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# Scientific results of the VSI-USGS cooperative volcanological program: January 1982 to June 1982

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## ABSTRACT

A variety of scientific studies related to the monitoring of active volcanoes were conducted from January to June 1982 in Indonesia. These studies, sponsored by the U. S. Agency for International Development (USAID), were part of a cooperative program between the Volcanological Survey of Indonesia (VSI) and the U. S. Geological Survey (USGS). During this six month period, a compilation of the geophysical and geochemical data collected at Merapi Volcano over the past six years was completed. In addition, a gravity survey was conducted over a 400 square kilometer area centered on Merapi. The method of monitoring active volcanoes by precise gravity measurements was initiated at Merapi, Tangkuban Prahu, and Kelut Volcanoes. Observations were conducted during the initial two months of eruptive activity at Galunggung Volcano, beginning in April 1982. Electronic distance measurements were also initiated at this volcano.

## INTRODUCTION

A cooperative program in volcanological studies has been undertaken by the Volcanological Survey of Indonesia (VSI) and the U. S. Geological Survey (USGS) in an effort to upgrade the Indonesian capability to assess potential hazards associated with volcanic activity and to introduce a variety of monitoring techniques which may provide forewarning of an imminent eruption. The U. S. Agency for International Development (USAID) has provided the in-country support for this project and the funds to purchase equipment for use in Indonesia and to train VSI personnel. This training has been conducted both within the United States and within Indonesia by several USGS specialists on short-term assignments.

This report details the scientific results of one short-term assignment in Indonesia. This assignment, originally intended to last from January to April 1982, was planned to focus primarily on establishment of a modern volcano observatory at Merapi Volcano in central Java (figure 1). On April 5, 1982, Galunggung Volcano in west Java began a sequence of explosive eruptions. At the request of the Indonesian government, this assignment was extended for an additional two months in order to assist in monitoring the ongoing eruptive activity at Galunggung.

Merapi Volcano was selected as the focal point for in-country training because of its recent history of frequent eruptive activity. It is intended that the monitoring techniques introduced at Merapi would be further developed and applied by VSI to other volcanoes within Indonesia.

A summary of activity at Merapi during the initial three months of this assignment is given in the appendix. A compilation of existing monitoring data for Merapi, initiated by Chris Newhall, was continued during this assignment with emphasis placed on a re-evaluation of the seismic records available for Merapi. In addition to this compilation, the technique of monitoring active volcanoes by repeated microgravity readings was introduced at Merapi. Because of limitations imposed by the lack of easy ground access to the summit region, sites selected to illustrate the gravity monitoring technique at Merapi were limited to the region around the base of the volcano. A gravity survey covering four hundred square kilometers centered on Merapi was also conducted to complement the regional gravity survey of central Java performed by Yokoyama et al. (1970).

Gravity-monitor stations were also installed on Kelut Volcano in east Java and on Tangkuban Prahu in west Java near Bandung. Both of these volcanoes have access roads to their summits and thus are more adaptable to gravity monitoring than Merapi.

A sequence of explosive eruptions at Galunggung Volcano began in April 1982 and continued for several months. An account of eruptive activity from April to June 1982 is presented in the final section of this report. Horizontal distance measurements were begun at Galunggung in mid-May 1982 by use of an electronic distance measuring (EDM) instrument in an effort to record ground deformation which may be related to eruptive activity.

## MERAPI VOLCANO

Merapi Volcano, situated in a region of high population density in central Java, has erupted explosively on the average every four years since 1800. Most eruptive sequences begin with a series of explosions accompanied by the production of pyroclastic flows and the generation of lahars. The initial explosive events are frequently followed by the extrusion of a summit lava dome several weeks to a few years after the onset of renewed explosive activity. The most recent episode of major explosive activity began in January 1969 after several weeks of increasing shallow earthquake activity (Shimozuru et al., 1969). The later lava dome growth stage, restricted to a small breached crater near the summit, began immediately following the explosive events and has continued to the present time with major collapses and landsliding of the lava dome in September 1973, March 1976, and November 1976.

A system of field observatories has been in existence around the base of Merapi for the past several decades (figure 2). At present, Babadan, Plawangan, Jrakah, and Ngepos field observatories are occupied twenty-four hours a day; Krinjing and Deles have been temporarily abandoned.

For at least the past several years, a monthly report (in Indonesian) for Merapi has been issued by VSI. These reports summarize the daily notes recorded by each field observatory which describe visual observations of weather and plume conditions and occasionally include hand-drawn sketches of the volcano. Copies of these reports may be found in the Yogyakarta VSI office. There also exists a partial set of monthly reports of volcanic activity throughout all of Indonesia on file in the VSI library in Bandung (1972-73 and 1975-78). These reports (Kegiatan Gunungapi di Indonesia oleh Seksi Pengawasan Gunungapi; in Indonesian) contain a variety of data which include temperature measurements of fumaroles and crater lakes, weather conditions and amounts of rainfall, seismic events, visual observations of rockfalls, and timing of venting episodes.

The most extensive, quantitative measurements of activity at Merapi are provided by seismic records. Weichert mechanical seismometers have been in operation at Plawangan and Babadan field observatories for the past few decades (figure 3). Electromagnetic instruments were installed at these same two locations in the early 1970's; the mechanical instrument at Babadan has since been removed. A listing of the permanent seismographs installed at Indonesian volcanoes by April 1982 is given in table I. The electromagnetic records from Babadan are the most reliable since this instrument has a higher sensitivity than the mechanical seismograph at Plawangan and has a more stable power supply than the electromagnetic instrument at Plawangan.

From these records the duration, maximum amplitude, and approximate time of occurrence of four types of seismic events are routinely made at the recording field observatory. The seismic events are classified as rockfalls (guguran), glowing clouds (awan panas), tectonic earthquakes (gempa tektonik), or volcanic earthquakes (gempa vulkanik). In addition, volcanic earthquakes are sometimes further identified as multi-phase events (fase banyak).

Rockfalls and glowing clouds from the active dome are intergradational; however, the term 'glowing cloud' is usually reserved for the more voluminous collapses of the lava dome which extend a few kilometers down slope from the summit. The signature of these landslides from the active dome is usually not as regular as earthquakes. Rockfalls and glowing clouds usually display erratic changes in amplitude, and so, these events may occasionally be misidentified as volcanic earthquakes. During times of increased landsliding activity, continuous occurrence of rockfalls and glowing clouds obscure the simultaneous recording of possible earthquake activity on the seismic records.

Earthquakes recorded at Merapi are classified as tectonic events if the time interval between the arrival of recognizable P and S waves is greater than four seconds. The location of these events is not possible owing to the lack of relative time control between seismic stations and limited station coverage.

Volcanic earthquakes recorded at Merapi are seldom reported to have been felt by people living on the slopes of the volcano. The apparent lack of earthquakes of sufficient magnitude to have been felt may be related to the frequent eruptive periods of Merapi. Both A and B-type volcanic earthquakes, based on a nomenclature devised by Minakami (1952), have been identified at Merapi, with the shallower B-type events much more numerous. Multi-phase events, first described by Shimozuru et al. (1969) during a two month study of the seismic activity at Merapi in 1968, are shallow volcanic earthquakes possibly corresponding to C-type events identified by Minakami (1952) during the growth of the lava dome Showa-shinzan at Usu Volcano in Hokkaido. At Merapi, it is the increasing number of these multi-phase events which provides the most promising seismic precursor to eruptive activity. Daily counts in excess of a hundred multi-phase events per day were recorded a few weeks prior to eruptive activity in 1967, 1969, 1973, and 1976.

A list of monthly seismic events have been compiled from the field observatory notes on file in the Yogyakarta VSI office. These lists are of limited use because of the lack of relative time control between instruments and occasional instrumental problems created by lightning and other environmental factors. The number of seismic events probably represents the minimum occurrence of each type of event at Merapi during a particular month.

The monthly totals of all seismic events recorded since 1976 at Babadan by the electromagnetic instrument and at Plawangan by the mechanical instrument are plotted in figure 4. A comparison of these two plots, which mainly reflect the frequency of rockfalls, indicate similar increases in the number of events during the latter half of 1977 and 1978. A large increase in the total number of seismic events was also recorded in 1976 by the more reliable instrument at Babadan.

The number of volcanic or tectonic earthquakes recorded at Babadan (figure 5 and 6) usually averages between five and forty events per month with occasional increases in the number of volcanic events in excess of one hundred. The frequency of occurrence of multi-phase events has remained low throughout the past three years. Since 1976, the maximum rate of occurrence of multi-phase events was 101 per month in October 1979.

The Merapi seismic data have been re-examined in order to identify and characterize the occurrence of volcanic earthquake swarms during the past six years. During this period no major explosive eruptions (letusan-letusan) occurred at Merapi; however, several sequences of large landslides from the summit dome (longsoran kubah lava) did take place in March 1976, November 1976, and November 1981. These landslides resulted in the emplacement of small pyroclastic flows down the southwest slope from the Batang breach. Volcanic earthquake swarms accompanied and followed each of these three periods of landsliding and, in addition, preceded by a few weeks the activity in November 1976.

Small swarms of volcanic earthquakes, apparently not related to surface activity, also occurred in mid-October 1979 and possibly in January 1976, October 1977, April 1978, and October 1978, and December 1980. Each of these small swarms, which persisted for several days, consists of no more than a few dozen recorded events. None of these swarms can be characterized as a mainshock-aftershock sequence.

In March 1976, the daily rate of volcanic earthquakes peaked on March 6 and then remained at a higher level for several weeks (figure 7). During March 1976, the first indication of changes occurring at Merapi was the visual sighting and the seismic recording of increased rockfalls and glowing clouds from the active lava dome. No visible changes in the plume are mentioned in the field observatory notebooks during March 1976.

The hourly frequency of seismic events during the three days of peak activity is shown in figure 8. Though the maximum rate of occurrence of volcanic earthquakes followed the period of major landsliding, this apparent delay may be due to the saturation of the seismic records by continuous avalanche activity.

No increased seismic activity has been recognized to precede the landsliding of the summit dome in March 1976 or in November 1981. The lack of precursory seismic activity suggests that the initiation of these landsliding events may be the result of structural failure of the lava dome and not the result of processes taking place beneath the surface.

The daily frequency of volcanic earthquakes in October 1979 (figure 7) also displays a sharp rise and partial drop to a higher level than that before the start of this sequence. This higher level of seismic activity persisted for several weeks. Almost all volcanic earthquakes recorded by the Babadan field observatory during October 1979 were identified as multi-phase events.

The amount of rainfall at each field observatory is recorded hourly. The monthly rainfall amounts recorded at Babadan and Plawangan observatories (figure 9) reveal the seasonal weather pattern in central Java.

Three proton precession magnetometers, which record the total magnetic field intensity, were installed by Robach and have been in operation since 1980. These instruments continuously transmit to a central receiver station at the Plawangan field observatory, where the data are digitally recorded on cassette tape once every minute. Local changes in the magnetic field intensity near active volcanoes may arise from a variety of processes including a change in stress conditions which may alter the susceptibility of magnetic minerals contained in the surrounding rocks (piezomagnetic effect).

Differences in monthly averages of the local midnight magnetic values measured by the three operating magnetometers do not indicate changes greater than two nanoteslas in the magnetic field intensity during 1981 (figure 10).

At several locations near Merapi, a spirit-level technique is employed to measure tilt changes which may precede major eruptive activity (Yamashita, 1981). These measurements have been rotated to a cylindrical coordinate system with the origin at the summit of the volcano. A positive radial tilt is defined as a downward deflection directed away from the volcano; a positive concentric tilt is defined as a downward deflection in a clockwise direction concentric to the volcano. At a radial distance of five kilometers from the summit, no measureable tilt changes occurred at Merapi between April 1981 and March 1982 (figure 11).

Gas samples and fumarolic temperatures are routinely measured in both the Woro and Gendol solfatara fields located within a few hundred meters of the active lava dome. An apparent increase in the atmospheric carbon dioxide concentration occurred in the Woro field in early 1980 (figure 12). Irregular increases have also been measured in other gas species.

Maximum temperatures measured in the Woro field (figure 12) also rose in 1980, though no similar rise in fumerolic temperature was recorded in the Gendol field.

## GRAVITY MEASUREMENTS

A model G LaCoste-Romberg gravimeter (G615), on loan from the Hawaiian Volcano Observatory, was employed in Indonesia to introduce the monitoring of active volcanoes by repeated precise gravity measurements. The intent of this technique is to re-measure the acceleration of gravity relative to a reference station far removed from an area of anticipated changes. If the original site can be re-occupied and if tidal contributions to the gravity field can adequately be taken into account, then a relative change in acceleration between two stations must either be the result of a vertical change in elevation (i.e., Bouguer change) or a lateral change in density structure (i.e., mass movement) or a combination of both.

In order to have confidence in the instrument response, it is necessary to monitor at least two nearby volcanoes so that the possibility of a change in instrument calibration may be evaluated. If the gravity monitor line at one volcano indicates a systematic change from an earlier survey but no change occurs in a monitor line at another volcano for the same time period, then the former variation probably represents a real change in the state of that volcano. Furthermore, these dual monitor lines allow the use of other gravimeters which have not been recently intercompared.

Gravity monitor stations were established at Merapi, because of its frequent periods of activity, and at Kelut (east Java) and at Tangkuban Prahu (west Java near Bandung). Both Kelut and Tangkuban Prahu have had explosive eruptions every ten to twenty years during historic time. Gravity monitoring is easily conducted at these two volcanoes since their summits are accessible by vehicle.

The primary advantage of precise gravity monitoring of volcanoes is that the instrument may be quickly transported (if roads are available) to determine relative changes over a broad area. The major disadvantage is the limitation in the precision of the instrument which necessitates several re-occupations of the same station during each monitoring survey. Typically, if a station is read on four different occasions, the relative change in gravity may be determined to within fifteen microgals, which corresponds to a possible free-air elevation change of seventy-five millimeters.

All gravity readings have been reduced using the calibration table provided by LaCoste-Romberg for our gravimeter. This instrument was run on the Hawaiian calibration line over Kohala Volcano in December 1981 and will soon be re-run along this same line.

Theoretical tidal values for central Java were evaluated by manually reading the instrument over a complete tidal cycle (figure 13). The standard deviation of the differences between these readings and theoretical tidal changes, computed from Longman's equations on a programmable calculator, was nine microgals.

In 1967-68, Yokoyama et al. (1970) conducted a gravity survey across central Java in the vicinity of Merapi using an early model G LaCoste-Romberg instrument. Photographs of many of their instrument setups were published in an earlier paper (Yokoyama et al., 1969). We re-occupied as many of their original sites in central Java as still existed, remeasuring each site on at least four different occasions over a two-day period. Daily variations in gravity values at our reference station, PPM Yogyakarta, were always less than 0.030 milligals. For each gravity station, our range of measured values with respect to the average value at PPM Yogyakarta was also less than 0.030 milligals. A comparison of our values with Yokoyama et al. (table II) indicates some very large differences. These differences are greater than anticipated at these distances from Merapi and display no correlation with gravity value or with radial distance from Merapi.

Yokoyama et al.'s purpose in conducting their gravity survey was to study the structure of the Indonesian island arc by making a traverse across Java. The published uncertainty in their measurements with respect to a reference station in Tokyo is 0.1 milligals; however, they make no statement regarding the lesser relative uncertainty between gravity stations within Java. From the large, nonsystematic differences in table II, we suggest that their measurements are probably not sufficiently accurate to reveal regional changes which may have occurred during the last fourteen years of volcanic activity at Merapi.

The results of a gravity survey, consisting of 65 stations near Merapi (figure 14) are listed in table III. All gravity values, expressed in milligals, are relative to a reference station at PPM Yogyakarta (Yokoyama et al., 1970). Gravity readings and elevations for some of these stations were taken from Yokoyama et al. (1970). Gravity readings for the remaining 37 stations were taken next to concrete triangulation posts of known elevations.

Gravity readings in table III are the values after instrument calibration and tidal corrections have been applied. Simple Bouguer values (also referenced to PPM Yogyakarta) are determined from the gravity readings after: 1) corrections have been made for latitudinal variations, 2) for the free-air gradient, assuming a value of 0.308 milligals per meter, 3) and the Bouguer corrections, using a density of 2500 kilograms per cubic meter (in accordance with the value adopted by Yokoyama et al. (1970)). A map of the simple Bouguer values (figure 15) illustrates the north-south gravity gradient across Java first reported by Yokoyama et al. (1970). In determining the contribution of the surrounding topography to the gravity field, Kane's (1962) method was applied using a square grid with one half kilometer spacing and a density of 2500 kilograms per cubic meter. The addition of the topographic corrections to the simple Bouguer values yields the complete Bouguer gravity field. The regional component remaining in the complete Bouguer field was removed by subtracting both a north-south and an east-west gradient determined by a least-squares fit to all stations. The resultant gravity field, termed the final Bouguer, is depicted in figure 16.

At the spacing of the gravity stations surveyed, the only apparent structure in the local gravity field near Merapi is a broad low located several kilometers west of the volcano (figure 16). This gravity low, which represents material of lower than average density, does not have any obvious relationship to the present day Merapi.

At Kelut Volcano, four gravity-monitoring stations were established along a jeep trail at radial distances of 1 to 4 kilometers from the summit crater lake. The reference station for the gravity readings at Kelut is located 6.5 kilometers from the summit at the Kelut field observatory. All gravity monitoring stations at Kelut were positioned over pre-existing spirit-level tilt benchmarks. Each gravity station was read on four different occasions over a two day period. The resultant relative gravity values and the associated uncertainties in our readings are listed in table IV.

Eight gravity stations were measured in west Java along the road from Bandung to the summit of Tangkuban Prahu. Six of these stations (DG0 to DGIV) constituted a pre-existing gravity calibration line (Adkins et al., 1978). The remaining two gravity stations were established at recently installed spirit-level tilt benchmarks south of the summit. Each station was reoccupied four times over a two day period. The average values of these measurements (taking DG0 as a reference station) and the associated uncertainties in our values are listed in table IV. Gravity values from Adkins et al. (1978) for these same six stations are also listed in table IV. The published uncertainty for Adkins et al.'s values is 0.030 milligals. In addition to these six gravity stations on Tangkuban Prahu, three stations in central Java measured by Adkins et al. and by us are also given in table

IV.

