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VOLCANIC INVESTIGATIONS IN THE COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS, APRIL TO MAY 1994

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ABSTRACT

A team of U.S. Geological Survey geologists, a seismologist, and technicians gathered new geologic, seismic, and deformation data in the Commonwealth of the Northern Mariana Islands (CNMI). Nine volcanic islands on the active East Mariana Ridge north of Saipan were examined between April 20 and May 3, 1994. In addition, a new radio-telemetry seismic station was installed on the island of Agrihan (also spelled Agrigan). This report describes our continuing efforts, that began in May 1981, to establish volcano monitors and to assess hazards in the CNMI. Our previous visits, from September 1990 to May 1992, are documented in Moore and others (1991, 1993).

Regional seismicity of the Mariana Island region, as recorded by the USGS National Earthquake Information Center (NEIC), included at least 324 events between January 1, 1991, and February 4, 1994. The largest event was a M 8.1 Guam earthquake on August 8, 1993, which caused extensive damage to that island and was felt on Saipan. Intermittent seismic activity continues to occur in the Anatahan-Sarigan, Guguan-Alamagan-Pagan, and Pagan-Agrihan-Asuncion areas.

Mount Pagan volcano was actively erupting ash during our 11 days on the island of Pagan. We were able to document seismicity and ground deformation associated with this volcanic activity. None of the other subaerial volcanoes in the chain showed signs of eruptive activity during our visit, but an overflight in a fixed-wing aircraft by geologist Richard Moore and CNMI Lieutenant Governor Jesus Borja detected an apparent submarine eruption between Farallon de Pajaros (also known as Uracas or Uracus) and Maug. The only surveillance of the three uninhabited islands of Farallon de Pajaros, Maug, and Sarigan was by aerial reconnaissance. Geologists studied the other six islands in greater detail by field mapping and aerial surveillance.

Electronic distance measurement (EDM) permanent-glass monitor lines were measured on Agrihan, Pagan, and Anatahan. The majority of line-length changes on Agrihan were insignificant (<16 mm). Mount Pagan's south EDM monitor was reestablished, and 1994 results, compared with 1983 measurements, show large changes associated with renewed volcanic activity. Contractions of 59 mm (stations INS to REF) and 157 mm (stations INS to MID) were measured on the south monitor. The southwest Pagan EDM monitor showed a 56 mm contraction for the same period (stations PAGAN 1 to RIDGE 2). Line-length change of this sense and magnitude usually indicates that inflation has occurred in the volcano. Measurements during the 1994 visit to Pagan Island showed no significant changes (for all measurements made during April-May 1994). Anatahan also showed changes as large as -50 mm, accumulated over a time span of approximately two years.

Temperatures and pH values of hot spring waters on Agrihan, Pagan, and Anatahan and fumaroles on Agrihan and Anatahan were measured. The temperature data indicated no significant change in the state of these volcanoes since 1992. We collected warm spring water from Lagoonam Sanhalom (Inland Lake) near Mount Pagan. In addition, we started geologic mapping on Asuncion and Guguan, collected charcoal to date three eruptions of Mount Pagan, and collected rocks on Asuncion, Guguan, Pagan, and Alamagan for petrographic and chemical studies.

We conclude that the low and infrequent shallow seismicity, lack of significant deformation, and low fumarole temperatures suggest that no eruption is likely soon on Agrihan and Alamagan. Anatahan's deformation pattern continues to behave in an erratic manner. Because

of the lack of seismicity, it seems unlikely that an eruption of Anatahan will occur soon. The persistent volcanic tremor and significant EDM changes on Mount Pagan mean that small explosive eruptions will continue to occur.

INTRODUCTION

At the request of the Commonwealth of the Northern Mariana Islands, a USGS team consisting of two geologists, a seismologist, a deformation expert, and an electronic technician visited CNMI (fig. 1) from April 18 to May 6, 1994. Nine volcanic islands on the active East Mariana Ridge north of Saipan were examined between April 20 and May 3, 1994. The team had several goals, all of which were accomplished: (1) assessment of the probability of eruption, especially on Agrihan, Alamagan, and Anatahan, using seismic records from permanent and portable stations, analysis of EDM (electronic distance measurement) data, measurement of fumarole temperatures, and geologic observations; (2) installation of a new radio-telemetry seismic station on Agrihan; (3) reestablishment of the south Mount Pagan EDM permanent-glass monitor; and (4) geologic studies on Agrihan, Pagan, Alamagan, Guguan, Asuncion, and Anatahan.

SEISMOLOGY

This preliminary compilation of seismic data related to volcanic activity in the Northern Mariana Islands and regional tectonic movements along the Mariana Trench is an update of our continuous evaluation of regional earthquake data furnished by the USGS National Earthquake Information Center (fig. 2) and daily analysis of seismograms collected from the CNMI seismographs. As in past years, the CNMI seismic network is composed of seismometer signals from Anatahan, Alamagan, and Pagan, which are radio-telemetered to the central recording station at the Emergency Operation Center (EOC) in Saipan. A new seismic station (AGRI) on the island of Agrihan has now been added to the link and is transmitting signals back to Saipan (fig. 3).

Instrumentation and field survey

During the period April 8-19, 1994, geophysicist John Hildebrand from Scripps Institute of Oceanography, University of California, installed a computer-based digital recording and data processing system for our CNMI seismograph array at the EOC. The digital records will be studied and used to provide guidelines in preparing rapid and effective means of accessing the seismic data.

Between April 18 and 29, seismic instrumentation specialist George Kojima and volcano seismologist Robert Koyanagi joined Frank Chong and Ramon Chong and members of the Disaster Control Office to implement planned expansion and improvement of the CNMI seismic monitoring system. The main objective was to install a new field seismometer on Agrigan and radio-link the signal back to Saipan using our Pagan-Alamagan-Anatahan relays. The seismic signal will be continuously recorded in conjunction with the other four revolving drum recorders presently in operation at EOC. Signals from Agrihan, Mount Pagan, South Pagan, Alamagan, and Anatahan now are recorded at Civil Defense headquarters on Saipan. Work also included evaluation of seismic records collected since the team's last trip in November 1993, as well as a field survey of the principal northern islands in conjunction with the geology and deformation monitors.

Regional Seismicity

The USGS National Earthquake Information Center (NEIC) catalogued 324 seismic events in the Mariana Islands region, within map coordinates 11°-21° north latitude and 140°-150° east longitude, for the period from January 1, 1991, to February 4, 1994 (fig. 2). These events were mostly earthquakes larger than 4.5 in magnitude, which is about the lowest measurable magnitude for earthquakes determined from the worldwide seismograph network. Seismometer stations of the worldwide network are sparse in the Mariana region and, consequently, earthquake detection capability is low and location errors of up to about 50 kilometers can be expected. Additional readings from the CNMI seismographs, since late 1993, substantially improved the NEIC locating capability for the Mariana earthquakes.

During the past three years, earthquake activity along the Mariana Trench was highlighted by a destructive M 8.1 Guam earthquake on August 8, 1993. The concentration of aftershocks from this major earthquake outlined an arcuate rupture zone, about 300 km long, centered on Guam (fig. 2). Along with the extensive damage in Guam, the main shock was felt in Saipan, with a maximum intensity of MM-V1, causing some damage to buildings.

The monthly number of large earthquakes (mostly M>4.5) from the NEIC data file since 1988 indicates episodic bursts and sustained high rates of seismicity in discrete localities between the principal islands of the Mariana chain and along the adjacent north-south axis of the Trench (fig. 4). The high number of earthquakes along the axis of the Mariana Trench in April and May 1990 includes aftershocks from a M 7.5 earthquake on April 5, 1990, located about 250 km east of Saipan. The burst of earthquakes in the Saipan-Guam area in August and September 1993 is attributed to the aftershocks of the M 8.1 Guam earthquake on August 8.

In the Sarigan-Anatahan area, a series of earthquakes occurred in the vicinity of Anatahan, some of which were felt by people residing at Anatahan at the time. Recurrent activity at Anatahan peaked again in February 1993, with episodic swarms of smaller events detected in greater numbers locally on the CNMI Anatahan seismograph station.

In the Alamagan-Guguan and Pagan areas, large earthquakes were separated by long intervals of time. The low rate of earthquakes in the Pagan area may be attributed to relief of internal stresses by the current high rate of eruptions of Mount Pagan, shown by the frequent detection of seismic tremor on PAGV seismograph.

During the six-year period, earthquakes persisted at a rate of nearly 2-4 per month in the Agrigan area (fig. 3), forming part of the cluster of earthquakes in the epicenter map (fig. 2). Earthquake frequency in the northernmost locality of Farallon de Pajaros-Asuncion remained low.

Alternatively, these earthquakes, plotted cumulatively according to their respective regions, show details of changes in the long-term trend of seismic activity (fig. 5). The trends that may relate to future volcanic eruptions are the sustained high rates in the Agrigan area and the episodic recurrence in the Anatahan area. These events are sometimes associated with swarms of small earthquakes that commonly precede initial phases of volcanic eruptions, whereas major earthquakes and aftershocks, such as those that accompanied the M 7.5 April 1990 earthquake in the Mariana Trench and the 8.1 M August 1993 Guam earthquake, do not necessarily precede major eruptions.

Local Seismicity

The CNMI seismographs recorded minor swarms of small (M<4.5) local earthquakes at Anatahan in May to July 1993, with scattered events since late 1990, when the station was first installed (fig. 4). In early 1990 residents reported feeling a series of earthquakes which led to their evacuation of the island. This type of episodic trend in seismicity may eventually lead to volcanic eruption.

North Pagan seismic station PAGV (fig. 13) persistently recorded volcanic tremor of varying intensity and duration (figs. 7-9). As observed in November 1993, tremor of increased amplitude preceded eruptive episodes. The number of local earthquakes remains relatively low; we attribute this to magmatic pressure being released by the ongoing eruption.

Stations at South Pagan and Alamagan show occasional local earthquakes, but not in significant swarms.

Seismic Summary

The continuous instrumental monitoring of local seismicity from the CNMI radio-telemetered seismic array since 1990 (fig. 9) is beginning to show trends of activity related to volcanism, primarily at Pagan and Anatahan Islands, and regional tectonics along the Mariana Trench and island chain. With many years of systematic collection, the database becomes increasingly effective for scientific evaluation of volcanic and seismic hazards. It will provide more detail in the short-term (monthly) events, as well as enable the researcher to gain perspective through patterns observed from the long-term (yearly) background levels of activity.

The repetition of seismic tremor, from vibrations due to the continuing eruption and the low number of local earthquakes at Pagan, collectively suggest that internal pressure of the volcano is being continually relieved. There was no substantial increase in local earthquakes to indicate blockage in the volcanic system that might lead to a stronger explosive eruption. Our most recent field observations since April 20, 1994, reconfirmed continuance of intermittent eruption and volcanic tremor at Pagan (figs. 7, 8, and 9). Moderate eruptions of volcanic ash, sometimes lasting many hours, occurred during days of high tremor amplitudes registered at Pagan's PAGV station. One of the most intense and sustained periods of tremor coincided with moderate ash emission, which lasted for more than 10 hrs between 04:49 and 15:00 on April 25. On April 27, at 09:13, a moderate earthquake located 120 km NW of Agrihan at coordinates 19.5° N and 144.8° E, and at a depth of about 100-150 km, was felt on Pagan and Agrihan (fig. 10). The earthquake registered first on the new Agrihan station, and sequentially later on the stations at Pagan, Alamagan, Anatahan, and Saipan.

The new station at Agrihan is composed of a sensor system using a Mark Products L-4 (1.0 Hz) vertical component seismometer and USGS-made J402 voltage-controlled oscillator, electrical power system utilizing a 12V battery charged by solar panel, and signal transmission via low-power (100 mv) Monition telemetry radio. The sensor system was installed in a corner room of a concrete utility building at the edge of Agrihan village. The radio transmitter and antenna were placed on the adjacent wall outside the building. Location parameters for the station are 18.733° N, 145.653° E, and 25 m elevation. Field installation at Agrihan was completed on April 22, and telemetry was linked with a continuous recorder on April 23, 1994.

The computer-based seismic recording and processing system added to the central receiver system at EOC in Saipan provides Ramon Chong and his CNMI seismic monitoring team with an accurate means of reading earthquake and tremor times and amplitudes, determining preliminary locations of earthquakes, and storing digital data that may be more accessible for statistical analysis of the seismic data. John Hildebrand will continue to assist in upgrading the digital processing system.

GEOLOGY AND DEFORMATION

In this section, we describe geologic observations, and EDM surveys where conducted, on each of the nine islands in the active arc north of Saipan, beginning with Farallon de Pajaros (also known as Uracus or Uracas) at the northern end down the chain to Anatahan at the southern end.

Farallon de Pajaros

When viewed from the fixed-wing airplane on April 23, 1994, Farallon de Pajaros (fig. 1) was fuming vigorously, but not erupting. We circled Farallon de Pajaros for 10-15 minutes before turning south. The crater floor did not appear to have been recently active and had a small, fine-grained deposit of mud in it.

As the plane headed south, back towards Pagan, the pilot noticed an anomalous discoloration on the ocean surface approximately 17-18 km (10-11 mi, GPS fix) south of Farallon de Pajaros. We circled this feature at a low (30 m) altitude three times and noticed that large bubbles were rising, presumably from a submarine eruption on the ocean floor. The area of most intense upwelling was perhaps 10-30 m in diameter. The narrow (20-40 m) trail of discolored water (light green to yellow, in contrast to the deep blue of the unaffected ocean) drifted several hundred meters to the north.

Maug

Observations made during a rapid fixed-wing airplane flight on April 23 across the three main islands that comprise Maug (fig. 1) showed no signs of steaming or other evidence of recent or impending volcanic activity.

Asuncion

We flew north from Pagan by fixed-wing airplane on April 23 and skirted the west coast of Asuncion (fig. 1). The view into the summit crater was clouded, and no eruptive activity was seen on the island.

Vigorous steaming was occurring at several locations in Asuncion's summit crater when viewed from the helicopter on April 30. This low-level activity probably is residual in nature and related to the most recent eruption in 1906. The geology team collected several rock samples and searched for charcoal to date flows by radiocarbon dating. The rock samples will be submitted for chemical and petrographic analysis.

Agrihan

Because of low-lying, thick clouds over Agrihan (fig. 1) caldera, observation from the fixed-wing aircraft on April 23 was impossible. A helicopter landed a survey team on the summit caldera floor on April 26. We remeasured the EDM permanent-glass network, sampled water, and measured fumarole and water temperatures (fig. 11a). The results of the measurement of four EDM lines showed no significant changes when compared to those of the surveys of September 1990 and May 1992 (fig. 11b). Line-length changes are all less than one centimeter (within the error of the instrument's precision), with the exception of the line from CENTRAL CONE (CEN) to COLUMNAR (COL), which had a -17 mm change (table 1).

The water temperature of the hot spring located in the fumarole area (fig. 11a) was measured at 98° C, the same as in 1990 and 1992. The volume of water issuing from the spring was less than in 1990, but about the same as in 1992. We attribute this phenomenon to seasonal variations in rainfall. The pH of the water was 2.7. The highest fumarole temperature measured also was 98° C, the same as in 1992.

Summary of geologic and deformation observations on Agrihan

The time-series plot for the EDM lines (fig. 12) shows small, long-term contraction on all lines. This type of line-length change suggests that the volcano is deflating. Agrigan's most recent eruption occurred in 1917. Future eruptions can be expected, but the lack of both significant deformation changes and local seismicity suggests that an eruption on Agrihan is not imminent.

Pagan

Mount Pagan (fig. 13), located on the northern section of the island of Pagan, continued to show signs of unrest. Volcanic activity varied daily during our 12-day visit between April 20 and May 1. EDM permanent-glass monitors were reoccupied and reestablished on the south and southwest flanks of Mount Pagan (fig. 13 and 14). Water sampling, temperature measurements from the Inner Lake, and geologic mapping were accomplished. We ran a PS2 portable seismometer daily and monitored Mount Pagan's eruptive activity during our stay on the island.

As noted in the preliminary seismic assessment, tremor of varying intensity and duration dominated the seismic records. Visual observations of the eruptive activity made over a 12-day period noted behavior that ranged from fuming (discrete degassing events with no ash discharge) to active eruption of ash. Low-level volcanic activity was characterized by episodic emissions of volcanic gases with no ash discharge, and the presence of long-period events on the seismograph. The eruptive episodes were variable. They ranged from intermittent, discrete bursts of volcanic gases and ash to continuous and voluminous discharge of ash. During these periods, continuous tremor was recorded on the PS2 portable seismograph; the amplitude of tremor varied with vigor of eruptive activity. The larger increases in tremor amplitude corresponded almost one to one with increases in the intensity of ash emissions.

On May 1, 1994, the eruptive activity was especially memorable. While preparing to break camp near the airport runway, we heard two distinct "booming" sounds. Upon checking with the rest of the field crew, we determined that the sounds originated from Mount Pagan (not from firearms discharge). This was the first time that any sound related to the volcano was heard.

These sounds were probably due to a jetting of volcanic gases associated with the ongoing eruption. Later we received a report of low-frequency "rumbling" sounds, originating from Mount Pagan, from a Macaw Helicopters pilot on his visit to Pagan Island on May 4, 1994. On May 1, the eruption changed from intermittent ash emissions to a continuous ash column within a few hours after the "booms" emanated from the volcano. The height of the main ash column was approximately 1,500 m (5,000 ft) to 1,800 m (6,000 ft) above the summit of the volcano. The coeval steam cloud, laden with fine ash, billowed even higher, ~3,000 m (10,000 ft) above the summit of Mount Pagan. This high level of eruptive activity created its own local weather pattern, changing the prevailing wind direction from ENE (normal trade wind direction) to SSE. At approximately 1700 hr upon leaving Pagan Island and the influence of the eruption, we found the offshore wind direction to be the normal ENE trades. The ash and steam in the air created local showers and cast a dark shadow over the island in the downwind direction.

When we reoccupied the southwest Pagan EDM network, we found that the RIDGE reflector was the only original EDM permanent-glass line (fig. 13) on the SW monitor (PAGAN 1 to RIDGE) to survive the elements. NOSE and BILLYGOAT were destroyed or buried by ashfall since May 1992, and new stations were installed. On line PAGAN 1 to RIDGE, we recorded a -54 mm of change in line-length (fig. 14). This shortening of the line-length suggests that an influx of new magma may have entered the volcanic system, exerting outward pressure on the volcano's flanks and resulting in the renewed activity. It also suggests shallow storage of magma in the volcano, which causes these measurable changes.

We reset NOSE (renamed NOSE RESET) EDM reflector and installed a new station named BILLYGOAT RESET to replace the original BILLYGOAT, which had been buried by several meters of new ash (fig. 13). This new station is approximately 100 m southeast of the original station. Measurements from PAGAN 1 to both of these stations showed no significant line-length changes during our 11 days of surveying (table 2).

We accomplished another of our primary objectives by reestablishing the south EDM monitor of Mount Pagan (fig. 13). We located two of the four original reflector sites established in May 1981 and last measured in 1983. Comparisons of line-length changes from 1983 to the present show a contraction of 156 mm from INS to MID and 50 mm from INS to REF (fig. 14). Although these are large line-length changes, the long time span of 11 years between measurements must be considered when interpreting the data. Therefore, we are unable to discriminate between long-term gradual inflation and short rapid episodic displacements as causes of the changes in line-length.

Two additional reflector sites called SCREE and SOUTH BREACH were emplaced higher on the slopes of the volcano. The former MID reflector site was replaced and renamed MID RESET (fig. 13). All measurements taken during the April-May 1994 occupation had no large significant line-length changes (tables 2 and 3). This, again, may be attributed to the open volcanic system.

Three charcoal samples were collected for radiocarbon dating from North Pagan, and temperature measurements were made and water samples collected from Inner Lake (Lagoonan Sanhalom). The charcoal samples were retrieved from three different pyroclastic-flow deposits erupted by Mount Pagan. The age determinations are pending.

Maximum water temperature from the area near the former warm springs site on Lagoonan Sanhalom was ~40° C. The pH of the water was 7.5 in the area of the highest water temperature.

The volcanoes on South Pagan have not erupted during historic time; occasional bursts of local seismicity have occurred, but not in significant numbers since the establishment of the South Pagan seismic station in 1990. Steam was again observed in a few areas near the station, but no temperature measurements were made.

