DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Geodetic Measurements at Indonesian Volcanoes

by

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Abstract

A cooperative program in volcanic studies between the Volcanological Survey of Indonesia and the U.S. Geological Survey has been in existence since 1979. As part of this program, geodetic monitoring using tilt and trilateration techniques has been carried out at several potentially active volcanoes on Java. The results for two volcanoes, Galunggung and Tangkuban Parahu, show consistent changes that indicate inflation of these two volcanoes. Simple models to these data are used to estimate the depth to the source and the volume of uplift. Geodetic measurements at Merapi and Kelut volcanoes have not shown any consistent changes.

Tilt and trilateration networks were established west of Lamongan volcano in response to a recent seismic swarm. These networks should be remeasured in 1986 to determine if any subsurface magma movement is currently taking place.

A list of recommendations to improve the geodetic monitoring of volcanoes by VSI is given at the end of this report.

Introduction

This report summarizes the activities during the assignment to Indonesia from December 1985 to January 1986 of John Dvorak, U.S. Geological Survey (USGS). The purpose of the assignment was to work with personnel of the Volcanological Survey of Indonesia (VSI) to improve their technique in making and analyzing geodetic measurements at potentially active volcanoes.

Approximately five weeks were spent at several volcanoes on Java; the remaining time was spent in the offices of VSI in Bandung. Tilt or trilateration measurements were made at previously established sites at Kelut, Merapi, Galunggung, and Tangkuban Parahu volcanoes (figure 1). New tilt and trilateration sites were established west of Lamongan volcano in response to a recent seismic swarm. In addition, field observations were made near Lamongan of the geometry and the extent of ground breakage and damage to local residences that resulted from recent seismic activity.

Kelut volcano

On 18-19 December, tilt measurements were made at Kelut volcano in east Java. The tilt measurements for Kelut have shown no consistent pattern since these measurements were begun in early-1981.

Lamongan volcano

Lamongan volcano in east Java was one of the most active Indonesian volcanoes during the 19th century; about 40 eruptions were recorded (Kusumadinata, 1979). Historic eruptive activity has been restricted either to the central vent or to lava flows produced from eruptive vents along the western flank. Since the last eruption, which occurred in February 1898, the region which extends several kilometers west of Lamongan, in a volcanic field of numerous maars and cinder cones, has been the site of three seismic swarms: September 1924, August 1978, and October 1985. Because of the potential for an explosive, maar-type eruption and because of the high population density of this region, a study of the recent ground breakage was made to document the effects of the most recent seismic activity.

An initial reconnaissance of the ground breakage was made in November 1985 by Suparto S., Tom Casadevall and Rudy Hadisantono. A further study was performed between 21 and 26 December by Rudy Hadisantono and John Dvorak. The region of recent ground breakage covers an area of about 25 square kilometers between Klakah and the western slope of Lamongan and between the observatory post at Gunung Meja, located north of Sumberpetung, and Duren (figure 2). Because the region is extensively cultivated and due to recent heavy rains, observations of ground breakage in December were mostly limited to rupture of plaster and brick walls and of concrete slabs.

Ground breakage appeared to occur in three major fracture zones: 1) from the northern edge of Ranu Lamongan (also called Ranu Klakah) to Sumberpetung, 2) from the southern edge of Ranu Pakis to Papringan, and 3) from Duren through Sumberwingin to Ranu Lading. The orientation of most of the ground breakage was between N60° and 70°E. Two exceptions to this orientation were a system of cracks a few hundred meters northwest of Ranu Lamongan, which was oriented N20°E and formed the southern extent of several left-stepping echelon cracks, and a small graben structure located a few hundred meters west of Ranu Lading, which varied in orientation from N50° to 70°E.

Except for the small graben, ground breakage occurred as simple tensional cracks. Within a fracture zone, the amount of crack opening generally increased to the northeast. Crack opening varied from hairline cracks at the western end of each fracture zone to the largest crack openings of up to 100 mm at a schoolyard in Sumberwingin.

Damage to buildings was generally slight, usually limited to single wall and floor cracks, and resulted in no structural damage. The only major damage was at a school in Sumberwingin where several walls were damaged and the concrete floor was severely broken.

The small graben near Ranu Lading formed in a coffee plantation. The maximum vertical offset was 120 mm; the horizontal spacing between bounding scarps was about 30 m.

From the observed minor damage to buildings and the report of felt earthquakes, the maximum earthquake magnitude during the October 1985 seismic swarm was VI on the modified Mercalli intensity scale: weak plaster and masonry cracked and earthquakes widely felt.

Projections of each fracture zone intersect a lake-filled maar. The occurrence of seismic activity and formation of the ground cracks may have resulted in a small amount of water loss in three maars: Ranu Lamongan (about 100 mm drop in water level), Ranu Pakis (about 1 m); and Ranu Lading (about 2 m). No change in water level was observed in either Ranu Bedali, five kilometers north of Ranu Lamongan, or Raun Logung, 4 km south of Ranu Lading.

The 1985 seismic swarm began gradually on 7 October, reached a maximum during the early morning hours on 10 October, and ended on 12 October. The first felt earthquake at the observatory post at Gunung Meja was reported at 14:54 local time on 8 October, more that 24 hours after the start of the earthquake swarm.

The 1924 seismic swarm began on 20 September and lasted about 5 days. During the next few months, a small increase in seismicity was noted. The 1978 seismic swarm began on 12 August and lasted until about 30 August. The peak in seismicity during this second swarm occurred between 16 and 19 August. The 1924 and the 1978 seismic swarms also resulted in ground breakage between Klakah and Lamongan. Individual cracks created in 1924 and in 1978 were oriented mostly NE-SW, similar to the crack orientation in October 1985.

Ground breakage and felt earthquakes were reported west of Lamongan prior to the last eruption of the volcano in 1898 (Verbeek, R. D. M., 1899). Felt earthquakes began on 3 February and a new fissure was observed on a coffee plantation near Papringan on 4 February. The eruption began about 01:30 on 5 February from an eruptive vent on the southwestern flank of Lamongan.

The three seismic swarms west of Lamongan during the 20th century and the related ground breakage are probably caused by the near surface movement of magma. This is suggested by the gradual increase in seismic activity and the gradual increase in earthquake magnitude during the 1985 seismic swarm--a seismic pattern typical of magma-related earthquake swarms. Further evidence for magma movement is the geometry of ground cracking, which indicates a tensional stress environment, and the separate fracture zones, which may be the initial formation of a large graben structure--a pattern frequently observed in volcanic rift systems. The pre-1898 eruption ground breakage reported near Papringan strongly suggests that the 20th century episodes of seismic activity and ground breakage are related to magma movement. Moreover, no fault scarps are recognized in the region west of Lamongan, which would have supported a tectonic origin for recurring seismic activity. Instead, this region is in a volcanic field with numerous, prehistoric volcanic vents.

