

SEISMICITY PATTERNS (1963-1983) AS STRESS INDICATORS IN THE SHUMAGIN SEISMIC GAP, ALASKA

BY EGILL HAUSSON*, JOHN ARMBRUSTER, AND STEVEN DOBBS†

ABSTRACT

Earthquakes (1963 to 1983) of magnitude 5.0 to 6.5 form a rim of high seismic activity around a central region of relative seismic quiescence that coincides with the Shumagin seismic gap. This pattern, which can be inferred both from local network and teleseismic earthquake locations, shows high activity near the eastern and western ends of the seismic gap and along the down-dip end of the main thrust zone. The rim of seismicity surrounding an area of seismic quiescence may reflect strong coupling along the elastic-brittle part of the plate boundary where the great earthquakes occur. The temporal behavior of the microseismicity recorded by the Shumagin network is characterized by a burst of activity in 1978 and 1979, and a low or average level of activity from 1980 to January 1983. The increased microearthquake activity during 1978-1979 is located mainly near the down-dip end of the main thrust zone and along the Benioff zone down to 100 to 200 km depth. Composite fault plane solutions of earthquakes occurring in 1978-1979 show down-dip tension between 50 to 120 km depth in the upper plane of the Benioff zone. Composite fault plane solutions of 1981 earthquakes, however, indicate in-plate compression in the same region. Hence, the rate of occurrence and focal mechanisms of microearthquakes located in the Benioff zone below the main thrust both show coincident temporal and spatial variations that may reflect fluctuations in local stresses.

INTRODUCTION

The Shumagin Islands region in the eastern Aleutians was identified by Kelleher (1970), Sykes (1971), and Kelleher *et al.* (1973) as one of the major seismic gaps in United States territory (see Figure 1). Davies *et al.* (1981) reanalyzed the history of great earthquakes and evidence of high seismic potential in the Shumagin region and concluded that there is a high probability that a great earthquake will occur in the Shumagins during the next one to two decades. The Shumagin region was designated as a potential site for a great earthquake within a few decades because the time (80 to 140 yr) since the last great earthquake is similar to estimates of average repeat times for the eastern Aleutian arc (70 to 80 yr). Estimates for probabilities for a great earthquake in the Shumagin seismic gap to occur during the 20-yr period 1983 to 2003 range from about 30 to 95 per cent (Jacob, 1984). The dimensions of the Shumagin seismic gap are inferred from the distribution of aftershocks of the adjacent 1946 and 1938 earthquakes as well as the intensity and duration of strong ground shaking, tsunamis and ground deformation by Sykes deformation by Sykes (1971) and Sykes *et al.* (1981).

Davies *et al.* (1981) described seismicity patterns in the Shumagin gap and showed that the gap was characterized by a rim of high activity surrounding a quiet central zone. Mogi (1969, 1981) found similar patterns of seismicity (doughnuts) along the Japan trench that he interpreted as precursors to large or great earthquakes. In southern Alaska, McCann *et al.* (1980) identified a doughnut pattern around the Yakataga gap. Numerous other studies along active plate boundaries have revealed doughnut patterns although how this pattern is causally related to the forthcoming

* Present address: Department of Geological Sciences, University of Southern California Los Angeles, Los Angeles, California 90089-0741.

† Present address: Gustavus Adolphus College, St. Peter, Minnesota 56082.

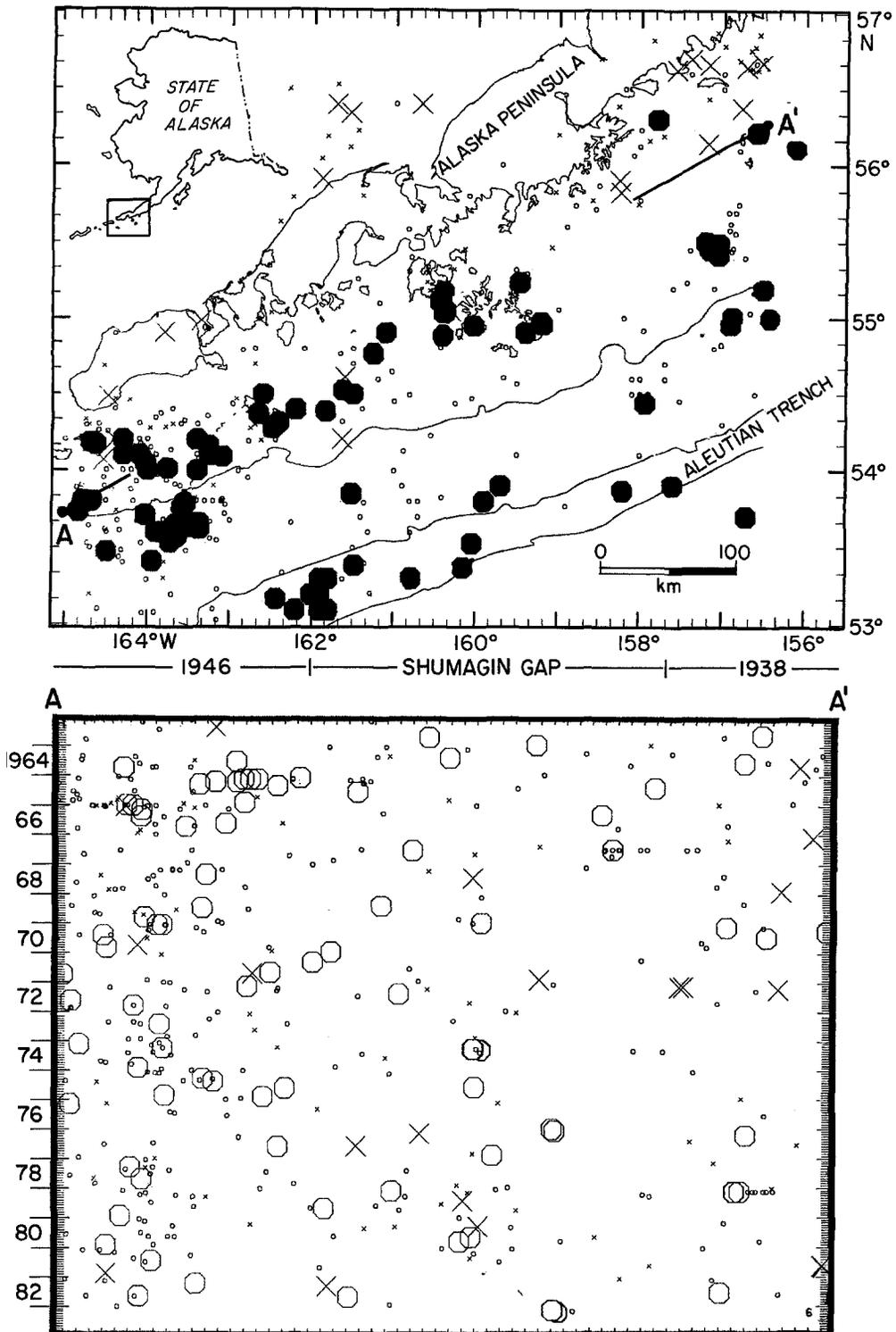


FIG. 1. (Top) Seismicity listed in the NOAA hypocentral data file or the *PDE Bulletin* for the Shumagin Islands region from 1963–1983. Shallow earthquakes (depth ≤ 50 km) of $m_b \geq 5.0$ are shown as large black symbols and smaller earthquakes ($m_b \leq 5.0$) are shown as open symbols. A high level of earthquake activity surrounds the main thrust zone. (Bottom) A space-time plot of the PDE seismicity projected onto the A–A' line parallel to the trench. The X's are earthquakes deeper than 50 km. The small symbols show earthquakes with $3.0 \leq m_b < 5.0$ and the large symbols are earthquakes of $m_b \geq 5.0$. The extent of the Shumagin gap and the 1946 and 1938 aftershock zones are shown in the middle. The insert in the upper left corner shows the state of Alaska and the location of the Shumagin Islands region.