Summary of the EDM measurements and seismicity on Pagan

1) No large line-length changes were observed over the period of 11 days that we made measurements on the volcano (tables 2 and 3), the largest being +16 mm on the PAGAN 1 to RIDGE RESET (line length had about 30 mm of total change) monitor line. The relative lack of deformation does not necessarily suggest that the intermittent eruptive activity is declining. It may suggest that there is a more open magmatic system. We believe that persistent eruptive activity does not allow the internal magmatic pressure of the volcano to significantly deform the edifice. It also appears to take a long period of time for strain to accumulate; therefore, the changes we record on our EDM lines during our short stay are small in comparison to the changes we see between visits. During our stay, there were times when no ash emissions were visible to us from the base camp, but the tremor varied in amplitude, supporting our observation of an open volcanic system. The results of the long-term time series plots, 1983 to 1994, and 1992 to 1994, also support our suggestions about strain accumulation by displaying large changes in line-length (figs. 14 and 15).

We are unable to tell whether the changes occurred episodically or accumulated gradually through the years. Stations closest to the volcano continue to be destroyed by ashfall or by debris flows and there is no continuity between surveys from year to year.

2) Despite the small line-length changes, we did observe some relationship to eruptive activity. Line-length changes on both the southwest and south Mount Pagan monitors, (although small in amplitude; figs. 14 and 15), show good correlation with our visual observations of the eruptive activity and the seismicity as recorded on the PS2 portable seismometer. During times of eruptive activity all the lines lengthen as pressure is being released. During periods of quiescence, line-lengths contracted slightly as pressure started building beneath the volcano. The extensions and contractions of line-length seem to also be partly dependent on the length and strength of the eruption activity and the length of the period of quiescence.

Although no visible ash plume was observed during periods of quiescence, very low-level tremor was continuously being recorded (fig. 8) resulting in minor extensions and contraction in line-length. There appears to be a correlation between long-period (L-P) earthquakes, which are typically identified with magma resupply and inflation, and the shortening of EDM line-lengths. This appeared to be true for the period spanning April 27 through April 30 (figs. 16 and 18) when there were many L-P earthquakes recorded and line-lengths on the EDM monitors were steadily contracting. We need much more data to be sure that this is the case.

Alamagan

The summit area of Alamagan (fig. 1) was obscured by clouds during the fixed-wing flight on April 20 from Saipan to Pagan. We flew there by helicopter on April 28 and sampled from several eruptive units on the southern end of the island. Alamagan has had no eruptions during historic time. Pyroclastic-flow deposits underlie about two-thirds of Alamagan. We plan to establish an EDM network there in the future. A permanent-glass line could be established from the summit toward the south coast of the island.

Guguan

Observations of Guguan (fig. 1) made from the fixed-wing airplane while flying north from Saipan to Pagan on April 20, and during field work conducted on April 29, showed no steam or fumes. Guguan last erupted in 1901 and produced a tephra cone and aa lava flows. The geologic team collected rock samples and surveyed for charcoal but found none. The rock samples will be submitted for chemical and petrographic analysis. The collection of these geologic samples is the first step of a mapping campaign in which we will attempt to ascertain the eruptive history and frequency for this volcano. There is a very good possibility of establishing an EDM monitor on the northern end of the island, where the most recent eruption occurred (see future recommendations section).

Sarigan

No visible steam or fume was sighted on Sarigan (fig. 1) on the flights north from Saipan to Pagan on April 20 via fixed-wing airplane, nor on the flight back to Saipan via helicopter on May 1. Sarigan has had no historic eruptions.

Anatahan

Anatahan (fig. 1) was observed from the air during the fixed-wing airplane flight on April 20, on the helicopter flight north from Saipan to Pagan, and from the ground and air by helicopter on May 3. The permanent-glass EDM network, water sampling, and temperature measurements were made during the May 3 visit (fig. 19).

Most line-lengths on the Anatahan EDM network were measured at least twice to minimize the effects of potential operator errors (fig. 19). The line between EC-2 and EC-3 is the only exception (read only once). All lines in the network contracted, with the largest changes being -55 mm (EC-1 to EC-5), -49 mm (EC-5 to EC-4), -45 mm (EC-5 to EC-6), -30 (EC-5 to EC-3), and -22 mm (EC-1 to EC-4), when compared to the 1992 survey (fig. 19a, table 3). This is in sharp contrast to the 1992 survey, when all the lines showed large extensions.

We also reset the EC-1 instrument station to a more stable and more easily accessible area (fig. 19) and renamed it MUGABE. All reflector stations measured from EC-1 were also measured from MUGABE.

Anatahan has had no historic eruptions, although a shallow earthquake swarm there in March-April 1990 prompted evacuation of its residents. The geology team measured the pH and temperature of several boiling pools and springs on the floor of the eastern crater. The temperature of the ponds, as well as the fumaroles, ranged from a maximum of 98.8° C to a minimum of 67.4° C. The pH ranged from 1.7 to 4.3.

Summary of the EDM measurements on Anatahan

1) As we found during the 1992 occupation (Moore and others, 1993), the larger line-length changes occurred in the western section of the caldera and not over the eastern crater, where the active fumaroles are located.

Although very little is known about the Northern Mariana island arc volcanoes, some of the deformation characteristics appear to be similar to those observed at shield volcanoes like Kilauea. The larger line-length changes seem to correlate with seismic swarms or intrusive episodes that occur on or near Anatahan. It is possible that the deformation pattern is sympathetic to a local magma chamber located to the west of a seemingly more active eastern crater. This is analogous to the deformation patterns that we see on Kilauea. Kilauea has a deformation center (magma chamber) located about 1 km south of Halemaumau, the summit crater. Judging from the lack of a consistent seismicity and deformation pattern, imminent eruption of Anatahan is probably not likely.

RECOMMENDATIONS

1. People who live in the northern islands should be aware of volcano and earthquake hazards. To this end, we have encouraged people in each of the villages to operate a portable seismograph and to learn to recognize the common seismic signals caused by earthquakes, weather conditions, cultural noise, or instrumental problems. Detection of warning signals should be communicated by radio with EOC in Saipan. Residents should prepare safety procedures and evacuation plans. It is essential that a log of seismic activity be kept, especially by the residents of Agrihan, Alamagan, and Anatahan, as well as by people who visit Pagan. This information should be archived and a copy faxed or relayed to us for our records and further analysis. Data such as estimates of the height of the ash column above the summit of the volcano and the vigor of the eruption should also be recorded in a log book of eruptive activity, to correlate with the seismicity.

2. Continued support for maintaining the seismic instrumentation and data analysis are critically important in monitoring the internal state of the volcanoes in the northern islands currently occupied by residents. It is essential that field repairs of seismic equipment be made as soon as possible and that evaluation and communication of the seismic data occur in a timely fashion. Funding allowances to obtain specialized training and assistance in instrumental maintenance and record analysis are necessary, as the seismic network improves and expands. Spare seismic components, particularly seismometers, telemetry radios, and discriminators are badly needed. Supplies of cables and other telemetry equipment will help prepare for an organized move into the new EOC building. Cabinets to properly house and link the recording systems are currently on order and marked for delivery in late July 1995. A backup air-conditioning system, along with standard office furnishings, will be needed for the instrument room.

3. Potential activity on Agrihan, Alamagan, and Anatahan is of concern because of the ongoing resettlement of residents, and the activity on Pagan Island is important because of possible widespread effects of the continuing eruption. The seismic activity on Anatahan has subsided since the 1990 swarm, but this may be a pause in a longer trend of intermittently increasing seismicity. Vigilance is of greater importance now with the reoccupation of the island; the EDM

monitors emplaced in 1990 should be measured as often as possible. A line connecting MUGABE and EC-6 should be established the next time the network is occupied. On Mount Pagan, the EDM lines should also be remeasured more often. Since it is the only volcano presently erupting in the active Mariana Island Arc, as much data as possible should be collected in order to ascertain how this type of volcano behaves. Data from Mount Pagan could be used to develop models for the other volcanoes in the chain. Ideal times for remeasuring the EDM monitor would be whenever visits to Pagan Island to repair seismic equipment are scheduled. As long as Mount Pagan is erupting, the monitors should be measured at least once every six months (a year at the longest). Additional reflector sites should be placed around the Inland Lake to provide additional constraints on the volcanic processes coincident with this eruption. The CNMI government may wish to consider purchasing the equipment necessary to conduct the ground deformation studies.

In concert with the increase in the seismic coverage, EDM networks should continue to be monitored and measured on Agrihan and Alamagan, which are presently being resettled. We should look at Alamagan more closely for EDM sites to monitor the volcano. A lower priority would be to establish other EDM networks to monitor all the potentially active volcanoes in the Northern Mariana Island chain.

Measurement of these EDM networks should be driven by the amount and type of seismicity. The results from Mount Pagan show that there was significant, measurable ground deformation. Yet, with such infrequent reoccupation of the EDM monitoring networks, we are unable to determine whether the deformation was episodic (coincident with changes in seismicity) or was accumulating gradually during our two-year absence.

4. Reconnaissance geologic studies have been carried out on Agrihan, Pagan, Alamagan, Sarigan, and Anatahan, but more work is needed on all these islands. We have expanded our studies to now include Asuncion and Guguan, but Farallon de Pajaros and Maug have not been studied at all. In particular, the eruption frequency on all islands in the chain is unknown, and any plans for development of the northern islands should consider this information. Geologic mapping provides us with the long-term insight necessary to better understand possible future eruptive activity, especially to determine the magnitude and frequency of eruptions that could be expected at each volcano. The geology team suggests that Guguan and Asuncion be the focus of its next concentrated work.

5. We understand the tremendous amount of resource expenditure associated with carrying out a volcano monitoring survey such as this one. We continue to support efforts to identify local resource people who could become knowledgeable in volcano monitoring. Ultimately, we would recommend that we take on the roles of resource and support personnel, and that our roles be secondary to those of local experts, instead of having them support us as primary observers and data gatherers. The CNMI needs to identify people who are willing to learn and can fulfill this role in order that the CNMI attain self-sufficiency in volcano monitoring. Sending people to training courses and encouraging them to pursue degrees in Earth Sciences would be a good beginning.

ACKNOWLEDGMENTS

We thank Governor Froilan C. Tenorio and the staff of the Emergency Operations Center for excellent support during our surveys. We especially appreciate the support of the CNMI field crew stationed on Pagan Island, including Ben Lieto, Joe Basa, Mark Pangelinan, and Juan Takai Camacho of the Division of Land and Survey. The seismic survey was conducted in cooperation with resident seismic specialist Ramon Chong and technician Ignacio "Ike" Borja of the CNMI Office of Disaster Control. Special thanks are due Frank Chong, Director of the Office of Disaster Control, for his overall supervision of this campaign, his experience, capability, and concern for hazard mitigation planning, and his attention to the medical needs of one of our staff. The USGS National Earthquake Information Center provided seismic data and figures. We thank Todd Hinkley and John Pallister for their constructive reviews of the manuscript.

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APPENDIX

Station Descriptions for South and Southwest Pagan EDM Permanent-glass Monitor lines.

These descriptions should be helpful in locating stations for people driving and walking to the sites to replace the permanent-glass or for measuring the monitor. All directions to the instrument and reflector site start at the small shack at the west end of the airstrip. Also, all of the stations can be reached by helicopter and short hikes.

EDM Stations: South Monitor

Station Name: INS
Former Name: None
Latitude: 18.1171° N
Longitude: 145.7899° E
Altitude: 80 m (262 ft)

Description: INS is an instrument station for the south monitor which shoots reflector stations REF 2, BASE 2, MID RESET, SCREE, and SOUTH BREACH (fig. 13). The station is located about two meters back from the top of the north-facing edge of the southern caldera wall, about 50 m right of a grove of ironwood trees and at the 80 m elevation. A six-inch white PVC pipe extending about six inches above the ground, with a 1/2" galvanized pipe cemented in it, is the centering mark. A dirt road passes about 25 m to the south and ~20 m lower than the station.

Directions to Find Station (See fig. 13)

Either fly by helicopter and land on the road below the station (easiest way to get to the station), walk, or drive to the station. If walking or driving to the station, follow the road that goes by the shack at the west end of the airstrip in a southerly (towards the caldera wall) direction. Take the left fork at the intersection near the ruins of the site of the first house. Keep following the road, eventually crossing the southern end of the 1981 aa flow. Go around a small rockfall at the east edge of the aa flow that blocked part of the road. There should be a road junction about 15-30 m past the rockfall. The junction may not be easily recognizable because of ashfall and erosion. Keep heading in a easterly direction along the road that parallels the caldera wall, which will take you up a prehistoric aa flow and under fairly thick tree canopy. About 200 m thereafter, the road turns sharply to the left and then sharply right. There are coconut trees at this second inflection on the right side of the road. Walk southeast off the road to the caldera wall (about 5 m), then scale the wall (~10 m). The station should be slightly to the left as you reach the top of the caldera wall. You can also walk about another 100 m along the road then turn right about 10 m and walk back along the top of the caldera wall to the station.

EQUIPMENT NEEDED: Hewlett Packard 3808A EDM gun or comparable instrument.
12v sealed battery
Tripod and tribrach
Electrotherm digital thermometer model M99 (Shade the probe from direct sunlight)
Altimeter (metric if possible)
Measuring Tape (Metric)
Data sheets/pen or pencil/clipboard
Signal mirror
Hand held portable two-way radio

Station Name: REF 2
Former Name: REF
Latitude: 18.1115° N
Longitude: 145.7960° E
Altitude: 25 m (82 ft)
Offset: 30 mm should be added to line-length for comparison prior to 4/21/94

Description: REF 2 is a reflector station located at the 25 m elevation southeast of INS just above and to the northeast of an old Japanese bunker and is measured from INS instrument station (fig. 13). There is a grove of coconut trees a few meters farther upslope from the bunker. This station was renamed because a new reflector system was installed. The station is a rebar protruding about 50 cm above the ground with one retro reflector housed in a white PVC end cap screwed on to a brass fitting, facing towards INS and clamped onto it. The rebar is painted white and sword grass will probably need to be cleared for line of sight to INS. Use radios, signal mirrors, and a fluorescent red-orange cloth to help locate each other.

Directions to Find Station (See fig. 13)

You can either fly by helicopter and land in an open area just below and to the north of the station (easiest way to get to the station), walk, or drive to the station. If walking or driving from the shack at the west end of the airstrip, follow the same directions used to get to INS instrument site. Instead of climbing up the caldera wall, go another quarter mile east beyond the road that leads to the top of the caldera wall, until you get to another road intersection that heads in a southerly direction, downhill towards the beach, passing a house and Japanese ruins. Walk east from the house on the ridge line, or continue down the road toward the beach about 200 m, then head left (easterly direction) on the road. By staying on the ridge and walking east, you will come to an old road about 300 m east of the house. Turn northeast on the road for about 50-100 m until you see a tree ~30 cm in diameter on the right with a blaze on the north side of the trunk. Turn east off the road at this tree, keeping on the ridge line until you come out in an open area. Beyond the open area, the slope steepens and there is another small patch of swordgrass. Go through this patch to a bunker which is a few meters below and to the southwest of the station.

EQUIPMENT NEEDED: 1 Retro reflector
1 brass fitting for reflector
Signal mirror and fluorescent red cloth (1 m x 1 m)
1 hand held portable two way radio
Machete or sickle

Station Name: BASE 2 (The previous site was not occupied because it could not be found)
Former Name: BASE
Latitude: 18.1305° N
Longitude: 145.7908° E
Altitude: 160 m (525 ft)

Description: BASE 2 is a reflector station located at the 160 m elevation on a pahoehoe tumulus, 25 m east of a prehistoric aa flow and is measured from INS instrument station (fig. 13). This station was renamed because a new reflector system was installed. The station is a rebar protruding about 50 cm above the ground with one retro reflector housed in a white PVC end cap screwed on to a brass fitting, facing towards INS and clamped onto the rebar. Use a radio, signal mirror, and fluorescent red cloth to locate each other.

Directions to Find Station (See fig. 13)

You can fly by helicopter, walk or drive part of the way to the site. If walking or driving from the shack at the west end of the airstrip, follow the directions to INS instrument site until you cross the 1981 aa flow and pass the first rockfall. Turn left at this point and head towards the summit paralleling the 1981 flow. Drive or walk about 700 m until you get to a grove of trees (from this point on, you need to walk). Go through the trees and now follow a prehistoric aa flow on the left for about 400 m. At this point, start looking for the pahoehoe tumulus with the rebar on it.

EQUIPMENT NEEDED: 1 Retro reflector
1 reflector holder
Signal mirror and fluorescent red cloth (1 m x 1 m)
1 hand held portable two way radio
Machete

Station Name: MID RESET
Former Name: MID
Latitude: 18.1367° N
Longitude: 145.7909° E
Altitude: 320 m (1050 ft)

Description: MID RESET is a new reflector station located on the highest point on a small ridge at the 320 m elevation and is measured from INS instrument station (fig. 13). The rebar protrudes about 50 cm above the ground and is a replacement for MID reflector site that was rusting away. One retro reflector housed in a white PVC end cap is screwed on to a brass fitting, facing towards INS, and is clamped onto the rebar. The rebar and a rock cairn (ahu) is painted white. Use a radio, signal mirror, and fluorescent red cloth to locate each other.

Directions to Find Station (See fig. 13)

You can fly by helicopter (landing area is dusty near the station), drive part of the way, or walk to the site. You can also land a helicopter in an old satellitic vent located on the southeast side of the volcano at the 450 m elevation and then walk downslope to the station. If driving and walking, follow directions to BASE then start climbing towards the summit of Mount Pagan along the same prehistoric aa flow described in the direction to BASE 2 for approximately 50-100 m. Go up a little ridge where a white box and antennas are located (may be destroyed). From that point, look up slope about 200-250 m and slightly to the right from the summit and you will see a prominent ridge among the eruption debris. The station is located on the highest point on that ridge.

EQUIPMENT NEEDED: 1 Retro reflector
1 reflector holder
Signal mirror and fluorescent red cloth (1 m x 1 m)

1 hand held portable two way radio

Station Name: SCREE
Former Name: None
Latitude: 18.1378° N
Longitude: 145.7910° E
Elevation: 396 m (1302 ft)

Description: SCREE is a reflector station located along the south monitor EDM Permanent-glass line of Mt Pagan Volcano at the 396 m elevation and is measured from INS instrument station (fig. 13). The site is about 150 m downslope among rocky debris and south of an old satellitic vent on the SSE side of Mount Pagan. The rebar protrudes about 50 cm above the ground and an ahu built near by marks the site. One retro reflector housed in a white PVC end cap is screwed on to a brass fitting, facing towards INS, and clamped onto a rebar. Use a radio, signal mirror, and fluorescent red cloth to locate each other.

Directions to Find Station (See fig. 13)

You can fly by helicopter, drive part of the way, or walk to the site. The easiest way to get to the station is to land a helicopter in the old satellitic vent located on the southeast side of the volcano at the 450 m elevation then walk downslope about 150 m to the station. If driving and walking to the station, follow the directions to MID RESET. From that station, start climbing up the cone slightly to the left edge of the old vent until you get to the station. The white PVC reflector holder should show up fairly well as you hike towards the station.

Station Name: SOUTH BREACH
Former Name: None
Latitude: 18.1394°
Longitude: 145.7910°
Elevation: 540 m (1772 ft)

Description: SOUTH BREACH is the highest reflector site on the south monitor located about five meters below the south rim of the summit of Mt Pagan and is measured from INS instrument station (fig. 13). The breach on the rim is now filled in with ash and volcanic debris and the station is to the left of the low point as you look at it from the instrument site. The station is a rebar painted white, pounded into the ground until refusal, protruding about half a meter above the surface of the ground. Two retro reflectors housed in a white PVC end cap, screwed on and attached to the rebar by a brass fitting, face towards the instrument site. An ahu also painted white is built just above the reflector. Use a radio, signal mirror, and fluorescent red cloth to locate each other.

Directions to Find Station (See fig. 13)

If the volcano is not erupting, you can land a helicopter on the rim just above the station. Otherwise, you can land in the satellitic vent and walk up to the station. If driving and walking to the station, follow the directions up to SCREE. From SCREE, head towards the old vent then keep along the western edge of the rim for 30 m. From that point, head towards the rim by going down off of the vent and then up towards the station which is marked by a white painted ahu and rebar. The white PVC reflector housing should show up fairly well as you hike towards the station.

EDM Stations: Southwest Monitor

Station Name: PAGAN 1
Latitude: 18.1287° N
Longitude: 145.7613° E
Altitude: 21 m (69 ft)

Description: PAGAN 1 is an instrument site for the southwest monitor with shots to BILLYGOAT RESET, RIDGE 2, and NOSE RESET. The station is a standard aluminum benchmark stamped PAGAN 1 cemented in solid bedrock at the top eastern edge of a peninsula that runs in a east-west direction along the pier. The benchmark is located about 15 m east of a old Japanese shrine or monument.

Directions to Find Stations (See fig. 13)

From the shack near the airport runway, follow the road that heads WNW along the shore line. The road leads towards the pier alongside the peninsula that the station is situated on. When you get to the base of the peninsula, the road takes a bend to the right towards the pier. At this point, climb up the peninsula to the first tier, turn to the right, and climb up another 2 m. The station is located at the top of the climb.