A simple strain network was installed in the region of recent seismic activity to record ground deformation which may accompany future activity (figure 2). The network consists of a set of seven lines radial to the observatory post at Gunung Meja. Line lengths range from 600 m to about 6 km. The mobile reflector points were selected for easy access; the seven lines may be remeasured in less than one day by use of a four-wheel drive vehicle. Description of the locations of each reflector station is given on page 17 in the appendix. Several remeasurements of this network between 28 December and 1 January showed no significant strain changes during this 5-day period (table I). This network should be reoccupied in a few months.

Five tilt stations were installed in the region of recent ground breakage. Tilt changes as small as 10 microradians can be recorded at these sites by precise leveling to three benchmarks separated by about 40 m at each site.

Advantage was taken of the 600-m diameter lake, Ranu Lamongan, located near the northern extent of the recent ground breakage, to record possible tilt changes. Four 3-m steel pipes were installed within a few meters of the shoreline around the lake. The geometry of the lake-level tiltmeter is shown in figure 3. Distances between pipes were determined by use of an electronic distance measuring instrument. North-south and east-west components of tilt can be determined by the relative change in height of each steel pipe above the water level. These heights can easily be measured to within a few millimeters, which corresponds to a tilt resolution of about 10 microradians. Repeated measurement of these heights should be made during the morning, when there is no wind. Wind shear on the lake will produce waves, which make it more difficult to estimate the water level, and will also produce an artificial tilt of the lake.

Each pipe was measured several times between 26 December 1985 and 2 January 1986 (table II). No significant tilt change was recorded during this period. Weekly measurement of this lake-level tiltmeter could be performed by the permanent VSI observer at Gunung Meja.

Tilt can be determined from each of the two triangles shown in figure 3. For triangle A-D-B, the equations for tilt are:

$$\text{Tilt(N-S)} = -1.20 * (D - A) + 1.91 * (A - B)$$

$$\text{Tilt(E-W)} = -2.57 * (D - A) - 0.51 * (A - B)$$

For triangle A-D-C, the equations are:

$$\text{Tilt(N-S)} = -1.17 * (D - A) + 1.63 * (A - C)$$

$$\text{Tilt(E-W)} = -3.20 * (D - A) + 0.44 * (A - C)$$

The differences in heights of the pipes (D - A), (A - B), and (A - C) are in millimeters and the tilt is in microradians.

Self-potential and gravity measurements were made in the region of recent ground breakage (Wimpy T., personal communication, 1986). An east-west and a north-south self-potential survey showed an anomaly confined to the region of ground cracking. Six gravity stations were installed and repeatedly measured during the last week of December. The purpose of these gravity stations is to record elevation changes which may accompany future activity in the region. The gravity technique can be used to determine elevation changes of at least 100 mm over a distance of tens of kilometers.

Bromo volcano

The afternoon of 31 December was spent at Bromo volcano in east Java. Because of easy access to the summit by paved road and the lack of vegetation in the summit region, both trilateration and tilt networks could be established and reoccupied with less expense and in less time than at other potentially active volcanoes on Java.

Merapi volcano

Reoccupation of the trilateration network at Merapi volcano in central Java was attempted on 4 and 5 January with little success. The instrument was setup at Deles and at Kaliurang to measure the distances to permanent reflectors on the south side of the volcano. Weather prevented measurements from Deles on either day. Only one reflector was measured from Kaliurang: reflector M4 located at the 2500-m elevation at a distance of about 6 km from Kaliurang. This single measurement indicated a decrease in line length of 55 mm since the previous measurement made on 29 July 1985 (figure 4). The return signal from the other permanent reflector visible from Kaliurang, M5, was too weak to complete a measurement.

Galunggung volcano

Reoccupation of the trilateration network at Galunggung volcano in west Java was attempted on 7 and 8 January (figure 5). Measurements were completed from only one instrument station, Rancapaku, to the three mobile reflector stations located at Cipanas (CP), Pasir Bentang (PB), and Walirang (WL). Weather and poor road conditions prevented measurements from the other instrument station, Sindanggalih.

Measurements from Rancapaku and from Sindanggalih were begun in December 1983. Earlier measurements, between March and October 1983, were made to the three mobile reflector stations from two instrument sites located near Rancapaku: Karangdan and Sayuran. The history of measured line lengths to Pasir Bentang and to Walirang are shown in figures 6 to 9. The vertical lines indicate an assumed uncertainty of 3 parts per million for each measurement. Open circles indicate measurements made either from Rancapaku or from Sindanggalih; filled circles indicate earlier measurements made either from Karangdan or from Sayuran. Since measurements were never simultaneously made from either Karangdan or Sayuran and from Rancapaku, we have assumed that no significant change occurred between the last measurements from Karangdan and Sayuran, made on 23 October 1983, and the first measurements from Rancapaku, made less than two months later on 21 December1983.

No significant changes are apparent in line length from the instrument stations to either Cipanas (not shown) or Pasir Bentang (figures 6 and 7).

Measurements to the reflector station on the crater rim, Walirang, showed significant contractions of the lines during 1984, suggesting inflation of the volcano. The initial set of measurements, made from Sayuran to Walirang (figure 8) between 30 March and 23 October 1983, indicate no significant line length changes during this period. The contraction apparently began in early-1984 and lasted several months. The measured contraction was 127 mm between Rancapaku and Walirang (figure 8) and 126 mm between Sindanggalih and Walirang (figure 9).

The amount of horizontal displacement can be determined graphically from these line length changes. The line geometries are shown in figure 10; the measured change in line length is indicated on each line. A perpendicular is constructed to each line at the point that corresponds to the measured change in line length. The horizontal displacement is the vector from the reflector station to the intersection of the two perpendicular lines. For Galunggung, the horizontal displacement vector is directed outward from the crater and has a magnitude of 155 mm.

Since significant changes in line lengths were measured only for the nearest reflector station, only a minimum depth to the source may be estimated. We apply a simple point source model and assume that the source is located beneath the 1982 eruptive vent, a horizontal distance of 300 m northwest of the Walirang reflector station and 1300 m from the next nearest station, Pasir Bentang. The horizontal displacement, H(r), as a function of radial distance from the source, r, is given by (Mogi, 1958):

$$H = \frac{V}{2\pi} * \frac{r}{(r^2 + d^2)^{3/2}}$$

where V is the volume of uplift and d is the depth to the source.

