Hawaii Geothermal Assessment Program

Geophysics Subtask: Microseismicity Survey and Imaging of Crustal Complexity in the Puna Geothermal Region on the Island of Hawaii Using the PANDA Seismic Array and Gravity Measurements

EXECUTIVE SUMMARY

This project provides funds to support a research effort by the University of Hawaii at Manoa (UH) to image the complex velocity structure of the Puna section of Kilauea's East Rift Zone (KERZ) using a combination of geophysical data collected by UH and Hawaiian Volcano Observatory (HVO) and to evaluate the local seismogenic potential. Early efforts during the Fall of 1992 comprised: (1) Obtaining phase information for earthquakes recorded by HVO during the period 1972-1992; (2) Contracting for use of the PANDA (Portable Array for Numerical Data Acquisition) array with Memphis State University; (3) Obtaining necessary permits; (4) site inspection and selection; and (5) Obtaining office space and housing for field crews. Seismic field work commenced January 12, 1993; 37 seismic stations were deployed in a dense elliptical array centered on KS-8, and with the long axis aligned with the Kilauea East Rift Zone. The outermost four PANDA stations were co-sited with HVO stations (KPO, POI, KLU, and HUL). Twelve PANDA stations form a closely spaced (< 0.5 km) array centered on the site of active drilling for geothermal exploration. The remaining stations fill in the area between the dense central array and the surrounding HVO instruments. The field program ended May 30, 1993. The principal goal for the field work was to collect high-resolution three-component earthquake data. The data will be used for (1) determination of 3-dimensional P- and S-wave velocity models, (2) the determination of 3-dimensional Q_p and Q_s models, (3) the imaging of lateral crustal anisotropy, (4) comprehensive background seismicity and ambient noise characterization studies.

As of June 1, 1993, data collection for a gravity map of Kilauea Volcano was about 90% complete; this task was undertaken by HVO, however, they were unable to complete the task because of lack of funds. This geophysics program is funding the acquisition and analysis of gravity data along the KERZ. This field program is currently underway.

Analysis of the seismic data and refinement of the velocity model is proceeding; to date, 371 earthquakes with magnitudes ranging from 0.0 to <3.0 have been located for the period 1/29/93 through 3/27/93. Generally, these earthquakes form a linear trend parallel to KERZ. The most seismogenic region within the array is the area in the immediate vicinity of the State's HGP-A facility; also, a linear trend of epicenters cuts across the

southeastern portion of the Leilani Estates subdivision. Depth determinations are highly dependent on velocity model; since our velocity model is not final, we caution that the depth distribution of the located events will change as the velocity model is refined. Hypocenters define a vertical pipe-like structure extending from 2.6 to about 13 km depth. Data quality is sufficient to complete all proposed work.

A recently added program goal is the installation and operation of a broad-band three-component seismometer downhole at HGP-A, possibly as early as December 1993. Temperature, pressure, and seismicity will be monitored simultaneously; the data will be collected by a personal computer at the Puna Research Center via logging cable. The purpose of the installation is to enable continuous monitoring of microseismicity levels in the immediate vicinity and to enhance detection capability for slightly larger (magnitude 1.0-3.0) events.

Hawaii Geothermal Assessment Program

Geophysics Subtask: Microseismicity Survey and Imaging of Crustal Complexity in the Puna Geothermal Region on the Island of Hawaii Using the PANDA Seismic Array and Gravity Measurements

INTRODUCTION

Geophysical techniques have the potential to provide a number of types of information necessary for resource assessment and reservoir management. For this reason gravity and seismic studies of the rift system associated with potential geothermal areas in Puna were proposed. Gravity surveys along Kilauea's East Rift Zone (KERZ) will permit definition of the orientation and estimates of the width of the dike complex within the rift with greater resolution than is currently available. Passive seismic surveys can be expected to provide structural information on the KERZ, and possibly the response of the hydrothermal system to development as indicated by microseismicity. Acquisition of current seismic activity data within the rift will also provide information regarding typical pre-exploitation baseline seismicity by which one may judge the impacts of removal and reinjection of geothermal fluids.

Hawaii Volcano Observatory (HVO) maintains an extensive telemetered seismic network (Fig. 1) on the island of Hawaii to monitor earthquake and volcanic activity. For more than 30 years the HVO network has provided earthquake data for many fundamental research projects leading to our current understanding of the seismotectonics of the Island of Hawaii. The entire HVO network, however, is still dependent mainly on traditional seismic network technologies characterized by limited dynamic range and single-component recording. It was not until recently that 12 out of a total of 52 HVO stations were upgraded to record three-components (Fig. 1). Spatial distribution of the three-component stations is unsuitable for detailed analyses of extremely complicated lateral velocity anomalies, and lack of shear-wave velocity information has severely restricted the accuracy of earthquake locations, especially the depth. The results of this study will enable (1) construction of high-resolution three-dimensional P- and S-wave velocity models, (2) determination of high-resolution,three-dimensional Q_p and Q_s models, (3) definition of lateral, crack-induced crustal anisotropy, and (4) comprehensive background seismicity and noise surveys. The network will also provide an excellent calibration for improvement of the existing HVO network.

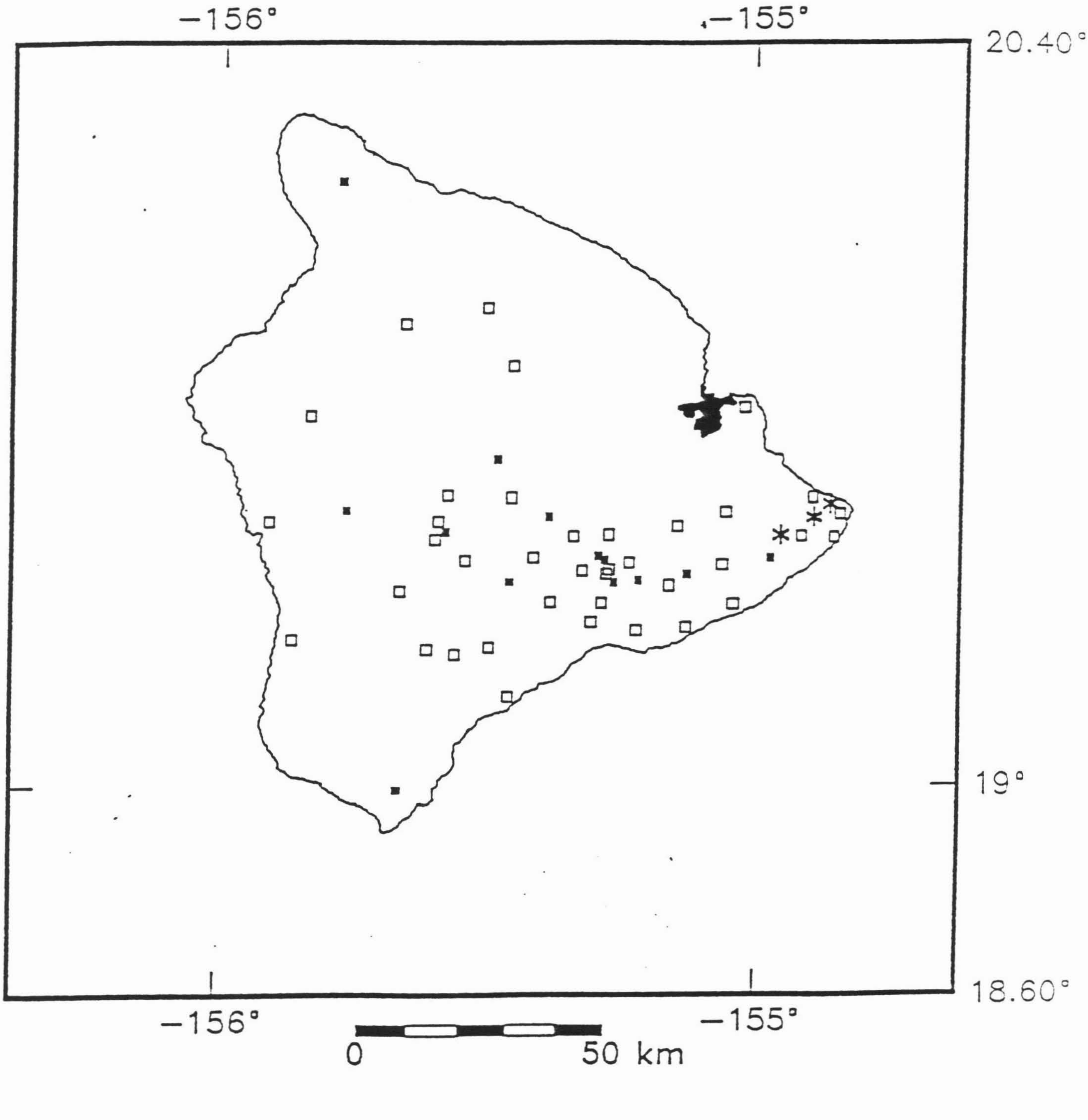


Figure1. The HVO telemetered seismic network consisting of 52 seismic stations. Open square represents the location of single-component station. Solid square represents the location of three-component station. Star represents the locations of three drilled geothermal wells.

Previous Studies in Hawaii

Many previous studies of crustal velocity structures for the island of Hawaii using single-component recordings from local (Eaton, 1962; Ward and Gregersen, 1973; Crosson and Koyonagi, 1979; Klein, 1981; Thurber, 1987) or teleseismic earthquakes (Ellsworth and Koyonagi, 1977) are limited to P-wave only. Imaging the three-dimensional structure of the island was attempted using gravity (Kinoshita et al., 1963) and a series of refraction profiles (Ryall and Bennett, 1968; Hill, 1969; Broyles et al., 1979; Zucca and Hill, 1980, Zucca et al., 1982; Hill and Zucca, 1987). However, none of these studies included reliable shear-wave velocity information.

Among the many earthquake focal mechanism studies (Endo, 1971; Ando, 1979; Estill, 1979; Furumoto and Kovach, 1979; Unger and Ward, 1979; Crosson and Endo, 1981, 1982; Klein, 1981; Bosher and Duennebier, 1985; Bryan and Johnson, 1991; Gillard et al., 1992; Wyss et al., 1992a, 1992b), one-dimensional velocity models were adopted despite evidence of strong lateral crustal heterogeneity. Thurber (1987), on the other hand, argued for the use of a three-dimensional velocity model obtained from inversion of P-wave traveltimes to determine focal mechanisms. The 'missing link' in all of the above studies is the use of shear-wave information. That is not only critical for the determination of epicentral depth, but also will affect the accuracy of the focal mechanism determinations.

In general, shear waves are more sensitive than P-waves to lateral anisotropy along ray paths. Shear waves will be reflected efficiently from the surface of a partially melted magma body (Mizoue, 1980; Sanford et al., 1973), will be attenuated significantly across hot material, and will split as a consequence of passing through aligned cracks along ray ray paths (Booth et al., 1992; Crampin and Booth, 1985; Crampin and Lovell, 1991). Determination of a reliable shear-wave crustal velocity model and accurate identification of shear-wave arrivals are also the most important factors for reliable determination of earthquake epicenters, especially the depths (Chiu et al., 1991).

