A FIELD STUDY OF EARTHQUAKE PREDICTION METHODS IN THE CENTRAL ALEUTIAN ISLANDS

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TECHNICAL SUMMARY

Investigations and Results. Detailed monitoring of the seismicity within the seismic zone covered by the Adak network continues to be the main routine task under this project. Standard procedures are now developed for rapid location of all detectable local earthquakes, the level of detectability depending primarily on the weather conditions. Various analyses show that the catalogue of Adak earthquakes compiled since August, 1974 is complete down to coda-duration magnitude of 2.2. The association of the spatial distribution of the small to moderate earthquakes with the tectonic features of the island-arc - subduction zone system is now reasonably well-defined, but the question remains of the interrelation of the small active seismic source regions during a large event.

Temporal variations in the patterns of occurrence of small earthquakes and premonitory changes in the orientation of their focal mechanisms appear to be the most promising indicators of the approach of a larger event. In order to monitor the former, monthly maps of the seismicity and plots of the cumulative number of earthquakes in each sub-region are now being prepared as standard products of the analysis procedure. The earthquake counts are also displayed for various magnitude bands, because changes within limited ranges of magnitude, equivalent to changes in "b-value," have been seen to be diagnostic of an impending earthquake in some other studies.

Two independent approaches to determining focal mechanisms of the small earthquakes, in spite of the limitations imposed by the inadequate azimuthal coverage of the observations imposed by the geography of the region, have been developed and applied. One of these compares the observed first motion polarities with all of the mathematically possible combinations that could be produced by the 13 stations of the network and objectively classifies the set (usually containing fewer than 13 observations) for each earthquake. The results to date have produced mechanism types that are physically, as well as mathematically, possible and show changes in time of the predominant orientation of the fault planes, even though reliable focal mechanism solutions cannot be derived from the observations. The other method uses the distribution of SV to P wave amplitude ratios at stations of the network as input to a procedure for solving for fault strike, dip and slip direction. This technique shows promise of providing more focal mechanism solutions from the data, now that digital seismograms are available for amplitude analysis.

Observations of gravity have now been made twice at all of the seismograph station locations, as well as at a net of points on Adak Island. These are spaced one year apart, tied to the annual major maintenance trip, and will be repeated in the future. More-frequently spaced observations are very desirable for detecting secular elevation changes, but are not feasible under the current mode of operation.

The tiltmeters in the Adak network are working well, with their stability improved by better installations. Recent results show slow tilt changes on two adjacent instruments that track very well over many months. The possible tectonic significance of these tilts is not yet known.

Technical Advances. Slow but steady progress has been made toward the conversion of the seismogram analysis to a fully automatic system using digital data and the PDP 11/70 computer. Analogue FM tapes from Adak are played back at four times the original recording speed through a system designed and built by the project, events are automatically detected and a digital seismogram tape written for use in further analysis. This first part of the procedure is carried out on the PDP 11/34. The digital tapes are then used as input to the PDP 11/70. Events detected are displayed and non-earthquakes are discarded. Using software developed at the University of Washington, the operator can then read the times of arrival of phases from a CRT display and a location for the event is rapidly calculated. This entire analysis capability came on-line only at the end of the contract period.

The principal remaining problem is with the use of the event detecting algorithm. Work is in progress to insure that all readable events are picked for storage on the digital event tapes, with the number of non-seismic triggers reduced to a minimum.

INTRODUCTION

This is the final report on Contract No. 14-08-0001-16716, entitled "A Field Study of Earthquake Prediction Methods in the Central Aleutian Islands." The present contract has provided for continuation and extension of research that began in 1974. Because a new contract, No. 14-08-0001-19272, has been awarded to the University of Colorado for the continuation of research on the same subjects and continued operation of the Adak Seismic Network, the contents of this report are mostly a summary of achievements under the contract during the past six months, 1 April - 30 September 1980.

The principal goals of the research are to establish the distribution in time and space of the seismicity within the zone monitored by the network, to relate the seismicity to regional tectonics and geological features, and to search for and test premonitory phenomena associated with large earthquakes in this typical island-arc subduction zone. Other basic studies relevant to achieving these goals are also carried out under the contract.

Because of the constraints imposed by the island-arc setting, seismological data recorded by the Adak network from the large number of small-to-moderate earthquakes are the principal source of input to the prediction studies. In addition, an effort has been underway for several years to use tiltmeters to detect crustal deformations that might result from the subduction process or the preparation of the source region for a large earthquake. Although a great deal has been learned about the techniques for installing and operating the tiltmeters, no data of clear tectonic significance have yet been acquired. A modest program of repeated gravity measurements was initiated in 1979, with one repetition of the observations in 1980. Of necessity, these observations are tied to the annual summer maintenance trip. More frequent measurements that are required for detecting possible premonitory gravity changes are not yet feasible under the present mode of operation (and funding). Relative gravity has been read at 12 of the seismograph stations and six other points on central Adak Island. All of these readings are tied to benchmarks at the airports at Adak and Anchorage.

The objectives of the research related to prediction clearly require a long-term effort and viewpoint. Baseline data suitable for revealing changes related to an impending great earthquake are being accumulated and systematically synthesized, but only the occurrence of a great earthquake in due time can establish the value these observations and methods of analysis. Meanwhile, every moderate earthquake within the geographic scope of the network is carefully scrutinized for the occurrence of precursors detectable with the existing observational network.

NETWORK STATUS

The 1980 summer field trip, from mid-July to mid-August, was a success. Using a helicopter provided at no cost to the project by the National Oceanic and Atmospheric Administration (NOAA) as part of the Outer Continental Shelf Environmental Assessment Program (OCSEAP), all of the seismometer stations were serviced during an 11 day period and made ready for at least another 12 months of operation. In addition, the work at the seismic sites progressed rapidly enough that we were able to release the helicopter during this period to transport Cornell University geologists on Adak Island to and from their field site on Tanaga Island, to transport personnel from the Fish and Wildlife Division on Adak to several sites of interest to them, and to transport NOAA personnel to and from the NOAA ship Surveyor to sites on southern Adak and on southern Tanaga so that they could install and later remove transponders to aid in their mapping of Adak Canyon.

During the summer field trip, the seismometers at site AK4 (Bobrof Island) were moved several hundred feet to more solid soil, and the background noise at this station is now much less. New amplifiers and voltage-controlled oscillators were added to the seismometers at site ADK and the data from this site are now being recorded on analogue magnetic tapes, along with the data from the rest of the network (which we started recording in the summer of 1979). A 30 ft. tower was erected to hold the receiver antennaes, replacing the installation of these antennaes on the struts of the White Alice microwave dishes. The value of gravity was read again this year at 12 of the seismometer sites and at six additional sites established in 1979 on Adak Island near the Navy base. Meteorological instrumentation packages were installed at several of the tiltmeter sites, the vault tiltmeter was moved to a new borehole at the west tiltmeter site, and tiltmeters at the north and south sites were re-installed. A mini-computer was installed at the Adak Observatory to record the tiltmeter and meteorological data digitally on floppy disks. A more complete description of the 1980 summer field work is being prepared as a special technical report by S. Morrissey.

The seismic data, consisting of two Develocorder films per two days and one analogue magnetic tape per 12 hours, are sent to CIRES by mail about once each ten days. Thus, a minimum delay of two weeks in the availability of the data for analysis results. Delays of up to one month in the transmittal of the magnetic tapes sometimes occur because of poor postal service. Such delays can be accepted while the work is in a research mode, but are clearly unacceptable if the work progresses to the point that real-time analysis for the purpose of prediction becomes necessary. The routine processing for event locations carried out at CIRES has been greatly expedited by the careful work of the U.S.G.S. scientist at Adak, who has been doing the initial scan of the seismograms for occurrence of events.

The goal of fully automated event processing, based on the capability of producing digital seismograms, has been vigorously pursued in the past six months, but not yet realized. The primary data source for the hypocenter location procedure is still the Develocorder film. However, even this procedure was made much more efficient by the installation of a terminal at the film-reader in the spring of 1979, allowing direct input of the readings to the PDP 11/70. All earthquakes in the study region through July, 1980 have been located and filed in computer storage, with parts of August and September also completed.

The routine production of digital event tapes from the analogue field tapes came on-line at the end of September, 1980. Rapid progress toward converting the entire location procedure to the use of the digital data was being made at the end of the contract period.

DIGITAL DATA ANALYSIS

The conversion from the use of the analogue (Develocorder) film records to analogue magnetic tapes as the base data form for the Adak project is continuing. There are two stages in the processing of the magnetic tape data. First, digital event tapes are generated from the continuously recorded analogue tapes. Second, off-line interactive digital processing and a graphics display terminal allow Adak project personnel to discriminate between real and spurious events, to pick phase arrival times and to locate hypocenters. After these processing steps, several archive files are generated, storing (1) hypocentral information, (2) hypocentral information augmented by arrival time readings, characterization of the quality of the phase arrivals, etc., and (3) digital seismograms. The over-all processing scheme is shown in Figure 1. The first two archive files were established last year and are documented in the previous Semi-Annual Technical Report. This chapter deals with the two stages of processing of the analogue magnetic tape data.

Analogue-to-digital processing. During the summer of 1979, a tape-recording system based on two TEAC 33-4 audio tape recorders was installed at the Adak Observatory to record on analogue magnetic tape the F.M. carriers telemetered from the seismic stations. A tape reproduce system was installed in the CIRES computing facility in March 1980. Both the record and reproduce systems were designed, built and installed by S. T. Morrissey of St. Louis University. The reproduce system (see "Special Technical Report: The Adak - CIRES 32 channel Seismic Telemetry Line") includes two TEAC 33-4 audio recorders, a tape speed frequency-compensation system and a bank of signal

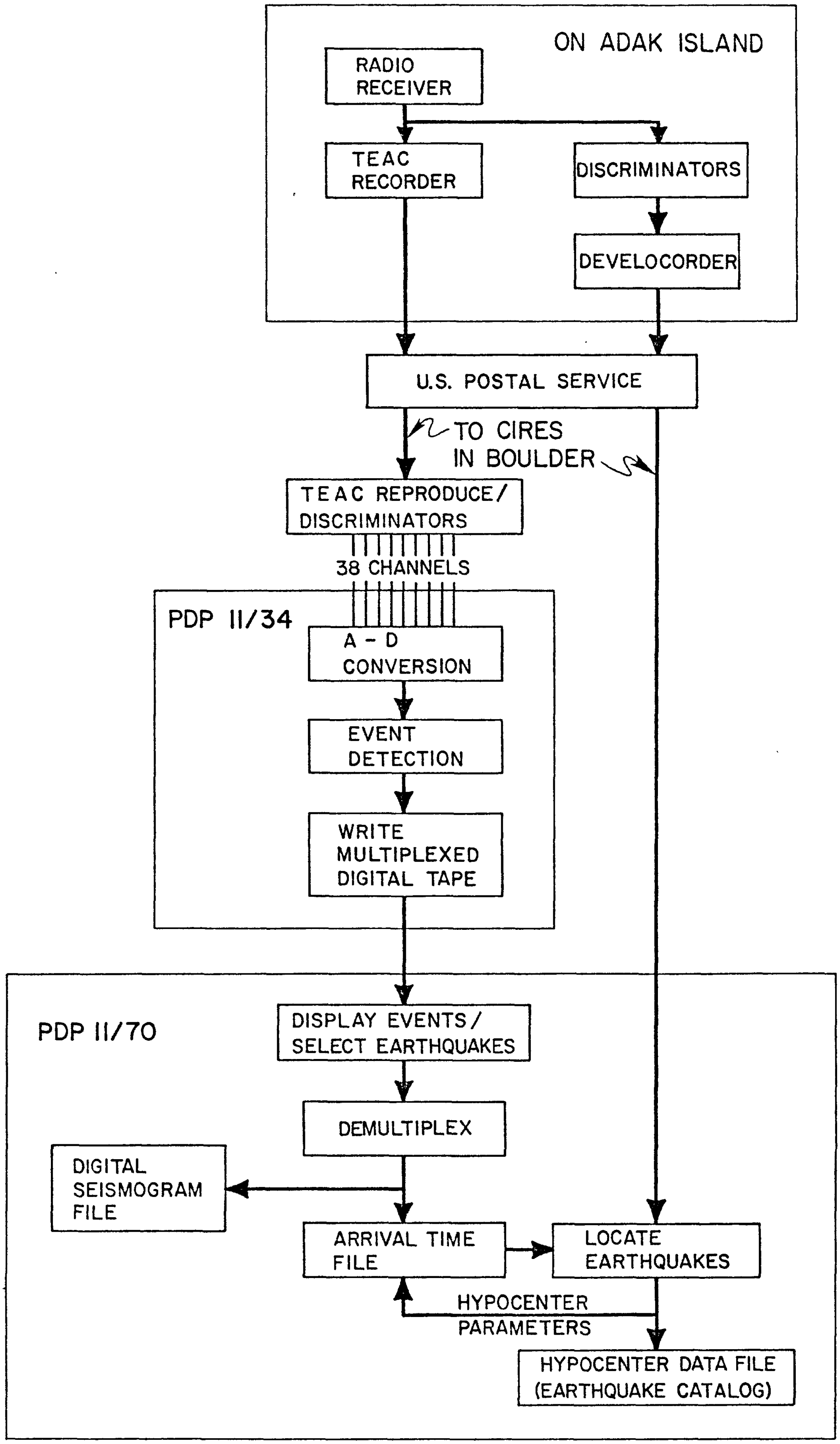

Figure 1. Flow chart representing data analysis. The primary data form for the project is still Develocorder film (right side of Figure), pending satisfactory implementation of the triggering algorithm.

discriminators which extract the seismic signal from the demodulated carriers recorded on the analogue tapes. The field tapes are played back at four times the original reading speed. The resulting analogue seismic data are then fed into a PDP 11/34 computer, which converts the data into digital form, detects events, and then writes digital event tapes, using software which was developed by S. Malone and his colleagues at the University of Washington.