For Walirang, the radial distance is r=0.3 km and the horizontal displacement is H=155 mm. For Pasir Bentang, the radial distance is 1.3 km and the horizontal displacement is H<50 mm, since the accuracy of the measurements to Pasir Bentang are 50 mm. Using these values, we have two equations and two unknowns: V and d.

$$155 \text{ mm} = \frac{V}{2\pi} * \frac{0.3 \text{ km}}{(0.3^2 + d^2)^{3/2}}$$

$$50 \text{ mm} < \frac{V}{2\pi} * \frac{1.3 \text{ km}}{(1.3^2 + d^2)^{3/2}}$$

The solution to these equations is:

$$d > 0.5 \text{ km} \qquad \text{and} \qquad V = 0.6 \times 10^6 \text{ m}^3$$

where the depth, d, is relative to the elevation of the reflector station Walirang.

Tangkuban Parahu

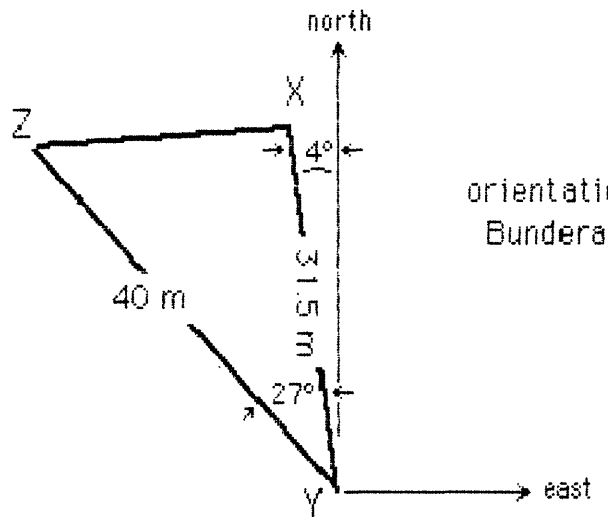
Tangkuban Parahu is a volcanic complex that lies 30 km north of Bandung. Recent eruptive activity has consisted of phreatic and phreatomagmatic eruptions confined to the summit craters Kawah Ratu and Kawah Upas (figure 11) (Kusumadinata, 1979).

The most recent eruption, which occurred in September 1983, was preceded by a swarm of shallow earthquakes, probably less than 1 km, centered beneath the southern edge of Kawah Upas. The eruptive vent in 1983, located in the southern portion of Kawah Ratu, produced a small convective column and was officially referred to as "a mud eruption".

Tilt measurements using the spirit-level, also called the dry-tilt, technique were begun in early-1981. Repeated measurements at the two stations located nearest the active craters, Pos Vulkanologi and Kawah Baru, have shown a continual, inflationary tilt change since 1981 (figures 12 and 13). (A downward deflection to the north or the east is arbitrarily assigned to be a postive tilt.) A slight change in tilt direction in late-1983 is evident along the north-south component for both Kawah Baru and Pos Vulkanologi. This change in direction may be related to a northward migration of the center of uplift. The station located about 3 km from the active craters, Cicenang, also shows an inflationary tilt (figure 14).

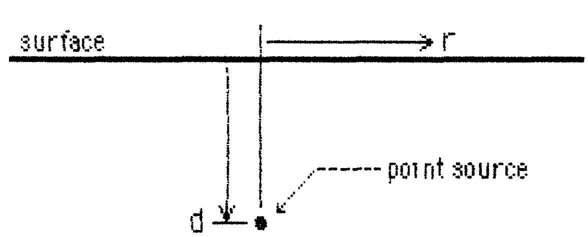
The other four tilt stations have all had stability problems; tilt changes of many tens to hundreds of microradians have been measured at these stations over time intervals as short as a few months. Since late-1983, however, tilt measurements at Kawah Domas and at Nagrak have shown consistent, and small, tilt changes to the east and to the southeast, respectively (figures 15 and 16). Except for a very large tilt offset of 150 microradians between 25 January and 28 March 1985, the measurements at Jayagiri have shown a consistent, and small, southwest tilt change since 1984. This offset has been removed in figure 17.

The tilt station Bunderan has continued to show erratic movement. The problem appears to be more pronounced on the east-west component (figure 18). Since the X-Y benchmarks for Bunderan are aligned within 4° of north-south and the Z-X benchmarks 10° of east-west, the instability is probably caused solely by the westernmost benchmark.



For all stations except Bunderan, an average annual tilt rate was estimated for the period 1984-1985, indicated by the line segments in figures 12 to 17. The resultant tilt directions and annual rates are shown as solid vectors in figure 11. An uplift center has been identified based on the intersection of the observed tilt vectors for Kawah Baru and Pos Vulkanologi. This center is within the epicentral area of shallow earthquakes that preceded the small September 1983 "mud" eruption.

A simple point source model has been applied to the annual tilt rates shown in figure 19 to estimate the depth to the source and the volume of uplift. This model treats the intrusion as a point source embedded in an elastic, semi-infinite half-space.



We further assume that the half-space is isotropic and homogenous. The elevation change, that is, the amount of vertical displacement, E(r), as a function of radial distance from the uplift center, r, is given by (Mogi, 1958)

$$E(r) = f \frac{d}{(r^2 + d^2)^{3/2}}$$

where d is the depth to the source and f is a factor which depends on the pressure and size of the source and on the elastic parameters of the half-space. f is related to the volume of uplift, V, which is determined by the integral of E(r) from r = 0 to infinity.

$$V = \int_0^\infty E(r)\, 2\pi r\, dr = 2\pi f$$

Note that the volume of uplift is independent of the depth to the source.

The tilt in the radial direction, Ø(r), is the differential of E(r) with respect to r (Eaton, 1962).

$$Ø(r) = \frac{d\,E(r)}{dr} = -\frac{3V}{2\pi} * \frac{r\,d}{(r^2 + d^2)^{5/2}}$$

From figure 11 we can graphically determine the radial component of annual tilt rate for each station. These tilt rates are plotted in figure 19 as a function of radial distance from the uplift center. Values for the depth, d, and the volume rate, V, are determined by trial and error by fitting theoretical curves to the observed radial tilt rates. The curve shown in figure 19 uses the following model parameters:

$$d = 1.2 \text{ km} \qquad \text{and} \qquad V = 2 \times 10^6 \text{ m}^3/\text{yr}$$

The tilt vectors computed from this model for each station are shown as dashed vectors in figure 11. The computed tilt rate vectors for Kawah

Baru, Pos Vulkanologi, and Cicenang are within a few microradians per year of the observed tilt rate vectors. For Nagrak and Jayagiri, the radial components of computed and observed tilt rates are almost identical, but there is an observed tangential tilt component that is not accounted by the model.

Recommendations

The VSI groups assigned to conduct the tilt and the trilateration surveys have been making useful measurements. The following recommendations have been made to improve the effectiveness of these groups.