EQUIPMENT NEEDED: Hewlett Packard 3808A EDM gun or a comparable instrument
12v battery
Tripod and tribrach
Electrotherm digital thermometer model M99 (Shade the probe from direct sunlight if possible)
Altimeter (metric if possible)
Measuring Tape (Metric)
Recording sheets/pen or pencil/clipboard
Signal mirror
Hand-held portable two-way radio
12v battery charger

Station Name: NOSE RESET
Former Name: NOSE
Latitude: 18.1359° N

Longitude: 145.7759° E
Altitude: 120 m (395 ft)

Directions: NOSE RESET is a reflector station located at the 120 m elevation on a ridge that points towards the EDM instrument site and is measured from instrument station PAGAN 1 (fig. 13). The station is a rebar implanted in the ground near a 4" (~10 cm) x 36" (92 cm) white PVC pipe which marks the site. One retro reflector housed in a white PVC end cap is screwed on to a stainless steel pipe fitting, facing towards INS, and clamped onto a rebar. A Japanese bunker is located down slope about 30 m southeast of the station. Remove the PVC pipe and be sure that the line of sight to the instrument station is clear. Use the signal mirror, fluorescent red cloth, and radio to help in locating each other.

Directions to Find Station (see fig. 13)

A short helicopter flight to the top of the ridge directly above the station is the easiest way to the site. If walking to the station from the shack at the west end of the airstrip, head in a north-northwesterly direction towards the village that is now buried by mud flows. Follow a well defined gully that heads towards the northeast direction until you get close to an area where it enters the forest. Get out of the gully (impossible to hike inside of the gully or cross it here) and follow it upslope along the right bank for approximately 100 m. Look for a way to cross at the first opportunity you can find. Once across, look for orange flagging on the left side of the gully marking the trail that leads to the reflector site. If no flagging is found, head upslope and away from the gully toward the first prominent ridge and hike to the top. The reflector site is set in an area just before where the slope starts to steepen and about 20-25 m from the end of the ridge. Search towards the south side of the ridge line and about 15 m down slope along the top of one of the more prominent furrows for a white PVC pipe that marks the location of the station. The PVC pipe may be obscured by swordgrass. If you are hiking from RIDGE 2, head downslope along the crest of the left ridge (the ridge splits into two just below station) for approximately 600-700 m.

EQUIPMENT NEEDED: 1 Retro reflector
Signal mirror and fluorescent red cloth (1 m x 1 m)
1 hand held portable two way radio

Station Name: RIDGE 2
Former Name: RIDGE
Latitude 18.1396° N
Longitude: 145.7820° E
Elevation: 210 m

Description: RIDGE 2 is a reflector site for the southwest Mount Pagan EDM permanent-glass monitor line, measured from instrument station PAGAN 1 (fig. 13). The reflector site is at 210 m elevation, about 50 m above and to the south side of the point where the ridge splits into a "Y". The station has one retro reflector screwed onto a brass fitting, housed in a white PVC end cap, and attached to a rebar. Ash and pumice probably should be cleared from the front of the reflector so there is line of sight to the instrument station. Use your radio, signal mirror, and fluorescent cloth to help locate each other.

Directions to Find Station (See fig. 13)

The easiest way to get to the site is to take a short flight by helicopter and land right at the station. If hiking to the site, follow the directions to reflector station NOSE RESET. From NOSE RESET climb about 15 to 20 m to the top of the ridge and walk up along the crest towards the summit crater for about 250-300 m. Go about 50 m past the "Y" in the ridge and walk along the right edge (south side). The station is located towards the edge of the ridge at a slight bend to the left, just above the junction where the ridge splits into a "Y".

EQUIPMENT NEEDED: 1 Retro reflector
1-1/4" x 1 1/2" hex head stainless steel bolt, NC thread
1-1/4" brass nut and washer
Entrenching tool
Signal mirror and fluorescent red cloth (1 m x 1 m)
1 hand-held portable two way radio

Station Name: BILLYGOAT RESET
Former Name: BILLYGOAT
Latitude: 18.1422°
Longitude: 145.7885°
Elevation: 500 m (1640 ft)

Station Description: BILLYGOAT RESET is located on the SSW summit rim of Mt Pagan at the 500 m elevation (fig. 13). The station is a rebar pounded through the new ashfall and into a more solid older ash and is about 5 m below the top of the rim. Two retro reflectors, each housed in a white PVC pipe for protection from the weather and ashfall, are fastened to the rebar by a brass fitting. This station is measured from PAGAN 1 on the SSW monitor of Mount Pagan. As seen from PAGAN 1, the station is located to the right of the high point on the skyline and to the left of a notch on the rim.

Directions to Find Station (See fig. 13)

If Mount Pagan is not erupting, you can land a helicopter somewhere on the rim above the station. Otherwise, you can land in the satellitic vent on the south-southeast side of the volcano and walk to the station. If driving and walking to the station, from the shack at the west end of the airstrip, follow the directions up to SOUTH BREACH. Then, continue walking west along the rim for about 150 m then look downslope for the rebar and white PVC reflector housing.

EQUIPMENT NEEDED: 2 Retro reflectors
Entrenching tool
Signal mirror and fluorescent red cloth (1 m x 1 m)
1 hand held portable two way radio

Figure 1. Regional index map of the Mariana Islands. The Commonwealth of the Northern Mariana Islands extends from Farallon de Pajaros to Rota. Volcanic islands of the active Mariana Arc extend from Farallon de Pajaros to Anatahan.

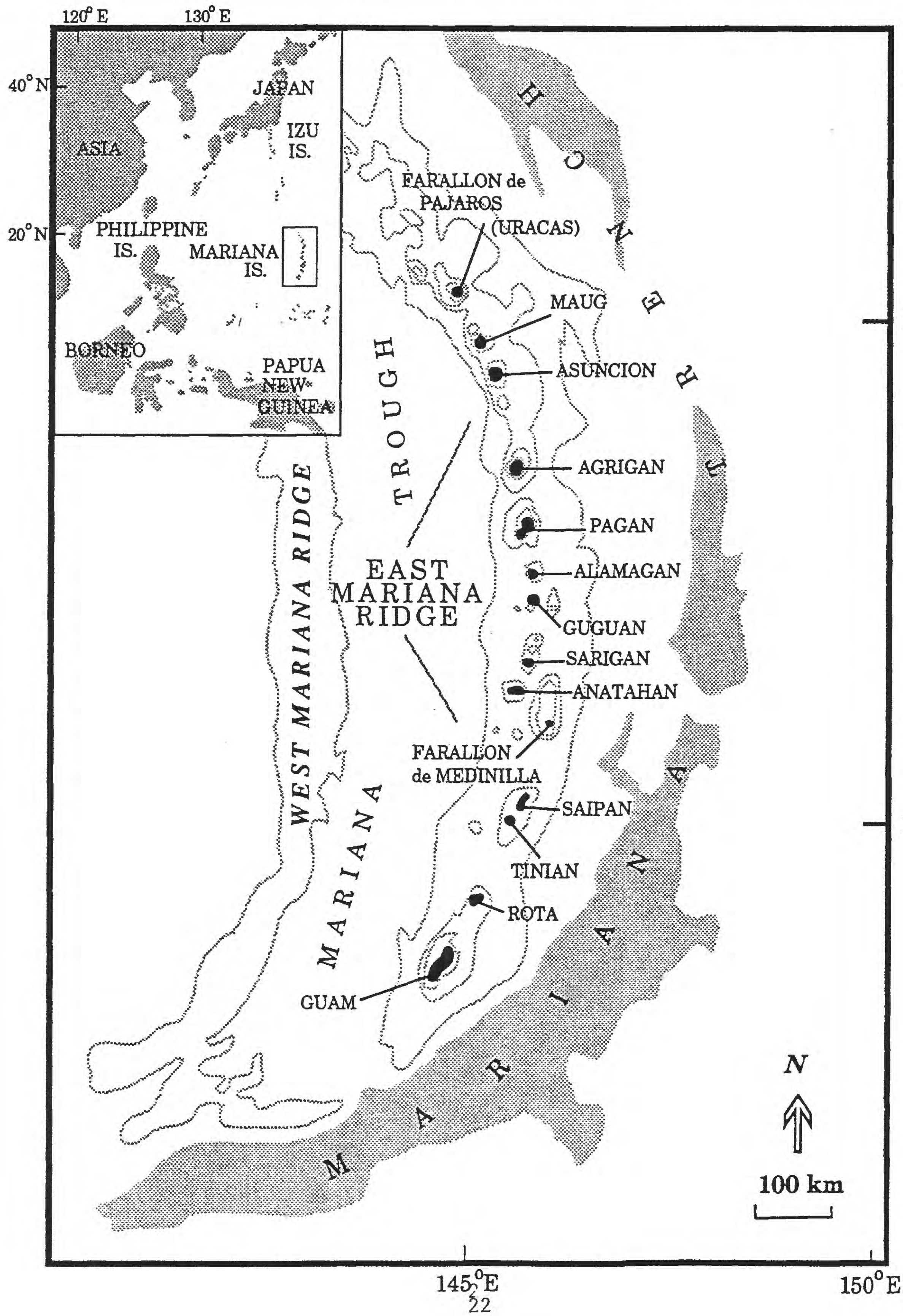


Figure 2. Earthquake location map of Mariana Islands regional events between January 1, 1991, and February 4, 1994, as recorded on the NEIC worldwide network.

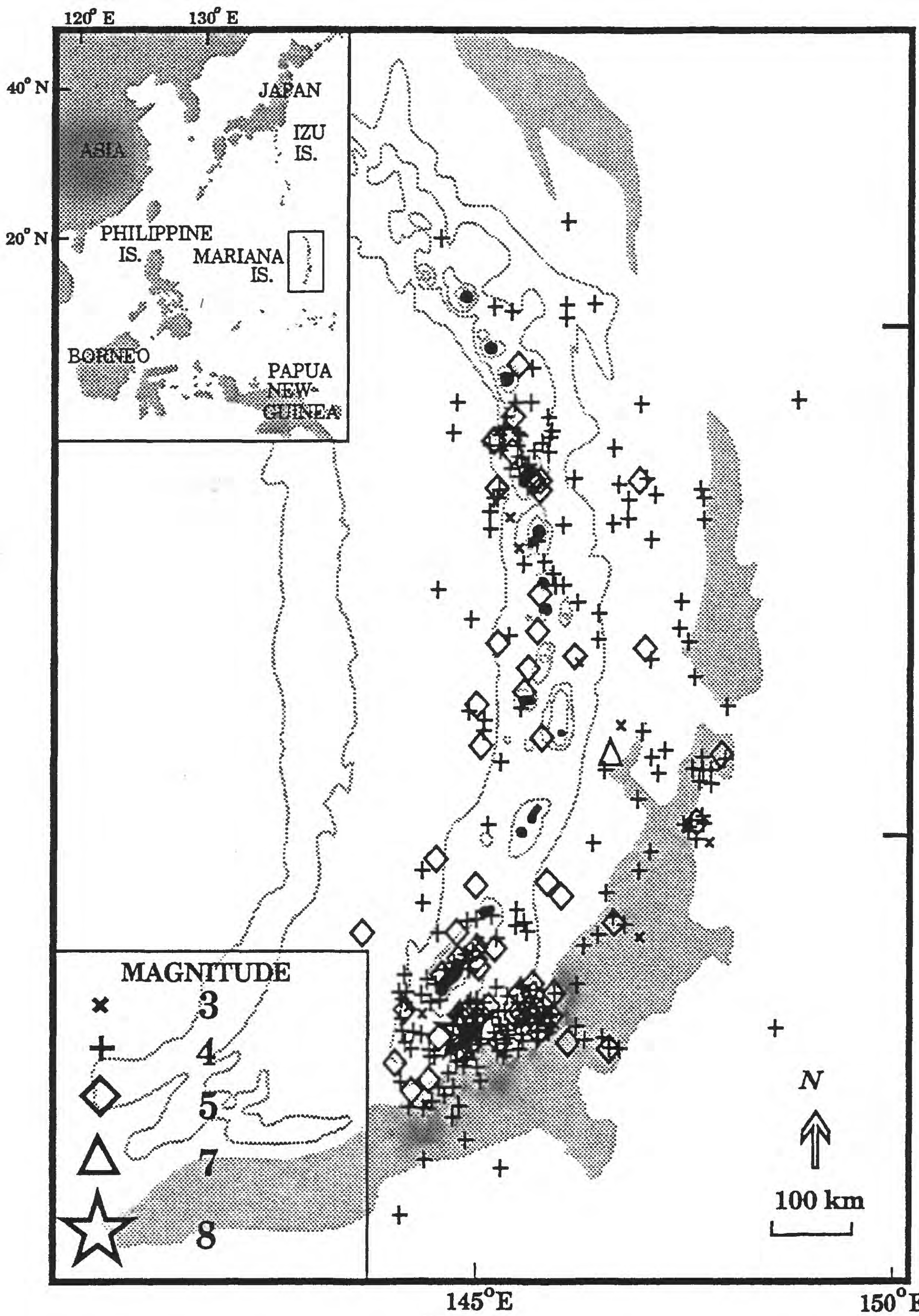


Figure 3. Map of CNMI seismic stations showing the six stations and sequential signal transmission scheme by radio sequentially from Agrihan, Pagan (2 seismometers), Alamagan, Anatahan, and ending at Saipan.

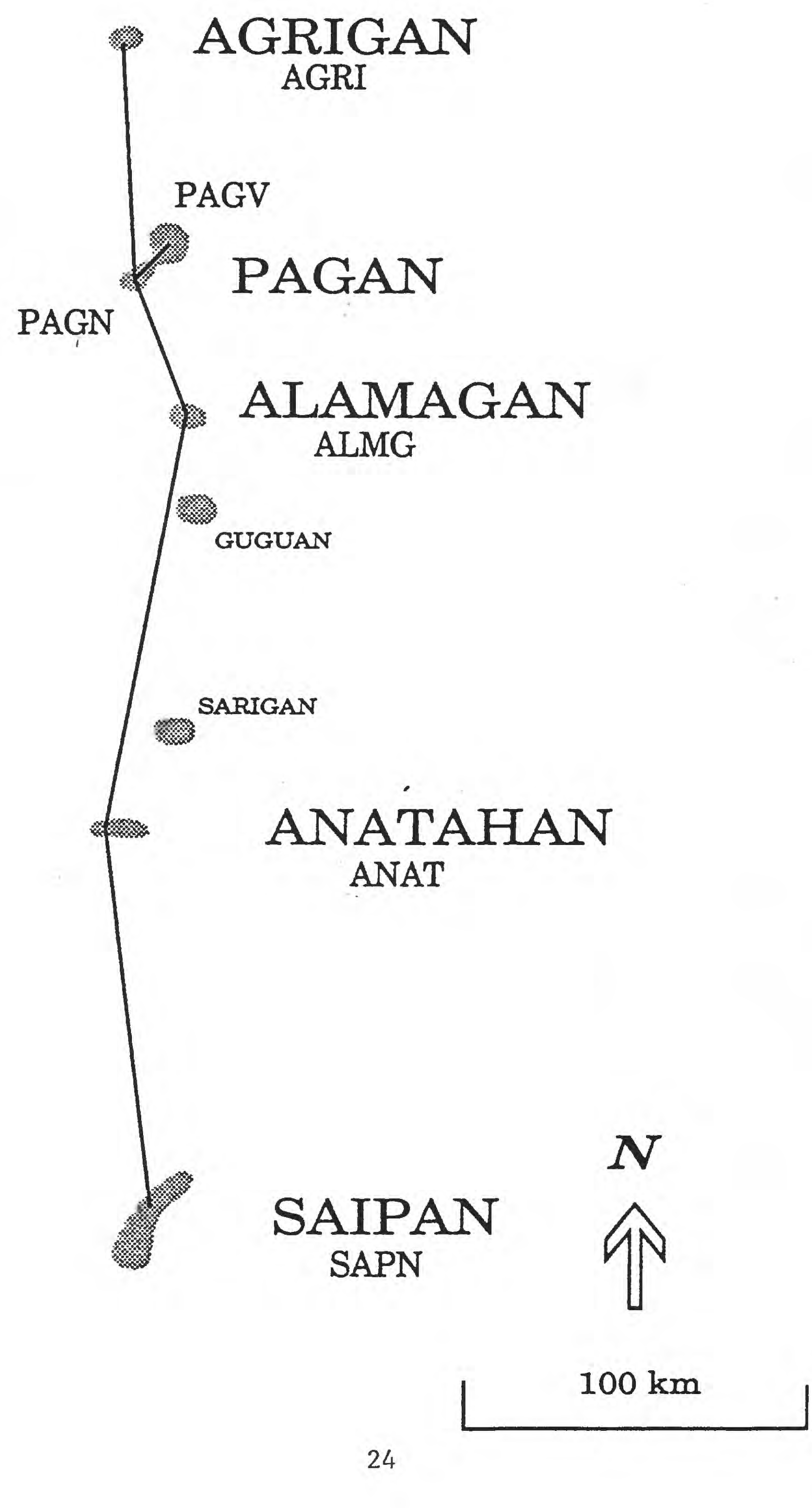


Figure 4. Histogram plot showing number of large earthquakes (M>4.5) each month from the NEIC datafile, January 1, 1988 to February 4, 1994. The February 5, 1994 to April 1994 data are presently being processed and are not included in the plot. Events in the catalogue were subdivided into areas encompassing the principal islands and those located along the axis of the Mariana Trench to the east of the island chain.

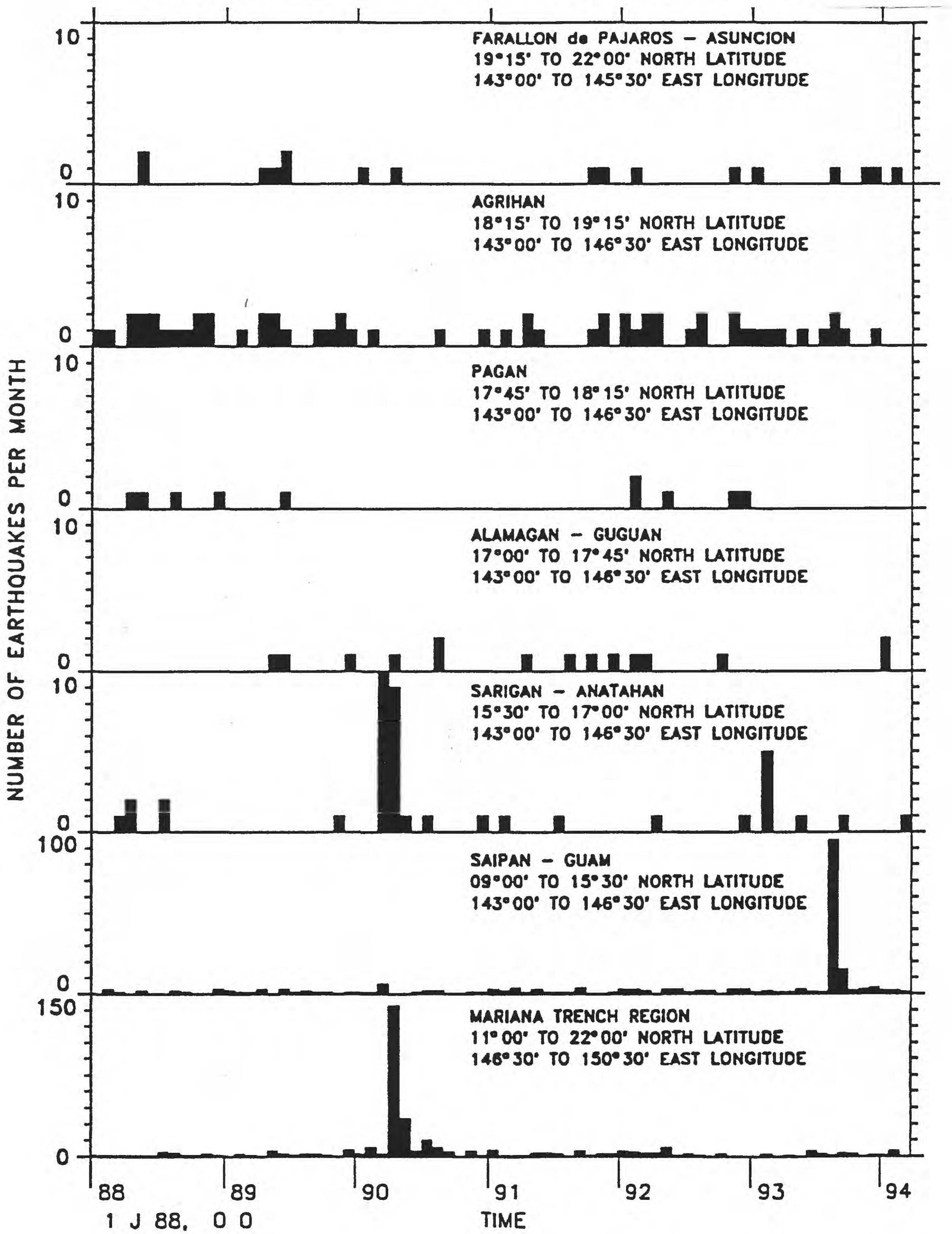


Figure 5. Number of large earthquakes (M>4.5) from the NEIC datafile January 1, 1988 to February 4, 1994, plotted cumulatively as a function of time. Earthquakes recorded after February are being processed and are not included in the plot. Events in the catalogue were subdivided into areas encompassing the principal islands and those located along the axis of the Mariana Trench to the east of the island chain.