Hawaii Seismicity

Figure 1 shows the current configuration of the HVO telemetered seismic network; of the 52 stations, two are low-gain multicomponent stations (optical), 12 are three-component, and 38 are vertical component only. The coverage is most dense on and around Kilauea Volcano. Several thousands of earthquakes are analyzed routinely each year by the HVO staff. Figure 2 shows 15 years of seismicity for Hawaii (1961-1976) together with seismicity for the year 1990. The improvement in location capability is readily apparent and can be attributed to better spatial coverage by upgraded instrumentation

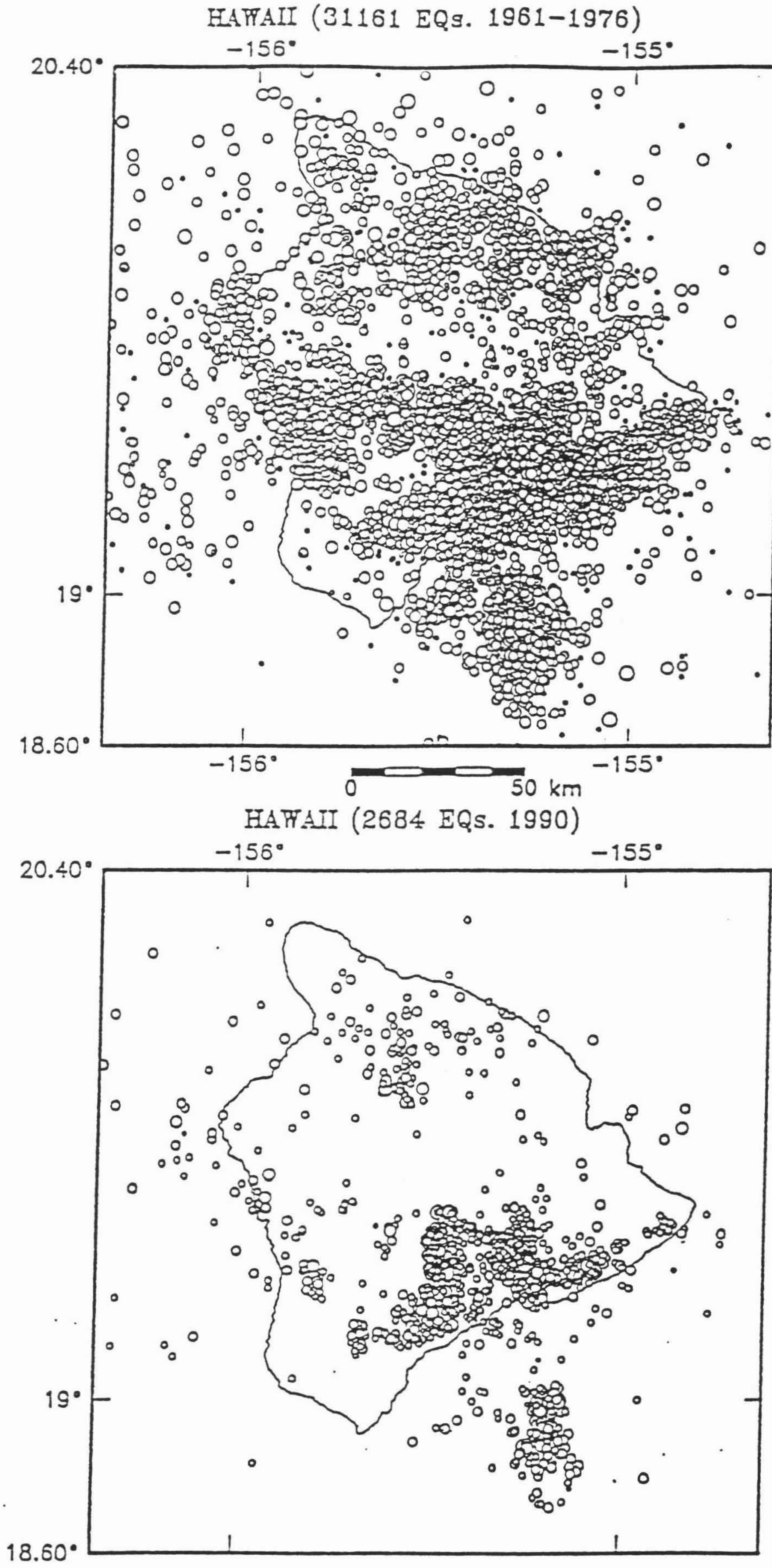


Figure 2. Seismicity in the Island of Hawaii from the HVO catalog from 1961 to 1976 (Top) and for the year of 1990 (bottom). The clustered seismic activities are mainly associated with volcanic activities around Kilauea and Mauna Loa volcanoes, and the Loihi Seamount about 55 km south of Kilauea. More clustered earthquake locations for the 1990 seismicity is probably due to the increasing number of stations which provide better spatial coverage of the island.

and better crustal velocity structure models for earthquake locations (Klein, 1981). Cross-sectional views of the 1990 data set (Figures 3 and 4) emphasize the association of seismicity clusters with volcanic activity including the ascent of magma from the upper mantle, the injection of magma into crustal rift zones, the eruption of lava at the surface, and the mechanical failure of crust due to volcanic loading. Hypocentral depths range from surface to as deep as 60 km and appear somewhat scattered, probably due to lack of shear-wave controls on depth determinations.

Originally, it was felt that analysis of the HVO seismic data set, together with gravity modeling, should precede collection of new seismic data. The reality is that the paucity of HVO traveltimes in the Puna region - there are only five instruments, one of which is three-component - contributes to a lack of knowledge of the velocity structure. The interpretation of the gravity survey is only as good as the seismic velocities used to constrain it.

Further, it became apparent after a cursory examination of the HVO data for the Puna region and an early relocation attempt using the Klein (1981) velocity model, that relocation of all seismicity in this region at this early stage (originally this was to be Phase I) would not be productive; it would be better to wait for an improved velocity model derived from our data, making locations more accurate and comparisons between the two data sets more meaningful. Relocation of events along the KERZ using a master-event (joint hypocentral determination) method and a new velocity model derived from the PANDA network data will definitely improve hypocenter locations. For this purpose, phase information on earthquakes occurring in our region of study was collected from HVO for the period 1972-1992. This part of the program will be completed after our velocity model is finalized.

PANDA ARRAY DATA SET

Contracting for Use of the PANDA Array with Memphis State University (September-October)

The PANDA (Portable Array for Numerical Data Acquisition) seismic array is the product of continuing development efforts by the Center for Earthquake Research and Information, Memphis State University. Use of PANDA, a telemetered array of three-component stations, was obtained under subcontract for $30,532. The PIs decided to use these instruments rather than the (originally planned) PASCAL instrumentation that could be obtained from National Science Foundation based on considerations of cost and data quality. PANDA could provide us with up to 40 instruments and the required technical

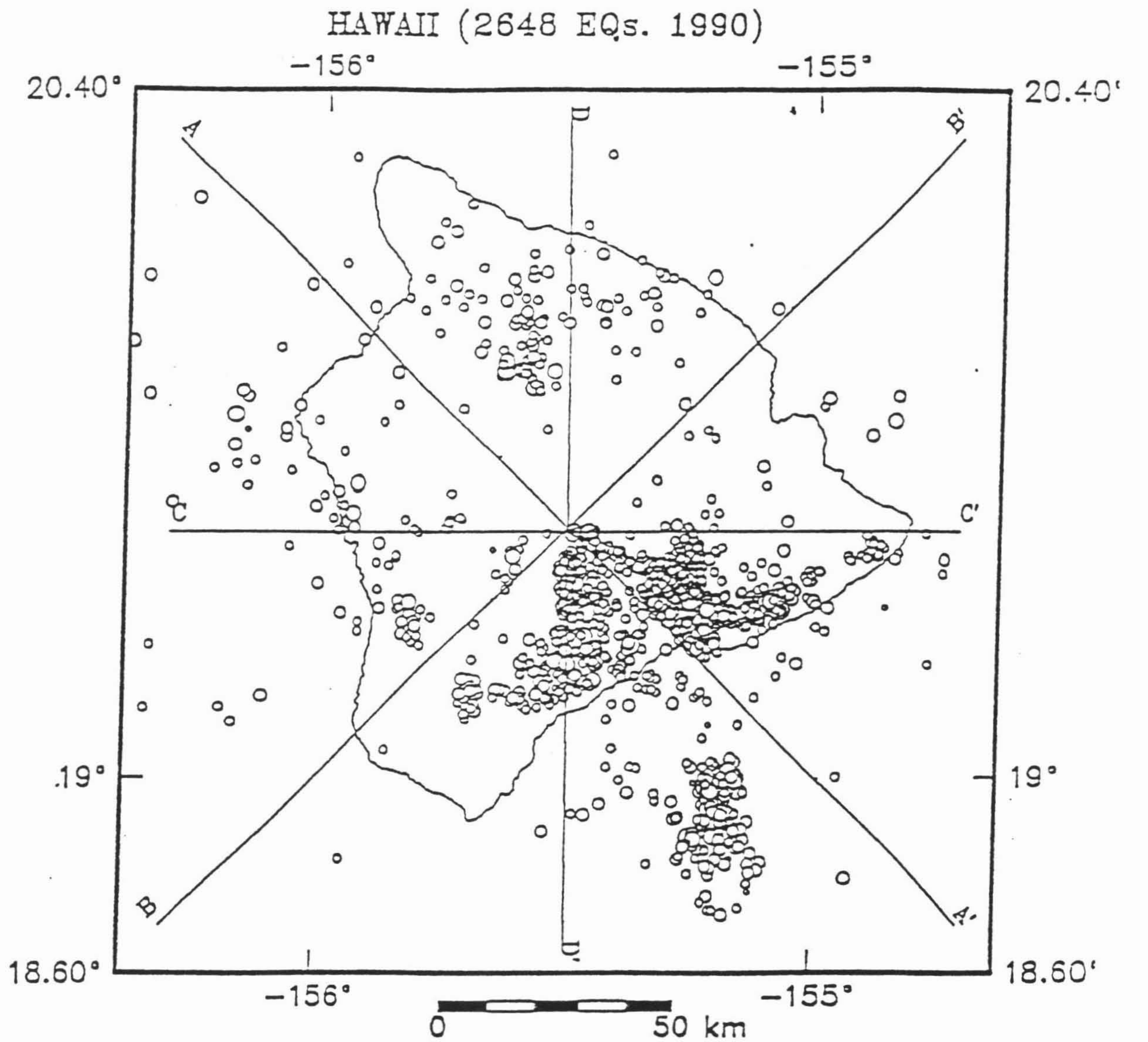


Figure 3. Indexed map for cross-sections (A-A' to D-D') to be shown in Figure 4.

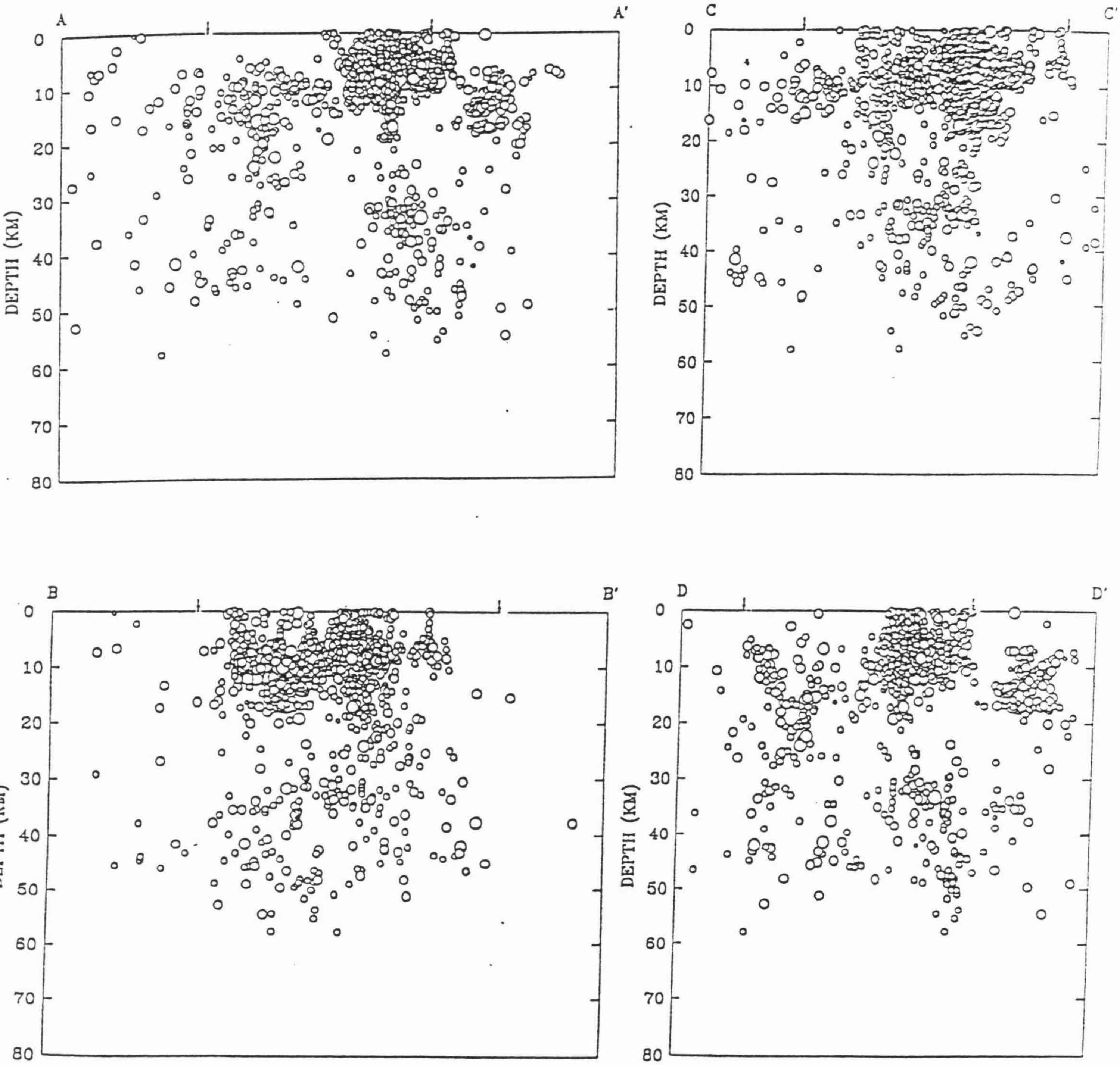


Figure 4. Cross-section views of the 1990 data from the HVO catalog. The clustered seismicity can be associated with the active volcanic sources.

field support for the cost of PASCAL instrumentation for about 14 sites, more than doubling the density of our proposed network. Use of the PANDA system is also a boon to data reduction, as the entire network is telemetered to and records at a central site using the same clock, eliminating the need to correct times on individual instruments.