large or great earthquake is not clearly understood (e.g., Kanamori, 1981; Tajima and McNally, 1983). Precursory seismicity or foreshocks that are sometimes observed prior to large or great earthquakes are more closely related to the occurrence of the main shock than the doughnut pattern (e.g., Mogi, 1981; Kanamori, 1981). Hsu *et al.* (1983) who studied seismicity preceding the Petalan, Mexico, earthquake (1979) found that possible foreshocks occurred within weeks or days of the main shock. Kanamori (1981) showed that both the 1964 Alaska earthquake and the 1957 Fox Island earthquake were preceded by preshock activity lasting for approximately 10 yr before the main shock.

This study that is a continuation of the work of Davies *et al.* (1981) consists of a detailed analysis of the last 20 yr of seismicity in the Shumagin region. In particular, the spatial and temporal patterns of local and teleseismic seismicity are analyzed to assess whether these patterns are anomalous or simply normal background activity. If these patterns are anomalous, they may aid in improving estimates of the time of occurrence of the forecast great earthquake (Davies *et al.*, 1981). Such quantitative estimates are, however, beyond the scope of this paper.

DATA

Teleseismic data. Teleseismic epicenters and body wave magnitudes (m_b) were taken from the NOAA Hypocenter Data File for the time period 1963 to 1981. The more recent data (1981–April, 1983) were obtained from the monthly or weekly editions of the *Preliminary Determination of Epicenters (PDE) Bulletin*, published by the National Earthquake Information Service (NEIS). All earthquakes located between 53° to 57°N and 157° to 165°W were included in plots and statistical analysis.

The uncertainties in depth determinations in the Aleutians can be large, and teleseismic epicenters are (consistently) displaced 20 to 30 km away from the trench axis toward the arc. These location errors do not affect the overall spatial patterns described here because the amount of displacement does not vary significantly across the study region. The depths of the earthquakes of magnitude ≥ 5.5 were corrected using the arrival times of depth phases (pP or pwP) as determined by House and Jacob (1983).

The focal mechanisms of most of these moderate-sized earthquakes are published by Davies *et al.* (1981) and House and Jacob (1983). They find normal faulting at shallow depths near the trench axis and thrust faulting near the down-dip end of the main thrust zone. An occasional strike-slip event occurs at shallow depths along the shelf. Davies and House (1979) defined the "main thrust zone" as the shallowly dipping seismic zone between the trench and the top of the Benioff zone at a depth of approximately 40 km, which is the terminology employed here.

Shumagin network data. L-DGO has operated the Shumagin network in the eastern Aleutians since 1973. The earthquakes recorded by the Shumagin network were located using the HYPOINVERSE program (Klein, 1978) with a flat-layered velocity structure (Rowlett and Jacob, personal communication, 1974; see also, Reyners and Coles, 1982). Both P and S arrivals from up to 15 stations are included in the determination of hypocenters.

It is difficult to evaluate the rate of seismicity recorded by the Shumagin network between 1973 and 1978 because of several significant gaps in the data. Since 1978, most of the seismic stations have operated continuously and the data recording has improved substantially. Reliable seismicity rates can, therefore, be determined during this period.

Composite focal mechanisms have been determined for the 1981 data recorded by the Shumagin network. The approach used here was similar to that of Reyners and Coles (1982) who determined composite focal mechanisms for the 1978–1979 data set. Only earthquakes whose epicentral distance to the nearest station was less than twice the hypocentral depth are included. In addition, at least three impulsive first motions had to be recorded for an earthquake to be included in the analysis. The selected earthquakes were grouped according to depth and epicentral region before constructing composite focal mechanisms.

RESULTS FROM TELESEISMIC DATA

Spatial patterns. The spatial pattern of teleseismically recorded earthquakes of depth less than 50 km in the Shumagin region is illustrated in Figure 1. Most of the earthquakes of magnitude greater than or equal to 5.0 (m_b) are confined to an annulus elongated in the east-west direction. The level of activity is highest to the southwest, inside the aftershock zone of the 1946 earthquake (Sykes, 1971; Davies *et al.*, 1981). This activity is fairly steady through time as indicated in Figure 1 where seismicity is plotted versus distance along the trench as a function of time. Clusters of earthquake activity extend along the lower edge of the main thrust zone as well as along the trench toward the east where they overlap with the aftershock zone of the 1938 earthquake. The earthquake activity within the 1938 zone shows significantly less seismicity than the activity within the 1946 zone. The absence of moderate-sized earthquakes within the main thrust zone is emphasized by the high level of activity along the surrounding rim. Earthquakes of magnitude less than 5.0 also form a pattern of scattered activity within the main thrust zone and concentrated activity along the rim.

Temporal patterns. Techniques described by Habermann (1981, 1983) were used to search for possible temporal changes in seismicity rate. No changes significant at the 99 per cent confidence level could be identified.

Both the z test and b value calculations suggest that the minimum magnitude of completeness for the set of teleseismically recorded earthquakes since 1963 is approximately 4.8 to 5.0 (m_b). The cumulative number of all the recorded earthquakes of magnitude equal or greater than 5.0 (m_b) that were reported between 1963 and early 1983 in the Shumagin region is shown in Figure 2. The high rate of seismicity observed from 1964 to 1966 coincides with the occurrence of the 1964 great Alaskan earthquake and the 1965 Rat Island earthquake. In general, the seismicity rate shows large short-term fluctuations, which lead to a mean rate with a large standard deviation. Hence, the observed changes in the seismicity rate of less than 50 to 100 per cent are not statistically significant.

RESULTS FROM SHUMAGIN NETWORK DATA

Spatial pattern. All epicenters of all of the earthquakes reported by the Shumagin network from 1973 to 1981 are plotted in Figure 3 where the symbol type depends on the depth range and the size of the symbol is proportional to the magnitude. The gross features of the Shumagin network seismicity are similar to the ones of the teleseismic data set (compare Figures 1 and 3). The pattern of seismic quiescence within the main thrust zone surrounded by an elongated annulus of high activity is observed at all magnitude levels above the detection threshold of approximately 2.0 to 2.5 (M_L). The most prominent feature of the local seismicity is the strong clustering of activity at shallow depths along the southern edge of the Shumagin shelf, which follows the 200-m bathymetric contour (see Figure 3). These clusters

are usually elongated in a northeast direction and form a trend subparallel to the down-dip end of the main thrust zone. The abrupt halt in this trend southwest of the Sanak Basin is probably real and coincides with a bathymetric high at the 200-m contour along the inner wall of the trench.

The resolution of the network decreases within the area of the 1946 aftershock zone (the area west of 163°W) but it appears that the activity is less clustered in that region and is spread across the entire main thrust zone, from the shelf edge (200-m bathymetric contour) down into the trench. It is noteworthy that the 1946 aftershock zone (which may have been located below the main thrust zone, K.