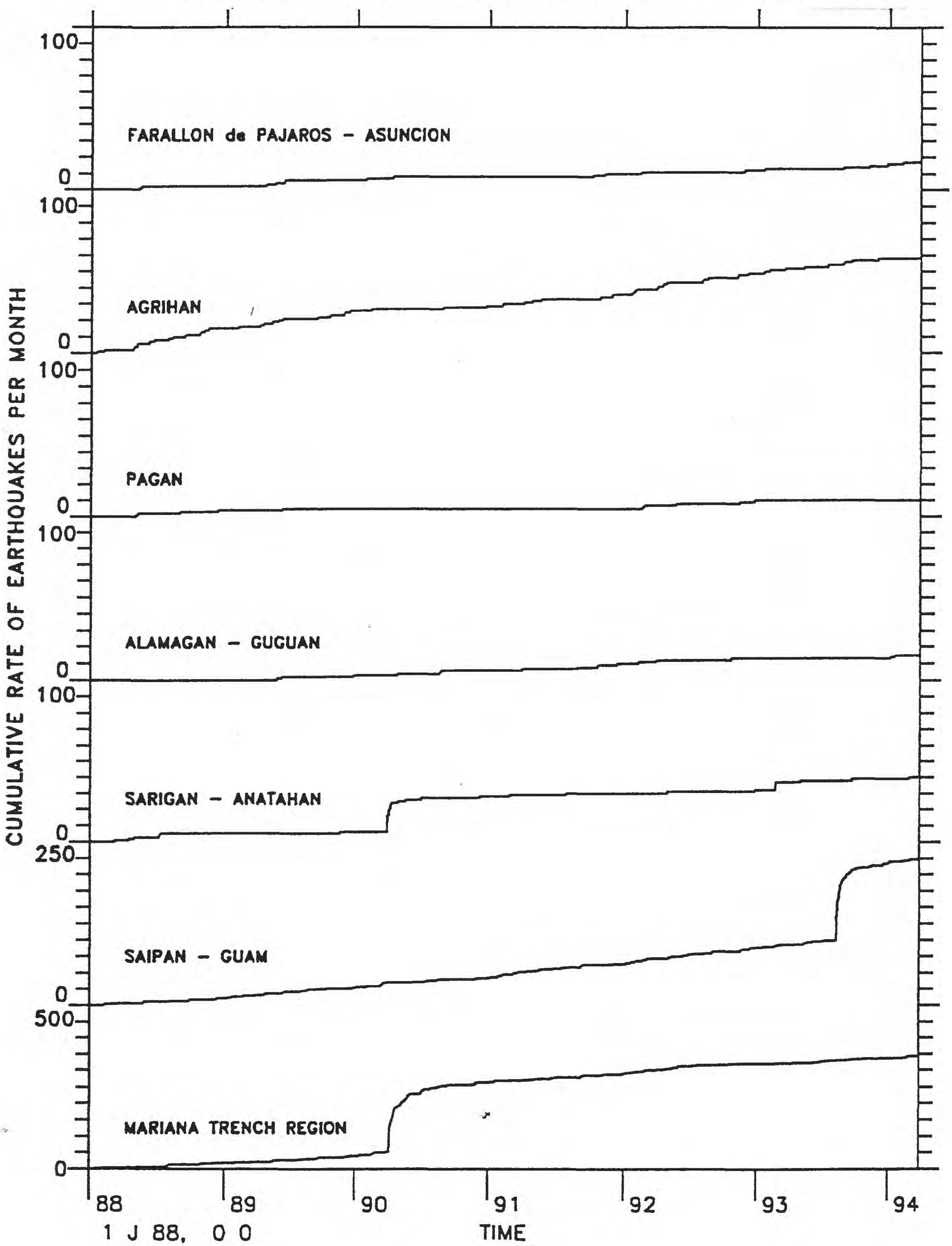


Figure 6. Daily number of local earthquakes (S-P <5 sec) recorded at Anatahan seismograph station ANAT from August 1990 to July 1993.

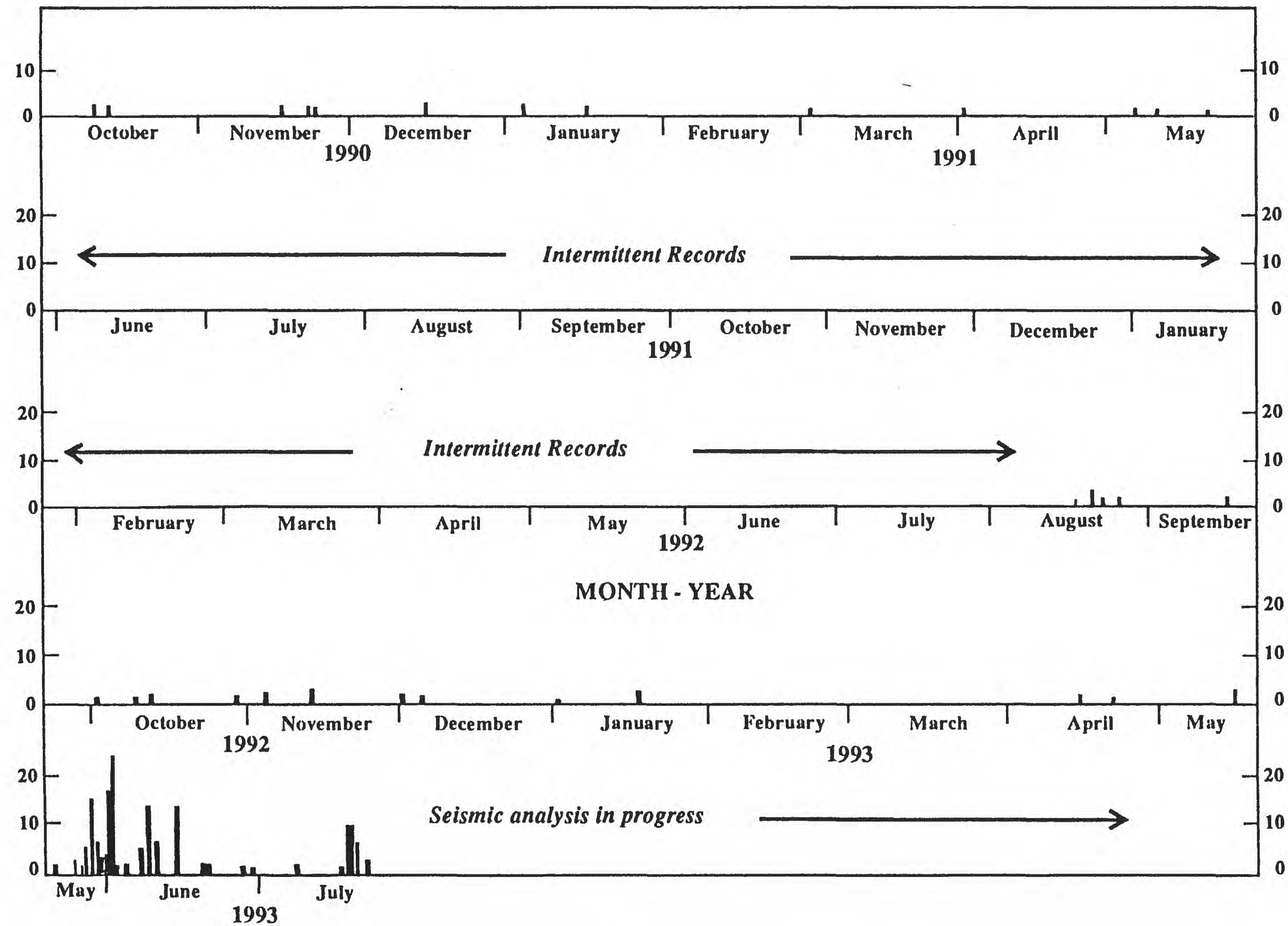


Figure 7. Seismogram copy portion from Pagan station PAGV showing alternating high and low amplitude tremor on April 23-24, 1994 and the intermittent long-period events between eruptive episodes of the volcano.

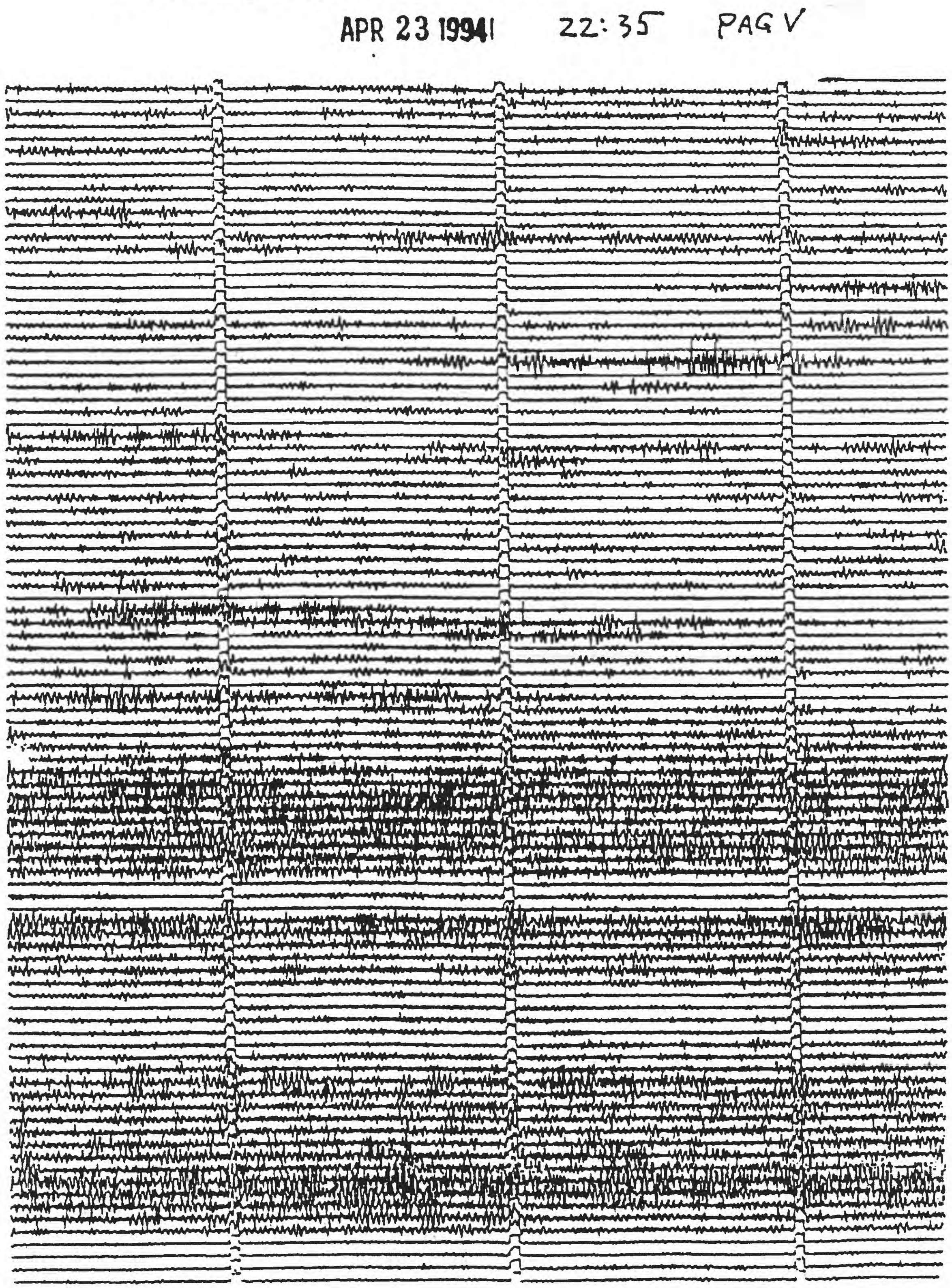


Figure 8. Seismogram copy from Pagan station PAGV showing sustained tremor associated with a moderate eruptive episode on April 25-26, 1994.

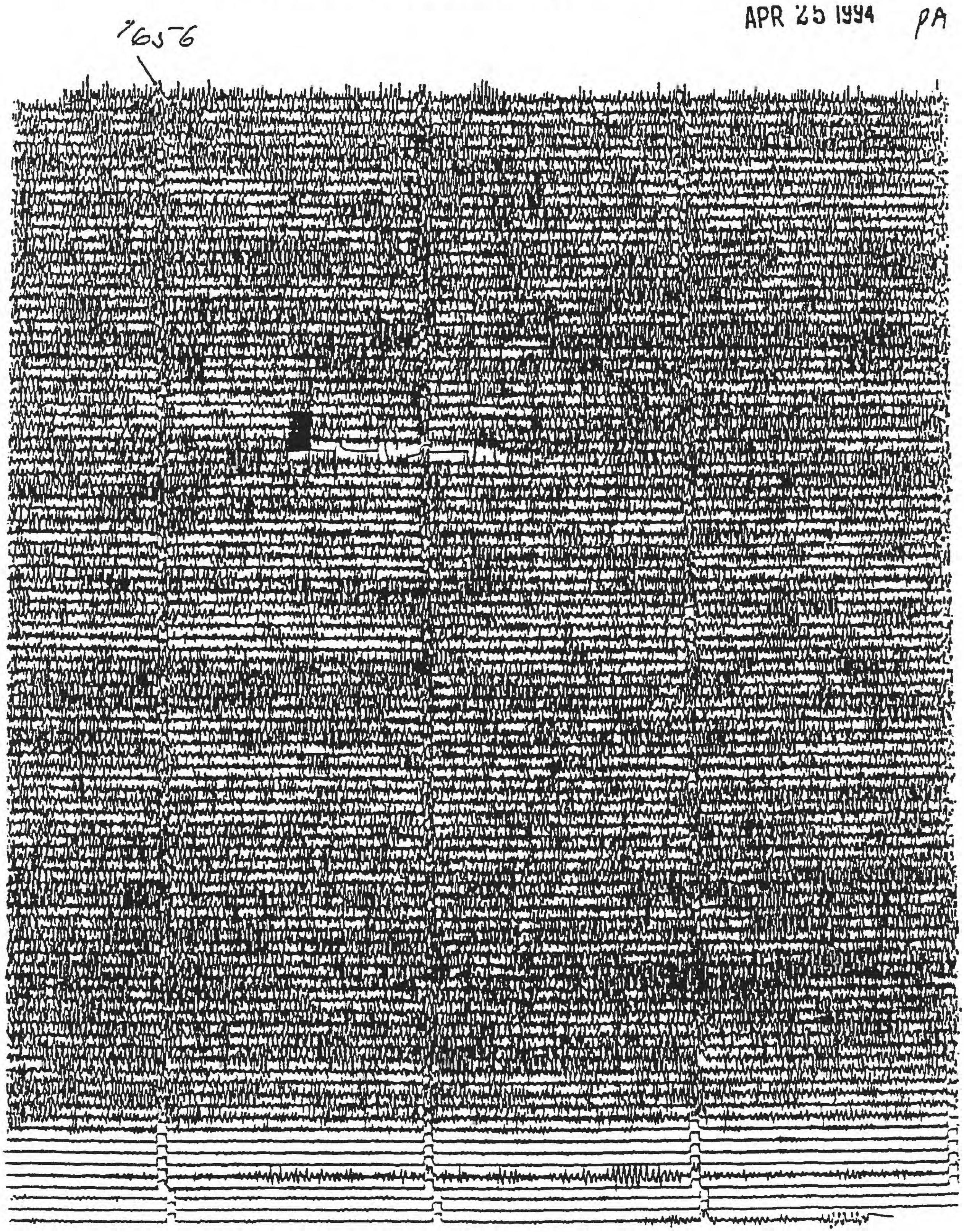


Figure 9. Seismogram copy from Pagan station PAGV showing long-period events and tectonic earthquake in low-background tremor associated with a non-eruptive period on April 26-27, 1994.

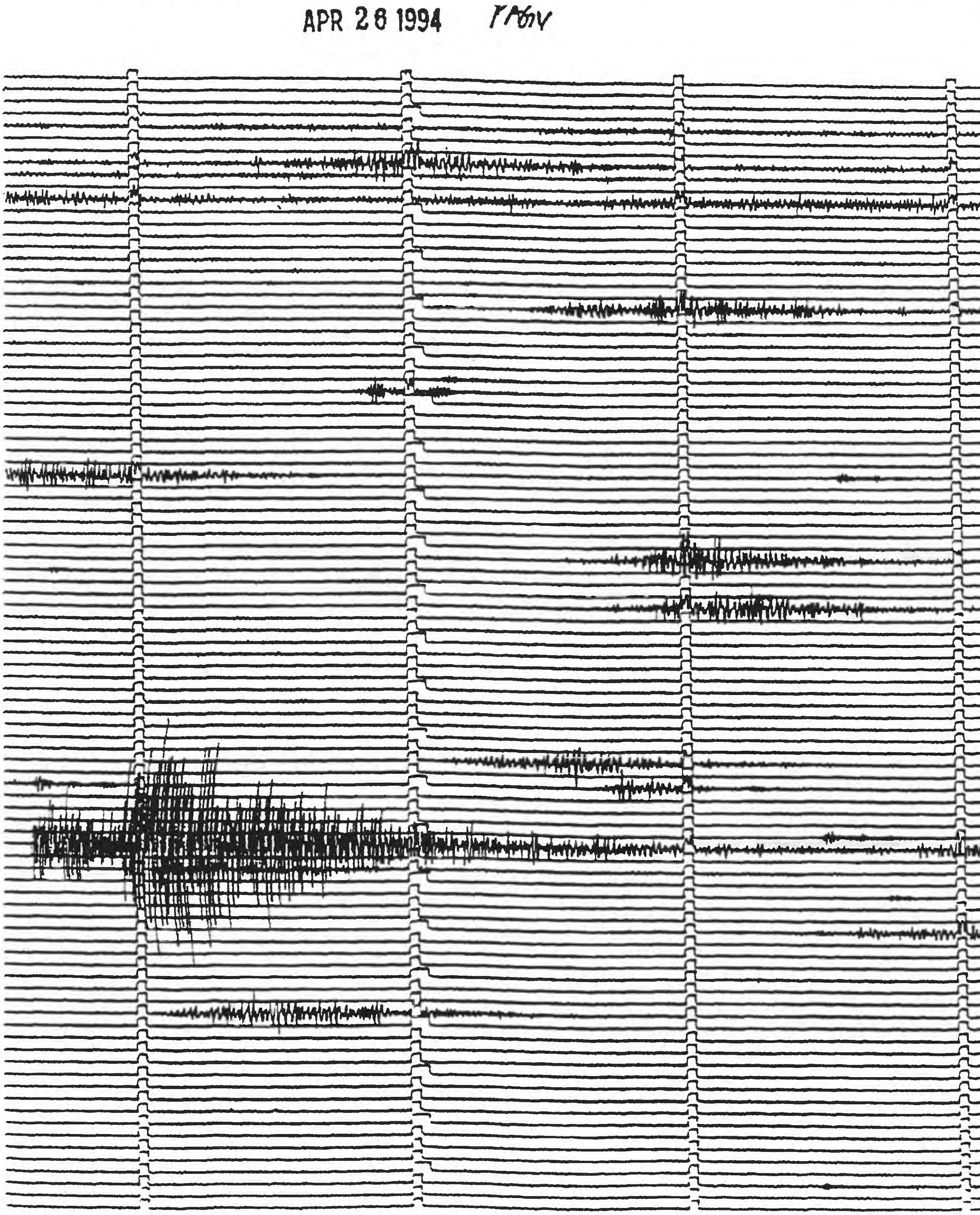


Figure 10. Seismogram from new Agrihan station AGRI showing a M 4.7 earthquake at 09:13 April 27, 1994, located 120 km NW of Agrihan.

