A and B and boundary 1 are intimately related in map view. Zone A is located between zone B and boundary 1 at their eastern ends (Figure 12). Also, three of the four concentrations of events with magnitude $M_W \geq 5.8$ which occurred in the region since 1960 are located on or near these three features (Figure 12). Note also that the March 1960 ($M_S = 6.7$) event is located at the western end of boundary 2 and that there is a concentration of main shocks south of boundary 3, while the region between zone B and boundary 3 has not experienced any major earthquake since 1960 (Figure 12).

The relation of these spatial features of the seismicity to the bathymetry is not simple but may be indicative of the localization of the seismicity by specific structures within the subduction zone. The southwest–northeast trend of zone B is parallel to the northwestern slope of the trenchward protruding "block" upon which Efate Island sits. North of this protrusion is the prominent embayment of the forearc which includes an unusual ridge and a deep trough (see Figure 1). Boundary 2 is located at the northern edge of the embayment (compare Figures 1 and 12). Zones A and B and boundary 1 are located east of the northern "end" of the South New Hebrides Trench (Figure 12), where the trench abruptly changes trend, shoals rapidly toward the north-northwest and is barely traceable west of southern Malekula [*Monzier et al.*, 1984]. Two of the concentrations of epicenters shown in Figure 12 coincide with zone A and boundary 1, and both are located above the unusual ridge-trough feature in the forearc embayment. The background zone terminates sharply just north of these features (Figure 12).

The intense aftershock activity within the suboceanic plate, triggered by the July 1981 earthquake, was located beneath a seamountlike bathymetric feature near the trench axis just west of the concentration of epicenters and zone B.

There is a striking alignment of features in the Efate region (Figure 12), which includes, from west to east (1) the ORSTOM seamount and the interruption in the 6000-m contour of the trench, (2) a zone of low background seismicity level, bounded to the north by boundary 1 and to the south by zone B, (3) zone A, with a very high level of background seismicity, and (4), farther east, the back arc activity related in time to the sequences occurring in the updip part of the interplate boundary.

From this alignment, in addition to the other spatial features reviewed above, it is thus reasonable to suppose that a complex interaction of irregularities in the structure and shape of the overriding island arc with relief on the subducted plate produce the variations in rheology, degree of coupling, and tectonic loading, which are manifested in the persistent spatial concentrations of seismicity.

Asperities. Structural complexities producing heterogeneous rheology and stress distributions have long been recognized as critical to understanding the earthquake generation process. The concepts of "asperities" and "barriers" have become convenient terms to describe, in a general way, relatively strong areas of an interplate boundary. The terms have also come to indicate somewhat contrasting ideas of the relationship of these strong patches to the seismicity [e.g., see *Lay et al.*, 1982; *Aki*, 1984]. In the asperity model the large interplate earthquakes accommodate failure of the strong patches or asperities, which are loaded to failure by creep occurring in the weaker areas surrounding the asperities. In this model, coseismic rupture may propagate into the adjacent weaker areas. The barrier model emphasizes the coseismic rupture of the weaker areas. In these areas, small unruptured patches or barriers are left behind, while the larger or stronger barriers localize the initiation and stopping of rupture. As *Aki* [1984] points out, the asperity model overall appears more appropriate to the relatively simple interplate boundary found in a subduction zone, since all the strong patches must eventually fail in order to accommodate the ongoing plate motions. Thus, unless failure is aseismic, the large barriers must become the asperities which control the major seismicity. It would seem that the notion of barriers is most useful in explaining aspects of strong motion radiation and the stopping of rupture, while the asperity model is a better view of the overall long-term process of earthquake generation in an interplate boundary.

The spatial features described in this paper are likely to be related to a major asperity complex—i.e. a group of closely related asperities rather than a single one—in the region of zones A and B and boundary 1. The major question, however, is how to associate the spatial concentrations and boundaries of the seismicity to the strong patches. Although we cannot give a unique distribution of strong and weak patches based only on the spatial features described in this paper, those features do probably delineate either the asperities themselves or the edges of asperities.