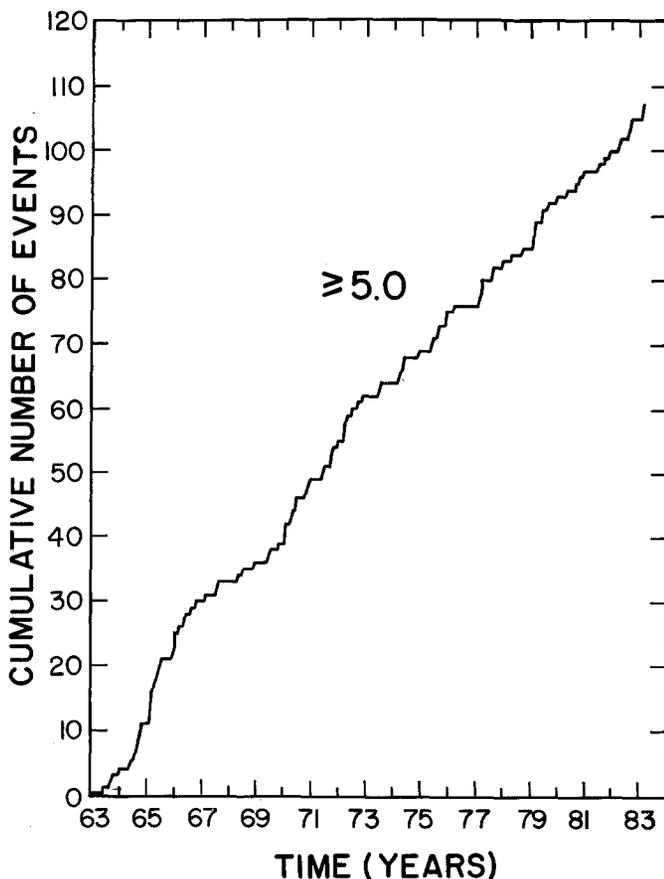


FIG. 2. Cumulative number of all NOAA/PDE epicenters in the Shumagin region for earthquakes of $m_b \geq 5.0$. No change in the seismicity rate can be identified using the statistical methods of Habermann (1983).

Jacob, personal communication, 1983) shows higher levels of activity than does the main thrust zone to the south. Similarly, reduced network detection causes the plotted seismic activity to taper off east of the Shumagin Islands although significant clustering of the larger network-located earthquakes can be seen well within the 1938 aftershock zone.

To the north, the lack of shallow activity along the volcanic arc and in the south Bering Sea are considered to be real. The low levels of seismicity within and south of the trench, however, may in part be caused by the Shumagin network being located in a shadow zone with respect to this source region, as was observed in the central Aleutians, near Adak Island by Frohlich *et al.* (1982).

The depth section of all the Shumagin network data (1973 to 1981) in Figure 4a extends 100 km east of and 200 km west of the line from A to A' in Figure 3. Since all hypocentral solutions are plotted together, the lower quality solutions may artificially make the zone of activity appear too wide. Figure 4b shows in depth section 740 high-quality solutions selected from the hypocenter catalog of approximately 4000 earthquakes. These earthquakes, which occurred between 1973 and 1982, were recorded at seven or more stations in the Shumagin network, and their

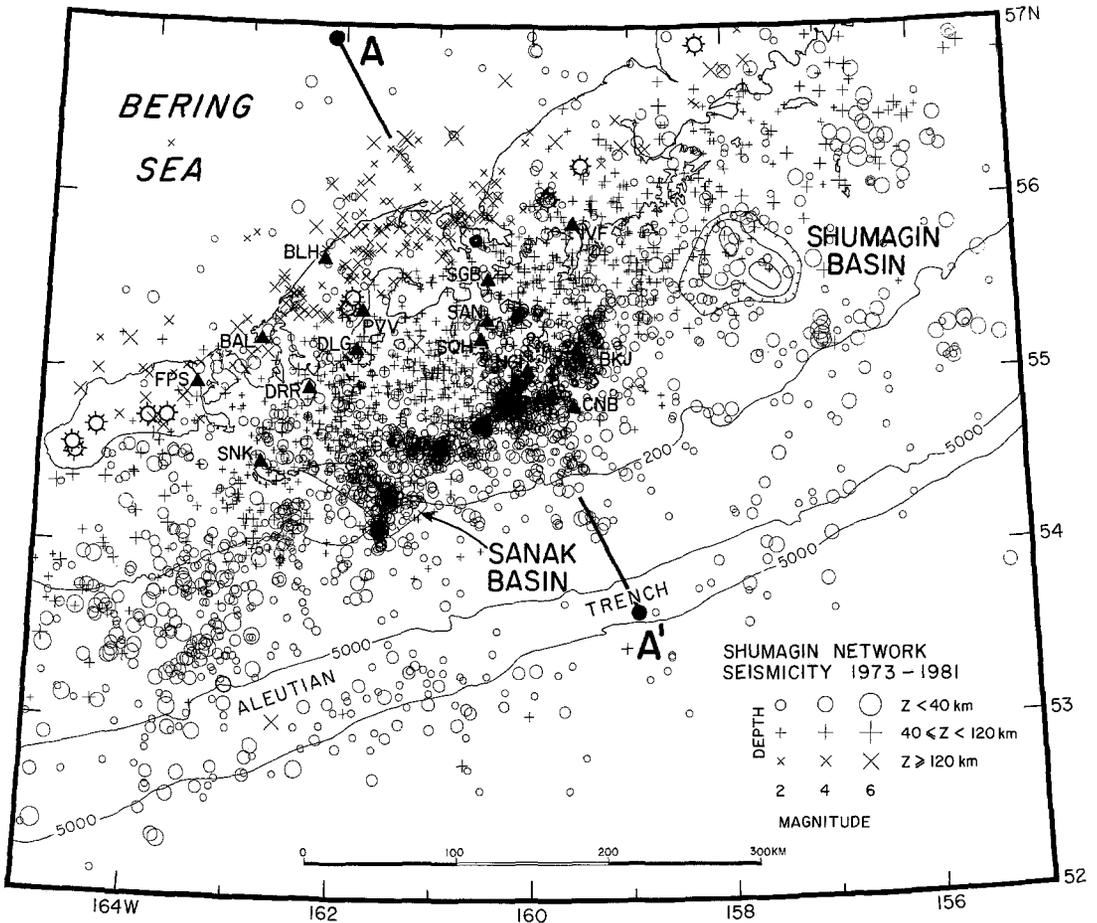


FIG. 3. Map of epicenters showing all the seismicity located by the Shumagin network, eastern Aleutians, Alaska, from 1973 to 1981. The symbol type indicates depth, and symbol size is proportional to magnitude. The filled triangles are high-gain, short-period seismic stations; stations SAN, SQH, NGL, BKJ, and CNB are located in the Shumagin Islands. The marked circles on the Alaska Peninsula indicate the location of active volcanoes.

epicentral and depth uncertainties are less than 8 km. These hypocenters clearly define a dipping slab with a double-planned Benioff zone.

The down-dip end of the main thrust zone and the overlying section of the overriding plate are by far the most seismically active parts of the plate boundary. Below 40 to 50 km depths, a double Benioff zone is formed by two somewhat overlapping bands of activity where the upper band is more active than the lower band. Around 120 km depth, the seismic activity decreases and the dip of the

Benioff zone steepens. The decrease in seismic activity may be related to a change in the character of the seismicity as well as to the decreasing detection capability of the network at distances greater than 250–300 km. The increase in the dip of the Benioff zone appears to be an artifact of the flat-layered velocity structure used in determining hypocenters which does not take into account the higher velocity structure of the downgoing slab, (Hauksson, 1984).