1. Increase the frequency of tilt and trilateration measurements
   Of four volcanoes on Java that have either dry tilt stations or a trilateration network, two volcanoes have shown consistent changes in ground movement: Tangkuban Parahu and Galunggung. Fortunately, these two volcanoes are near Bandung, so that they are easily accessible by personnel from VSI. Dry tilt measurements of Tangkuban Parahu have been made on an average of four times per year since 1981. This should be continued. Trilateration measurements have only been done twice at Tangkuban Parahu, in mid-1983 and in mid-1984. Trilateration measurements should also be done every four months at Tangkuban Parahu to support the results of the tilt measurements and to better constrain the source of the current ground movement.

2. Use of permanent reflectors for trilateration measurements
   The location of reflector stations on Indonesian volcanoes are remote and weather severely limits the ability to make frequent measurements. The establishment of more permanent reflectors will make it easier to make more frequent measurements and to complete these measurements in less time. The expected lifetime of permanent reflectors is about two years. Those volcanoes that should be considered for extensive trilateration networks using permanent reflectors--and should be remeasured about every four months--include Merapi, Tangkuban Parahu, Galunggung, Lamongan, and Bromo.

3. <u>Improve the installation of dry tilt benchmarks</u>
The three dry tilt stations installed by Arnold Okamura (USGS) at Tangkuban Parahu--Kawah Baru, Pos Vulkanologi, and Cicenang (figure 11)--have proven to be stable over the past five years. Three of the four sites installed since 1981--Jayagiri, Nagrak, and Bunderan--have had stability problems indicated by occasional tilt offsets between surveys of several tens to a few hundred microradians. Benchmark stability also seems to be a problem at some sites at Kelut, however, the two dry tilt stations installed at Galunggung in 1985--Pasir Bentang and Cipanas--have had no stability problems.
The method of benchmark installation for dry tilt stations needs to be reviewed. This would probably best be done by A. Okamura.

4. <u>Continue to concentrate on field techniques to make geodetic measurements</u>
The installation and operation of automatic instruments to record tilt should be discouraged until a satisfactory program to measure tilt by the dry tilt and the water-tube methods has been established. Experience has shown that the use of automatic tiltmeters requires a significant amount of manpower to maintain the instruments and to keep up with data analysis. Additional equipment and survey teams for tilt and trilateration measurements are needed. Tilt and trilateration measurements should be made more frequently and with more satisfactory results before a network of automatic instruments is established.

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Appendix: Locations of Instrument and Reflector Stations at Lamongan

Instrument stations

The three instrument stations are located on Gunung Meja are near the VSI observatory post. Each station is marked by a 1/2-inch diameter iron ribar anchored to the ground by a small cement pad. One station is located north of the observatory (reflector stations visible: Gunung Kendang, Ranu Bedali, and Gunung Cilik), a second east of the observatory (Gunung Anyar), and the third to the southwest between coconut palms (Microwave, Ranu Lamongan, and Gerobogan).

Reflector stations

Six reflector stations are marked the same as the instrument stations. The seventh, Gunung Anyar, uses one of the dry-tilt benchmarks.

Gunung Kendang (629 m): located a few meters west of the highest point on this cinder cone

Ranu Bedali (3001 m): located along the path that runs along the northeastern rim of Ranu Bedali; located near a tree west of the water storage building

Gunung Cilik (1711 m): not located near the highest point of this cinder cone; located along the eastern rim of the cone on a small mound

Gunung Anyar (3935 m): located on the lava flow above the resthouse at Anyar; this station is not marked by an iron bar, use the only dry-tilt benchmark that is line-of-sight to the observatory post

Microwave (2519 m): drive up the paved road toward the microwave station; located about 5 m above the road along a small ridge about 100 m from the end of the paved road; road makes a sharp, uphill, left turn here

Ranu Lamongan (1767 m): located at the northeast corner of the only abandoned building visible from the observatory post

Gerobogan (5708 m): located on the northside of the paved road about 2 m east of a 2-m high cement marker (or sign); east of a dirt road intersection; rice fields, not sugar cane fields, to the north

TABLE I

TRILATERATION MEASUREMENTS NEAR LAMONGAN VOLCANO
(mark-to-mark line lengths given in meters)

	28 Dec 85	29 Dec 85	30 Dec 85	1 Jan 86
Ranu Lamongan	1767.136	1767.137	1767.141	1767.144
Gerobogan	5708.614	5708.635	5708.629	5708.642
Microwave	2519.319	2519.326	2519.321	2519.321
Gunung Cilik		1711.774		1711.767
Ranu Bedali		3001.463		3001.454
Gunung Kendang		629.377		629.358
Gunung Anyar		3935.432		3935.429

TABLE II

LAKE-LEVEL TILTMETER - RANU LAMONGAN

	A	B	C	D
26 Dec 85	1208 mm	1176 mm	949 mm	860 mm
27 Dec 85	1241 (33 mm)*	1211 (35 mm)	---	894 mm (34 mm)
30 Dec 85	1260 (52)	1233 (57)	1006 (57)	914 (54)
2 Jan 86	1205 (-3)	1170 (-6)	945 (-4)	857 (-3)

*change in lake-level since 26 Dec 85 given in parenthesis

Figure 1. Location of the Indonesian volcanoes discussed in this report.

Figure 2. Lamongan volcano. The three major fracture zones that formed during the October 1985 seismic swarm are indicated by dashed lines. A 7-line, mobile reflector trilateration network was installed in December 1985. The instrument sites are located at the VSI observatory post, Gunung Meja.

Figure 3. Geometry of the lake-level tiltmeter at Ranu Lamongan. Distances were determined by use of an electronic distance measuring instrument.

Figure 4. Changes in line length along the south flank of Merapi volcano. Distances are given in meters. The vertical error bars indicate an assumed measurement accuracy of 3 parts per million.

Figure 5. Trilateration network at Galunggung volcano. (W-Walirang, PB-Pasir Bentang, C-Cipanas)

Figure 6. Changes in line length at Galunggung from the southern instrument stations to Pasir Bentang. Filled circles are measurements from Karangdan; open circles are from Rancapaku. Distances are given in meters. The vertical error bars in this and the next three figures indicate an assumed measurement accuracy of 3 parts per million.

Figure 7. Changes in line length at Galunggung from Sindanggalih to Pasir Bentang.

Figure 8. Changes in line length at Galunggung from the southern instrument stations to Walirang. Filled circles are measurements from Sayuran, open circles are from Rancapaku.

Figure 9. Changes in line length at Galunggung from Sindanggalih to Walirang.

Figure 10. Graphical determination of horizontal displacement from trilateration measurements at Galunggung.