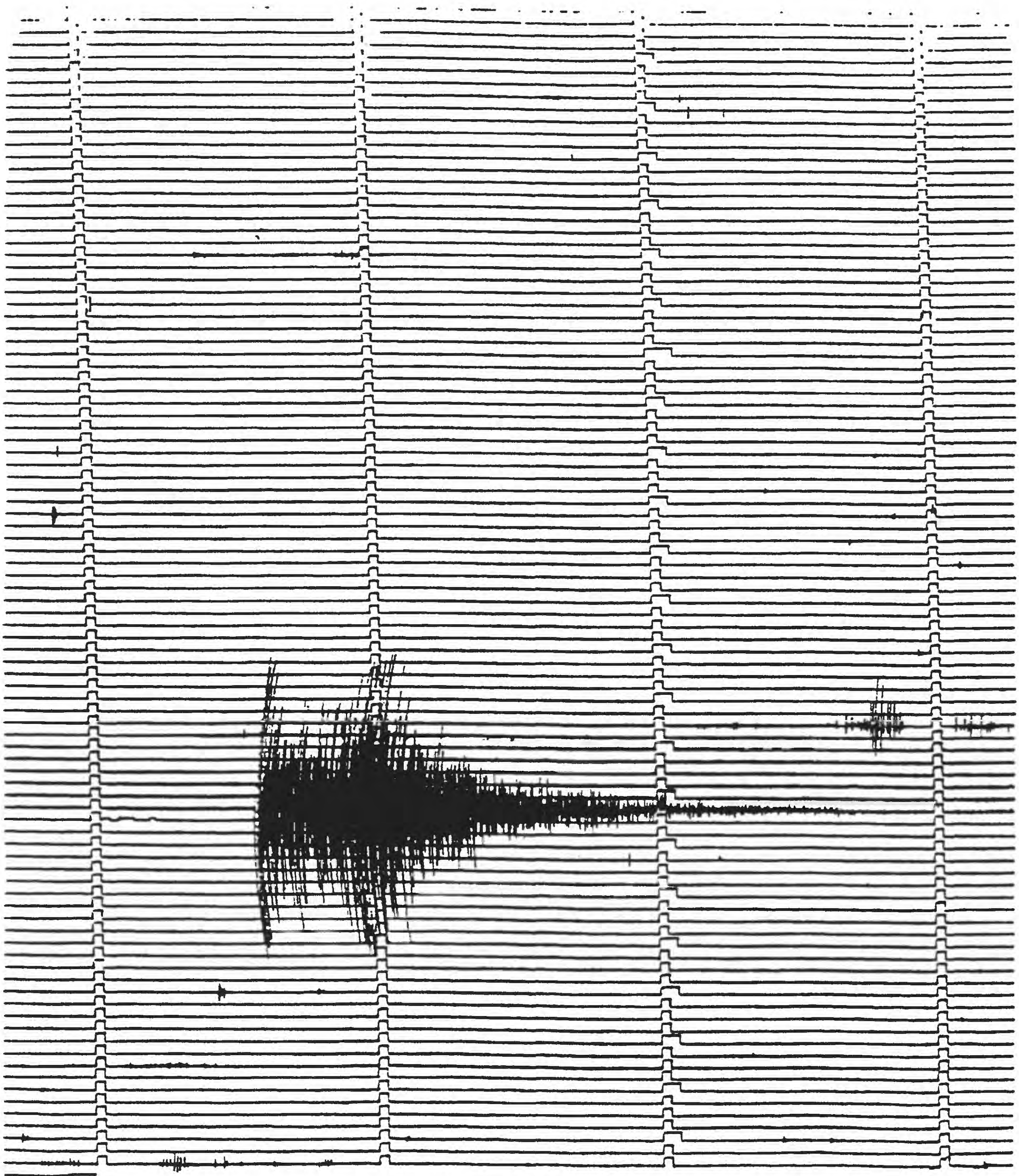


Figure 11a. Location map of the permanent-glass network and fumarole area of Agrihan caldera.

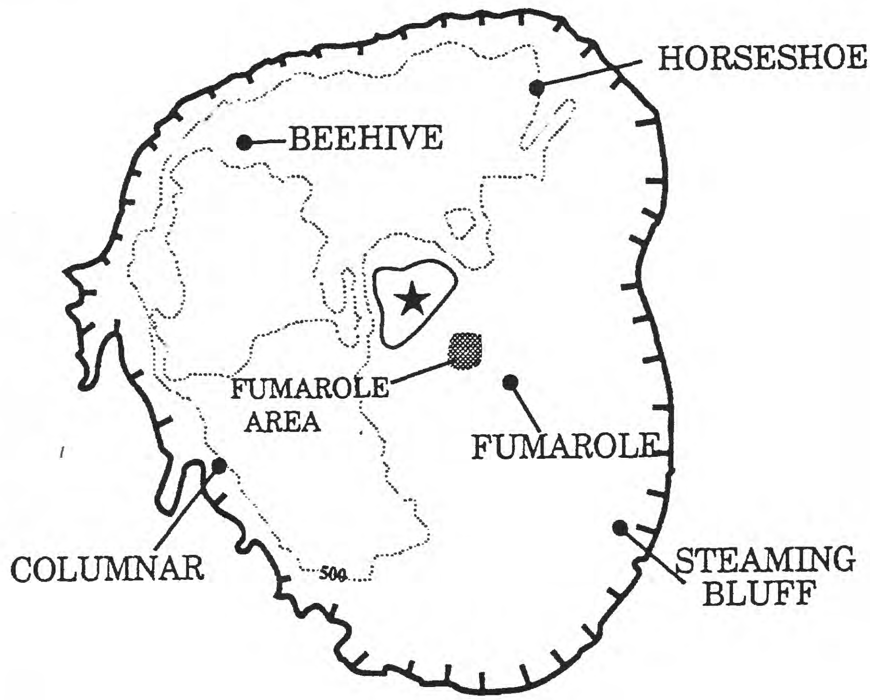


Figure 11b. EDM permanent-glass line-length differences (in mm) of Agrihan caldera network (5/92 to 4/94). Numbers in parentheses are cumulative differences (9/90 to 4/94).

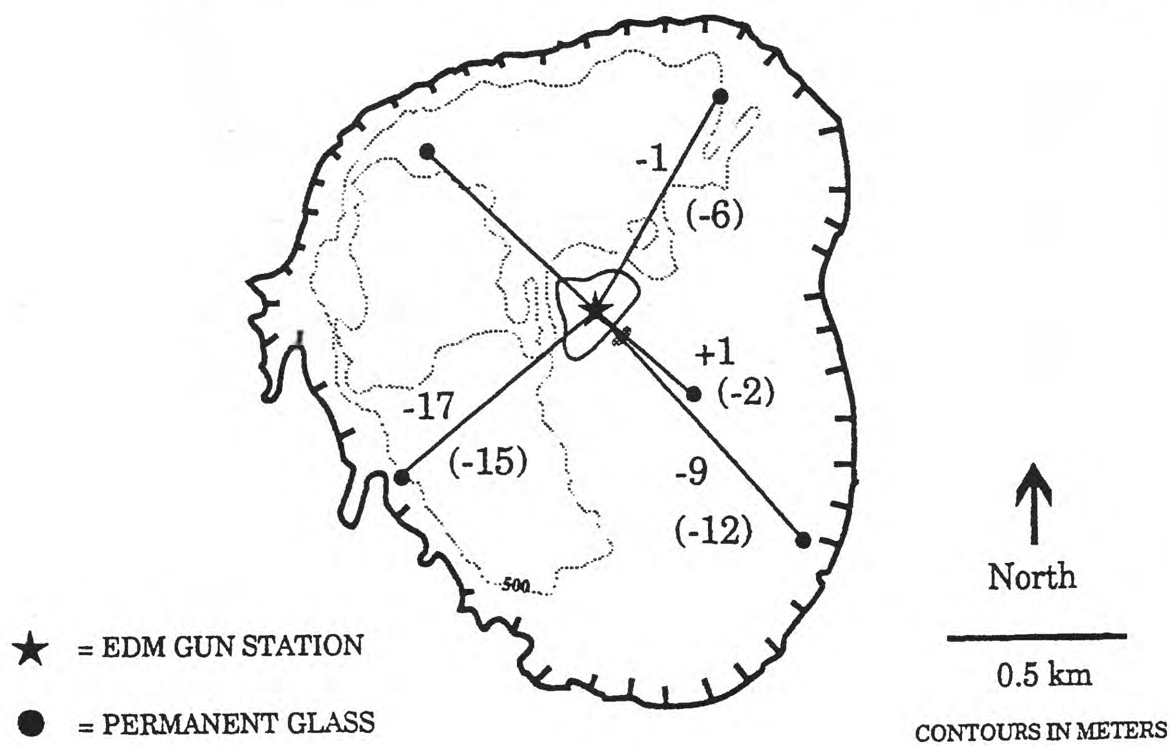


Figure 12. Time-series plot of line-lengths measured from instrument station CENTRAL CONE in Agrihan caldera to permanent-glass reflector sites that make up the EDM network.

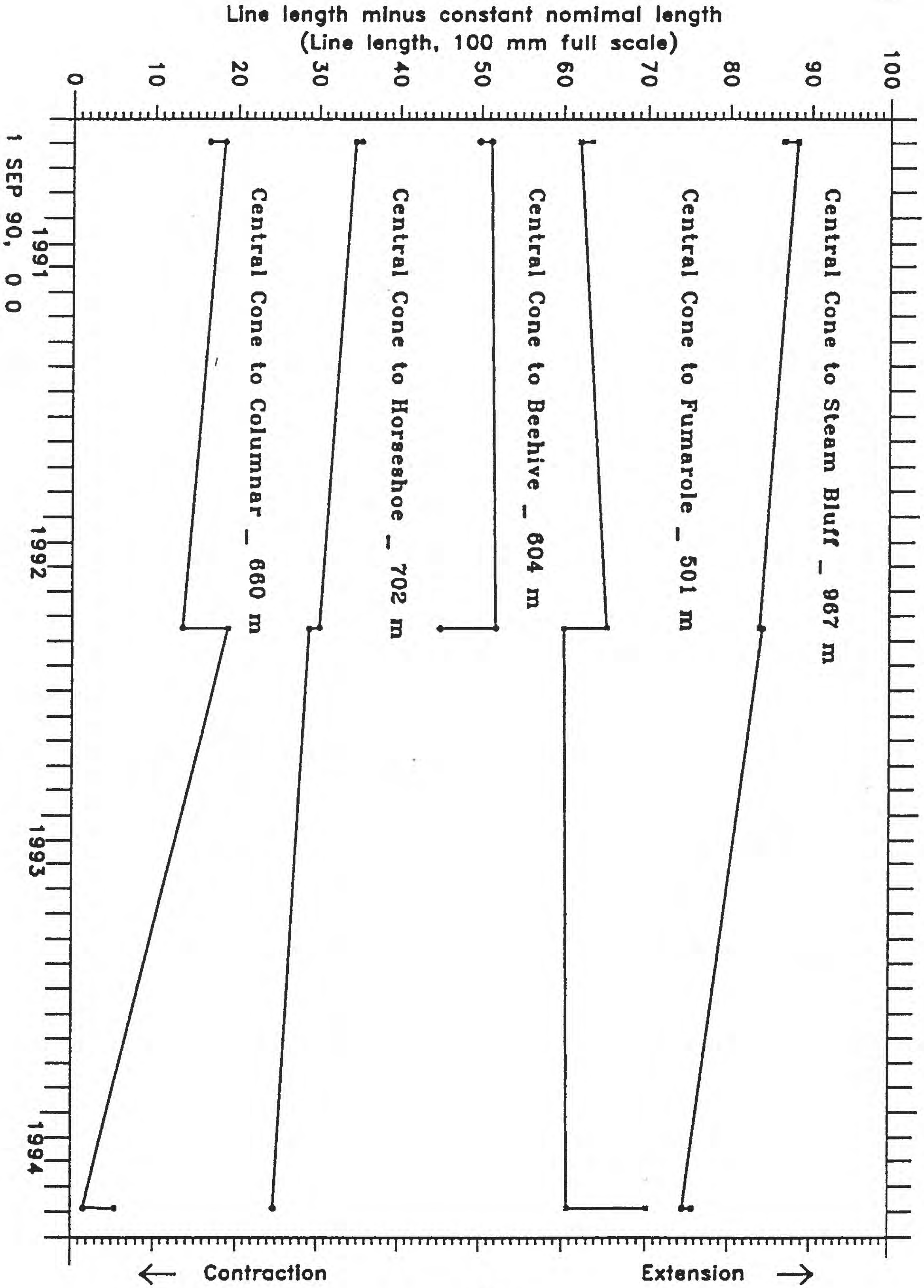


Figure 13. Location map of EDM permanent-glass lines of Mount Pagan South and Mount Pagan Southwest monitor lines.

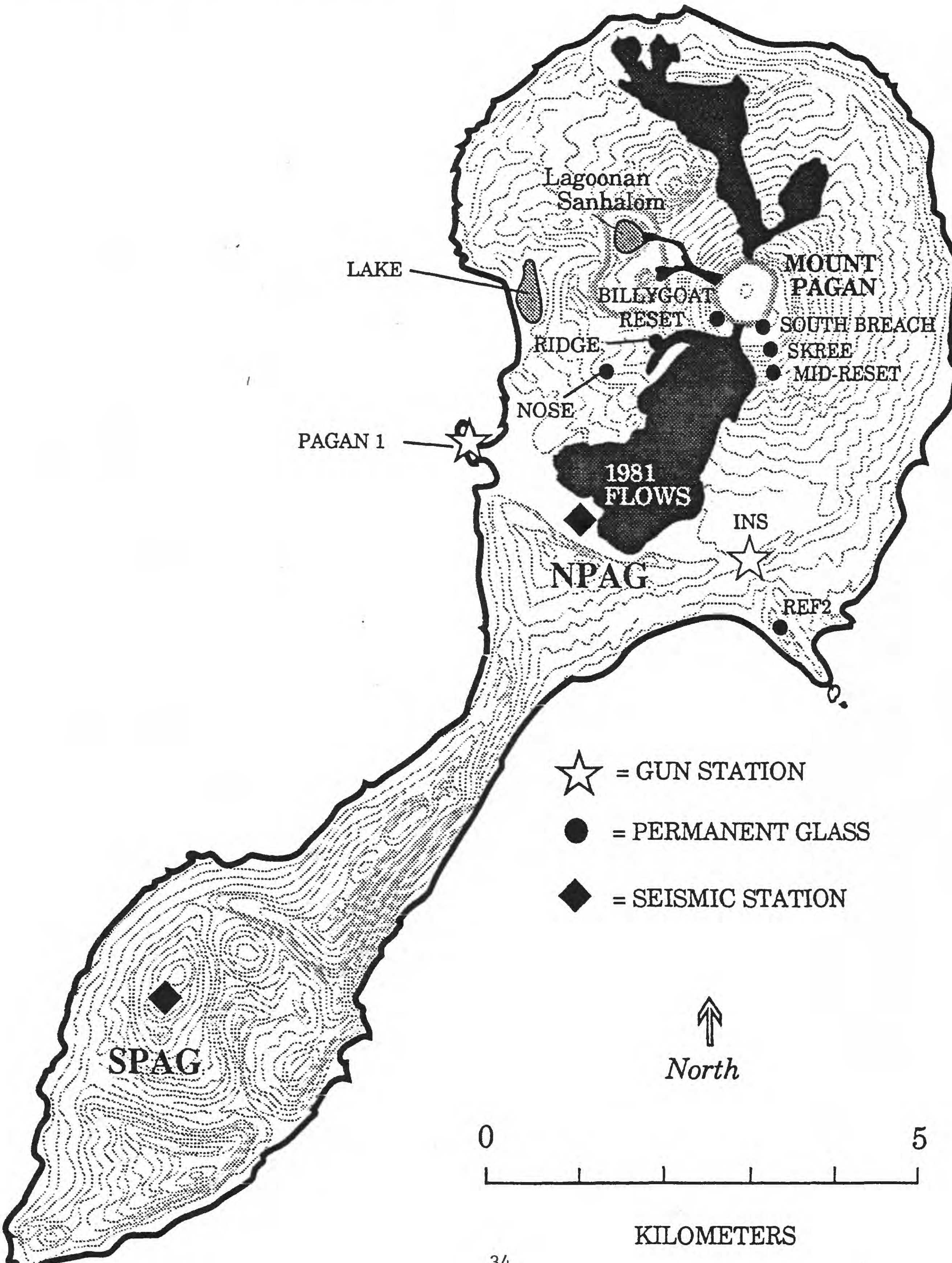


Figure 14. EDM permanent-glass line-length differences (in mm) of Mount Pagan south and southwest monitors. The south monitor is difference between 3/83 and 4/94 and the southwest monitor is difference between 5/92 and 4/94. Numbers in parentheses are cumulative differences between 3/83 and 4/94 (southwest monitor), and the numbers in brackets are differences between 5/81 and 4/94 (southwest monitor).

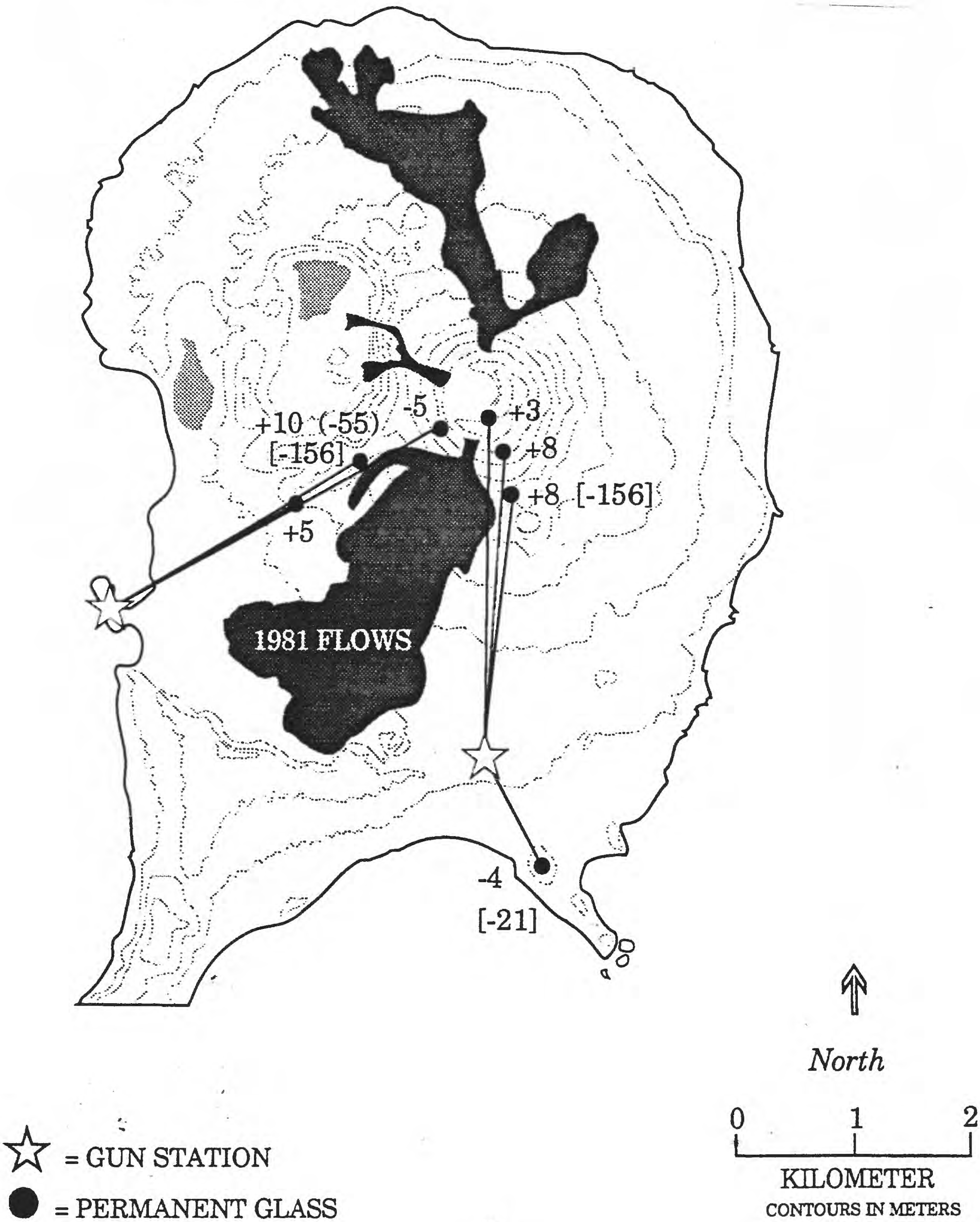


Figure 15. Time-series plot of line-lengths measured from instrument station INS on the south Mount Pagan permanent-glass EDM monitor between 1981 and 1994.

