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VOLCANOLOGIC INVESTIGATIONS IN THE COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS, MAY 1992

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ABSTRACT

U.S. Geological Survey volcanologists examined the ten volcanoes in the active Mariana Arc north of Saipan in May 1992, at the request of the Governor and the Disaster Control Office of the Commonwealth of the Northern Mariana Islands (CNMI). A shallow earthquake swarm on Anatahan in March-April 1990 and reports of possible new fuming on Agrigan in August 1990 had prompted the evacuation of all CNMI islands north of Saipan.

None of the volcanoes in the chain erupted during our visit. Five uninhabited islands (Farallon de Pajaros, Maug, Asuncion, Guguan, and Sarigan) were inspected only from the air, while the other four were studied in more detail.

The previously installed seismic stations on Anatahan, Alamagan, and South Pagan were upgraded. A new station was established at the southwestern base of the intermittently active Mount Pagan, on the northern end of Pagan Island. Portable seismometers were operated on Anatahan, Alamagan, Pagan, and Agrigan. The seismometers on Anatahan, Alamagan, and Agrigan recorded no local shallow earthquake swarms nor volcanic tremor indicative of shallow magmatic movement. On Mount Pagan, intermittent low-amplitude tremor indicated the continuing possibility of occasional small ash eruptions, which prior to our visit had been witnessed in April 1992. Ash eruptions resumed in February 1993.

Electronic distance measurement (EDM) lines were remeasured on Agrigan, Mount Pagan, and Anatahan. Line length changes were generally insignificant, in accord with the absence of significant shallow seismicity.

Hot spring waters were collected on Agrigan, Pagan, and Anatahan, and fumarole temperatures were measured on Agrigan, Pagan, Alamagan, and Anatahan. The temperature data showed no indication of an impending significant change in the state of these volcanoes.

We mapped the geology of Alamagan, collected charcoal to date eruptions of Alamagan and Mount Pagan, and collected rocks on Agrigan, Pagan, Alamagan, and Anatahan for petrographic and chemical studies.

We conclude that the low shallow seismicity, lack of significant deformation, and low fumarole temperatures suggest that no eruption is likely soon on Agrigan, Alamagan, or Anatahan. The persistent low-level volcanic tremor on Mount Pagan suggests that intermittent small explosive eruptions may continue to occur.

INTRODUCTION

At the request of the CNMI government, a USGS team consisting of geologists, seismologists, deformation experts, and electronic technicians visited CNMI (fig. 1) May 10-27, 1992. The team had several goals, all of which were accomplished: (1) assessment of the probability of eruption, especially on Agrigan, Pagan, Alamagan, and Anatahan; techniques employed were study of seismic records from permanent and portable stations, measurement of EDM lines, measurement of fumarole temperatures, and geologic observations; (2) reinforcement of the existing field seismic stations on South Pagan, Alamagan, and Anatahan; (3) installation of a new seismic station on Mount Pagan; and (4) geologic studies on Agrigan, Pagan, Alamagan, and Anatahan.

The normally populated islands Agrigan, Alamagan, and Anatahan were evacuated in August 1990 as a result of a shallow earthquake swarm on Anatahan in March-April 1990 and reports, which later proved erroneous (Moore and others, 1991), of increased fuming on Agrigan in August 1990. Except for brief visits by the authors, fishermen, and CNMI personnel, Pagan Island has been evacuated since the major Plinian eruption of Mount Pagan on May 15, 1981 (Banks and others, 1984). About ten residents returned to Agrigan during May 1992.

The volcanic islands that form part of the active Mariana Arc north of Saipan (fig. 1) are built 2-3 km above the East Mariana Ridge, which in turn rises about 2-4 km above the ocean floor. The >6-km-deep Mariana Trench adjoins the East Mariana Ridge on its east side, and the Mariana Trough, partly filled with young lava flows and volcaniclastic sediments, lies to the west of the East Mariana Ridge (Tanakadate, 1940; Hess, 1948; Karig, 1971; Karig and others, 1978; Banks and others, 1984). The submarine West Mariana Ridge, Tertiary in age (Kroenke and others, 1981), bounds the western side of the Mariana Trough. The Mariana Trench and East Mariana Ridge overlie an active subduction zone where the Pacific Plate, moving northwest at about 10.3 cm/year, is passing beneath the Philippine Plate, moving west-northwest at 6.8 cm/year (Simkin and others, 1989). Beneath the Northern Mariana Islands, earthquake hypocenters at depths of 50-250 km identify the location of the west-dipping subduction zone, which farther west becomes nearly vertical and extends to 700 km depth (Katsumata and Sykes, 1969). During this century, 36 earthquakes of magnitude 6.5-7.7 have occurred beneath the Mariana Trench. From January 1990-February 1992, nearly 400 earthquakes of magnitude >3.6 occurred below the Trench and East Mariana Ridge (National Earthquake Information Center, unpublished data, 1992).

The Mariana Islands form two parallel, concentric, concave-west arcs (fig. 1). The southern islands constitute the outer arc and extend northward from Guam to Farallon de Medinilla. They consist of Eocene to Miocene volcanic rocks and uplifted Tertiary and Quaternary limestone (G. Corwin, unpublished manuscript, 1971). The nine northern islands extend from Anatahan to Farallon de Pajaros and form the active inner arc. The inner arc extends south from Anatahan, where volcanoes, some of which are active, form seamounts west of the older outer arc (fig. 1; Karig, 1971; Stern and Bibee, 1984). Other volcanic seamounts of the active arc surmount the East Mariana Ridge north of Farallon de Pajaros (Karig, 1971). The ten volcanoes that form nine islands along the active inner arc are spaced an average of about 42 km apart; distances between volcanoes range from 10 km between South Pagan and Mount (North) Pagan to 92 km between Agrigan and Asuncion.

No volcanoes along the active inner Mariana Arc erupted during our visit. Five (Farallon de Pajaros, Asuncion, Agrigan, Mount Pagan, and Guguan) have erupted during this century (Tanakadate, 1940). Oral reports and photographs by CNMI personnel indicate that Mount Pagan resumed intermittent eruptive activity on February 13, 1993. These small ash eruptions apparently are continuing at this writing (July 1993).

This report summarizes the results of our visit and includes several recommendations to the CNMI government about monitoring seismic activity. A condensed summary of this report was published in Moore and others (1992).

SEISMIC EVALUATION OF THE NORTHERN MARIANA ISLANDS, MAY 1992

Introduction

The May 1992 seismic survey of the Northern Mariana Islands included (1) evaluation of data provided by the National Earthquake Information Center (NEIC), U.S. Geological Survey, from the Worldwide Seismograph Network; (2) field monitoring of Anatahan, Alamagan, Pagan, and Agrigan with portable seismographs; (3) upgrading of radio-linked permanent seismometer stations on Anatahan, Alamagan, and South Pagan; and (4) installation of a new test station near the active Mount Pagan.

Regional seismicity

Data from the Worldwide Seismograph Network indicate persistent seismicity along the Mariana Trench, in the region between longitude 144°-150°E and latitude 11°-21°N (fig. 2). From January 1990 to February 1992, 398 earthquakes of magnitude 3.6 to 7.5 were recorded and processed for location (table 1). Many of these earthquakes were aftershocks of the strong magnitude 7.5 earthquake on April 5, 1990, located about 150 km east of Saipan. Consequently, the total number of earthquakes per month peaked at 150 events in April 1990 and has gradually decreased since then (fig. 3). There was a minor increase of earthquakes on Agrigan in 1991 and 1992. The regional seismicity was low near Pagan and Alamagan. The high seismicity on Anatahan that caused concern in 1990 decreased to low levels in 1991 and 1992.

The magnitude distribution from the worldwide data file indicates a peak at about magnitude 4.5-5.0, which suggests that the data are complete above about magnitude 5.0 (fig. 4). However, effective monitoring of volcanic seismicity requires detection of earthquakes of magnitude 2.0 or less, which means that high sensitivity seismographs must be installed on these volcanic islands in order to detect these smaller earthquakes.

Between 1902 and 1990, there were 36 potentially hazardous earthquakes of magnitude larger than 6.5 in the Northern Mariana Islands region. Rates of occurrence for these events varied during those 88 years (fig. 5, top). From 1902 to 1930, the rate was low, averaging 1.3 events per decade. From 1930 to 1967, the rate increased to an average of 6.6 events per decade. During 1967 to 1990, the rate decreased to 1.5 events per decade. The overall average of M>6.5 events for the 88 years is four per decade. Seventeen M>7.0 earthquakes occurred during those 88 years, averaging two events per decade (fig. 5, bottom).

Local seismicity

Portable seismographs were operated for periods of one to several days on Anatahan, Alamagan, Pagan, and Agrigan, in order to detect small earthquakes that may be more relevant to possible volcanic activity than the occasional large earthquakes recorded by the NEIC regional network stations. The number of earthquakes and episodes of volcanic tremor were low at Anatahan (fig. 6), Alamagan, and Agrigan (fig. 7); the seismic data indicate no immediate threat of a volcanic eruption. On Pagan, there is intermittent low-amplitude tremor, indicating magmatic movement that might result in occasional ash and gas emissions from Mount Pagan (fig. 8).

As part of our long-term effort to build a remote sensing seismic system for CNMI, the field seismometer stations on Anatahan, Alamagan, and South Pagan were upgraded, and a new test station was installed at the southwestern base of Mount Pagan to monitor the low-level volcanic activity continuing there since the 1981 eruption (table 2; fig. 9). A new portable seismograph and test instruments were added to the CNMI inventory of volcano monitoring equipment. The seismic signals from the northern islands will continue to be monitored alternately on two portable seismographs at the Disaster Control Office, until critically needed permanent recorders are purchased by CNMI and development of the seismic laboratory can be implemented. Radio frequencies and field instrument identifications and specifications are outlined in table 3.

Seismic summary and recommendations

1. Studies of regional seismicity from 1990 to early 1992 and portable seismograph operations conducted in May 1992 indicate no immediate threat of major volcanic activity on Anatahan, Alamagan, and Agrigan. On Mount Pagan, there has been occasional low-level tremor that indicates the possibility of minor ash eruptions. We advise caution when approaching the active vent. Debris flows from the accumulated volcanic ash would be an added problem during heavy rainfall.
2. Continuously recording seismographs provide the most basic means of detecting an enhanced possibility of volcanic activity. Precursory activity characteristically includes increases in the number of small earthquakes and episodes of volcanic tremor. The residents of the northern islands should learn to recognize locally felt earthquakes and keep notes on their times and effects. At least one portable seismograph should be operated continuously at the principal village on each island. One responsible resident should be assigned the task of maintaining the daily operation of the portable seismograph; this person should learn to interpret the characteristic seismic signals of earthquakes and volcanic tremor. The seismograph operation could also encourage awareness of earthquake and volcanic hazards among the residents, and provide the basic tool and incentive for local students to study earth science in the Mariana Islands. Even more important is the systematic development of a remote sensing seismic telemetry system with signals recorded centrally at the Disaster Control Office on Saipan. This system would improve the Office's effectiveness in assessing potential volcanic activity and large earthquakes that may cause tsunamis and structural damage. Instrumental recording of the times and strengths of earthquakes that occur constantly along the Mariana Islands would furnish the quantitative data base necessary to better understand volcanic eruptions and strong earthquakes in this region. CNMI should acquire three more portable seismographs with companion seismometers, such as the PS-2 seismograph and L-4 seismometer routinely used by the Disaster Control Office, to be operated on each of the inhabited islands. Purchase of this equipment by CNMI ideally should be completed this year.
3. The Mariana Islands lie along an active subduction zone in the earth's crust and are affected by persistent large tectonic earthquakes, as well as intermittent volcanic activity. Emergency communication and evacuation procedures for residents of the northern

islands are necessary. Because many of the island people spend considerable time on the seacoast, they need advance warning of pending tsunamis or suspected volcanic activity. When residents feel an earthquake strong enough to prevent them from standing or when buildings start to collapse, they should immediately move to high ground and away from the danger of high sea waves; there may not be sufficient time for warnings of locally generated tsunamis to be issued by the Disaster Control Office. People should also move away from unstable buildings or steep cliffs that are subject to collapse from the strong shaking. Large earthquakes of magnitude 7 or greater result in numerous aftershocks during the subsequent weeks, some of which may be strong enough to cause tsunamis and damage to structures. The 7.5-magnitude earthquake in April 1990 was followed by nearly two months of intense aftershock activity. If this event had been located closer to Saipan, the effects of the main shock as well as the aftershocks would have been significant.

