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A Comprehensive Study of the Seismotectonics of the
Eastern Aleutian Arc and Associated Volcanic Systems

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ABSTRACT

Based on the historic seismic record and accurate hypocenter data obtained from the eastern Aleutian seismic network, a relationship between the subduction-zone seismicity, volcano-trench separation, and the occurrence of great thrust earthquakes has been established for the Aleutian arc. Based on strong-motion accelerometer data we found that high stress drops (540 to 650 bars) were associated with two moderate-size earthquakes ($m_b = 6.0$ and 5.8) within the Shumagin Islands seismic gap. This indicates that near the down-dip end of the major thrust zone, at depths of about 40 km, high tectonic stresses have accumulated within the gap segment of the arc. That such accumulation of stress is presently an ongoing process is corroborated by results from geodetic precision leveling on Unga Island. The leveling data indicate tilt rates of about 1 microradian/year. The tilting is directed down towards the trench and up towards the volcanic arc. Whether the recent activity of Pavlof, Shishaldin and Westdahl volcanoes indicates transmission of high tectonic stresses from the major thrust zone to the volcanic arc is unresolved. The search for a shallow magma chamber beneath the seismically monitored Pavlof volcano is still inconclusive although large amounts of recently acquired data remain to be analyzed. A geologic reconnaissance of the Shumagin Islands and the adjacent Alaska Peninsula revealed Quaternary uplifted marine terraces and evidence for Holocene faulting. Both findings have severe implications for long-term tectonic activity and seismic hazards in the region of this seismic gap, portions of which are presently considered for off-shore hydrocarbon exploration and development (i.e. in the Shumagin and Sanak Basins).

A critical analysis of the presently operating seismic data acquisition system reveals that a major change in remote sensing and central recording equipment is urgently needed for the Pavlof, Cold Bay, and Shumagin sections of the seismic array.

INTRODUCTION

This progress report summarizes the seismotectonic research and related technical field work carried out in the eastern Aleutian arc by Lamont-Doherty Geological Observatory personnel during the first three quarters of the contract year March 1, 1978 through February 28, 1979, and briefly comments on the work in progress and to be carried out during the remaining quarter of this period.

The scope of this study is to contribute to a broad and detailed understanding of the basic tectonic processes of an active subduction zone and its associated volcanic systems. Primarily, we achieve this by collecting and using mostly seismologic data from a variety of seismic stations, or network of stations operated in the eastern Aleutian arc; in addition we collect and analyse original data from a geodetic levelling program and a network of mean sea-level meters; geologic field information was also collected for the first time during the reporting period and is used in the crustal deformation study.

The DOE-supported basic research of the seismotectonic and volcano-geothermal processes of the eastern Aleutians has in the past year benefitted substantially from heavy logistic (helicopter) and some funding support by a closely coordinated study of the seismic and volcanic hazards to exploration and development of hydrocarbon resources in the outer continental shelves of the study area. This support is provided by NOAA under the Alaska/OCSEAP program. Maintenance of the remote stations of the seismic network and of sea-level-meters would have been impossible without this valuable support, and both studies rely in their respective research results on the same data base.

We have made a modest but sound progress in analyzing and interpreting the seismicity and seismic information, both from the telemetered seismic network and from strong-motion accelerometers. The volcano-geothermal study is in a transition from

pure data-collection and qualitative data-screening to quantitative in-depth analysis. The crustal deformation study - by necessity long-term in nature - shows the steadily increasing reliability of results indicating a systematic preseismic tilt in the arc-trench region. These data are most promising and have in our opinion great importance. The most unsatisfactory situation pertains to the type and age of some of the original equipment (given on loan from the USGS to the project) which is still used in the seismic network. Since two separate requests (one to DOE, one to the USGS) for replacing some of the most out-dated and highly unreliable central recording-equipment did not result in funding for the needed equipment we are facing now a serious situation. A very high probability exists that we loose our major data base for this study for increasingly long periods of time, despite our very time-consuming efforts to maintain the existing equipment in good shape. Some comments on proposed technical changes emerging from an engineering analysis of this problem are included in this report. More definite plans are being provided in the simultaneously submitted proposal for the forthcoming funding period March 1979 to February 1980.

The following sections describe the research results, discuss the unsolved problems encountered, and provide a brief insight in the technical and logistic field operations necessary for providing the data base for this research project.

Seismicity Studies

Our efforts in analyzing the seismicity of the study region have been three-fold: (1) We have continued to locate earthquakes using the data from the eastern Aleutian network, and in the interpretation of this seismicity we focussed on the shallow crustal seismicity in the arc-trench gap at depths from 0 to 25 km, above the major thrust zone; (2) A paper (Davies and House, JGR, in press; see also Appendix I) has been completed in which the configuration of the shallow and intermediate-depth Benioff-zone seismicity in the Shumagin Islands segment of the Aleutian arc is compared with similar configurations in the other arc-segments where good network coverage exists. The most important result of this study is the finding of a correlation between the dip of the shallow (0-40 km) major great thrust earthquakes. The results imply that the Shumagin section is likely to be capable of a great earthquake; and, (3) A global survey of the potential of seismic gaps associated with major plate boundaries has been completed, (McCann et al., in press) in which the seismic potential of the Shumagin Islands seismic gap is critically reviewed (see Appendix Ib). We present here only the recent seismicity (located within the network) and a preliminary interpretation of the shallow crustal seismic patterns (item 1). For detailed information on the comparative study (item 2) and the review of seismic gaps (item 3) we refer to Appendix I.

Seismicity of the Shumagin Islands region: While hypocenter data are analyzed in a preliminary way (first computer run) up to July 1978 we show and discuss here only the revised and finalized locations now updated to June 1977.

The epicenters of earthquakes that occurred during the period January through June 1977 are shown in Figure 1. Approximately 70 events are shown on this seismicity map. Several notable features are seen on this map: (1) The deepest event thus far recorded, 219 km deep, occurred NNE of BLH, (2) several events continue to cluster off the tip of Nagai Island (SW of NGI) in the vicinity of the aftershocks of the

April 6, 1974 Shumagin Islands earthquake sequence (see House and Boatwright, 1978), (3) only three shallow earthquakes (33 km deep or less) occurred on or north of the Alaska Peninsula, and (4) about 15 events are seen to the SW of the network, scattered generally along the 100 fathom isobath. The significance of these events will be discussed below.

In Figure 2 the events shown in Figure 1 have been added to all of the events previously recorded. One of the most obvious features is the series of three clusters of epicenters off the tip of Nagai Island (SW of NGI). As noted above, this zone was activated with the April 6, 1974 earthquakes (max. $m_b = 6.0, 5.7$) and continues to be active through June 1977. Note the SW-NE alignment of these clusters. Most of the epicenters shown in this map view are from earthquakes located in the Benioff zone, the inclined seismic zone related to the underthrusting of the Pacific plate beneath the North American (Alaska) plate.

The distribution of the earthquakes in the Benioff zone can best be seen in the hypocentral cross-sections shown in Figures 3-6. These cross-sections are vertical sections oriented transverse to the Aleutian arc. The location of the top of each of the four sections is the solid line labeled "C", as shown in Figures 1 and 2, except that the cross-sections extend 40 km to the NNW and 55 km to the SSE beyond the ends of this line. The cross-sections in Figures 3 and 5 sample a segment of the arc 140 km wide (measured parallel to the arc) and those in Figures 4 and 6 sample 70 km segments. The epicenters of the earthquakes in the 140 km wide segments are approximately located between the lines labeled "W" and "E"; those in the 70 km segments are approximately located within the dashed box labeled "C" (again, with the extensions mentioned above). Figures 3 and 4 show just those earthquakes located during January through June 1977 whereas Figures 5 and 6 show all of the events located between July 1973 and June 1977. It is clearly seen in these sections that the vast majority of the earthquakes located in the Shumagin Islands region are contained in the Benioff or inclined

zone of seismicity that results from the underthrusting of the Pacific plate beneath the Islands.

A comparison (Davies and House, 1978) of the Benioff zone beneath the Shumagin Islands region with that under other regions of the Aleutian arc and with other subduction zones suggests that the fault plane of a future great earthquake in the Shumagin Islands region will lie along the shallow portion of the Benioff zone (less than 40 km depth). This shallow portion of the Benioff zone (main thrust zone) is the interface along which stress accumulates as a result of the convergence of the lithospheric plates. This interface is not well defined by the hypocenters seen in Figure 6, e.g., but extends from the aftershock zone of the April 6, 1974 earthquakes (cluster at 40 km depth, about 100 km from the volcanic axis) to the trench. It is most likely that a great earthquake would nucleate near the deepest edge of this interface (future fault plane) and propagate obliquely along it toward the trench and along the strike of the arc. For a complete discussion of the Benioff zone seismicity and the implications for future great earthquakes in the Shumagin Islands region see Davies and House (1978).

To examine the question as to whether any of these earthquakes can be associated with faults other than the main thrust zone, we have plotted in Figure 7 the epicenters of all of the earthquakes whose depths are less than or equal to 25 km (for the period July 1973 through June 1977). A similar plot was included in last year's annual report. That plot showed so few epicenters that little could be learned from it. The data in Figure 7 are still sparse but we can begin to see some patterns developing.

One of the most striking features of the shallow seismicity shown in Figure 7 is how few epicenters have been located NW of a line extending from the south side of Sanak Island through Kupreanof Point. Most of seismicity is contained between this line and the 100 fathom isobath. Referring to Figure 7, it can be seen that most of these events occur in a diffuse zone sloping from the April 6, 1974 after-

shock zone toward the surface, "outcropping" along a line approximately subparallel to the volcanic axis and 70 km from it. This is suggestive (Mogi, 1969; Kelleher et al., 1974; Davies and House, 1978; House and Boatwright, 1978) that these events are occurring along zones of pre-existing weakness in a region of relatively high stress in the overthrusting plate. This zone of high stress appears to emanate from the lower edge of the main thrust zone and may be an edge effect of a future fault plane.

Two other features are notable in Figure 7: (1) the lack of activity in the region where the labels "BKJ" and "CNB" appear and the concentration of events in two linear zones along the North and West sides of this region, and (2) the somewhat diffuse cluster of events to the west of Sanak Islands. These features may have tectonic significance and are therefore plotted along with the seismicity limit discussed above on a partial reconstruction of Burk's (1965) tectonic map for the Shumagin Islands region (Figure 8). It should be cautioned, however, that the seismicity map in Figure 7 must be regarded as preliminary because of the relatively few events so far available and because many of these events have been located with only a subset of the seismic stations shown in the figure. The region within which the most reliable locations are possible is outlined by the dashed line shown in Figure 7; reflecting the fact that the original network was installed in this area (within the triangle formed by the stations PVV, IVF and CNB) and that therefore most of the locations are based on data from these stations. With this caution in mind we can proceed to a tentative tectonic interpretation of the shallow seismicity map as illustrated in Figure 8.

The seismicity limit discussed above has been plotted as a dotted line extending from the south side of Sanak Island to Kupreanof Point. This limit is generally subparallel to the trend of the recent volcanic centers (open circles with radial tic-marks), and many of the structural features along the Alaska Peninsula (faults, fold axes, and lithologic contacts). The seismicity limit is also essentially perpendicular to the direction of relative plate motion (open arrow). These geometric relationships are all consistent with the "high stress region"

interpretation given above in that one would expect this region to be subparallel to the general trend of the volcanic arc and perpendicular to the direction of plate motion.

A slight modification of this interpretation might take into account the small change in trend of the structural features in the vicinity of Pavlof Volcano (PVV). Note that these structural trends, which are oblique to the general trend of the arc, are subparallel to the "reef line" (approximately the 35 m isobath NW of Sanak Island), a prominent submarine topographic feature. Within the error limits of the seismicity data it would certainly be possible for the seismicity limit to be subparallel to the reef line between Sanak and Nagai Islands. We also note that the clusters of epicenters associated with the April 6, 1974 aftershock zone follow the same trend. These slightly oblique trends may suggest that the Pacific plate is segmented and that it has a slightly different plunge direction here than in adjacent regions of the Aleutian arc. If this segmentation exists it would have important implications for seismic hazards evaluations because it would imply major zones of weakness and stress concentration perpendicular to the trend of the arc.

The second seismicity limit plotted in Figure 8 is the L-shaped dotted line through Big Koniujiki Island. This limit marks a region of no seismicity to the south and east which has linear concentrations of seismicity along the northern and western sides as shown by the dotted lines. The coincidence of the western limit with a similarly trending, linear intrusive/sediment contact on Big Koniujiki Island suggests that the region of no seismicity may be related to the boundaries of the intrusive body here. It is noted, however, that intrusives on nearby Nagai and Bird (just west of CNB) Islands may be part of the same intrusive body as outcrops on Big Koniujiki Island. In any case, the concentrations of activity along these lines indicates that active faulting may be present here and suggests

that these lines would be good targets for detailed marine seismic refraction and/or ocean bottom seismograph study.

The diffuse cluster of epicenters near Sanak Island appears to be related to the boundary faults of the graben-like Sanak Basin (Bruns and vonHuene, 1977). We have replotted these boundary faults and the structural contours of this basin following Bruns and vonHuene (1977). Also plotted are the epicenters from Figure 2. A remarkable coincidence exists between these faults and the epicenters suggesting that this basin is tectonically active at present. Once again we caution that the location of these events is not well determined (especially the depth) so that this result must be regarded as preliminary. The coincidence is strong enough to suggest an intensive study of this area. As Bruns and vonHuene note, the trend of this unusual basin is along strike of the Bering Sea Shelf edge which was a plate boundary in Mesozoic time and lies on the boundary of several aftershock zones of large earthquakes. It is also perpendicular to the reef line and the other oblique structural trends discussed above and as such may be tectonically related to the possible segmentation mentioned earlier. Therefore, both from a tectonic and a seismic hazards point of view, this basin deserves further study.