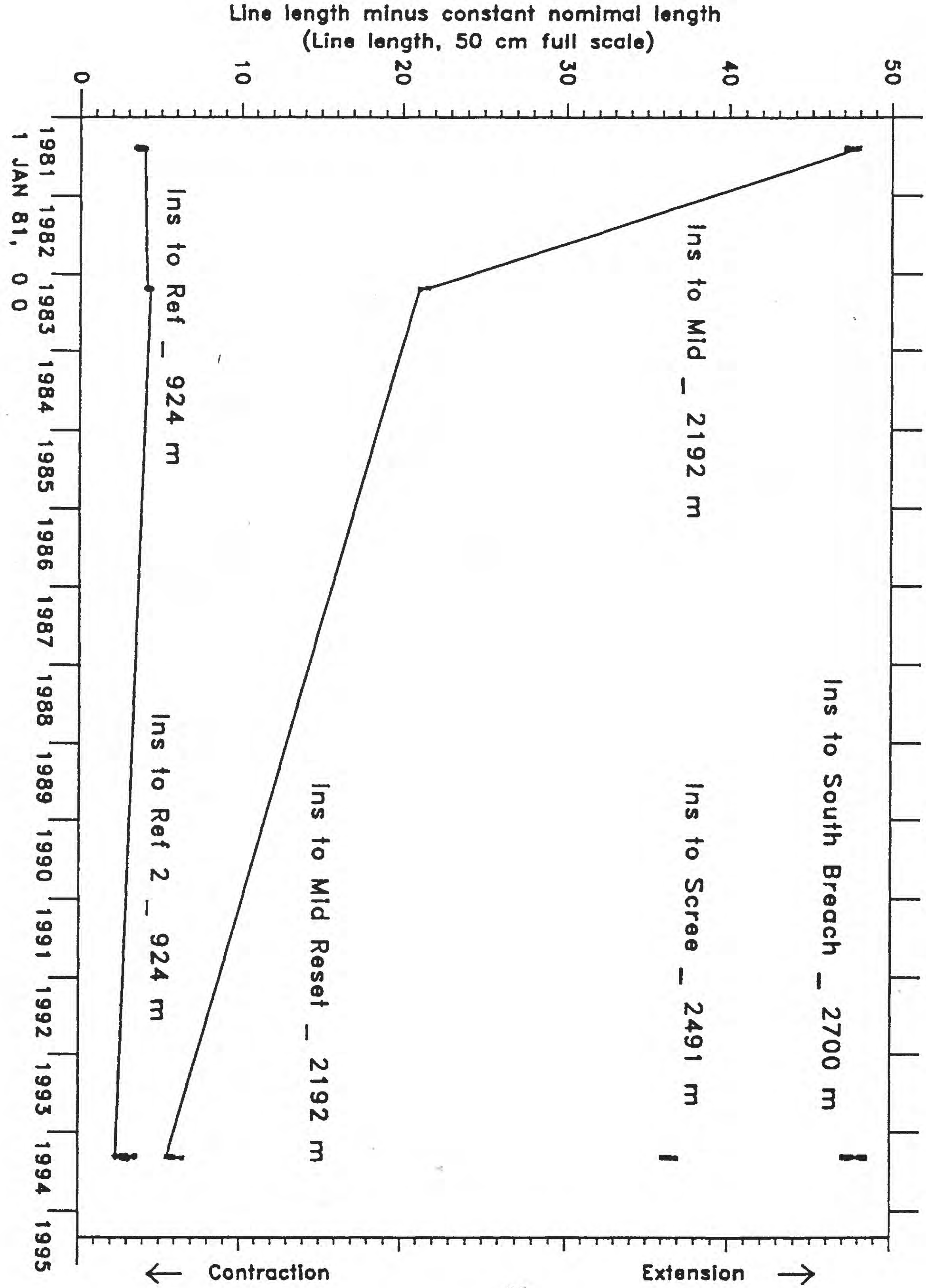


Figure 16. Correlation between L-P earthquake counts and continuous tremor recorded on PAGV seismic station and time-series plots of line-lengths measured from instrument station INS on the south Mount Pagan permanent-glass EDM monitor between 4/21/94 and 5/1/94.

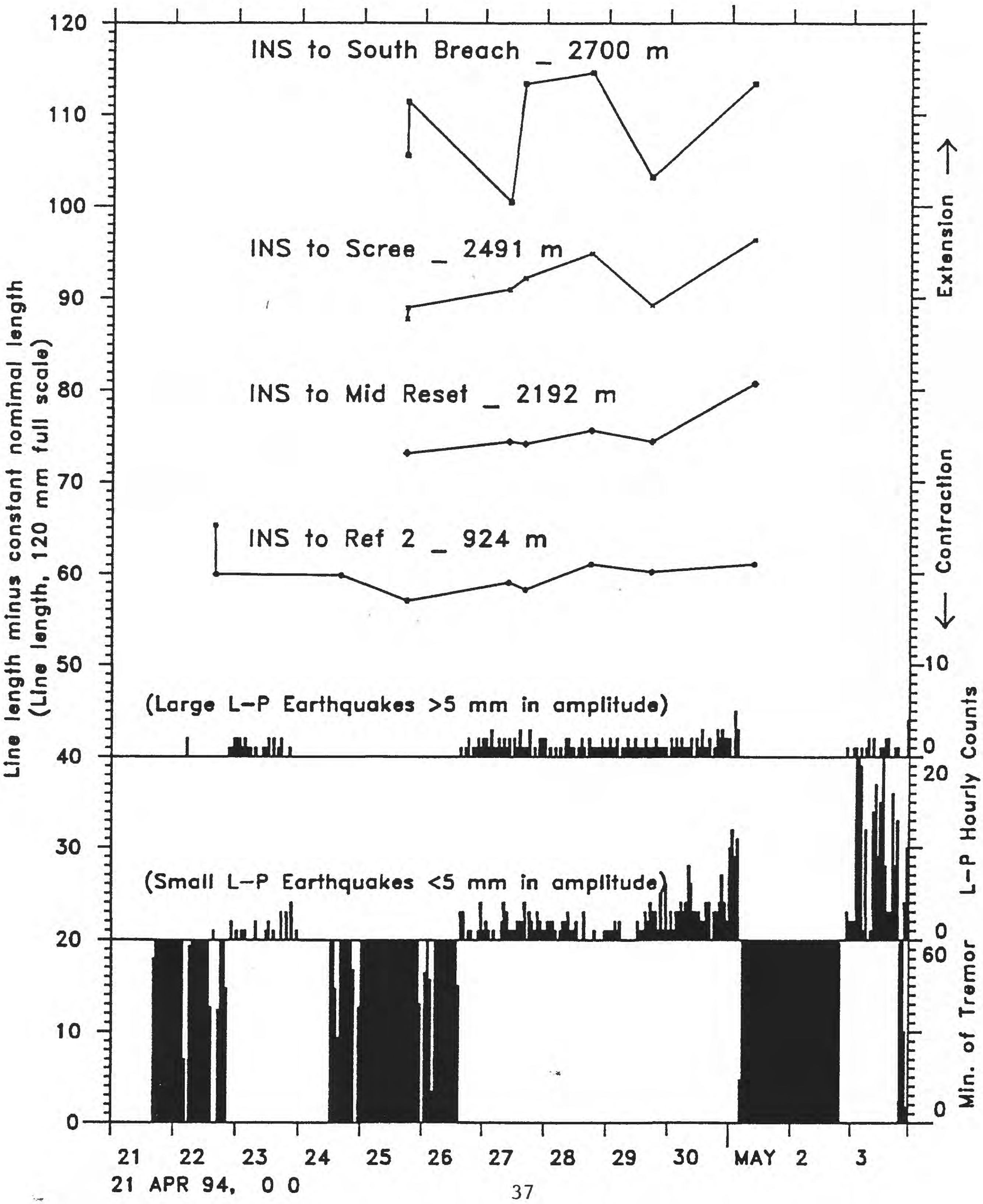


Figure 17. Time-series plot of line-lengths measured from instrument station PAGAN I on the southwest Mount Pagan permanent-glass EDM monitor between 1984 and 1994.

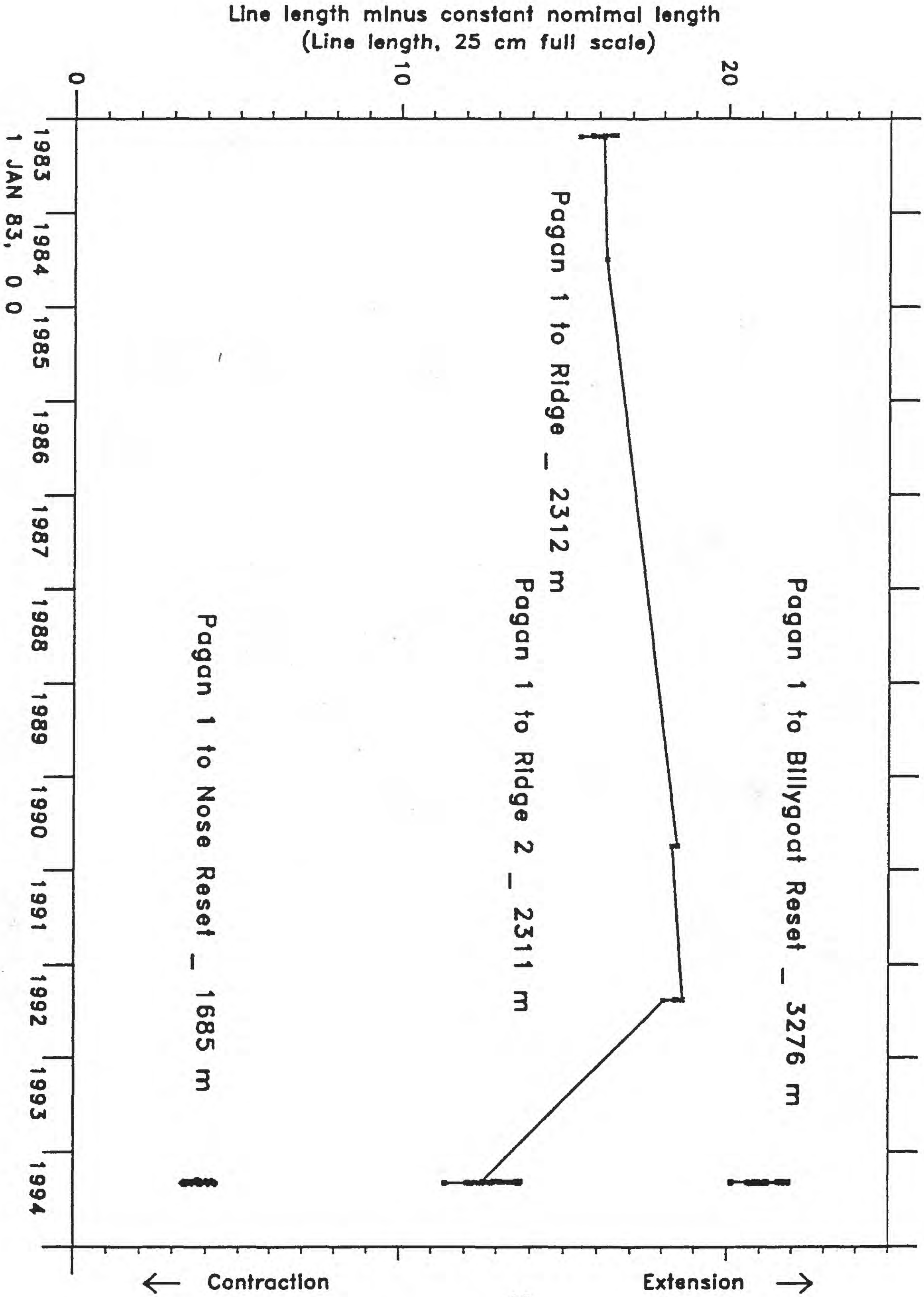


Figure 18. Correlation between L-P earthquake counts and continuous tremor recorded on PAGV seismic station and time-series plots of line-lengths measured from instrument station PAGAN I on the southwest Mount Pagan permanent-glass EDM monitor between 4/21/94 and 5/1/94.

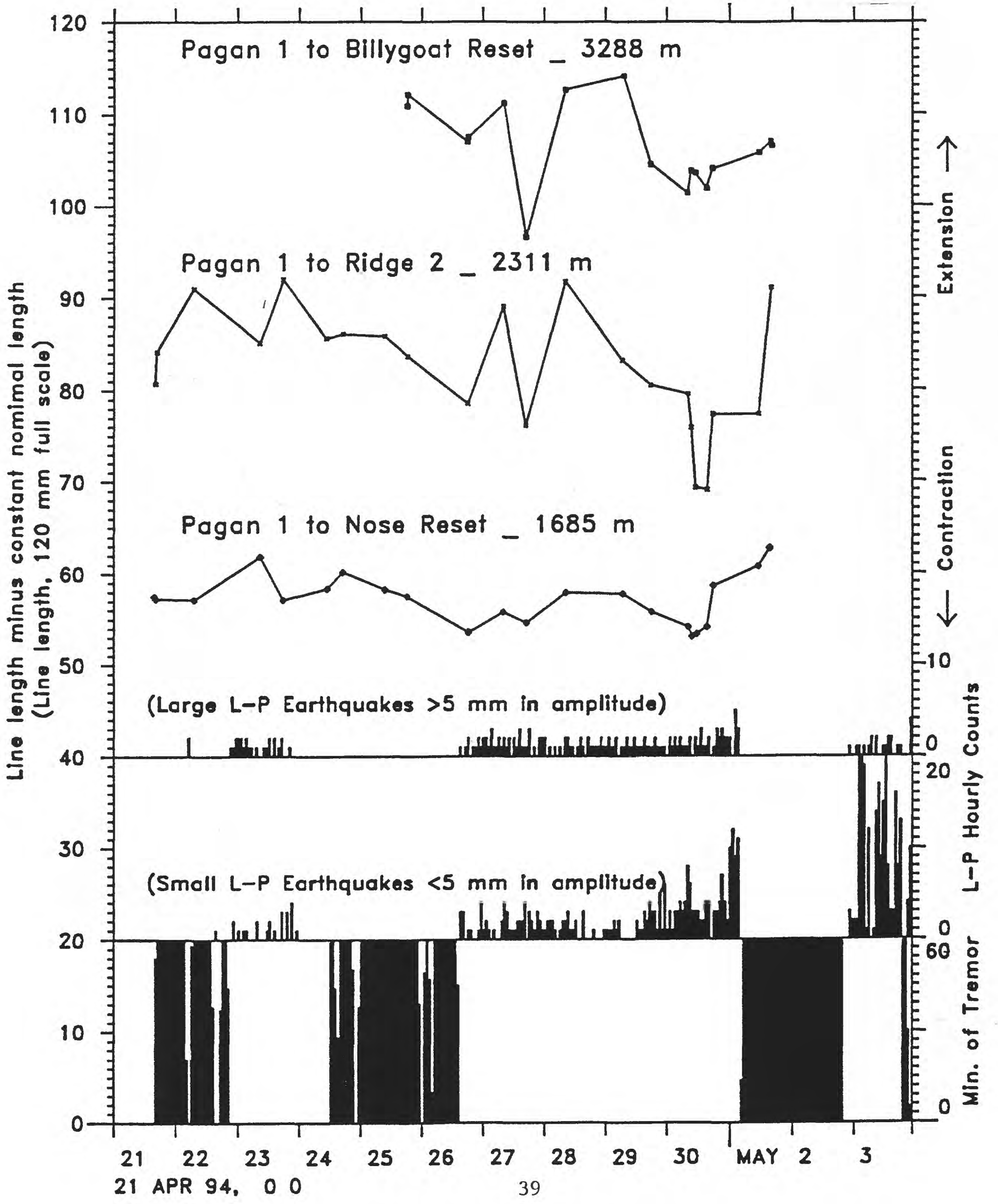


Figure 19a. Location map of the EDM permanent-glass network of Anatahan caldera.

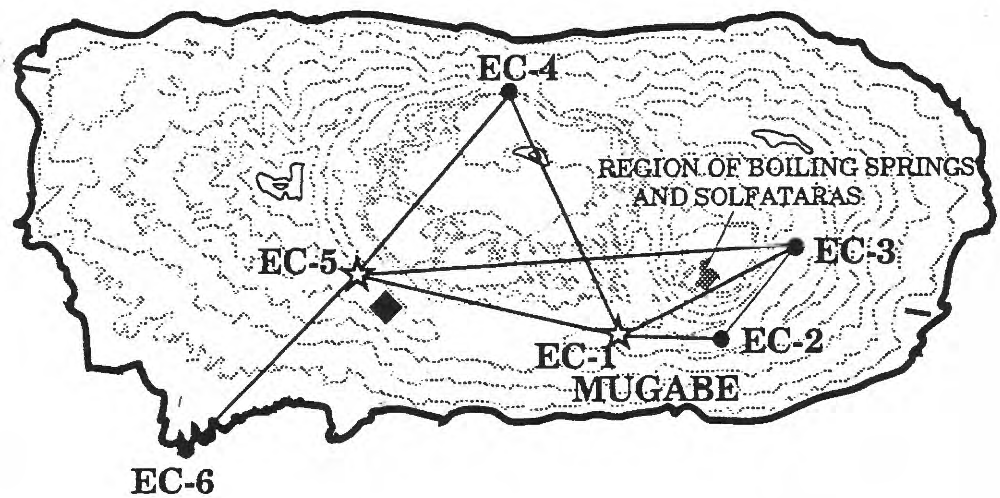
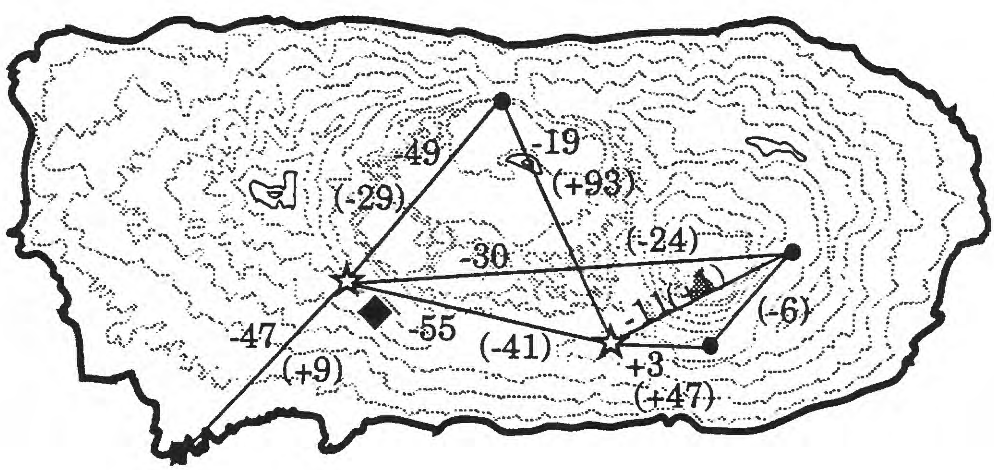


Figure 19b. EDM permanent-glass line-length differences (in mm) of Anatahan caldera between 5/92 and 5/94 survey. Numbers in parentheses are cumulative differences between 4/90 and 5/94 survey.



☆ = GUN AND REFLECTOR STATION
● = PERMANENT GLASS
◆ = SEISMIC STATION

North

0 1 2 3
KILOMETERS
CONTOURS IN METERS

Figure 20. Time-series plot of line-lengths measured from instrument stations EC-1, MUGABE (new instrument site replacing EC-1), and EC-2 spanning Anatahan caldera.