We consider several of many possibilities in Figure 13. These models attempt only to emphasize several important issues. The major problem is whether the asperity complex highlighted by zones A and B and boundary 1 forms an isolated complex or forms the edge of a larger asperity. In the first case, large creeping patches would be located to the north and south. In the second case the large asperity could be located in the Epi-southern Malekula segment, with the creeping segment located to the south (or even vice versa).

The northward progression of the 1979–1981 sequences could be interpreted to favor, in the case of the edge, the location of the large asperity to the north. This would imply a progressive failure of the edge inward toward the main asperity. The dramatic difference in seismicity between the Efate and the Epi-southern Malekula regions could be taken in a general way to favor the edge model.

On the other hand, in the case of the isolated asperity complex, the northward progression of the 1979–1981 sequence could be interpreted as the progressive failure of the complex, with the main seismic release centered near the

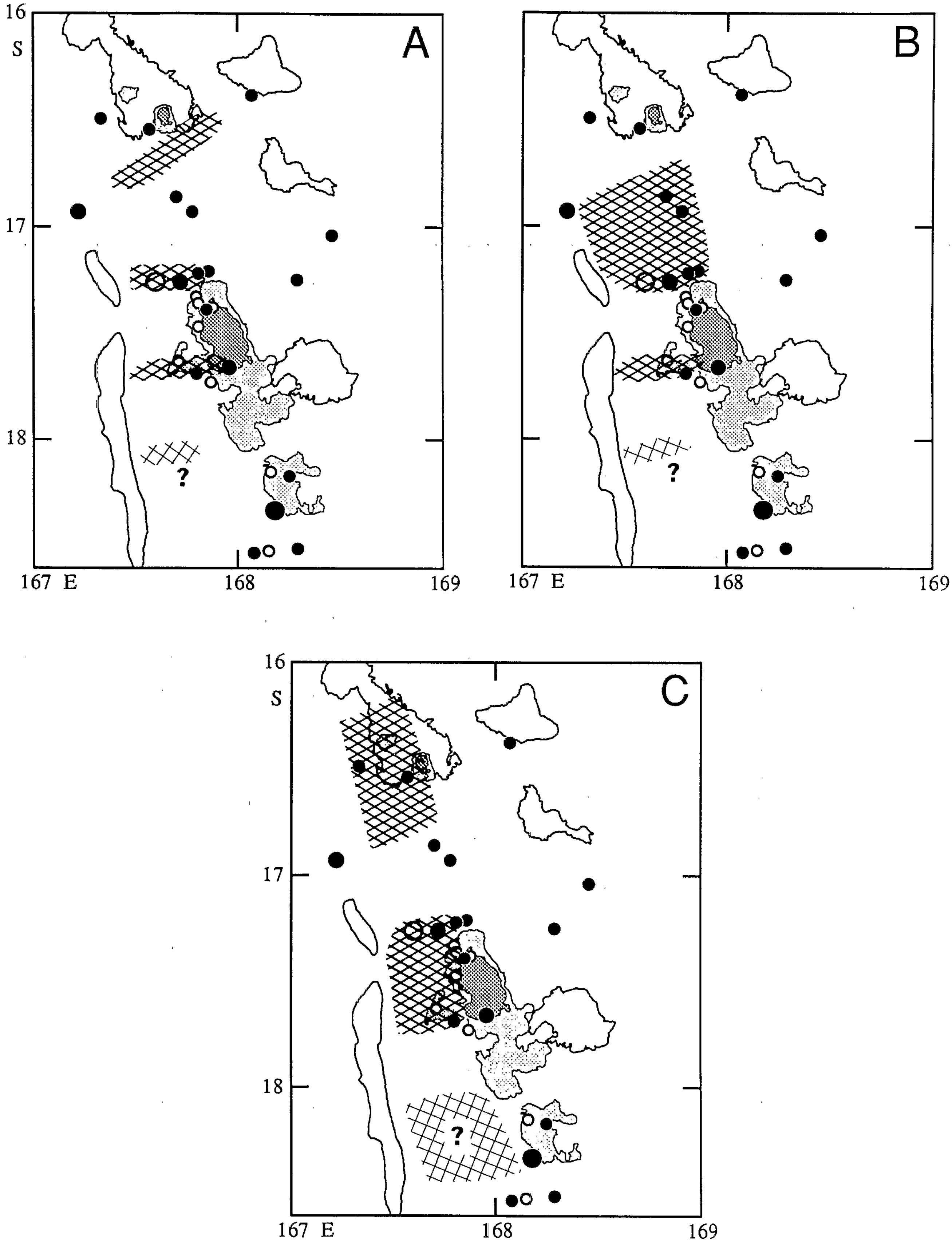

Fig. 13. Three possible models for the locations of asperities in the Efate-Malekula region. Format as in Figure 12. (*a*) Asperities located along zone B and boundaries 1 and 2; (*b*) asperities located along zone B and between boundaries 1 and 2; (*c*) asperities located (1) between zone B and boundary 1 and (2) between boundary 2 and the southern limit of the 1965 sequence. Also shown in each frame is the possible location of an asperity located along boundary 3 in Figures 13*a* and 13*b*, and south of boundary 3 in Figure 13*c*.

area of boundary 1. The aftershocks of the 1981 earthquake extended north of that area, but the main concentration of aftershocks reactivated the region between zone B and boundary 1. The oversized area of that aftershock zone is most simply explained as an effect of the rupture extending into weak patches surrounding the asperity. The main coseismic rupture is concentrated in the asperity. The region between boundary 1 and boundary 2 would then be a weak patch characterized by creep, while another possibly locked asperity, with boundary 2 as its southern edge, could exist beneath southern Malekula, as mentioned before (Figures 13*a* and 13*c*). That asperity might have formed the barrier stopping the southward rupture of the 1965 sequence.