Each PANDA station has two sets of three-component sensors, eliminating the need to install two instruments at each site; for stations outside the central zone, one set operated at high gain and the other at low gain giving a minimum of 90 dB dynamic range; for stations inside the central zone both sets of sensors operated at high gain and separated by up to 20 m, creating two stations. The standard sensor is a Mark Products L-28 4.5-Hz geophone. Each telemetry link to the central recording site transmits data from two stations using an 'inner' station/repeater combination (Fig. 5) to relay data transmitted from an 'outer' station (Fig. 6). At the central recording site a MASSCOMP 6600 computer workstation performs real-time event triggering, digital recording and preliminary data processing (Fig. 7). An extensive description of the array instrumentation has been given by Chiu et al. (1991).

Constant communications with Jer-Ming Chiu and CERI at Memphis State were necessary to finalize plans for shipping and receiving the instrumentation. It was also necessary to compile a list of equipment and materials that would be required during the field investigations.

Obtaining Necessary Permits (September-December)

A permit from the Federal Communications Commission (FCC) granting Special Temporary Authority was required to operate the radio-telemetered seismic network. It was necessary to first check all records the the Ewa Beach office to make sure that our chosen frequencies were not already in use. It was then necessary to monitor radio frequencies in the field to demonstrate to the FCC that the frequencies we requested were indeed not in use, either legally or illegally. (Although this was required by the FCC, it was also to our own advantage to ensure minimal interference during signal transmission.) A broad-band radio receiver was purchased for this purpose. The radio can be programmed to repeatedly sweep a selected band of frequencies and stop when signal is detected. Two days and nights were devoted to moving through the Puna region, during which no extraneous signals were detected.

A permit for temporary exclusive use of the frequencies listed in Table 1 was granted for the period January 8 through March 31, 1993. A copy of the permit is displayed as Figure 8.

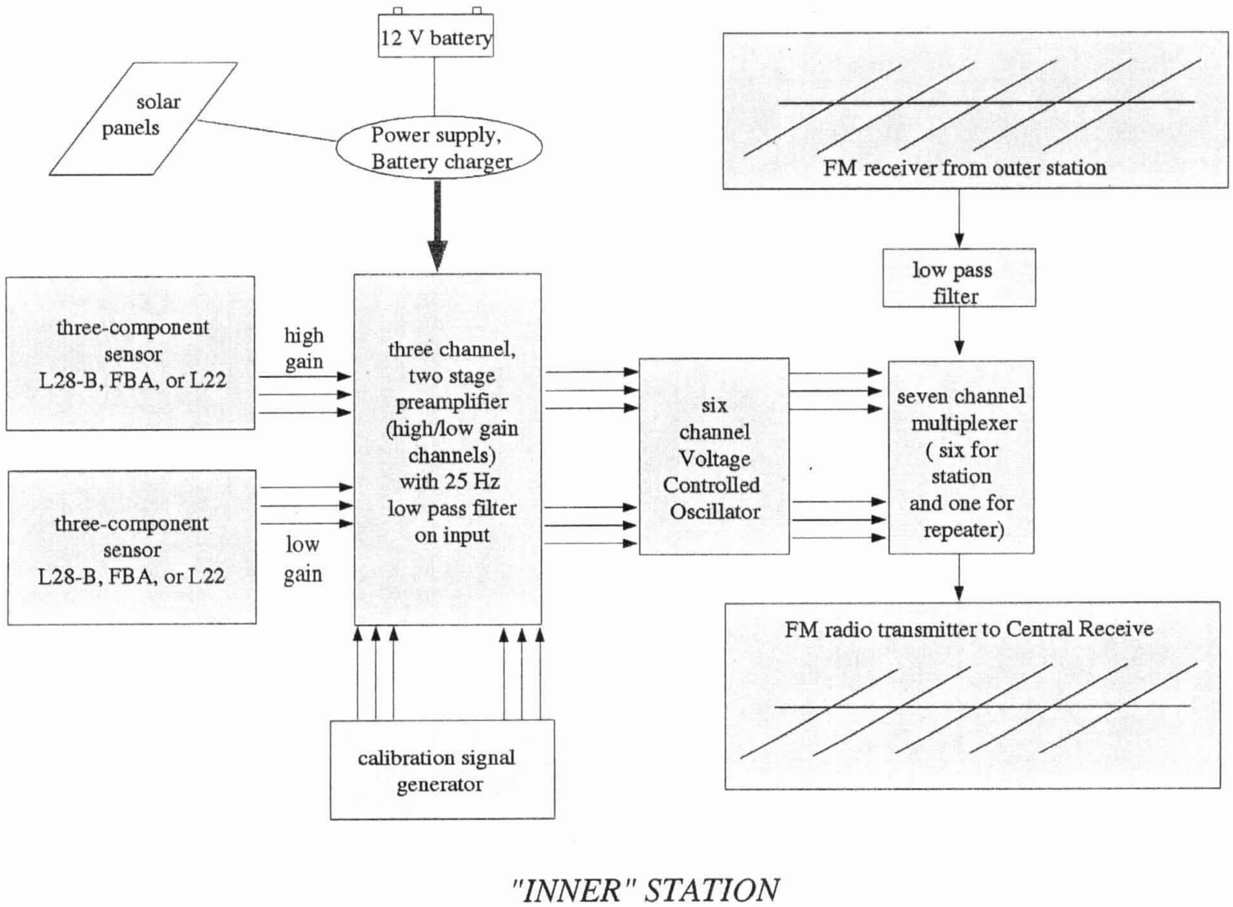
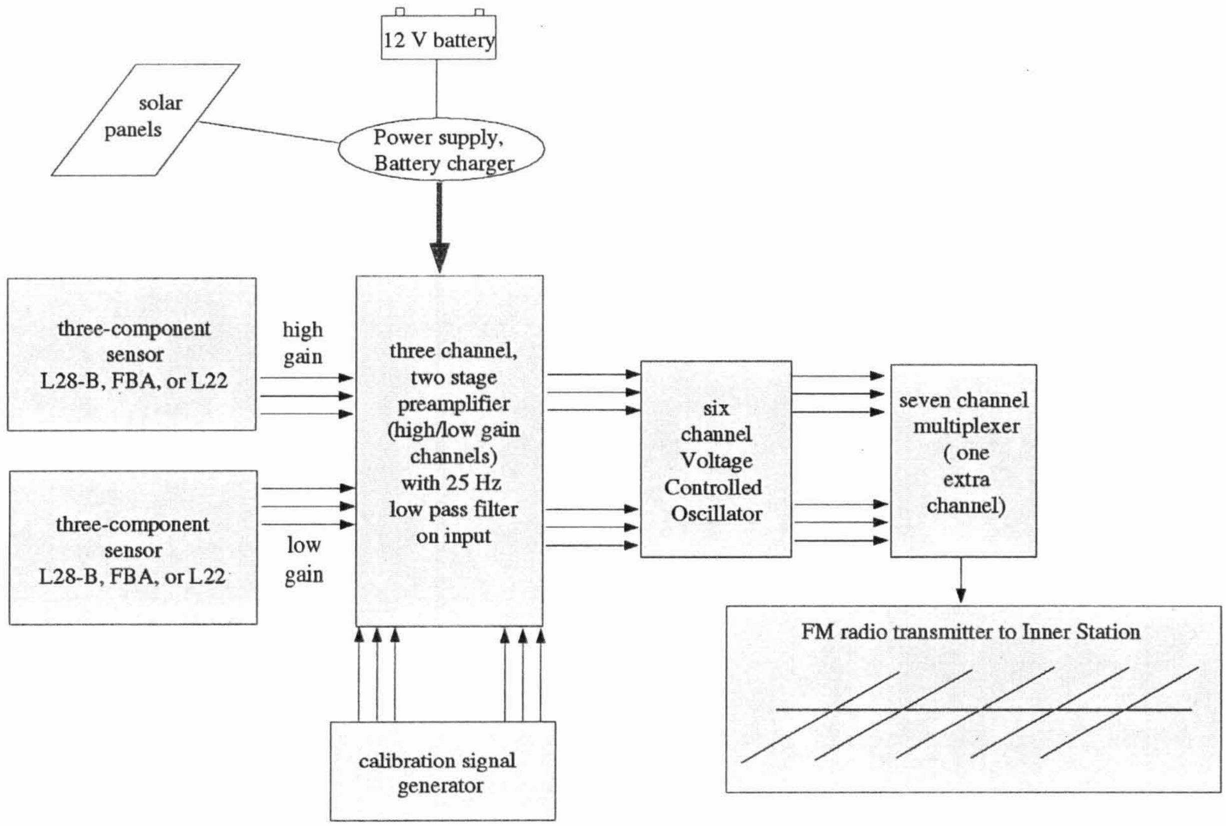


Figure 5. Schematic diagram illustrating components of an inner station. The station is powered by solar panels with a 12-volt battery as back-up. Signals from both three-component sensors are amplified, filtered, and multiplexed with signal from the outer station. Multiplexed signals are transmitted to central receive.



"OUTER" STATION

Figure 6. Schematic diagram illustrating components of an outer station. The station is powered by solar panel with a 12-volt battery as back-up. Signals from both three-component sensors are amplified, filtered, multiplexed, and transmitted to the inner station.

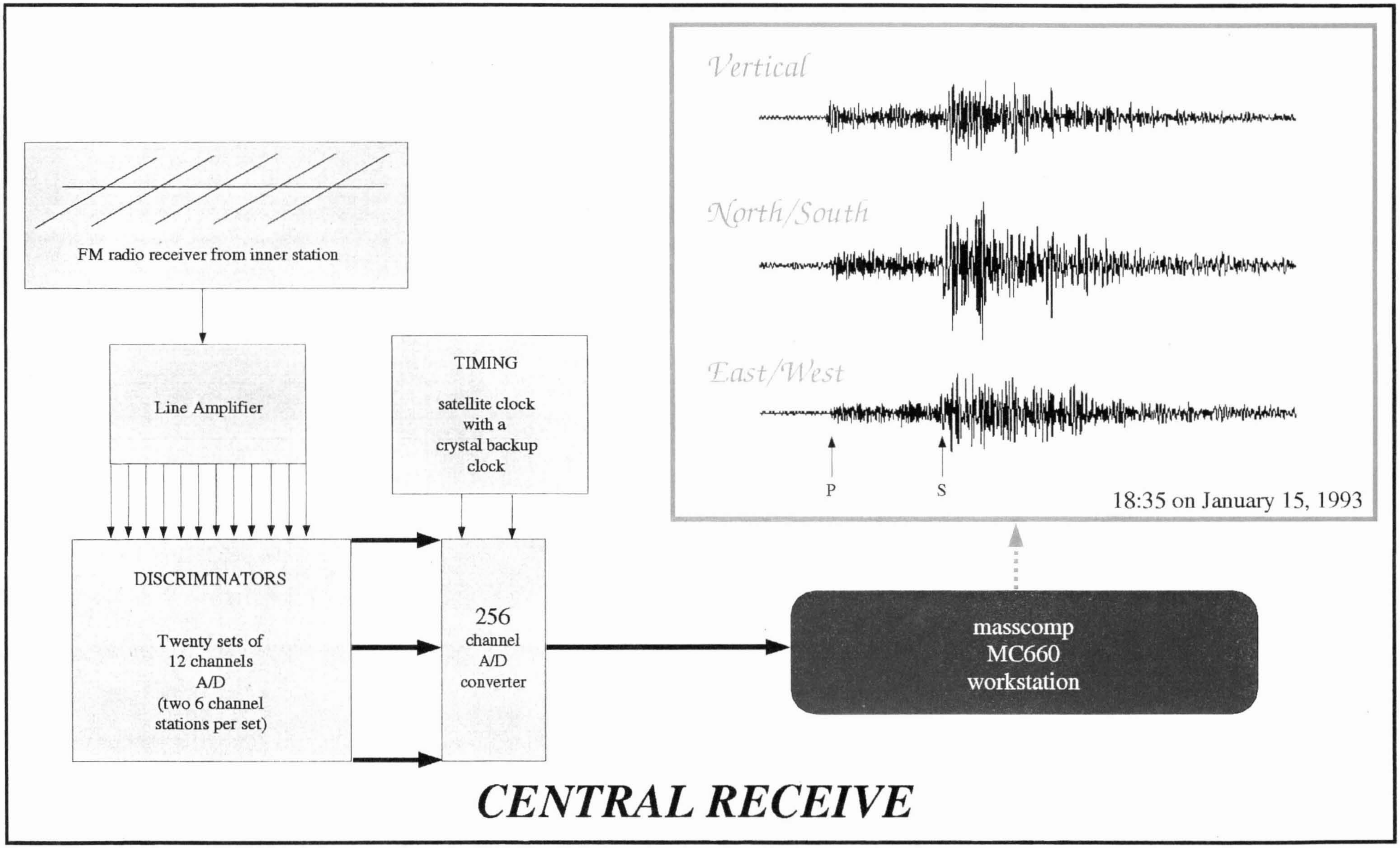


Figure 7. Components of central receive station; data sample.