Figure 2. Shumagin Islands region seismicity, July 1973-June 1977. Epicenters for all earthquakes located during July 1973 through December 1976 (good quality) plus those shown in Figure 1 are shown by numerals that give the depth (km) to the hypocenter. Seismic station locations are shown by the solid squares. The dashed box labeled "C" shows the surface projection of the volume from which hypocenters were taken to plot the hypocentral cross-section shown in Figure 6. The cross-section in Figure 5 has the same center line but twice the width (140 km) as that in Figure 6 (70 km). Bathymetric contours are given in fathoms.

Figure 3. Hypocentral cross-section of Shumagin Island earthquakes for January through June 1977. Cross-section width (parallel to the volcanic arc) is 140 km. See Figure 1 for location. Distance perpendicular to the axis of the volcanic arc and depth are given in km with no vertical exaggeration.

Figure 4. Hypocentral cross-section of Shumagin Islands earthquakes for January through June 1977. Cross-section width (parallel to the volcanic arc) is 70 km. See Figure 1 for location. Distance perpendicular to the axis of the volcanic arc and depth are given in km with no vertical exaggeration.

Figure 5. Hypocentral cross-section of Shumagin Islands earthquakes for July 1973 through June 1977. Cross-section width (parallel to the volcanic axis) is 140 km. See Figure 2 for location. Distance perpendicular to the axis of the volcanic arc and depth are given in km with no vertical exaggeration.

Figure 7. Shallow (depth of 25 km or less) seismicity for the Shumagin Islands region, July 1973 through June 1977. Epicenters are shown by solid circles. Seismic station locations are shown by solid squares (adjoined by their 3-letter designator codes). Volcanic centers are shown by open circles with radial tic-marks. The triangular region enclosed by the dashed line is the region within which hypocenters could be located most reliably; taking into consideration the operational status of the seismic stations during this period. Bathymetric contours are given in fathoms.

Figure 8. Abbreviated tectonic map of the Shumagin Islands region (after Burk, 1965). Selected tectonic features taken from Burk (1965) include: generalized lithologic contacts, heavy dashed lines; fold axes, heavy solid lines with transverse arrows; faults, heavy solid lines with the up- and down-thrown sides labeled "U" and "D", respectively; recent volcanic centers, open circles with radial tic-marks; Tertiary intrusives, hatched areas; and a linear intrusive/sediment contact on Big Koniui Island, heavy solid line. Some features of the Sanak Basin taken from Bruns and vonHuene (1977) are shown just east of Sanak Island: faults, heavy solid lines (some of these were queried in the original figure); and structural contours, light lines labeled with depth in km. Selected epicenters from Figure 8 are shown by the solid circles. Other features shown are: the "reef line" (approximately the 35 m isobath from US C & GS Chart 8802), which is the generalized limit of the Sandman and other reefs in the vicinity of Sanak Island, dot-dashed lines; two seismicity limits based on the epicenters shown in Figure 8, dotted lines; the local direction of the relative motion between the Pacific and North American (Alaska) plates (Jacob *et al.*, 1977 and Minster *et al.*, 1977), shown by an open arrow; and selected seismic stations labeled with their 3-letter designator codes, solid squares.

SEISMICITY OF THE SE BERING SEA

To monitor the seismicity of the SE Bering Sea we have operated a single short-period vertical seismometer on St. Paul Island, one of the Pribilof Islands. This seismometer is recorded on a helicorder located in the National Weather Service observatory there. Continuous records exist from 1 April 1977 through 22 March 1978, about 11 2/3 months.

These records have been carefully scanned for earthquake signatures. The date, time, period and S-P interval for all earthquakes and possible earthquakes recorded at St. Paul for the above time period are simply kept in listed format.

The record from a single seismometer is not sufficient data with which to locate an earthquake. We can, however, obtain an estimate of the distance between the epicenter and the seismometer from the S-P interval (the time difference between the arrival of the P-wave and the S-wave). We have done this for the 75 earthquakes reported during this period using the Jeffrey-Bullen Travel Time Tables (1958) and assuming a surface focus (zero depth).

Five events had S-P intervals of less than 10 seconds which corresponds to distances of less than about 90 km. These events occurred in the Pribilof Islands vicinity. Eleven events had S-P intervals between 10 and 35 seconds which corresponds to distances approximately between 90 and 310 km. These events could have occurred in the St. George basin: the distance is consistent with this possibility but, again, from the single record we cannot determine the azimuth. The occurrence of teleseismically located events in the St. George basin vicinity and no where else in the distance range 90 to 310 km from St. Paul suggests that these 11 events were located there, too. Three events had S-P intervals between 35 and 50 seconds which corresponds to distances between 310 and 460 km. These events could have occurred between the St. George basin and the Aleutian Arc. Thirty events had S-P intervals between 50 and 103 seconds which corresponds to

distances between 460 and 900 km. These events probably occurred along the Aleutian Arc between Kodiak and Amchitka Islands. Five events had S-P intervals greater than 103 seconds, corresponding to distances greater than 900 km. For 21 events, an S-phase could not be picked. Based on the dominant period of the wavetrains, these events were classified as "distant" or "teleseismic". Distant events probably occurred in the Aleutian arc. Teleseismic events probably originated beyond the Aleutian arc.

Investigation of two high stress-drop earthquakes in the Shumagin Seismic Gap, Alaska. Two moderate size ($m_b = 5.8, 6.0$) earthquakes occurred within the local network of short-period seismograph stations in the Shumagin Islands, Alaska, on April 6, 1974. They were followed by 69 aftershocks recorded over the next two weeks. Both main shocks triggered a strong motion accelerograph (SMA) located at Sand Point, 50 km NNW of their epicenters.

Location of the earthquake sequence in relation to the stations of the Shumagin Islands seismic network is shown in Figure 9. Five stations (SDP, SQH, SGB, CNB, and PVV) recorded the arrivals from the main shocks and 29 of the aftershocks. The station NGI unfortunately was not operational at the time. BKJ operated only intermittantly during this time period. P arrivals were picked to within 0.05 sec accuracy for all the 31 events studied. Making consistently reliable S-picks proved to be impossible except at SDP, where an E-W short period component was operated. Computed one standard horizontal errors for the best (A) quality locations were approximately 1 km (vertical slightly larger), errors for the B- and C-quality locations were about 2 and 3 km, respectively. Figures 10a and 10b show the earthquake locations in cross sections. As can be seen in Figure 10a the hypocenters define a plane with a dip of about 30° to the NW. Figure 10b is a view normal to the plane of the Benioff zone and shows that aftershock zones for the two mainshocks are adjacent, but relatively distinct. Aftershock zone dimensions (diameters) are about 3-4 km for the 0153 event and about 4-5 km for the 0356 event.

Long period data from WWSSN stations were used to determine the focal mechanism of the 0356, $m_b = 6.0$ earthquake. The mechanism is shown in Figure 11. Data for the 0153 event are fewer, but identical to those of this earthquake. P wave first motions were not sufficient to constrain either of the two nodal planes. Consequently it was important to use S wave polarizations. Also, the fact that

the S wave motion from the Sand Point SMA is nearly entirely SV provided important constraints on the mechanism. S wave polarization angles from 9 of the WWSSN stations with the large S arrivals, and from the SMA were used in an attempt to refine the mechanism determination and quantify the uncertainty in it. Focal parameters resulting from this refinement were strike of nodal plane chosen as the fault plane $254^\circ \pm 15^\circ$, dip $30^\circ \pm 5^\circ$ rake (of slip vector) $90^\circ \pm 15^\circ$. The error limits presented are one standard deviation. The tight constraint on dip was important for estimation of the source parameters.

This focal mechanism represent nearly pure thrusting. The choice of the gently NW dipping nodal plane as the fault plane is suggested by the tectonic setting of these earthquakes. Equally important, however, is the parallelism between the trend of the aftershocks as shown in Figure 10a and the NW dipping nodal plane. We therefore interpret these earthquakes as underthrusts which resulted from differential motion between lithosphere of the Pacific and North American plates.

Analysis of the Strong Motion Accelerograph (SMA) records was carried out using techniques described by Boatwright (1978 and 1979). The S wave arrivals from the SMA records were digitized, instrument-corrected, and rotated to S_v and S_h components. Since the S_h amplitudes were less than 10% of those for S_v , the subsequent analysis was restricted to the S_v component only. The free-surface corrected accelerograms are shown in Figures 12 and 13, as well as respective velocity and V^2 traces. Note the remarkable similarity of V^2 plots in pulse shapes and amplitudes for the two events. This probably indicates the events share a similar rupture geometry and velocity, since they have the same focal mechanism. The nearly equal amplitudes of the rupturing and healing phases suggest either down-dip propagation of rupture (towards the Sand Point SMA) or a slow rupture velocity, approximating 0.6 shear wave velocity, if the rupture was circular. The V^2 -plots from the final modelling are shown also (dotted lines, Figures 12 and 13).

Figures 14 and 15 show displacement spectra for the two events, as well as the final model spectra (dotted lines). A Q of 400 was assumed in correcting the spectra for attenuation.

Source dimensions were estimated by several different techniques, including corner frequency, characteristic frequency (Boatwright, 1978a) and width of the first pulse (rupture phase) of the V^2 plot. Estimates from these techniques (assuming a circular rupture) are summarized in Table 1. Using rupture velocities, V as $.558 < V < .88$, the source radii are $1.0 \text{ km} < a < 1.4 \text{ km}$ for the 0153 event, and $1.4 \text{ km} < a < 2.0 \text{ km}$ for the 0356 event.

An analysis of the short period P-wave pulse shapes at 6 WWSSN stations, all of which have a similar ($\sim 30^\circ$) take off angle from the hypocenter (relative to the fault plane) suggests that rupturing was nearly symmetric (circular).

Detailed source modelling was carried out using a circular version of the quasi-dynamic models discussed in Boatwright (1979) and Boatwright (1978b). These models have an "elliptical" or self-similar slip distribution and causal healing. Since the displacement spectra for these events falls off more steeply than ω^{-2} , we presume that the ruptures stopped gradually, rather than abruptly (Madariaga, 1978), and this gradual stopping was incorporated into the model.

Final modelling was done by filtering the data by circular ruptures. The V^2 pulse shapes and displacement spectra for the models are shown in Figures 12 to 15. Rupture velocities for the two models were $v = 0.68$ and $v = 0.558$ for the 0153 and 0356 events, respectively. Final model parameters are listed in Table 2.

The high stress drops for these two events may indicate either a regional stress build-up prior to a major earthquake or the release of a localized high strength region (asperity) which was unbroken by the most recent (1938) major earthquake.

Since these earthquakes are located near the deepest part of the rupture zone

of the 1938 earthquake (Davies and House, 1978), and since major earthquake ruptures often initiate at depth and propagate up-dip, the location and character of high stress-drop events are important results for an evaluation of seismic hazards in the Shumagin Islands area.

Figure 9. Location map of the Shumagin Islands and April 6, 1974 earthquakes (solid dot in circle). Shumagin network seismic stations are indicated by triangles and three letter station circles. For comparison the (mislocated) PDE epicenter is also shown (solid square in circle).

Figure 10. Cross section views of hypocenters of the main shocks and well located aftershocks. Symbol size is scaled to magnitude; full symbols are "A" quality locations; 1/2 full are "B" quality; empty are "C" quality. Tick marks are at 5 km intervals, both horizontally and vertically. Approximate rupture zone dimensions of the main shocks, as obtained from analysis of the SMA records, are dashed.

Figure 10a. Vertical cross section oriented normal to the arc. "View" is N60°E. The 0153 main shock is the shallower of the two. Note the distribution of events (especially the A and B quality) about a plane with a dip of approximately 30° northwest (left in the figure).

Figure 10b. Inclined cross section oriented parallel to the 30° dipping plane from (a). "View" is upward at the plane of the Benioff zone, with northeast to the right of the figure and down dip of the Benioff zone down in the figure. Note the separation of aftershocks of the two events.

APRIL 6, 1974 0356
 54.91 N 160.28 W 40 KM

re 11. Focal mechanism of the 0356 hrs event on April 5, 1974. First motions and S-wave polarizations are projected onto a lower hemisphere, equal area net. WWSSN long period first motions are circles, filled are compressions, empty dilatations; smaller symbols are less reliable data. Local network short period first motions are squares; filled are compressions; empty, dilatations. S-wave polarizations are lines on figure, less reliable determinations are only half the length.

SHUMAGIN ISLANDS 0153 EVENT

SAND POINT SMA1 SV

Figure 12. S_v component of S wave for 0153 event, April 6, 1974. Bottom: instrument and free surface corrected acceleration. Center: Velocity trace obtained from integrating baseline corrected acceleration. Top: Velocity-squared trace; dashed line is velocity-squared trace of final model.

SHUMAGIN ISLANDS 0356 EVENT

SAND POINT SMA1 SV

Figure 13. S_v component of S wave for 0356 event, April 6, 1974. Description similar to that of Figure 12.

Figure 14. Displacement spectra of S_v component of S wave for 0153 event, dashed line is displacement spectra of final model.

Figure 15. Displacement spectra of S_v component of S wave for 0153 event, dashed line is displacement spectra of final model.

TABLE 1
Characteristic Rupture Times

<u>Method</u>	<u>0153-event</u>	<u>0356-event</u>
Corner Frequency	.41 $\pm$.1 secs.	.62 $\pm$.2 secs.
Characteristic Frequency	.37 $\pm$.1 secs.	.53 $\pm$.15 secs.
Rise Time	.39 $\pm$.08 secs.	.60 $\pm$.1 secs.
Average	.34 $\pm$.05 secs.	.59 $\pm$.1 secs.