Differences between our gravity values and those of Adkins et al. are plotted as a function of the relative acceleration to the reference station in figure 17. The linear trend defined by points measured in both west and central Java suggest that the differences between our values and Adkins et al. are the result of differences in calibration of our two instruments. If this linear trend is removed, then there has been no apparent change in the gravity values at Tangkuban Prahu between 1977 and 1982. If a Bouguer gradient of -5000 millimeters per milligal is assumed and an uncertainty of 0.030 milligals is assigned to these gravity differences, then the uncertainty in our measurements indicate that the vertical elevation change between Bandung and the summit of Tangkuban Prahu has been less than 150 millimeters during the past five years.

## GALUNGGUNG VOLCANO

The overall size and shape of Galunngung Volcano, located sixty kilometers southeast of Bandung in west Java (figure 1), is remarkably similar in appearance to the present form of Mount St. Helens. Both volcanoes have breached craters approximately two kilometers in diameter and up to one kilometer of relief between the crater floor and rim. The breached crater at this latter volcano, located in the northwest United States, resulted from the cataclysmic eruption on May 18, 1980 (Lipman and Mullineaux, 1981). Central lava dome complexes have been emplaced within the breached crater at both volcanoes by eruptive activity which followed the cataclysmic eruptions which formed the breached craters.

The three eruptive sequences observed at Galunggung since 1800 each began with explosive activity originating from the breached crater. The first eruptive sequence (October 8-12, 1822) generated widespread pyroclastic flows and lahars which were responsible for over 4000 fatalities. The second historic eruptive sequence, apparently of much shorter duration (October 18-19, 1894), consisted of explosive activity which generated small lahars. On July 17, 1918, explosive activity from the breached crater began the third historic eruptive sequence. This activity continued for at least a few weeks, resulting in the emplacement of a lava dome, Gunung Jadi, 85 meters high and 500 meters across. Minor increases in fumarolic activity at Galunggung were noted in 1868, 1895, 1896, and 1958.

Galunggung began the most recent sequence of explosive eruptions on April 5, 1982. By June 13, 1982, a total of eight major and at least seven minor eruptive episodes had occurred (table V).

The 1982 eruptive sequence of Galunggung began by generating a large eruptive cloud which reached a maximum altitude of 10-20 kilometers by 06:20 local time on April 5. During the next hour, this ash cloud expanded laterally and had almost totally dispersed by late morning.

By April 6, the Volcanological Survey of Indonesia (VSI) had set up a temporary observatory in a private house 7 kilometers southeast of the breached crater in the village of Cikasasah (figure 18). The signal from one seismometer, installed on the morning of April 6 and located three kilometers from the breached crater, was returned to Cikasasah by cable and recorded on a smoke drum at the temporary observatory.

On April 8, from a position atop rice terraces two kilometers northwest of Sinagar, we observed lahars which moved down the Cibanjaran River. From this location, the active lahar was 100-200 meters across with a 30-50 meter wide central channel of rapidly flowing muddy water which occasionally surged and carryed meter size boulders further downstream. Unfortunately, cloud cover prevented a view of the crater region, though at our position northwest of Sinagar no devastated areas were visible beneath the cloud layer.

The second large explosion of Galunggung occurred during the evening of April 8. The aftermath of this eruption was viewed on April 16 from the same locations visited eight days earlier. The most recent lahars along the Cibanjaran River were more extensive than the lahars generated by the initial activity on April 5. By April 16, lahars had begun to flow into the eastern drainage which passes through the city of Tasikmalaya, located 17 kilometers southeast of Galunggung. The April 8 eruption also emplaced a pyroclastic flow along the Cibanjaran River a maximum distance of approximately five kilometers from the vent. A broad transitional, steaming zone at least a kilometer in extent had formed between the distal end of the April 8 pyroclastic flow and the lahar further downstream. A meter wide border of scorched vegetation outlined this transitional zone. Nearer the volcano, an area approximately 10 square kilometers in areal extent had been devastated along the east and northeast sections of the breached crater.

Relatively minor explosive activity occurred during the morning of April 20 and again during the early afternoon of April 21. No additional damage resulted from this activity.

During the early morning hours on April 25, the next major eruption produced a pyroclastic flow and lahars similar in extent to those generated two weeks earlier on April 8. On April 26, it was estimated that 10 to 20 million cubic meters of material, including both pyroclastic flows and lahars, had been deposited along the Cibanjaran River since April 8.

Both the April 8 and April 25 eruptions were followed by a period of little or no seismic activity. Seismic activity resumed after the April 8 eruption on April 11 and after the April 25 eruption on May 2.

During the second lull in seismic activity, a brief visit was made to the breached crater of Galunggung on May 1. We departed the observatory in CiKasasah at 05:00 and drove a short distance to the school in Kedung Village. At this point, minor lahars along the CiKunir River made it necessary for us to travel on foot the remainder of the way to the breached crater. Our pathway took advantage, whenever possible, of local high points along the ridge separating the villages of Citiis and Cipanas and continued onto Pasir Bentang (figure 18). We estimated that the April eruptive activity had produced several hundred impact craters ranging from 0.5 to 4 meters in diameter. The impact craters were concentrated in a region one to four kilometers southeast of the active vent. At Citiis, the bombardment of volcanic debris had caused only slight damage to buildings and in minor disruption of existing rice terracing. One kilometer downslope from Pasir Bentang, however, earlier eruptive activity had created a region of intensive impact cratering and tree blowdown.

By mid-morning on May 1, we had climbed the 200 meter scarp immediately in front of the breached crater and reached the southern end of Gunung Warirang. From this vantage point, we noted that the saddle region to the northeast between Gunung Warirang and the 1918 lava dome, Gunung Jadi, had been completely filled by new airfall material. Along the southeast base of Gunung Jadi, a line of steaming fumaroles, which had been visible from CiKasasah for the past few weeks, had no noticeable sulfur deposits or odor associated with them. Steam rising from these fumaroles persisted for three more weeks until the further disruption of Gunung Jadi by the explosive eruptions on May 17 and 18.

We continued around the southern end of Gunung Jadi across a region of the crater floor mantled by new ash nearly half a meter thick and containing a few isolated areas of minor steaming. As we approached the 1982 active vent, located adjacent to and north of Gunung Jadi, we observed that the 1918 lava dome was intact with no evidence of major surface disruption. Only a small portion of Gunung Jadi (approximately 10 percent) had partially collapsed into the active vent.

The 1982 active vent was contained within an irregular, steaming depression 200 to 300 meters across and 40 to 70 meters deep. Along the western edge of this depression, the inner wall slanted inward at a modest angle of 20 to 30 degrees. To the south, this irregular depression was enclosed by a steep scarp several tens of meters high which crossed Gunung Jadi and formed the boundary for material which had collapsed from this dome. During occasional clear views into this depression, we observed that the white steam plume rising above Galunggung originated from a circular area 30 meters across lying in the southernmost and deepest portion of this depression near Gunung Jadi. The remainder of the floor of this irregular depression was completely mantled with ash with no visible incandescence, cracks, faults, or recently extruded material. A few isolated light-colored patches were visible along the floor, though no sulfurous odor could be detected.

Since heavy steaming prevented further examination of this area from other points along the edge of the depression, we returned to Cikasasah retracing the path taken earlier that morning.

The next explosive eruption on May 6 resulted in measureable ashfall in Bandung (3 mm) and a trace in Jakarta. As in the earlier eruptions, the major ashflow and lahar activity was restricted to the Cibanjaran River. The morphology of the ashflow emplaced by the May 6 eruption was different from those produced by the April eruptions. The pyroclastic flows generated by explosive eruptions on April 8 and April 25 had no well-defined surface features, such as, discernible levees or lobate flow lobes, and their surfaces consisted almost entirely of ash. A broad gradational zone was present between the pyroclastic flows emplaced on April 8 and April 25 and their associated lahars further downslope. In contrast, the May 6 ashflow had a well-defined flow front, ranging from six to ten meters high, consisted of many individual flow lobes, and was covered with blocks as much as one meter across.

A second trip to the breached crater of Galunggung, was made on May 17. The purpose of this trip was to install permanent reflectors within a few hundred meters of the active vent for an electronic distance measuring (EDM) survey. The route taken to the crater on this second trip approximately retraced the one taken two weeks earlier. One reflector was installed on a vertical metal post at the top of Pasir Bentang and two more were placed along the crest of Gunung Warirang. After the installation of these reflectors, we continued to the northern end of Gunung Warirang to view the irregular depression north of Gunung Jadi that contained the active vent. The southeastern edge of the depression consisted of several concentric slump blocks which had partially collapsed into the depression which formed a steep scarp 40 to 60 meters high. The steam plume above Galunggung was still originating from a circular area approximately 30 meters across located in the deepest portion of this depression.

At this point we deviated from our original path on May 1 and crossed directly over Gunung Jadi. There was still no apparent surface disruption of the major portion of Gunung Jadi except for the same small northeast portion which had collapsed into the active vent region, and for the line of steaming fumaroles along the southeastern base of Gunung Jadi.

From a similar position reached on May 1 along the western edge of the irregular depression, it was clear that major structural changes had taken place in the vent area since our first trip. A central mound 100 meters across and 30 to 40 meters high had recently been uplifted within the irregular depression, approximately 150 meters north of Gunung Jadi. Evidence for recent uplift included very fresh landslide scars and slump scarps along the sides of the mound. Incandescence outlined a meter-long, vertical crack along the western face of this mound.

We continued along the western rim of the depression. To the northwest, a system of radial cracks and fault scarps were clearly visible which extended 100 to 150 meters north of the central mound. Two thrust faults, with maximum vertical offsets of approximately two meters, trended radially from the central mound along the western edge of the irregular depression. The eastern block was elevated along both thrust faults. Further to the east, cracks also radial to the central mound had deformed and warped the erosional scars produced by the most recent rain. Further to the east beyond the cracks, a complex of normal faults had formed horst and graben structures also trended approximately radially to the central mound.

The geometry of the radial cracks and horst and graben structure indicated the existence of a tensional stress environment, which had been recently active and, perhaps was still continuing.

At 19:40 on May 17, a 50 minute increase in seismic activity preceded the first of four major explosive eruptions which occurred during the next twenty-four hours. A significant drop in tremor amplitude preceded the onset of the initial explosion by about one minute. From Cikasasah, the initial eruptive outbreak appeared as a quick succession of bursts lasting less than two minutes which produced a partial umbrella of red incandescent streaks estimated to be about 500 meters high and 1500 meters across. A bright, red glow continued to be emitted from the crater for the next several minutes while a much brighter incandescent sheet rolled down along the base of the north wall of the breached crater toward the Cibanjaran River.

A very coarse airfall (maximum diameter 40 millimeters) reached Cikasasah at 21:01. The average particle size of this airfall, which consisted of a wide variety of rock types, progressively decreased over the next few hours.

A second explosion occurred at 05:20 on May 18. Poor weather conditions prevented observations of this eruptive activity; however, the accompanying lightning display and airfall were very similar to those which had taken place the previous night. By 07:30, most of the latest airfall had subsided; at Cikasasah only a light ash was still falling.

In order to make an assessment of the damage and of the potential for secondary lahar activity, a quick trip was made to the villages of Citiis and Cipanas by way of Kedung and the Cikunir River. In Kedung, approximately 40 percent of the clay roof tiles and many of the glass windows had been broken by falling rocks. No new lahar along the Cikunir River had reached the new diversion dam near Kedung. Closer to the volcano, ashflows had completely destroyed Citiis. The May 17-18 explosive eruptions had produced a pyroclastic flow along the southern drainage from the breached crater, and a hot ash cloud had toppled many of the coconut palms and severely scorched the banana palms in Citiis. Heat deformed glassware was uncovered in this area. Only one wooden building in Citiis had survived the recent explosive eruptions. This building, located near the edge of the hot ash deposit, was positioned on a hillside facing away from the active vent. Within the central drainage passing through Citiis, a steaming lahar was dammed by smoldering vegetation several hundred meters beyond the distal end of the ashflow.

In the next major drainage to the north, an ashflow had also passed through Cipanas destroying most of the wooden structures, though the few concrete buildings suffered essentially no damage to their walls.

A third explosive eruption occurred at 13:36 on May 18 following several minutes of increased seismic activity. Poor weather conditions again prevented observations of the eruptive activity; however, a convecting, glowing cloud was observed to pass through the crater breach several minutes after the onset of the lightning display accompanying this eruption. A very clear, low roar could also be heard from the crater and lasted twenty minutes. The average particle size of the subsequent airfall was noticeably less than during the two previous eruptions on May 17 and 18. This airfall also consisted of a wide variety of rock types.

The final explosion of this sequence began later that night at 22:23. There was no recognizable seismic precursor to this explosive eruption. The slightly improved weather allowed us to observe a bright orange-red cloud that remained over the crater region for almost an hour. No detail could be discerned in the bright region above the vent under the available light conditions; however, the enhanced contrast provided by a visual image intensifer showed that material was continuously being projected several hundred meters above the crater floor. This eruptive activity once again generated a continuous low roar from the volcano and a spectacular display of lightning and thunder. The average particle size of the airfall at Cikasasah from this last explosive eruption on May 18 was less (maximum diameter was 10 millimeters) than from the earlier events. This most recent airfall consisted of more scoriaceous material than had fallen during the earlier eruptions.

At Cikasasah, seven kilometers southeast of Galunggung, the accumulated airfall from the four explosive eruptions on

May 17-18 was 60 millimeters thick.

On May 19, gray convecting clouds were still rapidly rising from the active vent. Small amounts of light-colored ash occasionally swept as much as 500 meters downslope from the vent. On that same day, from a position along the southeast crater rim, we noted that the northeastern half of Gunung Jadi had disappeared from view. Either the bulk of this lava dome had been ejected by the latest explosive activity or it had collapsed into the active vent. Along the Cikunir River near Kedung, a steaming lahar continued to surge throughout the remaining daylight hours.

From May 20 to 22, a white steam plume rising from the crater appeared to be similar to that which had existed for several days prior to the May 17-18 eruptions. During the morning of May 23, a small, gray ash cloud rose from the crater and drifted to the west. Later that same afternoon, numerous dark, convecting clouds shot up a few hundred meters from the region of the active vent. Tremor amplitude increased on May 23 for several hours and again on May 24 without resulting in major eruptive activity. The latter increase in amplitude began to decline during the early morning hours of May 31. No noticeable change in condition of the plume accompanied these increases in tremor amplitude.

Clear weather on May 30 allowed the first examination of the breached crater following the series of explosions which began on May 17. From a vantage point along the southern rim at Gegeber Atas (figure 19), roughly 100 meters above the crater floor, we observed that the active vent had widened considerably to a diameter of 500 meters. We also confirmed that a major portion of Gunung Jadi had disappeared from view. A significant portion of Gunung Warirang had also either collapsed into the active vent or was deeply blanketed by new material.

The next eruptive activity, which began on June 3, was different in character from the earlier eruptions. Seismic activity had been continuous after the explosive events in mid-May, unlike the absence of activity immediately following the large explosive eruptions on April 8, April 25, and May 6. Prior to May 18, shallow earthquakes dominated the seismic activity, however, after May 18, the seismic activity consisted primarily of a continuous train of tremor. At about 10:00 on June 3, without any recognizable seismic precursor,a large amount of ash began to be emitted from the crater accompanied by lightning and thunder. The slow decline in intensity of this eruptive activity was interrupted several hours later by a more vigorous episode of ash emission. This second event on June 3 completely shrouded Cikasasah in total darkness by 16:40. Periods of strong ash emission, accompanied by lightning and thunder displays continued for the next several days with subsequent events generally decreasing in intensity.

From June 8 to June 13, a white steam plume had replaced the gray ash cloud over Galunggung, though tremor amplitude continued to fluctuate without apparent relationship to visual changes in plume conditions.

## Electronic Distance Measurements

A K+E Rangemaster III, an electronic distance measuring (EDM) instrument, and 28 retroreflectors arrived at Galunggung on May 15. Unfortunately, a series of four explosive eruptions which began during the night of May 17 destroyed the reflector stations installed that morning at Pasir Bentang and along the crest of Gunung Warirang. Additional reflectors were installed on May 19 at Gegeber Bawah and Pasir Ipis, two and five kilometers, respectively, from the active vent (figure 19). Daily measurements were begun on May 20 from Cikasasah to each of these new reflector stations and were continued to at least the middle of June. An additional reflector station was installed along the southern rim, Gegeber Atas, and two more instrument stations, Rancabogo and Sinagar, were established during May. Unfortunately, access to Sinagar was blocked by the rapid erosion of a recent lahar within a few days after the original occupation of this station.

An iron bar, driven vertically into the ground, served as the reference benchmark at each instrument setup, and permanent cement pads were used to position the fully extended tripod legs to ensure the same instrument positioning with respect to the benchmark at each instrument site.

Air temperature and pressure readings were made only at the instrument site and were entered directly into the Rangemaster (PPM correction) together with a zero offset correction. During one daylight period (May 22), hourly measurements were made along two lines from Cikasasah in order to determine the apparent line length changes that resulted from diurnal variations in the atmospheric thermal structure. The repeated measurements (figure 20) indicate that apparent changes as large as 20 millimeters may be expected along the longer of these two lines.

The results of daily measurements made from Cikasasah are shown in figure 21. The variations along the shorter line to Pasir Ipis are the result of changes in the temperature structure along the line path and of small variations in instrument setup. The slope distance between Cikasasah and Gegeber Bawah continued to indicate extension during the latter half of May, though these changes are not well beyond the expected uncertainty in the measurements.

## SUMMARY

From January to June 1982 a variety of scientific studies were conducted on several active volcanoes in Indonesia. These studies focused primarily on monitoring volcanic activity by geophysical techniques, in particular, an examination of available seismic records and several techniques designed to measure surface deformation.

The geophysical and geochemical monitoring data taken at Merapi Volcano over the past several years were compiled from available observatory notes. During this several year period, Merapi has been in a stage of almost continuous minor eruptive activity which include the continued extrusion of a summit lava dome and occasional small explosive bursts from the summit. The summit lava dome apparently becomes structurally unstable over a period of a few years, and large portions of this dome landslide down the southwest slope of the volcano and travel a maximum distance of about five kilometers. No definite geophysical or geochemical changes have yet been identified to precede these landsliding episodes. However, an increase in the number of shallow volcanic earthquakes preceded the last major explosive eruption of Merapi in January 1969 and may also have preceded some of the larger landsliding episodes in September 1973, March 1976, and November 1976 (Suparto S., private communication, 1982).

A gravity survey of the region near Merapi revealed no Bouguer anomaly associated with the present-day Merapi, although a broad gravity low area was identified west of the volcano.

