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EXPANSION OF THE AFTERSHOCK ZONE FOLLOWING THE VANUATU (NEW HEBRIDES) EARTHQUAKE ON 15 JULY 1981

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Abstract. Following a large (M_s=7.0), interplate earthquake on 15 July 1981 in the Vanuatu (New Hebrides) Islands, the area defined by the aftershocks dramatically increased over a two week period of time. The aftershocks were located using the Cornell/ORSTOM seismograph network that has been monitoring earthquakes with magnitudes larger than m_b=2.9 in the region since mid-1978. In the first few hours following the mainshock, the area defined by the aftershocks was consistent with the rupture zone of a typical interplate earthquake with the observed seismic moment of 5.8 x 10^{26} dyne-cm. However, during the 16 days following the mainshock, the area of the aftershock zone increased to approximately 10 times the area of expected coseismic rupture. The final aftershock zone included earthquakes that were located within the overriding and descending plates as well as along the interplate fault zone. The migration of aftershocks away from the rupture zone of the 1981 mainshock indicates that, at least in some cases, the aftershock zone can overestimate the extent of coseismic rupture.

Introduction

The extent of coseismic rupture during an interplate, thrust type earthquake is usually estimated from the area of the aftershock zone. For certain large earthquakes, however, the areas of the aftershock zones do not remain constant, but instead they appear to increase with time following the mainshock (Mogi, 1968; Isacks et al., 1981; Tajima and Kanamori, 1981). Aftershock zones that expand their areas over periods of weeks to months following the mainshocks make it difficult to determine the extents of plate boundary ruptures. Since aftershocks of most interplate, thrust-type earthquakes are located by using data from seismograph stations at teleseismic distances and not from local stations, there is always a question of whether such increases in area are real or whether they are due to hypocenter mislocations. To help answer this question aftershock locations were examined for recent earthquakes in the central Vanuatu (formerly New Hebrides) Islands that were recorded by a local seismograph network operated by Cornell University and ORSTOM. Only interplate, thrust-type events were examined because the fault planes dip at shallow angles, and the aftershock areas can be easily and accurately determined from earthquake epicenters. This letter presents observations of aftershocks of a large (M_s=7.0) earthquake that occurred on 15 July 1981. The results of this study clearly demonstrate that the area of the aftershock zone increases with time following the mainshock.

Oceanic lithosphere of the Australian plate is being subducted eastward beneath the Vanuatu Island arc. The 1981 earthquake occurred along the interplate boundary at the northernmost end of the South New Hebrides trench (Figure 1). The plate boundary continues to the north, although the bathymetric expression of the downward bending of the oceanic lithosphere is obscured by the subduction of the D'Entrecasteaux fracture zone and by a westward protrusion of the upper plate (Karig and Mammerickx, 1972; Isacks et al., 1981).

The central Vanuatu Islands have been monitored for seismicity since mid-1978 and for tilt since 1975. The Cornell/ORSTOM instrumentation in the region consists of a 19-station seismograph network, an 8-station borehole tiltmeter network, two long-baseline (100 m), water-tube tiltmeters, two one-km aperture releveling networks, and a tide gauge (Isacks et al., 1981; Bevis and Isacks, 1981). The coverage of the seismograph network for this region is uniform for events with magnitudes (m_b) 2.9 and larger.

The 1981 event occurred in the interplate region west of Efate Island where the rate of occurrence of small and moderate-sized earthquakes in the during the past 21 years has been persistently and anomalously high relative to other parts of the arc (Isacks et al., 1981). This region has been characterized by clusters of interplate earthquakes with magnitudes (M_s) near 6. The last of these clusters occurred in the period 1978-1981 and consisted of earthquakes on 1 September 1978 (M_s=5.9), 17 August 1979 (M_s=6.1), 26 August 1979 (M_s=6.0) and 15 July 1981 (M_s=7.0). The locations of these events and the maximum extents of their aftershock zones are shown in Figure 1. The 1978 event occurred two weeks before the installation of the local seismograph network was completed and, therefore, the maximum extent of its aftershock zone is uncertain. However, the 1979 and 1981 events were well recorded and all have anomalously large aftershock zones for their magnitudes and moments. In addition, the areas of the aftershock zones for all three events appeared to increase with time following the mainshocks. The clearest example of an expanding aftershock zone is presented below for the 1981 event.