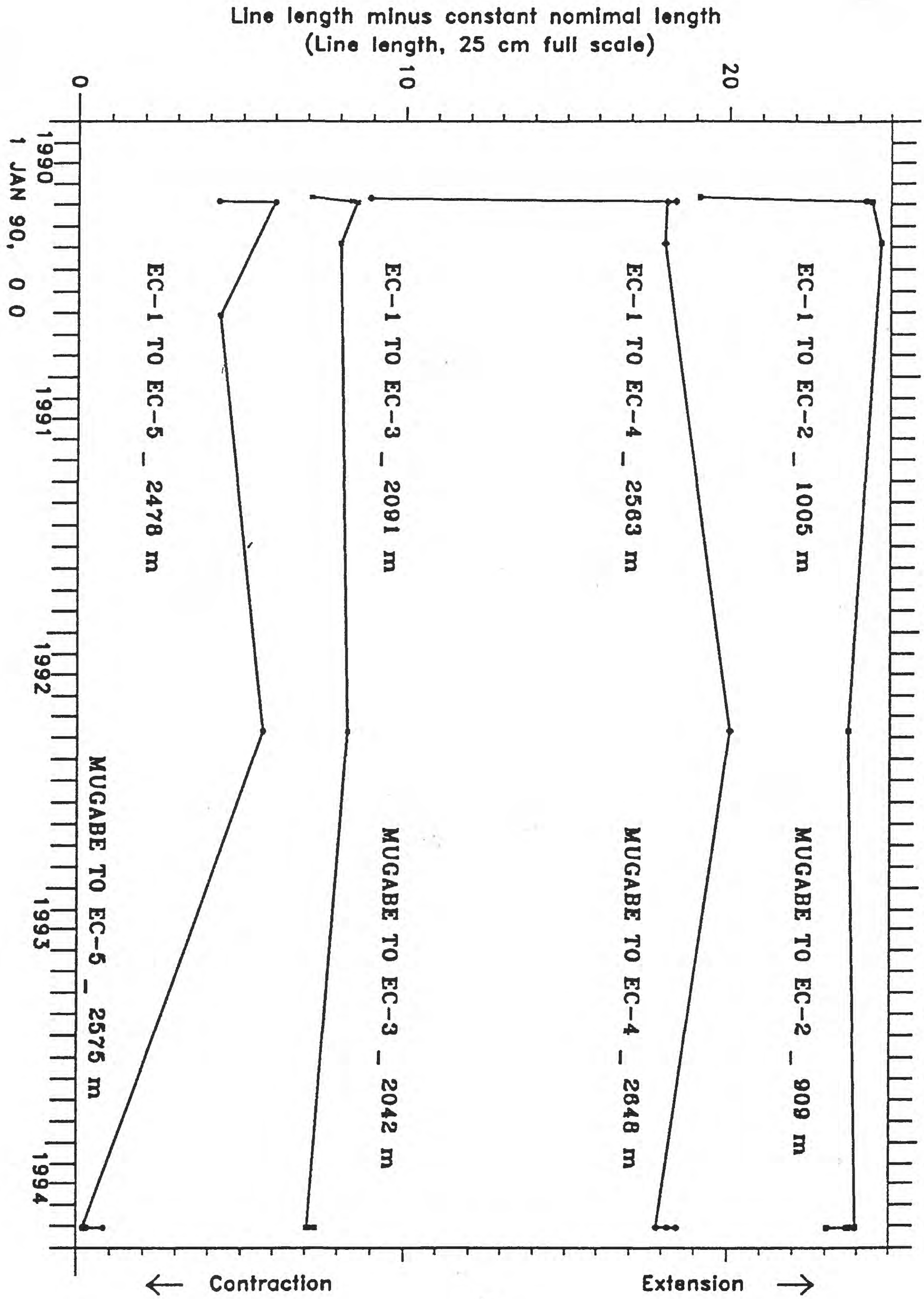


Figure 21. Time-series plot of line-lengths measured from instrument station EC-5 to lines spanning Anatahan caldera, plus one line to the coast.

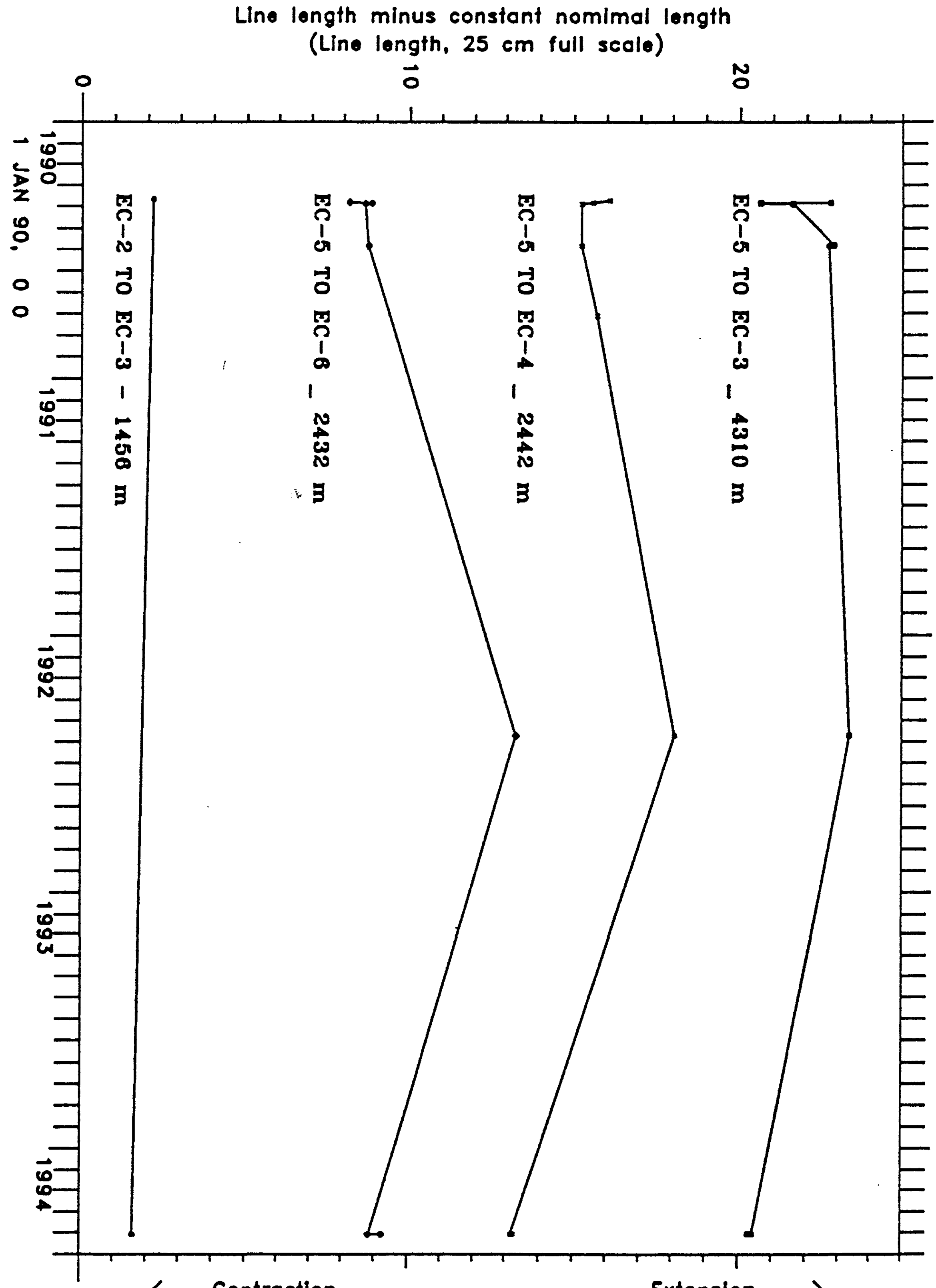


Table 1. Table of line-length changes and cumulative differences for Agrihan caldera EDM permanent-glass network.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
CEN	STM	09/29/90	967.882			0	0
CEN	STM	09/29/90	967.882	09/29/90	967.883	+1	+1
CEN	STM	09/29/90	967.883	05/15/92	967.879	-4	-3
CEN	STM	05/15/92	967.879	05/16/92	967.879	0	-3
CEN	STM	05/16/92	967.879	04/26/94	967.870	-9	-12
CEN	STM	04/26/94	967.870	04/26/94	967.871	+1	-11
CEN	FUM	09/29/90	501.468			0	0
CEN	FUM	09/29/90	501.468	09/29/90	501.467	-1	-1
CEN	FUM	09/29/90	501.467	05/15/92	501.470	+3	+2
CEN	FUM	05/15/92	501.470	05/16/92	501.465	-5	-3
CEN	FUM	05/16/92	501.465	04/26/94	501.466	+1	-2
CEN	FUM	04/26/94	501.466	04/26/94	501.475	+9	+7
CEN	BHV	09/29/90	604.458			0	0
CEN	BHV	09/29/90	604.458	09/29/90	604.459	+1	+1
CEN	BHV	09/29/90	604.459	05/15/92	604.460	+1	+2
CEN	BHV	05/15/92	604.460	05/16/92	604.453	-7	-5
CEN	HSH	09/29/90	702.793			0	0
CEN	HSH	09/29/90	702.793	09/29/90	702.793	0	0
CEN	HSH	09/29/90	702.793	05/15/92	702.788	-5	-5
CEN	HSH	05/15/92	702.788	05/16/92	702.787	-1	-6
CEN	HSH	05/16/92	702.787	04/26/94	702.783	-4	-10
CEN	COL	09/29/90	660.106			0	0
CEN	COL	09/29/90	660.106	09/29/90	660.107	+1	+1
CEN	COL	09/29/90	660.107	05/15/92	660.103	-4	-3
CEN	COL	05/15/92	660.103	05/16/92	660.108	+5	+2
CEN	COL	05/16/92	660.108	04/26/94	660.091	-17	-15
CEN	COL	04/26/94	660.091	04/26/94	660.094	+3	-12

Central Cone = CEN; Steam Bluff = STM; Fumarole = FUM; Beehive = BHV; Horseshoe = HSH; Columnar = COL

Table 2. Table of line-length changes and cumulative differences for Mount Pagan EDM southwest permanent-glass monitor lines.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
PAGAN 1	STEEP	03/06/83	3060.853			0	0
PAGAN 1	STEEP	03/06/83	3060.853	03/06/83	3060.860	+7	+7
PAGAN 1	STEEP	03/06/83	3060.860	03/07/83	3060.868	+8	+15
PAGAN 1	STEEP	03/07/83	3060.868	03/07/83	3060.861	-7	+8
PAGAN 1	STEEP	03/07/83	3060.861	03/08/83	3060.865	+4	+12
PAGAN 1	STEEP	03/08/83	3060.865	03/09/83	3060.859	-6	+6
PAGAN 1	STEEP	03/09/83	3060.859	03/11/83	3060.847	-12	-6
PAGAN 1	STEEP	03/11/83	3060.847	03/12/83	3060.855	+8	+2
PAGAN 1	STEEP	03/12/83	3060.855	03/13/83	3060.861	+6	+8
PAGAN 1	STEEP	03/13/83	3060.861	03/14/83	3060.855	-6	+2
PAGAN 1	STEEP	03/14/83	3060.855	06/28/84	3060.715	-140	-138

Destroyed by mudflows

PAGAN 1	BILLYGOAT	05/17/92	3276.678				0
PAGAN 1	BILLYGOAT	05/17/92	3276.678	05/17/92	3276.679	+1	+1
PAGAN 1	BILLYGOAT	05/17/92	3276.679	05/18/92	3276.681	+2	+3
PAGAN 1	BILLYGOAT	05/18/92	3276.681	05/19/92	3276.682	+1	+4

Buried by over a meter of ash deposit; cannot be found

PAGAN 1	BG RESET	04/25/94	3288.056			0	0
PAGAN 1	BG RESET	04/25/94	3288.056	04/25/94	3288.057	+1	+1
PAGAN 1	BG RESET	04/25/94	3288.057	04/26/94	3288.052	-5	-4
PAGAN 1	BG RESET	04/26/94	3288.052	04/26/94	3288.053	+1	-3
PAGAN 1	BG RESET	04/26/94	3288.053	04/27/94	3288.056	+3	0
PAGAN 1	BG RESET	04/27/94	3288.056	04/27/94	3288.042	-14	-14
PAGAN 1	BG RESET	04/27/94	3288.042	04/28/94	3288.058	+16	+2
PAGAN 1	BG RESET	04/28/94	3288.058	04/29/94	3288.059	+1	+3
PAGAN 1	BG RESET	04/29/94	3288.059	04/29/94	3288.050	-9	-6
PAGAN 1	BG RESET	04/29/94	3288.050	04/30/94	3288.046	-4	-10
PAGAN 1	BG RESET	04/30/94	3288.046	04/30/94	3288.049	+3	-7
PAGAN 1	BG RESET	04/30/94	3288.049	04/30/94	3288.049	0	-7
PAGAN 1	BG RESET	04/30/94	3288.049	04/30/94	3288.047	-2	-9
PAGAN 1	BG RESET	04/30/94	3288.047	04/30/94	3288.049	+2	-7
PAGAN 1	BG RESET	04/30/94	3288.049	05/01/94	3288.051	+2	-5
PAGAN 1	BG RESET	05/01/94	3288.051	05/01/94	3288.052	+1	-4
PAGAN 1	BG RESET	05/01/94	3288.052	05/01/94	3288.051	-1	-5

BILLY GOAT RESET = BG RESET established 4/25/94

Continue Table 2.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
PAGAN 1	RIDGE	03/06/83	2311.988			0	0
PAGAN 1	RIDGE	03/06/83	2311.988	03/07/83	2311.994	+6	+6
PAGAN 1	RIDGE	03/07/83	2311.994	03/07/83	2311.992	-2	+4
PAGAN 1	RIDGE	03/07/83	2311.992	03/08/83	2311.995	+3	+7
PAGAN 1	RIDGE	03/08/83	2311.995	03/09/83	2311.988	-7	0
PAGAN 1	RIDGE	03/09/83	2311.988	03/11/83	2311.985	-3	-3
PAGAN 1	RIDGE	03/11/83	2311.985	03/12/83	2311.990	+5	+2
PAGAN 1	RIDGE	03/12/83	2311.990	03/13/83	2311.991	+1	+3
PAGAN 1	RIDGE	03/13/83	2311.991	06/28/84	2311.993	+2	+5
PAGAN 1	RIDGE	06/28/84	2311.993	09/30/90	2312.015	+22	+27
PAGAN 1	RIDGE	09/30/90	2312.009	10/01/90	2312.013	-2	+25
PAGAN 1	RIDGE	10/01/90	2312.013	05/17/92	2312.016	+3	+28
PAGAN 1	RIDGE	05/17/92	2312.016	05/17/92	2312.014	-2	+26
PAGAN 1	RIDGE	05/17/92	2312.014	05/18/92	2312.014	0	+26
PAGAN 1	RIDGE	05/18/92	2312.014	05/18/92	2312.016	+2	+28
PAGAN 1	RIDGE	05/18/92	2312.016	05/19/92	2312.010	-6	+22
PAGAN 1	RIDGE 2	09/30/90	2312.015			0	0
PAGAN 1	RIDGE 2	09/30/90	2312.015	10/01/90	2312.013	-2	-2
PAGAN 1	RIDGE 2	10/01/90	2312.013	05/17/92	2312.016	+3	+1
PAGAN 1	RIDGE 2	05/17/92	2312.016	05/18/92	2312.014	-2	-1
PAGAN 1	RIDGE 2	05/18/92	2312.014	05/18/92	2312.016	+2	+1
PAGAN 1	RIDGE 2	05/18/92	2312.016	05/19/92	2312.010	-6	-5
PAGAN 1	RIDGE 2	05/19/92	2312.010	04/21/94	2311.956	-54	-59
PAGAN 1	RIDGE 2	04/21/94	2311.956	04/21/94	2311.959	+3	-56
PAGAN 1	RIDGE 2	04/21/94	2311.959	04/22/94	2311.966	+7	-49
PAGAN 1	RIDGE 2	04/22/94	2311.966	04/23/94	2311.960	-6	-55
PAGAN 1	RIDGE 2	04/23/94	2311.960	04/23/94	2311.967	+7	-48
PAGAN 1	RIDGE 2	04/23/94	2311.967	04/24/94	2311.961	-6	-54
PAGAN 1	RIDGE 2	04/24/94	2311.961	04/24/94	2311.961	0	-54
PAGAN 1	RIDGE 2	04/24/94	2311.961	04/25/94	2311.961	0	-54
PAGAN 1	RIDGE 2	04/25/94	2311.961	04/25/94	2311.959	-2	-56
PAGAN 1	RIDGE 2	04/25/94	2311.959	04/26/94	2311.954	-5	-61
PAGAN 1	RIDGE 2	04/26/94	2311.954	04/27/94	2311.964	+10	-51
PAGAN 1	RIDGE 2	04/27/94	2311.964	04/27/94	2311.951	-13	-64
PAGAN 1	RIDGE 2	04/27/94	2311.951	04/28/94	2311.967	+16	-48
PAGAN 1	RIDGE 2	04/28/94	2311.967	04/29/94	2311.958	-9	-57
PAGAN 1	RIDGE 2	04/29/94	2311.958	04/29/94	2311.956	-2	-59
PAGAN 1	RIDGE 2	04/29/94	2311.956	04/30/94	2311.955	-1	-60
PAGAN 1	RIDGE 2	04/30/94	2311.955	04/30/94	2311.951	-4	-64
PAGAN 1	RIDGE 2	04/30/94	2311.951	04/30/94	2311.944	-7	-71
PAGAN 1	RIDGE 2	04/30/94	2311.944	04/30/94	2311.944	0	-71
PAGAN 1	RIDGE 2	04/30/94	2311.944	04/30/94	2311.952	+8	-63
PAGAN 1	RIDGE 2	04/30/94	2311.952	05/01/94	2311.953	+1	-62
PAGAN 1	RIDGE 2	05/01/94	2311.953	05/01/94	2311.966	+7	-55

New type of permanent-glass system was employed 5/17/92.

Continue Table 2.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
PAGAN 1	NOSE	03/06/83	1685.848			0	0
PAGAN 1	NOSE	03/06/83	1685.848	03/07/83	1685.852	+4	+4
PAGAN 1	NOSE	03/07/83	1685.852	03/07/83	1685.849	-3	+1
PAGAN 1	NOSE	03/07/83	1685.849	03/08/83	1685.858	+9	+10
PAGAN 1	NOSE	03/08/83	1685.858	03/09/83	1685.857	-1	+9
PAGAN 1	NOSE	03/09/83	1685.857	03/11/83	1685.853	-4	+5
PAGAN 1	NOSE	03/11/83	1685.853	03/11/83	1685.852	-1	+4
PAGAN 1	NOSE	03/11/83	1685.852	03/12/83	1685.855	+3	+7
PAGAN 1	NOSE	03/12/83	1685.855	03/13/83	1685.854	-1	+6
PAGAN 1	NOSE	03/13/83	1685.854	06/28/84	1685.847	-7	-1
PAGAN 1	NOSE	06/28/84	1685.847	10/01/90	1685.867	+20	+19
PAGAN 1	NOSE	10/01/90	1685.867	10/01/90	1685.868	+1	+20
PAGAN 1	NOSE	10/01/90	1685.868	05/17/92	1685.860	-8	+12
PAGAN 1	NOSE	05/17/92	1685.860	05/17/92	1685.865	+5	+17
PAGAN 1	NOSE	05/17/92	1685.865	05/18/92	1685.864	-1	+16
PAGAN 1	NOSE	05/18/92	1685.864	05/18/92	1685.857	-7	+9
PAGAN 1	NOSE	05/18/92	1685.857	05/19/92	1685.858	+1	+10

The station was destroyed by ashfall and/or mudflows

PAGAN 1	NOSE RESET	04/21/94	1685.738			0	0
PAGAN 1	NOSE RESET	04/21/94	1685.738	04/21/94	1685.737	-1	-1
PAGAN 1	NOSE RESET	04/21/94	1685.737	04/22/94	1685.737	0	-1
PAGAN 1	NOSE RESET	04/22/94	1685.737	04/23/94	1685.742	+5	+4
PAGAN 1	NOSE RESET	04/23/94	1685.742	04/23/94	1685.737	-5	-1
PAGAN 1	NOSE RESET	04/23/94	1685.737	04/24/94	1685.738	+1	0
PAGAN 1	NOSE RESET	04/24/94	1685.738	04/24/94	1685.740	+2	+2
PAGAN 1	NOSE RESET	04/24/94	1685.740	04/25/94	1685.738	-2	0
PAGAN 1	NOSE RESET	04/25/94	1685.738	04/25/94	1685.738	0	0
PAGAN 1	NOSE RESET	04/25/94	1685.738	04/26/94	1685.734	-4	-4
PAGAN 1	NOSE RESET	04/26/94	1685.734	04/27/94	1685.736	+2	-2
PAGAN 1	NOSE RESET	04/27/94	1685.736	04/27/94	1685.735	-1	-3
PAGAN 1	NOSE RESET	04/27/94	1685.735	04/28/94	1685.738	+3	0
PAGAN 1	NOSE RESET	04/28/94	1685.738	04/29/94	1685.738	0	0
PAGAN 1	NOSE RESET	04/29/94	1685.738	04/29/94	1685.736	-2	-2
PAGAN 1	NOSE RESET	04/29/94	1685.736	04/30/94	1685.734	-2	-4
PAGAN 1	NOSE RESET	04/30/94	1685.734	04/30/94	1685.733	-1	-5
PAGAN 1	NOSE RESET	04/30/94	1685.733	04/30/94	1685.733	0	-5
PAGAN 1	NOSE RESET	04/30/94	1685.733	04/30/94	1685.734	+1	-4
PAGAN 1	NOSE RESET	04/30/94	1685.734	04/30/94	1685.739	+5	+1
PAGAN 1	NOSE RESET	04/30/94	1685.739	05/01/94	1685.741	+2	+3
PAGAN 1	NOSE RESET	05/01/94	1685.741	05/01/94	1685.743	+2	+5

New station was established on 4/21/94.