Figure 11. Location of dry tilt stations at Tangkuban Parahu volcano. Solid vectors are observed annual tilt rates recorded during 1984 and 1985. Dashed vectors are computed annual tilt rates based on a point source model.

Figure 12. Relative tilt measurements recorded at Pos Vulkanologi. A positive tilt change is arbitrarily assigned to be a downward deflection to the north or to the east.

Figure 13. Relative tilt measurements recorded at Kawah Baru.

Figure 14. Relative tilt measurements recorded at Cicenang.

Figure 15. Relative tilt measurements recorded at Kawah Domas.

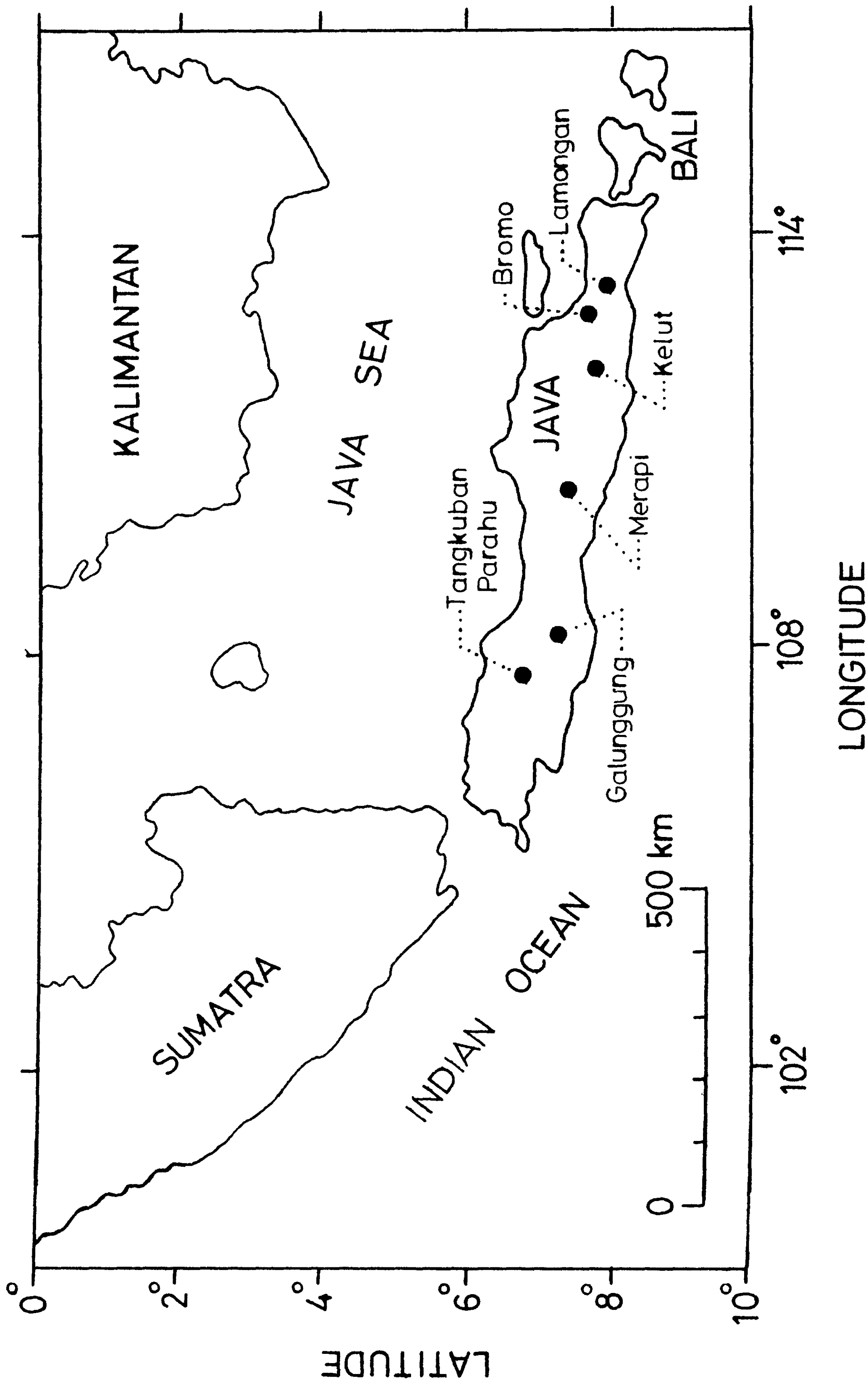
Figure 16. Relative tilt measurements recorded at Nagrak.

Figure 17. Relative tilt measurements recorded at Jayagiri.

Figure 18. Relative tilt measurements recorded at Bunderan.

Figure 19. Comparison of observed and computed annual radial tilt rates for Tangkuban Parahu. Circles denote annual radial tilt rates estimated for six tilt stations (see figures 12 to 17). The solid line is the computed annual radial tilt rate based on the model described in the text.