Mainshock

The mainshock occurred at 07:59 Coordinated Universal Time on 15 July 1981 about 85 km north-

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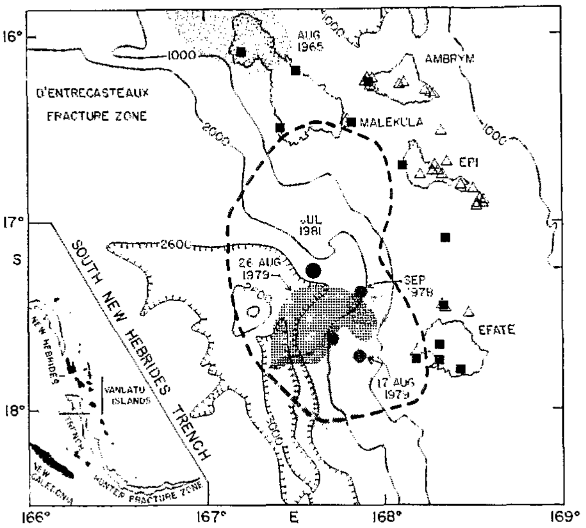

Fig. 1. Mainshock locations and maximum areas of the aftershock activity for recent earthquakes in the central Vanuatu Islands (dashed outline for the 1981 event, shaded regions for the 1978 and 1979 events). Small circles are moderate-sized (M_s=6) earthquake epicenters, large circle is the 1981 (M_s=7.0) epicenter. The maximum area of each aftershock zone is determined several weeks after each mainshock and is much larger than the inferred rupture zone. The previous seismic episode of major, interplate slippage in the region occurred in August 1965, and the shaded region in Malekula represents the best estimate of the rupture zone. Bathymetric contours in fathoms (1 fathom=1.82 m) are from Mammerickx et al. (1971). Squares represent stations of the local seismograph network. Triangles represent Quaternary and active volcanoes (Geological Map of the New Hebrides Condominium, 1975).

west of the closest seismograph station on Efate Island (Figure 2). The hypocenter was located at 17.26°S, 167.60°E using arrival time readings from local stations of the Cornell/ORSTOM network as well as worldwide stations (Preliminary Determination of Epicenters bulletin (PDE), 1981). Very few earthquakes have been located near the epicenter of the 1981 mainshock since the seismograph network began operating. However, a small cluster of earthquakes did occur a few days before the mainshock (upper left, Figure 2).

The moment tensor solution determined from amplitudes of long period body and mantle waves yields a seismic moment (M_o) of 5.8 x 10^{26} dyne-cm (PDE bulletin, 1981). This determination is nearly identical to the moment of 4 x 10^{26} dyne-cm estimated using the surface wave magnitude (M_s) and the moment-magnitude relationship ($\log M_o = 1.5 M_s + 16.1$) of Kanamori and Anderson (1975) for interplate earthquakes. The agreement between the moments determined from longer period (greater than 135 sec) mantle waves and shorter period (18 to 122 sec) surface waves indicates that the event is a typical interplate earthquake. There is no evidence from the radiated seismic waves that this event was a "slow" earthquake.

P wave first motions recorded at local and worldwide stations yield a fault plane solution for interplate, thrust-type faulting with a strike of 349°, a dip of 11° and a slip of 90° (PDE bulletin, 1981). A very similar mechanism is obtained from the best double couple solution determined from the moment tensor and has a strike of 338°, a dip of 27°, and a slip of 83° (PDE bulletin, 1981).

Development of the Aftershock Zone

Figure 2 illustrates the spatial and temporal development of the 1981 aftershock zone during the two week period following the mainshock. Included for reference in these figures are the locations of the previous three M_s = 6 events. Earthquakes that occurred in the first 1 1/2 hours following the mainshock are shown in Figure 2 (upper center). These initial aftershocks were located north of the aftershock zones of the 1 September 1978 and 26 August 1979 earthquakes (compare with Figure 1) and surround the mainshock. The small number of aftershocks immediately following the mainshock is striking. No earthquakes with magnitudes greater than about 2.9 have been missed because the Cornell/ORSTOM system records in both the continuous and event-triggered modes.

From 1 1/2 to 4 hours after the mainshock the area of the aftershock zone increased considerably. Aftershocks occurred along the South New Hebrides trench as far north as 17°N and occurred as far south as the epicenter of the 26 August 1979 earthquake.