The weak link in the series of operations currently is event detection. We have just started to experiment using different sets of "triggering" stations to discover the set which maximizes the detection of real seismic events while minimizing the number of spurious events detected. We are developing software to display values of triggering variables (average power on individual data channels in selected time intervals) during processing so that we can evaluate the system's performance while it is running. This should allow us to make more intelligent trigger refinements. Until our use of the triggering algorithm is satisfactory, we will continue to rely primarily upon the film records for routine analysis.

Other desirable improvements in the first stage of data processing include increasing the sampling rate. The central processing program responsible for the A/D conversion, directing the trigger, and writing events to digital tapes presently limits the sample rate to 250 Hz, which is 66 samples per second in real clock time. Higher sample rates cause the program to crash ungracefully. We are trying to eliminate disk I/O during processing to speed up the core program and allow use of higher sample rates.

By further automating the reproduce system, we are trying to minimize machine and operator time required for routine data processing. We are developing software to control the TEAC reproduce system from the computer. The PDP 11/34 will then be able to automatically queue analogue tapes at the beginning of one tape and switch the tape decks on and off at appropriate times, allowing the processing of 24 hours' data in six hours with one operation.

Digital event processing. This section describes off-line digital event processing operations for the Adak seismic network. While the CIRES on-line processing of data from the Develocorder films has been in operation for some time (Semi-annual technical report, April, 1980), the capability to locate and analyze local earthquakes with digital data was achieved only at the end of the current contract period. The CIRES digital event processing system is based on a code written by S. Malone and colleagues at the University of Washington.

Since the network was instituted in 1974, all hypocenter locations have been done manually by measuring arrival times from Develocorder records. In addition to being slow and subject to errors in data entry, this technique was often less than satisfactory for more fundamental reasons. Adjacent traces frequently overlapped, making phase identification difficult. First motion and amplitude determinations were handicapped by the condensed time scale and the limited dynamic range of photographic recording, which produces very faint traces when ground motion is rapid. Long hours of peering at the film viewer generated eye-strain and low morale among users of the old system. The digital event processing system eliminates all of these problems as well as providing new capabilities for the investigation of seismic hazards in the Aleutians.

Figure 2 shows a seismogram from a local earthquake recorded at station AK1Z. The trace is not obstructed by adjacent channels, has clearly defined P and S arrivals and a sharp first motion. Since this station is more distant from the hypocenter than most of the rest of the network, and since this event resulted in fairly high-amplitude traces, the Develocorder record of this station was largely obscured.

The operator of the digital event system has full control over horizontal and vertical scaling, trace positioning, and trace selection. The operator may, for example, wish to 'zoom in' on a section of the trace to aid in phase identification. Figure 3 shows expanded sections of seismograms at station AK1. The upper part of the figure shows the P-wave arrival on the vertical component with the time scale expanded by a factor of four over the previous figure. The direction of first motion is immediately apparent at this scale, and should remain fairly clear even on noisy days. The lower figure illustrates the S-wave arrival on the horizontal component of the same station. Since S-wave arrivals often are characterized by lower frequencies, judicious manipulation of the relative horizontal and vertical scales should improve accuracy of S-wave arrival times, resulting in improved depth determinations.

Expansion of traces can (theoretically) be continued to extreme. Thus the precision to which phase arrivals can be picked is limited only by the digitizing rate. Our effective digitizing rate is about 66 samples/second, so arrivals can be routinely read to within 0.015 second, where the data permit the onset to be picked with confidence. Develocorder records can seldom be read to better than 0.05 second precision.

The operation of the digital phase-picking system is relatively sim-

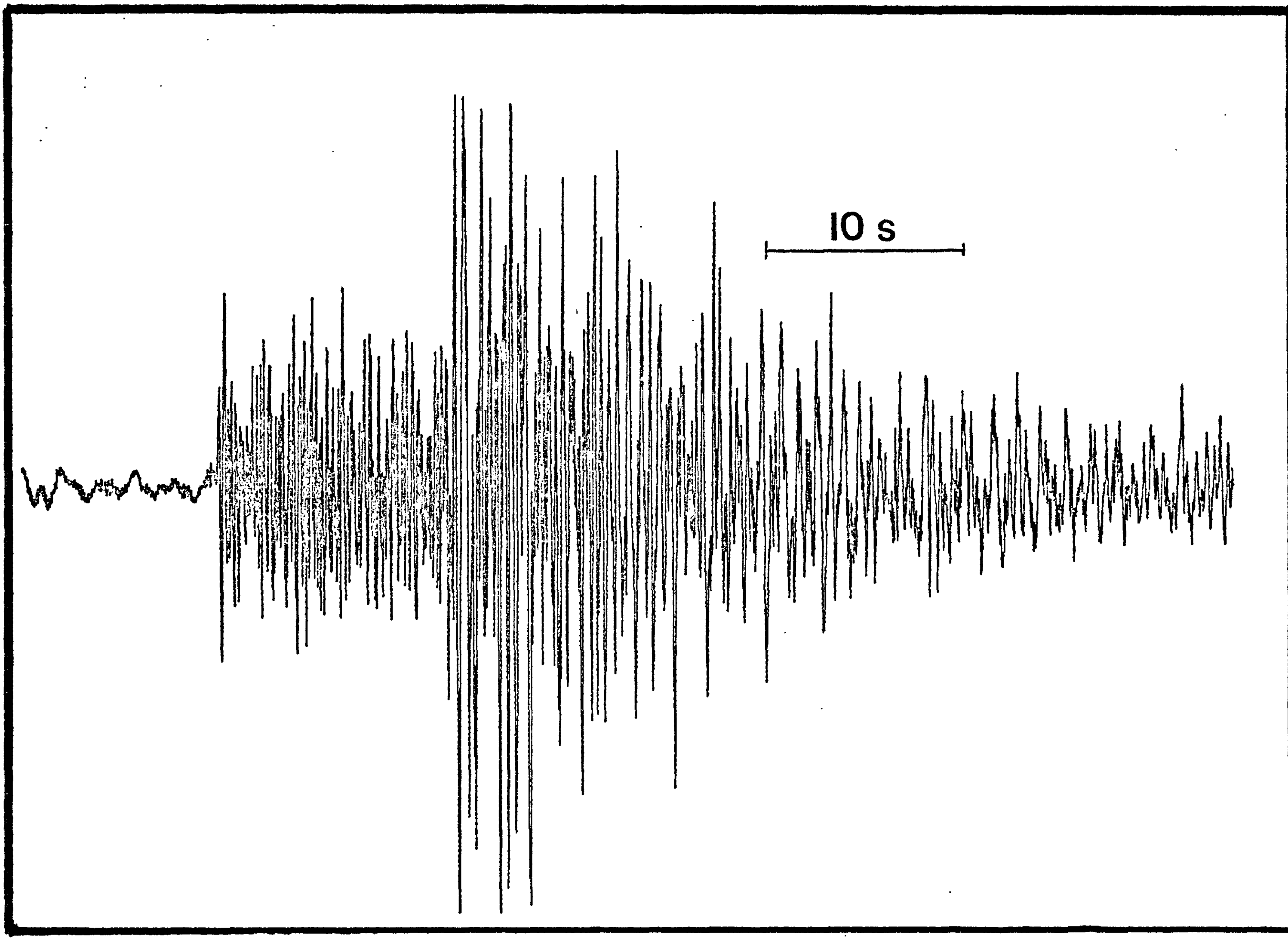

Figure 2. Seismogram from a typical, small (m<~2.5) local earthquake recorded on the vertical component of station AK1. This record is reproduced at approximately 1/3 the size it would appear on the Tektronix graphics display terminal. The first portion of this record is shown in expanded scale in Figure 3.

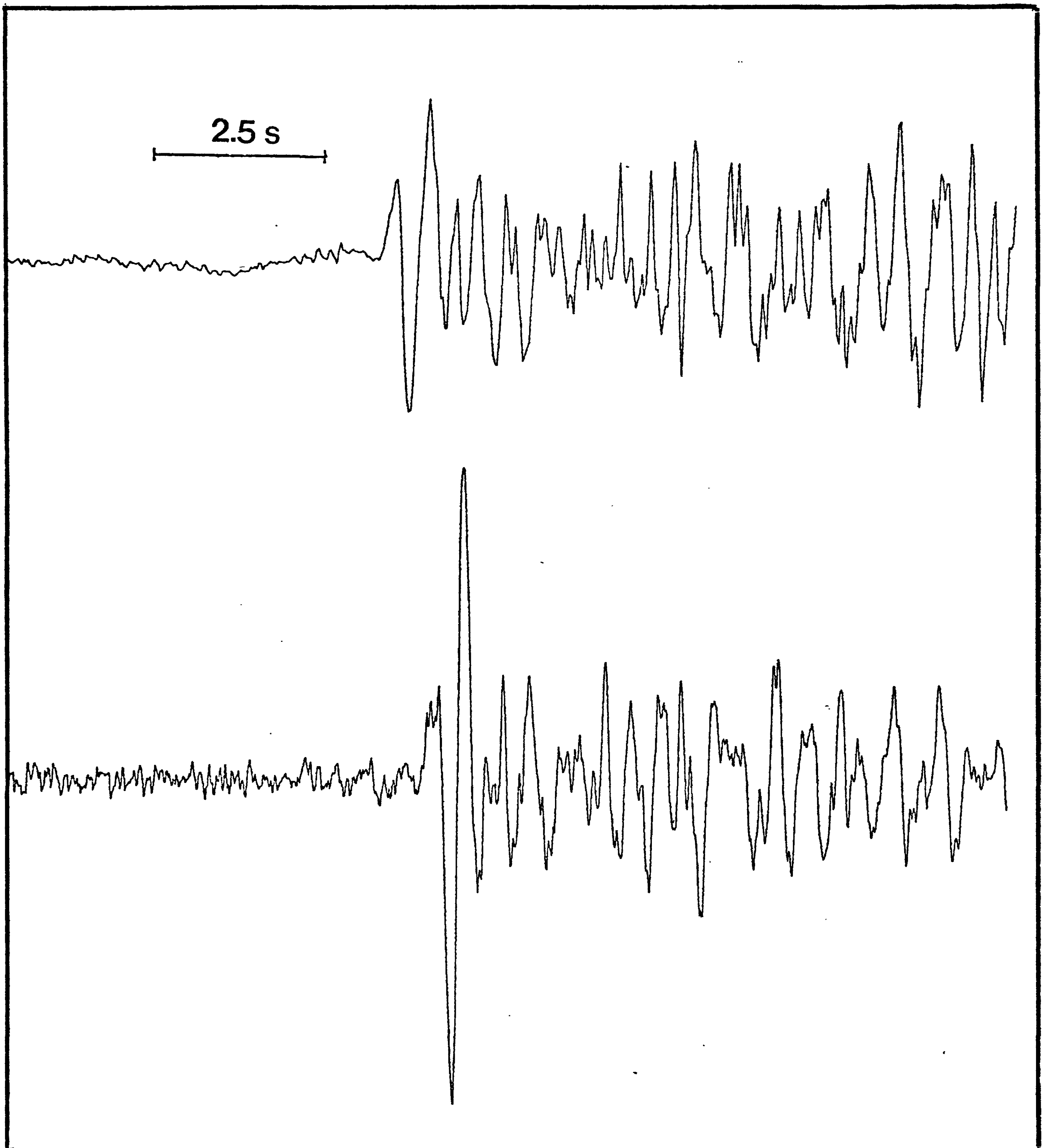

Figure 3. Expanded sections of seismograms from station AK1 for the same event as in Figure 2. Horizontal scale (time) is expanded by a factor of four. Vertical scale is the same as in Figure 2. The upper record shows the onset of the P wave on the vertical component. The lower section shows the S arrival on the horizontal (east-west) component, approximately 12 seconds after the P arrival.

ple, and locations can be accomplished very rapidly. Errors such as incorrectly read time codes should be eliminated when the software to read the IRIG time code is finished shortly. It is reasonable to expect that the time spent in locating a given number of earthquakes will be cut in half with the new system, even during the initial period of operator inexperience.

Digital data has many advantages over and above rapid location of earthquakes. The current system allows for fast filtering of the trace data. Figure 4 shows the same trace (AK1Z) as the previous figure filtered into very narrow frequency bands. Although these data were produced with a standard Butterworth filter, virtually any kind of filtering can be produced. This rapid filtering may provide a method for routine monitoring of the frequency content of Adak seismograms, enabling us to look for precursory changes in spectral content.