Figure 1


KALIMANTAN
JAVA SEA
SUMATRA
INDIAN OCEAN
JAVA
BALI
Bromo
Lamongan
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Tangkuban Parahu
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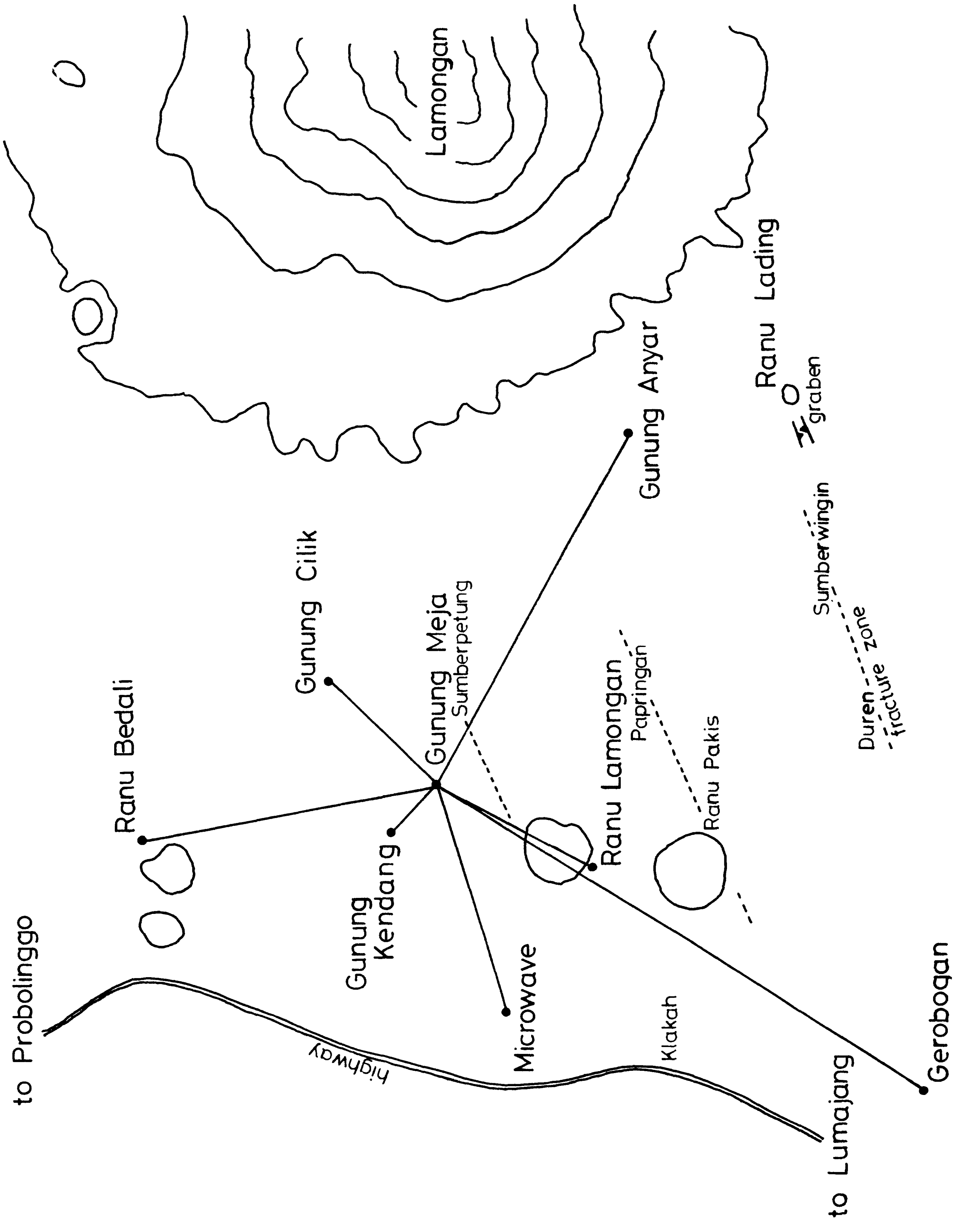
LATITUDE

Figure 2



Lamongan
Ranu Lading
graben
Gunung Anyar
Sumberwingin
Duren
fracture zone
Gunung Cilik
Gunung Meja
Sumberpetung
Papringan
Ranu Pakis
Ranu Lamongan
Ranu Bedali
Gunung Kendang
Microwave
Gerobogan
Klakah
highway
to Probolinggo
to Lumajang