TABLE 2

Derived Source Parameters

0153-eventRadius - $a = 1.2$ kmMoment - $M_0 = 3.5 \pm .8 \times 10^{24}$ dyne·cmStress drop - $\Delta\sigma = 890$ bars Range 600-1100 barsEffective Stress - $\tau_e = 1040 \pm 350$ barsRadiated Energy - $E_s = 8.7 \pm 3.0 \times 10^{20}$ dyne·cmApparent Stress - $\tau_a = 160 \pm 60$ bars0356-eventRadius - $a = 1.65$ kmMoment - $M_0 = 6.7 \pm 1.5 \times 10^{24}$ dyne·cmStress Drop - $\Delta\sigma = 650$ bars Range 350-800 barsEffective Stress - $\tau_e = 780 \pm 250$ barsRadiated Energy - $E_s = 12.4 \pm 4.0 \times 10^{20}$ dyne·cmApparent Stress - $\tau_a = 120 \pm 50$ bars

P-Residual Study

We have substantially increased the data base for examining P-residuals for teleseismic and local, well-located events and nuclear explosions to stations in Alaska and the Aleutians. Within this new data set we find unexpectedly large positive P-wave residuals of several seconds for local earthquakes, instead of the negative residuals generally observed previously for P-arrivals. Negative residuals were expected on the basis of energy propagating along the high-Q slab which dips beneath the Aleutians.

Rowlett and Jacob (1972) found large negative residuals (i.e. earlier than expected) for the nuclear explosions detonated on Amchitka Island. They explained their results as being due to energy traveling through or refracted laterally along the dipping slab, which represents a path of high velocity and less attenuation than that of a standard earth model. For three well-located Aleutian events of $5.8 \leq m_b \leq 6.0$ and with depths of ≤ 40 km, we find positive residuals with absolute values comparable to the negative residuals of Rowlett and Jacob. However, the residuals we find for Soviet nuclear explosions detonated on Novaya Zemlya and a deep (> 500 km) event in the southern Kurils are closer to zero or negative.

Part of the discrepancy between our results and those of Rowlett and Jacob for local events is only an apparent one and lies in the differences between residuals based on Herrin as opposed to Jeffreys-Bullen earth models.

Another source for the apparent discrepancy may lie in possible mislocation of supposedly well-located events. Barazangi and Isacks (in press) have shown that events deeper than 50 km may be systematically displaced trenchward relative to ISC location by local networks due to the narrow aperture of the network with respect to the spatial distribution of deep events. This may or may not apply to our event #2 (Figure 17), located by the Adak network. However, this event is

shallow (14.94 km). The other two events (events 1 and 3, Figure 17) were located by the L-DGO array, which spans roughly four degrees of longitude, and location errors are estimated to be minimal.

We feel that besides mislocations more likely causes must be considered for explaining the unexpected patterns of positive residuals. One possibility is defocussing and/or scattering of seismic energy by the dipping slab and/or by complex shallow structures, in the vicinity of the station. Thus, first arrivals from some of the Aleutian events (of m_b 5.8 and 6.0), which in a regular earth should produce clear arrivals at these distances may be obscured and the P waves are "picked" at later arrivals associated with a higher signal/noise ratio.

Figure 16 shows residuals for three Soviet nuclear explosions to Alaskan stations. These residuals were computed using a J-B earth model. Figure 17 shows P-wave residuals (using a Herrin-model) for three well-located Aleutian events to some Alaskan stations. Figures 18 and 19 show traces of representative seismograms of the events shown in Figure 17. Compare these traces with those shown in Figures 20 and 21, which show first arrivals for a nuclear explosion on Novaya Zemiya and a deep teleseism, respectively.

Barring errors in location and minor rounding errors in residual programs, it appears that inhomogeneities along the paths between shallow Aleutian earthquakes and Alaskan-Aleutian stations may be causing the weak or unclear first arrivals and result in apparent positive residuals when secondary arrivals are picked instead. To test these qualitative interpretations, we have started to trace rays between source and receiver, using a program developed by K. Jacob (1970). Massive ray-tracing computations are still required to simulate the observed data; in the course of these computations we hope to modify the laterally homogeneous velocity structure beneath the Aleutian arc, which was previously assumed.

In the ray-tracing program we are using a slab model based on cross sections of ISC-located hypocenters, contoured at 50 km intervals, similar to the one shown in Figure 22. Note that in this figure we also incorporated data from local networks noted by the four profile lines drawn perpendicular to the strike of the arc. At the four places where contours of the Benioff zone are drawn from network-located hypocenters, the contours are all displaced trenchward. This is consistent with the hypothesis of Barazangi and Isacks (in press) mentioned earlier, and may be significant for network locations. We plan to test our network locations by incorporating a slab structure based on ISC-located hypocenters in our location programs and comparing the results with previously-located hypocenters.

TABLE 3

Events Discussed in the Text

<u>Date</u>	<u>Location</u>	<u>m_b</u>	<u>Depth</u>	<u>Source</u>
07/25/75	55°3.6', -160°22.8'	5.8	17 km	ISC
08/13/74	51°8.9', -177°52.14'	5.8	14.94 km	Engdahl
04/06/74	55°7.8', -160°27.8'	6.0	40 km	L-DGO
09/10/73	42°28.8' , 131°09.00'	5.3	552.2 km	ISC
09/12/73	*73°19.20' , 54°58.20'	6.8	0 km	OSC
	*(Novaya Zemiya nuclear explosion)			
10/27/73	*70°48.00' , 53°55.20'	6.9	0 km	ISC
08/26/72	†49°56.40' , 77°48.60'	5.3	0 km	ISC
	†(Semipalatinsk nuclear explosion)

Figure 16. P-wave residuals to NOAA-operated Alaskan-Aleutian stations from three Soviet Nuclear explosions, computed using a J-B earth model.

Figure 17. P-wave residuals to representative Alaskan-Aleutian stations for three Aleutian earthquakes. Epicenters are shown as solid circles labeled 1-3. Residuals are computed using a Herrin earth model. Depths of events number 1, 2, and 3 are 17 km, 14.94 km, 40 km, respectively.

Figure 18. Traces of seismograms for stations TTA and PMR in southern Alaska, from the three Aleutian events shown in Figure 17. Solid arrows indicate picked P arrivals; dotted arrows indicate computed first arrivals, based on a Herrin earth model.

Figure 19. Traces of seismograms for the event of 4/06/74, which was accurately located by the L-DGO Shumagin array, and has been well-studied (House and Boatwright, 1979, e.g.). Symbols as in Figure 18. For location of respective stations compare Figure 1.

$m_b = 6.8$

Figure 20. Traces of three representative seismograms for Soviet nuclear explosion on Novaya Zemlya. Expected P-arrivals are for a JB-earth model.

42.48°N, 131.05°E
 $m_b = 5.8$, Depth = 552.2 km

Figure 21. Traces of seismograms to Alaskan-Aleutian stations from a deep Kurile event. Arrows indicate P arrivals. Residuals computed using Herrin earth model, as in Figures 18 and 19. Compare these clear, sharp first arrivals for this deep teleseism with the wave forms shown in Figures 18 and 19.

Figure 22. Contours of Benioff zone beneath the Aleutian arc, in 50-km intervals. Data points taken from ISC locations except where lines A-D cross the arc normal to it, showing where depths were taken from cross-sections of hypocenters located by local networks. Line A represents data of Engdahl (1976); B, Davies and House (1978); C, Lahr et al. (1974); D, Davies (1975). Data in the Cook Inlet region were taken from Davies (1975). Note the trenchward offsets in the contours where the local data fall. We do not imply that these offsets are real, but that they indicate the bias of locally-determined hypocenters with respect to those teleseismically located.

QUANTITATIVE HAZARDS ANALYSIS

Records of seismic ground motions, and the associated response spectra, are the most important data basis for a quantitative seismic hazards analysis. A number of energy exploration or development programs both onshore and offshore of the Alaska Peninsula and the eastern Aleutian arc are presently underway or planned for the next decade (see Alaska OCSEAP program). Therefore we searched during the period covered by this report through the entire data file stored at L-DGO for any records which can provide strong-motion seismic information for the region of the eastern Aleutian arc. We compiled the following useful data set consisting of (a) three strong-motion accelerograms from an SMA-1 instrument (manufacturer: Kinemetrics) operated since 1972 in Sand Point (SDP), and (b) some 30 records from an L-DGO assembled broad-band (BB) seismograph system also operated at SDP for a two-year period (1971-1973). Both data sets were collected in the earlier stages of this eastern Aleutian program (then funded by AEC or ERDA, respectively). Figure 23 shows the location of the Sand Point (SDP) station and the epicentral distribution of those earthquakes for which either BB or SMA records with suitable information exist. The location and other pertinent information on these earthquakes is summarized in Table 4.

The first important step towards quantitative use of this data for hazards analysis is to recover the actual ground motion from the seismograms or accelerograms. This is relatively trivial for the accelerograms since the response of the SMA-1 instrument is flat with regard to acceleration for all frequencies below the natural frequency of the mechanical (damped harmonic) oscillator used in the SMA-1, i.e. below about 30 cps.

Broad Band Instrument: For the L-DGO assembled broad-band system we had to reconstruct the exact response from original calibration records and design speci-

Figure 23: Location map of the Sand Point (SDP), Alaska station (solid circle) at which a broad-band (BB) and strong-motion accelerometer (SMA) seismograph was operated. Solid triangles are epicenters of earthquakes for which BB-records exist; solid squares are those for which SMA-records exist. The hypocenter and related information on these earthquakes is summarized in Table 4. The epicenter distribution covers a large portion of the Shumagin Islands seismic gap. Shaded areas indicate off-shore sedimentary basins with potential for hydrocarbon resources and development; they are (from left to right) the St. George, Sanak, and Shumagin Basin. Other basins with such a potential adjacent to the study area, are in the Bristol Bay and south of Kodiak Islands. Other SMA sites are shown by solid circles similar to the one for SDP.

TABLE 4

LIST OF EVENTS RECORDED BY L-DGO AT SAND POINT, ALASKA EITHER ON THE BROAD-BAND (BB)
INSTRUMENT OR STRONG-MOTION ACCELEROMETER (SM)

SDP-RECORD	DATE	ORIGIN TIME	LOCATION OR HYPOCENTER DISTANCE	DEPTH	REGION	MAG.
BB 4	9/23/71	13:31:14 GMT	53.81N 164.76W	45 km	Unimak Is. Region	5.3
BB 24	11/24/71	19:40*	30 km			
BB 24	11/25/71	10:59:06	56.37N 160.66W	136 km	Alaska Pen.	5.3
BB 27	12/2/71	23:06:25	53.86N 163.78W	20 km	Unimak Is. Region	4.7
BB 37	12/17/71	00:05:20	55.05N 161.13W	38 km	Alaska Pen.	
BB 50	12/31/71	08:44:47	54.85N 164.39W	33 km	Unimak Is. Region	4.5
BB 87	2/21/72	19:34:47	55.91N 158.28W	29 km	Alaska Pen.	5.7
BB 89	2/24/72	01:43:02	55.94N 158.27W	38 km	Alaska Pen.	5.3
BB 102	3/8/72	15:23:01	54.44N 162.49W	35 km	Alaska Pen.	4.6
BB 118	3/24/72	03:38:24	56.14N 157.14W	42 km	Alaska Pen.	6.0
BB 121	3/27/72	09:18:47	55.95N 161.81W	157 km	Alaska Pen.	4.5
BB 122	3/28/72	20:53:07	54.03N 163.37W	25 km	Unimak Is. Region	4.7
BB 134	4/9/72	22:41*	85 km			
BB 145	4/21/72	01:28:08	53.95N 166.82W	91 km	Fox Islands	5.8
BB 168	5/20/72	21:26:08	53.41N 160.00W	35 km	South of Alaska	5.2
BB 172	5/28/72	05:09*	120 km			
BB 305	9/7/72	09:05:41	55.7 N 161.2 W	56 km	Alaska Pen.	4.4
BB 313	9/22/72	07:27:06	55.52N 157.36W	26 km	Alaska Pen.	4.6
BB 318	10/1/72	12:55*	40 km			
BB 319	10/3/72	08:58*	35 km			
BB 323	10/12/72	04:47*	240 km			
BB 356	12/22/72	10:47:45	54.56N 159.49W	10 (+15) km	South of Alaska	
BB 365	1/10/73	17:13:10	55.35N 160.04W	58 km	Alaska Pen.	4.3
BB 368	1/16/73	09:57:38	54.05N 165.48W	75 km	Fox Islands	5.2
BB 412	4/21/73	05:27*	65 km			
BB 415	5/1/73	09:40*	32 km			
BB 426	5/25/73	13:17:26	53.43N 161.27W	34 km	South of Alaska	4.9
BB 428	5/29/73	06:14:18	53.97N 163.71W	0 (+ 7) km	Unimak Is. Region	6.1
SM 1	4/06/74	01:53:	54.87N 160.29W	} L-DGO 37 km 40 km 56 km	Alaska Pen.	5.7
SM 2	4/06/74	03:56:	54.91N 160.30W		Alaska Pen.	6.0
SM 3	7/25/75	10:40:	54.9N 160.4W (PDE)		Alaska Pen.	5.7

*Recorded time (nearest minute of P-arrivals at Sand Point) for events not located by the
International Seismological Center (ISC) Bulletins.

fications of the individual system components. Figure 24 shows the schematic layout of the broad-band system and its major components together with the characteristic envelope response spectra for each component. The sensor is a long-period vertical seismometer (manufacturer: Sprengnether) which can be operated at periods between 10 and 30 seconds. Our records were taken with a natural seismometer period set at $T_0 = 16$ seconds. The output signal is fed into a chopper amplifier with a one-pole low-pass filter ($f_0 = 5$ cps); it is then fed into a power-amplifier with a one-pole low-pass filter ($f_0 = 1$ cps) driving a curvilinear pen motor which has a natural frequency of about 20 cps. The resulting over-all frequency response of this system is shown in Figure 25 for a gain setting of 36 db of the variable-gain filter amplifier #1. In practice the gain was varied by ± 6 db from this standard gain depending on the general microseismic noise level, mostly induced by ocean wave action in the nearby Bering Sea shelf. Predominant periods of the microseisms are near 6 seconds.