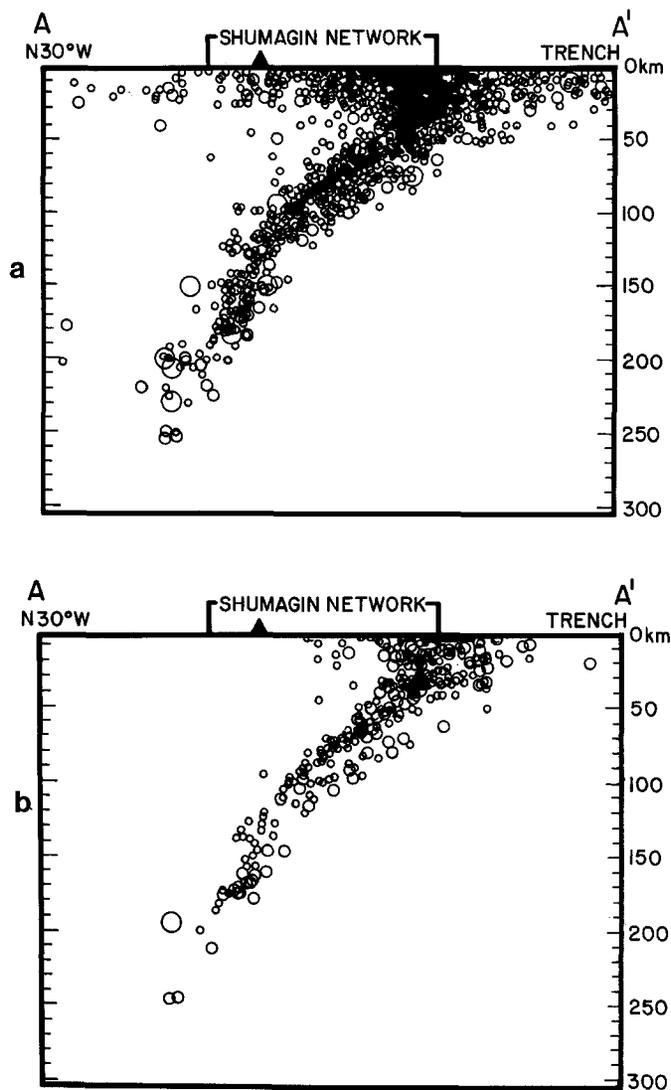


FIG. 4. (a) A depth cross section along line A-A' in Figure 3. All the hypocenters recorded from 1973 to 1981 by the Shumagin network are shown. The symbol size is keyed to magnitude. (b) The depth cross section as above except only high-quality hypocenters are plotted.

Temporal patterns. The z test for statistical significance of changes in the seismicity rate (Habermann, 1983) was applied to search for possible variations in the rate of seismicity recorded by the Shumagin network from 1978 to 1983. The seismicity rate in 1978–1979 was 100 per cent higher than the rate in 1980 to 1981 for earthquakes of magnitude 2.5 or greater. This rate difference is significant at the 99 per cent confidence level (Figure 5). The 1978–1979 rate is considered to be

the anomalous one since average counts of earthquakes recorded by the network prior to 1978 suggest a lower seismicity rate similar to that observed from 1980 to the present. The z test actually detected only the return to the lower rate in late 1979.

Focal mechanisms. Seven different composite focal mechanisms were determined for the events which occurred during 1981 (Figure 6). An epicentral map and depth section are shown in Figure 7. The symbols A through G are keyed to the regions

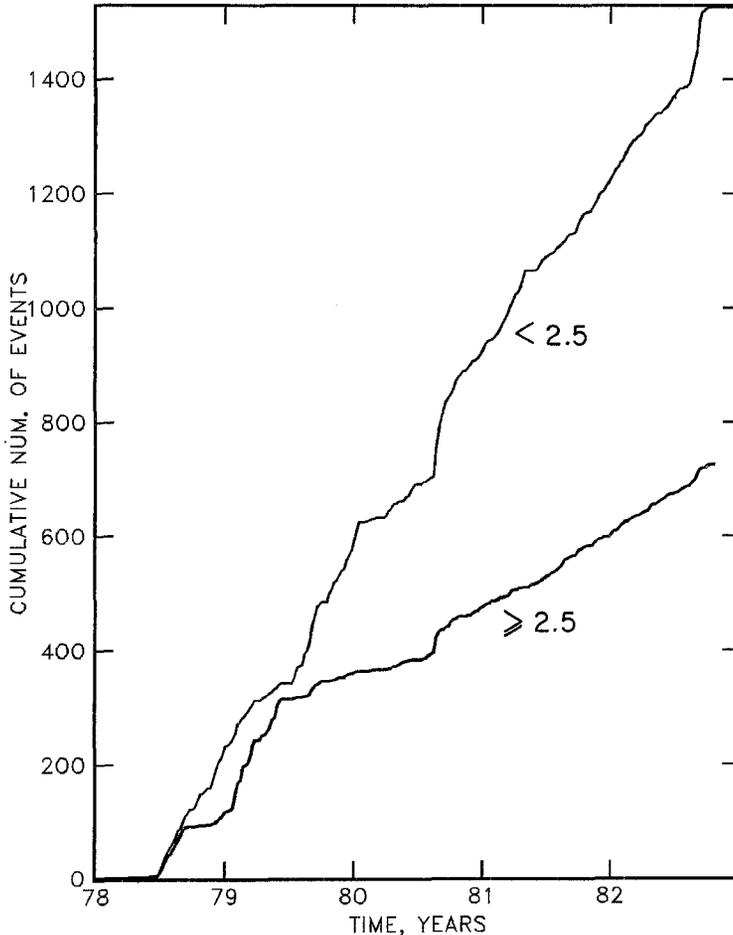


FIG. 5. Cumulative number of earthquakes recorded by the Shumagin network from 1978–1982. Techniques and computer programs developed by Habermann (1983) are used to show that for earthquakes of $M \geq 2.5$, there was a significantly higher rate of seismicity in 1978–1979 than there was in 1980–1981.

shown in cross section, where the depth range of each group is outlined. The upper hemisphere projections of these focal mechanisms and all possible B , P , and T axes that have been determined using the method of Guinn and Long (1977) are also shown in Figure 6. The mechanism in the A region, which is located at the down-dip end of the main thrust zone, indicates low-angle thrusting. Some other mechanisms that were also identified in this hypocentral region suggest complex patterns of subhorizontal thrusting. In the overriding plate, the mechanism in the B region shows a combination of strike-slip and thrust faulting although the small number