4. Training programs for operating seismographs and interpreting seismograms should be continued. Seismologists and technicians at the Hawaiian Volcano Observatory and the University of Hawaii's Center for the Study of Active Volcanoes could offer training in Hawaii or Saipan, in addition to programs available at CNMI educational institutions.

GEOLOGIC STUDIES AND EDM SURVEYS

Introduction

In this section we describe geologic observations and the results of geophysical and EDM surveys, where conducted, on each of the nine islands in the active arc north of Saipan. The islands are described in order from north to south.

Farallon de Pajaros (also known as Uracas or Uracus)

When viewed from the fixed-wing airplane on May 13, 1992, Farallon de Pajaros (fig. 1) was fuming vigorously, but was not erupting. The level of fuming appeared to be lower than shown on photographs taken by CNMI personnel in August 1990 (Moore and others, 1991), but any slight change in fuming could be related to weather conditions. Since it lies at the northern end of the island chain about 400 km from Saipan, Farallon de Pajaros is observed only intermittently and any low-level eruptive activity might be missed. Farallon de Pajaros has erupted several times during this century; the most recent known eruption occurred in 1953 (Kuno, 1962).

Maug

No steaming or other indications of recent or impending volcanic activity were visible from the fixed-wing airplane on May 13. Maug (fig. 1) has not erupted during historic time (Tanakadate, 1940).

Asuncion

Vigorous steaming was occurring at several locations in Asuncion's (fig. 1) summit crater on May 13. This activity probably is residual in nature and related to the most recent eruption of Asuncion in 1906 (Tanakadate, 1940).

Agrigan (also spelled Agrihan) (fig. 1)

Remeasurement of the five EDM lines (figs. 10 and 11) on May 15-16 showed no significant changes since September 1990. Line length changes are all less than 1 cm (table 4). Two seismometers temporarily operated on the caldera floor recorded no local shallow seismicity.

The temperature of the boiling hot spring in the solfatara area (fig. 10a) was 98°C, the same as in 1990 (Moore and others, 1991). The volume of water issuing from the spring was less than in 1990, but this phenomenon may be related to seasonal variations in rainfall. The highest fumarole temperature measured was 102°C, 4°C higher than in 1990, but this slight increase may be related to the lower water table.

An experiment using a geophysical instrument that receives a Very-Low Frequency (VLF; 15-25 kHz) radio signal was carried out across the solfatara area on the caldera floor on May 16. A traverse striking about S50°E (fig. 10a) was run perpendicular to the incoming signal transmitted from Northwest Cape (NWC), Australia (bearing about S40°W from Agrigan), to try to determine the size of the heat source and depth to its upper surface. A sizable anomaly was measured (fig. 12), and a preliminary model was derived using only the tilt angle. The model suggests that the top of the mass of hot rock is approximately 23.5 m below the surface; the mass has a width of about 53 m and length of 265 m. The conductivity of this body is about 1 ohm-m; the body is surrounded by rock having a ground conductivity of approximately 1000 ohm-m.

The team also collected previously unsampled rocks from the caldera walls and floor. Agrigan erupted most recently in 1917 (Tanakadate, 1940). Future eruptions may be expected, but the absence of shallow earthquakes and measurable inflation of the volcano indicate that no activity is likely in the immediate future.

Pagan

Mount Pagan, on the northern part of the island (figs. 1 and 13), continues to show signs of unrest, although it did not erupt during our visit from May 13-21. As noted above in the seismic section of this report, seismic activity is dominated by short bursts of long-period earthquakes and volcanic tremor. The highest temperature measured at a steaming fumarole was 76°C, but we have no previous data from the same area. Solfataras that are probably hotter are inaccessible deep within the summit crater. On the basis of observations over nine days, fuming from the crater was episodic, marked by periods of high SO_2 outgassing followed by quiescence.

Remeasurement of the two remaining EDM lines, PAGAN 1 to NOSE and RIDGE (the other reflectors have been destroyed by eruptions and debris flows), showed that no significant change in EDM line lengths occurred between 1983 and 1990, a period characterized by occasional small to larger ash eruptions (table 5; figs. 13 and 14). Our latest survey also shows no significant changes in EDM line lengths between September 1990 and May 1992. Measurements during our visit show no large line length changes over a period of three days. The lack of recent deformation does not necessarily suggest that the intermittent low-level eruptive activity is declining. Possibly, because there are no large long-term deformation changes, the volcanic conduit may be open (suggested by the absence of shallow seismicity apart from the volcanic tremor), and the two reflector sites may be located too far from the magma source to detect any significant changes. Measurements from PAGAN 1 to MID reflector (table 6), located closer to the magma source high on the flank of Mount Pagan, showed very large changes before MID was destroyed.

A new reflector, BILLYGOAT (fig. 13a), was installed on the southwestern rim of the summit crater of Mount Pagan (see Appendix for the station description). No significant line length changes between PAGAN 1 and BILLYGOAT were found during three days of measurements (table 5; figs. 13b and 14). If BILLYGOAT can survive ash eruptions and debris flows, it may prove to be more useful than the lower reflectors in monitoring deformation of Mount Pagan.

Three charcoal samples were collected for radiocarbon dating (Meyer Rubin, written communication, 1993). One sample, from the western part of the southern caldera rim, occurs in soil beneath a basaltic andesite a'a flow that underlies pyroclastic-flow deposits emplaced immediately prior to caldera collapse. Its age is 10,780±200 years B.P.; Mount Pagan's caldera, therefore, is somewhat younger. The other two charcoal samples are from within pyroclastic-flow deposits erupted by the modern Mount Pagan. Their ages are 600±89 and 370±60 years B.P.

South Pagan volcano, which has not erupted during historic time, shows no shallow seismicity. Steam was observed in a few areas near the summit, but no temperature measurements were made.

Alamagan

We mapped the geology of Alamagan (fig. 1) during this visit (Moore and Trusdell, in press A and B). We observed several steaming areas near the summit; one near the seismic station had a measured temperature of 72°C. Alamagan has had no eruptions during historic time. The two most recent eruptions, which both produced extensive pyroclastic-flow deposits, have been dated by radiocarbon at 1,077±87 and 1,410±80 years B.P. (Meyer Rubin, written communication, 1992). Pyroclastic-flow deposits underlie about two-thirds of Alamagan. As noted in the seismic section of this report, no shallow earthquakes nor volcanic tremor have been recorded on the Alamagan seismic station since its installation in September 1990.

Guguan

Observations of Guguan (fig. 1) from the fixed-wing airplane on May 13 and from the helicopter on May 21 showed no steam or fume, although we did not land. Guguan erupted in 1901 and produced an ash deposit and lava flows (Tanakadate, 1940).

Sarigan

Like Guguan, observations of Sarigan (fig. 1) from the fixed-wing airplane on May 13 and from the helicopter on May 21 showed no steam or fume, although we did not land. Sarigan has had no historic eruptions (Tanakadate, 1940).

Anatahan (fig. 1)

Remeasurement of the EDM network (figs. 15 and 16; table 7) on May 22 showed small line length changes across the eastern crater. Line lengths from EC-1 to EC-4 and EC-5, spanning the western crater, showed changes of about 20 mm since October 1990; these changes also are relatively small and in accord with the lack of shallow seismicity. Since April 27, 1990, slightly larger cumulative changes have been measured between the reflector (EC-6) near the southwestern coast across the western part of the caldera to the breach on the northwestern caldera rim (reflector EC-4). Between EC-5 and EC-4 about 29 mm of extension occurred, and between EC-5 and EC-6 about 46 mm of extension were measured (figs. 15 and 16; table 7). Possibly, this extension occurred soon after the April 27, 1990, survey at a time when the seismograph signal from Anatahan was not being recorded on Saipan. The largest extensions have occurred on the western section of the caldera, not where the active solfataras, fumaroles, and boiling ponds are located.

The team sampled hot water in small ponds, several of which were boiling vigorously, on the floor of the eastern crater. The maximum temperature of the ponds as well as fumaroles and solfataras at the base of the nearby crater wall was 98°C.

Anatahan has had no historic eruptions (Tanakadate, 1940), although a shallow earthquake swarm there in March-April 1990 prompted evacuation of its residents.

Saipan (fig. 1)

An EDM permanent-glass reflector calibration line was established on Saipan to make sure that the infrared gun was working properly. The line may be used to compare results if different types of EDM guns are used for future surveys. Table 8 presents the measured line lengths. The calibration line is described in the Appendix to this report.

GEOCHEMISTRY

Table 9 presents a partial chemical analysis, obtained from a private laboratory, of Agrigan hot spring water collected in September 1990 (Moore and others, 1991). This water had a pH of 2.0 and a temperature of 98°C. Reservoir geothermometer temperatures calculated from these data (A.H. Truesdell, written communication, 1991) range from 253°C to 264°C. These temperatures, along with the VLF data reported above, suggest that an exploitable geothermal resource exists in Agrigan's caldera. However, the caldera floor is accessible only by helicopter.

We recollected the hot spring water in Agrigan's caldera for additional chemical analysis. We also sampled the boiling hot springs in Anatahan's eastern crater, as well as water from a small lake that has covered hot springs about 1.5 km northwest of the summit of Mount Pagan. Analysis of these samples is in progress.

RECOMMENDATIONS

1. Since the 1990 earthquake swarm on Anatahan has subsided, only Mount Pagan is of immediate concern. The existing EDM lines on Mount Pagan should be measured frequently, and additional gun stations and reflectors should be installed on all flanks of the volcano in order to monitor deformation changes.

The EDM networks on Agrigan and Anatahan should also be measured frequently, since residents have returned to Agrigan and may return to Anatahan. Ideally, EDM networks and seismic stations should be installed on all of the potentially active volcanoes in the Northern Mariana chain.

2. Reconnaissance geologic studies have been carried out on Agrigan, Pagan, Alamagan, Sarigan, and Anatahan, but more work is needed on all these islands. Farallon de Pajaros, Maug, Asuncion, and Guguan have not been studied at all. In particular, the eruption frequency on each island in the chain is unknown, and any plans for development of the northern islands should consider this information. The geology team suggests that Guguan and Asuncion, both of which erupted this century, should be the targets of our next concentrated work.