Clearly, other scenarios could be imagined. Further critical information is needed, such as a detailed resolution of the spatial distribution of coseismic moment release for the 1981 earthquake, and knowledge about the long-term seismic history of the region. The instrumental record [*Isacks et al.*, 1981; *Marthelot*, 1983] suggests that frequent episodes of moderately large earthquakes ($M_s = 6–7$) such as the 1978–1984 episode are characteristic of the Efate-Malekula region, which would favor models with smaller asperities as shown in Figures 13*a* and 13*b*. However, the instrumental record is too short for a very confident extrapolation.

Temporal Relationships and Earthquake Prediction

In spite of the ambiguities in the interpretation of the asperity complex defined by the 1978–1984 episode, the seismicity does show remarkable temporal relationships. The progressive northward development of the episode is part of this. Other more subtle relationships, however, are apparent, and these have implications for earthquake prediction.

Only the sequences occurring in the updip part of the interplate boundary, i.e., the August 1979, July 1981, and June 1983 sequences, are preceded by obvious precursory activity. It is possible to distinguish three time scales of precursory activity including (1) the duration of the entire episode, (2) a period range from about a year to months before the different sequences in the 1978-1984 episode, and (3) a period range from about a week to hours before each of the main shocks.

In the 1978–1984 episode taken as a whole, the two August 1979 events and associated activity can be considered as precursors to the July 1981 main shock. The northward progression of this activity and the very intimate spatial relationships among the sequences indicate a strongly connected sequence. The August 17, 1979, sequence and the August 26, 1979, epicenter are both located on the southern edge of the July 1981 aftershock zone. The 1979 sequences show a clear migration of the activity northward from south of zone B toward the epicenter of the July 1981 main shock. The August 17, 1979, sequence occurred south of zone B. Ten days later the August 26, 1979, event occurred on the northern edge of the preceding aftershock zone, and its aftershock zone then developed north of zone B up to boundary 1. Finally, the July 1981 main shock occurred just north of boundary 1.