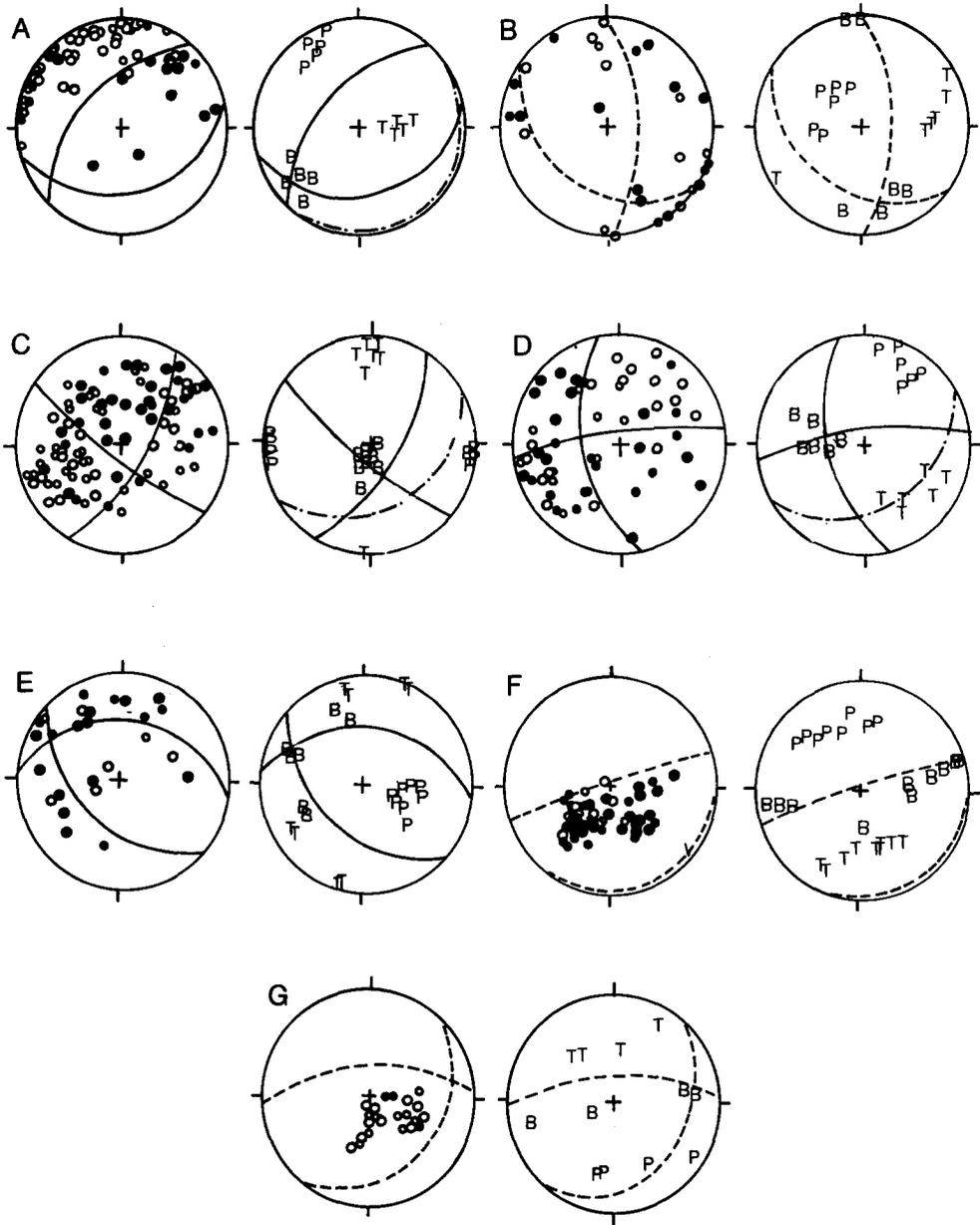


FIG. 6. Composite focal mechanisms determined for selected high-quality microearthquakes that occurred in 1981 (see also map and depth section in Figure 7). Upper hemisphere focal mechanisms A to G correspond to regions A to G in the depth section in Figure 7. Open symbols represent dilatational and solid symbols represent compressional P -wave first motions. Small symbols indicate less reliable readings. Next to each focal mechanism, a stereogram of all possible P and T axes is shown, which is determined using the approach of Guinn and Long (1977). Dashed curves indicate the approximate dip of the Benioff zone where the respective group of microearthquakes is occurring.

of available first motions makes the determination of nodal planes highly uncertain. The mechanisms in the C and D regions, which constitute the upper and lower planes of the Benioff zone between 40 and 120 km depth, are consistent with lateral, along-strike compression and down-dip tension, respectively, within the downgoing slab. The lateral, spatial distribution of the earthquakes along strike of the arc in

the C and D regions during 1981 is similar to what was observed during 1979 (see also Figure 2 in Reyners and Coles, 1982). The mechanism in the E region indicates complex stress patterns with overall-in-plate compression in the lower plane of the Benioff zone at depths between 60 to 80 km. The mechanisms of earthquakes located below depths of 120 to 140 km (F and G) can be separated into two groups of down-dip tension and down-dip compression, respectively.

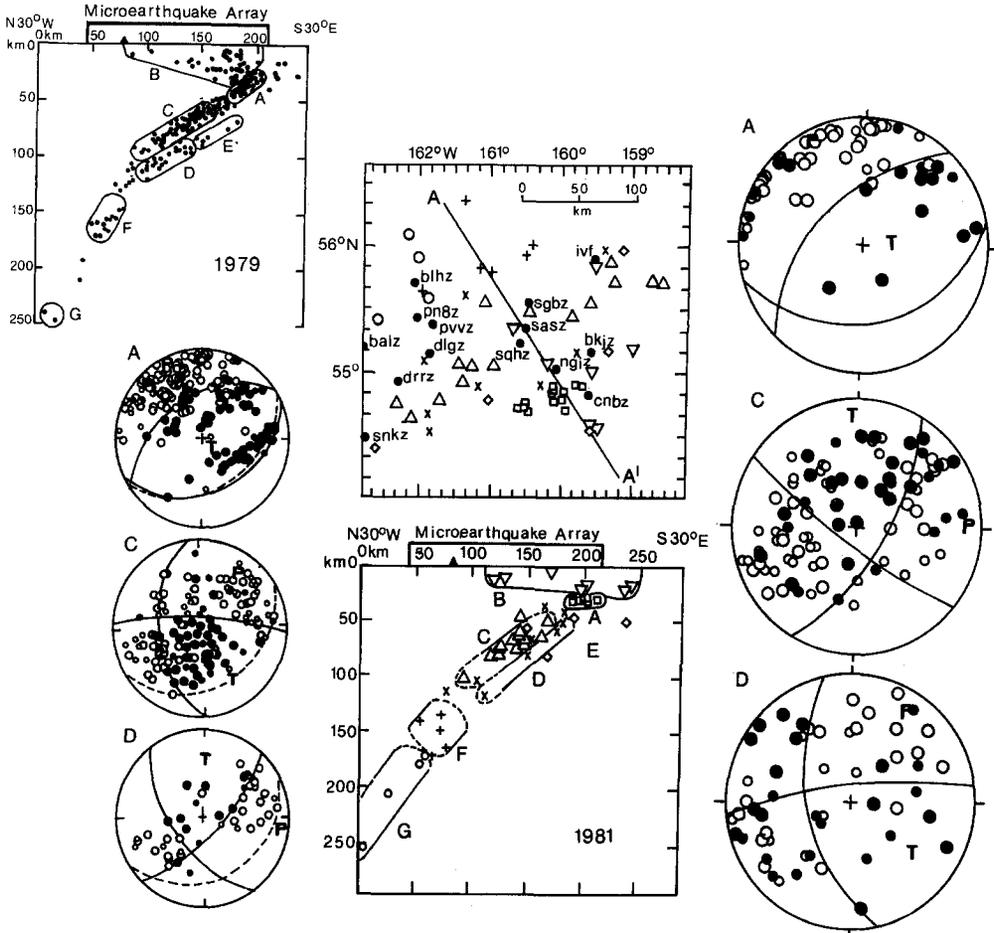


FIG. 7. (Left) Composite (upper-hemisphere) focal mechanisms constructed by Reyners and Coles (1982) from the 1978-1979 data recorded by the Shumagin network. (Right) Composite focal mechanisms from Figure 6 are shown for comparison. In depth section, regions A to D correspond to the mechanisms labeled A to D. In the epicentral map, the symbols correspond to the regions labeled in the cross section shown below. The A region has the same mechanism in both 1979 and 1981 although the shape of the hypocentral zone in cross section differs. In 1981, the C region, which showed down-dip tension in 1979, shows in-plate compression with the intermediate stress axis pointing approximately down-dip and the maximum stress axis pointing subparallel to the strike of the arc. The D region shows a similar stress reversal between 1979 and 1981. In 1979, the D region showed in-plate compression but in 1981 it shows down-dip tension.