ACKNOWLEDGMENTS

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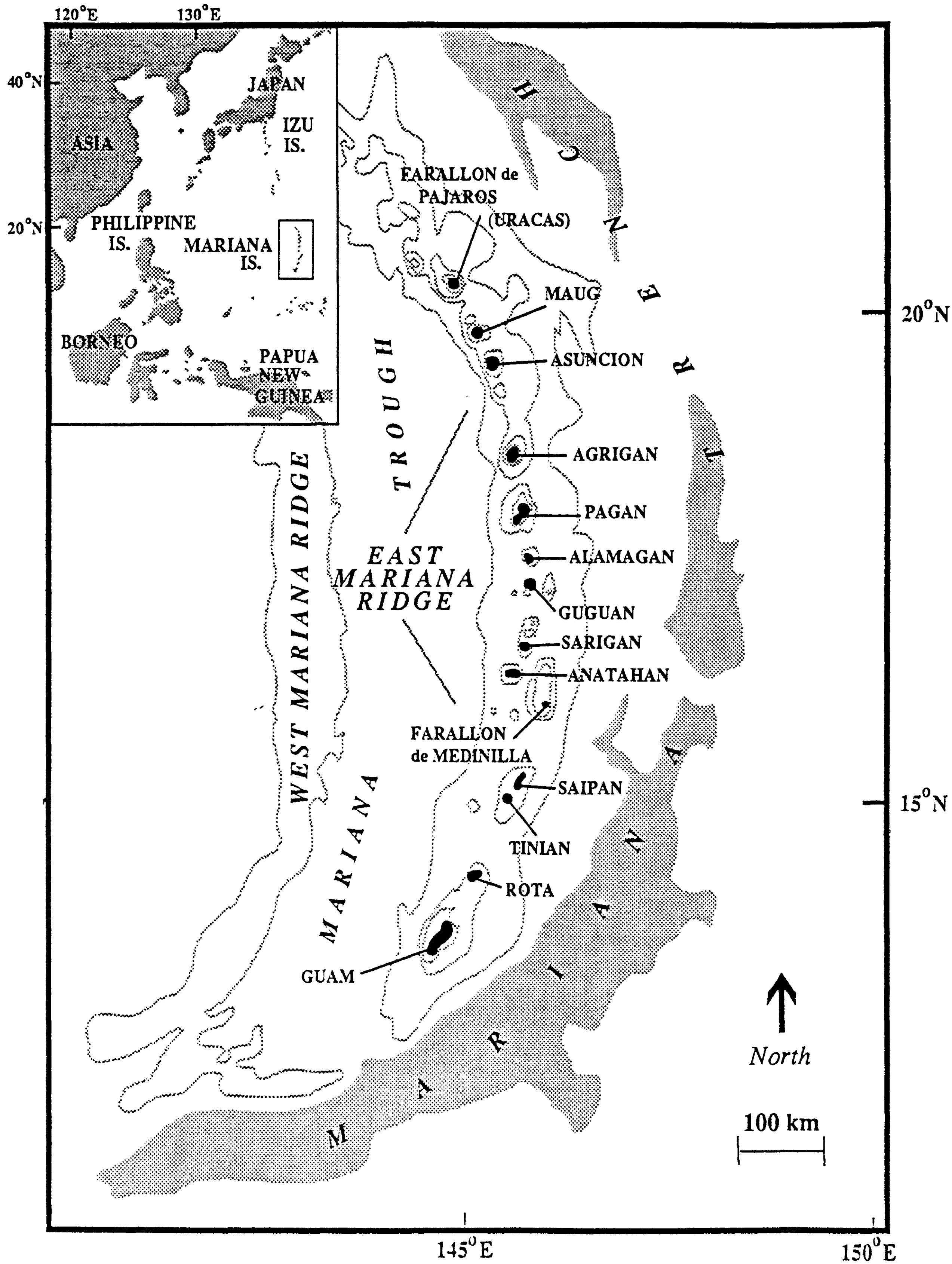


Figure 1. Regional index map of the Mariana Islands. The Commonwealth of the Northern Mariana Islands extends from Farallon de Pajaros to Rota. Volcanic islands of the active Mariana Arc extend from Farallon de Pajaros to Anatahan.

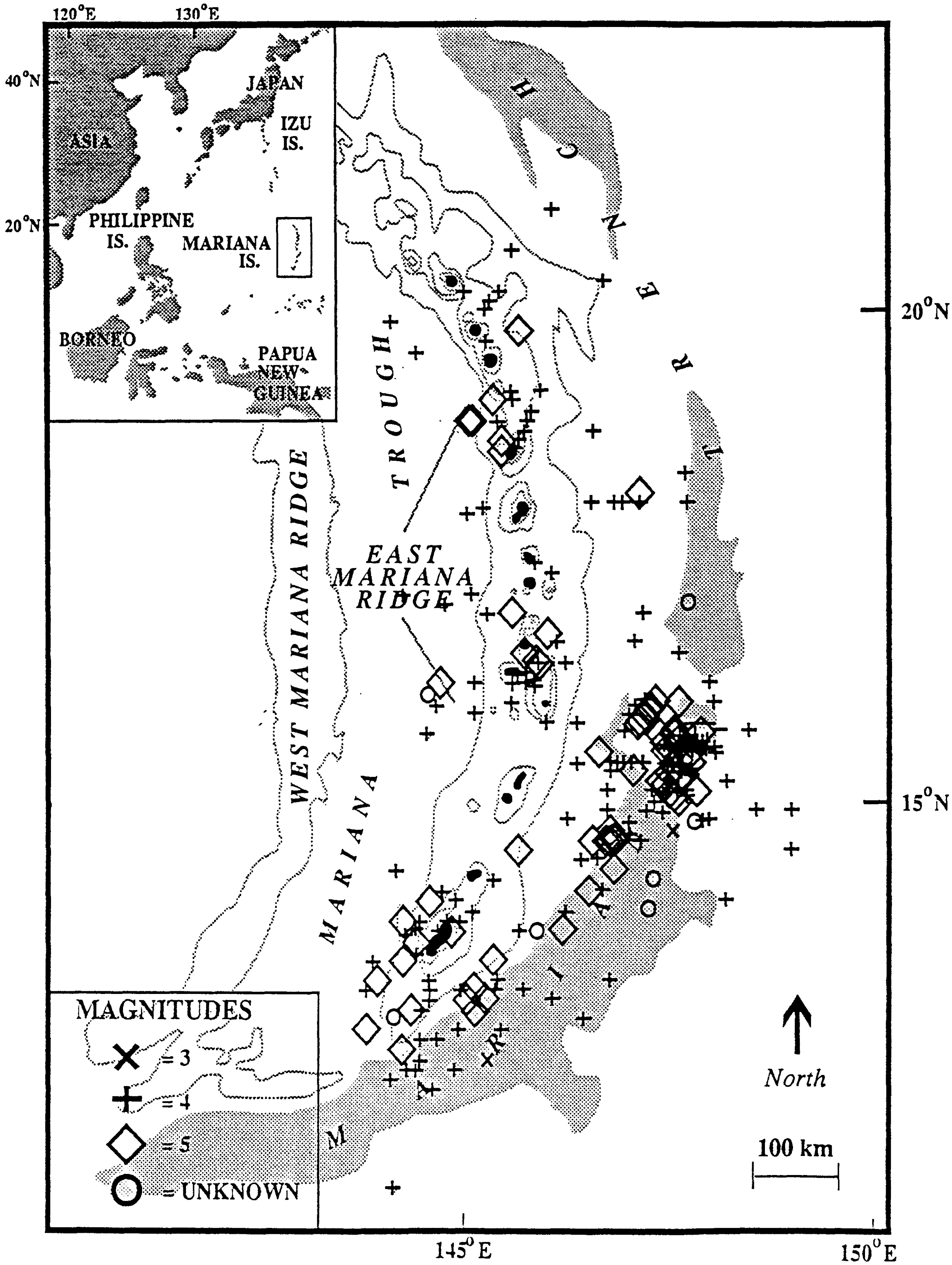
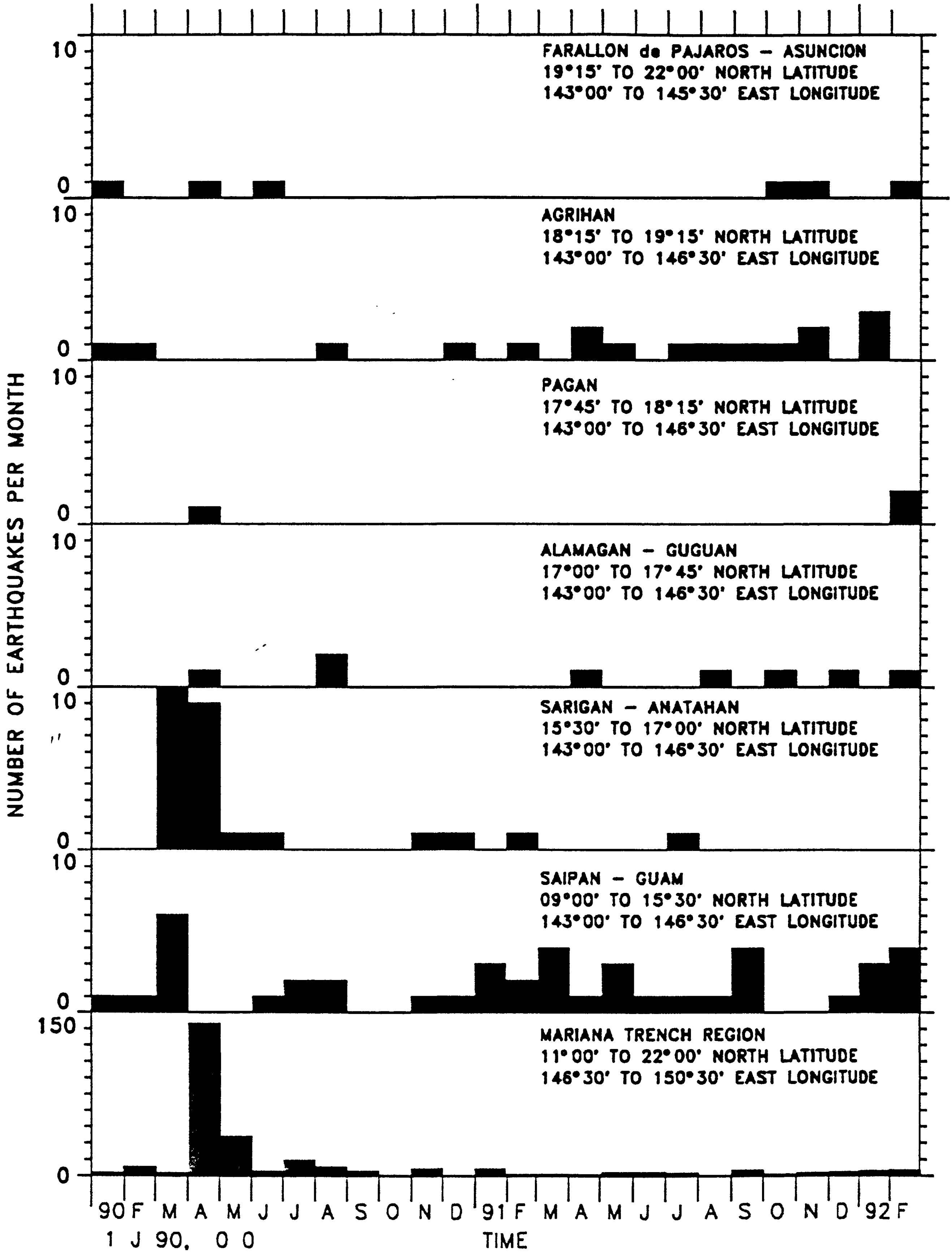


Figure 2. Earthquake locations in the Mariana Islands, January 1990-February 1992.

Figure 3. Monthly number of earthquakes, Mariana Islands region, January 1990-February 1992.