A few experiments have demonstrated that the digital seismograms will provide far more observations of SV and P amplitudes, as well as first motion directions, for use in focal mechanism determinations, than have been readable from the film seismograms. The improvement results primarily from the separation of the otherwise overlapping traces and not, unfortunately, from a basic increase in dynamic range. Because the seismograms are digitized from the demodulated FM signals and not at the seismometers, the problem of clipping at many of the stations for events bigger than about m_b 2.5 persists. Nevertheless, the digital data should provide the input needed for many more reliable focal mechanisms. These are important for their implications with regard to the regional tectonics and, especially significant, as promising precursors for larger earthquakes in this

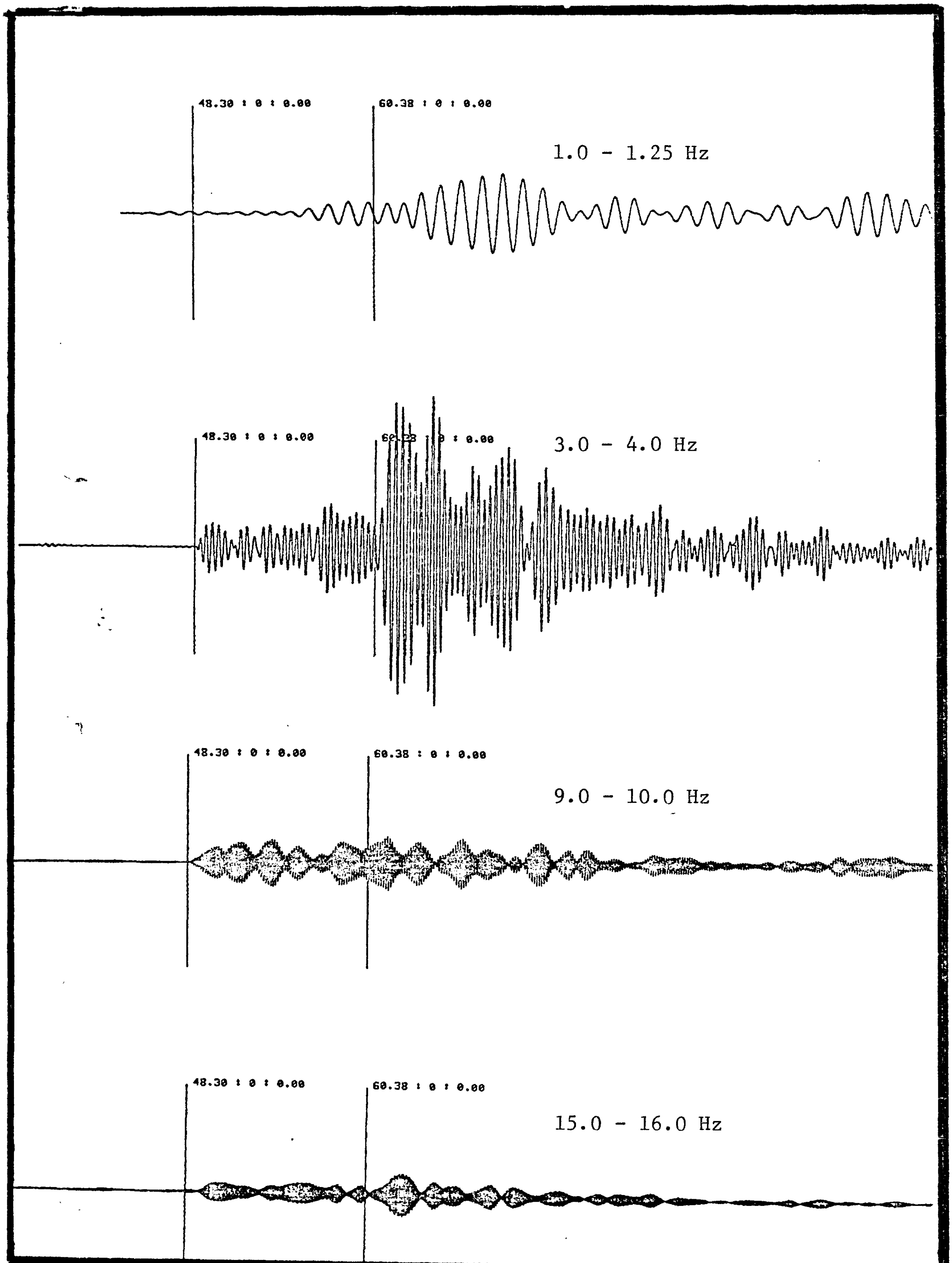

Figure 4. The event of Figure 2 bandpass-filtered through four bands. The arrival times of P and S are shown (vertical lines) for comparison. Relative spectral amplitudes determined in this way may provide a quick way of evaluating changes in earthquake spectra.

seismic zone.

Thought is being given to using the network in a 'beam-forming' mode. This technique might allow monitoring of the seismicity rate in a given region without the necessity of accurately locating each earthquake. This procedure, which is practical only with digital data, would not interfere with the routine operation of the network.

COMPUTERIZED SEISMICITY ANALYSIS

Since the Adak network was installed in 1974, a total of nearly 6,000 earthquakes have been located. The locations and origin times of events since January, 1979, along with magnitude and other information, are permanently stored on disk files in the CIRES PDP 11/70 computer. Earlier events are on magnetic tape, and have not yet been reformatted and combined with the data on disk files. Copies of locations with the times of P and S arrival at each station are also kept on magnetic tapes. Several programs have been developed at CIRES within the last few months to allow rapid access to and analysis of this large data set.

All seismicity analysis programs written for the Adak project use input in a standard format. This format is identical to that used in writing the so-called 'header cards' for each event. These 'header cards' (actually card images on disk files) include the type of the solution (fixed or free depth), the epicenter location, the depth, the magnitude, and information about the pattern of first motions across the network. The cards also contain coded information identifying the geographic subregion of the earthquake, and flags indicating the quality of the solution and any unusual features of the event. Header cards from the master file may be sorted by region, magnitude, depth, solution type, or any other stored parameter by use of the program *GEOSORT*. Output from *GEOSORT* is then available in the correct format for use in any of a number of analysis programs. Execution of *GEOSORT* requires less than 5 minutes for a search through the entire Adak data base.

Programs *MAPIT* and *PLOTIT* plot the locations of events in their input files onto the Hewlett-Packard four-color plotter or the Tektronix graphics terminal, respectively. Sample output from *PLOTIT* produced on a Versatec printer is shown in Figure 5, where the input file was the set of all located events in 1979.

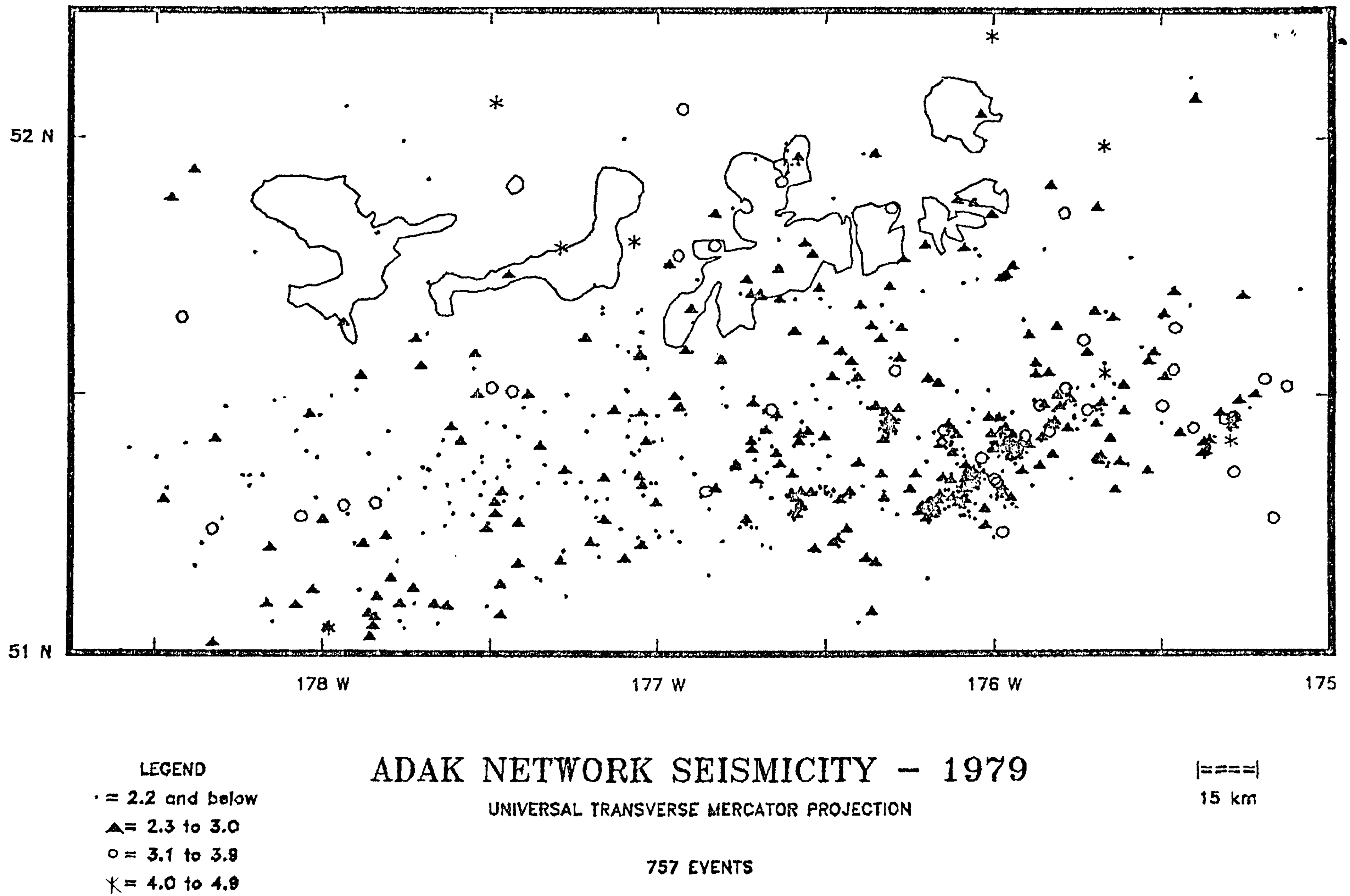

Figure 5. Map of seismicity near Adak which occurred during 1979. Epicenters located by the Adak seismic network. The islands mapped (from Tanaga on the west to Great Sitkin on the east) indicate the geographic extent of the Adak seismic network.

Programs *PLOTIT* and *MAPIT* require only a few minutes of execution time, once input files are prepared using *GEOSORT*.

Numerous authors have suggested variations in the rate of seismicity as an earthquake precursor. The rate of seismicity is conveniently monitored by plotting the cumulative number of events. The program *ACCUM* was designed for this purpose. Like the other analysis programs it is designed to work from a standard input file, so cumulative number plots by region, or sorted by magnitude band are immediately available. Figure 6 shows output of *ACCUM* for all events in the year 1979, broken down by arbitrary magnitude bands. The apparent increase in the rate of earthquake occurrences in July, 1979 is the result of the restoration of the full network during the summer maintenance trip. About half the network was taken out by a severe wind storm in October, 1977. While the larger events are locatable most of the time (their rate curve is essentially flat), smaller events can be consistently located only with the full network. This plot seems to confirm the general appraisal that the Adak catalogue is complete for events with magnitudes above 2.2. The levelling off of the curve for smaller events after September, 1979 was the result of the temporary loss of three stations and the onset of winter weather, with accompanying increased noise.

The portrayal of seismicity patterns which change in both time and space is a difficult problem. One approach is the use of space-time plots, in which one axis is time of occurrence and one axis is a spatial coordinate. Figure 7 shows output from program *SPATIM* which plots time vs. longitude of events. Relative sizes (magnitude) of events are shown by circles of differing radii. This figure shows events from January 1979 through the first quarter of 1980. Note the large gap at the lower left hand edge of the plot. This 'gap' is the result of the partial network outage described above, leading to a decreased capability to

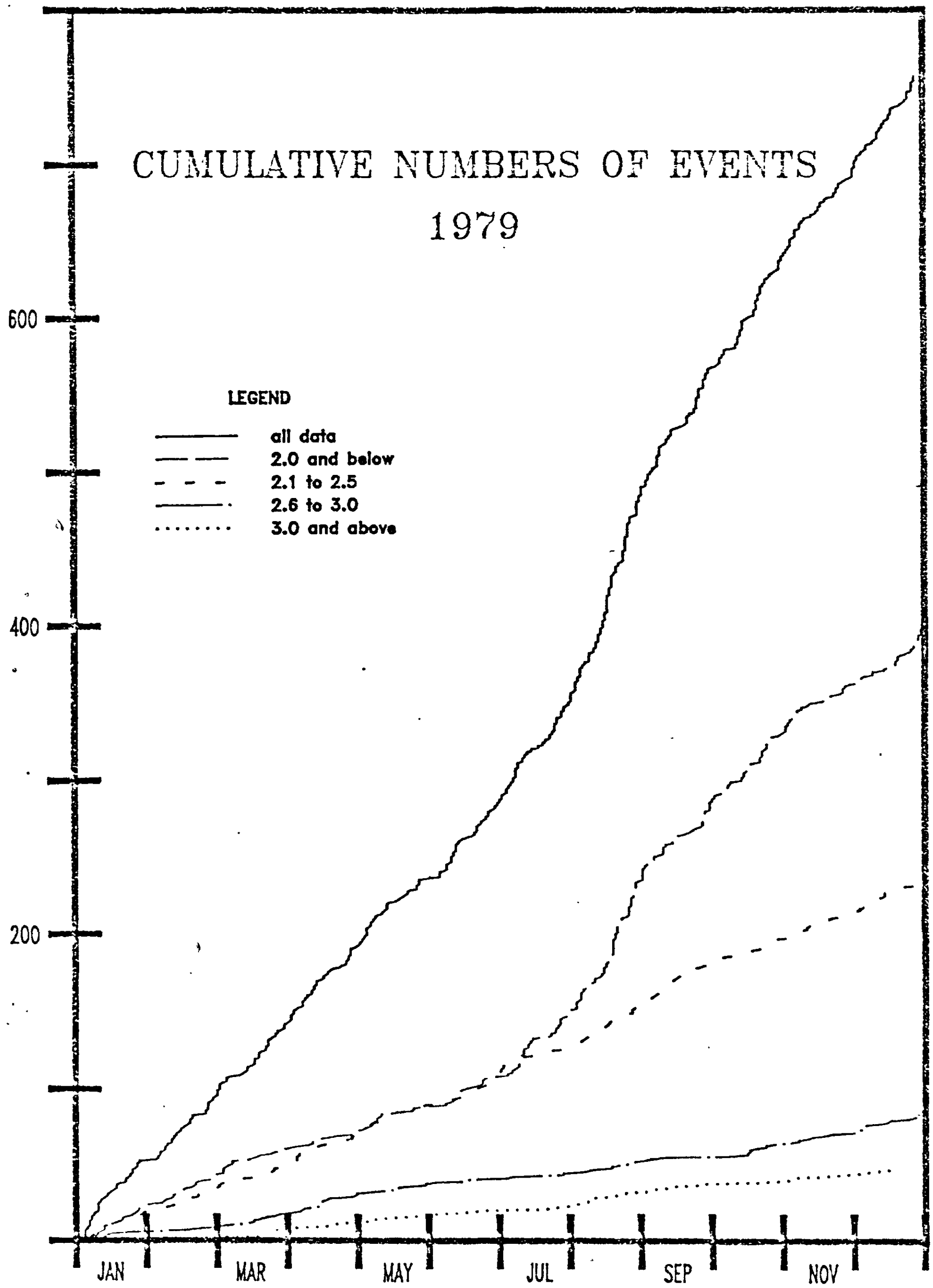

Figure 6. Plot of cumulative number of earthquakes as a function of time, broken down by arbitrary magnitude bands. All data from the network in 1979 is included. See text for explanation of apparent jump in activity rate in July, 1979.