LAKE-LEVEL TILTMETER
RANU LAMONGAN

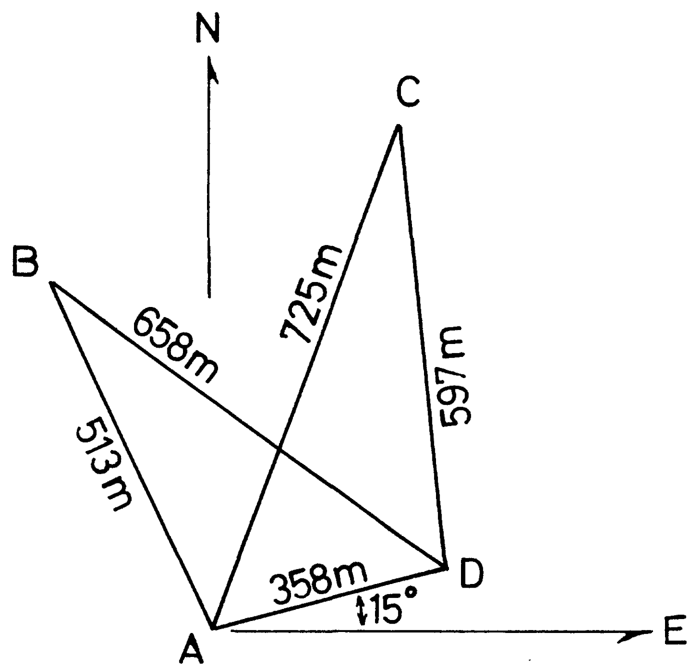


Figure 4

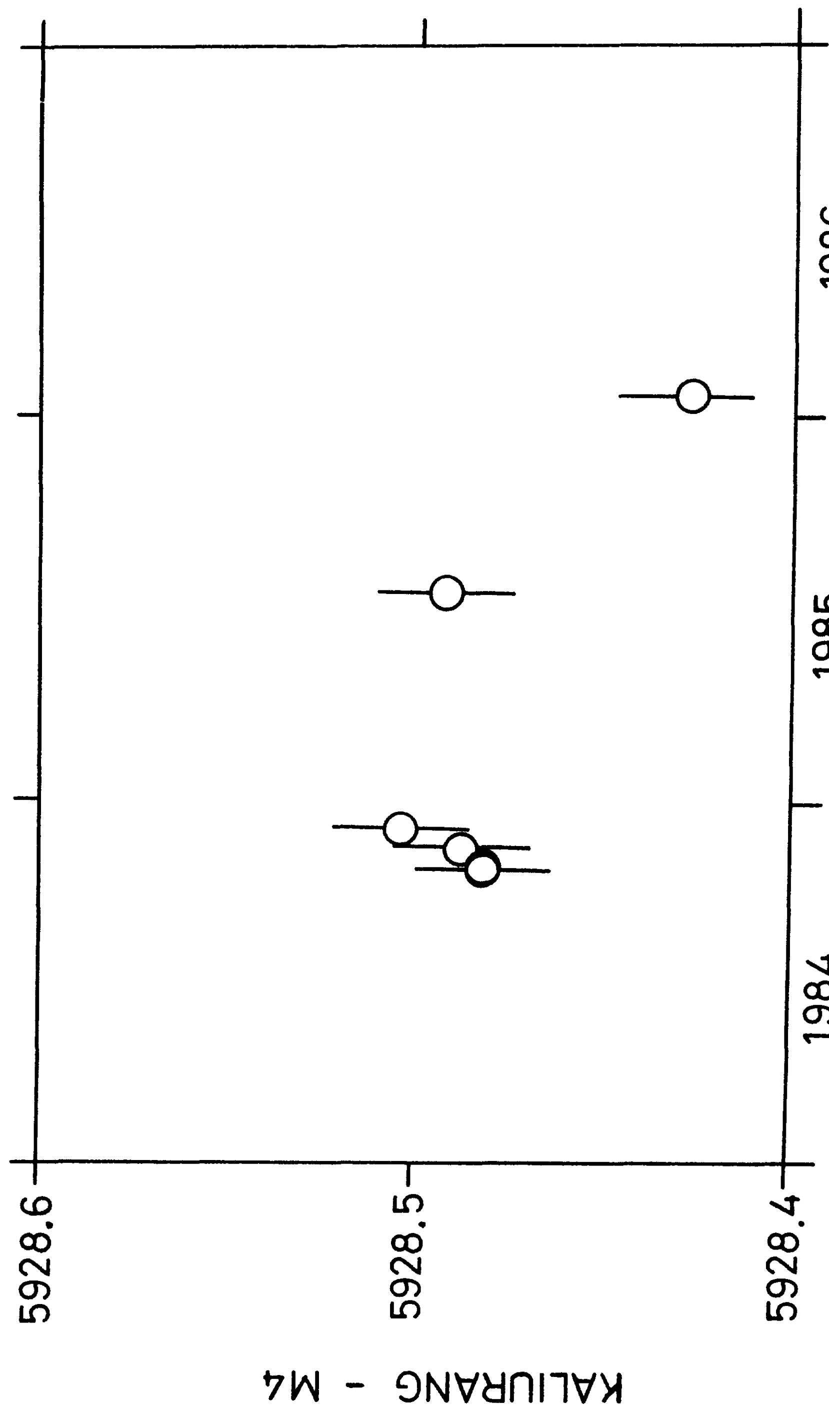
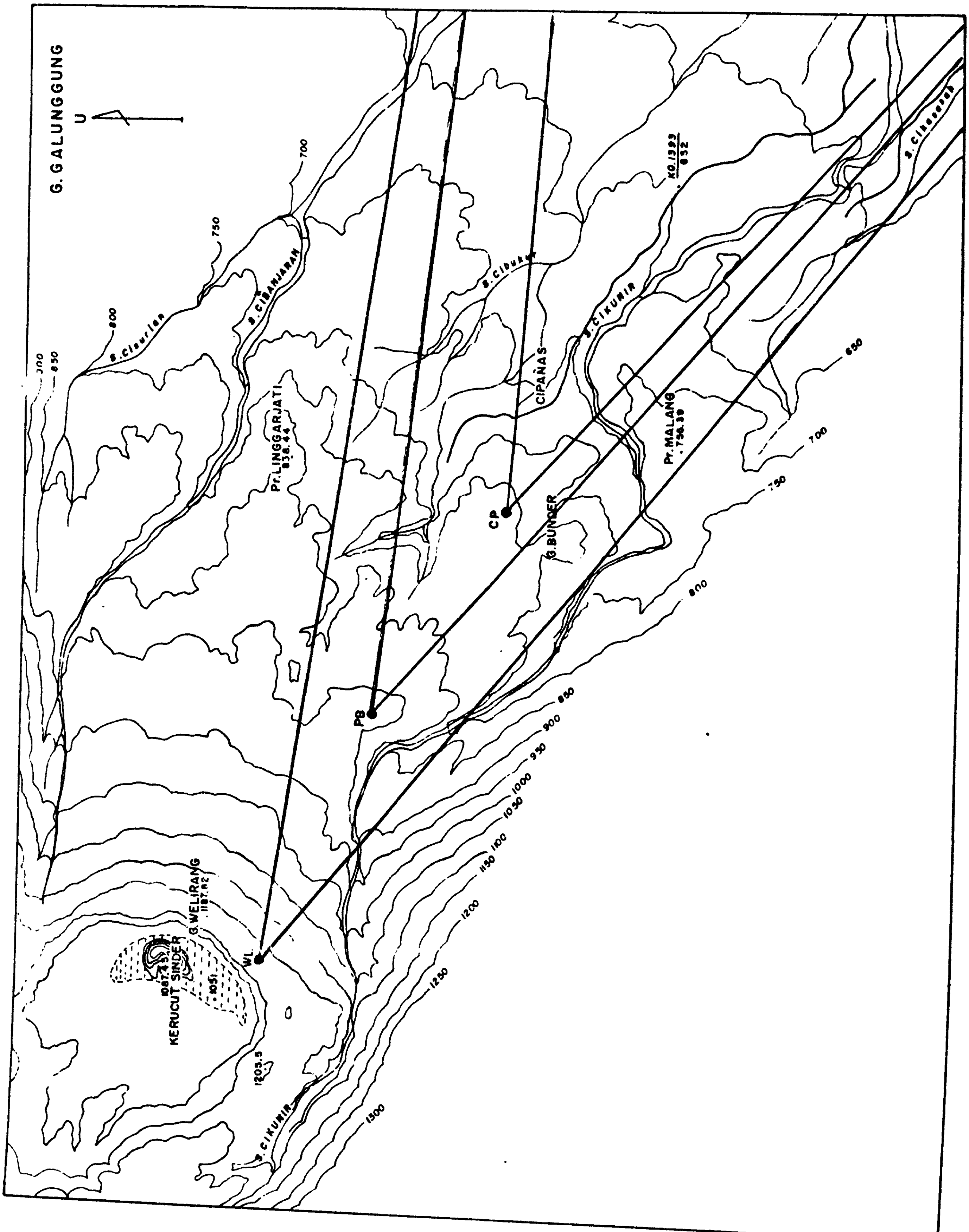


Figure 5



G. GALUNGGUNG
U
Pr. LINGGARJATI
838.44
CIPANAS
S. CIKUNIR
Pr. MALANG
756.39
CP
G. BUNDER
PB
WL
G. WELIRANG
1187.82
KERUCUT SINDER
1205.5
S. CIKUNIR
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300