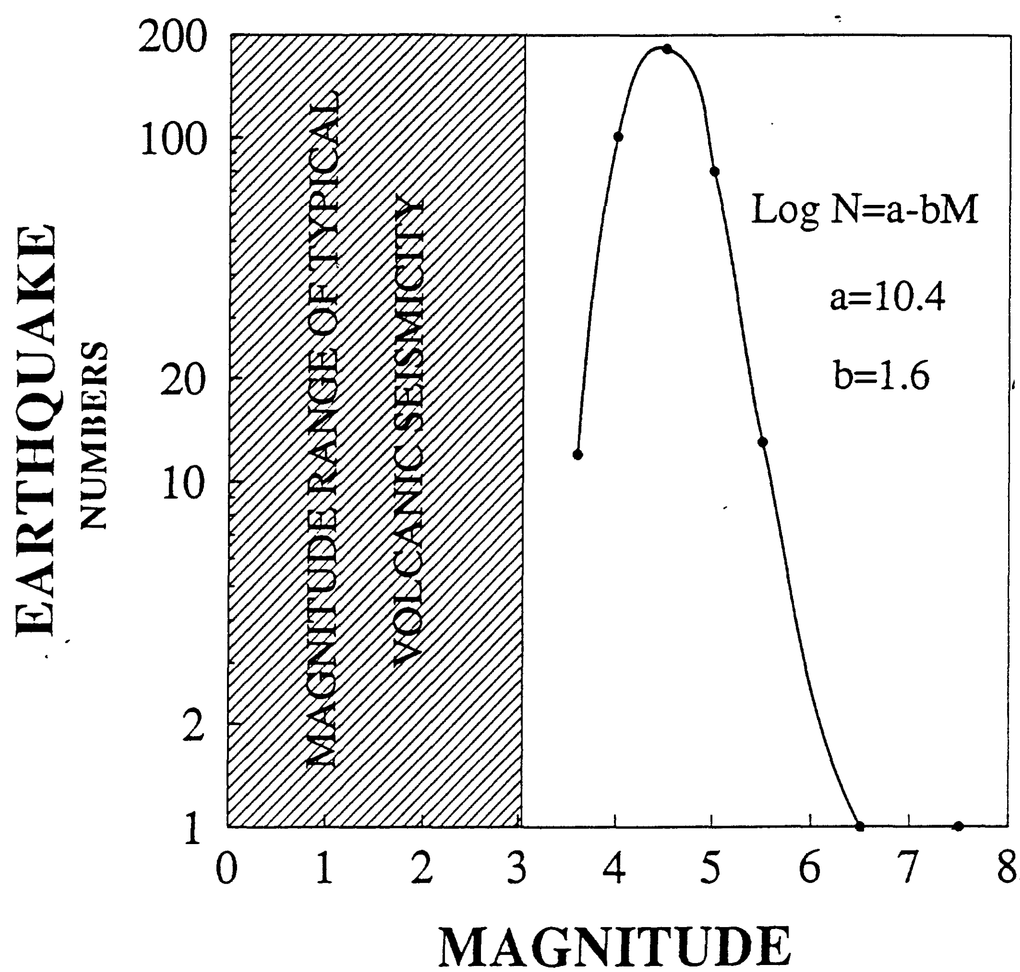


Figure 4. Magnitude-frequency distribution of earthquakes, Mariana Islands region, January 1990-February 1992. Data from National Earthquake Information Center, U.S. Geological Survey.

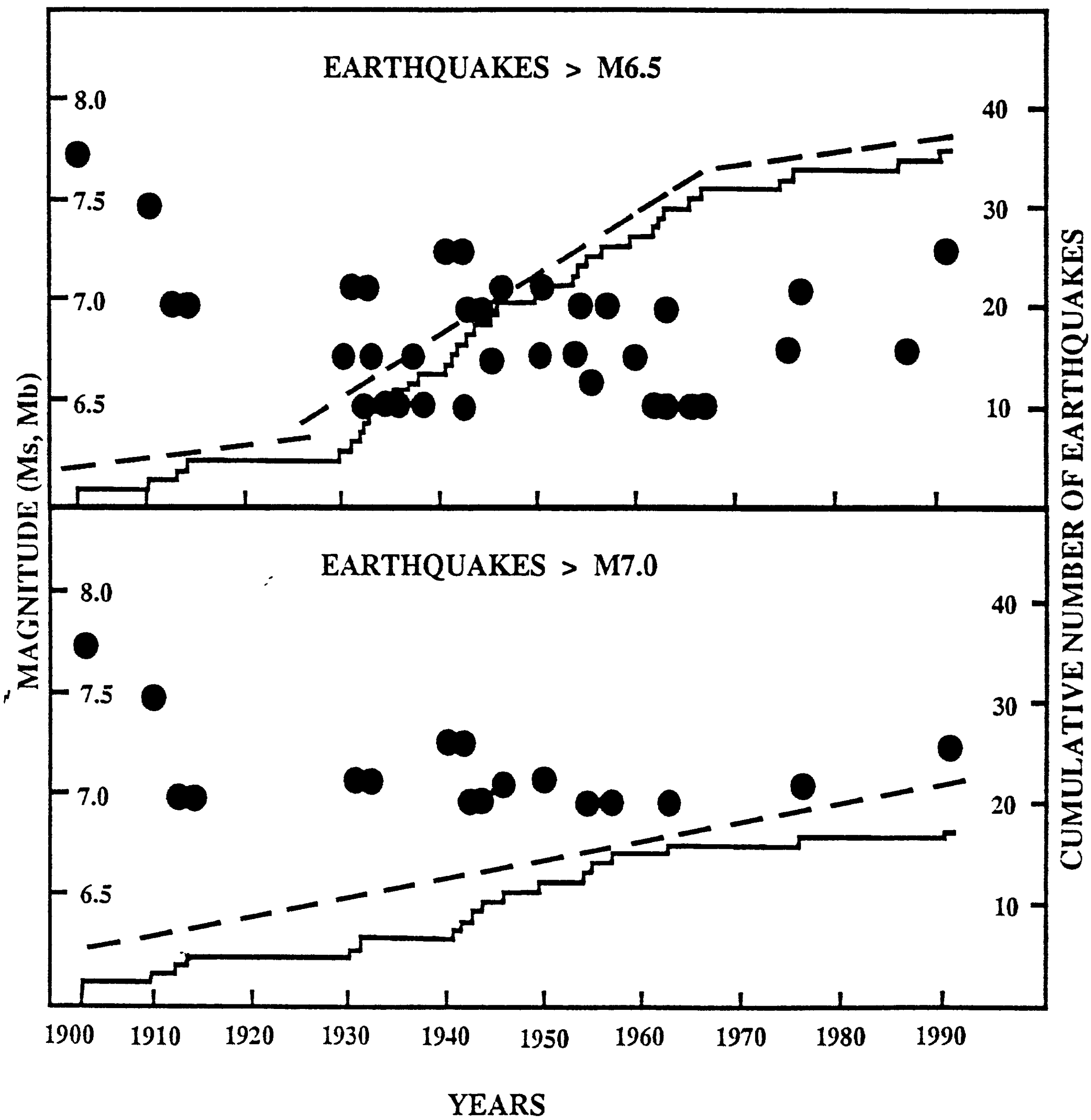


Figure 5. Earthquakes >M6.5 in the Northern Mariana Islands region during 1902-1990.

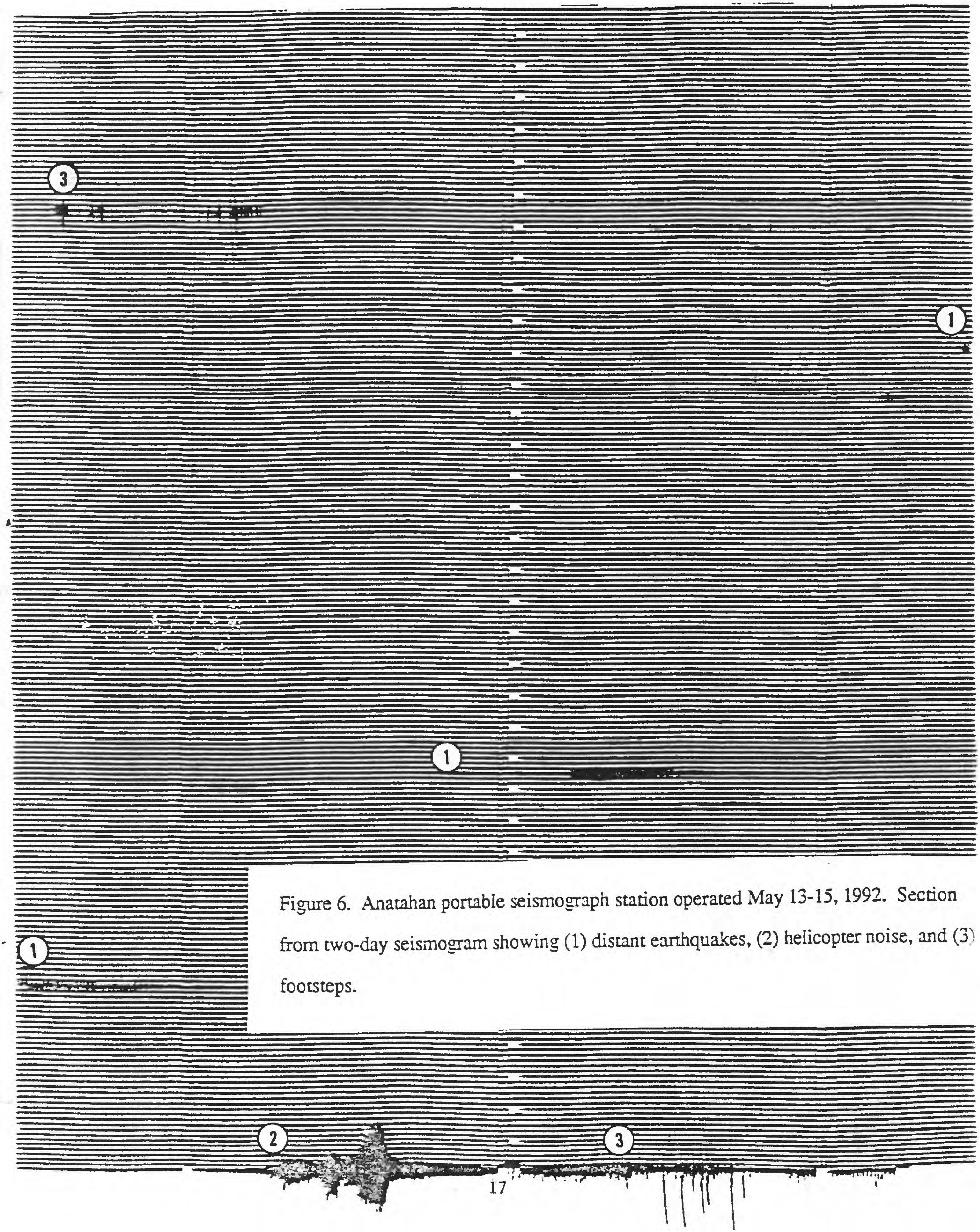


Figure 6. Anatahan portable seismograph station operated May 13-15, 1992. Section from two-day seismogram showing (1) distant earthquakes, (2) helicopter noise, and (3) footsteps.