Gravity-monitoring lines were installed at Merapi and also at Tangkuban Prahu and Kelut Volcanoes. These lines have not been reoccupied.

The initial two months of eruptive activity at Galunggung Volcano were observed during the tenure of this report. This activity consisted primarily of several distinct explosive eruptions which generated pyroclastic flows down the southeast slope of the volcano to a distance of five kilometers and extensive lahars. Following the climax of explosive activity on May 17-18, 1982, the eruptive character of Galunggung changed to a series of vigorous ash emission eruptions that occur on the average of a few days. The seismic activity at Galunggung also changed from predominantly shallow earthquake activity to continuous tremor after the May 17-18 eruptions.

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## TABLE I

## SEISMOGRAPHS PERMANENTLY INSTALLED AT INDONESIAN VOLCANOES BY APRIL 1982

| island | volcano | seismograph<br>mechanical | <br>electromagnetic |
|---|---|---|---|
| Sumatra | Talang | --- | 1 component |
| | Marapi | --- | 1 component |
| | Krakatau | --- | 3 component tripartite net |
| Java | Tangkuban Prahu | --- | 1 component |
| | Dieng | --- | 1 component |
| | Merapi | 2 component | 3 component tripartite net |
| | Kelut | 2 component | 3 component tripartite net |
| | Semeru | 2 component | 3 component tripartite net |
| | Kawah Ijen | --- | 1 component |
| Bali | Agung | 2 component | 1 component |
| Sulawesi | Mahawu | --- | 1 component |
| | Siau | --- | 1 component |
| | Awu | --- | 1 component |
| Maluku | Banda Api | --- | 1 component |
| | Kei Besi | --- | 1 component |
| Flores | Ebulobo | --- | 1 component |
| | Iya | --- | 1 component |
| | Kelimutu | --- | 1 component |
| Adonara | Ili Bloeng | --- | 1 component |

## TABLE II

## GRAVITY DIFFERENCES MEASURED AT MERAPI

| station | Gravity Readings<br>Yokoyama et al. (1970) | <br>this paper | gravity difference |
|---|---|---|---|
| Ambarrukmo Hotel | -3.45 mgal | -3.468 mgal | -0.02 mgal |
| Boyolali | -154.00 | -153.896 | -0.10 |
| west Merbabu | -222.07 | -221.559 | -0.53 |
| T845 | -226.38 | -226.216 | -0.16 |
| Babadan | -326.51 | -326.540 | -0.03 |
| Jrakah | -328.66 | -328.760 | -0.10 |
| Selo | -401.28 | -401.360 | -0.08 |

all gravity readings are referenced to PPM Yogyakarta

# TABLE III

## GRAVITY READINGS IN CENTRAL JAVA

## MERAPI VOLCANO

| No. | Station name | Longitude | Latitude | Elevation (meter) | Gravity Reading | Simple Bouguer | Topographic Correction | Complete Bouguer | Final Bouguer |
|---|---|---|---|---|---|---|---|---|---|
| 1* | Pajaman | $110^{\circ}$ 13'.9 E | $7^{\circ}$ 25'.3 S | 405 | -155.12 | -85.1 | 0.2 | -84.9 | 16.5 |
| 2* | Kramat | 13.4 | 27.3 | 388 | -142.90 | -77.2 | 0.2 | -77.0 | 15.2 |
| 3* | Mertojud | 13.4 | 30.2 | 347 | -118.97 | -62.7 | 0.2 | -62.5 | 16.8 |
| 4* | Blondo | 14.1 | 32.4 | 308 | -104.15 | -56.7 | 0.3 | -56.4 | 13.4 |
| 5* | Kedon | 13.2 | 34.3 | 261 | -66.63 | -29.5 | 0.2 | -29.3 | 31.5 |
| 6* | Bentingan | 15.5 | 34.1 | 311 | -99.10 | -51.7 | 0.4 | -51.3 | 11.5 |
| 7* | Gulon | 17.6 | 35.6 | 348 | -83.22 | -28.9 | 0.5 | -28.4 | 28.7 |
| 8* | Jagan | 19.4 | 38.7 | 322 | -78.00 | -20.2 | 0.4 | -19.8 | 24.3 |
| 9* | Medari | 20.3 | 40.8 | 266 | -56.08 | -20.5 | 0.3 | -20.2 | 14.9 |
| 10 | Q37 | 20.0 | 32.5 | 575 | -178.67 | -77.3 | 1.0 | -76.3 | -4.3 |
| 11 | Q36 | 20.9 | 32.1 | 666 | -203.00 | -82.8 | 1.4 | -81.4 | -7.1 |
| 12 | Q51 | 21.9 | 30.9 | 887 | -255.28 | -89.6 | 1.5 | -88.1 | -8.0 |
| 13 | T366 | 23.1 | 31.4 | 938 | -261.76 | -85.8 | 2.7 | -83.1 | -4.7 |
| 14 | Jrakah | 25.4 | 29.9 | 1290 | -328.34 | -80.1 | 6.4 | -73.7 | 12.5 |
| 15 | Q640 | 24.7 | 30.7 | 1164 | -302.85 | -80.6 | 4.6 | -76.0 | 6.3 |
| 16 | Selo | 27.4 | 29.9 | 1653 | -400.92 | -78.7 | 4.7 | -74.0 | 13.1 |
| 17 | Q637 | 26.7 | 30.8 | 1544 | -375.95 | -76.3 | 6.1 | -70.2 | 12.6 |
| 18 | Q639 | 26.0 | 31.2 | 1466 | -362.52 | -78.9 | 8.1 | -70.8 | 9.8 |
| 19 | Babadan | 24.6 | 31.6 | 1277 | -326.15 | -81.2 | 4.3 | -76.9 | 1.3 |
| 20 | T365 | 23.1 | 33.0 | 908 | -248.10 | -78.9 | 2.4 | -76.5 | -5.2 |

*taken from Yokoyama et al. (1970)

## TABLE III (continued)

## GRAVITY READINGS IN CENTRAL JAVA

## MERAPI VOLCANO

| No. | Station name | Longitude | Latitude | Elevation (meter) | Gravity Reading | Simple Bouguer | Tppographic Correction | Complete Bouguer | Final Bouguer |
|---|---|---|---|---|---|---|---|---|---|
| 21 | Q40 | 110° 22'.3 E | 7° 33'.9 S | 765 | -213.10 | -73.4 | 1.6 | -71.8 | -4.9 |
| 22 | Q41 | 23.5 | 33.7 | 912 | -257.69 | -88.0 | 2.5 | -85.5 | -17.2 |
| 23 | T363 | 23.7 | 34.5 | 961 | -249.42 | -69.6 | 2.2 | -67.4 | -2.6 |
| 24 | T360 | 21.6 | 35.6 | 630 | -116.04 | -54.7 | 0.9 | -53.8 | 5.1 |
| 25 | Q9 | 22.5 | 36.4 | 671 | -172.15 | -52.6 | 0.9 | -51.7 | 4.1 |
| 26 | T361 | 21.9 | 37.1 | 571 | -143.72 | -44.8 | 0.7 | -44.1 | 8.3 |
| 27 | T329 | 23.3 | 37.0 | 685 | -170.28 | -48.0 | 0.8 | -47.2 | 6.3 |
| 28* | Plawangan | 25.9 | 35.1 | 1295 | -321.82 | -74.7 | 8.0 | -67.7 | -4.1 |
| 29 | Q68 | 27.0 | 35.7 | 1038 | -259.77 | -65.0 | 1.7 | -63.3 | -2.3 |
| 30* | Kaliurang | 25.8 | 35.7 | 893 | -222.07 | -56.7 | 3.0 | -53.7 | 6.7 |
| 31 | T847 | 27.6 | 36.6 | 871 | -216.03 | -55.6 | 1.1 | -54.5 | 2.7 |
| 32 | Q309 | 28.4 | 35.8 | 984 | -246.30 | -62.6 | 1.6 | -61.0 | 0.2 |
| 33 | T891 | 29.2 | 35.6 | 900 | -227.82 | -61.2 | 1.5 | -59.7 | 2.8 |
| 34 | Q310 | 29.3 | 36.7 | 744 | -189.76 | -55.3 | 1.1 | -54.2 | 3.4 |
| 35 | T845 | 25.5 | 36.2 | 915 | -226.01 | -56.7 | 1.2 | -55.5 | 2.6 |
| 36 | Q69 | 24.7 | 36.9 | 759 | -188.16 | -50.8 | 1.0 | -49.8 | 4.8 |
| 37 | Q67 | 26.3 | 37.5 | 725 | -178.54 | -48.3 | 1.0 | -47.3 | 5.3 |
| 38 | | | | | | | | | |
| 39 | T843 | 24.4 | 37.8 | 521 | -153.56 | -64.1 | 1.1 | -63.0 | -12.6 |
| 40* | Sanatori | 25.4 | 37.9 | 606 | -149.65 | -43.9 | 1.0 | -42.9 | 7.5 |

*taken from Yokoyama et al. (1970)

## TABLE III (continued)

## GRAVITY READINGS IN CENTRAL JAVA

## MERAPI VOLCANO

| No. | Station name | Longitude | Latitude | Elevation (meter) | Gravity Reading | Simple Bouguer | Topographic Correction | Complete Bouguer | Final Bouguer |
|---|---|---|---|---|---|---|---|---|---|
| 41* | 19km Yogya | $110^{0}$ 25!4 E | $7^{0}$ 39!0 S | 512 | -123.11 | -36.7 | 0.7 | -36.0 | 9.5 |
| 42 | T826 | 25.2 | 39.4 | 438 | -104.26 | -33.2 | 0.7 | -32.5 | 11.1 |
| 43* | Degolan | 25.1 | 41.1 | 342 | -78.44 | -27.4 | 0.5 | -26.9 | 9.1 |
| 44 | T824 | 25.1 | 41.7 | 310 | -67.96 | -23.8 | 0.4 | -23.4 | 9.9 |
| 45* | Candi | 24.7 | 42.3 | 271 | -55.10 | -19.0 | 0.4 | -18.6 | 11.8 |
| 46* | 11km Yogya | 24.4 | 42.9 | 246 | -42.71 | -12.0 | 0.3 | -11.7 | 15.9 |
| 47 | T930 | 29.5 | 31.1 | 1248 | -315.52 | -76.3 | 2.7 | -73.6 | 9.1 |
| 48 | Cepogo | 30.9 | 30.8 | 960 | -258.07 | -77.5 | 1.8 | -75.7 | 9.0 |
| 49 | Q624 | 30.1 | 31.7 | 1133 | -290.51 | -75.0 | 1.9 | -73.1 | 7.2 |
| 50 | T927 | 31.0 | 32.4 | 985 | -255.90 | -70.8 | 1.3 | -69.5 | 8.1 |
| 51 | Q447 | 31.8 | 32.5 | 792 | -223.10 | -77.4 | 1.3 | -76.1 | 1.4 |
| 52 | T960 | 30.5 | 33.6 | 966 | -249.21 | -68.5 | 1.6 | -66.9 | 5.1 |
| 53 | Q444 | 31.9 | 33.8 | 765 | -210.99 | -71.3 | 1.0 | -70.3 | 1.5 |
| 54* | Tengaran | 31.6 | 25.4 | 719 | -246.74 | -112.8 | 1.4 | -111.4 | -2.2 |
| 55* | Ampel | 32.6 | 27.2 | 678 | -235.12 | -110.3 | 1.2 | -109.1 | -7.5 |
| 56* | Penggung | 34.3 | 29.5 | 544 | -193.61 | -96.9 | 0.8 | -96.1 | -4.0 |
| 57* | Plosoker | 35.1 | 30.8 | 487 | -174.31 | -89.7 | 0.6 | -89.1 | -2.4 |
| 58 | Boyolali | 35.8 | 31.9 | 424 | -154.00 | -82.7 | 0.5 | -82.2 | -0.1 |
| 59* | Mojosong | 38.1 | 32.3 | 279 | -130.90 | -90.3 | 0.4 | -89.9 | -8.6 |
| 60* | Kopen | 37.6 | 34.4 | 277 | -110.72 | -70.4 | 0.4 | -70.0 | 1.7 |

*taken from Yokoyama et al. (1970)

## TABLE III (continued)

## GRAVITY READINGS IN CENTRAL JAVA
## MERAPI VOLCANO

| No. | Station name | Longitude | Latitude | Elevation (meter) | Gravity Reading | Simple Bouguer | Topographic Correction | Complete Bouguer | Final Bouguer |
|---|---|---|---|---|---|---|---|---|---|
| 61* | T925 | 110° 37:2 E | 7° 35:5 S | 290 | -93.74 | -61.1 | 0.3 | -60.8 | 5.8 |
| 62* | SH282 | 36.4 | 37.4 | 282 | -94.59 | -54.4 | 0.3 | -54.1 | 3.7 |
| 63* | SH263 | 36.0 | 38.4 | 263 | -82.95 | -47.1 | 0.3 | -46.8 | 6.3 |
| 64* | Mranggen | 34.6 | 39.2 | 280 | -70.12 | -31.1 | 0.3 | -30.8 | 18.1 |
| 65* | Ngingas | 36.7 | 41.5 | 167 | -29.42 | -14.3 | 0.2 | -14.1 | 25.4 |

*taken from Yokoyama et al. (1970)

# TABLE IV

## GRAVITY STATIONS
## KELUT VOLCANO

| | | | |
|---|---|---|---|
| Kelut Observatory | 0* | | |
| Bambingan | -47.236 ± | 0.010 | mgals |
| Pedot | -84.612 | 0.017 | |
| Gajamugnkir | -122.900 | 0.011 | |
| Tunnel | -101.209 | 0.016 | |

## GRAVITY STATIONS
## TANGKUBAN PRAHU

| | this work | | Adkins et al. (1978) |
|---|---|---|---|
| west Java | | | |
| DG 0 | 0* | | 0* |
| DG I | 0.170 ± | 0.021 mgal | 0.17 mgal |
| DG II | -37.160 | 0.024 | -37.14 |
| DG III | -74.328 | 0.030 | -74.41 |
| DG V | -149.612 | 0.023 | -149.73 |
| DG VI | -229.389 | 0.019 | -229.62 |
| Ptt 1 | -282.678 | 0.030 | |
| Ptt 2 | -240.668 | 0.030 | |
| central Java | | | |
| PPM Yogya | 0* | | 0* |
| Ambarrukmo Hotel | -3.468 ± | 0.020 mgal | -3.47 mgal |
| St. Elizabeth Hospital | -102.808 | 0.030 | -102.89 |

*reference station

# TABLE V

## CHRONOLOGY OF ACTIVITY
## GALUNGGUNG VOLCANO, WEST JAVA
## APRIL TO JUNE 1982

| | | |
|---|---|---|
| 4 April | ~22:00 | possible felt earthquakes at Citiis (village 3 km from eruptive site) |
| 5 April | 04:30-06:30 | major explosions, minor ashflow and mudflow activity; maximum height of eruptive plume 10-20 km |
| 6 April | 07:40 | minor explosion |
| 5-8 April | | continues shallow earthquake activity |
| 8 April | 21:08-21:31 | major explosion; ~10 $km^2$ devastated (Pasir Bentang and along Cibanjaran River); major ashflow 5km and extensive mudflow 8 km along Cibanjaran River |
| 9-11 April | | no seismic activity |
| 11-25 April | | resumption of shallw earthquake activity |
| 20 April | ~08:00 | minor explosion |
| 21 April | ~14:15 | minor explosion |
| 25 April | 04:55-05:12 | major explosion; ashflow and mudflow along Cibanjaran River |
| 25 April-1 May | | no seismic activity |
| 2-6 May | | resumption of shallow earthquake activity |
| 6 May | 01:08-01:35 | major explosion; ashflow and extensive mudflow along Cibanjaran River; ashfall in Bandung (3 mm) and in Jakarta (trace) |
| 6-11 May | | no seismic activity |
| 11-18 May | | resumption of shallow earthquake activity |
| 13 May | 06:10 | minor explosion |

## TABLE V

### CHRONOLOGY OF ACTIVITY (continued)
### GALUNGGUNG VOLCANO, WEST JAVA
### APRIL TO JUNE 1982

| | | |
|---|---|---|
| 17 May | 19:40 | increase in tremor amplitude |
| | 20:48 | sudden drop in tremor amplitude |
| | 20:50 | dramatic increase in tremor amplitude coincident with onset of eruptive activity |
| | 20:55 | incandescent glowing cloud observed along north wall of breached crater toward Cibanjaran River |
| | 21:01 | beginning of coarse airfall at Cikasasah |
| | ~22:00 | beginning of ashfall at Cikasasah |
| 18 May | ~04:30 | gradual increase in tremor amplitude |
| | 05:20-05;47 | major explosion and ashflows along all major drainages from the crater (maximum distance 3 km from vent) |
| | ~12:30 | rise in tremor amplitude |
| | 13:36-13:56 | major explosion; ashflows down all major drainages |
| | 22:23-23:08 | ajor explosions; rise in tremore amplitude conincident in time with renewed eruptive activity |
| 18 May | | occurrence of several deep earthquakes beneath Galunnggung |
| 19 May-13 June | | continuous tremor activity generally decreasing in amplitude; few shallow earthquakes |
| 19 May | 07:53-11:59 | minor ash emission |
| 23 May | 07:20-07:50 | minor ash emission (maximum rise ~2 km) |
| 3 June | ~10:00 | strong ash emission |
| | ~13:00 | strong ash emission |
| | 16:40 | strong ash emission; Cikasasah in total darkness |
| | 23:23 | strong ash emission |
| 4 June | 00:30 | strong ash emission |
| | ~10:00 | strong ash emission |
| 5-7 June | every few hours | episodes of vigorous ash emission (maximum rise 1-3 km) lasting 10-30 minutes |

Figure 1. Geographic map showing locations of some major cities and volcanoes on Java mentioned in the text.

Figure 2. Locations of Merapi field observatories. Open squares denote observatories currently in operation. The Batang breach is the present direction of major landsliding from the active summit dome.

Figure 3. Location of frequently monitored sites at Merapi. The types of measurements taken at each locality are indicated. Measurements from several of these sites appear in figures 4 to 12.

Figure 4. Monthly values of the total number of seismic events recorded by the electromagnetic seismometer at Babadan (top) and the mechanical seismometer at Plawangan (bottom).

Figure 5. Monthly values of the number of volcanic earthquakes recorded by seismometers at Babadan and Plawangan field observatories.