Note that the over-all frequency response (with regard to ground displacement) has a very broad peak between 1 and 5 cps. The instrument resolves ground-motions well within a wide frequency range from 0.1 to 25 cps with gains that lie within 10% of the peak gains. Thus this instrument provides records with a good resolution in a frequency range most important for earthquake source studies and seismic engineering applications. It also has the advantage of operating at gains (of about 10^4 for displacement) which are intermediate between the WWSSN observatory-type seismic instrumentation and SMA-1 strong-motion accelerographs. This is corroborated by the number and magnitudes of earthquakes recorded by the different types of instruments. While to date, in a 5-year period from 1973 to 1978 we have obtained only 3 strong-motion accelerograms at SDF from earthquakes with magnitudes larger than 5.7, we have obtained almost 30 broad-band records for a two-year period (1971-1973) for earthquakes with magnitudes between about 4 and 6.1 (Table 4).

LP-SEISMOMETER FILTER-AMPLIF.#1 FILTER-AMPLIF.#2 PEN-RECORDER

Figure 24: Schematic diagram of broad-band (BB) seismograph operated at Sand Point (SDP), Alaska.

Bottom: Major system components. Top: Their respective schematic frequency response curves. For composite frequency response compare Figure .

Figure 25: Frequency response curve (displacement gain) for Sand Point (SDP) broad-band (BB) seismograph. Note that the frequency range within 10% of the peak gain extends from about 0.1 to about 25 cps, thus covering a frequency range important for earthquake source studies and engineering applications. The peak gain of about 20,000 applies for setting at 36 db for the variable gain of filter amplifier number 1.

Method of Analysis: We are presently preparing and programming the following data analysis scheme for the records shown in Figures 26a through 26d.

- (1) Direct digitization of unprocessed record.
- (2) Removal of curvilinear pen motion and fixed pen-angle offset.
- (3) Derivation of an equal-time-step time series for the seismogram.
- (4) Remove trend and DC from seismogram.
- (5) Deconvolution of the seismogram with instrument response to obtain "true" ground displacement.
- (6) Derive ground velocity and ground acceleration records in time domain, both unadjusted and with parabolic baseline adjustments.
- (7) Derive spectra (for displacement, velocity and acceleration) of the following type:
 - (a) Fourier amplitude spectra
 - (b) Response spectra
 - (c) Response envelope spectra

The final goal is to use the above data and data products to predict ground motions (on solid bedrock) in the eastern Aleutian arc from a variety of hypothesized earthquakes with magnitudes larger than those for which ground motions have been observed already. The magnitudes for which ground motions may be predicted could vary from about 6.5 to larger than 8. The latter event would be scaled to fit either the largest credible event or the largest probable event (within a certain time span). The theoretical approach for this ultimate goal is presently still in progress. Therefore, predictions for a completion date of a related data product (such as a set of maps with contours of expected ground motions) cannot be yet given. An earliest time would be late in 1980.

Results from SMA-records: Analysis of SMA records for the purpose of determining source parameters such as seismic moment, rupture velocity, fault area, average dislocation, and average stress drop was carried out by House and Boatwright (work in progress) as reported elsewhere in this report. The major finding to be noted here for hazards evaluation is that at least two of the three earthquakes occurring in the Shumagin Islands for which SMA records exist (i.e. records SM1 and SM2, see Figure 27) were associated with high stress drops of about 450 and

Figure 26a: Sample records from Sand Point (SDP) broad-band seismograph for regional earthquakes in the eastern Aleutian arc/Shumagin Islands region. For information on each earthquake compare corresponding BB record number in Table 4. Note that seismograms xeroxed twice which sometimes results in considerable loss of resolution. Maximum resolution on originals varies from about 0.04 to 0.1 seconds. Time between tick marks is 1 minute.

Figure 26b: Additional SDP-BB sample records. For earthquake source information, see corresponding record number in Table 4.

Figure 26c: Additional SDP-BB sample records. For earthquake source information see corresponding record number in Table 4.

Figure 26d: Additional SDP-BB sample records. For earthquake source information, see corresponding record number in Table 4.

Figure 27 : Strong Motion Accelerograms of two of the three events so far recorded at Sand Point, Alaska, in the Shumagin Islands segment of the eastern Aleutian arc. For these two events (SM1 and SM2, see Table 4) House and Boatwright (1978) determined the source parameters and found high stress drops associated with them amounting to 650 and 450 bars, respectively. T, L, V correspond to transverse, longitudinal and vertical component of the triaxial accelerometer. Note time scale, sensitivity and P and S arrivals as marked. If similar data from 4 installed accelerometers become available during the study period, we will include them into the proposed analysis.

650 bars, respectively. High stress drops almost always imply high accelerations for a fixed set of other source parameters such as surface-wave magnitude, seismic moment, or rupture dimensions. The high stress drops explain the higher than average peak horizontal accelerations for these two earthquakes when plotted against peak accelerations from earthquakes in the western United States. Figure 28 shows such a comparison with data collected by Page *et al.* (1972). Note that peak horizontal acceleration from event SM1 ($m_b = 5.7$) lies significantly above data points for events with the appropriate magnitude range ($m_b = 5.0$ to 5.9, solid triangles) and for the same hypocentral distance (60 km). Peak horizontal acceleration for event SM2 plots near the upper boundary for data points (open circle) appropriate for the hypocentral distance of 60 km and magnitude range $m_b = 6.0$ to 6.9, although its magnitude ($m_b = 6.0$) is near the lower end of this magnitude range. The acceleration measured for event SM3 (Table 4) appears to follow a similar pattern (Figure 28); this cannot be said, however, with the same confidence because fewer data points from the western U.S. are available for comparison at this distance and for this magnitude.

A well located event with magnitude $m_b = 4.3$ occurred on April 6, 1974 at a distance of 50 km from SDP and did not trigger the SMA-1 instrument which has a trigger level set at 0.01 g (vertical). Hence its peak vertical acceleration at SDP is assumed to have been less than 0.01 g. Note that we indicated in Figure 28 this trigger level as upper limit of associated vertical acceleration while all other data points on this plot indicate peak horizontal accelerations.

STATE OF HAZARDS ANALYSIS

It is obvious from Table 4 that the rate by which SMA records are being obtained in the eastern Aleutian arc is too slow to provide realistic estimates for strong earthquake ground motions before lease sales or oil exploration and develop-

Figure 28: Comparison of peak-horizontal accelerations (larger symbols) measured for 3 eastern Aleutian earthquakes at Sand Point (SDP), Alaska, with those compiled by Page *et al.* (1972) for the western United States (smaller symbols). For comparison with information on Table 4, the three events are: SM1: April 6, 1974. $M = 5.7$; SM2: April 6, 1974. $M = 6.0$; SM3: July 25, 1974. $M = 5.7$. An upper limit for vertical peak acceleration for a $M = 4.3$ event occurring on April 6, 1974 is also indicated (see text). Note that all recorded peak horizontal accelerations are slightly higher than those from the western U.S. for the equivalent magnitudes and distances.

ment may start in some of these Alaska outer continental shelf regions (say, between 1980 and 1985). This could be partially rectified by deploying more SMA instruments and at distances closer to the seismically active fault zone. We will request for FY 79 at least one additional SMA-1 for deployment in the Eastern Aleutian arc. Also we have moved the SMA-1 from Port Moller to Simeonof Island (Figure 23), reducing its distance from the seismogenic zone from about 100 to 30 km. Both means should increase the rate by which strongmotion records can be obtained.

A safer way is, however, to use the information contained in the already collected broad-band records as described above. These records measure ground motions at acceleration levels usually far below the SMA-1 trigger level of 0.01 g and from earthquakes 1 to 2 magnitudes below those typically recorded on SMA-1. The disadvantages are that analysis of BB records is time consuming and certain theoretical scaling assumptions about the source must be made to extrapolate the ground motions from the small magnitude earthquakes to those associated with large, potentially damaging earthquakes. We are confident, however, that within about two years of intensive work most of these difficulties will be overcome to produce realistic estimates for ground motions from future large earthquakes in the eastern Aleutian arc. Whether this goal, i.e. to produce seismic hazards maps contouring expected levels of groundmotions for the eastern Aleutian arc can be achieved within the present funding levels either from DOE or NOAA/OCSEAP, is highly questionable. Funds from NSF may be requested to accelerate completion of this task, the importance of which is growing as the number of energy development projects is increasing in this region of Alaska.

Crustal Deformation

1. Geodetic Measurements: The 1978 level-line measurements showed a continuing trenchward tilt of approximately 8×10^{-7} rads/yr at Squaw Harbor (Figure 31; see Figure 30 for level line locations). The line at Sand Point Airstrip (L_2) was repeated for the first time and showed an apparent southward tilt. The new 1 km line at Simeonof Island (L_3) had been decimated by surf action so no significant results were obtained between last year and this year. The line was reinstalled using higher quality concrete for cementing the pins in place and was measured in both directions with a closure error of 0.8 mm.

In comparison to level lines, the dry tilt measurements continued to give rather random results and an effort will be made next year to improve the data by taking multiple readings on the lines as suggested by Sylvester (1978).

2. Mean Sea Level Meters: Three additional mean sea level gauges were installed during the summer of 1978 (see Figure 30). Two of these were of "pore pressure" type and one was of "sea level" type (see Technical Discussion later). One gauge at Simeonof West was damaged beyond repair so the array now consists of seven gauges, four of sea level type (at PRC, EGH, EBT and SMH) and three of pore pressure type (at SDP, PRC, EBT). Installation of two additional gauges on the mainland was prevented by bad weather.

Sattelite transmitters (loaned to us by NASA) were connected to five of the gauges (two at PRC, one each at EBT, SDP and SMH) and the data are being received at Lamont via GSFC with about a four week delay. The mean sea-level data from late June through early October are plotted in Figure 32; the record from the pore pressure gauge at PRC is omitted as the gauge is malfunctioning. Full scale, 0 to 250, on the plot represents approximately 10 cm sea level change. Three of the

records are from sea level type gauges while the fourth (Sand Point, SDP) is from a pore pressure type gauge. The greater variability of this record is presumably due to rainfall and groundwater effects modifying the pore pressure. The records from SDP and PRC, both on Popof Island, tend to track each other; however, they are quite different from EBT and SMH which also tend to track each other.

Mean Sea Level Meters

A new "pore pressure" type of gauge was installed this summer. See Figure 33 for diagrams of both the conventional sea level type and the pore pressure type gauge. The pore pressure gauge relies on making a connection to the sea via the permeable sand or gravel of the beach and is therefore freed from the technical problems associated with the syphon. However it has the disadvantage that the pore pressure can be affected by variables other (for example, rainfall) than sea level changes. At two locations (PRC and EBT) the two types of gauge were installed side by side in order to evaluate their relative performance. A third pair of gauges was intended to be sited on the mainland but inclement weather prevented the completion of the installation.

Labarge convertible data collection platforms (DCP's) loaned to us by NASA were installed at SDP, PRC, EBT and SMH. At SDP, which is essentially accessible, the DCP is powered by air cells. At the other sites they are powered by 20 AH gel cells trickle charged from a solar panel. So far the panels have operated excellently, but it remains to be seen whether they will continue to keep the batteries under full charge during the winter.

Geodetic Levelling

The levelling pins installed on the beach of Simeonof Island during 1977 had suffered severely from surf action; we were only able to locate three pins

out of 17. We reinstalled the line using regular concrete rather than quick-set cement and we expect that it will survive much better in the future. Apparently the quick set cement is attacked by salt water as it has behaved perfectly at inland locations.

The pins on the Sand Point Airstrip line were reinforced with regular concrete. Some damage had occurred to intermediate markers on the Sand Point Original line; these were repaired but the line was not measured this year due to bad weather.

Figure 30. Existing and proposed sites of the Crustal Deformation Monitoring Program in the Shumagin Islands. The various symbols indicate precision level lines, geodetic dry-tilt figures, and sea-level gauges. The weather stations (temperature, pressure, humidity) are for correlating sea-level measurements with meteorologic effects.

Figure

Squaw Harbor Level Line results 1972 through 1978. A tilt rate of 0.8×10^{-6} rads/year down toward the trench is apparent. The dashed line representing 1.0×10^{-6} rads/year is only for scaling comparison.

Figure 32. Sea level gauge data transmitted by ERTS satellite from the Shumagin Islands. The horizontal scale is days in 1978. 250 units on the vertical scale corresponds to approximately 10 cm mean sea level change. Three of the records (East Bright, EBT; Pirate Cove, PRC; Simeonof Harbor, SMH) are from sea level type gauges. The fourth (Sand Point, SDP) is from a pore pressure type gauge.

Gaps in the data occur when the satellite is out of view of the transmitter for more than a few hours, and occasionally whole days of data are mislaid during ERTS processing.

The occasional full scale offsets in the data represent a complete revolution of the potentiometer sensor and can be used as a calibration signal; an offset corresponds to exactly 10 cm sea level change.

Figure 32 (con't.)

Figure 32 (con't.)

Figure 33a. Schematic of "sea level" type mean sea level gauge.