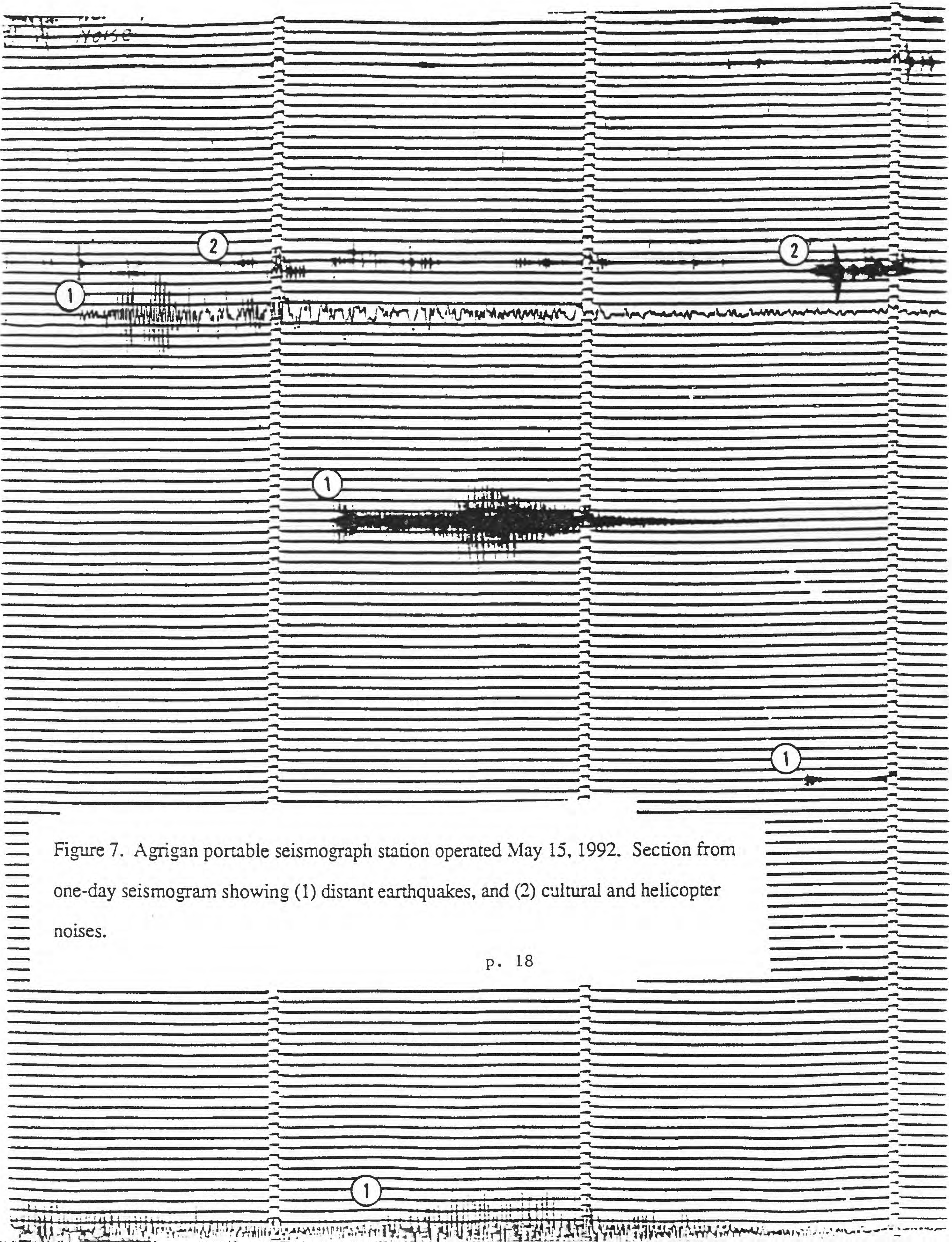


Figure 7. Agrigan portable seismograph station operated May 15, 1992. Section from one-day seismogram showing (1) distant earthquakes, and (2) cultural and helicopter noises.

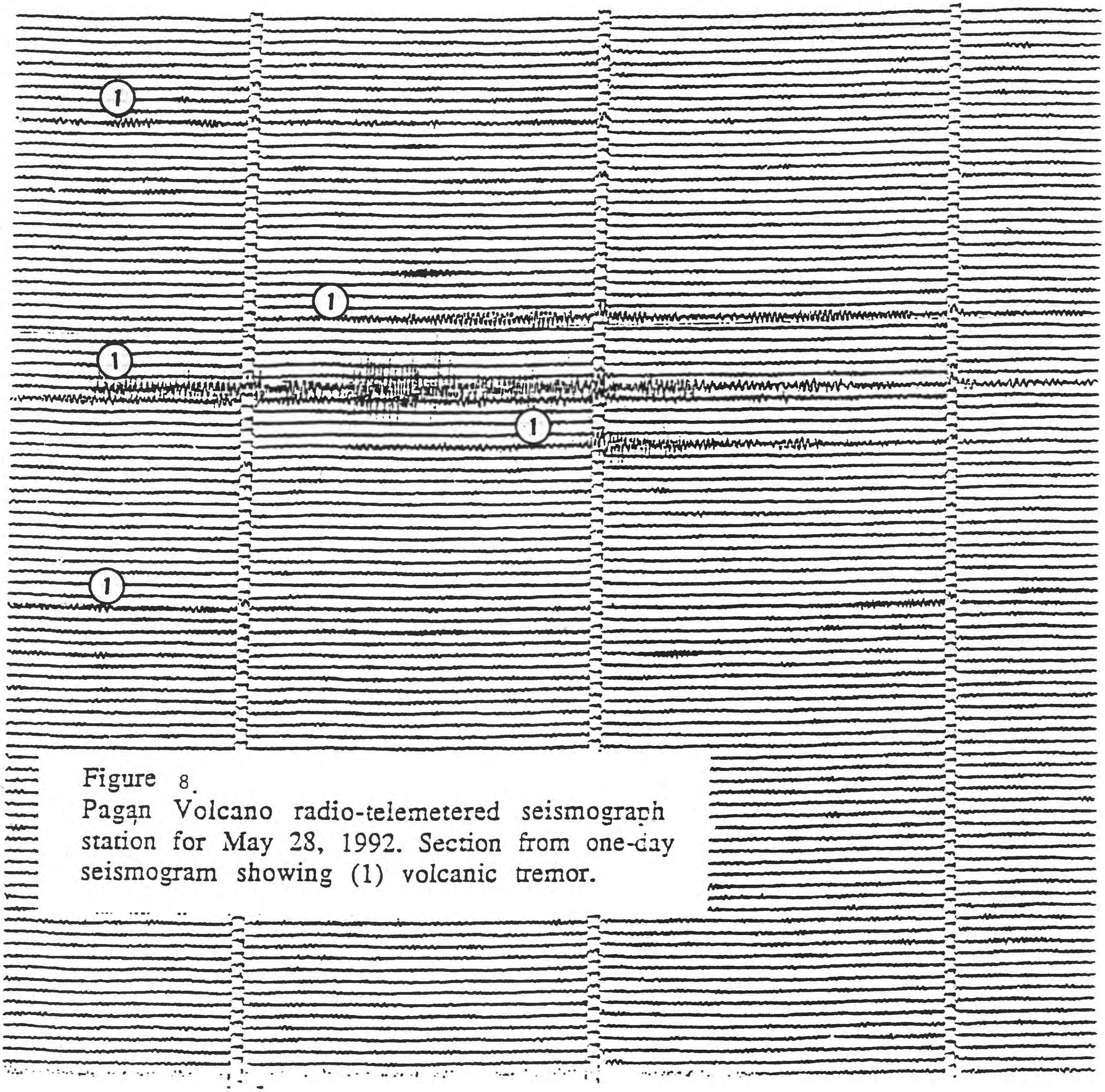


Figure 8.
Pagan Volcano radio-telemetered seismograph station for May 28, 1992. Section from one-day seismogram showing (1) volcanic tremor.

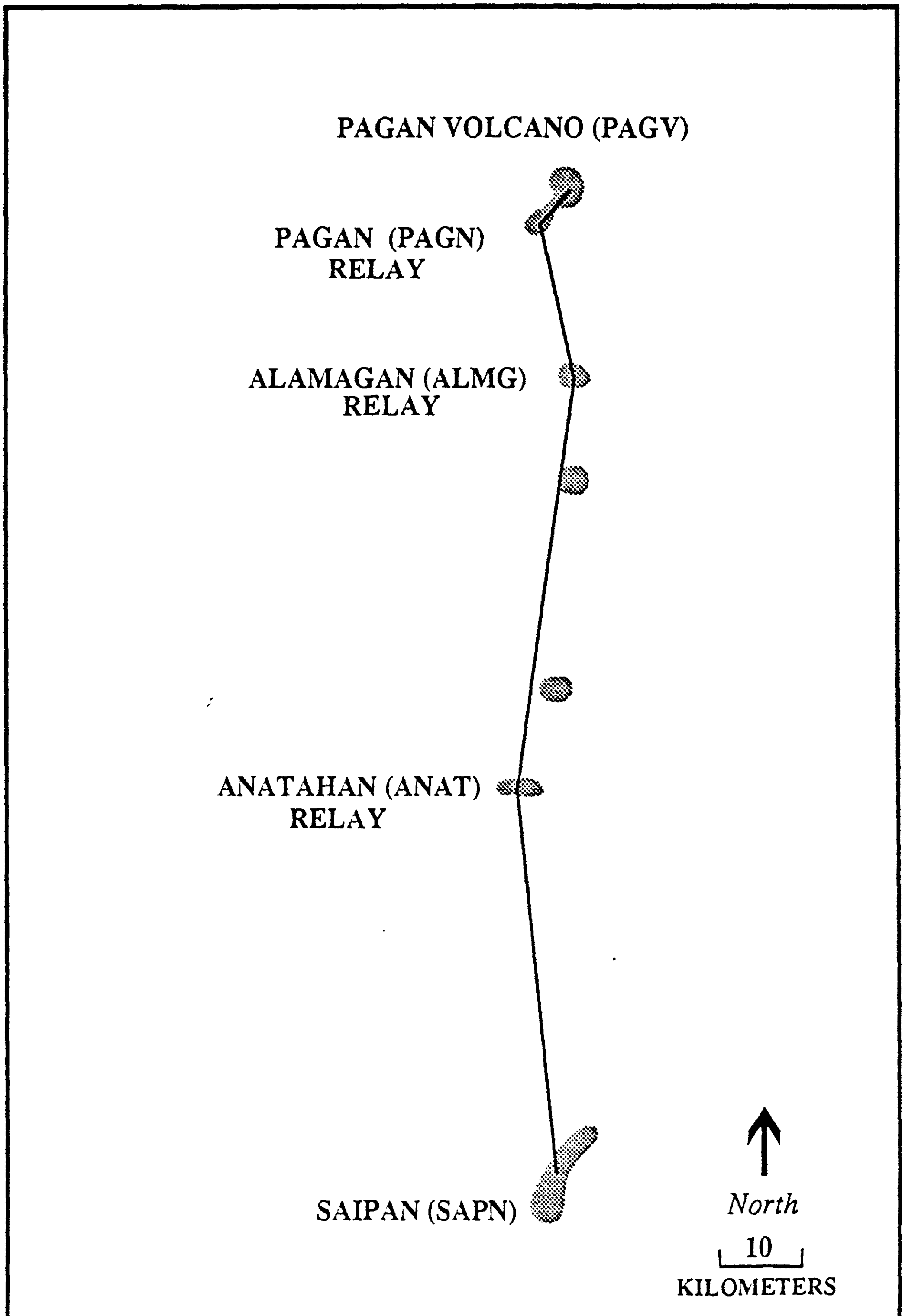


Figure 9. Location and configuration map of the CNMI radio-telemetry seismic network.