Several significant differences were found between the 1978-1979 and 1981 data sets (Figure 7). First, the C region, which showed down-dip tension in 1979, shows in 1981 in-plate compression with the intermediate stress axis pointing approximately down-dip and the maximum stress axis pointing (in a horizontal plane) subparallel to the strike of the arc and descending plate. Second, the D region shows a complementary stress reversal between 1979 and 1981. In 1979, the D region

showed in-plate compression but in 1981 it shows down-dip tension, where in both cases the maximum stress axis is pointing subparallel to the strike of the arc. For both the upper and lower plane of the Benioff zone, the slab appears to be acting as a stress guide with lateral along strike compression possibly caused by its northward concave curvature. Third, the cluster of activity that defines the A mechanism has only half as many events in 1981 as were observed in 1978–1979. The 1981 hypocentral distribution also suggests a somewhat shallower dip to the zone of seismicity than was found previously. The mechanisms of earthquakes below depths of 120 to 140 km did not change between 1978 and 1981.

INTERPRETATION OF SEISMICITY PATTERNS

The seismicity in the Shumagin region is characterized by distinctive regions or volume of persistently high activity and regions of relative seismic quiescence. These regions of high activity appear to be more sensitive to changes in stress or strain along small segments of the plate boundary. For instance, the burst in microearthquake activity in 1978–1979 and the change in stress orientations reflected by the variations in the composite focal mechanisms appear to occur mainly within these regions of high activity and not in the regions of relative quiescence. Hence, the seismicity patterns in the Shumagin region may be controlled by high stress asperities (House and Boatwright, 1980); or small-scale (<100 km) spatial and/or temporal variations in the state of stress along the plate boundary. Whether these patterns and their changes are related to precursors of a great earthquake is as yet unclear.

Spatial patterns. Since double bands of seismicity or doughnut patterns are observed beneath other segments of the Aleutian arc (such as in the Adak region; S. Billington, personal communication, 1983) where the main thrust zone has ruptured within the last 30 yr, this spatial pattern may only indicate that the latest period of aftershock activity in the respective thrust zone has come to an end and the plate boundary is coupled again. This interpretation is in agreement with the findings of Davies *et al.* (1981) who showed that the doughnut pattern in the Shumagin region may have existed since 1945. The doughnut pattern in the Shumagin region is thus a persistent feature that is not as easily perturbed as, e.g., the level of and the focal mechanisms associated with microearthquake activity. Therefore, the doughnut pattern itself does not appear to be a particularly strong indicator of where within the late stages of the earthquake cycle the Shumagin gap is.

Apart from the possible precursors to a great earthquake, the spatial pattern of seismicity indicates that the 40- to 80-km-wide rim of activity surrounding the main thrust zone is more likely to experience a moderate sized earthquake ($M_S \leq 7$) than the thrust zone itself or the Aleutian shelf north of the aseismic front. The moderate-size earthquakes that can be considered as random sources in a seismic hazard analysis, contribute to a short-term seismic hazard on the eastern Aleutian shelf. The longer term hazard is however dominated by the forecast great earthquake in the Shumagin gap, and its potential for damage can be expected to be orders of magnitude greater than that of the moderate size earthquakes (Davies *et al.*, 1981). 1981).

Temporal patterns. A period of seismic quiescence lasting from 3 to 8 yr has been proposed as a precursor to many large or great earthquakes (Mogi, 1969; Habermann, 1981; Kanamori, 1981; Fedotov *et al.*, 1982; Wyss *et al.*, 1983). In the Shumagin region, however, the low rate of occurrence of moderate earthquakes in the last 20 yr makes it difficult to evaluate in a statistically significant way whether the rate

of activity is changing with time. It is not possible to tell at the 99 per cent confidence level whether the current level of activity is unusually high or low as compared to the seismicity rate since 1966 (see Figure 2). At the 95 per cent confidence level, however, a decrease in the seismicity rate may have occurred in late 1979 for earthquakes of $m_b \geq 5.5$ (see Figure 8). At the present stage, where only 34 earthquakes of magnitude greater than 5.5 are available, it is not possible to evaluate whether this pattern constitutes an initiation of seismic quiescence in the Shumagin gap or a random variation in the background activity.

Episodic subduction at depth. Leveling data (Beavan *et al.*, 1983a), the increase in seismicity rate and changes in focal mechanisms (this study) all indicate that

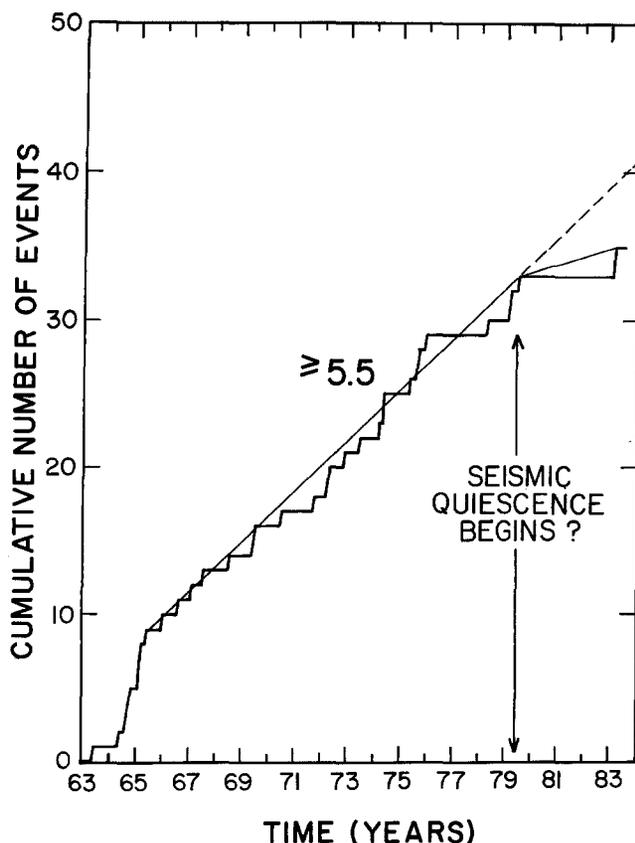


FIG. 8. Cumulative number of NOAA or PDE epicenters in the Shumagin region for earthquakes of $m_b \geq 5.5$. Beginning in late 1979, the rate of occurrence of $m_b \geq 5.5$ earthquakes is significantly lower at the 95 per cent confidence level.

significant changes in strain may have occurred during 1978 and 1979 within the Shumagin gap. Beavan *et al.* (1983a,b) interpret the leveling data in terms of a slip event on the interface between the descending slab and overlying mantle at depths between 20 and 70 km below the Shumagin Islands. The slip event is modeled as a buried dislocation dipping at 30° in an elastic half space with approximately 80 cm displacement.