The seismic history of the Efate region from 1960 to 1978, for earthquakes with magnitude $M_s \geq 6.0$, shows four concentrations of earthquakes. Two of these concentrations are located near boundary 1 and zone B. Just north of boundary 1, two events occurred in 1962 and one in 1973, while two events occurred near zone B in 1966 and 1974. It is thus possible to distinguish two other sequences somewhat similar to the 1979–1981 sequence, in 1962–1966 and 1973–1974. These two sequences, however, show a development of the activity from the north to south, as opposed to a south to north development in 1979–1981.

Some activity appears to be related to the 1979 and 1981 sequences in the period range from about a year to months preceding these sequences. If the August 1979 doublet is considered as a single "event," then the pattern of clusters located in zone B relative to this event and the July 1981 earthquake shows an interesting repetition. In both cases the events were preceded by a few months by clusters along zone B (Figures 5 and 9). This repetition suggests the possibility that activity on zone B is a precursory signal for significant interplate events. Since the last cluster in February 1981 (preceding the July 1981 main shock), not a single cluster occurred on zone B.

Other long-term precursory activity includes a cluster near the location of the August 17, 1979, epicenter in the month preceding the earthquake, two clusters occurring a year before the July 1981 event and located near boundary 1, and a cluster in the back arc region during the month preceding the July 1981 event. Comparison with historical data is difficult because these phenomena can be in a magnitude range too small for detection by the worldwide network.

Only the August 17, 1979, event was preceded by an outstanding and substantial short-term foreshock sequence. This activity occurred south of zone B during the 8 days preceding the main shock. The cluster which can be considered as precursory activity to the August 26, 1979, event is difficult to isolate from the aftershocks of the August 17 event. The July 1981 main event was preceded by two small clusters during the 9 days preceding the main shock. A small cluster also preceded the June 1983 sequence, near the position of the first cluster which preceded the August 17, 1979, event. Note also that although the June 1983 sequence was similar to the 1979 precursory activity and occurred at the same place, the sequence itself, taken as a possible foreshock sequence, did not in fact lead to a major event. The pattern of short-term foreshock activity is thus sufficiently variable that the use of foreshocks as precursory signals remains quite difficult.

Almost all the clustered activity of the Efate region can be related to the occurrence of the seismic sequences in the updip part of the interplate boundary. To this extent the seismicity appears to be controlled by the failure of the locked updip part of the interplate boundary. It seems that rather than a fixed seismic cycle during which specific zones are always activated in a specific temporal relationship to failure in the updip part of the interplate zone, there are instead specific zones which can be activated either before or after these failures, including the possibility that all the zones are activated only after a particular sequence. It is also possible that depending on the magnitude of the main shock of the sequence, for example, the zones will not all be affected. In spite of these complexities, it is possible that the seismicity of the spatially discrete features, revealed by the clusters and aftershocks of the 1978–1984 episode, may be indicators of times of increased probability of major rupture along the plate boundary. The times of increased probability of rupture might occur after episodes of creep along the downdip part of the plate boundary. Propagation of creep along the New Hebrides arc is one possible explanation for the apparent episodic activation of the entire arc that *Marthelot* [1983] describes. In particular, the 1978–1981 sequence occurs during the period when magnitude 7.5–8 events occurred 300 km to the north, near the Santa Cruz Islands, and a major sequence of moderately large earthquakes occurred 200 km to the south, near the Loyalty Islands. The manifestation of slippage of the interplate boundary as a sequence of events forming a 4-year episode (rather than as a single event) implies a process with characteristic time delay between events on the order of days to years. This aspect of seismicity is especially well developed in the New Hebrides island arc, as shown by *Lay et al.* [1982] and *Marthelot* [1983]. The shorter end of this spectrum of delay times is manifested in the expansion of the aftershock zones. Nearly all of the expansion takes place in the first 2 days, with the most rapid and obvious expansion occurring during the first day. These time delays, in conjunction with the progressive rupture discussed in the simple asperity models above, are in general agreement with the model of rupture discussed by *Das and Scholz* [1981].

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