Table 1.

Generalized scheme for PANDA frequency designations in the 216-220 MHz Band

Central Receive uses one vertically polarized omni-directional antenna:

	Inner Station Frequency (MHz)	Polarization	Outer Station Frequency (MHz)	Polarization
1	216.025	vertical	218.025	horizontal
2	218.075	vertical	216.075	horizontal
3	216.125	vertical	218.125	horizontal
4	218.175	vertical	216.175	horizontal
5	216.225	vertical	218.225	horizontal
6	218.275	vertical	216.275	horizontal
7	216.325	vertical	218.325	horizontal
8	218.375	vertical	216.375	horizontal
9	216.425	vertical	218.425	horizontal
10	218.475	vertical	216.475	horizontal
11	216.525	vertical	218.525	horizontal
12	218.575	vertical	216.575	horizontal
13	216.625	vertical	218.625	horizontal
14	218.675	vertical	216.675	horizontal
15	216.725	vertical	218.725	horizontal
16	218.775	vertical	216.775	horizontal
17	216.825	vertical	218.825	horizontal
18	218.875	vertical	216.875	horizontal
19	216.925	vertical	218.925	horizontal
20	218.975	vertical	216.975	horizontal

These frequencies (MHz) were reserved for (1) repeaters, (2) as substitutes if there are other (unauthorized) users in the band, (3) to eliminate intermod problems and (4) to install replacement stations:

217.050	219.050
217.100	219.100
217.150	219.150
217.200	219.200
217.250	219.250
217.300	219.300
217.350	219.350
217.400	219.400
217.450	219.450
217.500	219.500
217.550	219.550
217.600	219.600
217.650	219.650
217.700	219.700
217.750	219.750
217.800	219.800
217.850	219.850
217.900	219.900
217.950	219.950

Table 1, continued.
Complete Listing of Frequencies Licensed to PANDA Hawaii

Frequencies (MHz)	Station Class	No. of Units	Emission Designator	Output Power	E.R.P
216.025	MO	1	10K0F2D	1.000	5.000
216.075	MO	1	10K0F2D	1.000	5.000
216.125	MO	1	10K0F2D	1.000	5.000
216.175	MO	1	10K0F2D	1.000	5.000
216.225	MO	1	10K0F2D	1.000	5.000
216.275	MO	1	10K0F2D	1.000	5.000
216.325	MO	1	10K0F2D	1.000	5.000
216.375	MO	1	10K0F2D	1.000	5.000
216.425	MO	1	10K0F2D	1.000	5.000
216.475	MO	1	10K0F2D	1.000	5.000
216.525	MO	1	10K0F2D	1.000	5.000
216.575	MO	1	10K0F2D	1.000	5.000
216.625	MO	1	10K0F2D	1.000	5.000
216.675	MO	1	10K0F2D	1.000	5.000
216.725	MO	1	10K0F2D	1.000	5.000
216.775	MO	1	10K0F2D	1.000	5.000
216.825	MO	1	10K0F2D	1.000	5.000
216.875	MO	1	10K0F2D	1.000	5.000
216.925	MO	1	10K0F2D	1.000	5.000
216.975	MO	1	10K0F2D	1.000	5.000
217.050	MO	1	10K0F2D	1.000	5.000
217.100	MO	1	10K0F2D	1.000	5.000
217.150	MO	1	10K0F2D	1.000	5.000
217.200	MO	1	10K0F2D	1.000	5.000
217.250	MO	1	10K0F2D	1.000	5.000
217.300	MO	1	10K0F2D	1.000	5.000
217.350	MO	1	10K0F2D	1.000	5.000
217.400	MO	1	10K0F2D	1.000	5.000
217.450	MO	1	10K0F2D	1.000	5.000
217.500	MO	1	10K0F2D	1.000	5.000
217.550	MO	1	10K0F2D	1.000	5.000
217.600	MO	1	10K0F2D	1.000	5.000
217.650	MO	1	10K0F2D	1.000	5.000
217.700	MO	1	10K0F2D	1.000	5.000
217.750	MO	1	10K0F2D	1.000	5.000
217.800	MO	1	10K0F2D	1.000	5.000
217.850	MO	1	10K0F2D	1.000	5.000
217.900	MO	1	10K0F2D	1.000	5.000
217.950	MO	1	10K0F2D	1.000	5.000
218.025	MO	1	10K0F2D	1.000	5.000
218.075	MO	1	10K0F2D	1.000	5.000
218.125	MO	1	10K0F2D	1.000	5.000
218.175	MO	1	10K0F2D	1.000	5.000
218.225	MO	1	10K0F2D	1.000	5.000
218.275	MO	1	10K0F2D	1.000	5.000
218.325	MO	1	10K0F2D	1.000	5.000
218.375	MO	1	10K0F2D	1.000	5.000
218.425	MO	1	10K0F2D	1.000	5.000
218.475	MO	1	10K0F2D	1.000	5.000
218.525	MO	1	10K0F2D	1.000	5.000

Table 1, continued.

218.575	MO	1	10K0F2D	1.000	5.000
218.625	MO	1	10K0F2D	1.000	5.000
218.675	MO	1	10K0F2D	1.000	5.000
218.725	MO	1	10K0F2D	1.000	5.000
218.775	MO	1	10K0F2D	1.000	5.000
218.825	MO	1	10K0F2D	1.000	5.000
218.875	MO	1	10K0F2D	1.000	5.000
218.925	MO	1	10K0F2D	1.000	5.000
218.975	MO	1	10K0F2D	1.000	5.000
219.050	MO	1	10K0F2D	1.000	5.000
219.100	MO	1	10K0F2D	1.000	5.000
219.150	MO	1	10K0F2D	1.000	5.000
219.200	MO	1	10K0F2D	1.000	5.000
219.250	MO	1	10K0F2D	1.000	5.000
219.300	MO	1	10K0F2D	1.000	5.000
219.350	MO	1	10K0F2D	1.000	5.000
219.400	MO	1	10K0F2D	1.000	5.000
219.450	MO	1	10K0F2D	1.000	5.000
219.500	MO	1	10K0F2D	1.000	5.000
219.550	MO	1	10K0F2D	1.000	5.000
219.600	MO	1	10K0F2D	1.000	5.000
219.650	MO	1	10K0F2D	1.000	5.000
219.700	MO	1	10K0F2D	1.000	5.000
219.750	MO	1	10K0F2D	1.000	5.000
219.800	MO	1	10K0F2D	1.000	5.000
219.850	MO	1	10K0F2D	1.000	5.000
219.900	MO	1	10K0F2D	1.000	5.000
219.950	MO	1	10K0F2D	1.000	5.000

Figure 8.

Federal Communications Commission

1270 Fairfield Road
Gettysburg, PA 17325-7245

In Reply Refer To:
7110-22

January 8, 1993

University of Hawaii at Manoa
Dept. of Geology and Geophysics, SOEST
2525 Correa Rd.
Honolulu, HI 96822

Attn: Patricia Cooper

Dear Ms. Cooper:

Special Temporary Authority is granted effective January 8, 1993 and expiring March 31, 1993, under call sign KA77435, in the Radiolocation Radio Service, to utilize 40 portable seismometer stations. The stations will be used to monitor seismicity in the vicinity of the Hawaii Geothermal Project - A geothermal well on the Big Island, HI, in the area between 19 27 N to 19 30 N and 154 52 W to 154 56 W, with antennas less than 8 feet AGL. See attached listing for specific frequencies, emission designator, output power, and ERP.

This Special Temporary Authority is authorized on a secondary non-interference basis. This action will not prejudice the disposition of any formal application for these radio facilities. Retain the original of this authorization with station records and post a photocopy at the control point location.

Sincerely,

Kathy Davis

for Terry L. Fishel
Chief, Land Mobile Branch

cc: Frank Wright, OET

Attachments

PUNA GEOTHERMAL VENTURE

A Hawaii Partnership

STEVEN E. MORRIS
Vice-President & General Manager

January 5, 1993

Dr. Patricia Cooper
Department of Geology and Geophysics
School of Ocean & Earth Science & Technology
UNIVERSITY OF HAWAII at MANOA
2525 Correa Road
Honolulu, Hawaii 96822

RE: Proposed Seismograph Network on Puna Geothermal Venture Leases

Dear Dr. Cooper:

In your letter of October 17, 1992, you requested permission on behalf of the Department of Geology and Geophysics (DG&G) to install and operate a network of seismographs on and around the Puna Geothermal Venture (PGV) project site. Puna Geothermal Venture hereby grants you permission to install and operate the network as described, subject to the following conditions:

1. Processed data from the survey will be supplied to the PGV geologic staff as soon as it is available. The format for transfer of data will be mutually agreed upon by the PGV and DG&G staff.

2. All permits, licenses, and notifications required for execution of the proposed program including the detonation of explosive charges will be the sole responsibility of DG&G.

3. Prior to installation of the network, the DG&G staff will meet with representatives of the PGV power plant, security and drilling operations staff to coordinate installation activities and provide notification to our lessors of your proposed operations on our leases. Network installation and operation will be done in such a manner that will not interfere with power plant and drilling operations or with ongoing agricultural activities of the landowner.

4. Twenty-four hour and one-hour notification prior to the detonation of explosive charges will be given to the PGV Power Plant Manager, Mr. Dave Berube.

5. The DG&G staff will adhere to all safety and security rules currently in effect on PGV leases.

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We have enclosed two (2) maps; one being yours on which we have shown the larger "KLP" lease outlined in red and the other showing the current PGV lease ownership position in the "small parcels" area outlined in blue. For access to other parcels, that we do not have under lease, you will need to contact the landowners to receive their permission to enter their property.

We appreciate the opportunity to cooperate with the academic community in furthering the geoscientific understanding of Hawaii's geothermal resources. We wish you much success in this interesting project.

If the above conditions are agreeable to you, kindly signify so by your execution of a copy of this letter and return to the undersigned.

Very truly yours,

Steven E. Morris

Accepted and agreed to the above conditions this 11th day of Jan, 1993.

Department of Geology and Geophysics

By ____________________
Chairman, Staff

SEM:ri
Enclosures (2 pages)

cc: D. Berube
P. Hansen
W. Teplow

No special permits were required for explosives. The process of obtaining permission for access to lands leased by Puna Geothermal Venture (PGV; see Fig. 9) and lands held by large landowners was begun as early as September. Permission to enter property held by individual (residential) landowners was deferred until after final site selection.

Throughout November-December the PIs met with local police and various agency heads (for example, Dave Clague, HVO; Harry Kim, Civil Defense; Harold Matsuura, Board of Health) to inform them of our plans to install the seismometer stations. Harry Kim's suggestion to involve the community as much as possible was certainly very fruitful.

Site Inspection and Selection (September-December)

A preliminary grid of stations was prepared together with a plan outlining all station requirements, such as power, communications, accessibility, resources and access restraints. Geological and topographic maps (Fig. 10) for the region were assembled and computerized; aerial photographs were available, but were too outdated to be useful. All seismic data previously obtained in this area was collected and reviewed prior to site selection.

An elliptical, dense inner array of 12-13 stations with spacing of 0.3-0.5 kilometer was laid out with its long axis parallel to the trend of KERZ. We anticipated that the reference times between the HVO network and the PANDA stations would differ, creating some problems in trying to merge data from the two networks. Four of the PANDA stations were co-sited with the HVO stations to allow correlation of reference times between the two systems. These four stations definined the outer boundaries of the array, with the remaining stations spaced 1-2 km apart to fill the intervening space. With the assistance of Elizabeth Novak, each site was located using topographic maps and a hand-held GPS receiver. Primary criteria important to site approval were: (1) low noise level, (2) ground conditions suitable for geophone burial, and (3) accessibility. Additionally, low relief and low vegetation in the immediate area were preferred to marked relief and tall trees.