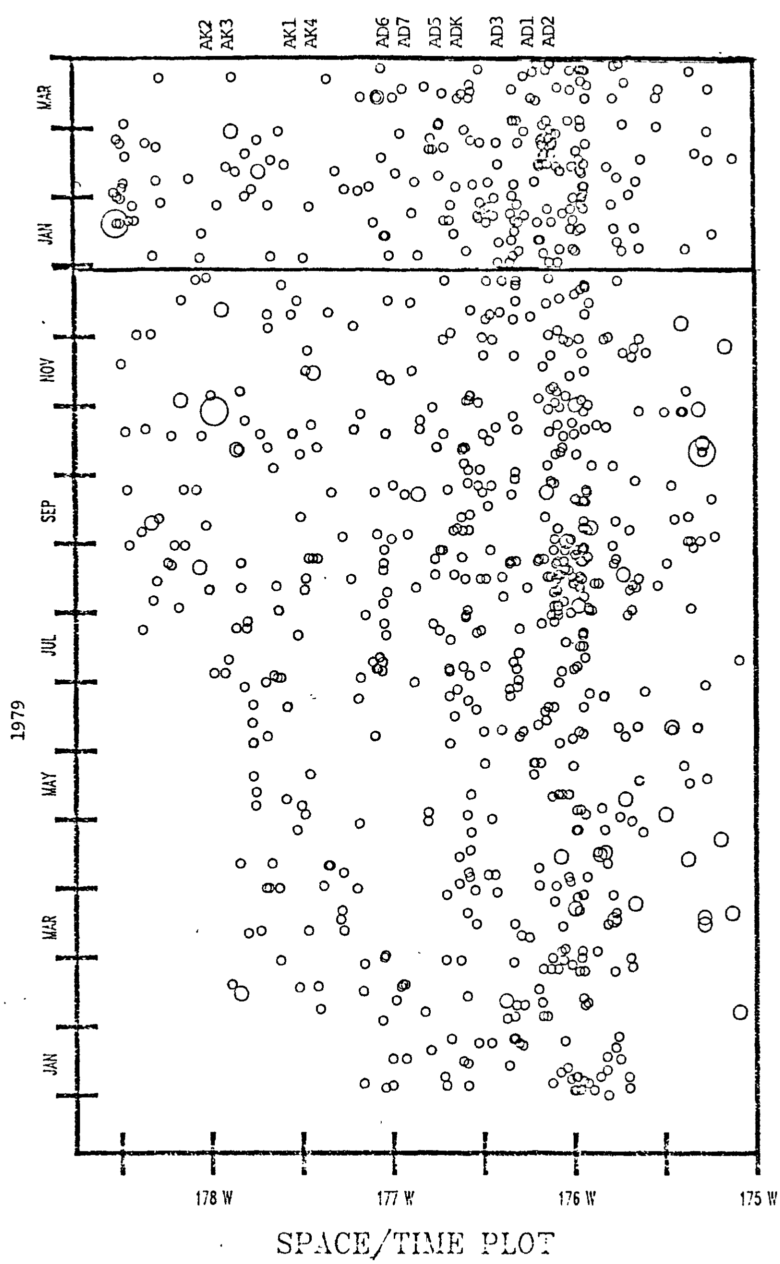

Figure 7. Plot of longitude of seismic events versus occurrence date. Plot includes all seismicity recorded by the network during 1979 and the first quarter of 1980. Circle sizes are scaled to magnitude: small circles for m<3.0; medium-sized circles for $3.0 \leq m < 4.0$; and large circles for $4.0 \leq m < 5.0$. No events occurred during this time with $m \geq 5.0$. Station names are marked at the appropriate longitude for reference.

adequately record events in the western part of the network early in 1979. This problem disappears in July, when the summer field trip restored the western part of the network to operation. This figure also shows intensified activity at about 176° W, through most of the time period shown. This area is the aftershock zone of the November 1977 earthquake, which has been active ever since that event. This 'clustering' also shows up on the seismicity map, Figure 5, illustrating the way in which these plots compliment one another. *SPATIME* is a very versatile program which can also be used to plot variation in latitude, depth, or first motion pattern with time.

The set of programs described here are all intended to compliment one another and to be fast and easy to use. A variety of studies are possible with very little effort. A user may, for example, wish to study those events within the network which are poorly located. *GEOSORT* can be used to find events with large travel-time residuals, then *MAPIT* to examine the locations of those events. It may be possible to locate areas of unusual velocity characteristics in this fashion. Alternately a user may notice a change in the seismicity rate in a given magnitude band by examining the output of *ACCUM*. The user could then use *SPATIM* only on events in that magnitude band to examine the spatio-temporal variation and use *PLOTIT* to map out the locations of those events. Additional analysis programs are currently being developed.

Monthly seismicity maps for the first quarter of 1980 are shown in Figures 8. Such maps are run as standard product of the data processing procedure.

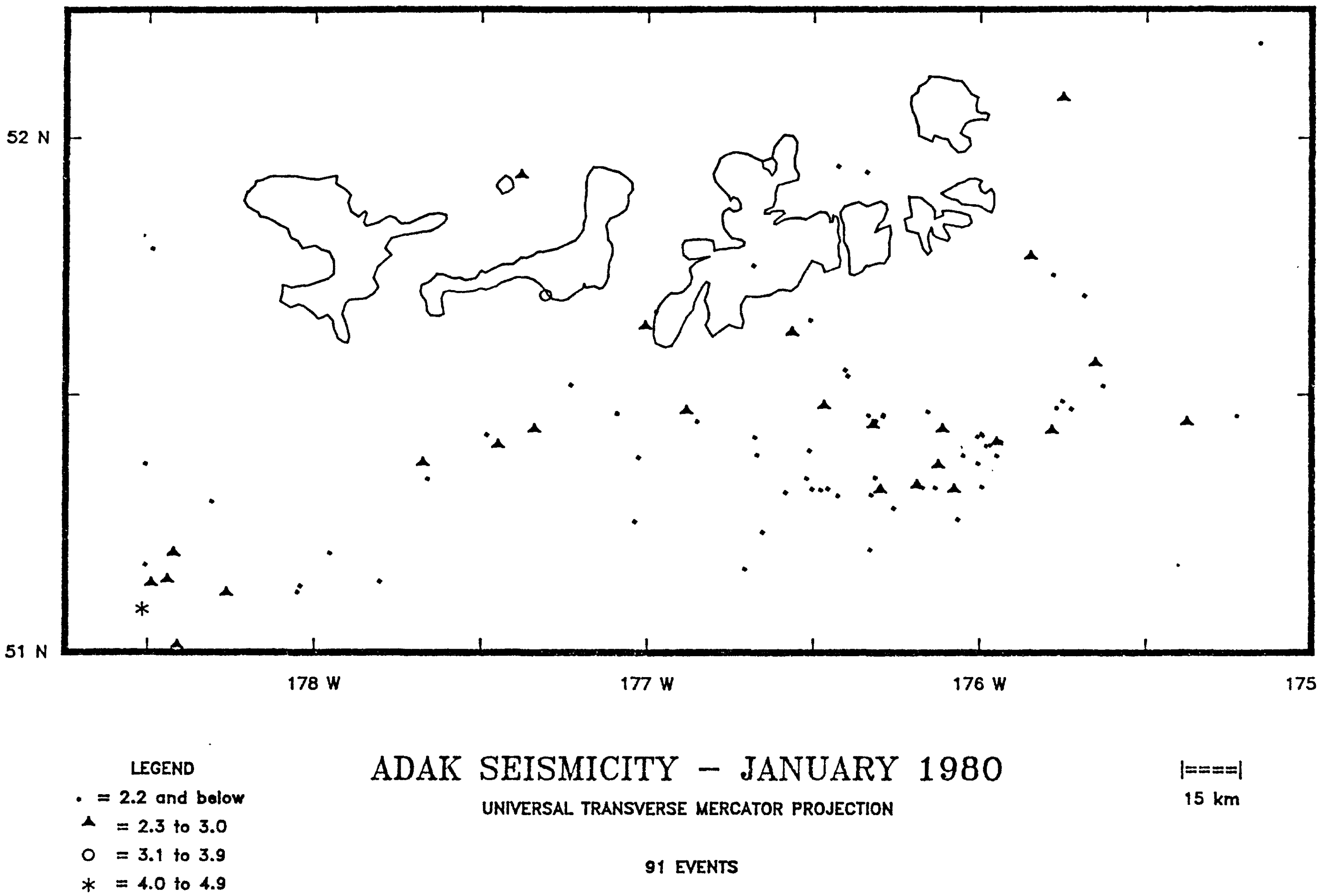

Figure 8a. Seismicity map for January 1980. Epicenters located by the Adak network. The islands shown are as in Figure 5.

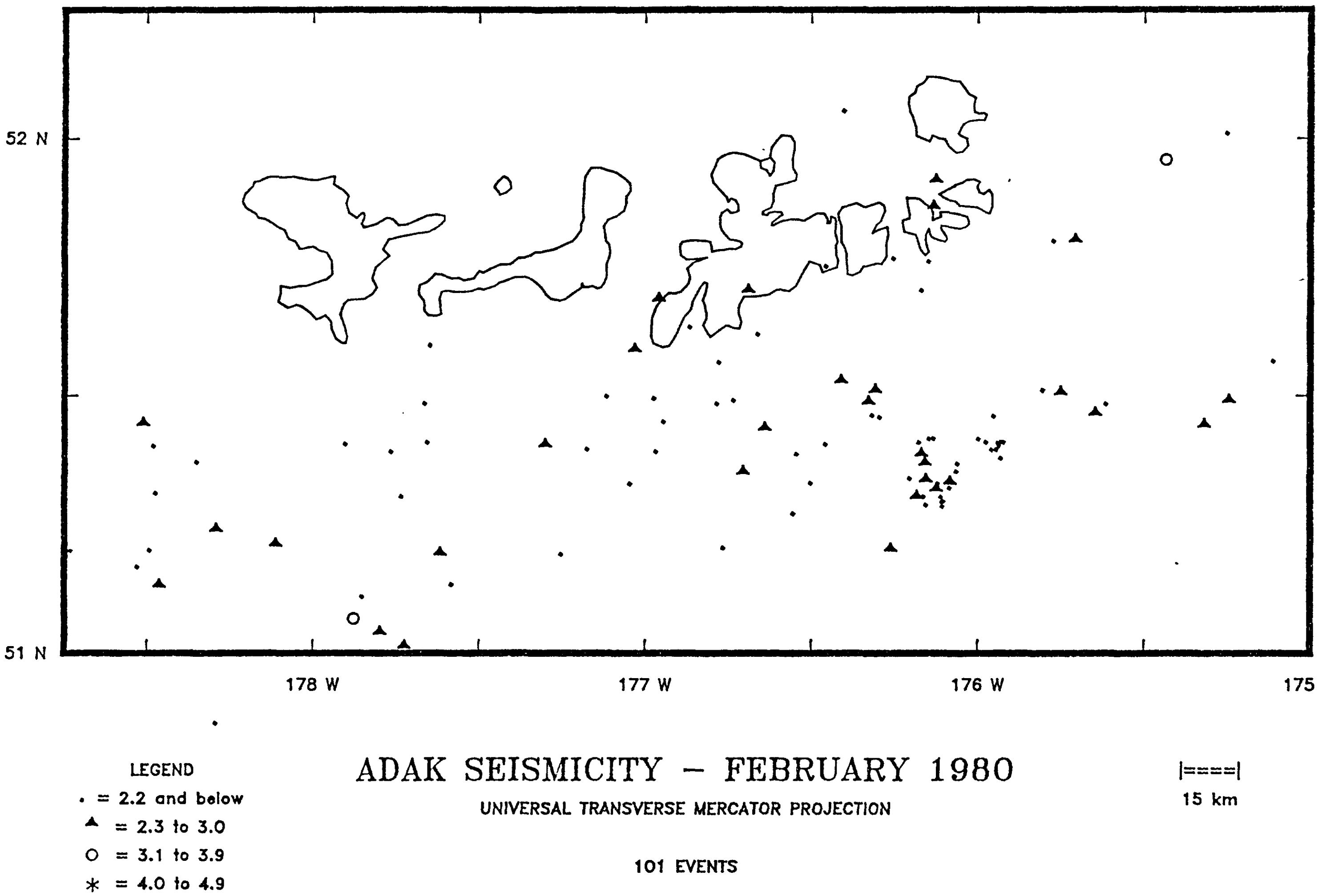

Figure 8b. Seismicity map for February 1980. Epicenters located by the Adak network. The islands shown are as in Figure 5.