Table 3. Table of line-length changes and cumulative differences for Mount Pagan EDM south permanent-glass monitor lines (1981 line-length differences from Banks and others, 1984).

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
INS	REF	05/24/81	924.848				0
INS	REF	05/24/81	924.848	05/24/81	924.845	-3	-3
INS	REF	05/24/81	924.845	05/25/81	924.848	+3	-0
INS	REF	05/25/81	924.848	05/26/81	924.846	-2	-2
INS	REF	05/26/81	924.846	05/28/81	924.850	+4	+2
INS	REF	05/28/81	924.850	03/07/83	924.852	+2	+4
INS	REF	03/07/83	924.852	03/13/83	924.854	+2	+6
INS	REF	03/13/83	924.854	04/22/94	924.833	-21	-15
INS	REF 2	04/22/94	924.805			0	0
INS	REF 2	04/22/94	924.805	04/22/94	924.800	-5	-5
INS	REF 2	04/22/94	924.800	04/24/94	924.800	0	-5
INS	REF 2	04/24/94	924.800	04/25/94	924.797	-3	-8
INS	REF 2	04/25/94	924.797	04/27/94	924.799	+2	-6
INS	REF 2	04/27/94	924.799	04/27/94	924.798	-1	-7
INS	REF 2	04/27/94	924.798	04/28/94	924.801	+3	-4
INS	REF 2	04/28/94	924.801	04/29/94	924.800	-1	-5
INS	REF 2	04/29/94	924.800	05/01/94	924.801	+1	-4

New permanent-glass system was employed on 4/22/94.

INS	BASE	05/21/81	1446.363				0
INS	BASE	05/21/81	1446.363	05/22/81	1446.368	+5	+5
INS	BASE	05/22/81	1446.368	05/22/81	1446.363	-5	+0
INS	BASE	05/22/81	1446.363	05/24/81	1446.368	+5	+5
INS	BASE	05/24/81	1446.368	05/24/81	1446.362	-6	-1
INS	BASE	05/24/81	1446.362	05/25/81	1446.371	+9	+8
INS	BASE	05/25/81	1446.371	05/26/81	1446.372	+1	+9
INS	BASE	05/26/81	1446.372	05/27/81	1446.372	0	+9
INS	BASE	05/27/81	1446.372	05/28/81	1446.370	-2	+7
INS	BASE	03/28/81	1446.370	03/07/83	1446.359	-11	-4
INS	BASE	03/07/83	1446.359	03/13/83	1446.363	+4	+0

The permanent glass site could not be found.

INS	MID	05/22/81	2192.809				0
INS	MID	05/22/81	2192.809	05/24/81	2192.801	-8	-8
INS	MID	05/24/81	2192.801	05/24/81	2192.801	-0	-8
INS	MID	05/24/81	2192.801	05/25/81	2192.808	+7	-1
INS	MID	05/25/81	2192.808	05/26/81	2192.804	-4	-5
INS	MID	05/26/81	2192.804	05/27/81	2192.801	-3	-8
INS	MID	05/27/81	2192.801	05/28/81	2192.807	+6	-2
INS	MID	05/28/81	2192.807	03/07/83	2192.546	-261	-263

Continue Table 3.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
INS	MID	03/07/83	2192.546	03/13/83	2192.541	-5	-268
INS	MID	03/13/83	2192.541	04/25/94	2192.385	-156	-424

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
INS	MID RESET	04/25/94	2192.617			0	0
INS	MID RESET	04/25/94	2192.617	04/27/94	2192.619	+2	+2
INS	MID RESET	04/27/94	2192.619	04/27/94	2192.618	-1	+1
INS	MID RESET	04/27/94	2192.618	04/28/94	2192.620	+2	+3
INS	MID RESET	04/28/94	2192.620	04/29/94	2192.619	-1	+2
INS	MID RESET	04/29/94	2192.619	05/01/94	2192.625	+6	+8

The rebar for the original station was being rusted out so MID RESET was established on 4/25/94.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
INS	SCREE	04/25/94	2491.461			0	0
INS	SCREE	04/25/94	2491.461	04/25/94	2491.462	+1	+1
INS	SCREE	04/25/94	2491.462	04/27/94	2491.464	+2	+3
INS	SCREE	04/27/94	2491.464	04/27/94	2491.465	+1	+4
INS	SCREE	04/27/94	2491.465	04/28/94	2491.468	+3	+7
INS	SCREE	04/28/94	2491.468	04/29/94	2491.462	-6	+1
INS	SCREE	04/29/94	2491.462	05/01/94	2491.469	+7	+8

New reflector site established on 4/25/94

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
INS	TOP	05/22/81	2612.636			0	0
INS	TOP	05/22/81	2612.636	05/24/81	2612.608	-28	-28
INS	TOP	05/24/81	2612.608	05/24/81	2612.590	-18	-46
INS	TOP	05/24/81	2612.590	05/25/81	2612.597	+7	-39
INS	TOP	05/25/81	2612.597	05/26/81	2612.585	-12	-51
INS	TOP	05/26/81	2612.585	05/27/81	2612.570	-15	-66
INS	TOP	05/27/81	2612.570	05/28/81	2612.570	0	-66

Destroyed by ashfall and debris flows.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
INS	S. BREACH	04/25/94	2700.396			0	0
INS	S. BREACH	04/25/94	2700.396	04/25/94	2700.401	+5	+5
INS	S. BREACH	04/25/94	2700.401	04/27/94	2700.391	-10	-5
INS	S. BREACH	04/27/94	2700.391	04/27/94	2700.403	+8	+3
INS	S. BREACH	04/27/94	2700.403	04/28/94	2700.405	+2	+5
INS	S. BREACH	04/28/94	2700.405	04/29/94	2700.393	-12	-7
INS	S. BREACH	04/29/94	2700.393	05/01/94	2700.403	+10	+3

SOUTH BREACH = S. BREACH established on 4/25/94.

Table 4a. Table of hourly counts of L-P earthquakes from beneath Mount Pagan as recorded on seismic station PAGV between April 22 and May 3, 1994.

Date: Yr 1994	Hour Interval	Number of L-P Events Per Hour	
		Large (≥ 5 mm)	Small (< 5 mm)
4/22	0400 - 0500	0	0
"	0500 - 0600	2	0
"	1439 - 1500	0	0
"	1500 - 1600	0	1
"	1600 - 1700	0	0
"	2045 - 2100	0	0
"	2100 - 2200	1	0
"	2200 - 2300	1	2
"	2300 - 2400	2	0
4/23	0000 - 0100	2	1
"	0100 - 0200	2	0
"	0200 - 0300	1	1
"	0300 - 0400	2	1
"	0400 - 0500	1	0
"	0500 - 0600	1	0
"	0600 - 0700	0	0
"	0700 - 0800	1	2
"	0800 - 1028	-- dead signal --	-- dead signal --
"	1028 - 1100	1	0
"	1100 - 1200	1	1
"	1200 - 1300	2	2
"	1300 - 1400	0	0
"	1400 - 1500	2	1
"	1500 - 1600	0	0
"	1600 - 1700	1	0
"	1700 - 1800	2	3
"	1800 - 1900	0	0
"	1900 - 2000	0	3
"	2000 - 2100	1	0
"	2100 - 2200	0	4
"	2200 - 2300	0	0

Continue Table 4.

Date: Yr 1994	Hour Interval	Number of L-P Events Per Hour	
		Large (≥ 5 mm)	Small (< 5 mm)
4/23	2300 - 2400	0	1
4/24	0000 - 2400	-- no record --	-- no record --
4/25	0348 - 0400	0	0
4/26	1500 - 1600	1	3
"	1600 - 1700	0	3
"	1700 - 1800	1	0
"	1800 - 1900	2	1
"	1900 - 2000	0	1
"	2000 - 2100	1	0
"	2100 - 2200	1	0
"	2200 - 2300	2	1
"	2300 - 2400	1	4
4/27	0000 - 0100	2	1
"	0100 - 0200	2	2
"	0200 - 0300	1	1
"	0300 - 0400	3	0
"	0400 - 0500	1	1
"	0500 - 0600	1	0
"	0600 - 0700	2	0
"	0700 - 0800	1	2
"	0800 - 0900	2	4
"	0900 - 1000	1	3
"	1000 - 1100	2	1
"	1100 - 1200	0	1
"	1200 - 1300	2	1
"	1300 - 1400	1	2
"	1400 - 1500	3	2
"	1500 - 1600	1	2
"	1600 - 1700	1	4
"	1700 - 1800	1	0
"	1800 - 1900	3	3
"	1900 - 2000	0	2

Continue Table 4.

Date: Yr 1994	Hour Interval	Number of L-P Events Per Hour	
		Large (≥ 5 mm)	Small (< 5 mm)
4/27	2000 - 2100	1	1
"	2100 - 2200	0	3
"	2200 - 2300	2	2
"	2300 - 2400	2	1
4/28	0000 - 0100	2	1
"	0100 - 0200	0	2
"	0200 - 0300	1	2
"	0300 - 0400	0	2
"	0400 - 0500	1	1
"	0500 - 0600	0	0
"	0600 - 0700	1	1
"	0700 - 0800	0	2
"	0800 - 0900	2	2
"	0900 - 1000	2	3
"	1000 - 1100	1	1
"	1100 - 1200	1	1
"	1200 - 1300	0	2
"	1300 - 1400	1	0
"	1400 - 1500	2	0
"	1500 - 1600	1	3
"	1700 - 1800	2	0
"	1800 - 1900	1	0
"	1900 - 2000	1	1
"	2000 - 2100	1	0
"	2100 - 2200	1	0
"	2200 - 2300	2	0
"	2300 - 2400	1	1
4/29	0000 - 0100	1	1
"	0100 - 0200	2	1
"	0200 - 0300	1	1
"	0300 - 0400	1	2
"	0400 - 0500	2	1

Continue Table 4.

Date: Yr 1994	Hour Interval	Number of L-P Events Per Hour	
		Large (≥ 5 mm)	Small (< 5 mm)
4/29	0500 - 0600	0	2
"	0600 - 0700	1	0
"	0700 - 0800	1	0
"	0800 - 0900	2	0
"	0900 - 1000	1	0
"	1000 - 1100	1	0
"	1100 - 1200	2	0
"	1200 - 1300	1	2
"	1300 - 1400	1	1
"	1400 - 1500	1	1
"	1500 - 1600	2	3
"	1600 - 1700	1	2
"	1700 - 1800	1	4
"	1800 - 1900	1	3
"	1900 - 2000	2	3
"	2000 - 2100	1	1
"	2100 - 2200	1	5
"	2200 - 2300	1	1
"	2300 - 2400	1	6
4/30	0000 - 0100	0	1
"	0100 - 0200	2	3
"	0200 - 0300	1	1
"	0300 - 0400	2	3
"	0400 - 0500	1	3
"	0500 - 0600	2	4
"	0600 - 0700	1	3
"	0700 - 0800	1	4
"	0800 - 0900	1	8
"	0900 - 1000	2	6
"	1000 - 1100	0	3
"	1100 - 1200	2	3
"	1200 - 1300	1	3

Continue Table 4.

Date: Yr 1994	Hour Interval	Number of L-P Events Per Hour	
		Large (≥ 5 mm)	Small (< 5 mm)
4/30	1300 - 1400	3	2
"	1400 - 1500	1	2
"	1500 - 1600	1	4
"	1600 - 1700	2	4
"	1800 - 1900	1	3
"	1900 - 2000	3	3
"	2000 - 2100	2	4
"	2100 - 2200	3	7
"	2200 - 2300	2	4
"	2300 - 2400	2	2
5/01	0000 - 0100	2	10
"	0100 - 0200	0	12
"	0200 - 0300	5	9
"	0300 - 0445	3	11
5/02	2200 - 2300	1	3
"	2300 - 2400	0	2
5/03	0000 - 0100	0	2
"	0100 - 0200	1	2
"	0200 - 0300	1	22
"	0300 - 0400	0	28
"	0400 - 0500	1	19
"	0500 - 0600	0	1
"	0600 - 0700	1	12
"	0700 - 0800	2	cont. tremor 1 mm ave
"	0800 - 0900	0	1
"	0900 - 1000	2	14
"	1000 - 1100	0	17
"	1100 - 1200	0	9
"	1200 - 1300	1	15
"	1300 - 1400	1	27
"	1400 - 1500	2	8
"	1500 - 1600	2	3

Continue Table 4.

Date: Yr 1994	Hour Interval	Number of L-P Events Per Hour	
		Large (≥ 5 mm)	Small (< 5 mm)
5/03	1600 - 1700	0	3
"	1700 - 1800	0	16
"	1800 - 1900	1	8
"	1900 - 2000	1	13
"	2230 - 2300	0	4
"	2300 - 2354	4	10

Table 4b. Table of tremor duration beneath Mount Pagan as registered on PAGV seismic station. Tremor recording was classified according to amplitude measured on the PAGV revolving drum seismograph at 40 mv gain--high greater than or equal to 5 mm and low less than 5 mm.

PAGV 4/21 -- 5/06 1994 (Local Saipan Time)

YY	MM	DD	HH	MN	YY	MM	DD	HH	MN	COMMENTS
94	04	21	16	06	94	04	22	04	21	continuous high tremor
94	04	22	04	22	94	04	22	06	01	continuous low tremor
94	04	21	06	02	94	04	22	14	38	continuous high tremor
94	04	22	14	39	94	04	22	17	22	continuous low tremor
94	04	22	17	23	94	04	22	20	44	continuous high tremor
94	04	22	20	45	94	04	24	12	00	continuous low tremor
94	04	24	12	01	94	04	24	14	44	continuous high tremor
94	04	24	14	45	94	04	24	15	31	continuous low tremor
94	04	24	15	32	94	04	24	21	50	continuous high tremor
94	04	24	21	51	94	04	24	23	21	continuous low tremor
94	04	24	23	22	94	04	25	23	39	continuous high tremor
94	04	25	23	40	94	04	25	01	10	continuous low tremor
94	04	25	01	11	94	04	25	03	47	continuous high tremor
94	04	25	03	48	94	04	25	04	49	continuous low tremor
94	04	25	04	50	94	04	26	14	45	continuous high tremor
94	04	26	14	46	94	05	01	04	45	continuous low tremor
94	05	01	04	46	94	05	02	19	59	continuous high tremor
94	05	02	20	00	94	05	03	20	00	continuous low tremor
94	05	03	20	01	94	05	03	22	30	continuous high tremor
94	05	03	22	31	94	05	03	23	54	continuous low tremor
94	05	03	23	55	94	06	---------------			continuous high tremor

Table 5. Table of line-length changes and cumulative differences for Anatahan caldera EDM permanent-glass network.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
EC-1	EC-3	04/20/90	2091.096			0	0
EC-1	EC-3	04/20/90	2091.096	04/26/90	2091.108	+12	+12
EC-1	EC-3	04/26/90	2091.108	04/27/90	2091.110	+2	+14
EC-1	EC-3	04/27/90	2091.110	06/25/90	2091.105	-5	+9
EC-1	EC-3	06/25/90	2091.105	05/22/92	2091.107	+2	+11
EC-1	EC-3	05/22/92	2091.107	05/03/94	2091.096	-11	0
EC-1	EC-3	05/03/94	2091.096	05/03/94	2091.097	+1	+1
MUGABE	EC-3	05/03/94	2042.513			0	0
MUGABE	EC-3	05/03/94	2042.513	05/03/94	2042.511	-2	-2

MUGABE replaced EC-1 as instrument station; established on 5/03/94

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
EC-2	EC-3	04/20/90	1456.202			0	0
EC-2	EC-3	04/20/90	1456.202	05/03/94	1456.196	-6	-6
EC-2	EC-1	04/20/90	1005.526			0	0
EC-1	EC-2	04/20/90	1005.526	04/26/90	1005.577	+51	+51
EC-1	EC-2	04/26/90	1005.577	04/27/90	1005.579	+2	+53
EC-1	EC-2	04/27/90	1005.579	06/25/90	1005.582	+3	+56
EC-1	EC-2	06/25/90	1005.582	05/22/92	1005.572	-10	+46
EC-1	EC-2	05/22/92	1005.572	05/03/94	1005.575	+3	+49
EC-1	EC-2	05/03/94	1005.575	050394	1005.573	-2	+47
MUGABE	EC-2	05/03/94	909.197			0	0
MUGABE	EC-2	05/03/94	909.197	05/03/94	909.191	-6	-6

MUGABE replaced EC-1 as instrument station; established on 5/03/94

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
EC-4	EC-1	04/21/90	2562.984			0	0
EC-1	EC-4	04/21/90	2562.984	04/26/90	2563.079	+95	+95
EC-1	EC-4	04/26/90	2563.079	04/27/90	2563.076	-3	+92
EC-1	EC-4	04/27/90	2563.076	06/25/90	2563.075	-1	+91
EC-1	EC-4	06/25/90	2563.075	05/22/92	2563.095	+20	+111
EC-1	EC-4	05/22/92	2563.095	05/03/94	2563.073	-22	+89
EC-1	EC-4	05/03/94	2563.073	05/03/94	2563.077	+4	+93
MUGABE	EC-4	05/03/94	2648.115			0	0
MUGABE	EC-4	05/03/94	2648.115	05/03/94	2648.118	+3	+3

MUGABE replaced EC-1 as instrument station; established on 5/03/94

Continue Table 5

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
EC-1	EC-5	04/26/90	2478.043			0	0
EC-1	EC-5	04/26/90	2478.043	04/27/90	2478.060	+17	+17
EC-1	EC-5	04/27/90	2478.060	10/04/90	2478.043	-17	0
EC-1	EC-5	10/04/90	2478.043	05/22/92	2478.057	+14	+14
EC-1	EC-5	05/22/92	2478.057	05/03/94	2478.002	-55	-41
EC-1	EC-5	05/03/94	2478.002	05/03/94	2478.003	+1	-40
MUGABE	EC-5	05/03/94	2575.1394			0	0
MUGABE	EC-5	05/03/94	2575.139	05/03/94	2575.145	+6	+6

MUGABE replaced EC-1 as instrument station; established on 5/03/94

EC-5	EC-4	04/22/90	2442.111			0	0
EC-5	EC-4	04/22/90	2442.111	04/25/90	2442.106	-5	-5
EC-5	EC-4	04/25/90	2442.106	04/27/90	2442.102	-4	-9
EC-5	EC-4	04/27/90	2442.102	06/26/90	2442.102	0	-9
EC-5	EC-4	06/26/90	2442.102	10/04/90	2442.107	+5	-4
EC-5	EC-4	10/04/90	2442.107	05/22/92	2442.131	+24	+20
EC-5	EC-4	05/22/92	2442.131	05/03/94	2442.082	-49	-29
EC-5	EC-4	05/03/94	2442.082	05/03/94	2442.082	0	-29
EC-5	EC-3	04/25/90	4310.747			0	0
EC-5	EC-3	04/25/90	4310.747	04/26/90	4310.726	-21	-21
EC-5	EC-3	04/26/90	4310.726	04/27/90	4310.736	+10	-11
EC-5	EC-3	04/27/90	4310.736	06/25/90	4310.748	+12	+1
EC-5	EC-3	06/25/90	4310.748	06/26/90	4310.747	-1	0
EC-5	EC-3	06/26/90	4310.747	05/22/92	4310.754	+7	+7
EC-5	EC-3	05/22/92	4310.754	05/03/94	4310.724	-30	-23
EC-5	EC-3	05/03/94	4310.724	05/03/94	4310.723	-1	-24
EC-5	EC-6	04/25/90	2431.981			0	0
EC-5	EC-6	04/25/90	2431.981	04/26/90	2431.988	+7	+7
EC-5	EC-6	04/26/90	2431.988	04/27/90	2431.986	-2	+5
EC-5	EC-6	04/27/90	2431.986	06/26/90	2431.987	+1	+6
EC-5	EC-6	06/26/90	2431.987	05/22/92	2432.033	+46	+52
EC-5	EC-6	05/22/92	2432.033	05/03/94	2431.988	-45	+7
EC-5	EC-6	05/03/94	2431.988	05/03/94	2431.992	+4	+11

Table 6. Table of line-length changes and cumulative differences for Saipan EDM calibration line.

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
CD1	COCONUT	05/23/92	3063.365			0	0
CD1	COCONUT	05/23/92	3063.365	05/23/92	3063.371	+6	+6
CD1	COCONUT	05/23/92	3063.371	04/19/94	3063.346	-25	-19
CD1	COCONUT	04/19/94	3063.346	04/19/94	3063.346	0	-19
CD1	COCONUT	04/19/94	3063.346	04/19/94	3063.346	0	-19
CD1	COCONUT	04/19/94	3063.346	05/02/94	3063.322	-24	-43