A noise survey was conducted to obtain information on background noise levels and frequency content. A fully portable and self-contained short-period vertical seismometer and visual data recorder (on loan from Carl Johnson at UH-Hilo) was installed at the HGP-A wellhead. The station operated continuously from October 15 through Nov. 29. The method used to determine a relatively unbiased estimate of the noise was the "percentage-of-occurrence method." This method is limited compared to spectral

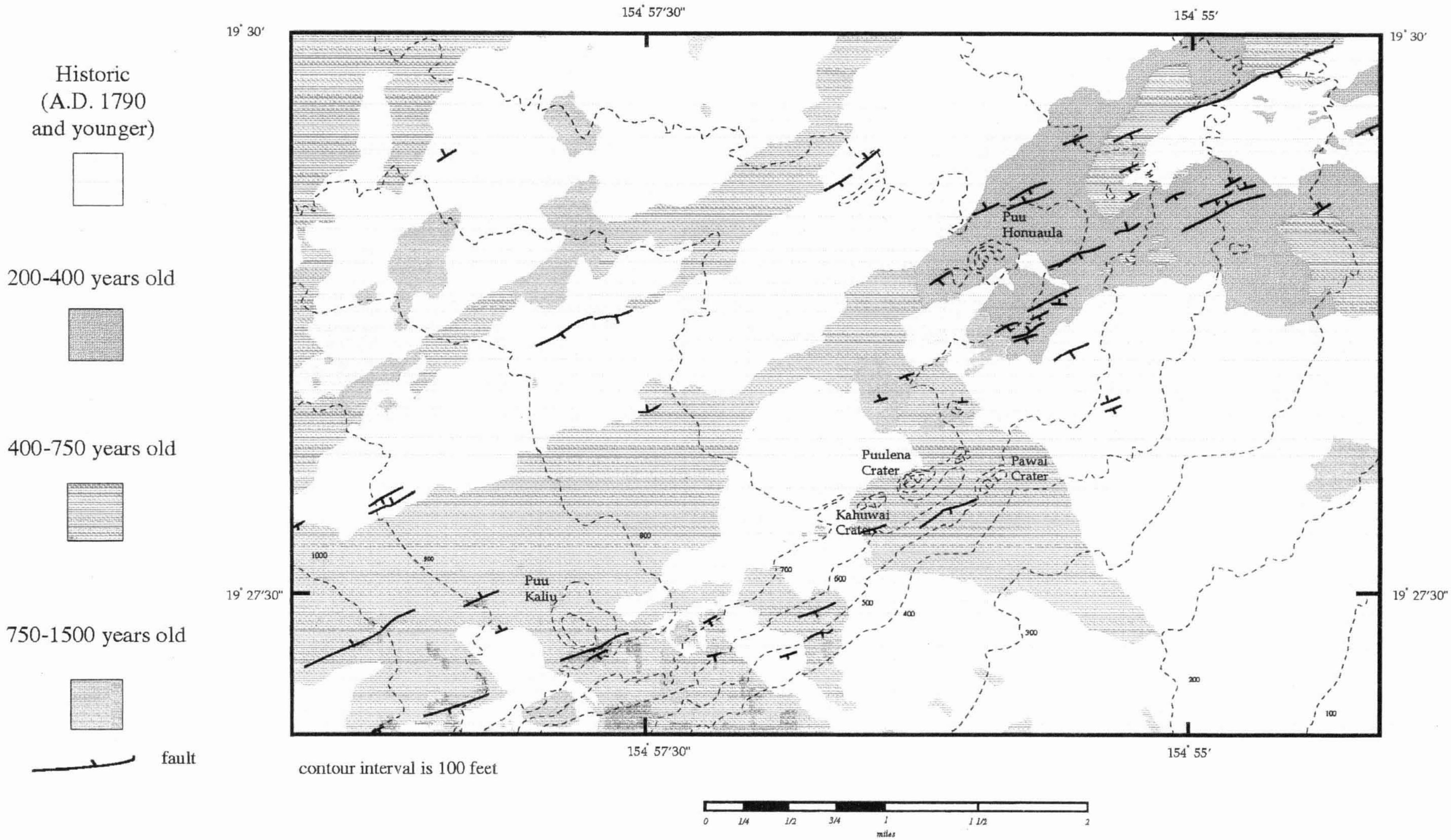


Figure 10. Local geology, after Moore and Trusdell, 1991, showing known surface flows and known locations of cracks and faults.

analysis methods as the frequency component of the noise is solely determined by the bandpass of the filters. However, the computations are relatively simple and can be performed quickly. Peak-to-trough trace amplitude is measured in a one-minute window at predetermined sampling points. The peak measurements are recorded in terms of trace amplitudes in the various cells of a table. When the measurements are completed, each cell will contain the number of times that the trace amplitude was equal to that particular value. The cumulative total points are determined for each cell; the cumulative number indicates the number of times that the trace amplitude was equal to or less than the cell value. The cumulative number of samples for each cell is then expressed as a percentage of the total number of samples. Next the trace amplitudes are converted to ground displacement (zero-to-peak) using the calibration data for the record. Finally, the curves are plotted on semi-log paper with cumulative percentage plotted on the linear vertical scale and amplitude plotted on the logarithmic horizontal scale (Fig. 11).

The final site locations (Fig. 12) differ from those in the proposal both because of the use of the PANDA array and as a result of site inspections. The high-resolution capabilities of the PANDA instruments allowed emplacement of one large array, covering the entire area that we originally proposed to cover with two small arrays for very short time periods (approx. 2 weeks). After a discussion with Bill Teplow (PGV) regarding known and postulated geologic structures, the array was centered on PGV's KS-8, rather than the HGP-A well as proposed. Before installation began, a final meeting with PGV personnel was held to obtain the final OK regarding location of stations on PGV leased land, as per our agreement. The PGV property manager also arranged for permission to install on adjoining property owned by Lyman. Several stations were moved slightly to avoid power lines and sources of cultural noise. Many stations were placed on private property with the enthusiastic cooperation of local residents. A list of station locations and property owners is shown in Table 2.

Telemetry Links (December-January)

Telemetry links were set out on a preliminary basis, as a base plan for installation. Unless problems are encountered, the installation proceeds link-by-link. Two teams of three persons each install the inner and outer stations simultaneously; one person remains at central receive to maintain radio contact and ensure clear signal reception. The gains and antennae heights are optimized in the field before the geophones are buried and the power/electronics box is sealed. Despite taking all obvious precautions, some problems with intermittent radio interference from an undetermined source were encountered. Within the densely spaced inner array, the polarity was changed on a few of the antennae to avoid

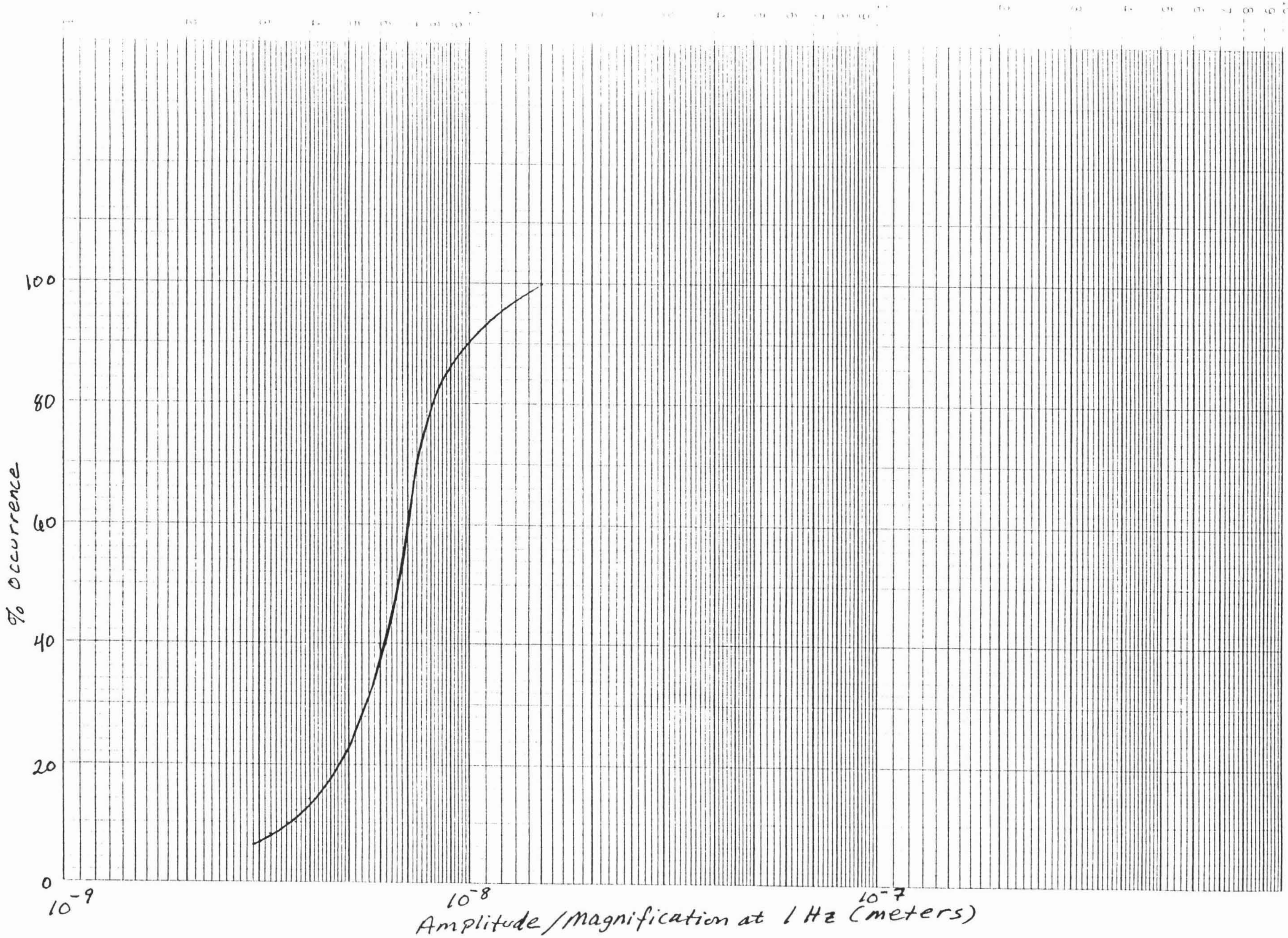


Figure 11. Noise characteristics at HGP-A, October-November, 1993.