Figure 33b. Schematic of "pore pressure" type mean sea level gauge.

GEOLOGIC RECONNAISSANCE OF RECENT CRUSTAL MOVEMENTS

Evidence of Pleistocene to Recent uplifts in the Shumagin Islands was suggested by several investigators in the region (Eakins, 1970; Moore, 1972; Burk, 1972). Reconnaissance surveys to evaluate these proposed terraces began in June, 1978. The purpose of this preliminary study was to assess post-Pleistocene uplift and tilting, and to identify recently active faults in order to commence a more systematic mapping project in the area. The evaluation of long-term tectonic activity, as indicated by the uplifts and fault scarps will complement ongoing seismicity and tilt studies, and provide a longer time base for assessing seismic risk in this major seismic gap.

In addition, with future age dating planned, long-term rates of uplift and tilt can be compared to:

- 1) short-term levelling surveys in progress in the Shumagins; and
- 2) tectonic uplift studies conducted outside the seismic gap area (Plafker, 1967, 1969; Plafker and Rubin, in press, 1978; Prescott and Lisowski, 1977), as well as terrace studies on the Bering Sea side of the Alaska Peninsula (Hopkins, 1967). Comparisons with studies from other tectonically active areas will provide a basis for evaluating the geological evidence for potential earthquake activity in the area.

Procedure and scope of study. An aerial reconnaissance was begun in the area of the Shumagin Islands and adjacent Alaska Peninsula in order to pinpoint those areas of greatest potential. Six areas were chosen for an isobase survey based on obvious terrace development and suitable

geological structures. Terrace development was least ambiguous in the tightly folded Upper Cretaceous rocks, where the surfaces cut across all lithologic boundaries. In areas of flat-lying strata, planar surfaces of erosional origin obscured potential terraces, and were thus avoided, except where surfaces crossed lithologic boundaries. The intrusive rocks show the least evidence for terrace formation. However, terrace surfaces can be traced into the igneous terrain by a slope break. In certain localities, wind gaps aligned with surveyed terraces and were therefore surveyed as well.

An isobase survey was conducted for each sub-area using an alidade to triangulate and locate separate terrace levels as shown by sea cliffs, wave-cut platforms, former dunes, and slope breaks. Due to the inaccuracies of the topographic maps and paucity of geodetic bench marks, it was determined that an isobase study, independent of the topographic maps, would be preferable to plotting the terraces directly onto the available maps.

Aerial reconnaissance indicated the presence of several post-Pleistocene faults which were recognizable as distinct, linear valleys, coast lines, and linear changes in vegetation. Only those lineaments which cut across lithologies and formed scarps were recorded. Three of these were examined in the field. The azimuth, height, and dip of the scarps were measured, and field relationships were noted. Small scale fracture sets and tension gashes were measured along one of these faults. Although their displacements have not yet been determined, the inland faults do not appear to affect terrace heights, nor do they control major block boundaries.

Data. Uplifted marine and river terraces are found on Nagai, Korovin, Dolgoi, Popov, and Simeonof Islands (Figure 34). The terraces are recognized by major sea cliffs, which can be followed inland as slope breaks and river terraces. The relief on these surfaces varies somewhat, but sub-planar surfaces are present regardless of lithologic changes. The most pronounced uplifted marine and river terraces are found in the poorly indurated Tertiary-age rocks and tightly folded upper Cretaceous sedimentary rocks. Cretaceous intrusives show slope breaks that can be followed along strike toward marine terraces. Soft sediments form the lowest level marine and river terrace levels.

The terrace levels were established, using an alidade for preliminary mapping and to establish planar surfaces. The survey indicates at least one to three terrace levels per island, varying in height from a few meters above sealevel to over 170 meters. There is an indication of trenchward tilting on the lowest terrace level. The apparent southward tilt produces a change in elevation of -45 meters in 20 km. However, actual correlation of surfaces from island to island awaits the determination of absolute age dating. The highest surfaces observed post-date the deposition of Miocene shallow marine and continental sediments, and most of the terrace development is post-Pleistocene in age. Pleistocene U-shaped valleys have terrace levels superimposed on their morphology.

On Nagai Island, wind gaps (of similar elevation regardless of lithology) were included in the survey if they could be traced along strike to major slope breaks and sea cliffs. The consistency of the levels obtained from several different features, as well as across major lithologic

Figure 34. Terraces and faults in the Shumagin Island region of the Aleutian Island arc. Terrace heights are given in feet.

boundaries, lends confidence to the existence of erosional terrace levels away from the coasts of the islands and peninsula. Also, the continuity of planar surfaces in areas of complexly folded strata points toward their origin as peneplanation features. Until age dating and examination of the fossils occur, the determination of former baselevels, however, can only be inferred.

Evidence for Holocene faulting was seen on Nagai, Korovin, and Unga Islands. Fault traces are visible from the air as 1-3 km long scarps, fissures, and as linear valleys and coasts. Although fault displacements were not determined due to poor exposures, the fault scarps and fissures cut across structures and lithologies obliquely, and are visible in unconsolidated alluvium. Steep scarps on three of these faults strike at high angles to the trench and generally face east or southeast. Fracture sets and tension gashes were measured across one of these NNE striking faults, but did not reveal a unique displacement direction, except to suggest a right-lateral component to an apparent high-angle thrust.

Conclusions. The variation in both terrace level heights and the number of terraces from island to island suggests uplift along several semi-independent blocks. Those faults which are exposed on land are minor, and do not appear to delineate block boundaries. These faults strike at high angles to the trench, but the high ratio of water to land does not permit the direct determination of block boundaries. Such faults may be discernible from marine seismic and/or gravity and magnetic data.

The presence of late Tertiary to Recent block uplifts and tilting in the Shumagin Islands and Alaskan Peninsula suggests continuing, long-term

earthquake hazards. The presence of small faults in the area, especially near Popov Island may explain the weak seismicity recorded in the vicinity. The suggestion of a trenchward tilt is consistent with evidence obtained from recent levelling data on Simeonof Island. Correlation of tilting toward or away from the trench since the consumption of the Kula Ridge in Oligocene times will result in a refinement of crustal models for the rest of the seismotectonic zone.

Future studies. This preliminary study confirmed the presence of uplifted marine terraces, and located several others on a small sampling of islands. In addition, a few recent fault scarps were seen, which warrant further study. The future study, presently proposed, will systematically map these terraces as well as locate others. Moreover, soft sediment cores from the terraces, wind gaps, river terraces, and prominent non-lithologic slope breaks will be obtained in order to do palynological, paleontological, and radiometric age determinations. Absolute age dates will then permit the delineation of separate block movements, and correlate terraces of equal age. Rates of differential tectonic uplift can be obtained from the isobase and age data, thus providing a longer time base to ongoing seismic and tilt studies in the region.

VOLCANO STUDY (PAVLOF VOLCANO)

General Comments: Physical Volcanology in general and volcano-seismology in particular are in their early stages of development compared to some other well advanced disciplines in seismology or in the Earth Sciences in general. The reasons for this deficiency are obvious: Volcanic processes are physically very complex; they occur only intermittently or in a rapidly changing form and in often hostile environments; therefore, they are difficult to monitor. Even on a world-wide basis only very few coordinated attempts have been made in the past to collect sufficient data for sufficiently long periods in the vicinity of active volcanic features (e.g. Hawaii, Sicily, Japan, Kamchatka, New Zealand). The necessity to consider geothermal energy as one of the alternate energy sources to those of fossil and nuclear origin has spurred a new interest in understanding volcanic processes for the purpose of assessing the potential for geothermal energy extraction from active volcanoes or volcanic fields. Our seismic volcano study in the Eastern Aleutian arc, presently focussing on Pavlof volcano, is a modest attempt to collect seismic data with the purpose to develop an understanding of the physical processes of magma emplacement in and beneath a volcano, and their time dependent aspects prior, during, and after an eruption. In particular we study the specific properties of explosive island-arc volcanism at an actively convergent plate boundary, which differ in many aspects from already better studied volcanic processes in non-convergent tectonic settings (i.e. those in Hawaii or in the western U.S.). One or more of the following aspects are known or suspected to be highly variable with the tectonic setting: Chemistry and rheology of eruptiva; Regional tectonic stress system; Explosiveness; Permeability and porosity of volcanic strata; Residence time of magma in magma "chambers" and their size and shape. These and other characteristics of the volcanic processes may be so severely modified by the tectonic environment that at this stage

it is not clear whether or not explosive-type volcanoes in island arcs will ever be serious candidates for reliable geothermal energy extraction. Hitherto made estimates of depth and size of "magma chambers" beneath explosive-type volcanoes are rarely more than educated guesses. Practically nothing is known about stability and residence time of these magma chambers. The primary reason for this situation is that neither do exist sufficiently realistic theoretical models for the volcanic processes nor do exist the data to test these models. At this early stage of our eastern Aleutian volcano study we cannot report a major break-through or result. We have, however, collected - and continue to collect - a substantial amount of natural seismic data from Pavlof volcano. We have focussed during the present reporting period on screening this large amount of data to search systematically for different types of seismic signals, their occurrence patterns in time related to visually observable (eruptive) patterns on Pavlof volcano. The motivation behind this synoptic screening of seismic data and of visual reports is to hopefully isolate physically distinct processes which occur in and beneath the volcano, and to derive individually appropriate data analysis methods for each type of volcano-seismic signature with the attempt in mind to test it against a model of the process likely to be associated with it.

Before we illustrate this approach in more detail by showing a few examples of different types of volcano-seismic recordings obtained from Pavlof volcano, we briefly outline the two basic classes of phenomena that determine the seismic signals: (1) sources of volcano-seismic excitation and (2) propagational effects. Either of these two factors are likely to be more variable and complex, than in ordinary tectonic seismological environments. Tectonic earthquakes stem from brittle shear failures on more or less planar faults. The sources for volcanic events are thought to consist of either (1) oscillations of a (more or less) spherical magma chamber (Shima, 1958; Kubotera, 1974), (2) organ-pipe-like oscillations

in a (more or less) cylindrical central vent of a strato volcano (Steinberg, 1965); (3) jerky motion associated with the growing of magma-filled cracks (radial dykes) driven by the over-pressure of the magma (Aki, Fehler and Das, 1977); (4) partly seismic, partly acoustic radiation from steam or gas explosions near the top of the central vent; or (5) tectonic (dry brittle) events near the volcano; or (6) any combinations thereof with variable weight of source strength as the eruption progresses.

The distinction of these different possible volcano-seismic sources by analyzing the volcano-seismic signals radiated and their variation in time is impeded by the wave-propagational effects in the laterally very complex and heterogeneous volcano structures. The heterogeneities have often dimensions similar to those of the wavelength of excited signals. Hence refraction, scattering and attenuation effects may mask the source-related wave shapes to a degree where extraction of the source function may be difficult or impossible except in special circumstances. Nevertheless, volcano seismology is one of the few means to "X-ray" and monitor the emplacement of magma bodies, and to study the physical processes in the island-arc environment associated with magma emplacement. Without this knowledge it will be difficult to develop geothermal energy extraction schemes in this tectonic regime. Keeping the before mentioned complexities in mind we now discuss some of the observational data and our attempts to classify them.

Pavlof Network and Data

In the summer of 1976 an array of 12 seismometers was set up on the flanks of Pavlof volcano to locate and investigate associated magma reservoirs and processes of magma transport. Figure 35 shows the locations of the seismometer sites together with those of two other stations (PVV and Black Hills) from the Shumagin network. Enough data has now been collected to warrant part-time employment of a

data analyst starting with November 1978 and the full-time participation of a graduate student in the Pavlof project starting in January 1979. We discuss here those aspects of the Pavlof investigation which on the basis of the preliminary data analysis will receive the most attention during the intensive analysis in the upcoming year: temporal variations in seismicity, harmonic tremors, explosive events, impulsive events of non-explosive origin, and attenuation of signals from local tectonic events.

Temporal Variations in Seismicity

Records from the PVV station are nearly continuous from October 1973 to the present. A summary was made (DOE Annual Progress Report for 1977/1978) of the number of volcanic events per day for the first four months of the station's operation. We are presently continuing this count up to the present day. As before, events are being classified by amplitude and the number of events in each amplitude class per day versus time is graphed. This information, together with visual eruption reports from local sources and others such as the Smithsonian Institution's Center for Short-Lived Phenomena, provide us with an overall picture of Pavlof's activity during the past five years. With this information, other phenomena can be more easily interpreted in light of their temporal relation to the pre-eruptive, eruptive, and post-eruptive stages of Pavlof's activity. Knowledge of the temporal behavior of volcanicity is also important for testing a hypothesis in earthquake prediction studies of major island-arc-type earthquakes. The underlying idea is that eruptive cycles of the island-arc volcanoes are controlled by the tectonic stress-accumulation in the adjacent seismo-genic thrust-zone of the arc-trench gap.

Harmonic Tremors

Figure 36 shows a typical volcanic tremor (Event 1) recorded on 20 September 1976 during a period of time when the Center for Short-Lived Phenomena and local sources in the Shumagin Islands reported intense emissions of smoke, steam, and

ash from Pavlof¹. These tremors, which are predominantly harmonic in character, are presumed due to either the actual eruption of material or the oscillations of magma "chambers" or columns (organ pipe effect). We are presently preparing an analysis scheme involving a moving-window spectral analysis of these tremor signals to study their source- and path-dependent characteristics.