During 1978–1979, the seismicity rate recorded by the Shumagin network was significantly higher than that from 1980 to 1983. The teleseismic data, however, do not show an increase in the occurrence of moderate earthquakes in the Shumagin region. Hence, the slip event at depth is considered to be essentially aseismic and

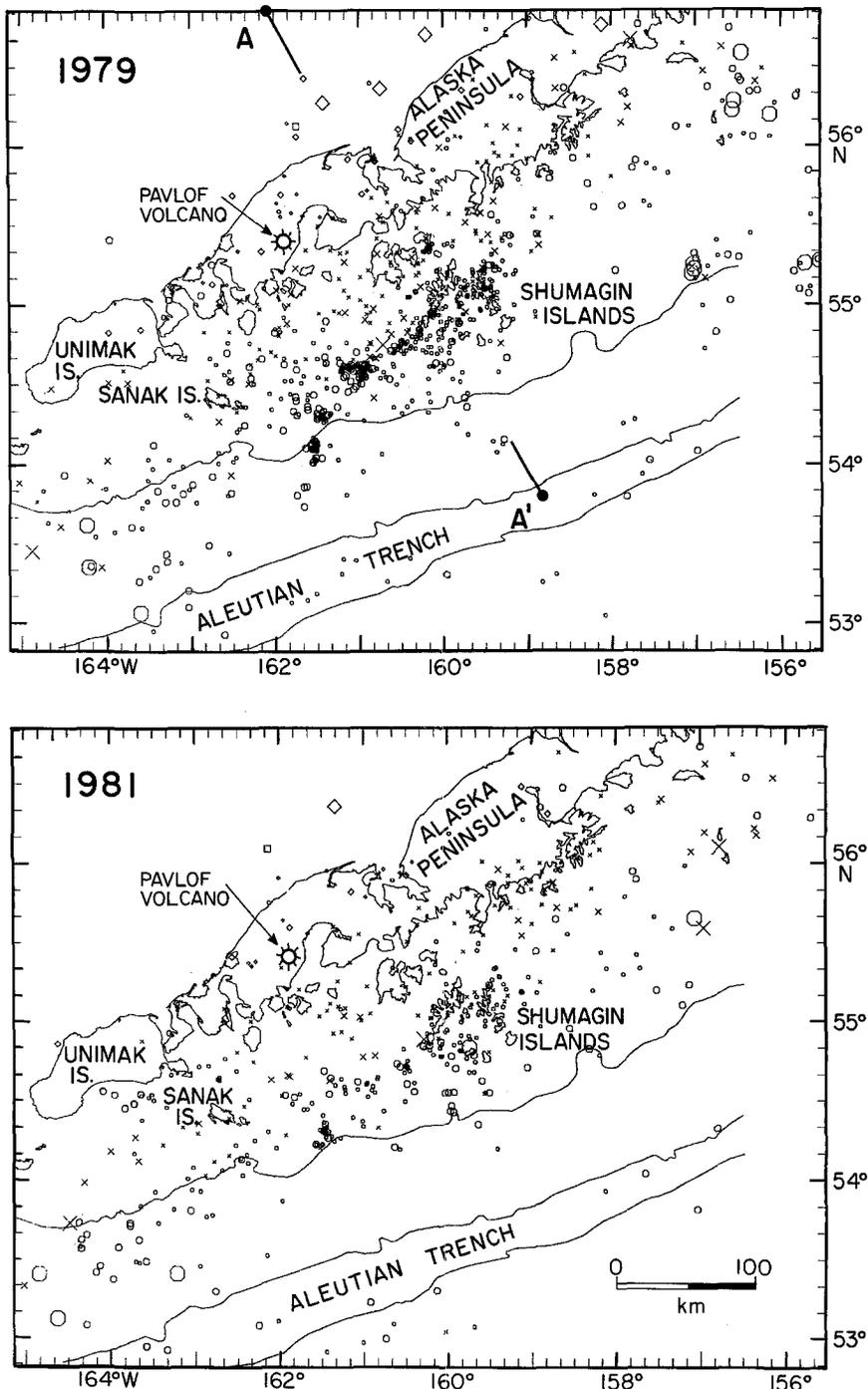


FIG. 9. (Top) Seismicity recorded by the Shumagin network in 1979. (Bottom) Seismicity recorded by the Shumagin network in 1981. Note the preferential clustering in 1979 versus 1981. The symbol size is keyed to magnitude (see Figure 3), and the symbol type is keyed to depth: circle (0 to 40 km); X's (40 to 120 km); diamonds (120 to 250 km); squares (250 to 350 km).

the observed increase in microearthquake activity is interpreted to be a secondary result of the slip event. The observed increase in microseismicity near the down-dip end of the main thrust zone, for instance, can be interpreted to result from a stress concentration around the upper edge of the inferred dislocation. In Figure 9,