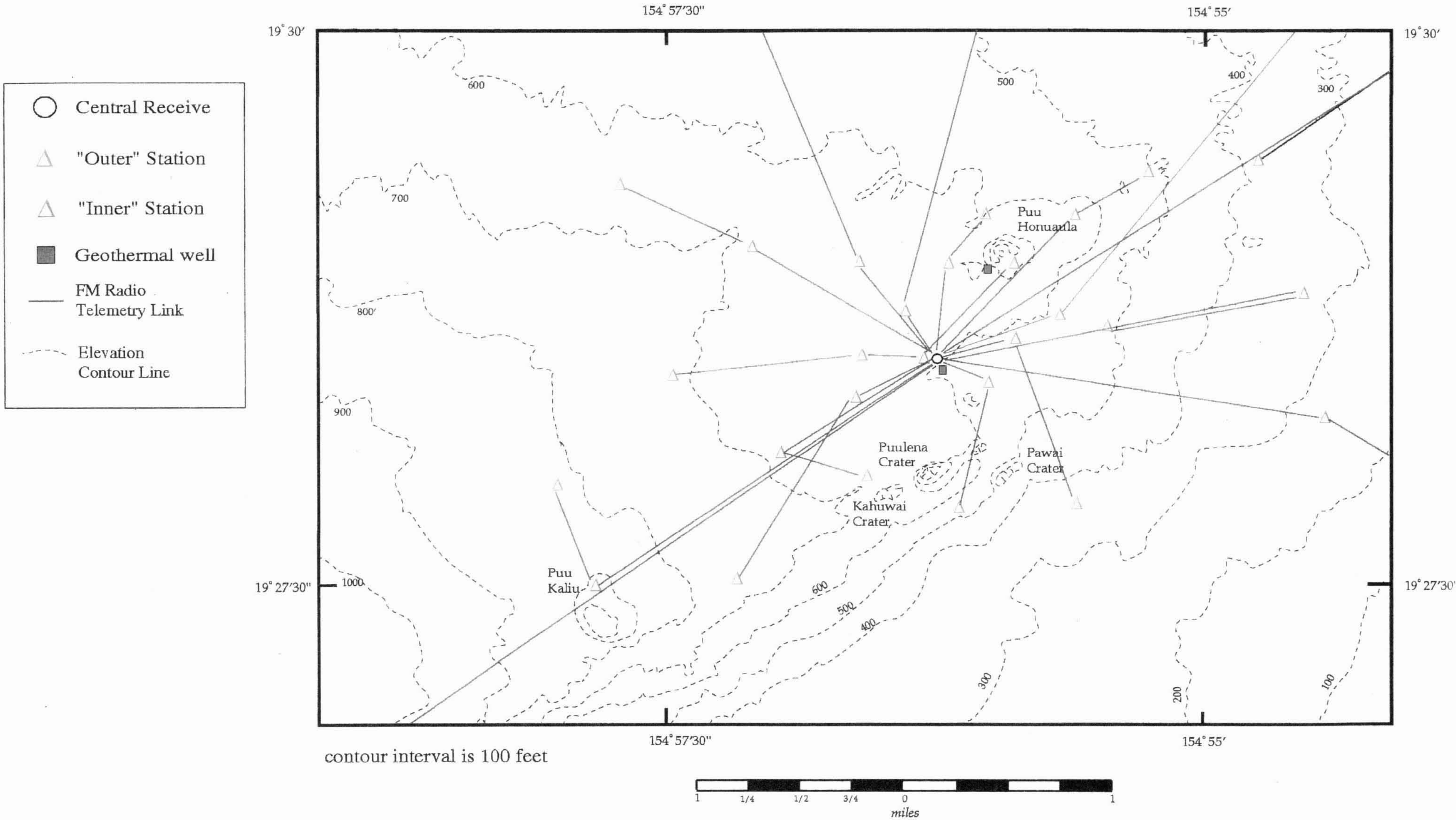


Figure 12. Station locations, central receive location, and telemetry links shown on topographic base map. Contour intervals are in feet above sea level.

Table 2. Station locations and property owner information.

Station	Elev.(ft)	Latitude°N	Longitude°E	Owner/contact
I-01 hh	580	19°28.75'	154°53.58'	State of Hawaii; Tom Daniels, 329-7341. verbal ok
O-01 hl	670	19°28.53'	154°54.00'	PGV/Pete Hansen, 961-2184, verbal ok
I-02 hh	650	19°28.80'	154°53.76'	PGV
O-02 hl	560	19°29.61'	154°53.73'	Yamanaka Enterprises, Vern Yamanaka, 935-9766, 1266 Kam Ave., Hilo, 96720; lessee Martin Anderson
I-03 hh	650	19°28.94'	154°53.67'	PGV
O-03 hl	600	19°29.19'	154°53.55'	PGV
I-04	760	19°29.00'	154°53.45'	PGV
O-04	500	19°29.65'	154°52.63'	Yamanaka Enterprises
I-05 hh	680	19°29.13'	154°53.10'	Zone 20, inactive lease; co-site with cellular phone tower
O-05 hl	580	19°29.30'	154°52.88'	Zone 32, no lease, Clayton White; PGV has entry rights
I-06 hh	390	19°28.80'	154°53.23'	Zone2, active lease; Barney (PGV's landman) will call lessee
O-06 hl	200	19°30.17'	154°50.55'	HVO (KPO); Murray Air, 961-6601; HVO has the key
I-07	600	19°28.75'	154°53.22'	PGV
O-07	450	19°30.08'	154°51.93'	Kapoho Land & Dev., Lyman
I-08	530	19°28.68'	154°52.94'	Tolmie Properties, John Tolmie (Carol), 961-6648, 688 Kinoole St., Hilo, 96720; call Ron Sewell, 965-8538
O-08	340	19°29.95'	154°51.93'	Kapoho Land & Dev., Lyman
I-09	580	19°28.61'	154°53.45'	PGV
O-09	330	19°27.75'	154°53.18'	UH , Dennis Ida (Waiakea), supervisor, 959-8477; Miki, foreman; usually open weekdays, need key to gates on weekends
I-10	270	19°28.15'	154°51.96'	AMFAC, Puna Sugar, Ann Shimazu, 945-8363 (Honolulu); Dennis Maeda, 966-7435 (Puna)
O-10	60	19°27.42'	154°51.22'	HVO (POI), AMFAC, Puna Sugar
I-11	520	19°28.30'	154°53.40'	Wayne DeLus, 935-2920,TMK1-3-8, parcel 6, call back with exact location
O-11	500	19°27.18'	154°53.55'	Bob Kochy, 965-7646
I-12	660	19°28.27'	154°53.85'	Ernie Hicks, 965-6095; possible cess-pool blasting site
O-12	660	19°27.44'	154°54.45'	John or Heather Hedenshaw, corner Hookupu & Malama, Leilani, 965-9605
I-13 hh	900	19°27.48'	154°55.30'	HVO (KLU), Jussi Makrisen, end of Moku St, 965-7121
O-13 hl	820	19°27.95'	154°55.48'	Ira Earll, 13-3547 Alapai St., Pahoa, HI, (Leilani) 965-6546
I-14	710	19°28.05'	154°54.66'	Myra Neiga & Gary, 13-3471 Makamae, 965-8234
O-14	680	19°28.00'	154°54.15'	Alisa, 965-9415, 965-8186(office)
I-15 hl	1420	19°25.50'	154°59.04'	HVO (HUL); Glover construction, Mr. Van Orden
O-15	350	19°31.89'	154°53.89'	HVO (HAB)
I-16	640	19°28.47'	154°54.33'	Dario & Don, 13-3337 Hookupu St. (Leilani)
O-16	700	19°28.46'	154°55.30'	Michael Jackson, 13-3443 Kupono St. (Leilani), TMK 1-3-35:65,

Table 2, continued.

				Lot 36
I-17 hh	680	19°28.95'	154°54.67'	end of Luana St., next to vacant lot
O-17 hl	640	19°29.38'	154°54.87'	Water Resources International, TMK 1-4-90, parcels 23,24,25; 2828 Paa St., Honolulu, 96819, 839-7727, 833-5577 (fax); gate.
I-18	620	19°28.80'	154°54.12'	Bill Teplow, 965-6583; leased to Troy Stevens
O-18	620	19°29.44'	154°54.25'	Wallace Chow (Jim Chow,son, 965-8923)
I-19	620	19°29.00'	154°54.03'	PGV
O-19	480	19°30.16'	154°54.16'	

interference. Tree mounts were used in a few cases, but, in general, the topography was working to our advantage, and there was not enough forest to cause telemetry problems. The final telemetry plan and station distribution, as it evolved throughout the project, is shown in Figure 12.

Obtaining Office Space and Housing for Field Crews (December-January)

Office and storage space was obtained through Don Thomas. Shipping crates and unused equipment were to be stored in a bay at the Puna Research Center; an office (temporarily vacated by Don's student, Elizabeth Novak) was to be used to house the computers for central receive. A house was rented in the Ainaloa subdivision, about halfway between Hilo and the field experiment.

Deployment (January-February)

Storage bays at Puna Research Center were cleaned out Jan. 18 in preparation for delivery of the container of instruments on January 19. The following three days were spent unloading the container, unpacking crates, and setting up computers and communications equipment in the office which was to be central receive. Robert Kochy (Puna Research Center maintenance) provided assistance with the fork-lift. By January 22, the 70-ft communications tower was operational; the tower base was set in concrete behind the central receive office and the tower was erected section-by-section by Memphis State technicians. The cable from the tower was brought into the central receive office through an air vent.

There were some problems with the back-up power generator because of the humidity, and with the main computers because of insects in the central receive office. The generator was moved away from air vents and elevated onto two-by-fours. To resolve the computer-insect conflict, the air vent in the central receive office was removed and replaced by an air conditioner and the room was sealed.

Installation of the seismometers began January 23 with the help of three technicians from Utah State (they operate a similar system), Greg Moore (Co-PI), Mark Dustman, Rick Hagen, and Andy Goodliffe (UH graduate students). A GMC "Jimmy" Jeep was rented largely for transportation of personnel and use of a four-wheel-drive pickup was provided by P. Cooper. All sites were accessible by car and/or foot; no helicopter support was necessary.

Installation involved the following steps: (1) positioning and securing the tripod that supports the antenna, (2) orienting the antenna - two antennae for inner stations - and confirming reception at the inner station and central receive, (3) digging in, leveling and orienting both sets of geophones, (4) attaching battery and solar panel, (5) testing geophone response, power source, and electronics, (6) burying all geophones, trenching (burying) all cables, and (7) securing the electronics box. The entire process requires from 3 to 4 hours per station. Thirty-four stations were installed during the time period January 23-February 11. Three additional stations were installed during the time period February 27-March 1, bringing the total number of stations to 37.

Data Collection and Routine Maintenance (January 29-May 12)

Continuous monitoring of background seismicity was underway from January 24 through May 2, recording more than a thousand very small (magnitude < 0.0) to small (magnitude 2-3.0) events. Files of noise data were collected on a daily basis for spectral analysis. Sensors at sixteen stations were changed out during the last week of March; the Mark Products L-28s in use until that date were replaced by Mark Products L-22s at stations i-01, i-02,o-03, i-05, i-07, o-07, i-09, o-09, i-10, i-11, i-13, o-13, o-14, i-16, o-16, and o-18 (o=outer, i=inner). The L-22 sensor has a peak response at 4.5 Hz, enabling characterization of background noise over a broader spectral range. As of April 19, seven instruments surrounded the PGV plant and remained operational through May 2.

Because of the close station spacing, radio interference was occasionally experienced. This problem was addressed as the the array grew; some of the station pairs were reversed, that is, the outer station was made the inner station. In other cases, the polarization was changed. Several stations experienced problems with intermittent radio interference. It was determined that the source of the interference was probably illegal use of radio frequencies within the PANDA band.

Two technicians from Memphis State University stayed with the array for daily maintenance and trouble-shooting during February and March; one during April. Patricia Cooper and Mark Dustman collected and sorted earthquake data on a daily basis for the duration of the experiment. Data was downloaded from the MASSCOMP to magnetic tape; two copies are stored at University of Hawaii, one copy at Memphis State.

The array was in place for approximately 3 months instead of the originally proposed 20 days because of delays in start-up at PGV; the area surrounding PGV was instrumented for approximately one week following the late April start-up to enable us to compare 'before and after' seismicity levels. Essentially, we installed more and better instruments with smaller spacing over a longer period of time for less money than proposed.

Surface Calibration Shots

Five shots were detonated on March 2, 1993, in an attempt to fix surface-layer velocities to neaby stations. The shooting was contracted to Earth Brothers Home Lot Improvement, which provided all equipment, explosives and permits. A six-foot-deep hole was bored to accept the charge; the hole was filled with dirt and rocks, covered with a chain-tire net, and the charge was detonated. Five charges were detonated at the four sites listed in Table 3. Charge size varied from 1-2 sticks of dynamite; larger charges were impractical because of the residential nature of the area. An average P-wave velocity of 0.97 km/s for the top 0.5 km, overlying a layer with velocity of 2.25 km/s, was calculated from these shots; this velocity was incorporated into the starting velocity model used to located the events shown on Figure 14.