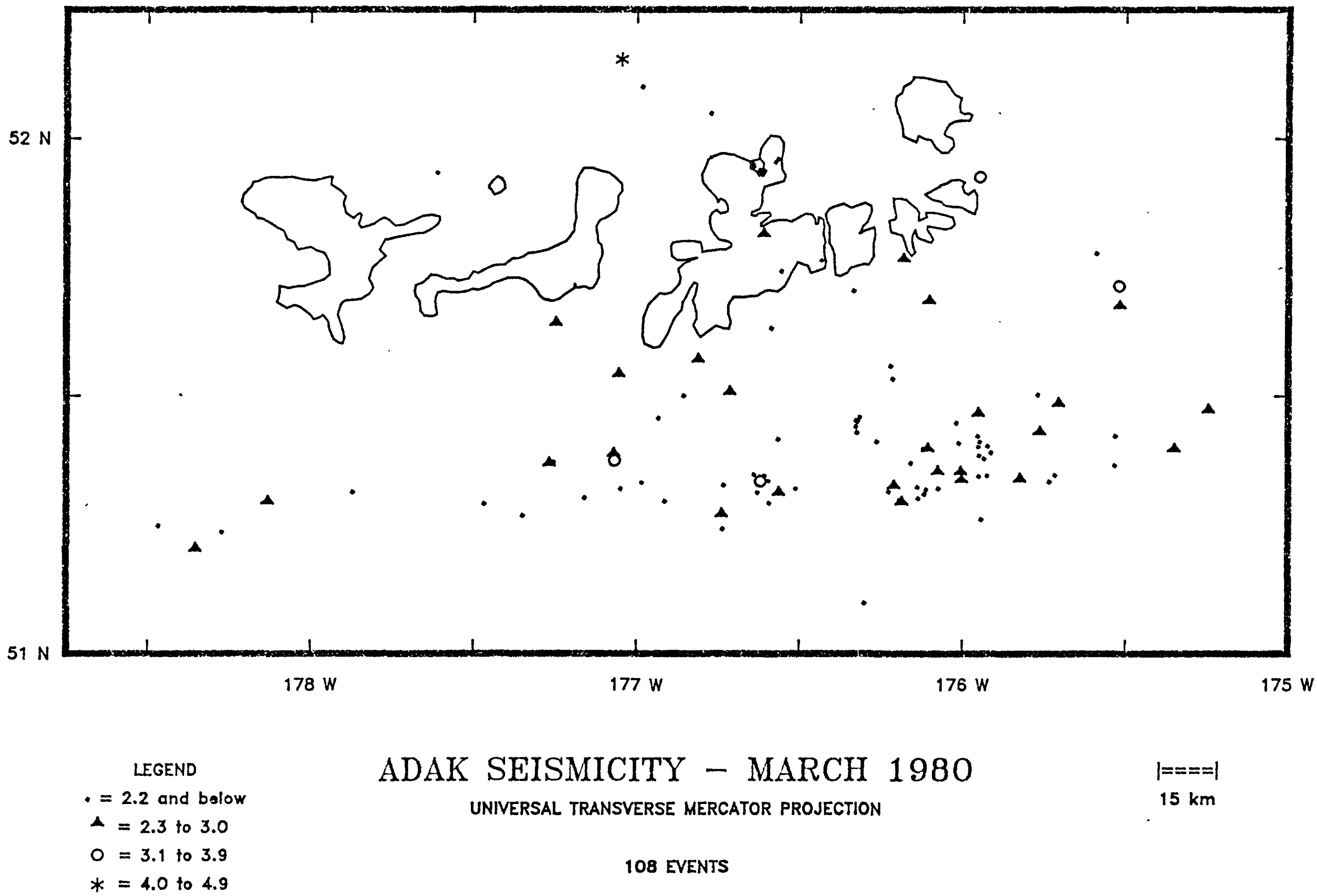

Figure 8c. Seismicity map for March 1980. Epicenters located by the Adak network. The islands shown are as in Figure 5.

FOCAL MECHANISM STUDIES

Variations in the Mechanism of Small Earthquakes before the 04 November 1977 M_S 6.7 Earthquake. A study has been completed of the mechanism of small earthquakes in the source region of the 04 November 1977 M_S 6.7 earthquake, which occurred in the southeastern region of the Adak network coverage. A manuscript describing the study and its results has been submitted for publication in the Fourth Ewing Symposium Volume. The study depended upon the development of a method to objectively generate composite focal mechanism solutions using P-wave first motion data from 13 local stations of the Adak net. The method itself is based on a correlation between the observed first motion data for a set of earthquakes and each of the 2^{13} mathematically possible patterns of P-wave first motions for a network of 13 stations. A detailed discussion of the method, the data used, and the results for the small source region which we term SE2 is presented in previous Semi-Annual Technical Reports. Therefore the emphasis of this report will be on a comparison of results from the five small source regions in the southeastern region of Adak network coverage for which the method was successful.

Figure 9 is a map of the region of interest for this study. Circles on the map are epicenters of events with duration magnitude of 2.2 or greater which occurred from August 1974 through June 1978. The epicenter of the November 1977 mainshock is shown as a solid square; it is located on the boundary between the small source regions which we term SE2 and SE4. Aftershocks of the M_S 6.7 earthquake occurred only in the regions we term SE2, SE4, and SE6. Data for this study were obtained by careful re-reading of the P-wave first motions for all of the 357 events shown in Figure 9 from Develocorder records of 13 vertical component seismometers of the Adak network.

The small source regions shown as rectangles on the map were used to del-

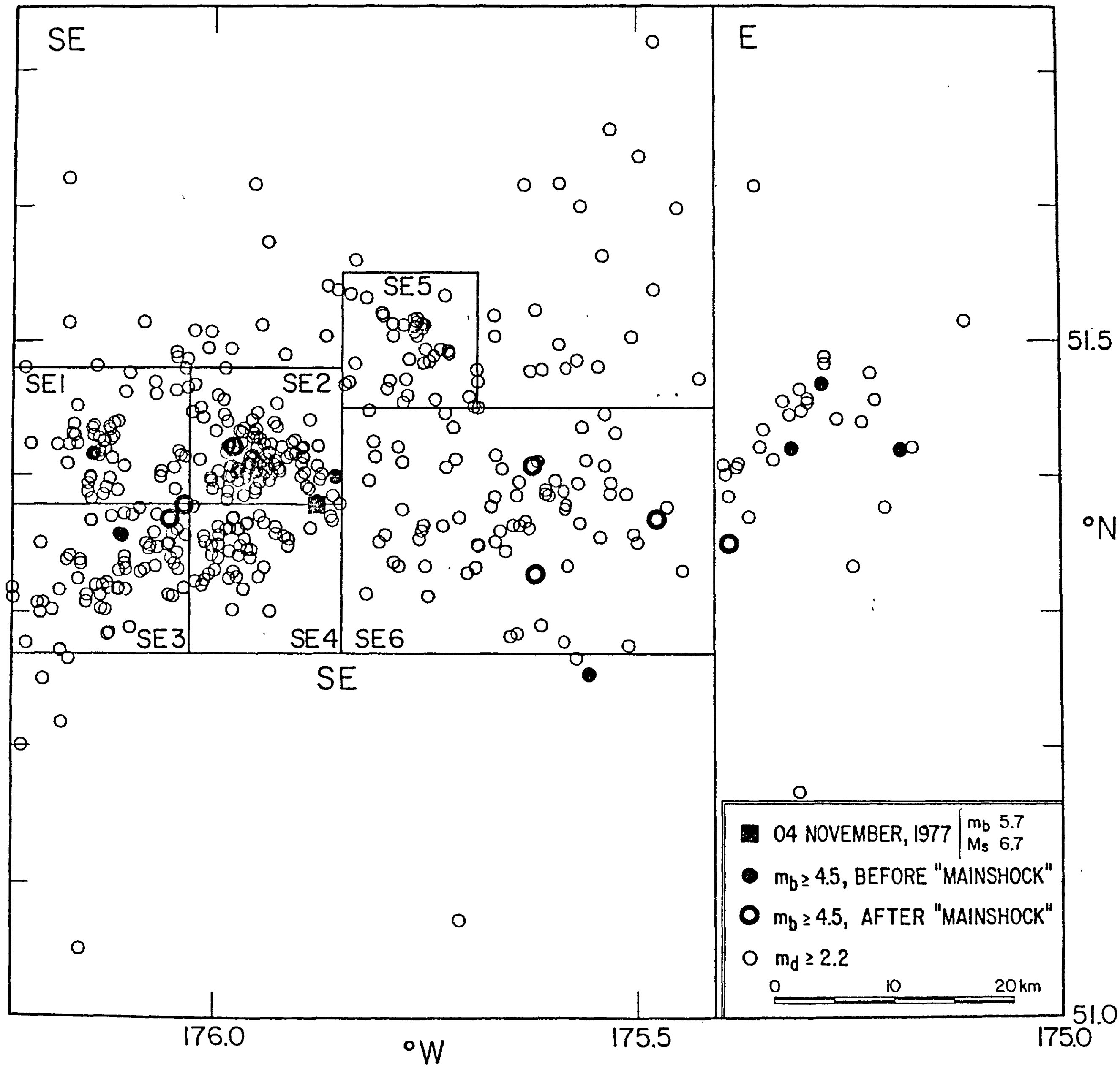

Figure 9. Map view of seismicity in the southeastern portion of the network coverage area for the time period from August 1974 through June 1978. Circles mark events with duration magnitude (m_b) greater than or equal to 2.2 (or body-wave magnitude greater than or equal to about 2.7). The filled square is the epicenter of the November 4, 197 main shock. Epicenters of events with m_b greater than or equal to 4.5 which occurred before the main shock are marked by filled circles; those which occurred after the main shock are marked by heavy open circles. One m_b 5.0 earthquake, which probably occurred in the map area in August 1976, is not shown; it occurred when one of the two Develocorders was off and the galvanometer traces on the other were being interchanged. The straight line segments define small regions used by Adak personnel to classify seismicity occurring in small spatial clusters.

imit the events considered together in the analysis. The method has been applied to each of the regions shown on the map, and has successfully selected patterns of first motion which fit the observed data for the regions which we term SE1, SE2, SE3, SE4, and SE5. These few special patterns for each region are compatible with physically plausible focal mechanism solutions, and different sets of events are associated with each of the different special patterns for each region. Generally, the data for each of the few special patterns are insufficient to uniquely determine a solution, but it can clearly be shown that the different special patterns of first motions represent different mechanisms. The analysis of the data in the region we term SE6 was not successful, because the region is relatively large, because there were very few earthquakes occurring in the region before November 1977, and because of the greater distance from this region to the network.

Since different sets of events are associated with each of the few special patterns, an immediate output of this method is obviously a sorting of events according to the focal mechanism with which they are associated. Sorting events within small regions by mechanism allows a search for possible variations in mechanism as a function of time. For example, time-space plots of events with different mechanisms in the SE10 region are shown in Figure 2. The left column showns the distribution in time of all of the events in the SE2 region which have body-wave magnitude of about 2.7 or greater (duration magnitude of 2.2 or greater). The other four columns in Figure 10 each show a subset of these events. The middle three columns show the temporal distribution of events associated with the three special patterns of first motion determined for the SE2 region, and the column on the right includes all events in SE2 which were not associated with any particular pattern or focal mechanism. Similar time-space plots for regions SE1, SE3, SE4, and SE5 are shown in Figure 11.

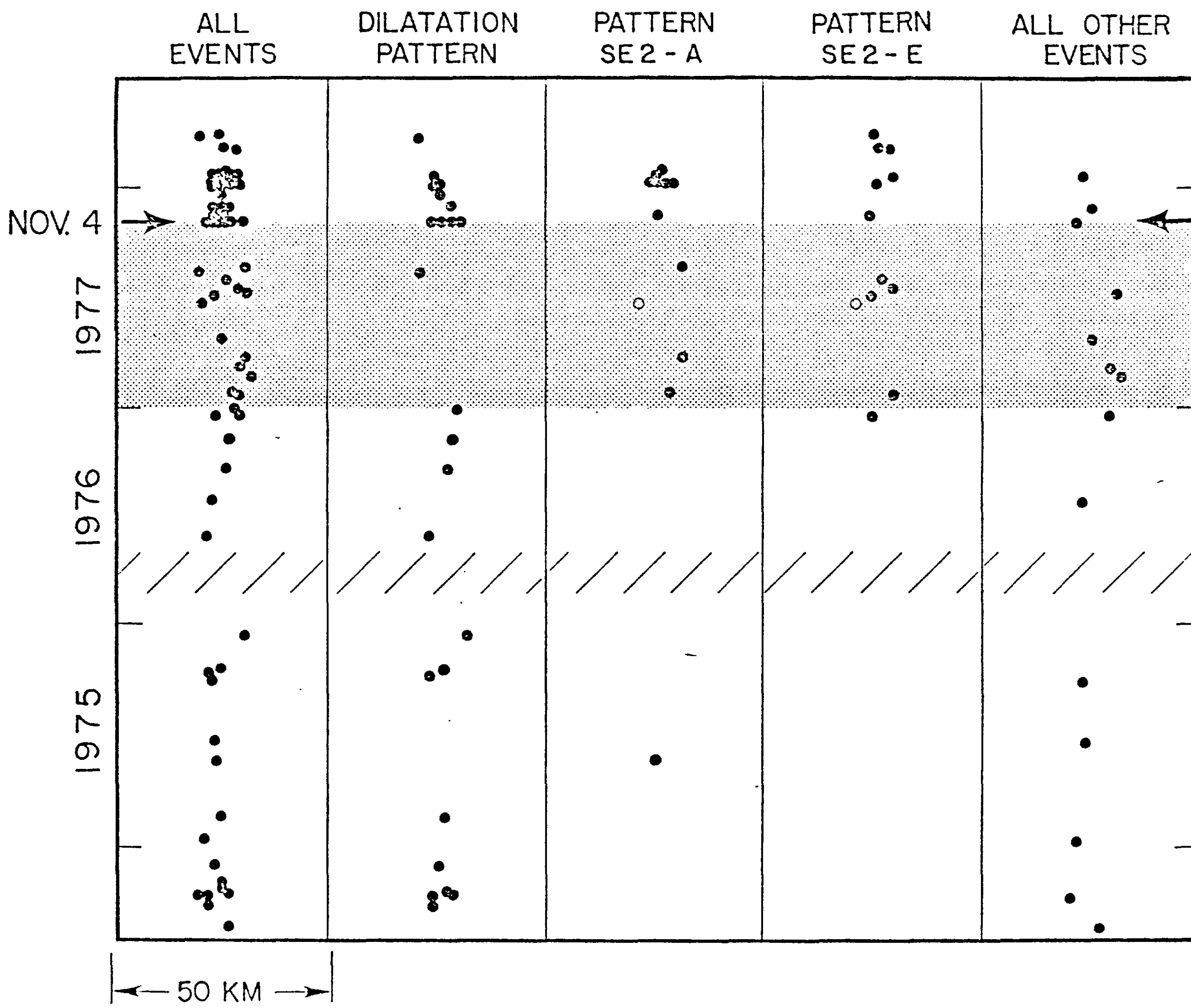

Figure 10. Five time-space plots for events located in the SE2 region. The vertical axis is time from August 1974 through June 1978. Each of the horizontal axes is distance from west on the left to east on the right. The horizontal stripe in early 1976 represents a time period in which no data were collected due to a lightning strike. The time-space plot in the left column shows all events in SE2 with m_b of about 2.7 or greater. The middle three columns show subsets of events in SE2, corresponding to the first motion patterns with which the events are associated. The open circles show events which might be associated with either of patterns SE2-A or SE2-E. The column on the right shows events which fit none of the three special first motion patterns. The stippled region shows the time period in which the mechanism of most events in the SE2 region changed from the typical background mechanism (dilatation pattern) to different mechanisms (patterns A and B). Stations which are critical for determining pattern SE2-A were not installed until the summer of 1975, so that the lack of events with this pattern during the first year of the time-space plot is not meaningful.