Figure 6. Monthly values of the number of tectonic earthquakes recorded by seismometers at Babadan and Plawangan field observatories.

Figure 7. Daily number of volcanic earthquakes recorded at Merapi in March 1976 (top) and in October 1979 (bottom).

Figure 8. Hourly number of glowing clouds (top) and volcanic earthquakes (bottom) recorded by the electromagnetic seismometer at Babadan from March 6 to 8, 1976.

Figure 9. Monthly rainfall recorded at Babadan and Plawangan observatories.

Figure 10. Differences in local magnetic field intensity at Merapi. Station locations are indicated in figure 3.

Figure 11. Tilt changes at three sites near Merapi. Station locations are indicated in figure 3. A positive radial tilt is defined as a downward deflection away from the volcano; a positive azimuthal tilt is a downward deflection in a clockwise direction concentric to the volcano.

Figure 12. Changes in gas concentrations and maximum temperature measured in the Woro solfatara field.

Figure 13. Comparison of theoretical gravity tides and measured gravity values for central Java.

Figure 14. Locations of gravity stations around Merapi. Gravity values taken from Yokoyama et al. (1970) are indicated. Topographic contour interval is 200 meters. Merapi is located in the center of this figure; Merbabu lies ten kilometers to the north.

Figure 15. Simple Bouguer gravity map of the region near Merapi. The 1200 meter contour around Merapi and Merbabu is indicated by the dotted line.

Figure 16. Final Bouguer gravity map of the region near Merapi. A density of 2500 kilograms per cubic meters has been used in computing topographic corrections. A linear regional gravity component has been removed.

Figure 17. Comparison of differences in gravity values measured at several stations in west and central Java by us and by Adkins et al. (1978).

Figure 18. Location map of place names near Galunggung volcano in west Java mentioned in the text.

Figure 19. Initial trilateration network at Galunggung. Solid lines denote trilateration lines electronically surveyed in May and June 1982. Dashed lines are proposed extensions of the network.

Figure 20. Apparent changes in line length between Cikasasah and Pasir Ipis and between Cikasasah and Gegeber Bawah on May 22, 1982. These apparent changes are the result of variations in atmospheric thermal structure.

Figure 21. Daily measured changes in line length along three lines from Cikasasah.

Figure 1

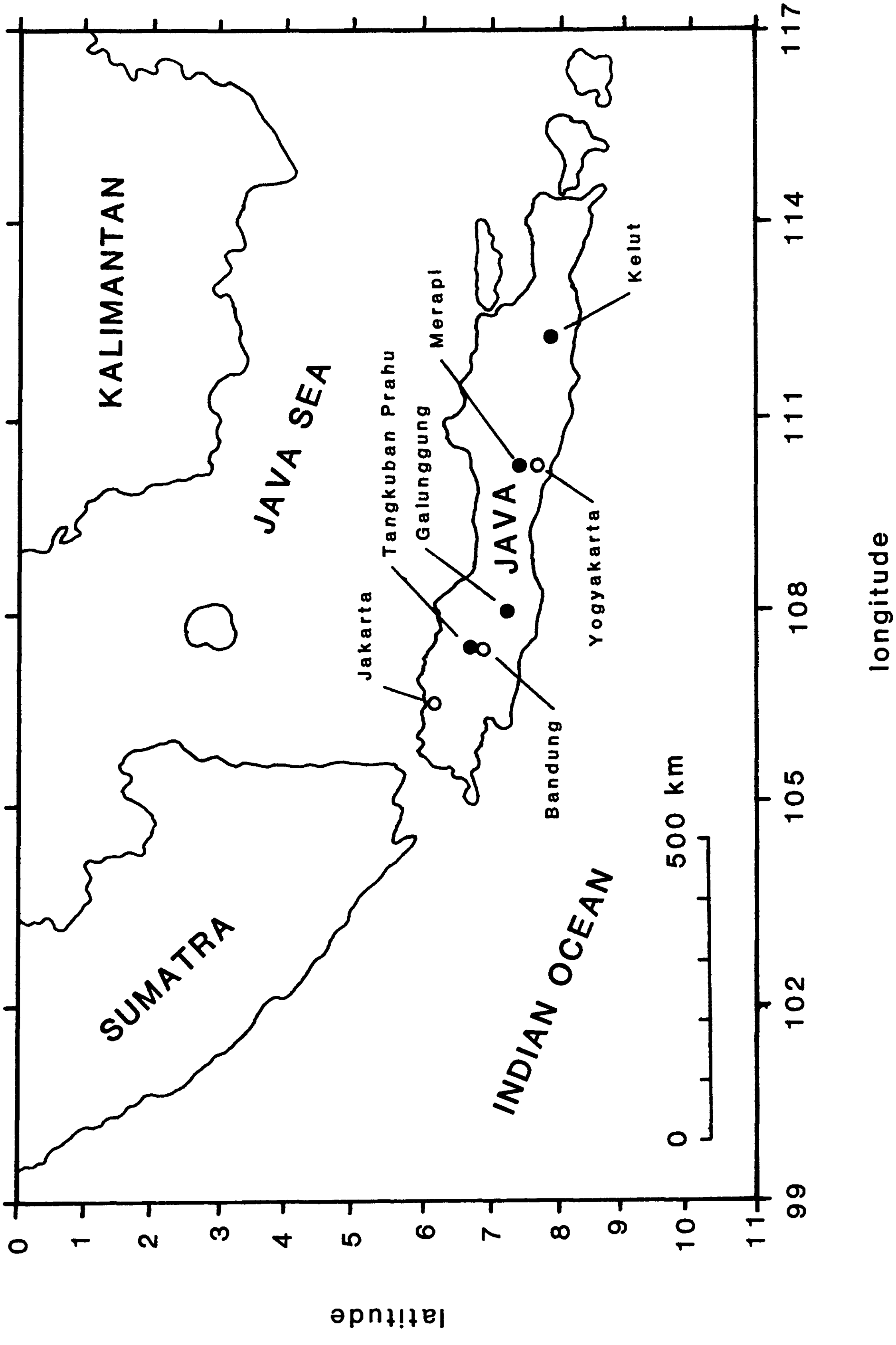

KALIMANTAN
JAVA SEA
SUMATRA
INDIAN OCEAN
JAVA
Jakarta
Tangkuban Prahu
Galunggung
Merapi
Kelut
Yogyakarta
Bandung
0
500 km
99
102
105
108
111
114
117
longitude
0
1
2
3
4
5
6
7
8
9
10
11
latitude

Figure 2

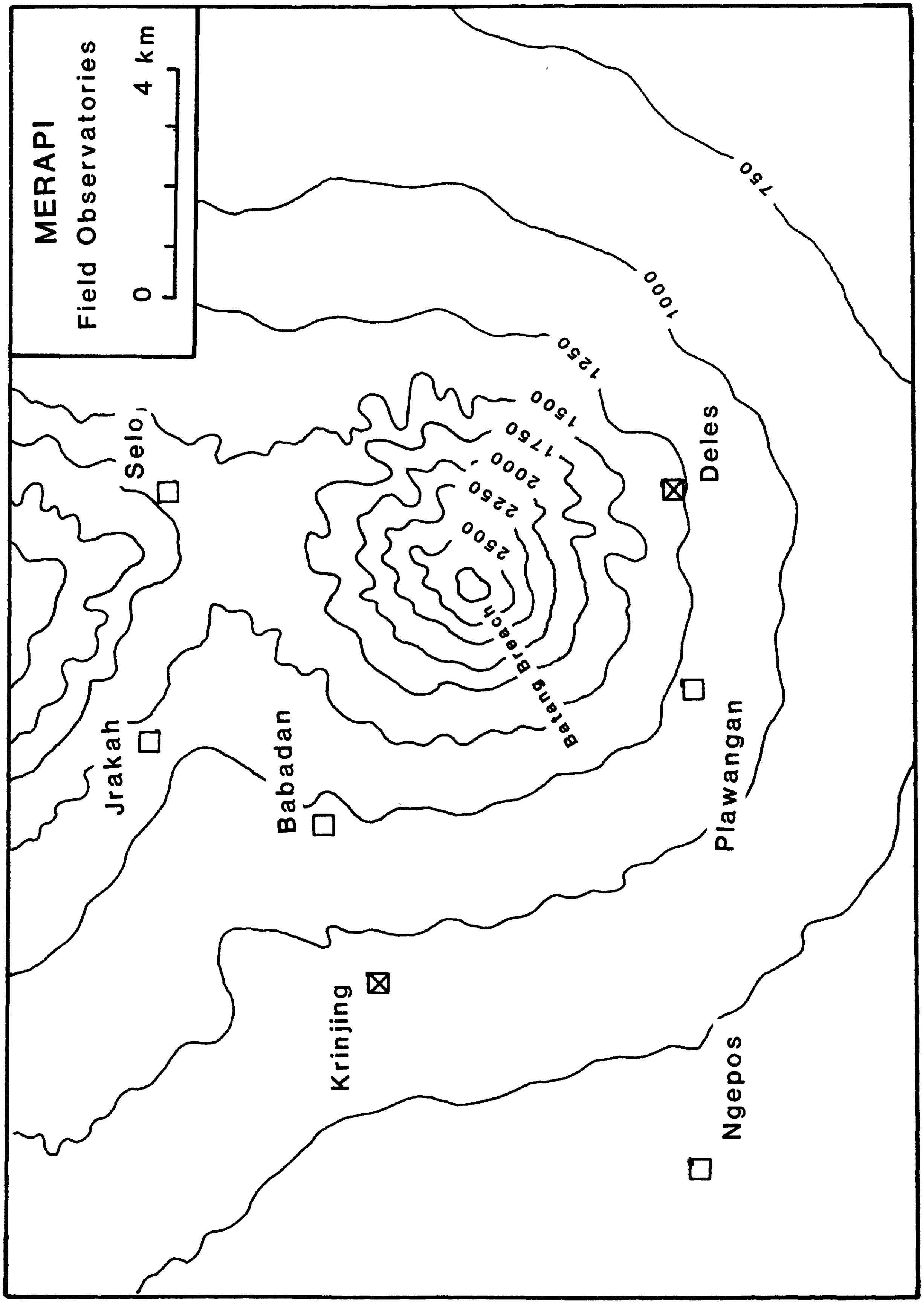
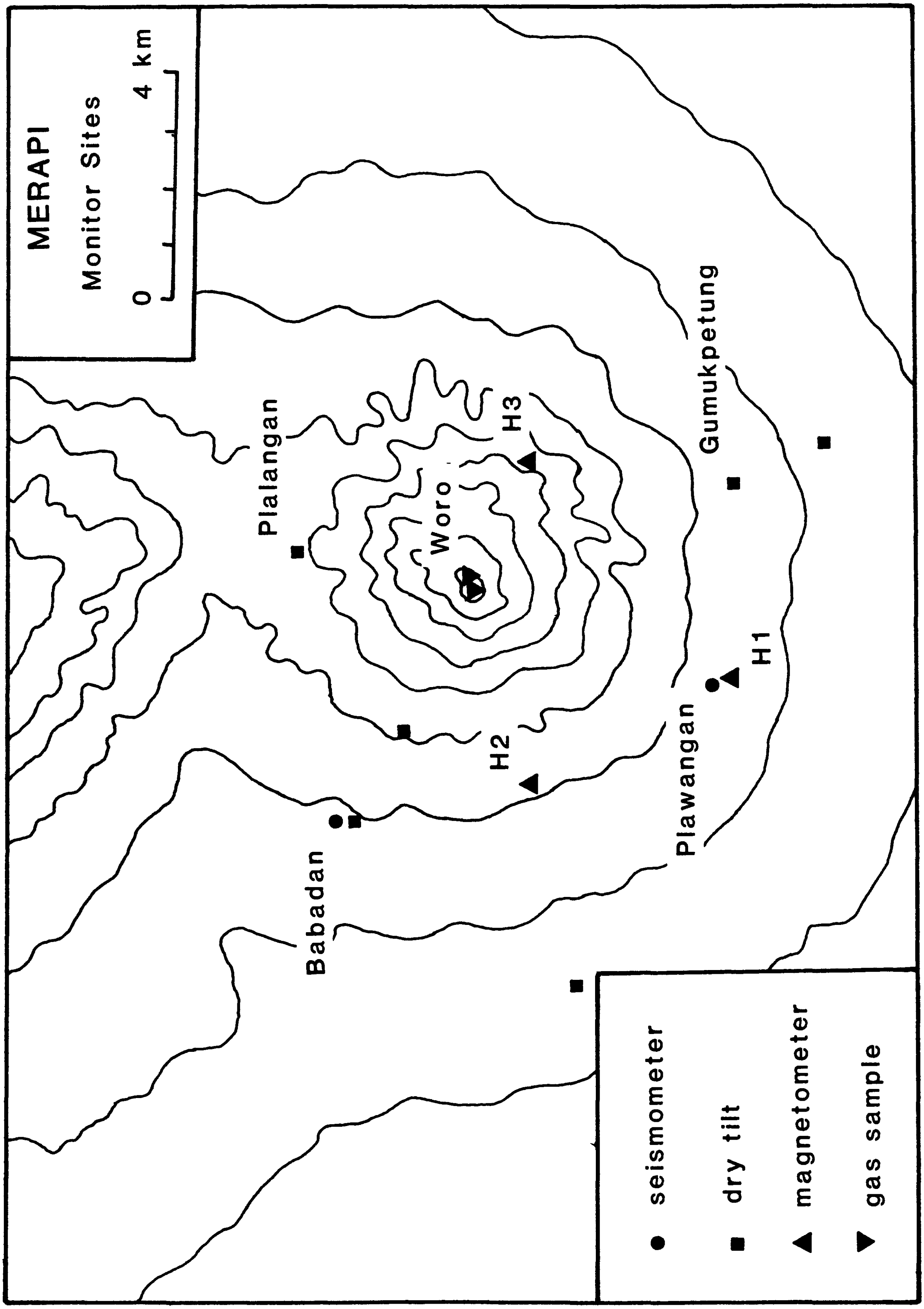

MERAPI
Field Observatories
0
4 km
contour interval 250 m
750
1000
1250
1500
1750
2000
2250
2500
Batang Breach
Selo
Jrakah
Babadan
Krinjing
Deles
Plawangan
Ngepos

Figure 3


MERAPI
Monitor Sites
0
4 km
Plalangan
Woro
H3
Gumukpetung
H1
H2
Plawangan
Babadan
● seismometer
■ dry tilt
▲ magnetometer
▼ gas sample

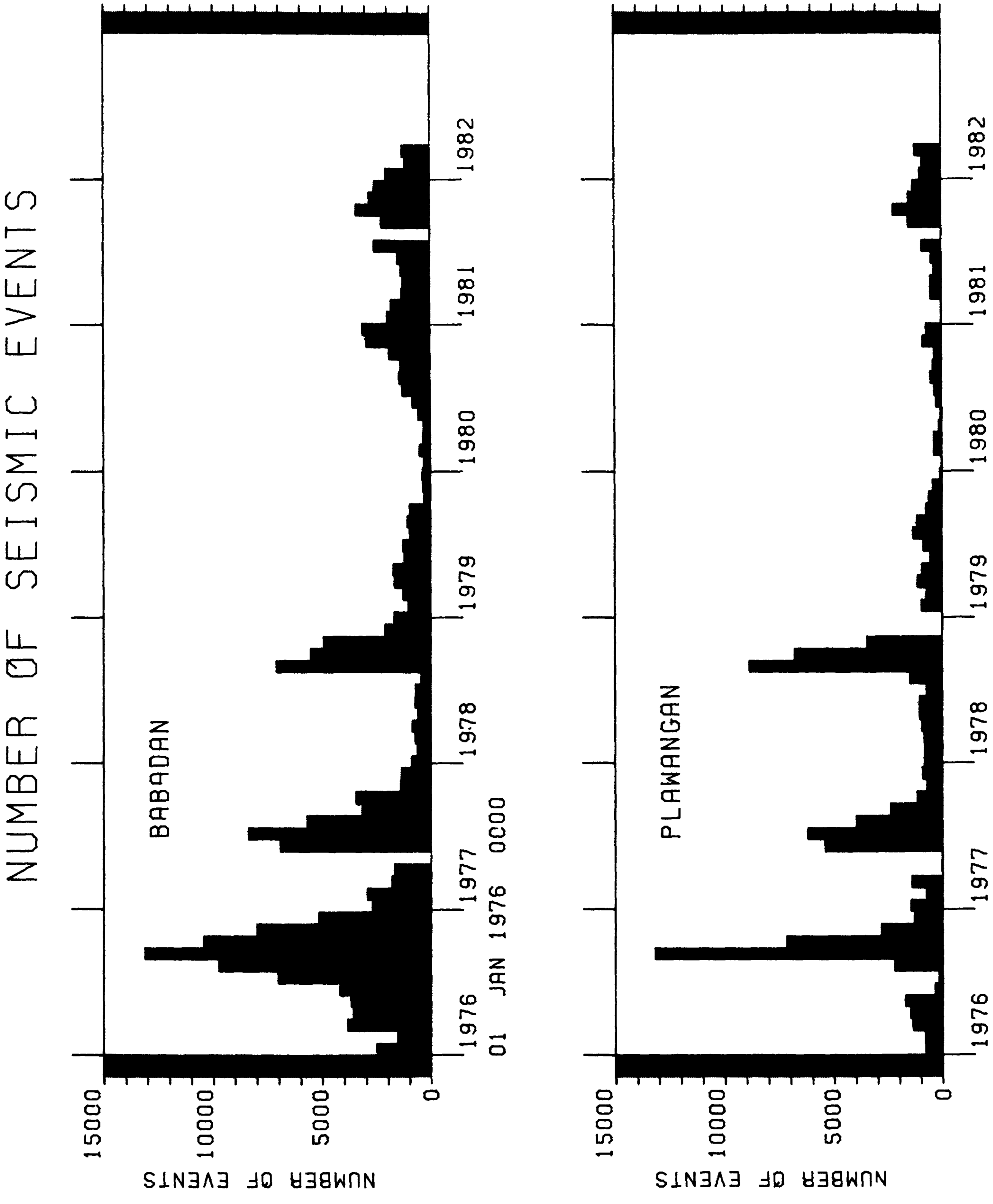

NUMBER ØF SEISMIC EVENTS
BABADAN
PLAWANGAN
NUMBER ØF EVENTS
15000
10000
5000
0
01 JAN 1976 0000
1976
1977
1978
1979
1980
1981
1982