Array Removal (May 2-May 13)

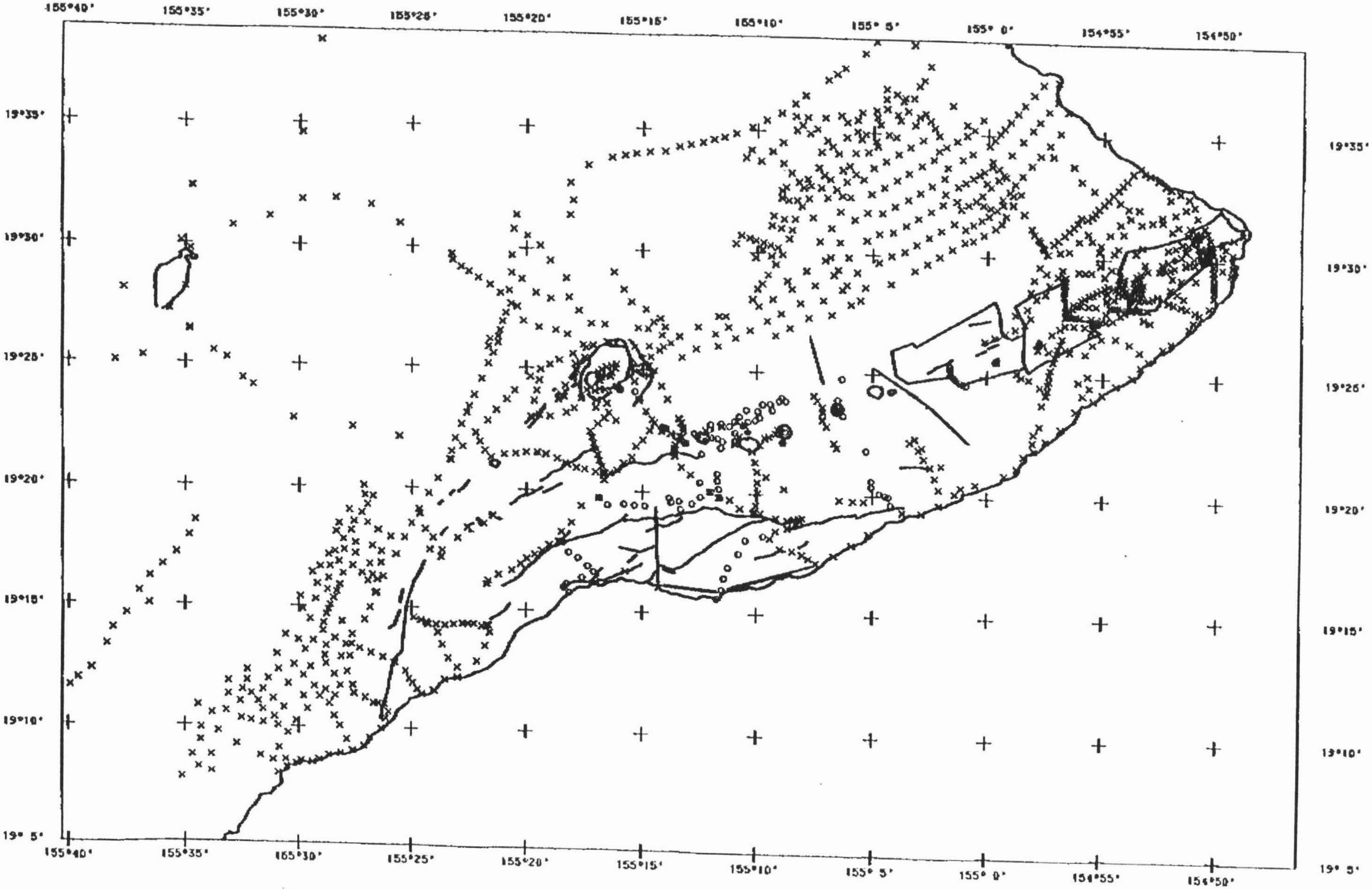
During the first week of May, following the start-up, the instruments surrounding PGV were removed for cleaning and packing. An additional Memphis State technician arrived May 6 to assist with dismantling and crating the central receive discriminators, power supply, and computers. Two day workers were hired for May 13; again, Robert Kochy provided fork-lift assistance. The entire Panda array was loaded into a container, and the storage bay and office at Puna was cleaned out. The lease on the rental house in Ainaloa was terminated May 30.

GRAVITY SURVEY (May 1 - present)

James Foster (formerly of HVO) was hired as of May 1 to complete the gravity portion of the field work. As of July 1993, the data collection phase for the gravity map of Kilauea Volcano was about 90% complete, however, the remaining unsurveyed 10% is located in the most inaccessible regions of the volcano (Fig. 13). These data will be crucial to the gravity map since they are along the structurally complex East Rift Zone of Kilauea. Collecting these data will be both difficult and time consuming, requiring the field technician to hike in to the chosen site, bringing whatever equipment is appropriate to the terrain to locate and constrain the elevations of the gravity stations. The techniques needed for station location, primarily use of hand-held global positioning computer (GPS), are the same as were used for previously collected data. Estimated accuracy for horizontal positioning is 50-100 m; estimated accuracy for vertical positioning is .05-1.0 m. Gravity measurements are obtained using a LaCoste Romberg gravimeter; estimated accuracy for gravity measurements is $\pm$ 100 μgal.

Table 3. Blast Sites and Detonation Times.

Detonation Time (UT)	Blast Site	Elevation (ft)	Surface Geology
19:35:22.068	19° 28.0'N 154° 53.8'W	300	cinder over basalt
Operator error	19° 28.3'N 154° 53.2'W	500	cinder over basalt
21:14:12.119	19° 28.3'N 154° 53.2'W	500	cinder over basalt
00:27:44.274	19° 30.2'N 154° 49.7'W	100	basalt rubble
02:42:25.689	19° 30.0'N 154° 55.3'W	100	cinder over basalt



(as of 10th August 1993)
Jim Kauahikaua and others, USGS-HVO

Figure 13. Gravity Data collection for the Kilauea region; x indicates data collected during the period prior to May 93; o indicates data collected during 1 May through 10 August, 1993. Lines define areas where data collection is in progress.

Once collected, the data must be checked for errors and reduced; data values that have been entered into the computer incorrectly must be removed, and any obvious discrepancies must be resolved. This must be done before calculation of gravity anomalies to ensure that the anomalies revealed are real, and not artifacts of data collection or reduction.

To complete the reduction of the gravity data, corrections must be made for the effects of topography - the terrain correction. The computer programs necessary to do this are being revised currently to accomodate newly acquired, more accurate topography data files. A final correction to be made is that for "island effect." This corrects for the large-scale, long-wavelength anomaly caused by the density contract between the island and the surrounding ocean.

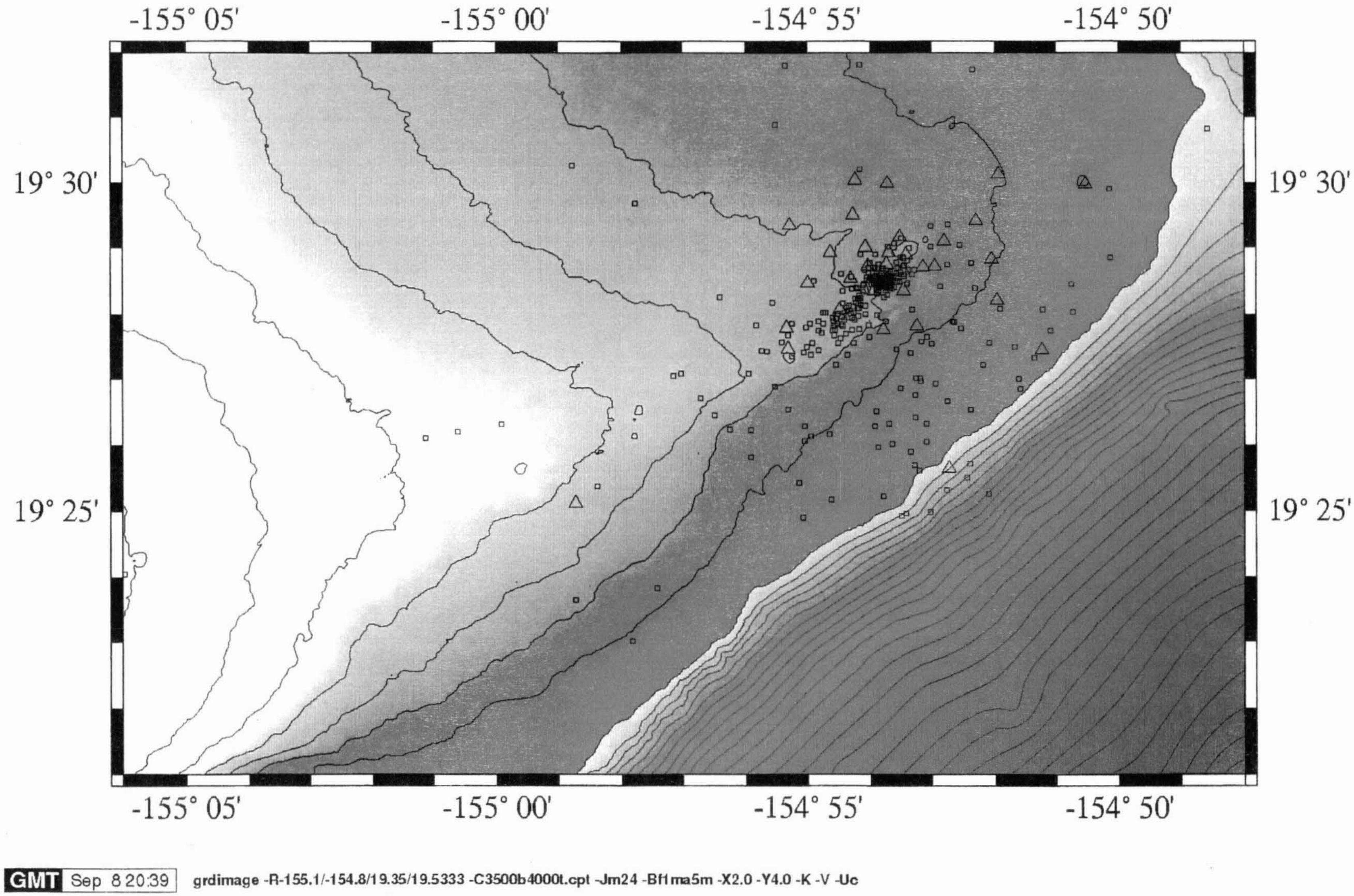
When the above corrections have been applied, the data will be mapped and published. A preliminary interpretation of the anomalies will be offered; this, and a more detailed interpretation and modelling of the gravity will constitute Foster's the M.S. thesis.

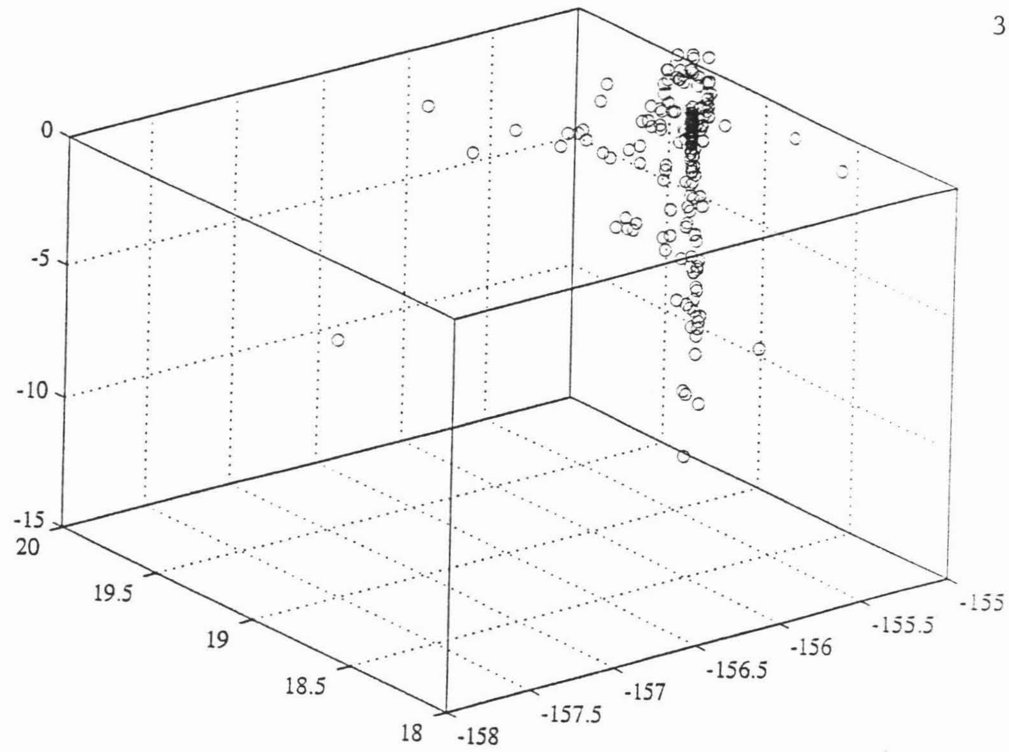
DATA PROCESSING (June-present)

The first order of business following the field work was the conversion of all data display and processing software to be compatible with a Sun™ SPARCstation, purchased for the exclusive use of this project. The programs were originally written to be used with a mainframe computer and graphics terminal, however, the mainframe computer service available at Hawaii Institute of Geophysics was terminated July 1, 1993. At present, earthquake display, picking, and location programs are working, as are filtering, focal mechanism and body-wave inversion programs; interactive 3-d display programs and programs to invert for attenuation (Q) structure are not.