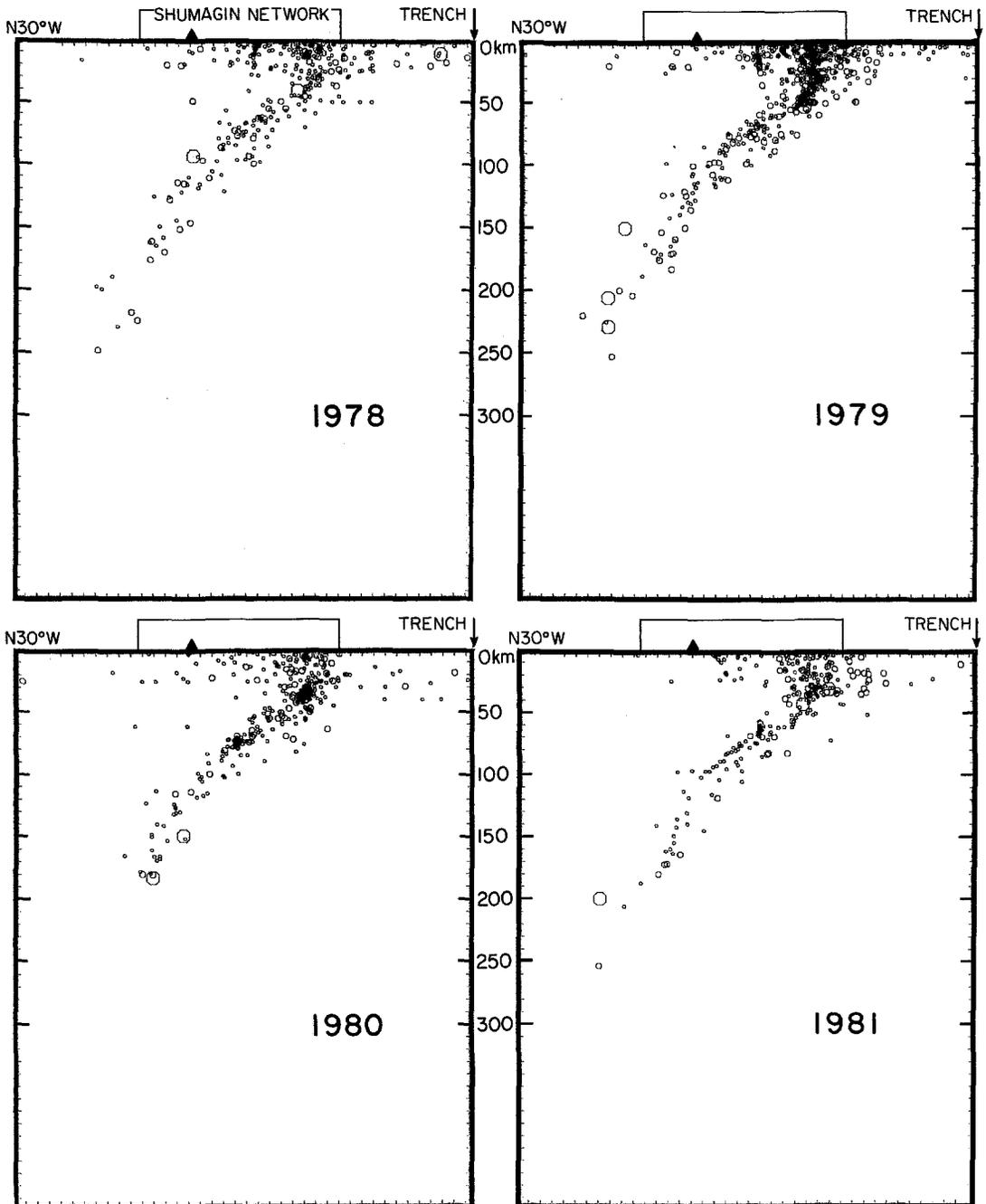


FIG. 10. Depth sections taken along the profile A-A' (see Figure 8) for all the seismicity recorded in 1978, 1979, 1980, and 1981. Note the spatial clustering of hypocenters in 1979 compared to 1981. The symbol size is keyed to magnitude (see also Figure 3).

the epicentral maps of the 1979 and 1981 seismicity illustrate the clustering of seismicity that was observed in 1979 but was absent in 1981. A narrow band of clusters of earthquakes at a depth of 40 ± 10 km extends approximately 100 km along strike subparallel to the down-dip end of the main thrust zone. Similarly, the 1978, 1979, 1980, and 1981 depth sections of hypocentral distributions indicate

stronger clustering in 1979 than is observed during previous and the two subsequent years (Figure 10). In particular, during 1979 both the upper and lower planes of the Benioff zone are well defined by the hypocentral distribution. Further, the shallow seismic activity (depth less than 20 km) indicates stronger clustering and higher levels of activity in 1978–1979 than was observed in 1980–1981.

The proposed slip event in 1978–1979 indicates that fluctuations in the rate of subduction of the slab below the main thrust zone may in part influence the state of stress just below the main thrust zone, down to depths of at least 100 km. These fluctuations in the state of stress are manifested through changes in the rate of microearthquake activity and complex temporal patterns in the composite focal mechanisms. The changes in the rate of microseismicity appear not only within the Benioff zone, but also within the overriding plate as it responds to stress changes near the plate interface.

The interpretation of the changes in focal mechanisms (see Figure 7) in terms of a slip event presumes that these composite mechanisms are truly representative of the state of stress within the descending slab and at the plate interface. Alternatively, these temporal and spatial fluctuations in composite focal mechanisms of microearthquakes may reflect local stress perturbations around spatially restricted asperities or inhomogeneities in the descending plate. In this case, the state of stress is probably better represented by focal mechanisms of moderate-size or large earthquakes ($m_b \geq 5.5$) that relieve stresses over spatially large regions at or near the plate boundary.

During the slip event in 1978–1979, the main thrust zone (where a future great Shumagin earthquake is expected) may have experienced increased loading stress since it probably remained the only locked portion of the plate boundary. This conclusion, however, is based solely on geodetic data observed at the surface, because the main thrust zone is at present almost aseismic, and there are no other stress indicators available.

DISCUSSION

No obvious changes in the rate of teleseismically recorded earthquakes that have occurred in the Shumagin gap during the last 20 yr can be identified. A slip event at depth in 1978–1979 inferred from surface geodetic data is associated with a temporary increase in the microseismicity but is not associated with spectacular changes in the overall long-term trend of the spatial and temporal patterns of teleseismically recorded seismicity. The occurrence of earthquakes of magnitude greater than or equal to 5.5 is lower by 1 or 2 earthquakes per year since late 1979, but the low level of background activity above magnitude 5.5 makes it difficult to evaluate the statistical and physical significance of this observation.

Seismicity patterns in and near seismic gaps are thought to contain important information about the state of stress along the plate boundary, which, in turn, influences the time of occurrence of the coming great earthquake (e.g., Mogi, 1981; Kanamori, 1981; Fedotov *et al.*, 1982). Case histories of forerunning activity in similar tectonic settings such as along the Central American trench, however, indicate that the forerunning activity varies between locations and perhaps from one large earthquake to the next in the same location (Tajima and McNally, 1983). Hence, experiences about precursory activity gained in different seismic gaps need to be thoroughly evaluated before they are transferred from one region to another.

Enhanced basic understanding of the tectonics and of the spatial and temporal changes in the local seismicity patterns may provide a better background to identify

anomalous precursory activity in the Shumagin gap than case histories from other seismic gaps. For instance, the inferred slip event in the 1978–1979 provides basic understanding of the relationship between subduction at depth and changes in the rate of shallow seismicity. In earlier studies, the shallow seismicity was thought to be mainly controlled by strong lateral coupling between the two converging plates (Reyners and Coles, 1982). During the slip event in 1978–1979, when the slab below the main thrust zone is being subducted at an accelerated rate, the changes in seismicity and focal mechanisms expose areas that are sensitive strain indicators. One of these regions is the down-dip end of the main thrust zone where the forthcoming great earthquake may nucleate (Davies *et al.*, 1981). Temporal and spatial variations of seismicity patterns and focal mechanisms have also been reported by Seno and Pongsawat (1981) and Kawakatsu and Seno (1983). They studied regional changes in the seismicity along northern Honshu, Japan, and suggested that plate coupling and the temporal proximity of the next great earthquake strongly influence the state of stress along the plate boundary. Therefore, continued seismic monitoring that is sensitive to the microearthquake level, in conjunction with geodetic observations, are essential for detection of possible forerunners to a future great earthquake in the Shumagins.

CONCLUSIONS

Analysis of the spatial and temporal seismicity patterns in the Shumagin seismic gap using data from the Shumagin seismic network and the NOAA hypocenter catalogue, lead to the following results.

1. A doughnut pattern made up of moderate-size earthquakes has persisted during at least the last 20 yr in and surrounding the Shumagin seismic gap. This pattern of seismicity may reflect strong coupling along the elastic-brittle part of the plate boundary where great earthquakes occur. Further, this pattern of seismicity appears to be relatively insensitive to local fluctuations in the state of stress at depth beneath the elastic-brittle part of the plate boundary. Hence, it is possible that any precursory seismicity preceding a great earthquake will not replace the existing pattern but instead will be superimposed on the fairly stationary doughnut pattern.
2. The rate of microearthquake activity within the down-dip end of the main thrust zone and the nearby region of the overriding plate is sensitive to small changes in strain along the plate boundary as was observed during 1978–1979. Hence, this region should be both seismically and geodetically monitored carefully to catch possible seismic or strain precursors to a forthcoming great earthquake in the Shumagin seismic gap.
3. The reported changes in focal mechanisms of earthquakes located in the subducting slab below 40 to 60 km depth indicate that microearthquake activity is an indicator of local stress changes that can be either spatially or temporally dependent, and may be related to episodic subduction at depth beneath the locked plate contact.

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LAMONT-DOHERTY GEOLOGICAL OBSERVATORY OF COLUMBIA UNIVERSITY
PALISADES, NEW YORK 10964
CONTRIBUTION No. 3716

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