During the period from 4 to 37 hours after the mainshock much of the activity continued to occur in the region between the 1981 mainshock and the

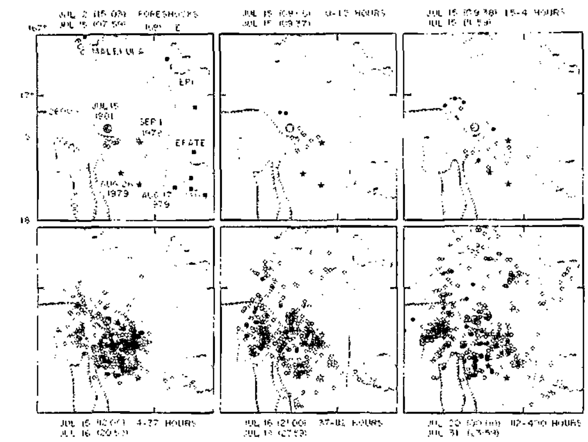

Fig. 2. Maps of the central Vanuatu Islands showing the spatial distribution of foreshocks (upper left) and aftershocks of the 15 July 1981 earthquake. Earthquake epicenters are represented by circles; stars represent locations for the three moderate-sized (M_s=6) earthquakes in 1978-1979 included for reference; the largest circle represents the 1981 earthquake. Solid dots represent epicenters of the largest earthquakes (M_s > 4.5) located using both worldwide and local seismograph data. The dashed outline represents an estimate of the rupture zone for the 1981 mainshock. Note that the area of the aftershock zone appears to expand with time. Other symbols are as in Figure 1.

26 August 1979 event. The northern limit of aftershock activity expanded north of 17°N. The southern limit of the aftershock activity expanded as far south as the epicenter of the 17 August 1979 event. During this interval earthquakes began to occur within the descending plate as indicated by the earthquakes located beneath and seaward of the northern projection of the South New Hebrides trench.

From 37 to 112 hours after the mainshock the aftershocks occurred as far north as a prominent east-west trend in the bathymetry lying just south of Malekula. Although the region of greatest density of aftershocks remained north of the 17 August 1979 epicenter, some earthquakes occurred south of the latitude of Efate. Seismicity in the descending plate continued to occur beneath the northward extension of the South New Hebrides trench.

During the final 12 days of the month (July 20-31) the northern limit of aftershock activity expanded north into Malekula. There was also expansion of the aftershock zone eastward toward the volcanic arc. The activity near Epi is shallow and probably located in the upper plate and not along the interplate thrust zone. The aftershock zone also expanded westward within the descending plate. The greatest concentration of activity was around a topographic high marked by the closed 2600 fathom contour. This topographic high is probably a seamount. The region defined by the first four hours of aftershock activity and located between the 1981 and 1979 epicenters continued to have the greatest concentration of seismic activity. A separation began to develop between this seismicity along the interplate thrust zone and the seismicity along the trench and its northward extension.

Discussion

Since the dip of the fault plane is very shallow (11°) it is unnecessary to distinguish the aftershock area measured in the plane of the fault from the aftershock area defined by epicenters on the surface. By the end of July 1981 the area activated by aftershocks had grown to approximately 15,000 km^2. For the remainder of 1981 the maximum area of the aftershock zone did not increase beyond that shown for the end of July. The largest aftershock was only a magnitude M_S=5.5 event and none of the increase in aftershock area appeared to be associated with any of the larger aftershocks. A typical aftershock area for an interplate earthquake with a moment of 5.8 x 10^{26} dyne-cm is about 1350^2 km (Kanamori and Anderson, 1975). This area would correspond to the area (1530 km^2) of the 1981 aftershock zone about four hours after the mainshock (dashed outline in Figure 2). The final aftershock area is 10 times larger than the expected area.

Expanding aftershock zones with anomalously large final areas also occurred following other recent earthquakes in the Vanuatu arc (Isacks et al., 1981). Growth in the areas of aftershock zones has been documented for other subduction zones besides the Vanuatu arc. The final aftershock area of the 1979 Petatlan, Mexico earthquake was over three times the area at 11 hours when the local seismograph network began operating (Valdes et al., 1982). Using data from teleseismic stations Mogi (1968) and Tajima and Kanamori (1981) found growth of aftershock areas for subduction zones in Japan, Aleutian, Alaska, Kermadec, Santa Cruz, Peru and Columbia.

Figure 2 shows that much of the growth in the area of the aftershock zone occurs in the first day. Although not all earthquakes show expanding aftershock zones, the expansion of the aftershock zones may have been missed for some earthquakes because most aftershock zones are examined at periods greater than one day.