We hope to differentiate between source effects and path effects through study of the distance and azimuthal variations in frequency spectra. Wave-form characteristics produced by behavior of the source would be in a different way dependent on distance and azimuth (via the radiation pattern and directivity, if any) than those produced by purely propagational effects, such as layering, attenuation and scattering. If the frequency of harmonic tremors can be related to source size and growth of magma filled cracks (Aki *et al.*, 1977) then spectral analysis of source related portions of the signals should define such parameters as magma pressure, orientation and depth of magma filled cracks or pipes. Using much simpler models than Aki *et al.*'s. (1977), Kubotera (1974), for example, through comparison of observed and predicted frequency spectra for tremors from Aso volcano, Japan, determined the radius of its assumed magma chamber to be between 2 and 4 km. Path effects, however, would presumably be in the form of dominant modes produced by the propagation of shear waves through layered media of contrasting velocities. They should have dispersive character and, hence, could be recognized by the moving-window analysis as a function of distance. Analysis of the characteristics of such guided waves may shed some light on the velocity structure of the volcanic cone and underlying crust.

If tremors can be found whose onsets are impulsive enough to allow for source locations, then phenomena such as upward and/or outward migrations of the source

¹Only four out of the twelve seismic channels have been played-back for presentation in this report. Of these four channels PS3 was inoperative during this eruptive episode.

along presumed magma pipes or dikes could be studied. It would be especially interesting to correlate vertical migrations with visually observed eruptions. Directions of preferred azimuthal migration could be compared with those predicted from a simple model of magma-fracturing operating within a uniform principal tectonic stress field. This would provide a "real-time" test of the proposal by Nakamura et al. (1977) that tectonic stress orientation in the Aleutian Island arc determines the preferred orientation of radial and parallel dike swarms.

Provided the tremors contain a sufficiently wide frequency band, but do not show impulsive onsets, another analysis technique can be developed: The cross correlation technique, which uses a delay-and-sum process on the signals to obtain a best fit correlation between recordings at different stations of the same event, would be an alternative method by which "travel times" of tremors could be determined and used for locating the source.

Explosive Events

Explosive blasts from Pavlof have been reported during a previous eruptive episode in 1975 where air shocks were strong enough to "rock boats in Pavlof Bay" (R. Motyka, personal communication). A sample of an event (Event 2) of probable explosive origin from 22 September 1976 is shown in Figure 36. Arrows indicate the first impulsive arrivals of ground phase (G) presumed to be a P-wave and an air phase (A). We assume these events to be located at the apex of the Pavlof cone - a reasonable assumption based on reports we received from visual observations of Pavlof eruptions by local people. Figure 37 shows a plot of arrival times for each phase against slope distance from the apex of Pavlof to the recording station. A theoretical value of 0.331 km/sec for the velocity of sound in air (STP) shows a good fit to the observed arrivals for the air phase. The value

of 3.70 km/sec for the ground phase was obtained as a best fit to the observed first arrivals. The failure of these two velocity lines to converge on the same origin time could be due to an increase in seismic velocity with depth below the surface of the volcanic cone. If this explanation were valid, the ground phase line would be expected to resemble that for a refraction study in which points closer to the origin correspond to successively lower velocities. The mismatch of intercept times could also be due to different "origin" times resulting from slow propagation to the vent of a pressure pulse inside the magma column.

Using characteristics such as air phases to indicate explosive events, we may be able to correlate specific types of seismic phenomena (e.g., air shocks) with certain types of volcanic activity (e.g., explosive ejection of material) to give us much more precise knowledge of when Pavlof is actually erupting, and the mode of eruption (i.e., Strombolian type, phreatic mode). This is especially important in working with Aleutian volcanoes because persistent cloud cover and remoteness from population centers make visual reports very unreliable. This information would make more meaningful any attempts to correlate specific aspects of Pavlof's seismicity with its pre-eruptive, eruptive, and post-eruptive stages.

Impulsive Events

Events with impulsive arrivals but without air shocks have also been recorded on the Pavlof array. If these events can be accurately located, then we can study changes in hypocentral depth with time with regular earthquake relocation procedures. We then will search for upward or other spatial migrations of events preceding a period of high volcanic activity. In addition, if certain types of events are found to correlate with probable emplacement of dikes and dike swarms then this would be another method for investigating the validity of using dike orientation as an indication of tectonic stress.

The focal mechanisms of impulsive volcanic events could also be elucidated through first-motion studies. Minakami(1974) reports significant variations in focal mechanism with depth for Kakuto caldera and Asama and other volcanoes in Japan. Events in the depth range of 1 to 20 km, for example, were found primarily to have initial motions quite similar to those for tectonic quakes. Explosive events, however, consistently showed an initial upward pulse at all recording stations.

Tectonic Events

Events of tectonic origin, located using the Shumagin Array, have already been used to study P- and S-wave attenuation and travel time delays for ray paths passing beneath Pavlof volcano (Davies, unpublished data, 1977). The initial results of this preliminary study suggest that this technique will allow us to define a magma "chamber" (region concentration of magma) beneath Pavlof Volcano. More work along this line is presently being undertaken by the newly hired research assistant (S. McNutt) working with the Pavlof network in cooperation with J.N. Davies.

In summary, the Pavlof study presently is undergoing a marked change from a state of data collection and qualitative screening to one of systematic quantitative analysis. Since this change is taking place only in late 1978, during the present reporting period, first results from this new analytic effort are not yet at hand, and will not be available until probably later in 1979.

Figure 35. Locations of stratas of the Pavlof seismograph array.

EVENT 1

EVENT 2

Figure 36. Examples of volcanic events recorded at the Pavlof array during an eruptive episode late in 1976. Event 1 is a harmonic tremor from 20 September 1976. Event 2 is an explosive event showing an impulsive ground phase (G) followed by a much slower air phase (A) from 22 September 1976. For both events the PS3 station was inoperative.

Figure 37. Graph of arrival times of the ground (G) and air (A) phases recorded from Event 2 against slope distance of each station from the apex of Pavlof volcano. The first arrivals of the air phase are compared with a line giving the theoretical value for the velocity of sound in air (0.331 km/sec at STP). The value of 3.70 km/sec for the ground phase was obtained as the best fit to the data. The failure of these two lines to converge on the same arrival time may be due to a layered velocity structure where velocity increases with depth. The actual velocity value, therefore, may be expected to decrease with decrease in slope distance.

A CRITICAL EVALUATION OF SEISMIC DATA ACQUISITION TECHNOLOGY

Introduction: Shortly after installation of the Pavlof seismic network in the summer of 1976, a volcanic eruption commenced and excited strong seismic tremors for a period of more than two months. The tremors almost completely saturated the dynamic range of the data acquisition system and, hence, only limited information could and can be extracted from the records collected during this period. If a fly-by remote gain ranging ability had existed at this time and for this network, probably very valuable data to study the physical processes associated with magma emplacement could have been obtained. For this reason, and in consultation with DOE, we assumed as one of the sub-tasks to the present Pavlof project to undertake an engineering study whether a fly-by gain ranging capability would be feasible. A survey revealed that fly-by gain ranging is only one of a number of possible solutions to the problems associated with seismic data acquisition. The basic problem of gain-ranging can be overcome altogether if data acquisition can be implemented with instrumentation capable of recording over such a wide dynamic range that gain ranging is an obsolete approach. If a wide dynamic range cannot be achieved then either remote or automatic gain ranging could be employed to adjust variable signal levels to the limited dynamic range of the instrumentation. We discuss below some of the viable technical options, and their economic and logistic implications. For this discussion we keep in mind that the components of the present data collection system, - not only the remote units, and telemetry, but also the central low-cost recording units - are not a modern system but a system, at least parts of which need replacement. This is the case not only for the purpose of widening of the dynamic range, but simply for achieving higher reliability, wider frequency-band resolution, and higher efficiency in data analysis. The optimal (but presently unrealistically expensive) solution lies

in digital data collection, transmission, and recording. For economic reasons we conclude that an event-editing analog recording system with automatic gain control at the remote sensor sites is less rigorous but economically a more realistic solution.

The Problems and Possible Solutions: In addition to having a small dynamic range (about 36 db) the data collection systems presently in operation in the eastern Alutian arc have two main problems: poor operating reliability, and physical formats which are difficult to use, particularly with regard to data reduction.

After screening the presently available technology, we have studied three somewhat different data collection systems. All three use magnetic tape as the recording medium, primarily to facilitate automatic or semi-automatic data playback and analysis in conjunction with either the existing general-user L-DGO computer system, or the new USGS-supplied seismologic computer system (scheduled to be in operation early in 1979).

Type A (continuous analog recording): A continuous recording system (TYPE A) utilizing analog data could be used. L-DGO has experience with two such systems. The first is currently used at L-DGO to record data from the short-period N.Y. State network, and consists primarily of a Honeywell Model 101 Recorder. This is a 14 track unit, using 1" tape on 14" reels; and using one reel per day at 15/16 IPS speed. It records data in FM format, using the standard USGS VCO frequencies (680-3060 Hz). The maximum capacity is 112 data channels, however, some recording capacity must be used for time codes. Since the data is recorded in FM format, the number of discriminators required in the field is reduced to just a few for periodically monitoring the incoming data. The disadvantage of this system is that some means of playing back the data must be developed that will handle the large quantity of data (most of which is "noise" that is quiet times between rare events). Either the playback speed is increased (8X is an upper limit) or some means of

prescreening the data must be used. In N.Y. State, for example, a number of heli-corders are used in parallel, and events of possible interest are noted. This permits relatively rapid sampling of the tape data. It is generally not practical to store the original tapes indefinitely since they cost ~ \$60 each. Events of interest are transferred to an archive tape and the original tape is recycled. The cost of the tape recorder is \$18,000 to \$22,000 depending upon the number of record/playback channels required.

Another continuous recording system which could be used is one which L-DGO developed in conjunction with a Venezuelan agency, FUNVISIS. This system employs two TEAC Model 33-4 Recorders. This recorder is a four track unit using 1/4" tape on 10 1/2" reels at a speed of 15/16 IPS. The recording capacity is somewhat greater than 12 hours; hence two units are used to provide 24 hour capacity. The total capacity is 32 channels, less time codes. The daily cost of tape is \$20, without recycling. The cost of tape recorder is presently about \$2,000 each. The playback considerations are the same as those of the Honeywell unit, except that additional attention must be paid to flutter compensation in order to maintain a S/N ratio of at least 40 db.

Type B (event-editing analog recording): Another data collection system currently in use provides recording of events only, in analog format (TYPE B). This system uses two four track, 1/4" tape recorders: TEAC A2340SX. One of the units is modified to serve as a delay unit, by reversing the read and write heads, and using a continuous tape loop (approximately 2 m long). The maximum delay time is 20 seconds at a tape speed of 3.75 IPS. Whenever an event is detected, the data on the loop is read and transferred to the second recorder, for as long as the event continues. The event detection is accomplished using L-DGO designed units employing the familiar STA/LTA (short-term/long-term average) ratio technique. The capacity of the recorder is 1 1/2 hours. The data is recorded in FM format. Discriminators are re-

quired for each channel used for event detection. The cost of the tape recorders and electronics is about \$3,000. Some minor problems have been encountered due to the loop tape splice, which introduces a significant noise impulse. It is anticipated that continued work on this problem will result in satisfactory performance. At present, four of these systems are in use. The big advantage of this technique is the reduced amount of data to be processed, since only "events" are recorded on the tape produced in the field.

Type C (digital event-editing recording): Two systems (TYPE C) using digital recording of events only are presently nearing completion: one for a network in the Caribbean and one for a network in the U.S.S.R. Both systems continuously convert received analog data into digital format, store it temporarily (10-25 sec) and transfer it to a nine track digital recorder whenever an event is detected. The U.S.S.R. system employs analog event detection, while the Caribbean system employs digital event detection. Both systems utilize SBC80 series microprocessor components. Systems of this type will cost \$10,000 and \$25,000 depending upon capabilities. One of the main advantages of this type of system is that the data is directly computer compatible. Another advantage is the ability to easily make changes in operating characteristics, even by remote control.

Comparative Evaluation: A review of the three types of systems (A, B, C) was conducted, with these conclusions:

- a) Type A and B minimize the amount of equipment in the field (good), and Type B, because it is event-detected data, permits time-sharing of the playback equipment.
- b) Type B is the lowest cost system, excluding the cost of playback equipment.
- c) Type C permits computer/software event detection, and has considerable operational flexibility.
- d) Type C permits direct computer analysis.
- e) Type C facilitates growth to digital transmission.

S/N ratio optimization is necessary in order to effectively cope with two related problems: variations in site noise levels, and insufficient dynamic range.

Three general solutions to these problems were studied:

- a) Increased dynamic range.
- b) Remote gain control (RGC).
- c) Automatic gain control (AGC).

The upper achievable limit in dynamic range using minor modifications of the present type of analog system is 50 db, due to S/N limitations. Still it would require replacing some of the units of the existing system with better equipment. One method for increasing its dynamic range is to use two transmission channels for each signal, separated in gain by about 30 db. This required an increase in equipment and doubles the required transmission band-width and recording capacity.

Digitization of the seismic signal at the seismometer, followed by digital transmission and recording, effectively provides unlimited dynamic range. For example, a 12 bit A/D conversion with 4 bits of binary gain ranging provide a dynamic range of 96 db. Alternately, use of the non-linear $\mu 255$ transfer characteristic provides 72 db of dynamic range with an eight bit code. Digitization does, however, pose a number of potential problems:

- a) It requires increased bandwidth. For example, at 100 samples per second and an eight bit digitization, asynchronous transmission requires a 1000 BAUD transmission capacity. Using sixteen bit digitization (12 bits A/D + 4 bits gain ranging) doubles this to 2000 BAUD. The maximum capacity of voice grade channels is 9600 BAUD, using fairly sophisticated signalling techniques.
- b) Synchronization of signals from different sources, at a repeater station, is a difficult technical task, particularly if the data rate is close to channel capacity.