Figure 5

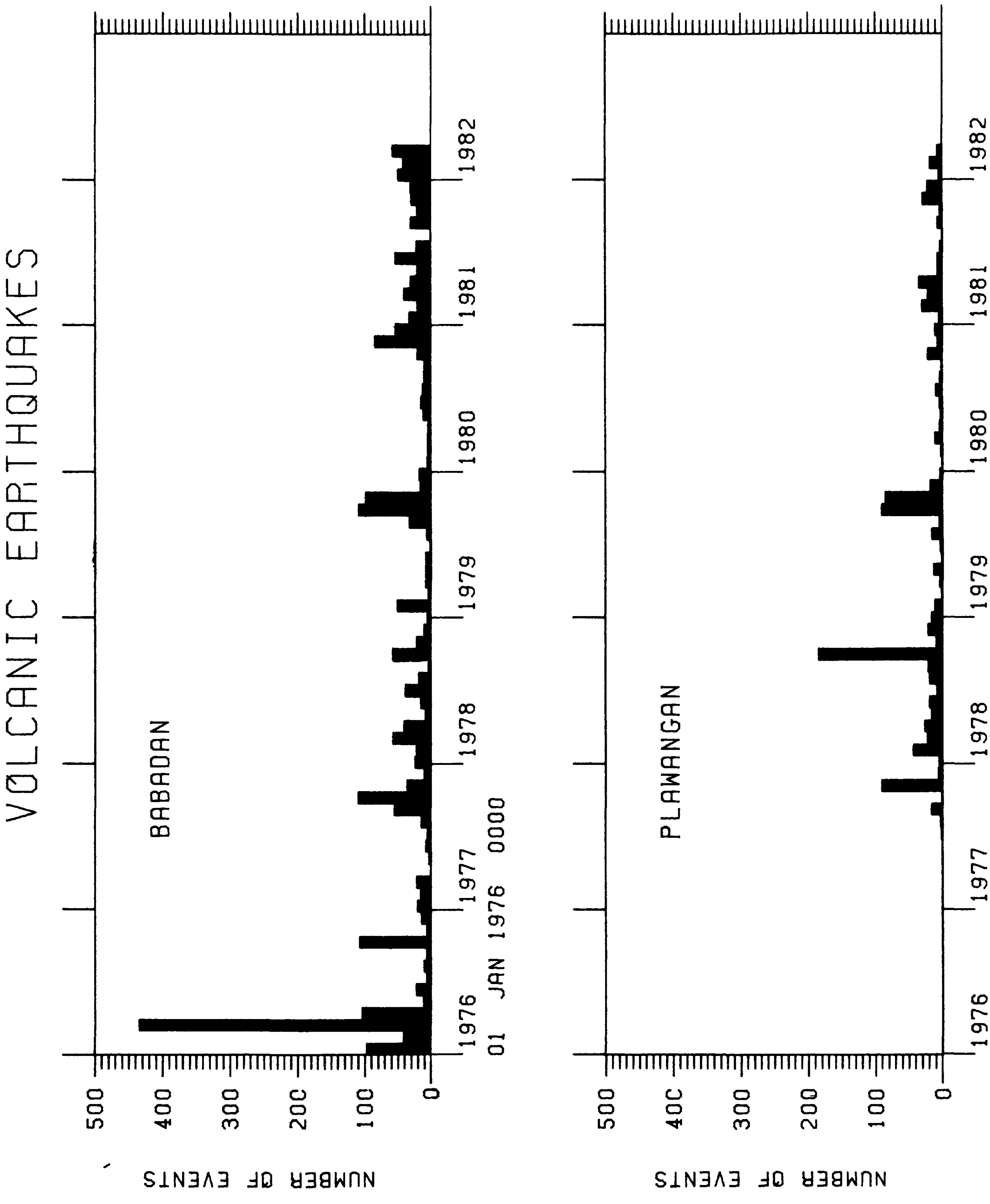
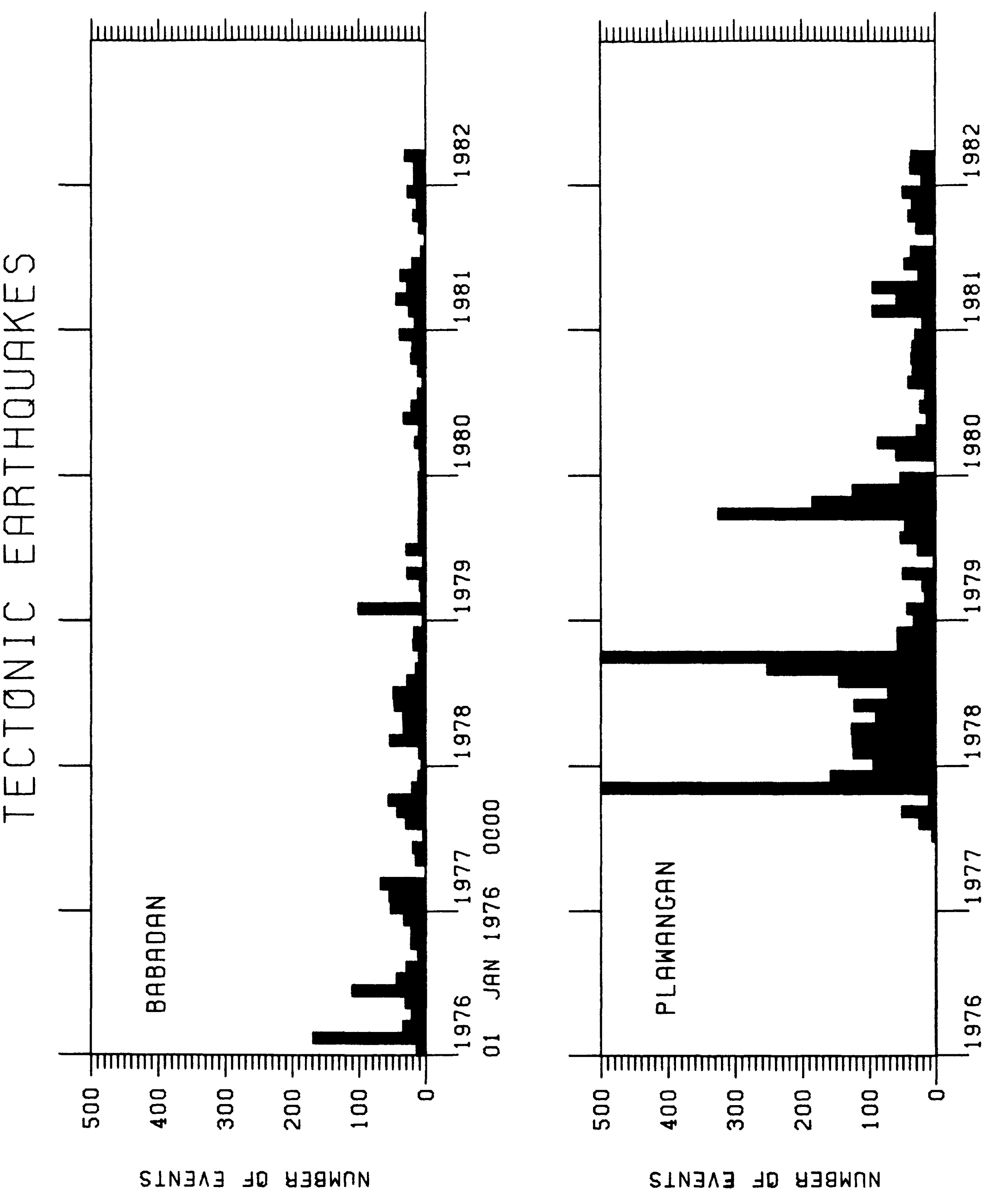
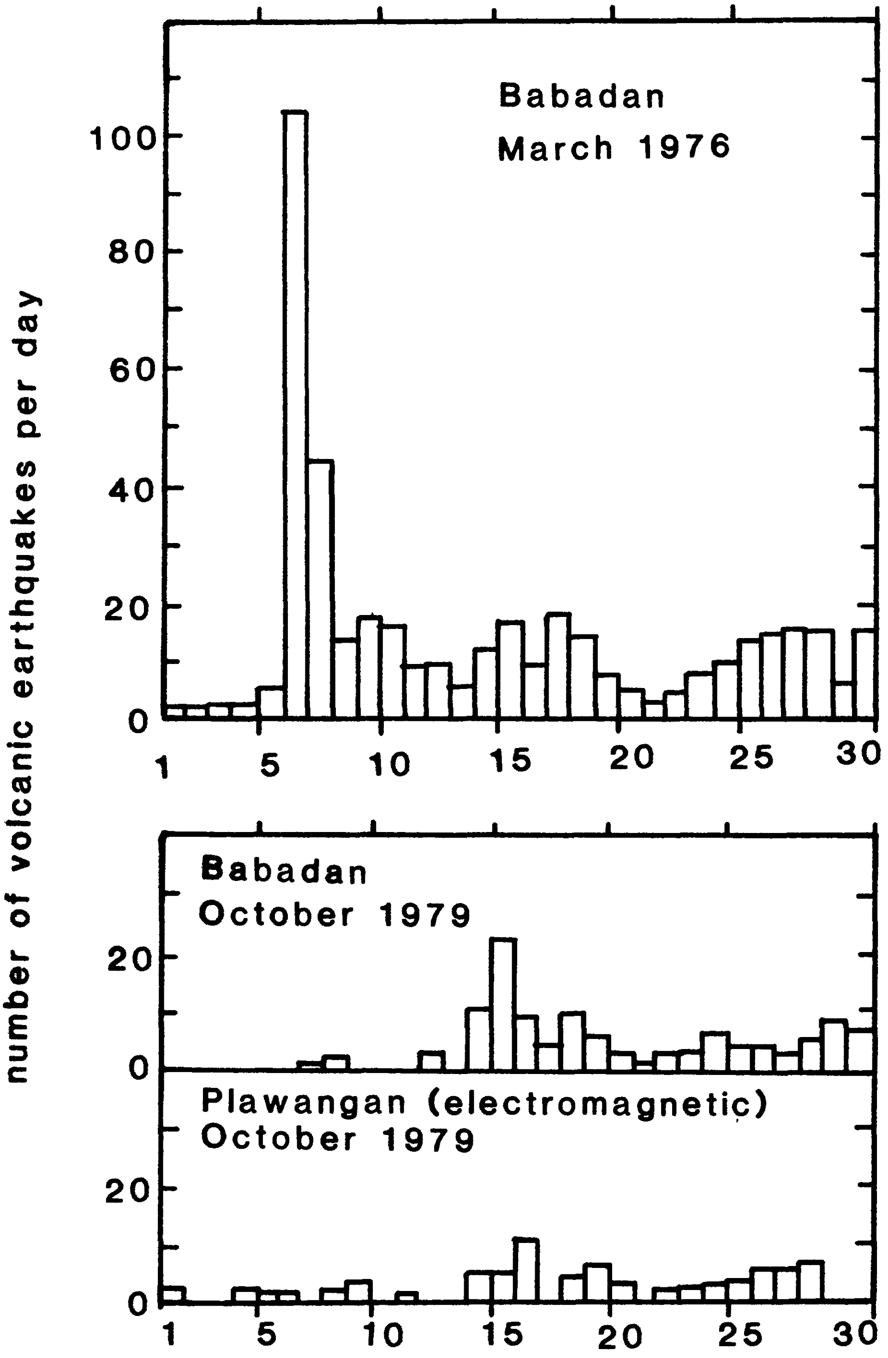

VOLCANIC EARTHQUAKES
BABADAN
PLAWANGAN
NUMBER OF EVENTS
NUMBER OF EVENTS
500
400
300
200
100
0
01 JAN 1976 0000
1976
1977
1978
1979
1980
1981
1982

Figure 6


TECTONIC EARTHQUAKES
BABADAN
PLAWANGAN
NUMBER OF EVENTS
NUMBER OF EVENTS
500
400
300
200
100
0
01 JAN 1976 0000
1976
1977
1978
1979
1980
1981
1982


number of volcanic earthquakes per day
Babadan
March 1976
0
20
40
60
80
100
1
5
10
15
20
25
30
Babadan
October 1979
0
20
Plawangan (electromagnetic)
October 1979
0
20
1
5
10
15
20
25
30

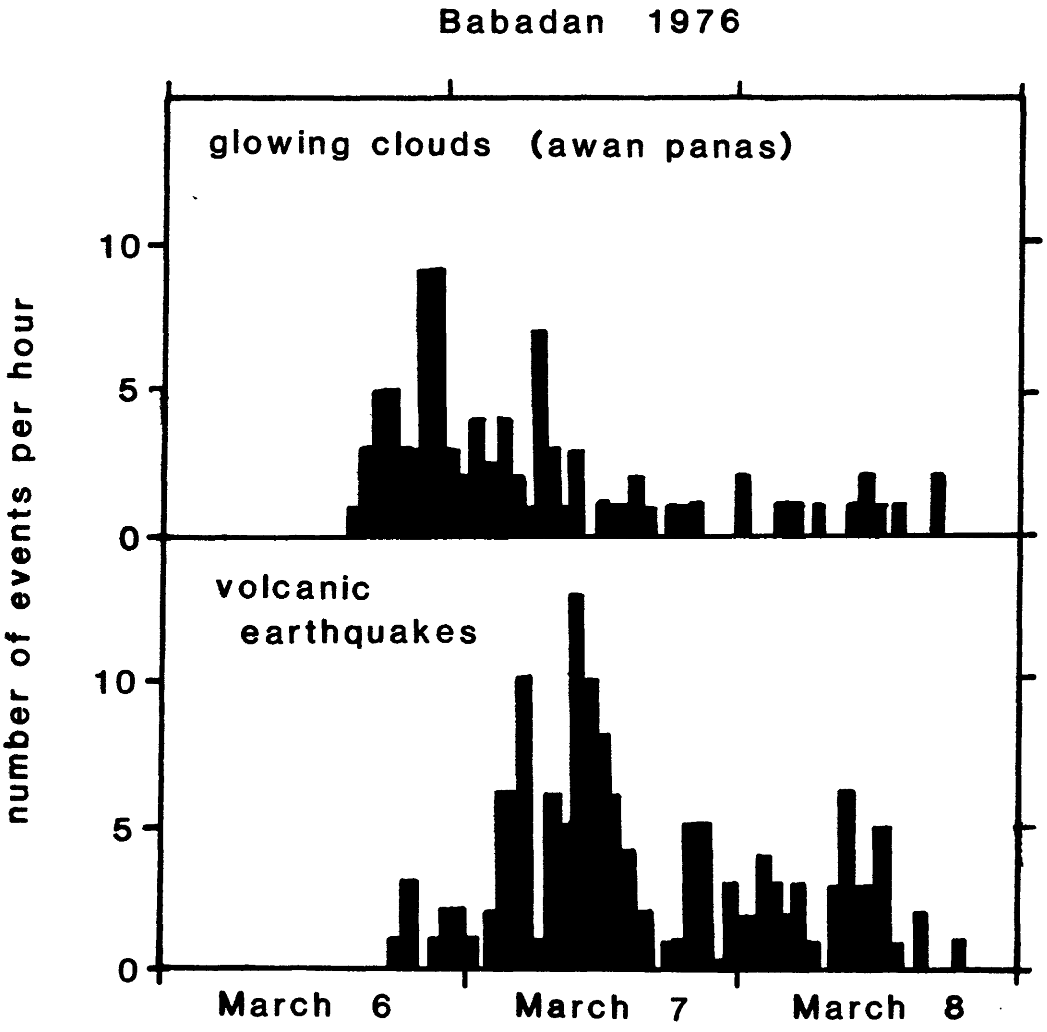
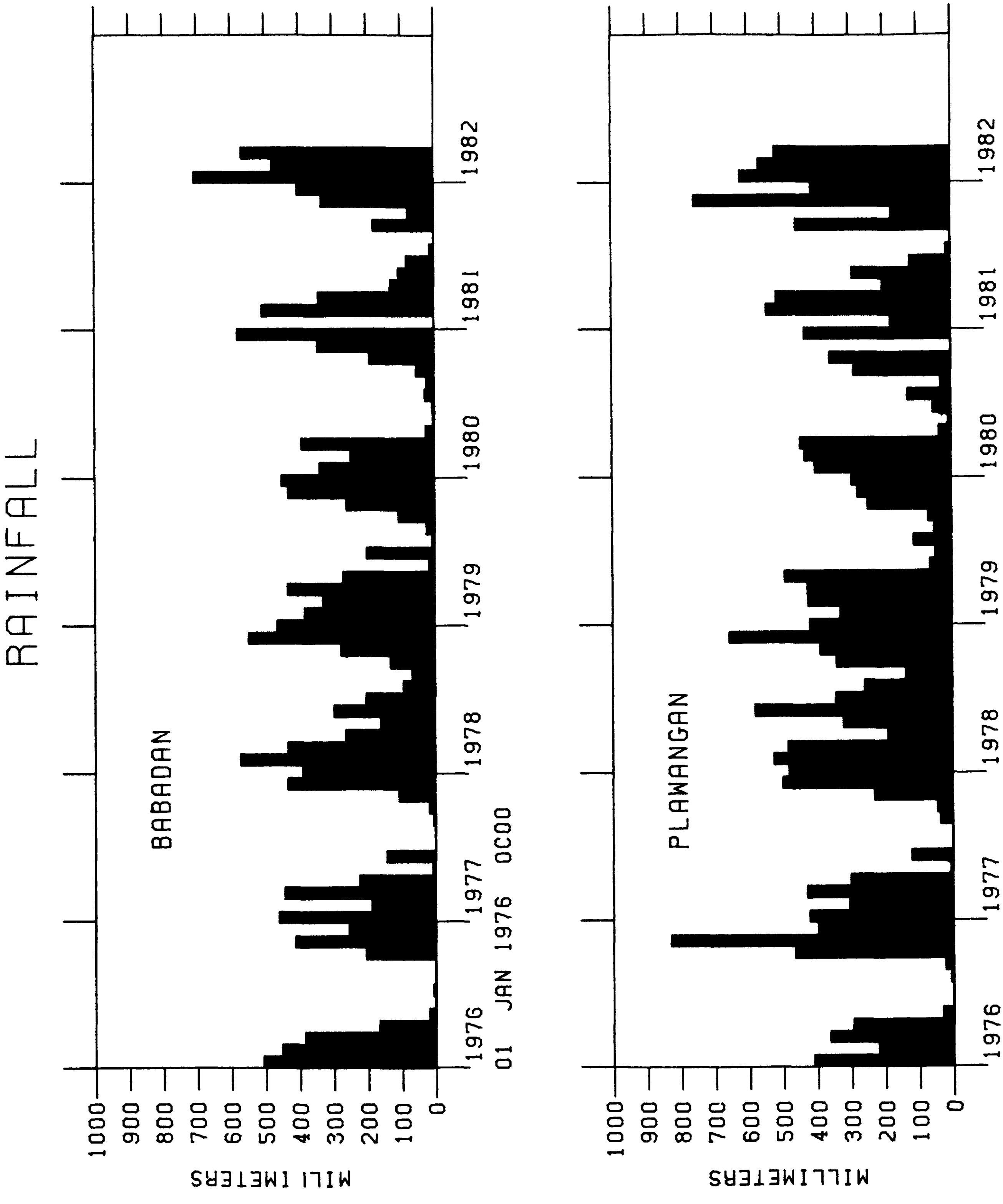
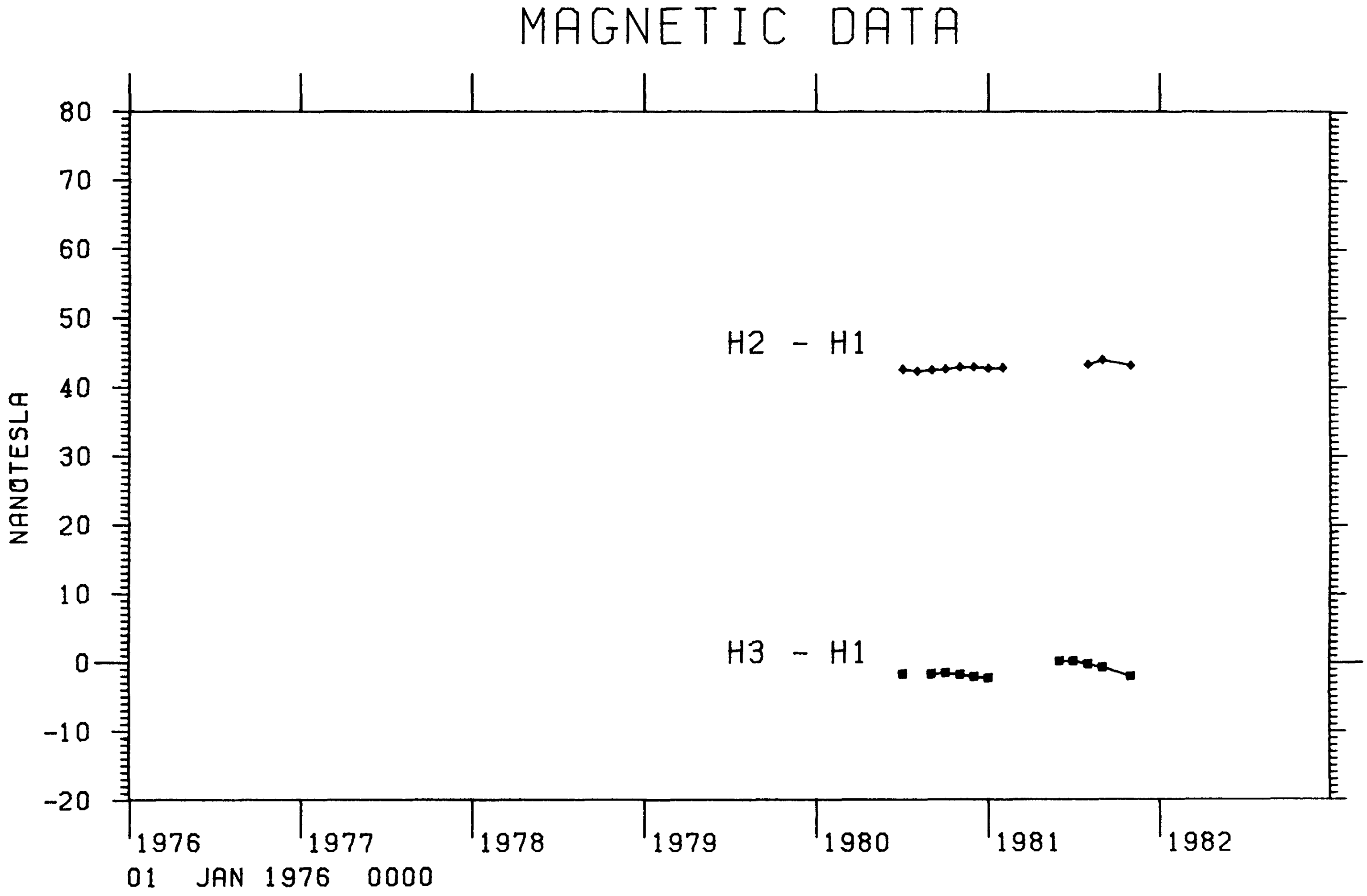