The final area of the 1981 aftershock zones is larger than the expected area of the coseismic rupture zones. One explanation for the discrepancy may be that the entire area of the final aftershock zone ruptured coseismically,but that the initial aftershocks occupied only a small portion of the fault zone. However, measurements of tilt on Efate Island using two long-baseline, water-tube tiltmeters suggest that only a small area ruptured coseismically (Cardwell et al., 1982). The tiltmeters recorded a coseismic tilt of 0.1 μR which agrees with the tilt calculated from a dislocation model using only the area of the aftershock zone in the first four hours. If the entire area of the final aftershock zone had ruptured aseismically at the time of the mainshock, then the tilt on Efate should have been over an order of magnitude larger (i.e. greater than 1 μR). This observation suggests that only a small region ruptured coseismically.

Another explanation to account for the discrepancy between the initial and final aftershock areas may be that there was minor slip following the mainshock along the interplate thrust zone outside of the region of coseismic slip. No tilt anomalies were observed with the instruments on Efate Island following the mainshock, but if the magnitude of the afterslip were less than coseismic slip, the tilt instrumentation on Efate would not be sensitive enough to detect the movement. If such movement is responsible for the expansion of the aftershock zone, then it appears also to have activated earthquakes both along the interplate thrust zone and in the surrounding (descending and overriding) plates.

Conclusions

The area of the aftershock zone two weeks after 15 July 1981 earthquake in the central Vanuatu arc was approximately 15,000 km^2. The moment-area relationship of Kanamori and Anderson (1975) for interplate, thrust-type earthquakes predicts a coseismic rupture area of only about 1350 km^2. The coseismic tilt observed on two long baseline, water-tube tiltmeters also indicates a small area for the coseismic rupture. Thus, the final aftershock area is 10 times larger than the expected area of coseismic rupture.

The area of the aftershock zone grew rapidly during the first few days following the mainshock and then grew more slowly toward the end of the period of expansion. The expanding aftershock zone included events within the overriding and descending plates as well as along the interplate thrust zone.

These observations show that, at least in some cases, the area of the aftershock zone can overestimate the area of coseismic rupture. Significant expansion in the areas of aftershock zones may occur only for moderate and large-sized earthquakes and does not necessarily invalidate the seismic gap hypothesis for great (M_s>7.8) earthquakes.

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References

Bevis, M., and B. Isacks, Leveling arrays as multicomponent tiltmeters: Slow deformation in the New Hebrides island arc, J. Geophys. Res., 86, 7808-7824, 1981.

Cardwell, R.K., B.L. Isacks, J.-L. Chatelain, and M. Bevis, Postseismic expansion of aftershock zones following interplate thrust-type earthquakes in the Vanuatu (New Hebrides) island arc (abstract), paper presented at the AGU Chapman Conference on Fault Behavior and the Earthquake Generation Process at Snowbird Utah on October 11-15, 1982.

Geological Map of the New Hebrides Condominium Ministry of Overseas Development, D.O.S., British Residency, Vila, New Hebrides, 1975.

Isacks, B.L., R.K. Cardwell, J.-L. Chatelain, M. Barazangi, J.-M. Marthelot, D. Chinn, and R. Louat, Seismicity and tectonics of the central New Hebrides Island Arc, in Earthquake Prediction, Maurice Ewing Series 4, D. Simpson and P. Richards, Eds., American Geophysical Union, Washington, D.C., 93-116, 1981.

Kanamori, H., and D. Anderson, Theoretical basis of some empirical relations in seismology, Bull. Seis. Soc. Am., 65, 1073-1095, 1975.

Karig, D., and J. Mammerickx, Tectonic framework of the New Hebrides island arc, Marine Geology, 12, 187-205, 1972.

Mammerickx, J., T. Chase, S. Smith, and I. Taylor, Bathymetry of the South Pacific, map, Chart 12, Scripps Inst. of Oceanography, La Jolla, California, 1971.

Mogi, K., Development of aftershock areas of great earthquakes, Bull. Earthq. Res. Inst., 46, 175-203, 1968.

Preliminary Determination of Epicenters (PDE), monthly bulletin, National Earthquake Information Service, U.S. Geological Survey, Alexandria, VA., 1981.

Tajima, F., and H. Kanamori, Global variation of expansion pattern of aftershock area (abstract), EOS, Trans. Am. Geophys. Union, 62, 949, 1981.

Valdes, C., R.P. Meyer, R. Zuniga, J. Havskov, and S.K. Singh, Analysis of the Petatlan aftershocks: numbers, energy release, and asperities, J. Geophys. Res., 87, 8519-8527, 1982.

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