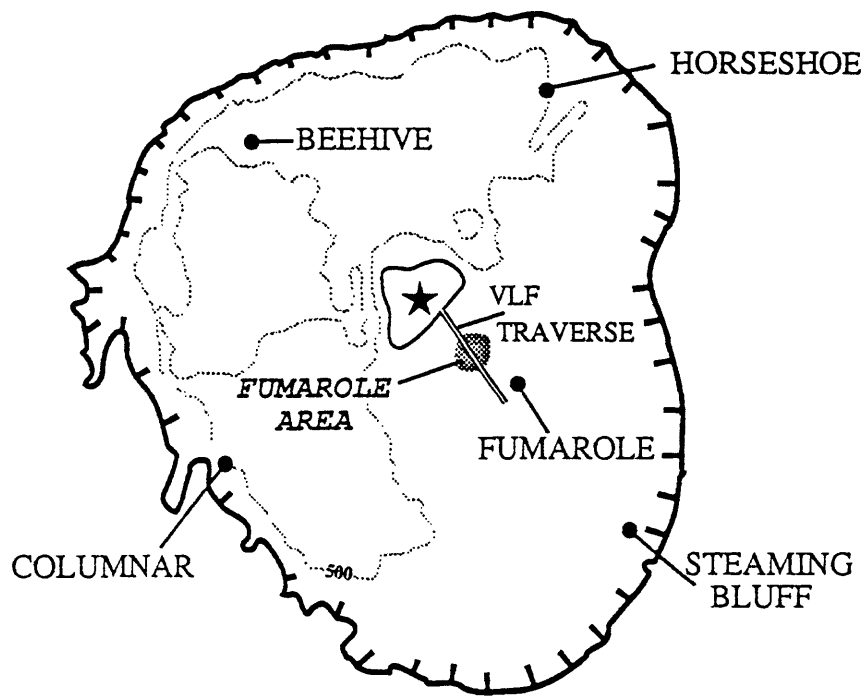


Figure 10a. Location of the VLF traverse, EDM permanent-glass reflectors, EDM gun station Central Cone, and the solfatara area in Agrigan caldera. Dotted line is the 500-m elevation contour.

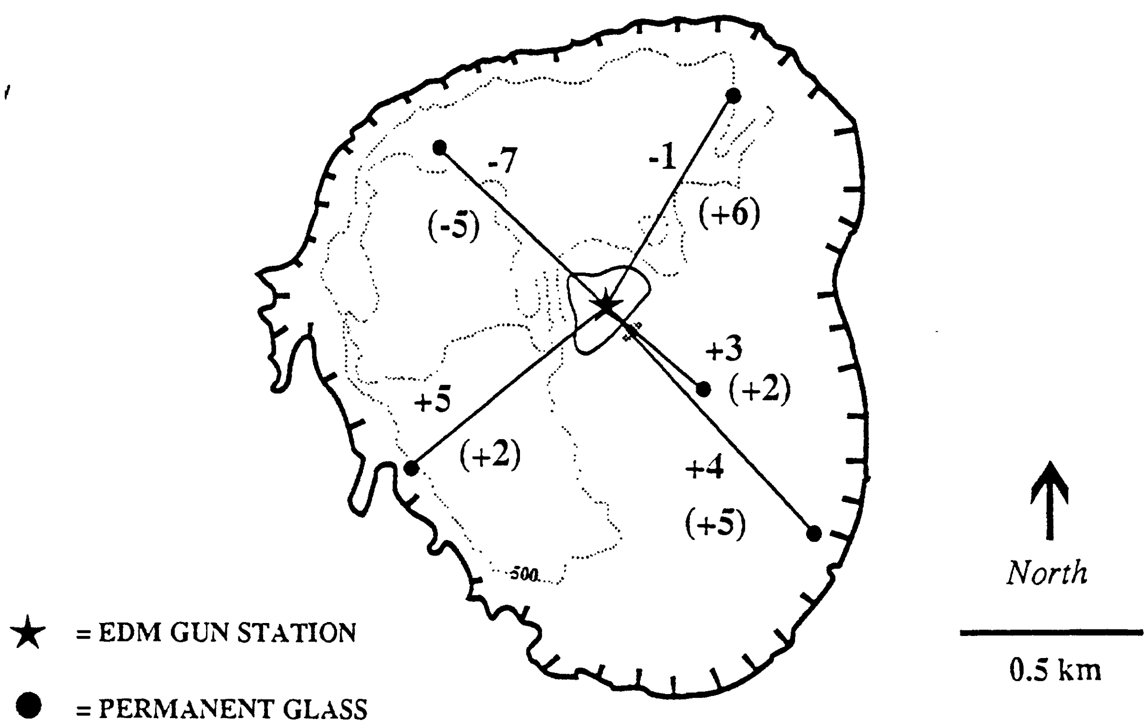


Figure 10b. EDM line length differences (mm) in Agrigan caldera between October 1990 and May 1992. Numbers in parentheses are cumulative differences.

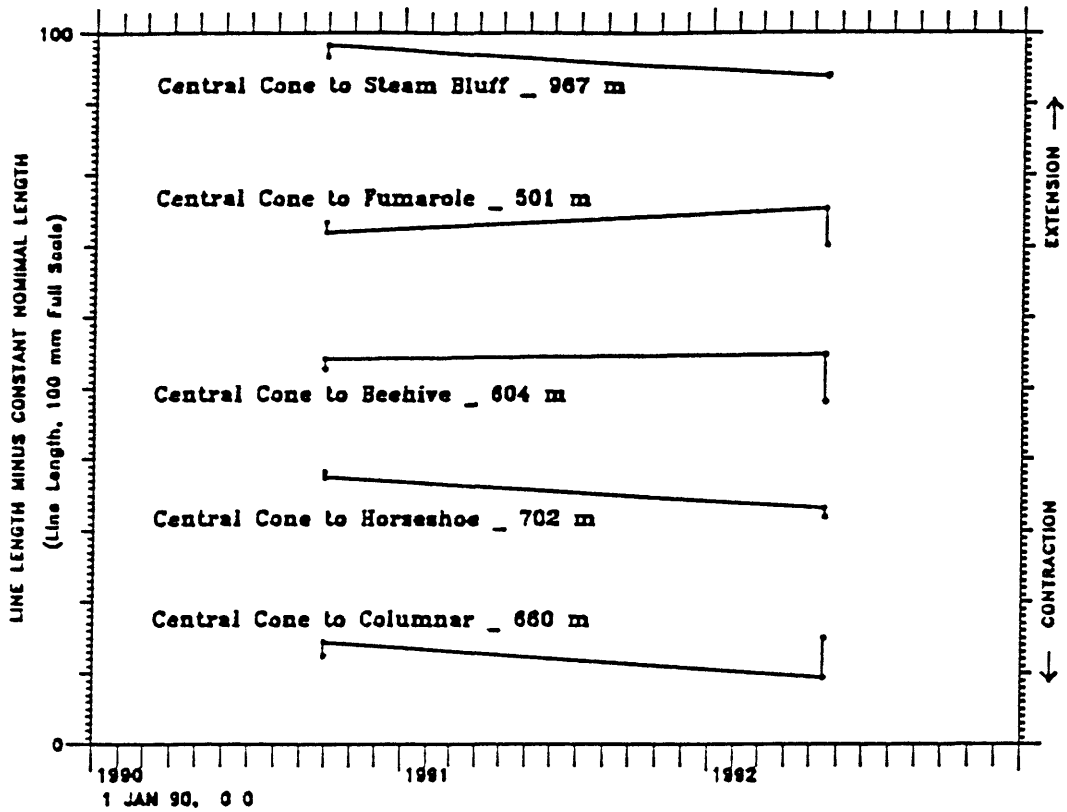


Figure 11. Time-series plot of Agrigan caldera permanent-glass EDM monitor lines.

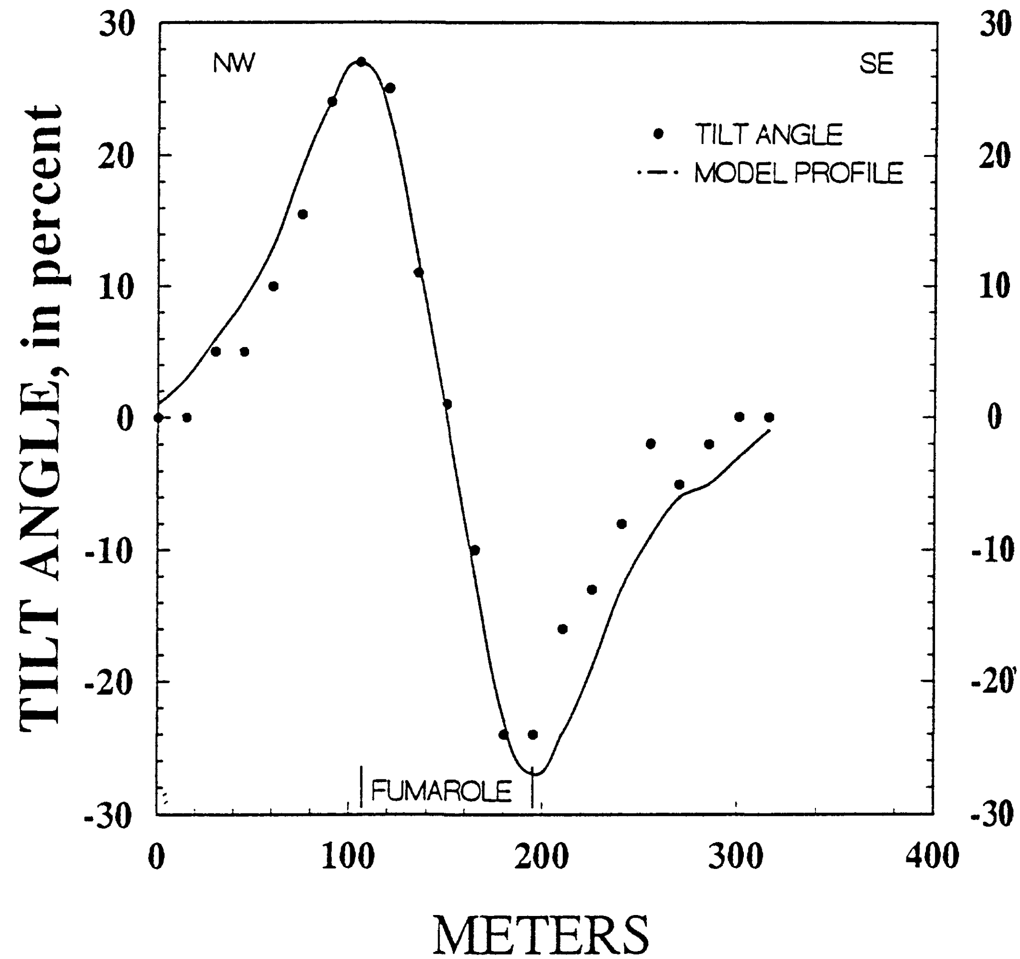


Figure 12. Profile of the VLF traverse across the solfatara area in Agrigan caldera.

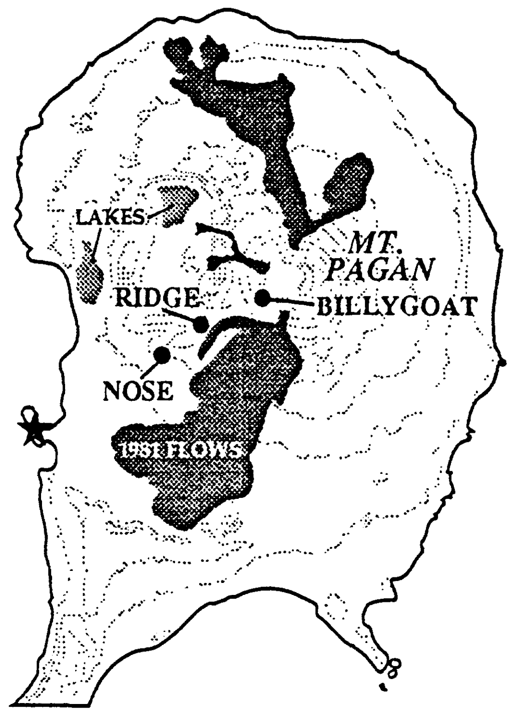


Figure 13a. Location map of EDM permanent-glass reflectors, EDM gun station PAGAN 1, and water sampling sites on Mount Pagan.