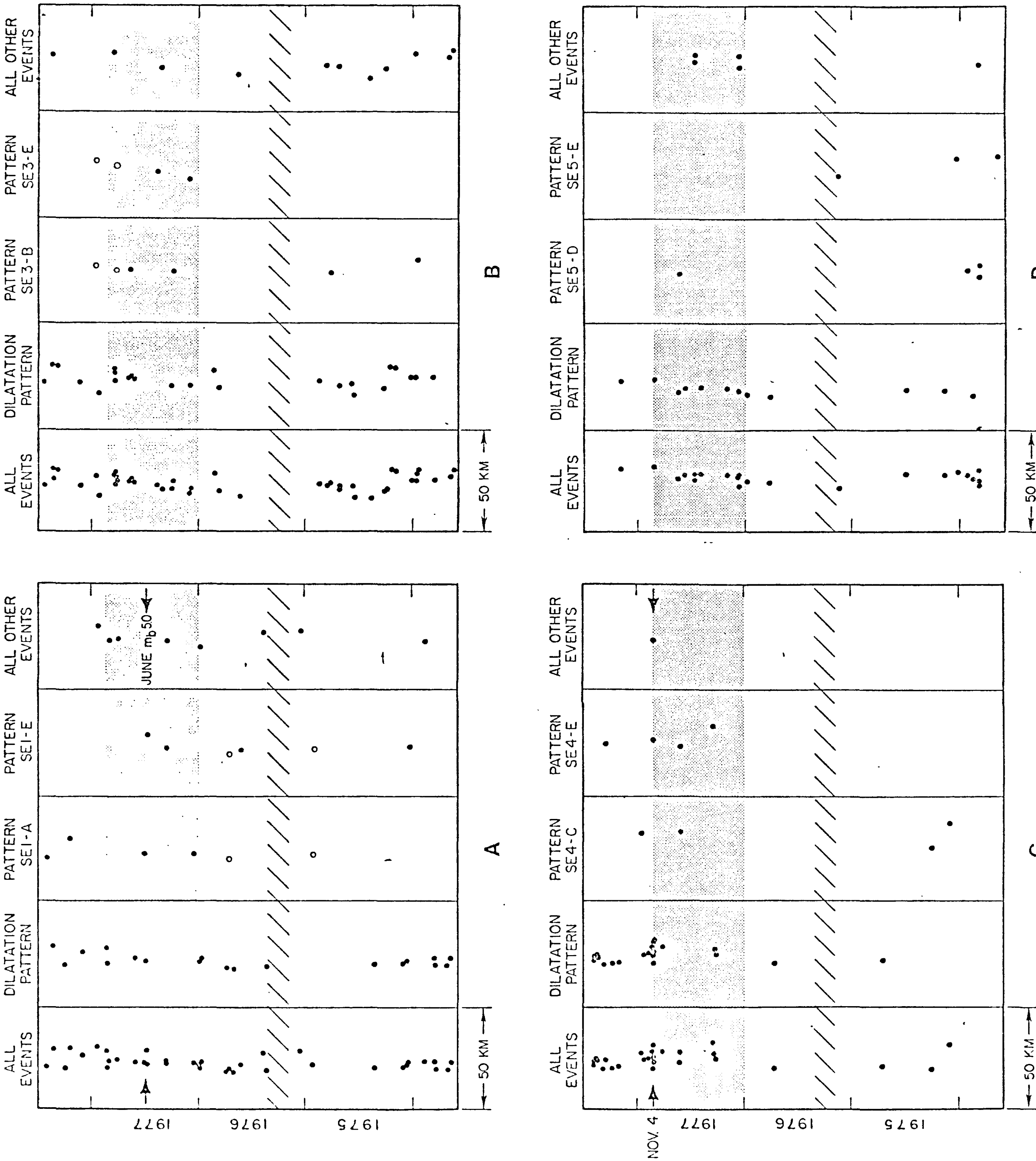

Figure 11. Time-space plots for events located in the (a) SE1, (b) SE3, (c) SE4, and (d) SE5 regions. The caption to Figure 10 describes the plots. Stations which are critical for determining patterns SE1-A and SE3-E were not installed until the summer of 1975, so that the lack of events with these patterns during the first year of the time-space plots is not meaningful.

The first pattern of interest for each region is the dilatation pattern because only dilatational first motions are recorded at the local network for the events associated with this pattern. The pattern is compatible with the thrust mechanism expected from the direction of convergence of the Pacific and North American lithospheric plates and with the thrust mechanism solutions determined teleseismically for larger earthquakes in the central Aleutians. For each region, events which fit the dilatation pattern were treated separately from the rest of the events; the events shown in the three columns on the right of Figures 10 and 11 were sorted by the method after the removal of the dilatational-type events from the data sets for each region.

Events in the SE2 region (Figure 10) which fit the dilatation pattern occur from the beginning and to the end of the time period of the study. In contrast, events associated with the two other special patterns found in the SE2 region are seen to occur mostly after the beginning of 1977. During this same time period, there is an unusual lack of events which have the background dilatation pattern. These comparisons show that starting about 10 1/2 months before the November 1977 earthquake, the mechanism of most small to moderate-sized events in the SE2 region changed. Moreover, starting about 6 1/2 months before the mainshock, there also appears to be a change in the mechanism of earthquakes in the SE4 region (Figure 11c) from the background dilatation pattern. There is clearly no evidence of a change in focal mechanism in the SE5 region (Figure 11d) during, say, the year preceding the November 1977 mainshock, nor is there conclusive evidence for such a change in the SE3 region (Figure 11b). The only other place and time in which a change in the mechanism of earthquakes is observed is in the SE1 region (Figure 11a) during the first six months of 1977. This period, in which only unusual mechanisms occurred, was terminated by an earthquake of m_b 5.0 in the SE1 region.

To summarize the variations seen in the time-space plots, no change in mechanism associated with the November 4, 1977 M_S 6.7 earthquake is seen in regions SE1, SE3, or SE5. None of these regions was later part of the aftershock zone. A clear change in the mechanism of most small to moderate-sized earthquakes is seen in the SE2 region before the mainshock, and also perhaps in the SE4 region. Aftershocks to the November 1977 earthquake occurred only in the SE2, SE4, and SE6 regions. This suggests that the zone over which the mechanism of earthquakes changed before the November 1977 earthquake might be the same area as the eventual aftershock zone.

The nature of the change in mechanism is seen by looking at the first motion data for each of the special patterns for regions SE1 through SE5 on lower hemisphere projections of the focal sphere (Figure 12). For any one of the special patterns of first motions, there are insufficient data to uniquely determine a focal mechanism solution. However, the dilatation pattern for each of the regions apparently represents the same mechanism, which is probably a thrust mechanism similar to the composite focal mechanism determined tleeseismically by LaForge and Engdahl (1979) for earthquakes in the Adak Canyon area. Also, all of the events associated with the various patterns labeled E apparently have an other focal mechanism. The E patterns themselves differ from region to region, of course, because the azimuth and take-off angles to the stations of the network differ from region to region.

One possible interpretation of each of the first motion patterns is shown in Figure 12 by the dashed nodal planes. This interpretation of the mechanism represented by pattern E compares well to another teleseismically determined composite focal mechanism solution by Engdahl and LaForge (1979). Moreover, this interpretation of the first motion data is similar both to the (counterclockwise) 65° rotation of the strike of the thrust planes observed for small earth-

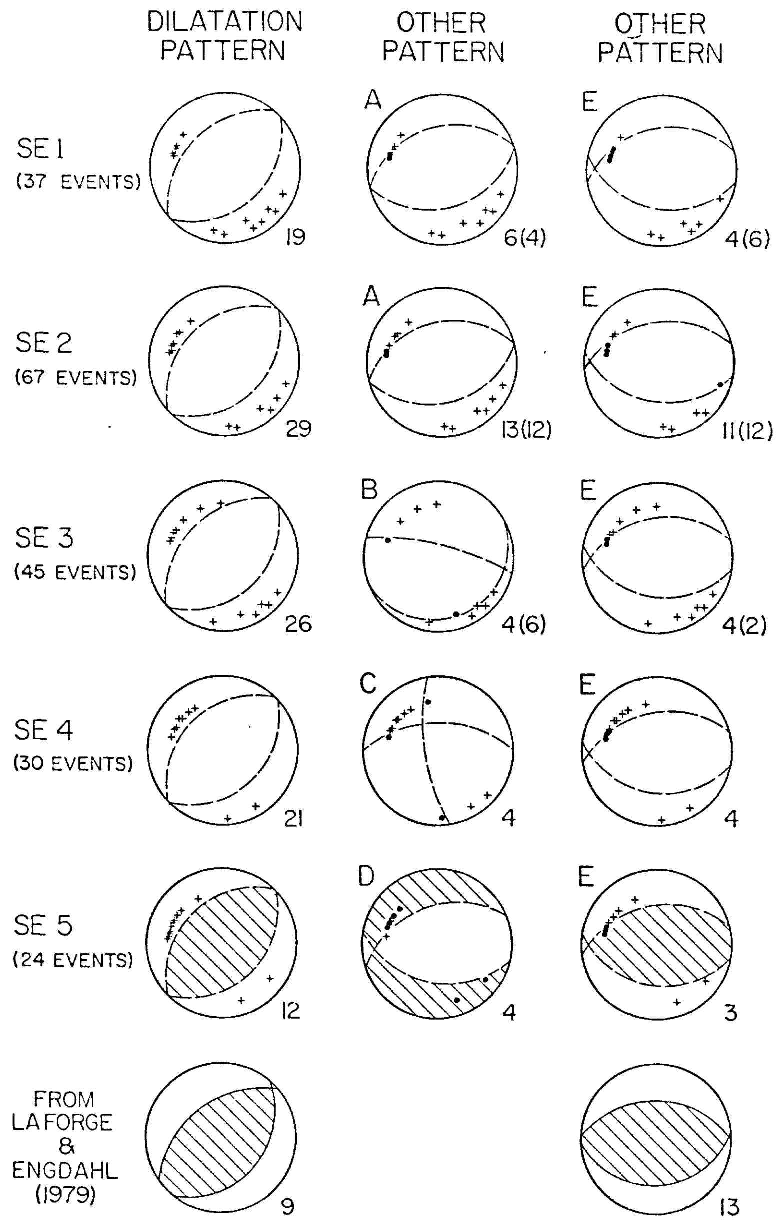

Figure 12. Lower hemisphere projections of the focal sphere for hypothetical hypocenters located in the middle regions SE1 - SE5. Data are P-wave first motions of the special first motion patterns determined by the methods of objectively compositing data for focal mechanisms. The special patterns are labelled by letters corresponding to pattern names in Figures 11. The subscripts indicate the number of events associated with each pattern. For the few cases in which an event could be associated with either of the special patterns A (or B) or E, subscripts in parentheses indicate different possible interpretations of the number of events associated with each pattern. Plus-symbols are dilatational P-wave first motions at stations of the local seismographic network; black dots are compressional first motions. To aid in the comparison of these data with teleseismically determined composite focal mechanisms for other earthquakes in the Adak area (last row; from LaForge and Engdahl, 1979), the compressional quadrant has been hatched for a few of the focal spheres. The nodal planes drawn as dashed lines represent only one of the possible focal mechanism solutions allowed by the first motion data.

quakes before an m_b 5.0 earthquake (Engdahl and Kisslinger, 1977) in the Adak region and to the rotation of nodal planes between foreshocks and aftershocks observed by Lindh et al. (1978) in California.

Focal Mechanisms from Network Amplitude Data. The technique for determining the focal mechanism of an earthquake from the distribution of the ratio of the vertical component of SV to the vertical component of P, $(SV/P)_z$, at the stations of a regional network, has been developed and a paper describing the method published in August, 1980 issue of the Bulletin of the Seismological Society of America. A computer program for executing the procedure automatically has been written and is under test. Input to the program consists of the hypocenter location, the azimuth and take-off angle to each station and the observed value of log $(SV/P)_z$. A decision is made on the basis of a combination of available first-motion information and knowledge of the local tectonics as to whether the focal mechanism is expected to be fundamentally strike-slip of dip slip. The program then finds the solution of that kind (i.e., the strike and dip of the fault) that gives the best fit to the observations. This solution is then used as the starting solution in a least-squares iterative procedure in which the strike, dip and slip direction are free parameters, and the best fitting solution in the least-squares sense is produced.

The search for precursory variations of the focal mechanisms of small earthquakes has been limited in the past to examination of the waveforms recorded on the Benioff instrument at station ADK. The chief reason for this is that it is very difficult to impossible to take consistent amplitude information, especially for S-waves, from the Develocorder films. Although the observations at ADK have been diagnostic in one well-documented case, the theoretical distribution with azimuth of the amplitude ratio shows that for focal mechanisms typical of the Adak region, there is a very wide range of fault strikes for which no significant change in the ratio will be seen at any one station.

Tests of two events using the digital seismograms shows that much better data will be available for small magnitude (less than about m_b 2) events. We are optimistic that routine production of focal mechanisms will be a practical procedure once the digital data are available on a regular basis.