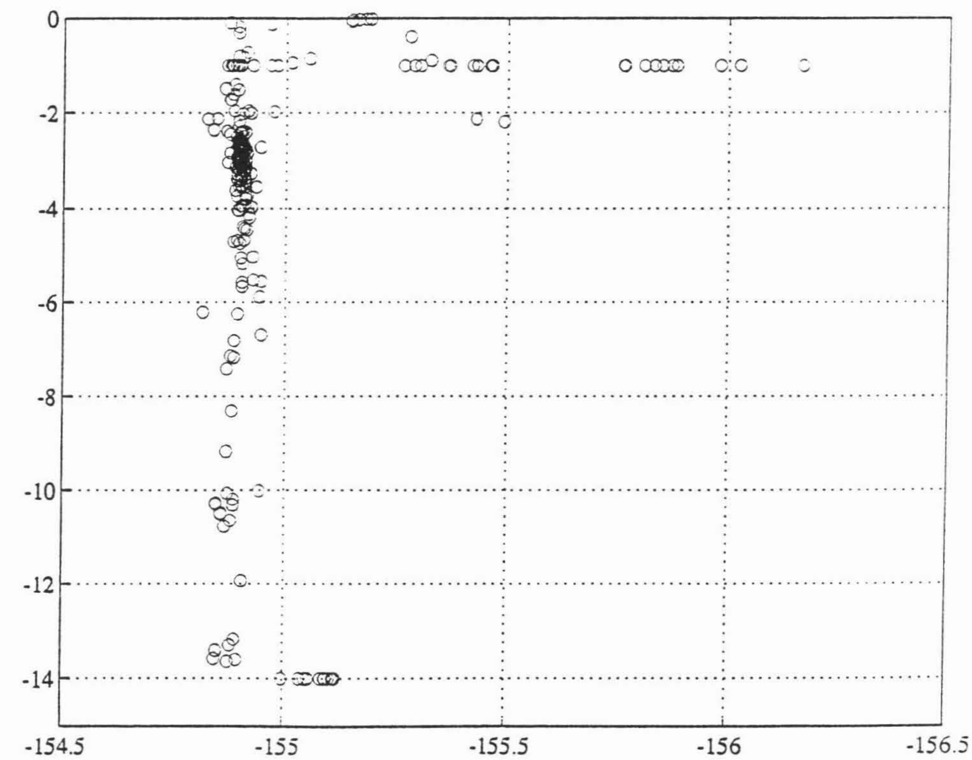
Earthquake data tapes are first sorted according to quality; this is a subjective grading scheme based on the number of stations that detected the quake. Almost all detected events can be located with our array configuration, so our grading scheme has only two classes of events - acceptible (>5 stations) or unacceptible (<5 stations). Figure 7 shows a typical three-component seismogram of a local earthquake recorded by a PANDA station. Both P- and S-arrival times are picked interactively on the Sun using software developed at UH for this purpose. About two months of earthquakes has been located to date (January 29-March 27) and is shown in Figure 14. Many events form a dense concentration slightly southwest of the center of the array, close to the HGP-A well. A linear band of earthquakes slices across the southern portion of the Leilani Estates and continues south along the KERZ. The fall-off in number of earthquakes away from Leilani

Figure 14. Map view of epicenters, Jan. 29-March 27, 1993.





(a)



(b)

Figure 15. Depth sections showing seismicity viewed from SW to NE (a) and from S to N (b). Hypocenters span time period 1/29/93-3/27/93.

Estates may reflect the diminishing detection capability of our array in that direction. The lack of seismic activity north of PGV, from Nanawali to Hawaiian Beaches is probably real.

Work Remaining

The primary goals of the seismic experiment, namely determination of three-dimensional velocity and Q models and imaging of lateral crustal anisotropy, required closely spaced shear-wave observations. The quality of the data certainly will allow us to fulfill those goals in a timely manner (see Figure 16). Once the remaining earthquakes are located, arrival times will be inverted to image the velocity structure. The P- and S-wave arrival times will be input independently for layered velocity inversion using programs developed by Roecker (1982) and Roecker et al., 1987. This velocity structure then will be used in a master-event scheme to relocate earthquakes recorded by HVO, giving some historical perspective to the current study.

Although the exact relationship between seismic attenuation and temperature is not well defined, the thermal regime of geothermal systems, in general, exhibits high seismic attenuation. A generalized discrete linear inversion technique will be applied to the observed differential attenuation data for P- and S-waves in order to obtain a "Q" model.

Mapping of local variations in the velocity ratio, Vp/Vs, or alternatively, Poisson ratio will be used in an attempt to locate production zones. A decrease in P-wave velocty (Vp) in an area of high heat flow leads to a low Poisson ratio; the decrease may be caused by steam-filled fractures. Information contained in the shear wavetrain, shear-wave splitting and polarization, will be interpretted in terms of the percentage and alignment of cracks and/or pores.

Accurate magnitude determinations and focal mechanism studies will provide some control over the regional-scale geologic structures in the target area.

FURTHER EFFORTS

A Guralp CMG-3ESP borehole seismometer has been ordered from Digital Technology Associates, Inc. to be installed in the HGP-A well during December/January 1993/94. The greatest advantage to downhole instrumentation is the reduced ambient noise. This instrument will provide a means of continuously monitoring microseismicity near the PGV site as well as an enhanced location capability for seismicity along the Puna section of the KERZ. The reasoning behind the request for a downhole instrument (more expensive than a surface installation) is that microseismicity studies using surface

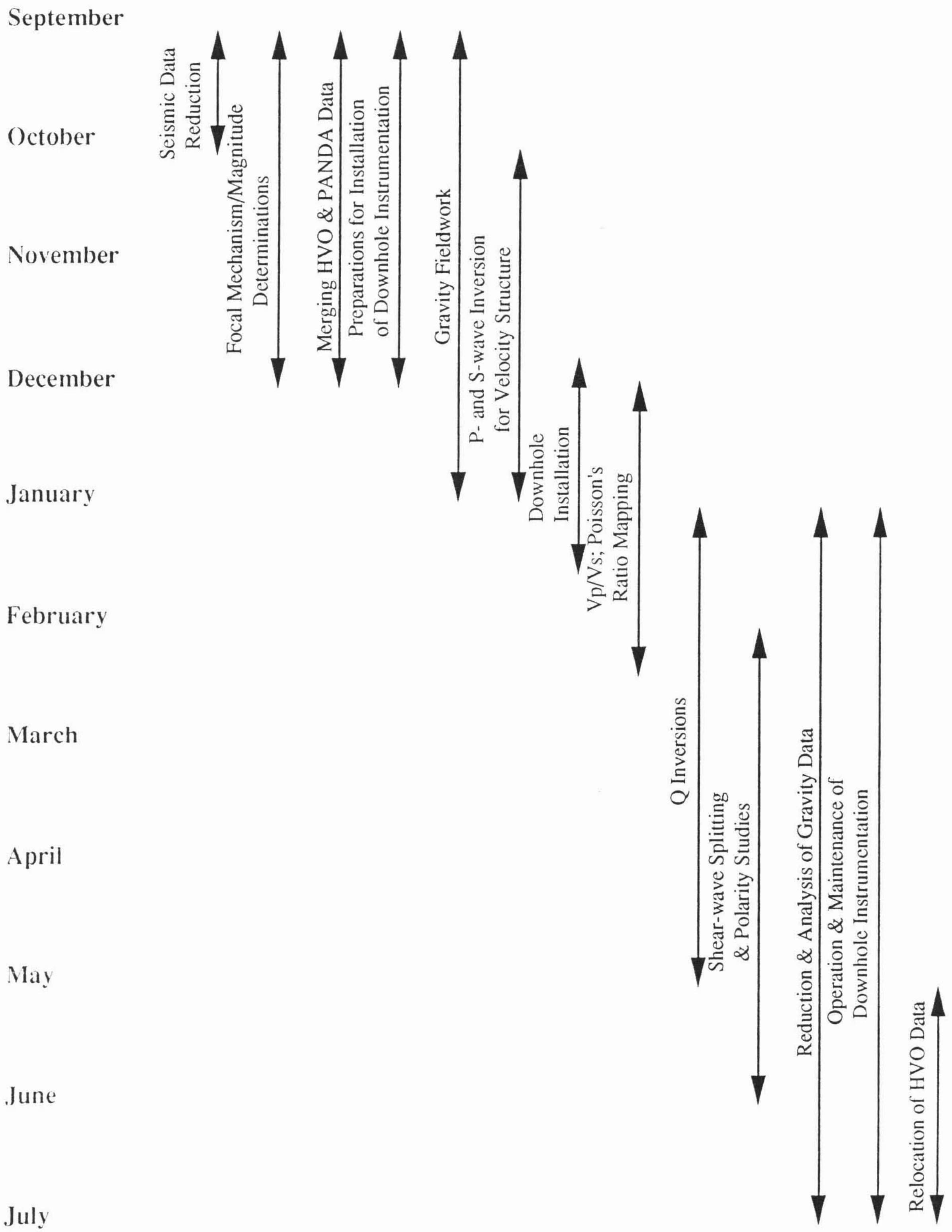


Figure 16. Timeline for remaining tasks.

installations have not proved very successful in imaging of hydraulic fracture. Sorrells (1988) reports that attempts to lay out a surface-receiver array, record fracturing noise for a while, and image the induced fracture in a sedimentary (petroleum) environment have failed. The seismic activity generated by hydraulic fracture is estimated to have magnitudes below the detection capabilities of standard surface instrumentation. [While this is generally true, several cases of induced seismicity - for example, in Denver, 1962, and at Rangely oil field, 1970 - produced events with magnitudes in the 3.0-4.5 range.] Use of borehole recording of the magnitude -6 to -2 microseismic activity has been more successful in imaging induced fractures in both crystalline and sedimentary rocks.

The Guralp CMG-3ESP is a rugged, dependable instrument that can withstand downhole conditions encountered in a geothermal field; there follows a table of specifications for the instrument (Table 4). This instrument was selected after conversations with previous users (e.g., Dr. Holly Given, UCSD). Seismic, pressure, and temperature data will be transmitted from the well head *via* logging cable to an IBM (or IBM clone) personal computer located in the Puna Research Center and dedicated solely to data collection. [Both HVO and Civil Defense have expressed some interest in the data; HVO may provide for telemetering to its observatory at Kilauea, as well.] As mentioned above, a single downhole instrument will provide information on changes in local seismicity levels. This is particularly important for the rapidly developing residential areas surrounding PGV. The downhole instrument also provides for improving detection and location capabilities for the existing HVO network. HVO does not routinely locate small (<3.0 magnitude) events along this section of the rift because of inadequate instrumentation. Considering the unstable nature of the South Flank, that is unacceptible from a civil defense standpoint. Future expansion to a network requires the availability of suitable downhole sites (<100°C, within 5° of vertical, 7-9" diameter, with casing in good condition) and the purchase of seismic and telemetry instrumentation. An ideal network would combine three downhole stations surrounding the site of exploitation of geothermal resources with a portable array of surface instrumentation for local "trouble-shooting."

CMG-3ESP TRANSDUCER SPECIFICATIONS - Table 4.

Outputs and Response

Full scale outputs:	+/- 20 V dc differential velocity output (1000 V/m/s for 30 sec sensor)
	+/- 10 Vdc mass position output (1000 V/m/s^2 for 30 sec sensor)
Standard response:	Flat velocity 0.033 to 50 Hz
Optional response:	Flat velocity 0.01 to 50 Hz
Optional NSN response:	Flat accel. 0.005 to 0.033 Hz, flat velocity 0.033 to 50 Hz
Clip level and self noise:	See Figure 6

Controls

Mass recentering:	Controlled remotely
Mass lock:	External access through ports in jacket
Remote mass lock:	Available as an option
External calibration input:	The cal input can be connected to each axis separately

Physical

Lowest spurious resonance:	140Hz, vertical; > 140Hz, horiz.
Temperature change before recentering required:	+/- 10 deg C
Operating temperature range:	-10 to +65 deg C
Pressure jacket material:	Stainless steel
Base plate and top cap:	Stainless steel
Power/signal connector:	Milspec connector on top cap, KPT02E-16-26P
	Stainless, 1500 psi connector available
Pressure relief valve:	On top cap
Carrying handle:	On top cap
Case diameter:	168mm (6.61in.)
Case height with handle:	367mm (14.45in.)
ESPV vertical unit height:	280mm (11in.) including electronics

Power

Standard power supply:	+/- 12 Vdc
Optional power supply:	+ 12 Vdc with internal dc-dc converter
Current at +/- 12Vdc:	+/- 40 mA
Current at + 12 Vdc:	90 mA
Additional calibration current:	+25 mA

Downhole Accessories

Refer to separate brochure, 'CMG-3 Downhole Systems for 7-inch and 4-inch Holes'

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