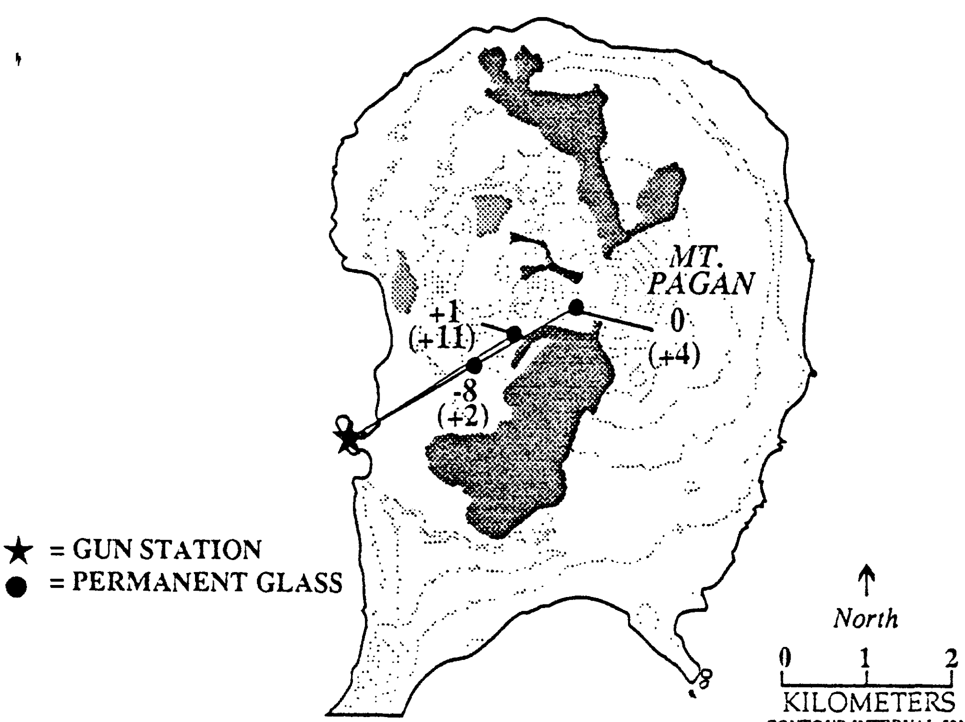


Figure 13b. Map of EDM differences (mm) for Mount Pagan between October 1990 and May 1992 (numbers in parentheses are cumulative differences).

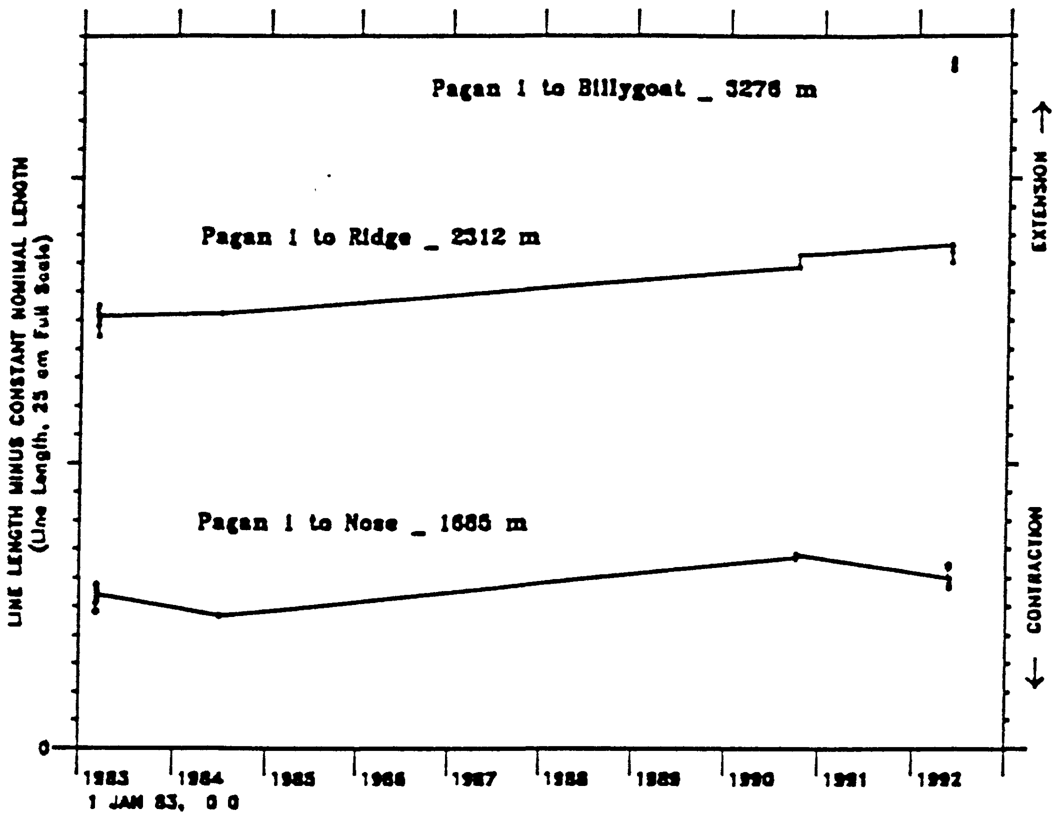


Figure 14. Time-series plot of Mount Pagan southwest permanent-glass EDM monitor lines.

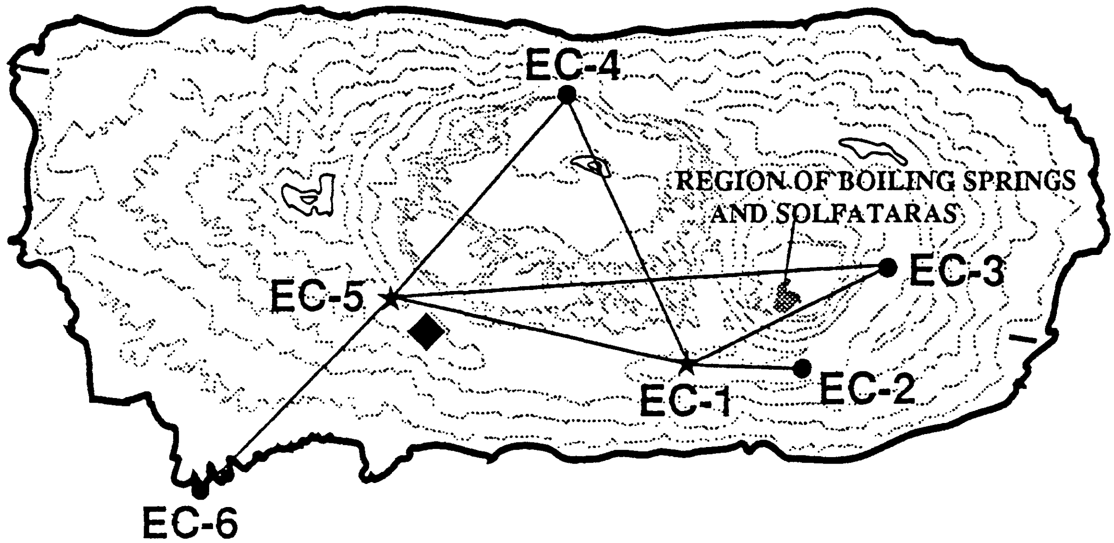


Figure 15a. Location map of the EDM network, boiling springs, and solfataras in Anatahan caldera. Contour interval is 100 m.

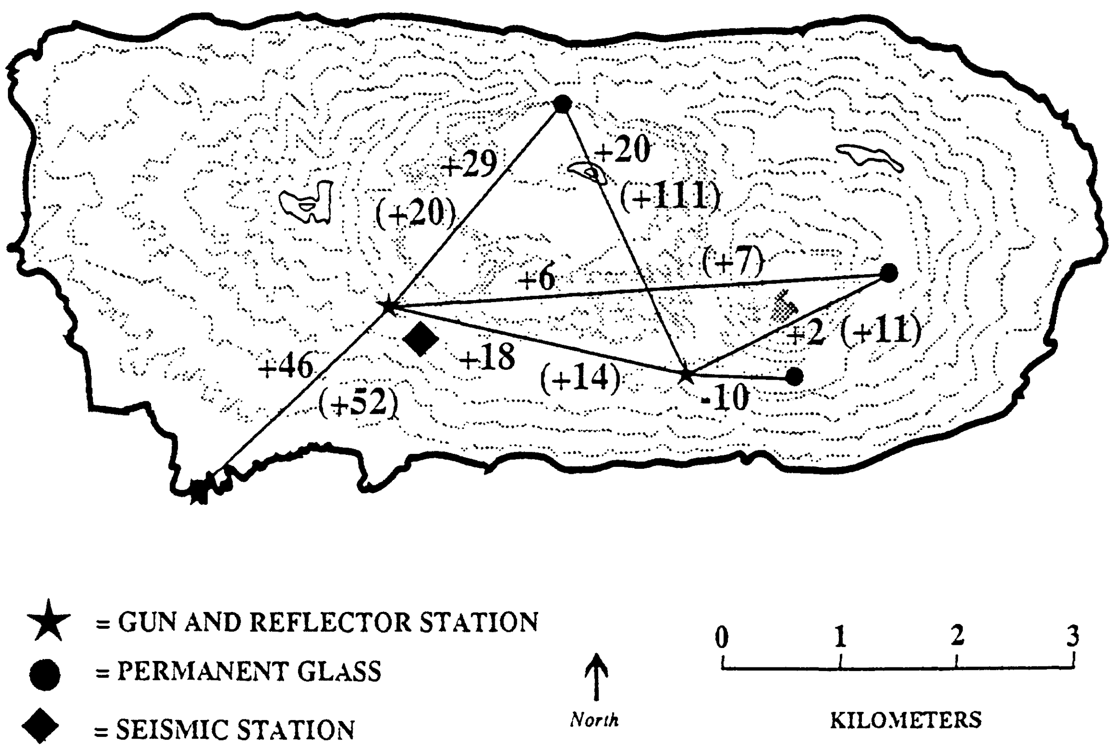


Figure 15b. Map of EDM differences (mm) for Anatahan caldera between October 1990 and May 1992 (numbers in parentheses are cumulative differences).

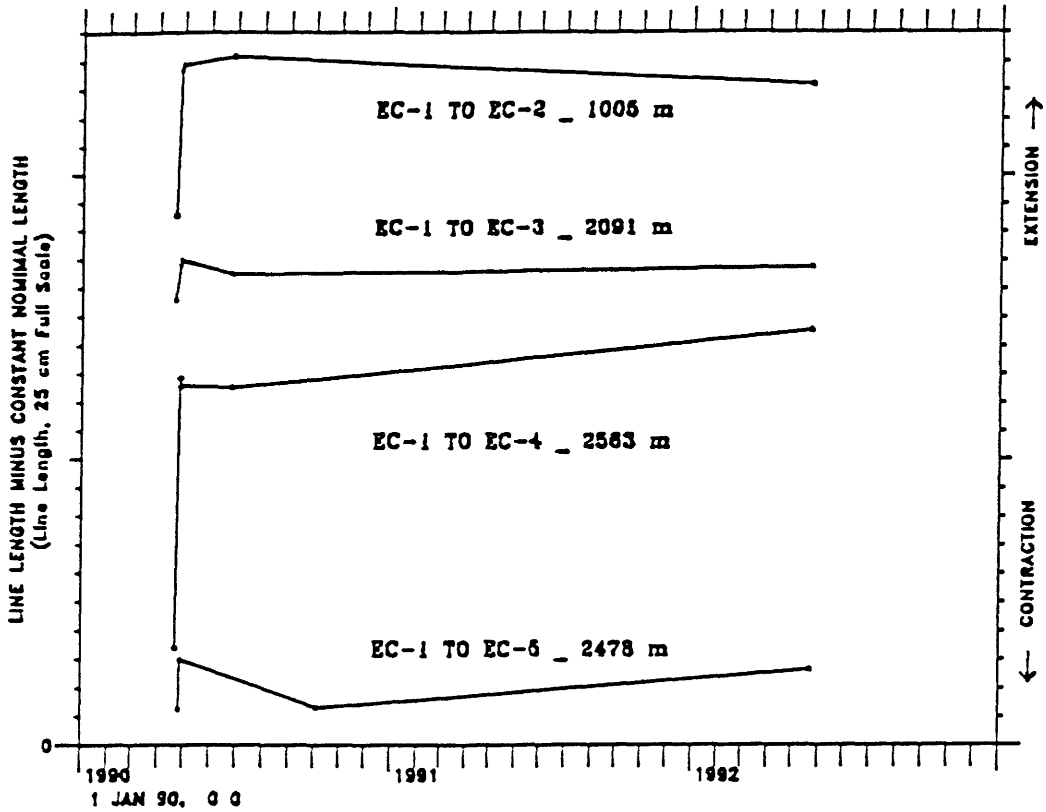


Figure 16a. Time-series plot of Anatahan caldera permanent-glass EDM monitor lines (lines measured from instrument station EC-1).