- c) Conversion of a system from analog to digital transmission, or operation in a mixed mode, would be a substantial problem.
- d) Recording of digital signals requires digital recording equipment, and requires event-only recording.

Remote gain control (RGC) systems were considered only with regard to analog systems, since digital ones already have considerable dynamic range, and can easily be made compatible with automatic gain ranging. RGC systems require a receiving capability at each seismic station. In addition to the added cost, the additional power consumption can be a problem. In order to minimize both, relatively low-power, simple receivers could be used. This requires either very high power transmission capability, or a transmitter located close to the receiver, or fly-by techniques.

Some means of determining the appropriate gain level are required. This can be done either automatically or via an operator. The disadvantage of using an operator is that the time response may be not matched to the requirements.

An indication of the gain setting, or a calibration signal must be used in order to insure an unambiguous gain setting.

An RGC capability using fly-by setting via an airplane does not appear desirable for a number of reasons. Bad weather, a characteristic of this area, would severely limit accessibility. Because of this and financial limitations, (in hiring airplanes), the time response achievable would probably be on the order of weeks or greater.

Automatic gain control (AGC) systems considered were also limited to analog signals. AGC systems have a number of advantages:

- a) Flexibility as to time constant. Gain changes can be done on a schedule, response ranging from minutes through days as desired.
- b) They can easily provide gain ranging of 40 db or more.
- c) The equipment cost and power consumption are probably acceptable, primarily

since low power digital electronics would be the primary means of implementation.

An AGC system, like the RGC one, would require either a gain setting indication or an automatic calibration signal.

A typical AGC system is shown in block diagram in Figure 38. From a long-term viewpoint, an all digital system appears to be the desired configuration. There are, however, enough unsolved problems, including the conversion cost, to conclude that further modification to the existing analog system is desirable. An AGC system is preferred over an RGC system, because of the relatively flexible time response capability.

Conclusions for Immediate Action:

1. Depending upon funding, install in 1979 at the central recording site at SDP either a digital event recording system (preferred) or an analog event recording system.
2. Install and evaluate in 1979 one to two AGC prototype systems at remote sites for a one year test run.

Figure 38. Block diagram of Automatic Gain Control (AGC) system.

REFERENCES

- Aki, K., M. Fehler and S. Das (1977). Source mechanism of volcanic tremor: Fluid-driven crack models and their application to the 1963 Kilauea eruption, Jour. Vol. Geothermal Res., 2, 259-287.
- Barazangi, M. and B. Isacks. A comparison of the spatial distribution of mantle earthquakes determined from data produced by local and by teleseismic networks for the Japan and Aleutian arcs, in press.
- Boatwright, J. (1978a). Radiated seismic energy and the implications of energy flux measurements for strong motion seismology, Proceedings at a seminar-workshop on strong ground motion; Cal Tech (in press).
- Boatwright, J. (1978b). Pseudo-dynamic models of simple earthquakes and the implications of energy flux pulse shapes as modelling constraints, Abstract for XII Symposium on Mathematical Geophysics, Caracas, Venezuela.
- Boatwright, J. (1979). A spectral theory for circular seismic sources; simple estimates of source dimension, effective stress and radiated energy, submitted to BSSA.
- Bruns, T.R. and R. vonHuene (1977). Sedimentary basins on the Shumagin Shelf, Western Gulf of Alaska, paper presented at the Ninth Annual Offshore Technology Conference, Houston, Texas, May 2-5, OTC #2732, p. 41 ff.
- Burk, D.A. (1965). Geology of the Alaska Peninsula - island arc and continental margin, GSA Mem. 99, part 1, 250 p.
- Burk, C.A. (1972). Uplifted eugeosynclines and continental margins, In: Shagan (ed.), Studies in Earth and Space Science: Geol. Soc. Amer. Mem., 132, 75-86.
- Davies, J.N. (1975). Seismological investigations of plate tectonics in South-Central Alaska, Ph.D. Thesis, University of Alaska, Fairbanks, Alaska.
- Davies, J.N. and L. House (1978). Aleutian subduction zone seismicity, volcano-trench separation and their relation to great thrust-type earthquakes, Accepted for publication in the Jour. Geophys. Res., JGR MS #4847.

- Eakins, G.R. (1970). A petrified forest on Unga Island, Alaska, Spec'l. Rpt. #, Div. Mines and Geology, Dept. of Natural Resources, State of Alaska, July.
- Engdahl, E.R. (1976). Seismicity and plate subduction in the Central Aleutians, In: Island Arcs, Deep Sea Trenches and Back-Arc Basins, AGU Maurice Ewing Volume 1, M. Talwani, W.C. Pitman III (eds.), Washington, D.C.
- Hopkins, D.M. (1967). Quaternary marine transgressions in Alaska, In: "The Bering Land Bridge" Hopkins (ed.), Stanford University Press, 47-90.
- House, L.S. and J. Boatwright (1978). Manuscript in progress.
- Jacob, K.H. (1970). Three-dimensional seismic ray tracing in a laterally heterogeneous spherical earth, Jour. Geophys. Res., 75, no. 32, 6675-6689.
- Jacob, K.H., K. Nakamura and J.N. Davies (1977). Trench-volcano gap along the Alaskan-Aleutian arc: Facts, and speculations on the role of terrigenous sediments for subduction, In: Island Arcs, Deep Sea Trenches and Back-Arc Basins, M. Talwani, and W.C. Pitman III (eds.), Am. Geophys. Un. Washington, D.C., 238-258.
- Kelleher, J., J. Savino, H. Rowlett and W. McCann (1974). Why and where great thrust earthquakes occur along island arcs, Jour. Geophys. Res., 79, 4889.
- Kubotera, A. (1974). Volcanic tremors at Aso Volcano, In: L. Civetta, P. Gasparini, G. Luongo and A. Rapolla (eds.), Physical Volcanology, Elsevier, Amsterdam, 29-48.
- Lahr, J.C., R.A. Page and J.A. Thomas (1974). Open-file report, U.S.G.S.
- McCann, W.R., S.P. Nishenko, L.R. Sykes and J. Krause (1978). Seismic gaps and plate tectonics: Seismic potential for major plate boundaries, Manuscript submitted for publication.
- Minakami, T. (1974). Seismology of volcanoes in Japan, In: L. Civetta, P. Gasparini, G. Luongo and A. Rapolla (eds.), Physical Volcanology, Elsevier, Amsterdam, 1-28.

- Minster, B., T. Jordan, P. Molnar and E. Haines (1974). Numerical modelling of instantaneous plate tectonics, Geophys. Jour. Roy. Astro. Soc., 36, 541-576, Also EOS, 54, 4, April AGU, p. 238, 1973.
- Mogi, K. (1969). Some features of recent seismic activity in and near Japan, 2, Activity before and after great earthquakes, Bull. Earthquake Res., Inst. Tokyo University, 47, 395-417.
- Moore, J.C. (1972). Uplifted trench sediments: southwestern Alaska - Bering Shelf Edge, Science, 175, March, 1103-1105.
- Nakamura, K., K.H. Jacob and J.N. Davies (1977). Volcanoes as possible indicators of tectonic stress orientation - Aleutians and Alaska, In: Stress in the Earth, Max Wyss (ed.), PAGEOPH, 115, 87-112.
- Page, R.A., D.M. Boore, W.B. Joyner and H.W. Coultner (1972). Ground motion values for use in the seismic design of the Trans-Alaska Pipeline System, United States Geological Survey Circular No. 672.
- Plafker, G. (1967). Surface faults on Montague Island associated with the 1964 Alaska earthquake: U.S.G.S. Prof. Paper 543-G, p. GL-G42.
- Plafker, G. (1969). Tectonics of the March 27, 1964 Alaska earthquake: U.S.G.S. Prof. Paper 543-I, 74p.
- Plafker, G. and M. Rubin (1978). Uplift history and earthquake recurrence as deduced from marine terraces on Middleton Island, Alaska, preprint, paper presented at the Conference on seismic gaps and earthquake recurrence, May 25-27, 1978.
- Prescott, W.H. and M. Lisowski (1977). Deformation of Middleton Island, Alaska during the decade after the Alaska earthquake of 1964: Seism. Soc. Am. Bull., 67 (3), 579-586.
- Rowlett, H. and K.H. Jacob (1972). Anomalous upper mantle velocities in the Aleutians and Alaska from P-wave residuals, Abstract from Spring Meeting of AGU, 1972.

Shima, M. (1958). On the second volcanic micro-tremor at volcano Aso, Bull.

Disaster Prevent Inst., Kyoto University, 22, 1-6.

Steinberg, G.S. (1965). Genesis of volcanic tremors and the long-range forecasting of eruptions, Dokl. Akad. Nauk, 165, 1294-1297.

Sylvester, A. (1978). The dry-tilt method of measuring crustal tilt, In: Conference on Measurement of Ground Strain Phenomena Related to Earthquake Prediction, September 7-9, 1978, U.S.G.S., Menlo Park, in press.

APPENDIX I

Papers prepared during reporting period accepted for
publication in journals

reprints removed

APPENDIX II

Oral presentations during reporting period

reprints removed

pgs 97-109

APPENDIX III

Helicopter Operations Report (to NOAA/OCSEAP)

Since this report summarizes most of the field activity - except for installation of the new tape recording system at Dutch Harbor underway at the time of writing of this annual report November 1978 - we append the helicopter/operation report for brief documentation of the most important field-related work.

SUMMARY OF HELICOPTOR OPERATIONS

June and August/September 1978

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RU #16

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Prepared September 22, 1978

INTRODUCTION

Helicopter operations during the field season 1978 were provided by NOAA for logistic support of the project "A seismotectonic analysis of the seismic and volcanic hazards in the Pribilof Islands - Eastern Aleutian Islands region of the Bering Sea". This project is carried out by Lamont-Doherty Geological Observatory (L-DGO) of Columbia University under Contract NOAA-03-5-022-70 (research unit #16) for the OCSEAP project. The purpose of the L-DGO project is to collect and analyze seismic and volcanic data to accelerate evaluation of the natural hazards from volcanoes and earthquakes in the eastern Aleutians and Bering Sea regions for the OCSEAP program.

The following report summarizes the 1978 helicopter operations for this project in the eastern Aleutians. For the Pribilof Islands region L-DGO did not request any helicopter support since air travel could be accomplished there using commercial fixed-wing planes. Most of the planned tasks requiring helicopter support were completed during the field season of 1978. This was possible, however, only by NOAA extending the helicopter time beyond the number of flying days originally allotted to the project. In addition to summarizing the main achievements of the work related to the helicopter operations we also discuss remedies for future field seasons to minimize recurrence of overtime requests for helicopter support.

It is a firm fact that without the NOAA-provided helicopter support much of the necessary technical fieldwork on the seismic network in the Aleutian-Bering Sea region would not be possible. Without such support the entire project would be severely jeopardized first because it would be impossible to maintain the present seismic data collection system and secondly because without sound data base hazards evaluation would be meaningless.

MAINTENANCE OF SEISMIC NETWORK STATIONS

The major purpose of the helicopter operation in relation to this project is to provide transportation to and from all remote seismic stations and telemetry relay sites for their annual routine servicing. This includes replacing batteries for power supply, faulty electronic components, and reinforcing or repairing the mechanical installations which may have suffered damage from bears, wind, ice and snow action. A special effort was undertaken this year to replace cable guy-wires with rigid guybars at the telemetry antennas to increase their mechanical resistance against any of the above adverse forces. Also a major rerouting of the telemetry link for the Pavlof volcano station network was implemented since the central recording site at the White-Alice site at Port Moller had to be abandoned because of its termination as a permanent USAF Communication site. Instead we now record all data at Sand Point which necessitated installation of a new repeater site (Beaver Bay, EVB) on the Alaska Peninsula to relay all seismic signals coming from the Pavlof north-side (8 channels) and Black Hills (1 channel) to Sand Point. Seismic network support was the major and predominant task and required the bulk of helicopter operations.

OTHER TASKS FOR WHICH LIMITED HELICOPTER SUPPORT WAS PROVIDED

Three other tasks received some helicopter support, although the support was limited in extent and was provided on a lower priority basis whenever potential conflict with the seismic network maintenance was encountered. First, a few trips to sites for maintenance and installation of sea-level meters were arranged, mostly when visiting nearby seismic stations.

Second, a team of two geologists was dropped on several islands, when possible on way to or from seismic site visits. This team surveyed for tectonically raised beaches and marine terraces to carry the hazards evaluation and related data basis from the historic times back into geologic Recent times, covering in part Holocene and some Quaternary deformation.

Finally, the geodetic leveling work on Unga Island, near Squaw harbor, also required helicopter support for part of one afternoon. In the subsequent day-by-day summary the station visits are labeled according to their purposes with the following code:

SM	seismic station maintenance
TG	sea-level-meter (tide gauge) work
GS	geologic surveys
PL	precision leveling

The actual sequence of station visits and related tasks is described below on a day-by-day basis.

DAY-BY-DAY OPERATIONS

The sites visited, their coordinates and station labels are summarized in Table 1. The following is an account of helicopter activity for the two support periods in June and in August/September 1978. Considerable deviations from the originally submitted flight schedule occurred. Many of those deviations can be attributed to unusually bad weather conditions, particularly during June. We believe, however, that other factors contributed also to these deviations and they are discussed under "Comments".