Babadan 1976
glowing clouds (awan panas)
volcanic earthquakes
number of events per hour
10
5
0
10
5
0
March 6
March 7
March 8

Figure 9


RAINFALL
BABADAN
PLAWANGAN
MILLIMETERS
MILLIMETERS
0
100
200
300
400
500
600
700
800
900
1000
1976
1977
1978
1979
1980
1981
1982
01 JAN 1976 0000



MAGNETIC DATA

Figure 11

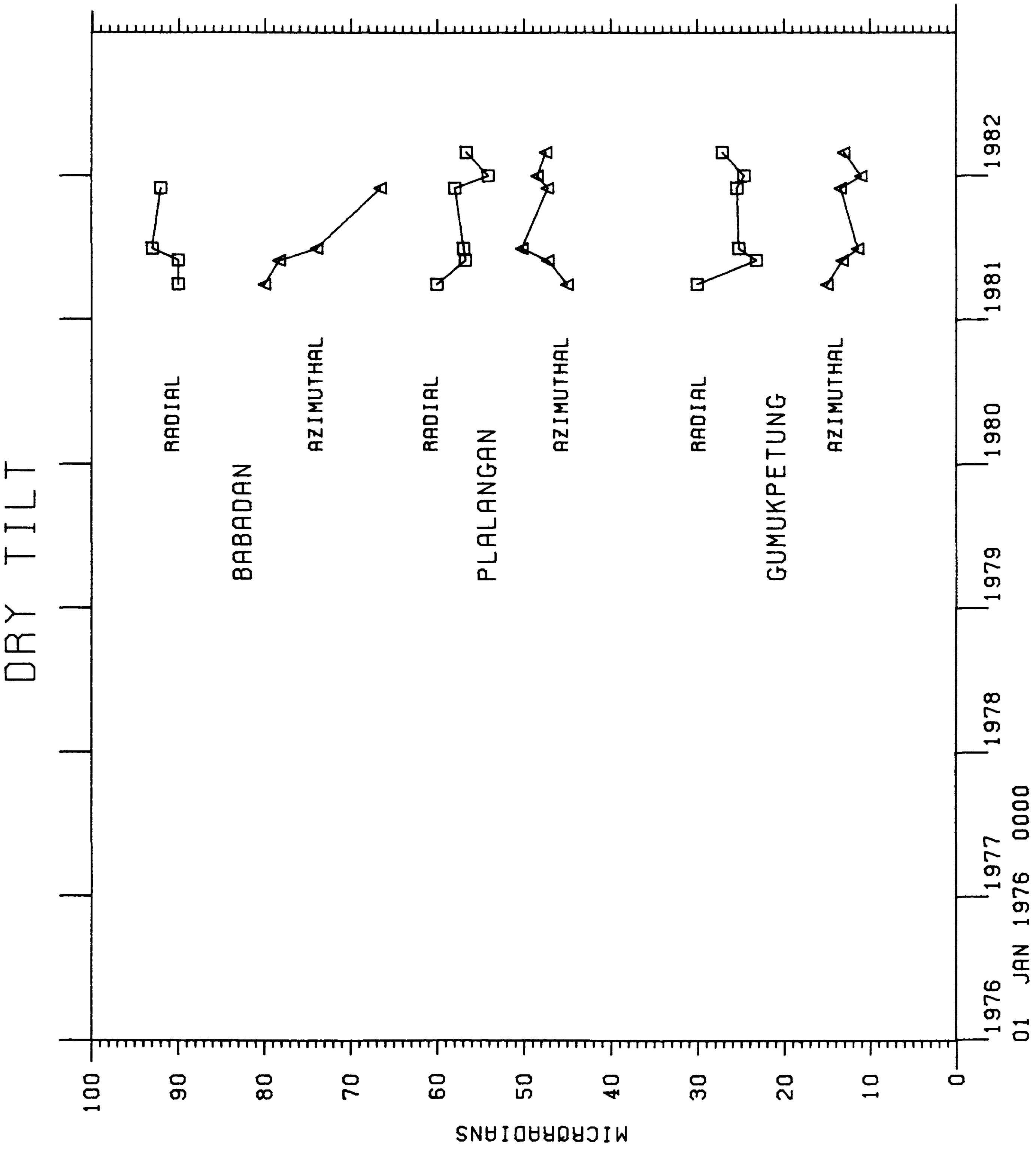

DRY TILT
BABADAN
PLALANGAN
GUMUKPETUNG
RADIAL
AZIMUTHAL
RADIAL
AZIMUTHAL
RADIAL
AZIMUTHAL
MICRORADIANS
100
90
80
70
60
50
40
30
20
10
0
1976
1977
1978
1979
1980
1981
1982
01 JAN 1976 0000

Figure 12

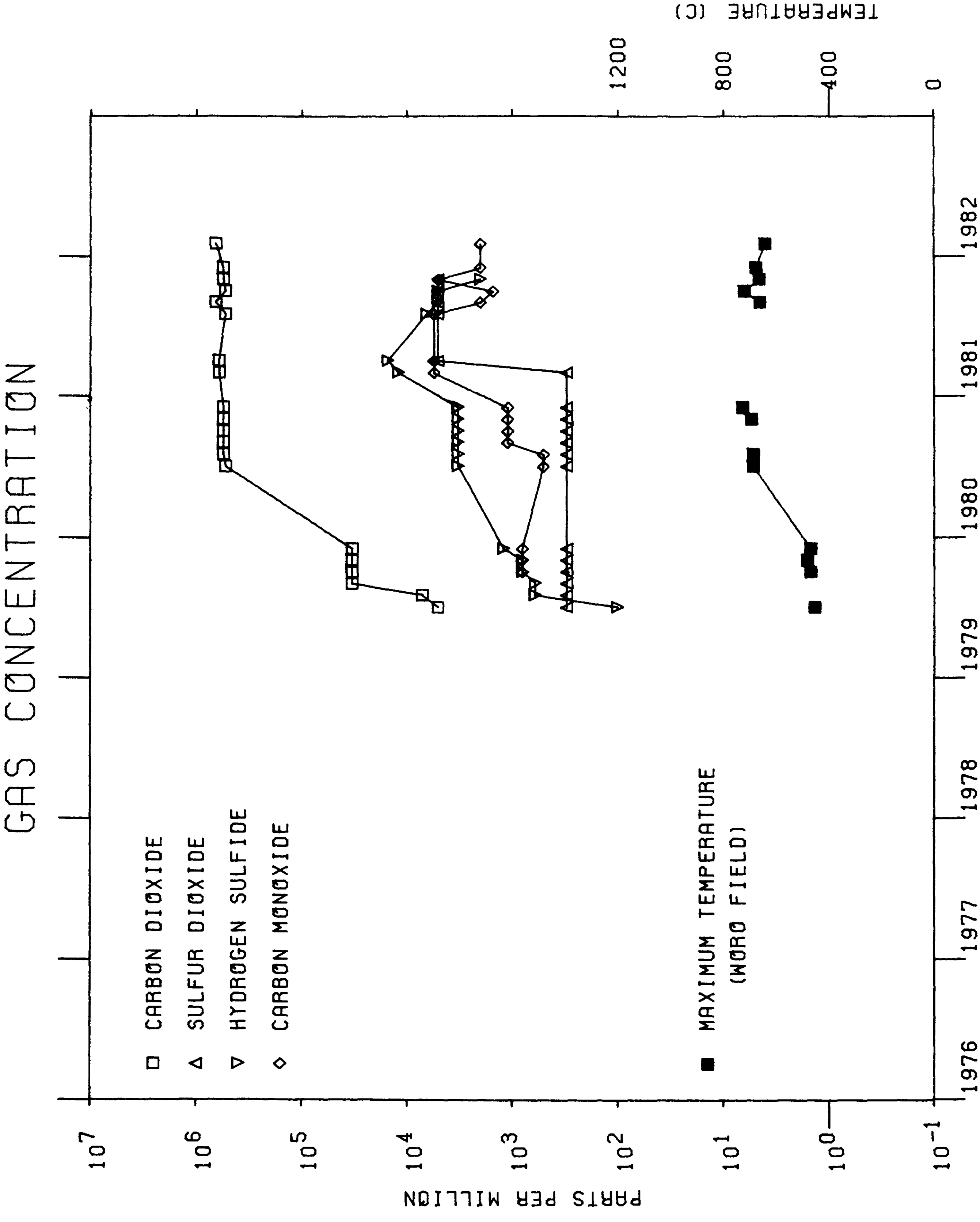

GAS CONCENTRATION
□ CARBON DIOXIDE
△ SULFUR DIOXIDE
▽ HYDROGEN SULFIDE
◇ CARBON MONOXIDE
■ MAXIMUM TEMPERATURE (WORO FIELD)
PARTS PER MILLION
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
TEMPERATURE (C)
1200
800
400
0
1976
1977
1978
1979
1980
1981
1982
01 JAN 1976 0000