ADAK TILTMETER DATA

The Adak shallow borehole tiltmeter array has undergone many changes since the first few tiltmeters were installed in the summer of 1976. The configuration of the array from the summer of 1979 to the summer of 1980 is shown in Figure 13. Improvement in installation techniques and modifications in electronics has led to a significant reduction of short term meteorological effects from tens of microradians to only a few microradians during heavy rainfalls. Short term effects lasting hours to days have been found to be associated with rainfall, barometric pressure, and temperature variations. These effects over the long term appear to recover to a baseline which shows an annual cycle.

There is found to be little coherence at frequencies above tidal frequencies. The dominant signal on all the tiltmeters is the M_2 semidiurnal tide which has an amplitude of approximately 0.25 microradians. The observed M_2 tide agrees with the combined theoretical solid earth and ocean load tide. Strong diurnal thermal influences reported from other shallow borehole sites around the world are not found on properly functioning Adak tiltmeters.

In order to examine long term secular tilt, one year of digital data, from 14 August 1978 - 14 August 1979, has been processed and plotted in Figures 14 and 15. Meteorological measurements made over the same time period are plotted in Figure 16. The digital cassette data obtained during this interval, since connection to the uninterruptable power supply, have been remarkably free of gaps or timing problems.

The most stable tiltmeters over the long term are the east tiltmeter at the west side (W-E) and the east tiltmeter at the south site (S-E). The W-E tiltmeter shows a clear yearly cycle with amplitude of 5 to 6 microradians. The same cycle was observed on the W-E tiltmeter the previous year (not plotted). The x-component of the S-E tiltmeter shows an almost identical yearly cycle but in the

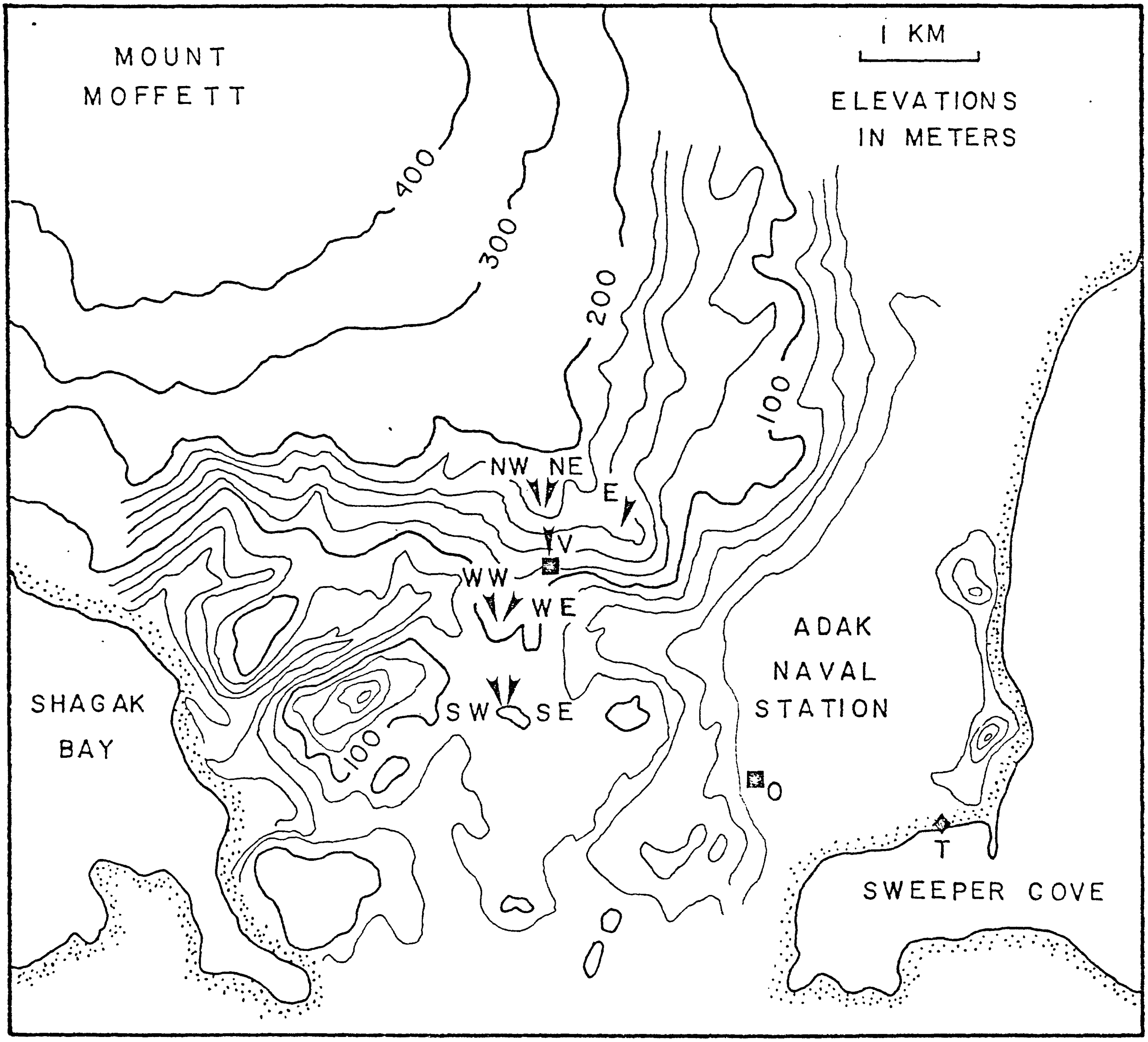

Figure 13. Map of the Adak tiltmeter array, from the summer of 1979 to the summer of 1980; and major topographic features. The arrows shows the locations of the tiltmeters, which are identified by station code. The individual instruments at each of the north (N-W, N-E), west (W-W, W-E), and south (S-W, S-E) sites are 10 meters apart. The seismometer vault (V) contains one of the tiltmeters and is the site of the meteorological instruments. The site of the Adak Observatory is shown by an O. The sweeper Cove tide gauge is shown by a T. Major contours are given in meters and a fine contour interval of 20 meters is shown in the vicinity of the tiltmeter sites.

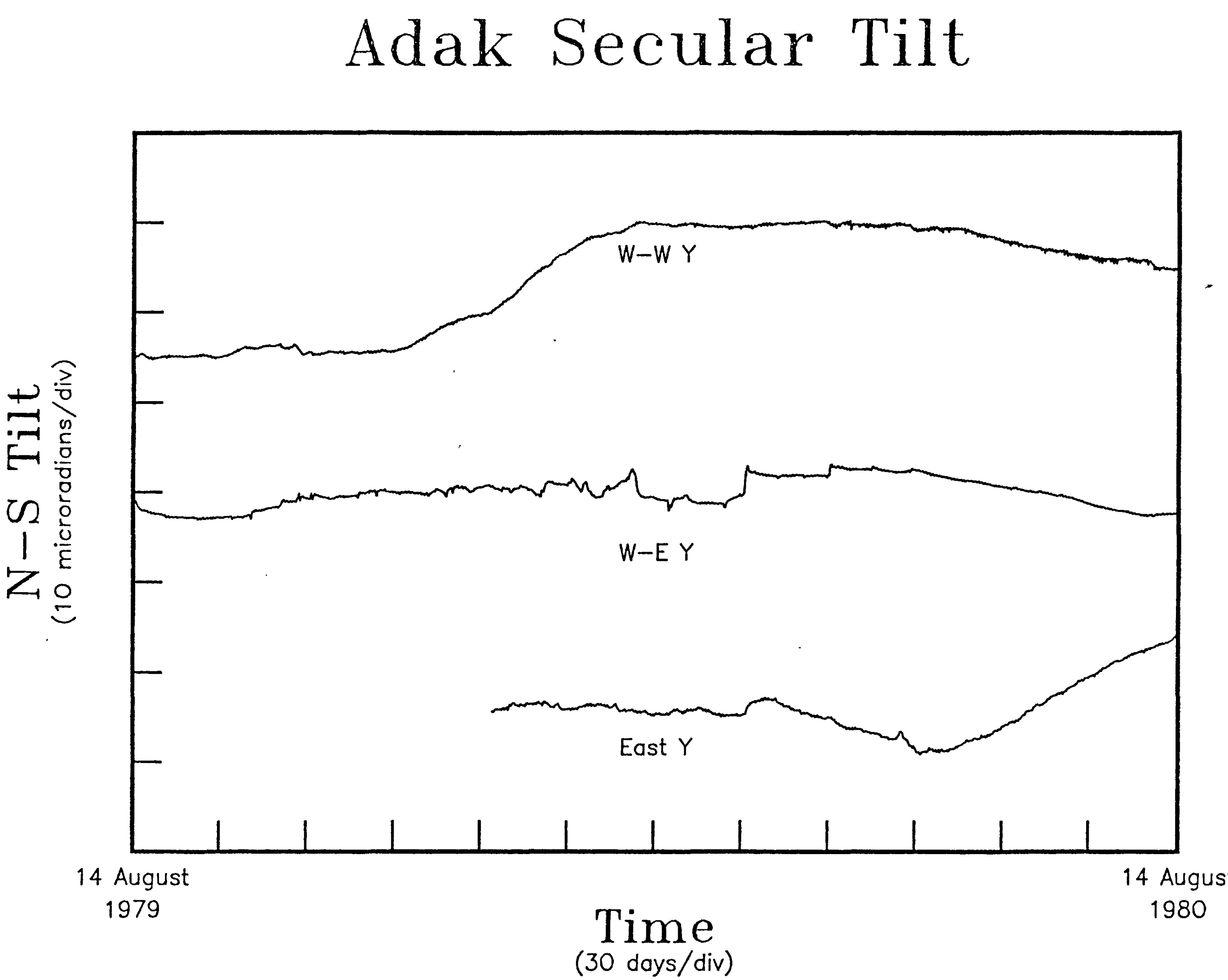

Figure 14. Adak secular tilt from 14 August 1979 to 14 August 1980, north-south (y) components.

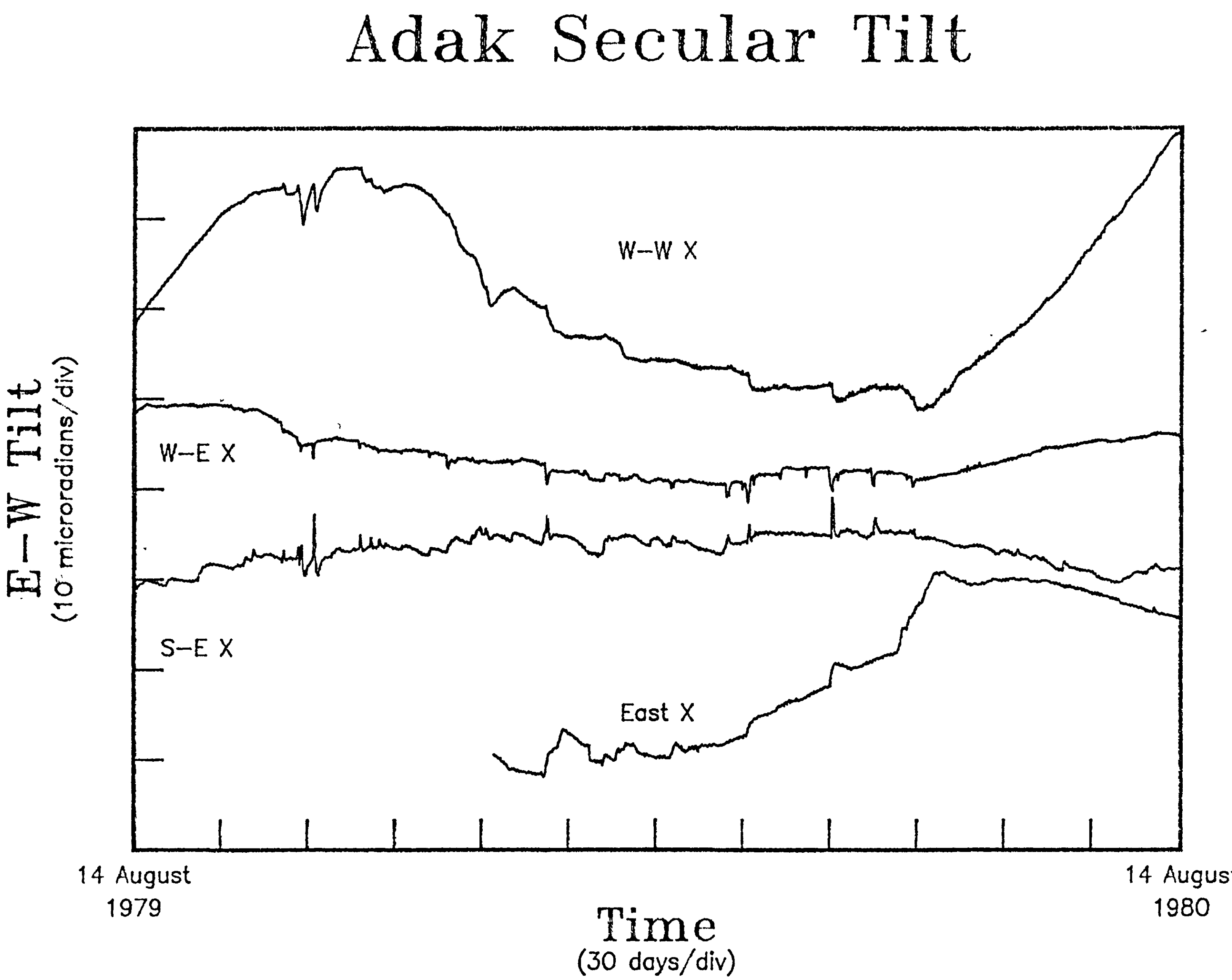

Figure 15. Adak secular tilt, east-west (x) components.