FIRST HALF OF FIELD SEASON - JUNE

<u>Date</u>	<u>Itinerary</u>	<u>Helio-Field Services</u>
June 1	Helicopter Bell 205 arrives at SDP in late afternoon for first contact and strategy meeting. No station visits	None
2	Station visits to NGI, CNB (SM) and GS sites on Nagai Island	Full Day
3	No Helio - rain and winds	None
4	No Helio - rain and winds	None
5	No Helio - rain and winds	None
6	Station visits to NGI, SQH (twice), SGB (all SM); return of geologists from Nagai Island (GS), drop of material at EGH (TG)	Full Day
7	Station visits (SM) at IVF (also GS), ZKB, CHR, TG work at PRC	Full Day
8	No Helio	None
9	No Helio	None
10	Helio arrived at SDP at 5 p.m. with new pilot/mechanic-team. Station visits at EGH (TG) and NGI, ZKB (SM).	1/2 Day
11	Stations serviced SQH (SM), PRC and BBE (TG), PR3 (SM) removed, stop at Port Moller, BLH, PR3 (SM) Port Moller, BLH (SM), return to SDP.	Full Day
12	No stations (SM) serviced due to late arrival of helicopter (rains, winds). Pick up GS team at nearby Korovin Island	1/2 Day
13	Bell 206 from 'RV Surveyor' base picks up L-DGO team at SDP to service BKJ (SM) and returns, despite heavy fog, rains. No Bell 205 flights to stations possible.	1/2 Day
14	Bell 206 SDP - Cold Bay for transfer of L-DGO personnel to truck for visit of BAL (SM). Return to SDP to service Nagai Island (TG) and drop GS team near DLG (SM); return to Cold Bay.	Full Day
15	Service from Cold Bay FPS, SNK (SM)	Full Day
16	No Helio - winds	None
17	Late start because of heavy winds; Can't reach DRI (fog). PS1 (SM) successful; return to SDP	1/2 Day
18	No Helio - winds, no visibility	None

<u>Date</u>	<u>Itinerary</u>	<u>Helio-Field Services</u>
une 19	Late start because of bad weather. Finally succeed pick up of GS and TG teams from Dolgoi and Nagai Islands. No SM related station visits possible. Instead, complete PL work at SQH.	1/2 Day
20	No Helio - grounded, bad weather	None
21	No Helio - grounded, bad weather	None
22	Station service at ZKB (SM), GS team on Peninsula, TG to BBB. Operations severely handicapped by fog.	Full Day
23	Late start at CDB because of cleanup operations there. DRI and DLG (SM) successful. Departure of Bell 205 for Kodiak.	1/2 Day

SECOND HALF OF FIELD SEASON - AUGUST/SEPTEMBER

<u>Date</u>	<u>Itinerary</u> (All SM work)	<u>Helio-Field Services</u>
August 14	Scheduled helicopter arrival	None
15		None
16 } 17	Delayed due to maintenance problems	None
18 } 19	Delayed enroute due to weather	None
20	Arrive in Cold Bay	None
21	SGB	Full Day
22	SBG, BVB, ZKB	Full Day
23	No Helio - weather	None
24	PS2, PS3, PVV; Helio stays at SDF	Full Day
25	ZKB, PVV, PS4, PS1; Helio stays at SDF	Full Day
26	BVB (late start weather)	1/2 Day
27	Weather	None
28	Weather	None
29	SQH (late start weather)	1/2 Day
30	Change pilots, bad weather Cold Bay; did SQH by boat	None
31	PN2, PN5, BVB	Full Day

<u>Date</u>	<u>Itinerary</u>	<u>Helio-Field Services</u>
September 1	Late start (weather), SGB	1/2 Day
2	Weather	None
3	PN3, PN4, PN6, PN7, PN8	Full Day
4	Weather, BAL by motorcycle	None
5	PN1, BLH	Full Day
6	Weather	None
7	PN2, BLH, BVB; scientists stay at CDB	Full Day
8	Transfer from Cold Bay to Dutch Harbor; all crew and scientists stay at DUT, service MKV	Full Day
9	AKV, MKV, DUT, CPS; all crew and scientists stay at CPS	Full Day
10	Transfer of scientists from CPS to SDP	Full Day
11	BKJ, IVF, SGB, one scientist to CDB	Full Day
12	Depart for Kodiak	None

STATISTICS ON JUNE HELICOPTER OPERATIONS:

Total helicopter days: 23

Number of full service days: 7 (i.e. June 2,6,7,11,14,15,22)

Number of days with limited service: 6 (i.e. June 10,12,13,17,19,23)

Days without helicopter available for station services: 10, of which at least 7 were due to bad weather conditions.

STATISTICS ON AUGUST/SEPTEMBER OPERATIONS

(EXCLUDING LOST DAYS PRIOR TO AUGUST 20):

Total helicopter days: 24

Number of full service days: 12

Number of days with limited service: 3

Number of days without helicopter services: 9

COMBINED STATISTICS, ENTIRE FIELD SEASON 1978

Total helicopter days: 47

Full service days: 19

Days with limited service: 9

Days without helicopter service: 19

COMMENTS

From the summary of the day-to-day operations it is apparent that during the entire season the full day was available for helicopter-supported field operations only 40% of the time. Roughly 20% of the days, helicopter operations were possible only for part of the day: high winds, low ceiling and low visibility often imposed limitations onto which stations could be reached. During these days often we could not reach those sites which from a technical point of view needed attention most urgently. More than 40% of the days helicopter support was not available at all due to unsuitable weather conditions, or (only a few days) because of helicopter maintenance and change of helicopter crew, respectively.

The no-service days and the limited service days could be somewhat reduced in number, even given the same (unusually) bad weather conditions that existed in June 1978, if in forthcoming field seasons the helicopter is stationed at Sand Point rather than Cold Bay. It is the most common weather situation in this region that flying weather exists either on the Bering-Sea/Cold Bay side or on the Pacific/Sand Point side of the Alaska Peninsula, but rarely exists on both sides simultaneously. Since the scientific crew was stationed (primarily) at Sand Point and the helicopter and its crew (primarily) at Cold Bay the chances were high that the helicopter could not leave from Cold Bay at all or only later in the day, even when flying conditions may have existed out of Sand Point. Also the loss of at least two hours round trip Cold Bay/Sand Point/Cold Bay for most flying days reduces at least in some cases the flying time available for station servicing. We appreciate the past efforts of the helicopter crews to minimize these negative effects by sometimes staying overnight in Sand Point. But a more basic solution of this

problem seems possible. The major difficulty is the absence of a commercial jet fuel supply at Sand Point. Provided a sufficient number of barrels of jet fuel is shipped prior to the beginning of the field season to Sand Point this problem can be overcome. We realize that the pure fuel-costs may be raised somewhat by this logistic approach. But we believe that the over-all number of days that the helicopter would have to be stationed with this project could be reduced enough to more than off-set the increase in fuel cost. Note also that the fuel costs associated with two hours/day for round trip Cold Bay/Sand Point/Cold Bay could be saved. We seriously encourage NOAA to check further into this matter and hopefully to follow our suggestion of stationing the helicopter and its crew at Sand Point and providing enough jet fuel at this base in advance.

We fully acknowledge the fact that NOAA, and in particular the logistics office at Juneau, made all efforts to provide sufficient helicopter time in the second half of the field season in August by extending helicopter support far into September, beyond the scheduled time. Without this support and the energetic attitude of pilots and mechanics, the necessary servicing of the seismic station network could not have been achieved.

CONCLUSION

Due to the extended helicopter support we achieved 100% of the set tasks for fieldwork. The Shumagin array is almost fully operative, although some signal problems could not be resolved for IVF which operates intermittently. The entire Pavlof array is now recorded at Sand Point. The entire Cold Bay array is operative and is also recorded at Sand Point. All 3 stations of the Dutch Harbor array are serviced and operating, but central recording of MKV and AKV cannot be resumed until final installation of the new central

recording device about two months from now. In addition we obtained excellent results from precision leveling on Unga Island (Squaw Harbor) and during the geological surveys of recent faulting and uplifts throughout the visited sites in the Shumagin Islands and portions of the Alaska Peninsula. The only optional task not complete was installation and servicing of sea-level-meter installations. Since this was handled on a low priority level and is not a task funded under the NOAA/OCSEAP program it cannot be counted as non-achievement.

ACKNOWLEDGEMENTS

We express our sincere thanks to all pilots and mechanics for their professional and enthusiastic performance throughout the entire field operation.

LAMONT-DOHERTY ALEUTIAN STATIONS, MAY 1978

<u>STATION</u>	<u>CODE</u>	<u>COMPONENTS</u>	<u>N. LAT</u>	<u>W. LONG</u>	<u>ERROR (m)</u>	<u>ELEV. (m)</u>	<u>ELEV. (ft)</u>
Saint Paul [†]	SNP	SPZ, LPZ	57°09.28'	170°13.09'	~ 1000	5	16
Dutch Harbor [†]	DUT	SPZ, SPH, LPZ	53°53.9'	166°32.2'	~ 1000	60	197
Makushin Valley [†]	MKV	SPZ	53°55.8'	166°39.0'	~ 1000	275	902
Akutan Volcano [†]	AKV	SPZ	54°07.8'	166°03.8'	151	381	1250
Sand Point*	SDP	A	55°20.48'	160°29.75'	22	30	98
Sand Point*	SAN	SPZ, SPN, SPE	55°20.40'	160°29.83'	22	23	75
Sand Point*	SAN	LPZ, LPN, LPE	55°20.40'	160°29.83'	22	23	75
San Diego Bay*	SCB	SPZ	55°32.75'	160°27.23'	31	275	902
Ivanof Bay*	IVF	SPZ	55°53.75'	159°31.80'	22	275	902
Big Koniugi Island [†]	BKJ	SPZ	55°09.64'	159°33.92'	~ 30	240	787
West Unga Island [†]	WUN	A (see CHR)	55°19.9'	160°44.4'	~ 500	150	492
Pavlof Volcano**	PVV	SPZ	55°22.451'	161°47.399'	10	164	538
Squaw Harbor*	SQH	SPZ	55°13.20'	160°33.74'	307	360	1181
Nagai Island*	NGI	SPZ	55°02.36'	160°04.15'	27	240	787
Chernabura Island*	CNB	SPZ	54°49.22'	159°35.30'	~ 50	90	295
Zachary Bay [†]	ZKB	SPZ	55°18.66'	160°44.43'	~ 10	183	600
False Pass [†]	FPS	SPZ	54°56.5'	163°26.2'	~ 2200	120	394
Sanak Island [†]	SNK	SPZ	54°28.44'	162°46.52'	70	159	522
Deer Island*	DRR	SPZ	54°55.41'	162°16.99'	28	380	1246
Dolgoi Island*	DOL	A	55°05.75'	161°45.20'	32	275	902
Dolgoi Island*	DLG	SPZ	55°08.46'	161°50.15'	32	367	1204
Baldy Mountain [†]	BAL	SPZ	55°11.593'	162°47.208'	1	28	918
Black Hills [†]	BLH	SPZ	55°42.15'	162°03.95'	40	390	1279
Coal Harbor Repeater [†]	CHR	R	55°19.9'	160°44.4'	~ 500	150	492
Cape Sarichef [†]	CPS	SMA	54°35.8'	164°55.6'	178	30	98
Eagle Harbor ^{††}	ECH	TG	55°06.8'	160°05.9'	~ 1500	1	3
Pirate Cove ^{††}	PRC	TG	55°21.5'	160°21.9'	~ 1000	1	3
Kalboa Bay ^{††}	BBB	TG	55°33'	160°45'	~ 5000	1	3

<u>STATION</u>	<u>CODE</u>	<u>COMPONENT</u>	<u>N. LAT</u>	<u>W. LONG</u>	<u>ERROR (m)</u>	<u>ELEV. (m)</u>	<u>ELEV. (ft)</u>
Pavlof South 1**	PS1	SPZ	55°25.339'	161°44.173'	10	300	983
Pavlof South 2**	PS2	SPZ	55°24.402'	161°48.154'	10	459	1506
Pavlof South 3**	PS3	SPZ	55°23.517'	161°49.014'	10	450	1476
Pavlof South 4**	PS4	SPZ	55°21.238'	161°52.091'	10	520	1707
Pavlof North 1**	PN1	SPZ	55°33.629'	161°57.118'	10	522	1712
Pavlof North 2**	PN2	SPZ	55°30.482'	161°58.177'	10	344	1127
Pavlof North 3**	PN3	SPZ	55°30.353'	162°00.495'	10	330	1082
Pavlof North 4**	PN4	SPZ	55°28.819'	162°01.369'	10	434	1424
Pavlof North 5**	PN5	SPZ	55°28.487'	161°53.524'	10	622	2040
Pavlof North 6**	PN6	SPZ	55°27.118'	161°54.888'	10	814	2670
Pavlof North 7**	PN7	SPZ	55°26.591'	161°56.781'	10	780	2258
Pavlof North 8**	PN8	SPZ	55°26.623'	162°01.246'	10	605	1984
Pavlof Repeaters 1,2	PR1,2	R	SEE BLH	SEE BLH	SEE BLH	SEE BLH	SEE BLH
Pavlof Repeater 3†	PR3	R	55°45.5'	161°12.1'	~ 500	488	1600
Beaver Bay††	BVB	R	55°31.9'	160°59.2'	~ 1000	518	1700

†† picked from C and GS chart 8802, September 1978

* picked from 1:63K maps, May 1978

† picked from 1:250K maps, May 1978

taken from October 1975 list of station coordinates

** taken from geodimeter/theodolite surveys made during June - August, 1977

‡ measured from nearby benchmark, June - August 1977

A abandoned station

R repeater only

APPENDIX IV

Time devoted by Principal Investigators

First three quarters (March 1 to November 30, 1978):

J.N. Davies	4.00 mo.	(44% of time)
K.H. Jacob	3.85 mo.	(42% of time)
L.R. Sykes	.60 mo.	(6% of time)

Expected time devoted during final quarter:

J.N. Davies	1.00 mo.	(33% of time)
K.H. Jacob	1.40 mo.	(46% of time)
L.R. Sykes	.40 mo.	(13% of time)