Figure 13

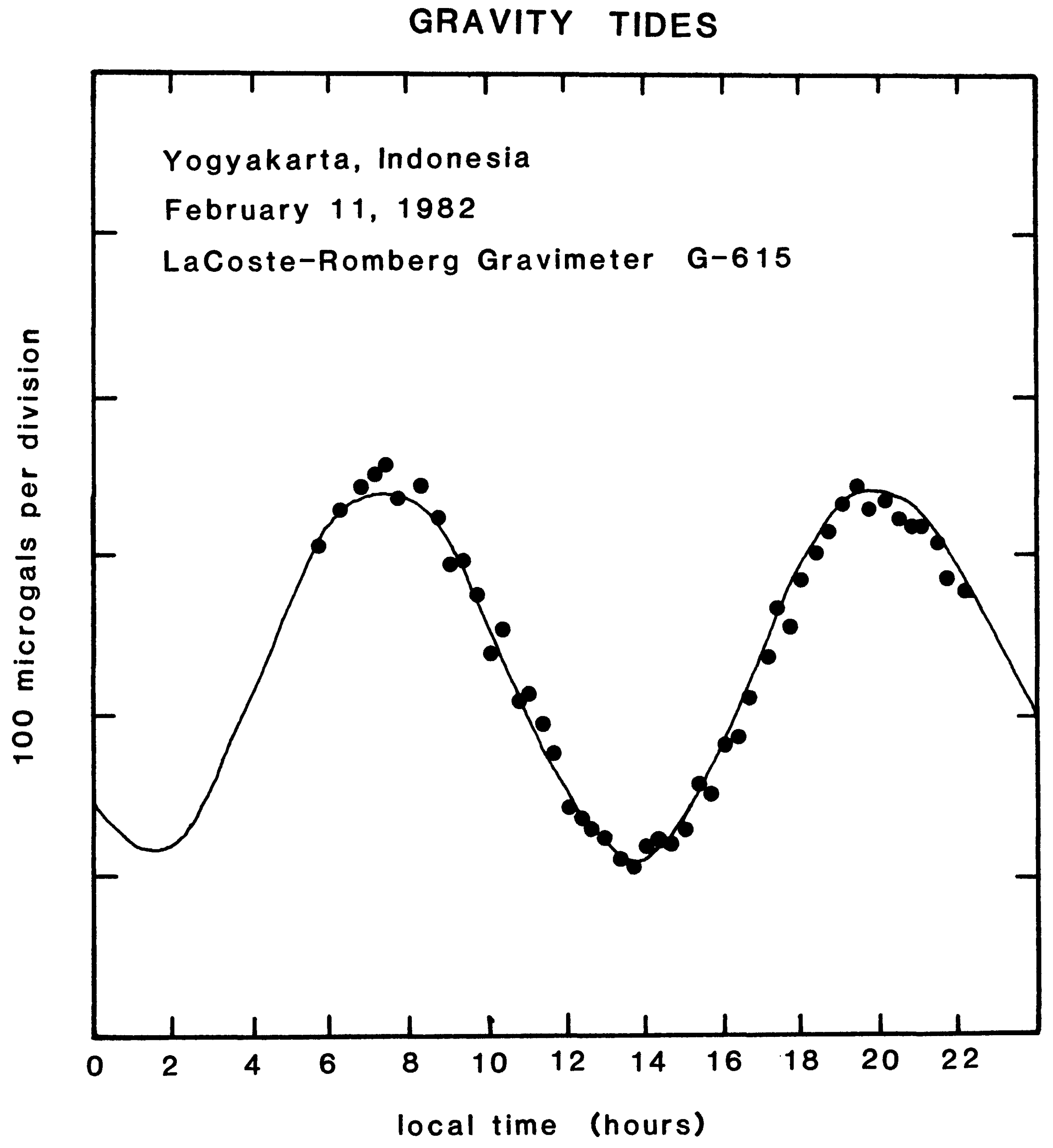
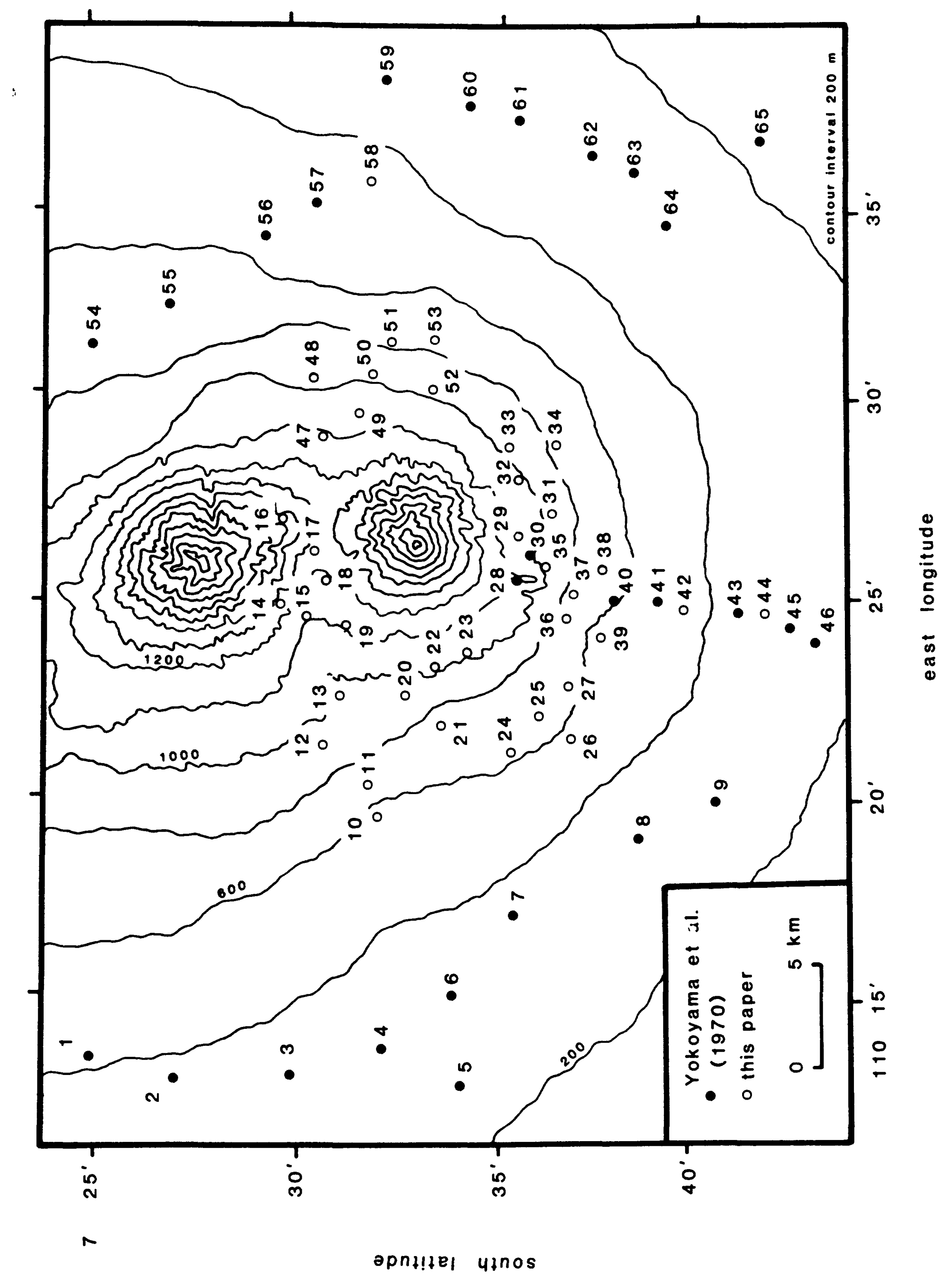
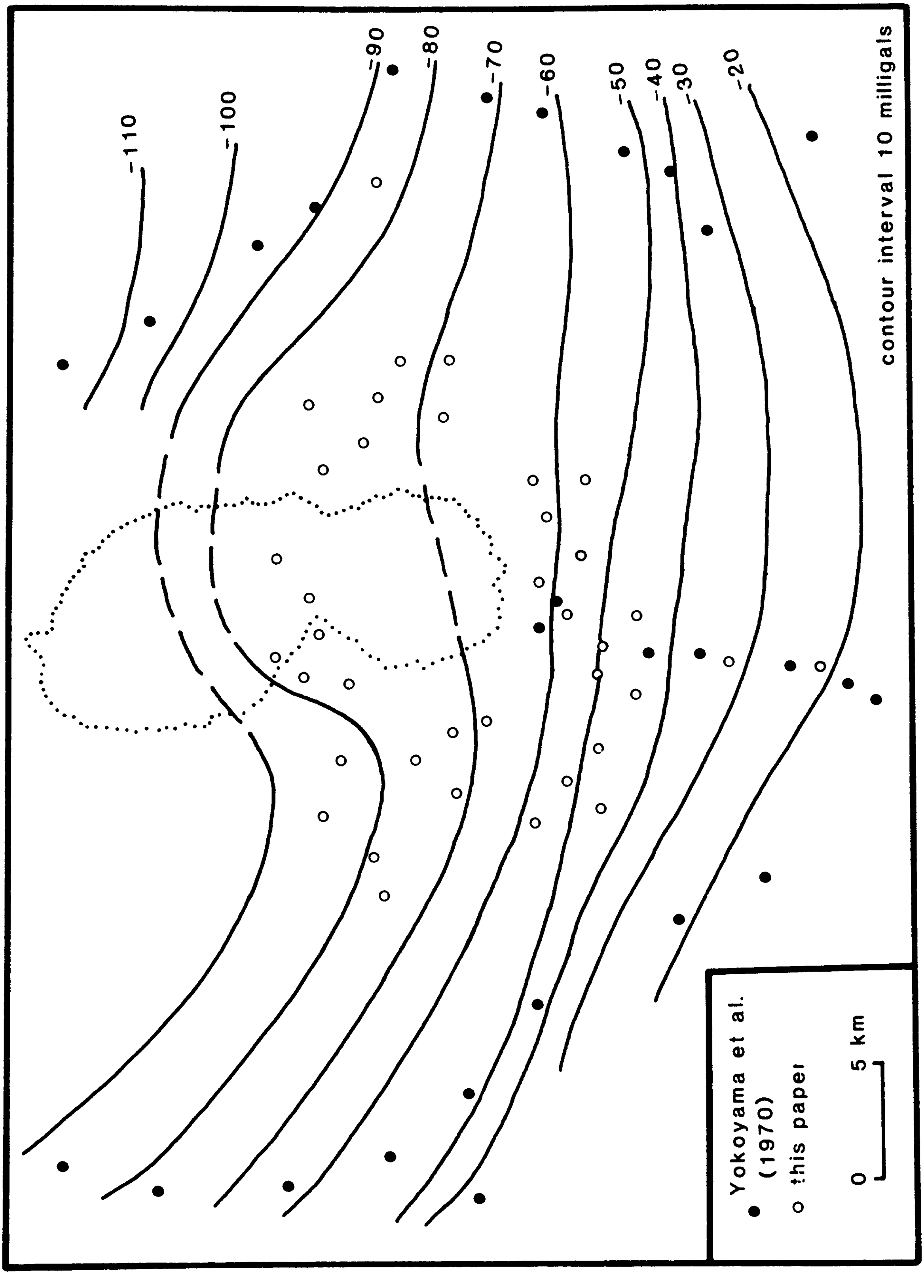
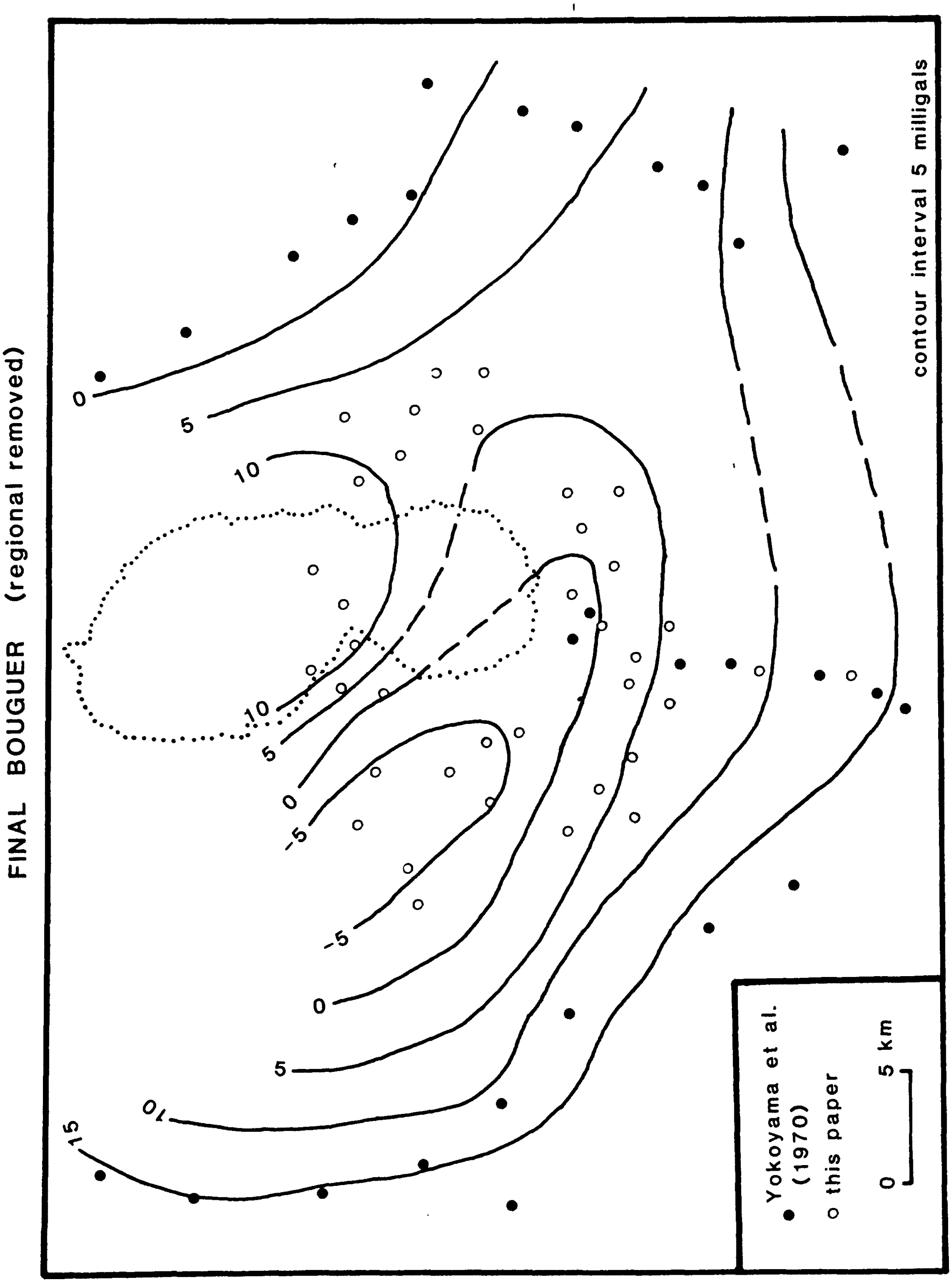

GRAVITY TIDES
Yogyakarta, Indonesia
February 11, 1982
LaCoste-Romberg Gravimeter G-615
100 microgals per division
0
2
4
6
8
10
12
14
16
18
20
22
local time (hours)

Figure 14


contour interval 200 m
east longitude
south latitude
110
15'
20'
25'
30'
35'
7
25'
30'
35'
40'
200
600
1000
1200
● Yokoyama et al. (1970)
○ this paper
0
5 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

SIMPLE BOUGUER





FINAL BOUGUER (regional removed)

contour interval 5 milligals

Figure 17

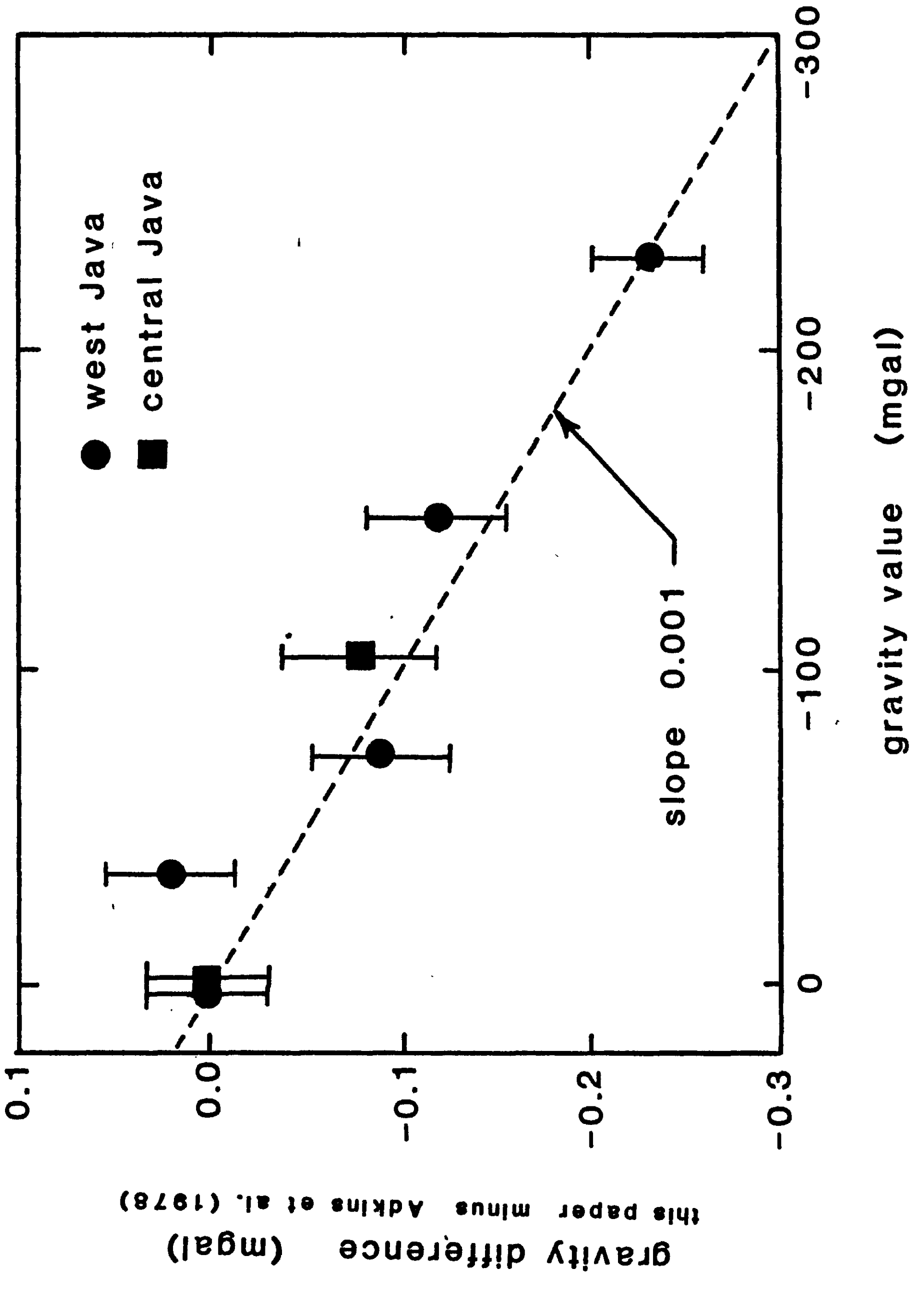

● west Java
■ central Java
slope 0.001
0
−100
−200
−300
gravity value (mgal)
0.1
0.0
−0.1
−0.2
−0.3
gravity difference (mgal)
this paper minus Adkins et al. (1978)