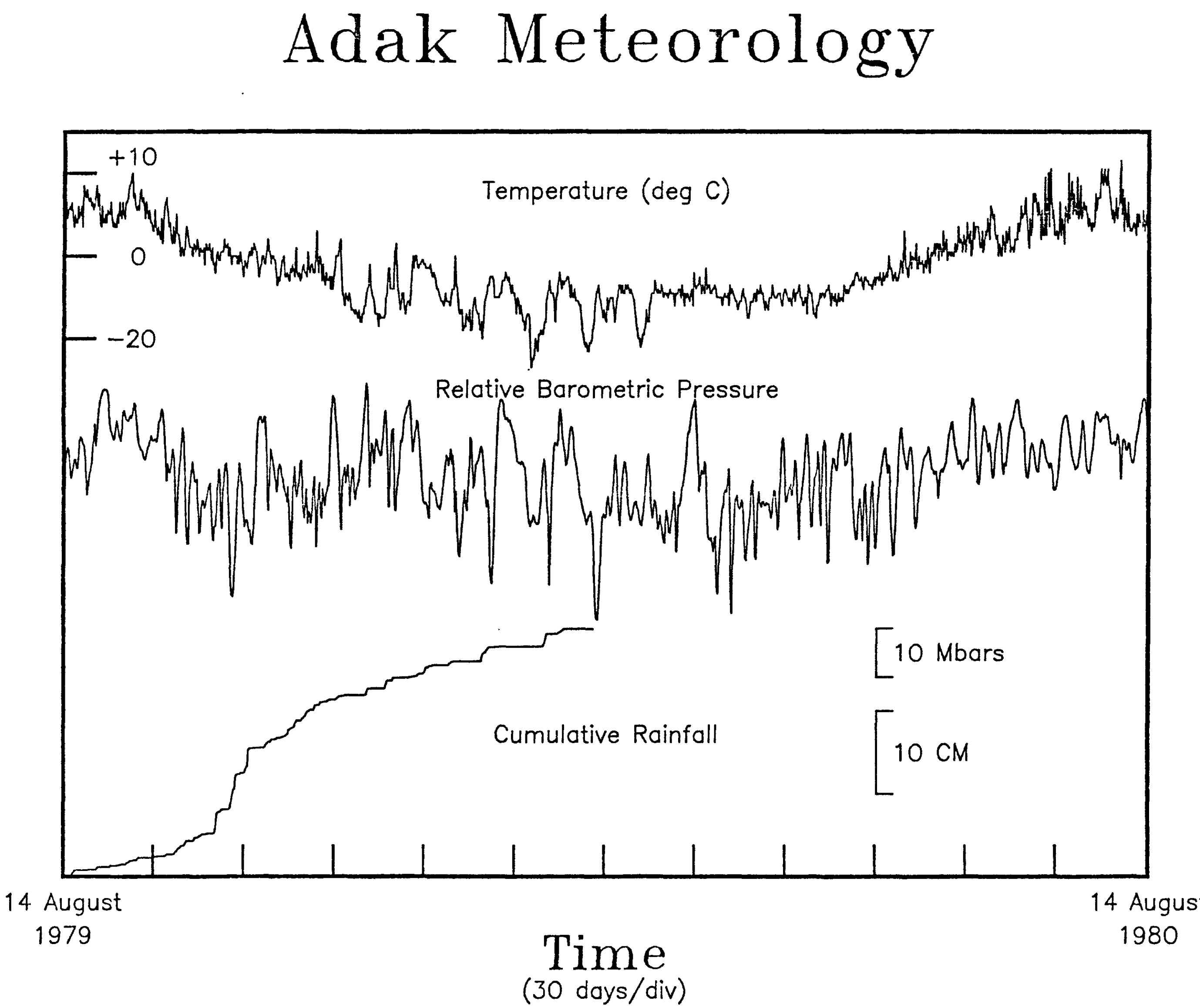

Figure 16. Adak meteorology over the same time interval as in Figures 14 and 15.

opposite direction of the x-component of the W-E tiltmeter. This yearly cycle also closely matches the seasonal changes in temperature and rainfall as suggested by Wideman, 1974. It is interesting to note that this tilt signal is also in phase with the yearly strain signal (amplitude 10^{-5}) previously observed by Wideman, 1974, with shallow strain meters on Adak. It remains uncertain whether it is rainfall, temperature, or both which affects the tiltmeter, producing the annual cycle. New meteorological measurements may help to identify the cause.

The tiltmeter at the east site and the x-component of the west tiltmeter at the west site (W-W) are not nearly as stable over the long term. The y-component of the W-W tiltmeter generally follows the y-component of the W-E tiltmeter with the exception of a larger unexplained drift after three months. The y-component of the W-W tiltmeter also shows the least contamination to rainfall. Rainfall effects on the other tiltmeters appear as spikes or steps on these plots. A third tiltmeter was added to the west site in the summer of 1980 with the hopes that the relatively good long-term stability of the W-E tiltmeter and the insensitivity of the W-W tiltmeter to meteorological effects can be achieved with this new deeper W-S tiltmeter.

1980 Summer Field Work. During the 1980 field season, our digital data capabilities were greatly increased. S. Morrissey at St. Louis University (S.L.U.) designed the data acquisition system which uses a modified A.D. Data Systems datalogger at the south, north, west and vault sites. Four channels of 8 bit data and 10 channels of 12 bit data are transmitted from each site to a Smokesignal microprocessor located at the observatory and are then written onto floppy disks with a specially packed format. The floppy disks are presently sent to S.L.U. where the data are read using a matching microprocessor system and are rewritten onto a Unix compatible 9 track tape using the S.L.U. 11/70 computer.

The 9 track tapes will be sent to CIRES where the data can then be rapidly accessed and processed using the CIRES 11/70 computer and the interactive programs brought up by D. Agnew. These programs are successfully being used to edit and analyze the Adak 12-channel cassette data.

In addition to the new data logging system, new meteorological instruments were added and some tiltmeters were re-installed. The vault tiltmeter was installed in a new hole at the west site. The new W-S pit is approximately 2 meters deep with the actual tiltmeter hole drilled into solid rock. The tiltmeter settled down rapidly and appears to be quite stable over the first month of record. The tiltmeters at the north site were found to be loose in a liquefied sand pack and were re-installed using a bonding agent in the sand. The old S-W tiltmeter was faulty and completely replaced with a new tiltmeter.

Since all the tiltmeters are only buried halfway into the sandpack, a plastic pipe with base plate was slipped over the exposed pipe and was then covered with 25 to 30 cm of soil. This should serve to protect and insulate the upper pipe yet still isolate the tiltmeter from the previously observed experimental pipe bending effects which occur when the pipe is completely buried. It will be interesting to see if this reduces the short term rainfall effects.

To further understand and then possibly remove meteorological effects, an extensive meteorological package was developed and installed. Newly added were temperature probes at the bottom of all the tiltmeter pits and solar radiometers at two of the sites. Presented in Table I is a list of all the meteorological instruments and tiltmeters connected to the new digital recording system and the Farrell datalogger.

The continual improvement in installation techniques has resulted in increased long term stability and reduction of meteorological contamination. The possibility of earthquake-related tilting remains untested at Adak since no

Table I. Digital Data Acquisition System

Channel	Unit 31 South Site	Unit 32 North Site
1	rain gauge	.608 volt test
2	solar radiometer	microbarometer
3	wind speed	wind speed
4	wind direction	wind direction
5	* S-E x tilt	N-E x tilt
6	* S-E y tilt	N-E y tilt
7	S-W tilt	N-W x tilt
8	S-W y tilt	N-W x tilt
9	S-E borehole temp.	N-E borehole temp.
10	S-W borehole temp.	N-W borehole temp.
11	Surface temp.	short
12	1.35 volt test	1.35 volt test
13	.1 times system voltage	.1 times system voltage
14	wind direction	microbarometer (same as ch. 2)
	Unit 33 West Site	**Unit 34 Vault**
1	not used	* rain gauge
2	not used	solar radiometer
3	not used	wind speed
4	not used	wind direction
5	* W-E x tilt	* East x tilt
6	* W-E y tilt	* East y tilt
7	* W-W x tilt	* microbarometer (from Observatory)
8	* W-W y tilt	* ocean tide gauge
9	W-S y tilt	solar radiometer (same as ch. 2)
10	W-S y tilt	wind speed (same as ch. 3)
11	W-E borehole temp.	wind direction (same as ch. 4)
12	W-W borehole temp.	1.35 volt test
13	W-S borehole temp.	vault temp.
14	surface temp	* surface temp.

Note: Channels 1-4 are 8-bit, channels 5-14 are 12 bit.
* Also recorded on Farrell 12-bit Cassette Datalogger.

earthquakes larger than magnitude 4.5 have occurred within 100 km of the array since the stability of the tiltmeters was improved with reinstallation in 1978. The finite element model of Wahr and Wyss (1980) can be used to show that earthquakes of this magnitude or less would produce tilts with less amplitude than the earth tides ($\sim 0.25 \mu rad$). The increased meteorology information and datalogging capacity will allow detailed comparisons between tiltmeters and with meteorological effects.

REFERENCES

Engdahl, E. R. and C. Kisslinger, Seismological precursors to a magnitude 5 earthquake in the central Aleutian islands, **J. Phys. Earth**, *25*, S243-S250, 1977.

LaForge, R. and E. R. Engdahl, Tectonic implications of seismicity in the Adak Canyon region, central Aleutians, **Bull. Seism. Soc. Amer.**, *69*, 1515-1532, 1979.

Lindh, A., G. Fuis and C. Mantis, Seismic amplitude measurements suggest foreshocks have different focal mechanisms from aftershocks, **Science**, *201*, 56-59, 1978.

Wahr, J. and M. Wyss, Interpretation of post-seismic surface deformation by a visco-elastic inclusion model, in press, **J. Geophys. Res.**, 1980.

Wideman, C. J., Earth strain measurements; Amchitka and Adak Islands, Alaska; Colorado School of Mines, Graduate Thesis T-1685, 1974.

PUBLICATIONS UNDER THE CONTRACT

1. Abstracts of presentations at meetings

Price, S. J., C. Kisslinger, and E. R. Engdahl, Microearthquake activity precursory to the magnitude-6.5 Adak earthquake of November 4, 1977, **EOS,** *59,* 330, 1978.

Billington, S., and E. R. Engdahl, A shallow earthquake sequence in the Central Aleutian Islands, **EOS,** *59,* 1127, 1978.

Topper, R. E., and E. R. Engdahl, Fine structure of the double Benioff zone beneath the Central Aleutian Arc, **EOS,** *59,* 1195, 1978.

LaForge, R., and C. Kisslinger, Seismotectonics of the overriding plate in the Adak region, Central Aleutians, **EOS,** *59,* 1195, 1978.

Dewey, J. W., S. Billington, E. R. Engdahl, and W. Spence, Teleseismic search for seismicity patterns precursory to large earthquakes in Peru and near Adak, Alaska, presented at UNESCO International Symposium on Earthquake Prediction, Paris, April 1979.

Price, S. J., Distribution in space and time of b-values in the Adak seismic zone, **EOS,** *60,* 312, 1979.

Billington, S., A field study of earthquake prediction methods in the central Aleutian Islands, presented at the Alaska Science Conference, Fairbanks, Sept. 1979.

Frohlich, C., G. V. Latham, J. Lawton, S. Billington, C. Kisslinger, E. R. Engdahl, A. Malahoff, and J. G. Caldwell, Ocean bottom seismograph results from the central Aleutian subduction zone, **EOS,** *60,* 878, 1979.

Meertens, C. M., Analysis of tiltmeter results from the central Aleutians, **EOS,** *60*, 936, 1979.

Morrissey, S. T., Promising new developments in installation and operation of shallow borehole tiltmeters, **EOS** *60*, 935, 1979.

Billington, S., E. R. Engdahl, and S. Price, Changes in the seismicity and focal mechanism of small earthquakes prior to an M_S 6.7 earthquake in the central Aleutians, presented at the Ewing Symposium on Earthquake Prediction, New Paltz, New York, May, 1980.

Kisslinger, C., The application of body-wave amplitude ratios from local network seismograms to prediction studies, presented at the Ewing Symposium on Earthquake Prediction, New Paltz, New York, 1980.

Billington, S., and E. R. Engdahl, Changes in the seismicity and focal mechanism of small earthquakes prior to an M_S 6.7 earthquake in the central Aleutions, **EOS,** *61*, 293, 1980.

2. Publications

Harrison, J. C., J. M. DeMay, and C. Meertens, Tiltmeter results from Adak, in Proceedings of Conference VII: Stress and strain measurements related to earthquake prediction, U.S.G.S. Open-File Report 79-370, Menlo Park, 1978.

LaForge, R., and E. R. Engdahl, Tectonic implications of seismicity in the Adak Canyon region, Central Aleutians, **Bull. Seism. soc. Amer.,** *69*, 1515-1532, 1979.

Kisslinger, C., Evaluation of S to P amplitude ratios for determining focal mechanisms from regional network observations, **Bull. Seism. Soc. Amer.,** *70*, 999-1014, 1980.

Kisslinger, C., and K.-P. Bonjer, Wann, Wo und wie stark? Probleme und Moglichkeiten der Erdbebenvorhersage, **Umschau in Wissenschaft und Technik,** *80*, 425-431, 1980.

Harrison,. J. C., J. M. DeMay, and C. Meertens, Tiltmeter results from Adak, in Proceedings of the Int. Wrkshp. on Monitoring Crustal Dynamics in Earthquake Zones (A. Vogel, editor), Friedr. Vieweg & Sohn, Braunschweig, 1980.

Billington, S., E. R. Engdahl, and S. Price, Changes in the seismicity and focal mechanism of small earthquakes prior to an M_S 6.7 earthquake in the central Aleutian island arc, submitted to the Fourth Ewing volume, 1980.

Billington, S., A method to objectively composite P-wave first motions for focal mechanism solutions, in preparation, 1980.

Frohlich, C., S. Billington, E. R. Engdahl, and A. Malahoff, Detection and location of earthquakes in the central Aleutian subduction zone using land and ocean bottom seismograph stations, in preparation, 1980.

3. Theses

Topper, R. E., Fine structure of the Benioff zone beneath the Central Aleutian Arc, M.S. Thesis, University of Colorado, 1978.

Meertens, C.M., Tidal and secular tilt at Adak, Alaska, M.S. Thesis, University of Colorado, in preparation, 1980.

Price, S. J., A search for microearthquake precursors to the magnitude 6.7 Adak earthquake of November 4, 1977, M.S. Thesis, University of Colorado, in preparation, 1980.