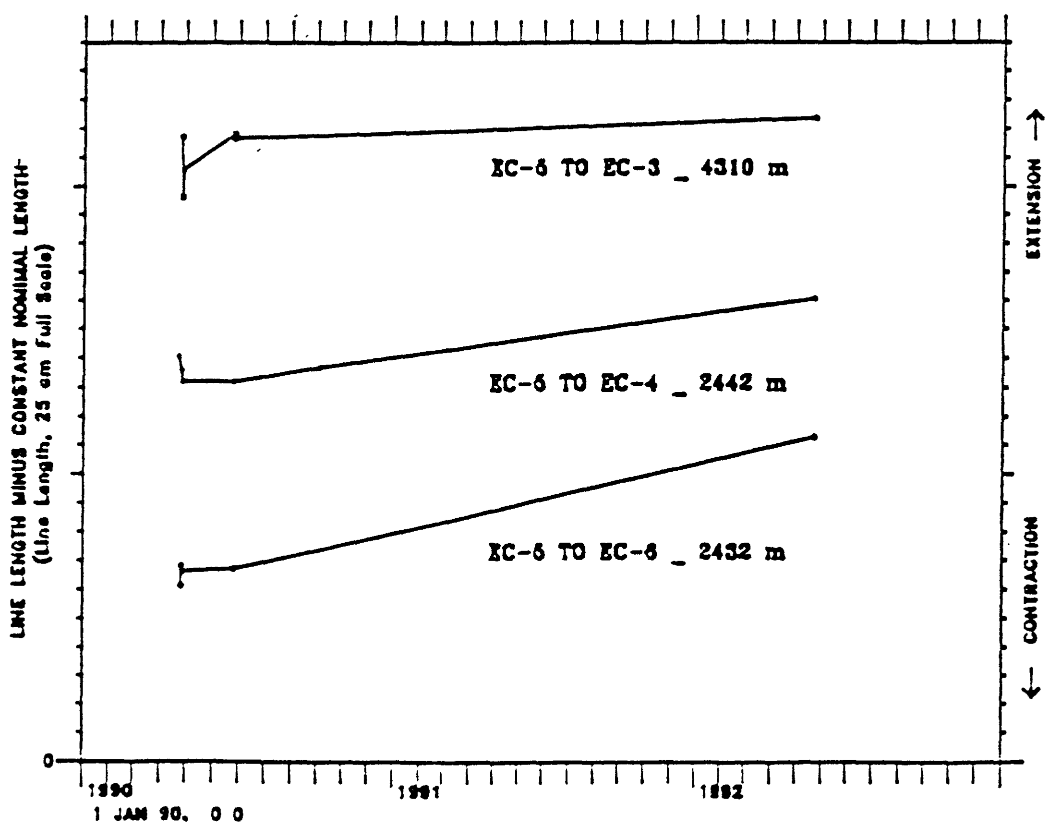


Figure 16b. Time-series plot of Anatahan caldera permanent-glass EDM monitor lines (lines measured from instrument station EC-5).

Table 1. Magnitude-frequency distribution of earthquakes in the Commonwealth of the Northern Mariana Islands between 11°-21° N-lat. and 144°-150° E-lon., January 1990 to February 1992.

Magnitude (Mb, Ms)	Number of Earthquakes
3.6	4
3.7	2
3.8	1
3.9	5
4.0	9
4.1	15
4.2	11
4.3	31
4.4	35
4.5	32
4.6	41
4.7	34
4.8	39
4.9	37
5.0	31
5.1	22
5.2	11
5.3	12
5.4	4
5.5	6
5.6	2
5.7	2
5.8	2
5.9	1
6.5	1
7.5	1

Table 2. CNMI seismic station locations (coordinates and elevations) and four-letter code name. SAIPAN COLLEGE is run by Northern Marianas College as part of its earth science program and is not part of the regular seismic network.

ANATAHAN (ANAT)
Location: 16.353° north latitude, 145.656° east longitude
Elevation: 510 m

ALAMAGAN (ALMG)
Location: 17.601° north latitude, 145.838° east longitude
Elevation: 490 m

PAGAN (PAGN)
Location: 18.075° north latitude, 145.731° east longitude
Elevation: 540 m

PAGAN VOLCANO (PAGV)
Location: 18.125° north latitude, 145.770° east longitude
Elevation: 10 m

SAIPAN CD (SAPN)
Location: 15.207° north latitude, 145.748° east longitude
Elevation: 250 m

SAIPAN COLLEGE
Location: 15.150° north latitude, 145.716° east longitude
Elevation: 100 m

Table 3. Instrument specifications for USGS/CNMI radio-telemetered seismic stations, May 1992.

No.	Station	MHZ	Type	Subcarrier			VCO	Seismometer	
1	ANAT/SAPN	164.009375	MON	1234	.17	36 db	J402	L-4	#7682
2	ALMG/ANAT	166.659375	MON	234	.30	36 db	J402	L-4	#7511
3	PAGN/ALMG	167.1968	MON	34	.30	36 db	J402	L-4	#7509
4	PAGV/PAGN	165.8062	MON	4	.16	36 db	J402	L-4	#9346

All radios are 0.1 watt; horizontal Yagis; RF-3=164.009375, RF-5=165.809375, RF-7=166.659375; 25 watt solar panel with one 50 AHr. lead acid battery per station; other northerly stations should repeat through South Pagan.

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	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	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	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

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

Table 4. Line lengths, line length changes, and cumulative differences for Agrigan caldera permanent-glass EDM network.

Southwest Mt. Pagan EDM Monitor

Ins. Stn.	Refl. Stn.	1st Survey Date	Dist. (m)	2nd Survey Date	Dist. (m)	Diff. (mm)	Cumulative Diff. (mm)
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
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	2312.009	+16	+21
PAGAN 1	RIDGE	09/30/90	2312.009	10/01/90	2312.013	+4	+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	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

Table 5. Line lengths, line length changes, and cumulative differences for the Mount Pagan southwestern permanent-glass EDM monitor.

South Mt. Pagan Permanent-glass EDM Monitor Line

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	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
INS	MID	05/22/81	2192.809				0
INS	MID	05/22/81	2192.809	05/24/83	2192.801	-8	-8
INS	MID	05/24/81	2192.801	05/24/83	2192.801	-0	-8
INS	MID	05/24/81	2192.801	05/25/83	2192.808	+7	-1
INS	MID	05/25/81	2192.808	05/07/83	2192.804	-4	-5
INS	MID	05/26/81	2192.804	05/07/83	2192.801	-3	-8
INS	MID	05/27/81	2192.801	05/07/83	2192.807	+6	-2
INS	MID	05/28/81	2192.807	05/07/83	2192.546	-261	-263
INS	MID	03/07/83	2192.546	03/13/83	2192.541	-5	-268

Table 6. Line lengths, line length changes, and cumulative differences for the Mount Pagan south permanent-glass EDM monitor (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)
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-2	EC-3	04/20/90	1456.202			0	0
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-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-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	10/01/90	2442.097	-5	-14
EC-5	EC-4	10/01/90	2442.097	05/22/92	2442.131	+34	+20
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-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-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	2478.039	-21	-4
EC-1	EC-5	10/04/90	2478.039	05/22/92	2478.057	+18	+14

Table 7. Line lengths, line length changes, and cumulative differences for the Anatahan EDM network.

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				
CD1	COCONUT	05/23/92	3063.365	05/23/92	3063.371	+6	+6

Table 8. Line lengths, line length changes, and cumulative differences for the Saipan EDM calibration line.

Table 9. Partial chemical analysis of water from the boiling hot spring on the Agrigan caldera floor. All values in parts per million.

SiO_2	721
Al	5.5
Fe	9.48
Mn	5.62
As	2.92
Ca	20.3
Mg	20.91
Sr	0.018
Ba	0.044
Na	916
K	168
Li	0.56
Rb	0.66
Cs	0.1
SO_4^{-2}	1700
Cl	945.3
F	8

Appendix

Descriptions of new EDM gun and permanent glass reflector sites

Station Name: *BILLYGOAT*
Latitude: 18.1422°N
Longitude: 145.7884°E
Elevation: 500 m

Station Description: *BILLYGOAT* is located on the summit of Mount Pagan along the outer southwest rim of the crater approximately 100 m from the edge of the pit crater. The station is a 3/4" diameter rebar painted fluorescent yellow-green, pounded ~1.2 m into the ash with two permanent glass reflectors attached to it. The reflectors are held in place by two brass clamps with 1/2" diameter holders. This station replaces *STEEP* reflector station which was located on the slope of the volcano and was destroyed by erosion. This reflector site will be used as part of the WSW Mount Pagan permanent glass monitor. The angle from *PAGAN 1* to *BILLYGOAT* is ~N68°E and barely above the skyline.

Station Name: *CD-1*
Latitude: 15.1856°N
Longitude: 145.7410°E
Elevation: 466 m

Station Description: *CD-1* is a standard U.S. Geological Survey brass bench mark cemented into solid limestone stamped CD-1, 1992. This bench mark is an instrument site located on the summit of Mt. Tapochau, Saipan and will be used as part of an EDM calibration line. This line has two purposes: 1.) to insure that the instrument is working properly after the plane trip and 2.) because almost all instruments have different instrument constants, we would be able to obtain the differences between the two instruments so comparisons of line lengths would be comparable to the EDM instrument being presently utilized.

To get to the station from the Emergency Operation Center, take the road that heads uphill in a southwesterly direction for ~3.3 km (~2.0 mi). Stay on the main road until you reach the summit of Mt. Tapochau (lots of radio antennas on the top of the ridge). Climb the ridge near the statue of Jesus Christ. The station is located about 1.5 m north of the statue in limestone. The direction to the reflector station *COCONUT* is N25°E (sight toward the right of and slightly above the TTPI headquarters building).

Station Name: *COCONUT*
Latitude: 15.2108° N
Longitude: 145.7525° E
Elevation: 205 m

Station Description: *COCONUT* is a permanent glass reflector station located on the grounds of the government legislative complex. This reflector is shot from instrument station *CD-1* as part of a calibration monitor for the EDM instrument. The station is a 3/4" rebar painted fluorescent yellow-green pounded into the ground ~1.2 m, with one brass clamp for a 1/2" stud attached to it. The rebar is located next to the third coconut tree from the end as you approach the station from the parking lot for the Mariana Land Survey Offices in the back of the TTPI headquarters building.