Figure 18

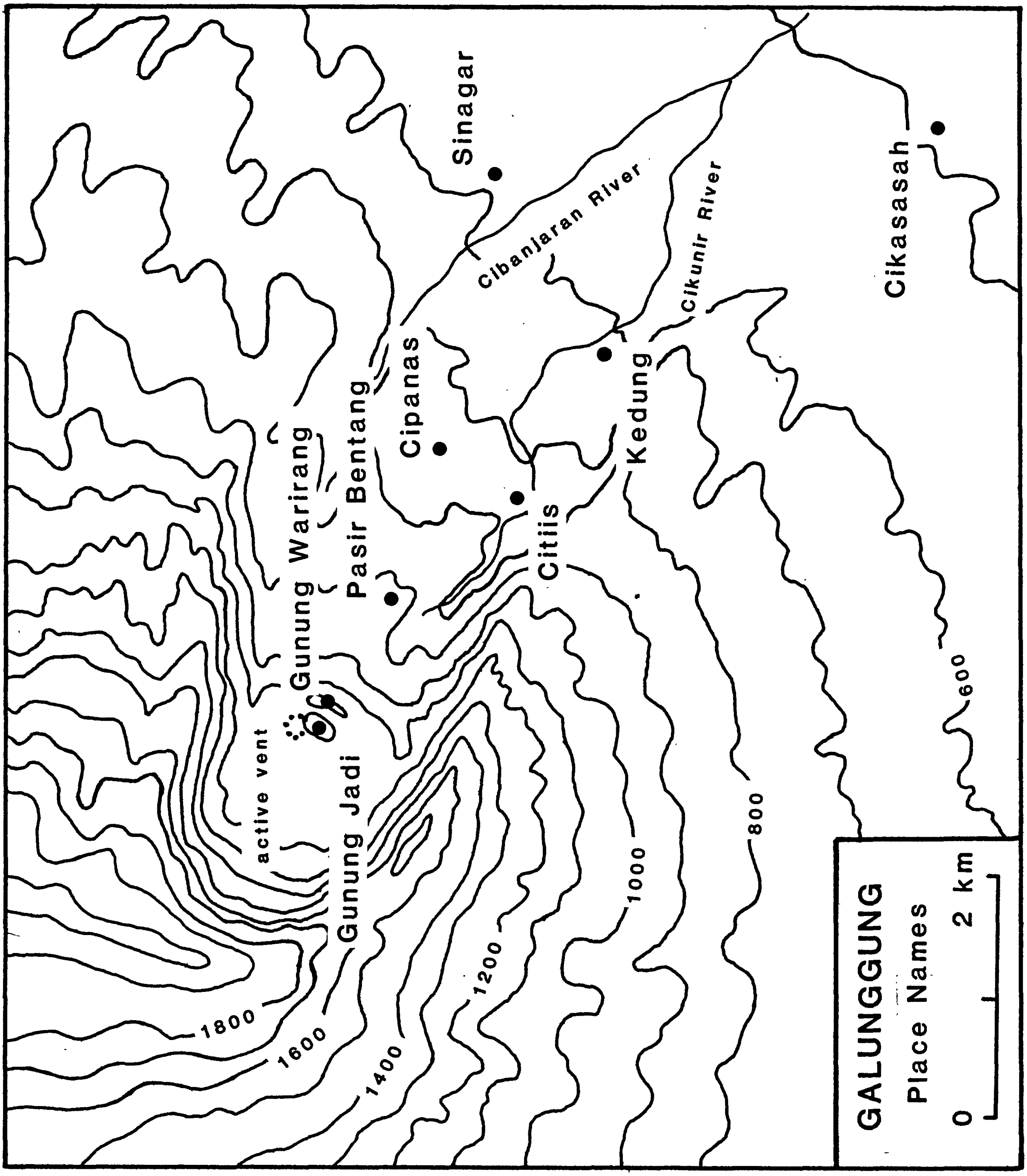
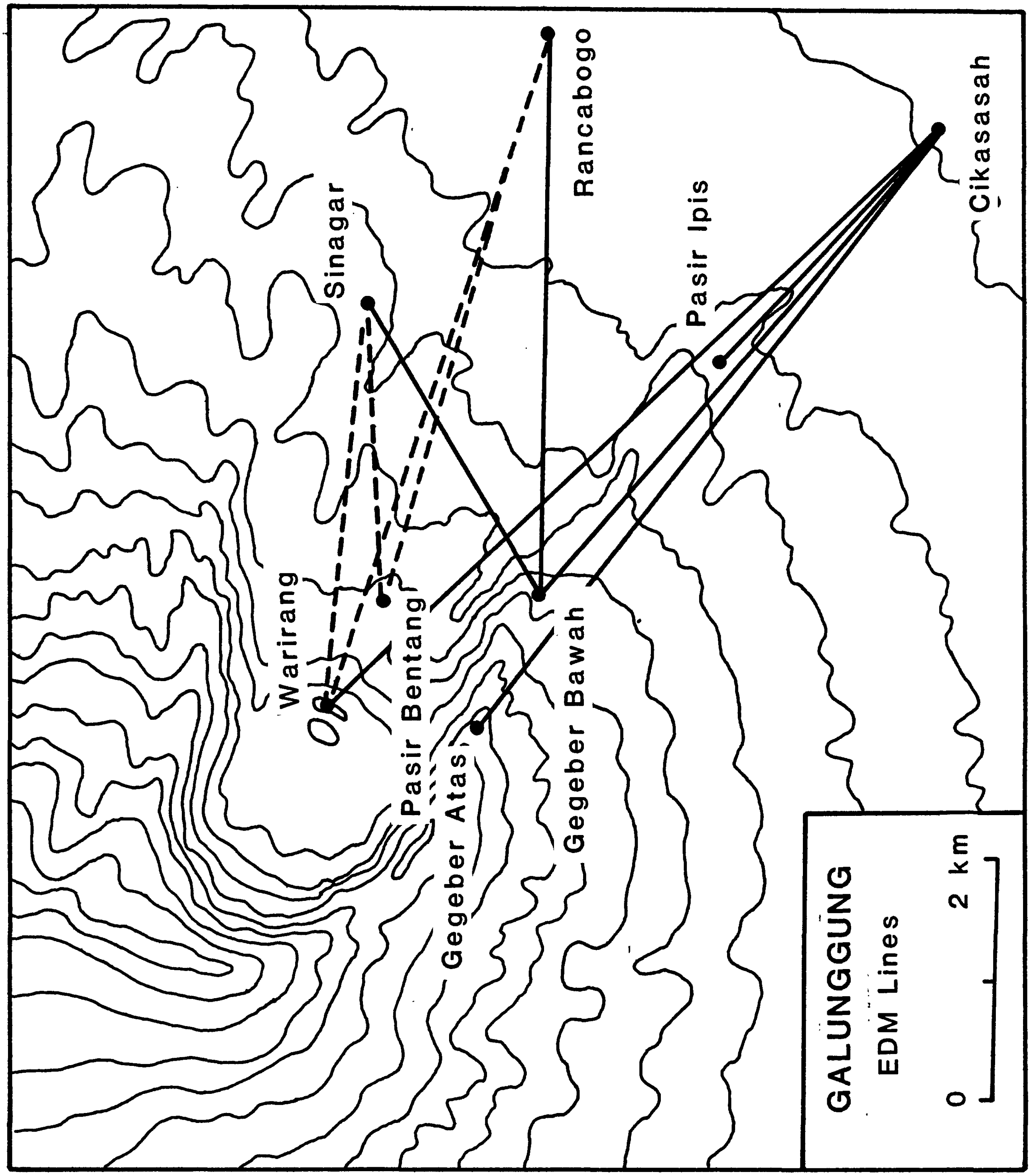
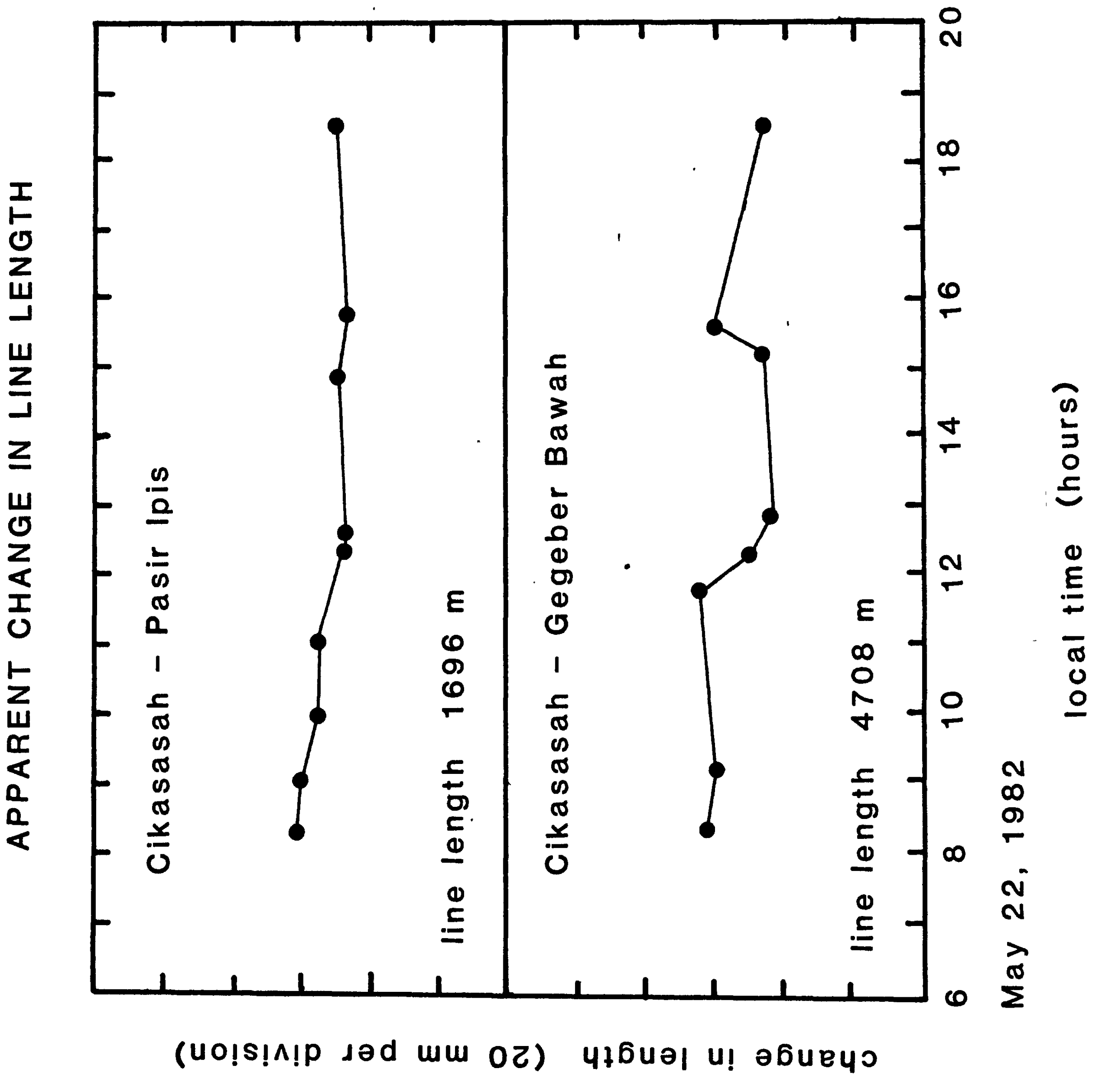
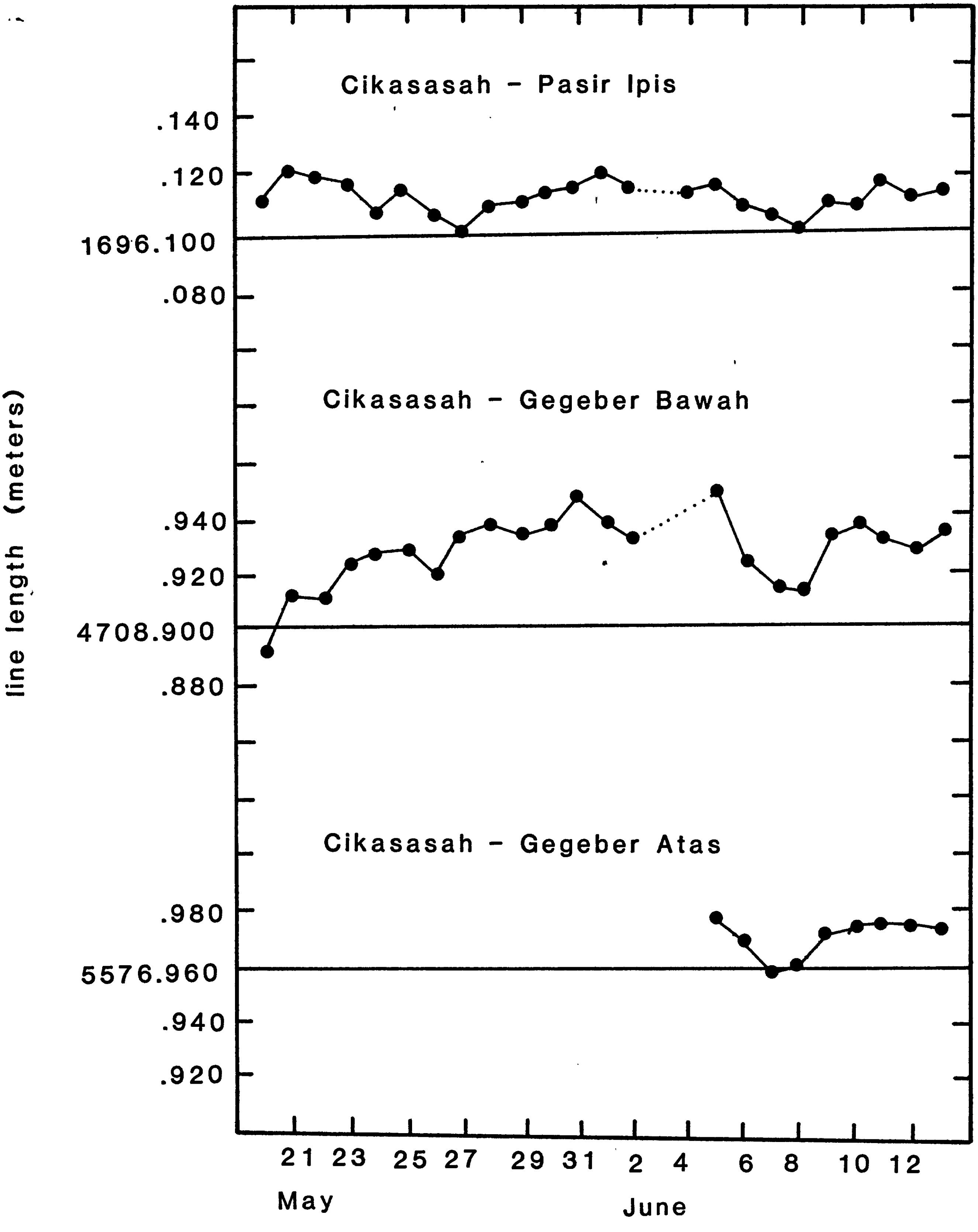

GALUNGGUNG
Place Names
0
2 km
contour interval 100 m
Sinagar
Cibanjaran River
Cikunir River
Cikasasah
Cipanas
Kedung
Pasir Bentang
Citiis
Gunung Warirang
active vent
Gunung Jadi
1800
1600
1400
1200
1000
800
600

Figure 19


Rancabogo
Cikasasah
Pasir Ipis
Sinagar
Warirang
Pasir Bentang
Gegeber Atas
Gegeber Bawah
GALUNGGUNG
EDM Lines
0
2 km


APPARENT CHANGE IN LINE LENGTH
Cikasasah - Pasir Ipis
line length 1696 m
Cikasasah - Gegeber Bawah
line length 4708 m
change in length (20 mm per division)
6
8
10
12
14
16
18
20
local time (hours)
May 22, 1982

# GALUNGGUNG EDM LINES



# APPENDIX

Merapi monthly reports -- January 1982
February 1982
March 1982

# MERAPI MONTHLY REPORT
## JANUARY 1982
## SUMMARY OF ACTIVITY

The frequency of rockfalls and glowing clouds continued to decline throughout January 1982. This activity was confined to the southwest of Merapi along the Batang River and reached a maximum distance of five kilometers from the summit.

The daily number of seismic events steadily decreased throughout the past month, probably representing the end of activity which began on November 29, 1982. A small swarm of multi-phase volcanic earthquakes, presumably related to lava dome extrusion, was recorded at Babadan field observatory on January 18-19. These events were too small to also be recorded by the mechanical seismograph at Plawangan.

Summary of seismic activity, January 1982:

| | Babadan | Plawangan | |
|---|---|---|---|
| | (electro) | (mech) | (electro) |
| Total seismic events | 2058 | 1470 | 971 |
| Volcanic earthquakes | 49 | 0 | 5 |
| multi-phase events | 37 | 0 | 0 |
| Tectonic earthquakes | 16 | 8 | 19 |

Few visual observations of Merapi were possible owing to the low cloud cover throughout most of January 1982. Three glowing clouds from the summit lava dome were visually observed at 1607 on January 21, at 0817 on January 16, and at 0704 on January 29. A very light ashfall near Deles, five kilometers southeast of Merapi, accompanied the occurrence of the first event. Weather conditions made it impossible to estimate the volume of the active dome.

Dry tilt measurements were made on January 24-27 at six stations near Merapi. A comparison of these data with the previous measurements on December 14-17, 1981, indicated a maximum measured change of 4.3 microradians at Babadan. Though all measured changes were less than the expected precision for this type of measurement, there is a suggestion of a slight deflation of the volcano.

Temperature measurements made on January 26 at nine fumeroles in the Woro solfatara field yielded a temperature range of 70-560 degrees Celsius. Temperatures in this field were cooler by 20-230 degrees from the previous measurements made in December 1982. Rain and cloud conditions prevented temperature measurements from being made in the Gendol solfatara field.

# MERAPI MONTHLY REPORT
## FEBRUARY 1982
## SUMMARY OF ACTIVITY

Rockfalls and glowing clouds continued to be observed to spall from the active dome. During February 1982, these landslides traveled down the Batang breach a maximum distance of 2.5 kilometers from the summit.

Seismic activity during February was similar to that of the previous month. A number of multi-phase events, recorded by the seismograph at the Babadan field observatory, occurred during the last week of February.

Summary of seismic activity, February 1982:

| | Babadan | Plawangan | |
|---|---|---|---|
| | (electro) | (mech) | (electro) |
| Total seismic events | 1147 | 953 | 872 |
| Volcanic earthquakes | 41 | 16 | 18 |
| multi-phase events | 38 | 0 | 0 |
| Tectonic earthquakes | 16 | 35 | 36 |
| Glowing clouds | 4 | 7 | 6 |

Weather conditions limited visual observations of Merapi; no new measurements of the active dome were possible. Glowing clouds were observed at 0600 on February 1, at 1645 and 1648 on February 13, at 0620 on February 15, and at 0623 on February 21.

No dry tilt or summit temperature measurements were made during February 1982.

The total amount of rainfall recorded at the Plawangan and Babadan field observatories during February was 563 and 476 millimeters, respectively.

On February 17, a minor flood occurred along the Putih and the Bebeng Rivers. Some damage occurred to a check dam near Krangagan village on the Bebeng River.

Gas samples were collected from the Woro solfatara field. Weather conditions prevented gas samples from also being collected in the Gendol field.

# MERAPI MONTHLY REPORT
## MARCH 1982
## SUMMARY OF ACTIVITY

Material continued to fall from the active dome producing rockfalls and one visually observed glowing cloud which traveled down the Batang breach a maximum distance of 1.5 kilometers from the summit.

Seismic activity during March 1982 slightly increased over that of the preceding months. The increased number of multi-phase events recorded by the Babadan seismograph may be related to unconfirmed growth of the summit dome.

Summary of seismic activity, March 1982:

| | Babadan | Plawanagan | |
|---|---|---|---|
| | (electro) | (mech) | (electro) |
| Total seismic events | 1291 | 1005 | 1207 |
| Volcanic earthquakes | 57 | 6 | 7 |
| multi-phase events | 52 | 0 | 0 |
| Tectonic earthquakes | 30 | 39 | 34 |
| Glowing clouds | 3 | 4 | 2 |

Cloud cover throughout most of March 1982 restricted visual observations of Merapi from the field observatories. A glowing cloud was observed at 1029 on March 15 by observers working along the Krasak River near the 1969 pyroclastic flows. On March 3, a team working in the summit area observed continuous small rockfalls from the lower end of the active lava dome; however, plume conditions prevented detailed observations from being made.

Dry tilt measurements were made on March 5-8 at six stations near Merapi. The maximum measured change with respect to the previous set of measurements made in January 1982 was 7 microradians at Babadan. There is a suggestion in the tilt changes since January 1982 of a radially outward directed pattern; however, these small changes may be the result of statistical variations in the measurements.

Measurements of fumerolic temperatures made on March 3 indicated no significant change since January 1982. The maximum measured temperature in the Woro field was 580 degrees Celsius.

The total amount of rainfall recorded at Plawangan and Babadan field observatories during March was 516 and 566 millimeters, respectively.

A geochemical team took temperature measurements, gas and condensate samples, and ash samples in the summit region on March 9. In the Gendol field, the carbon monoxide concentration was lower than the previous measurement made in November 1981; the carbon dioxide concentration was roughly the same. The sulfate concentration dropped drastically between November 1981 and March 1982 in both the Gendol and Woro fields. Overall, the summit temperatures and gas concentrations have decreased since the major rockfall activity in late November 1981.

A. Djumarma, L. Pardyanto, F. Suparban, J. Matahelumual, M. Badruddin, L. Djohrman, H. Said, S. Dwipa, S. Harto, and J. Dvorak