Figure 6

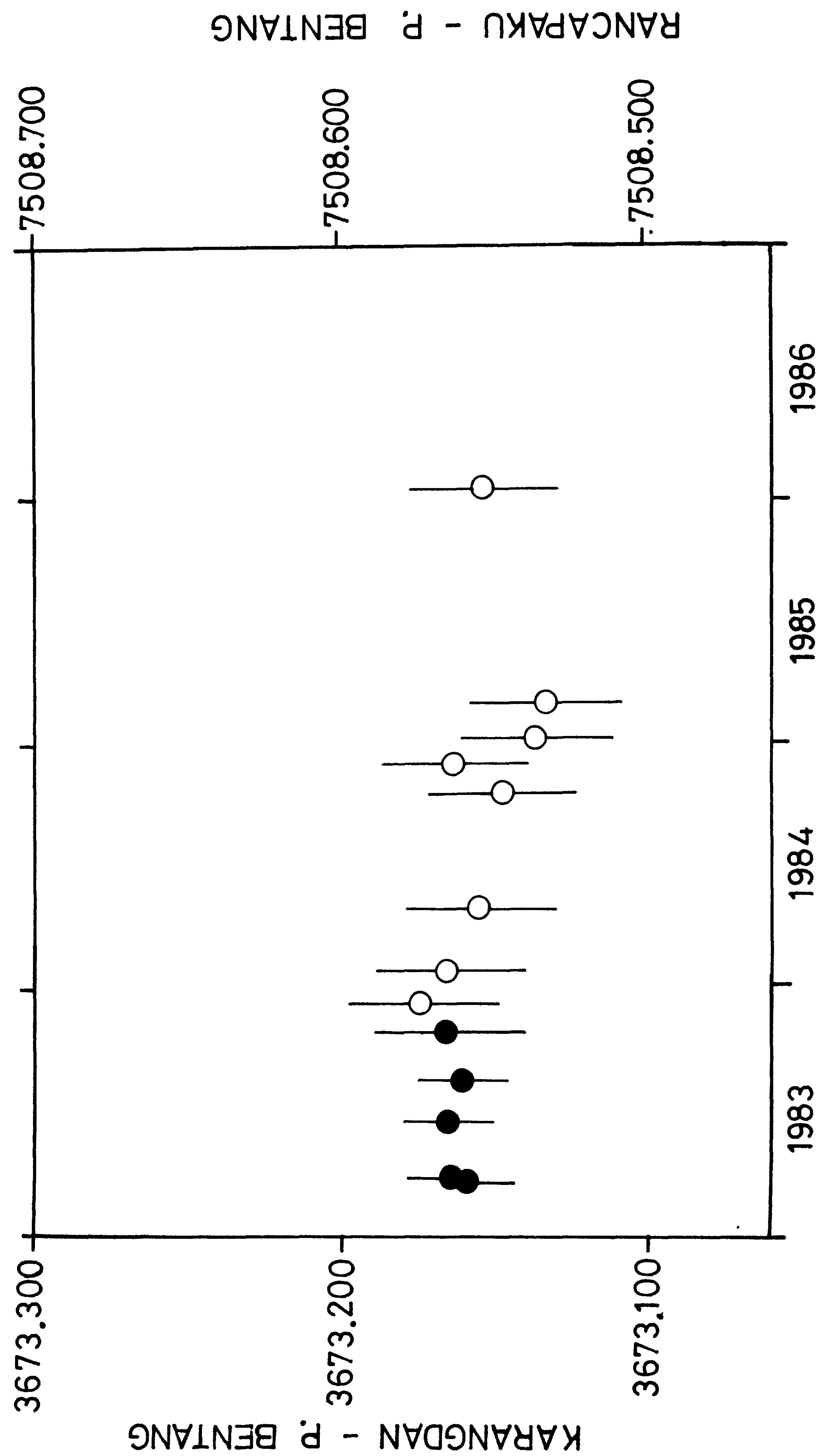

RANCAPAKU - P. BENTANG
7508.700
7508.600
7508.500
1983
1984
1985
1986
3673.300
3673.200
3673.100
KARANGDAN - P. BENTANG

Figure 7

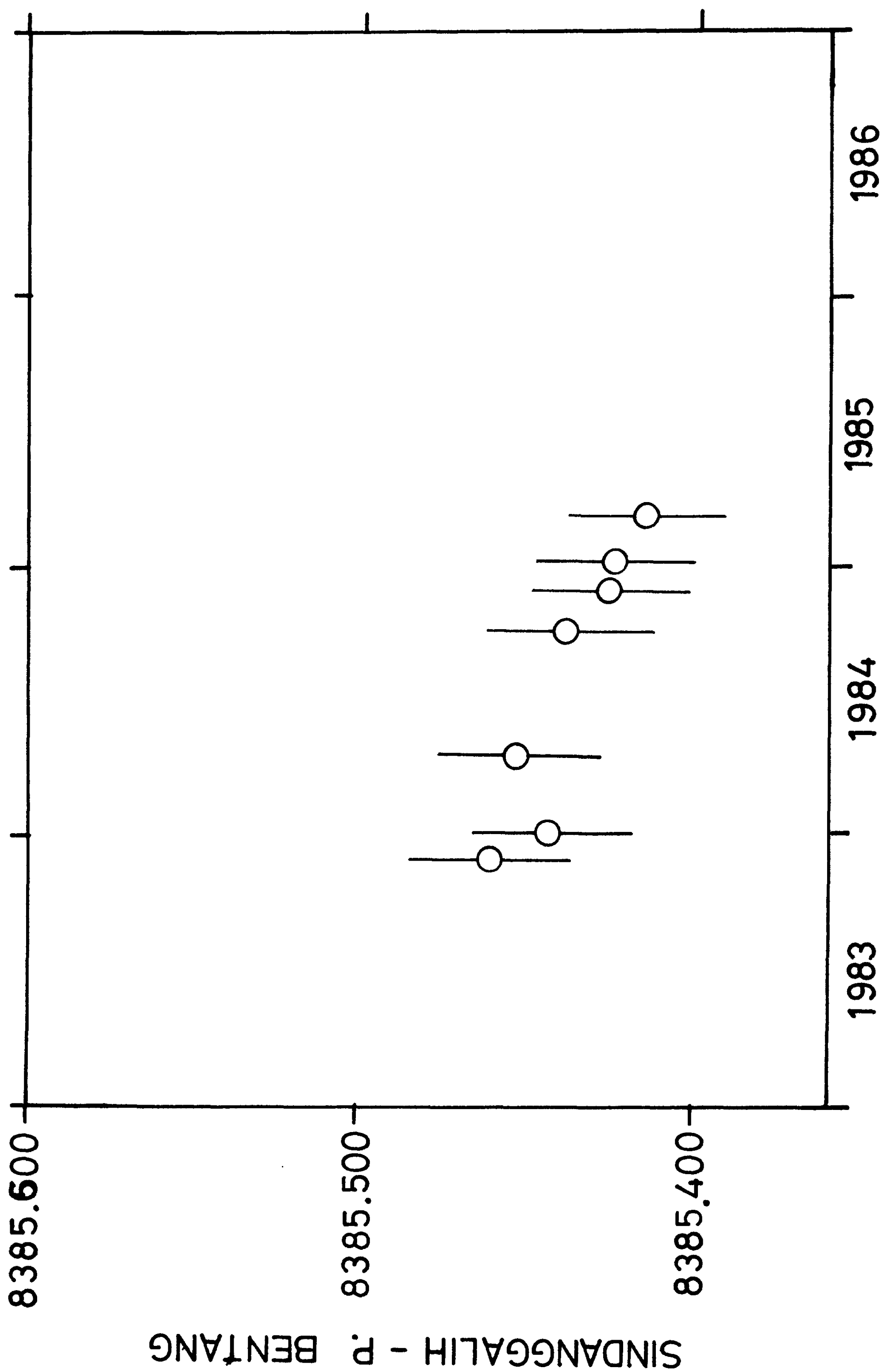
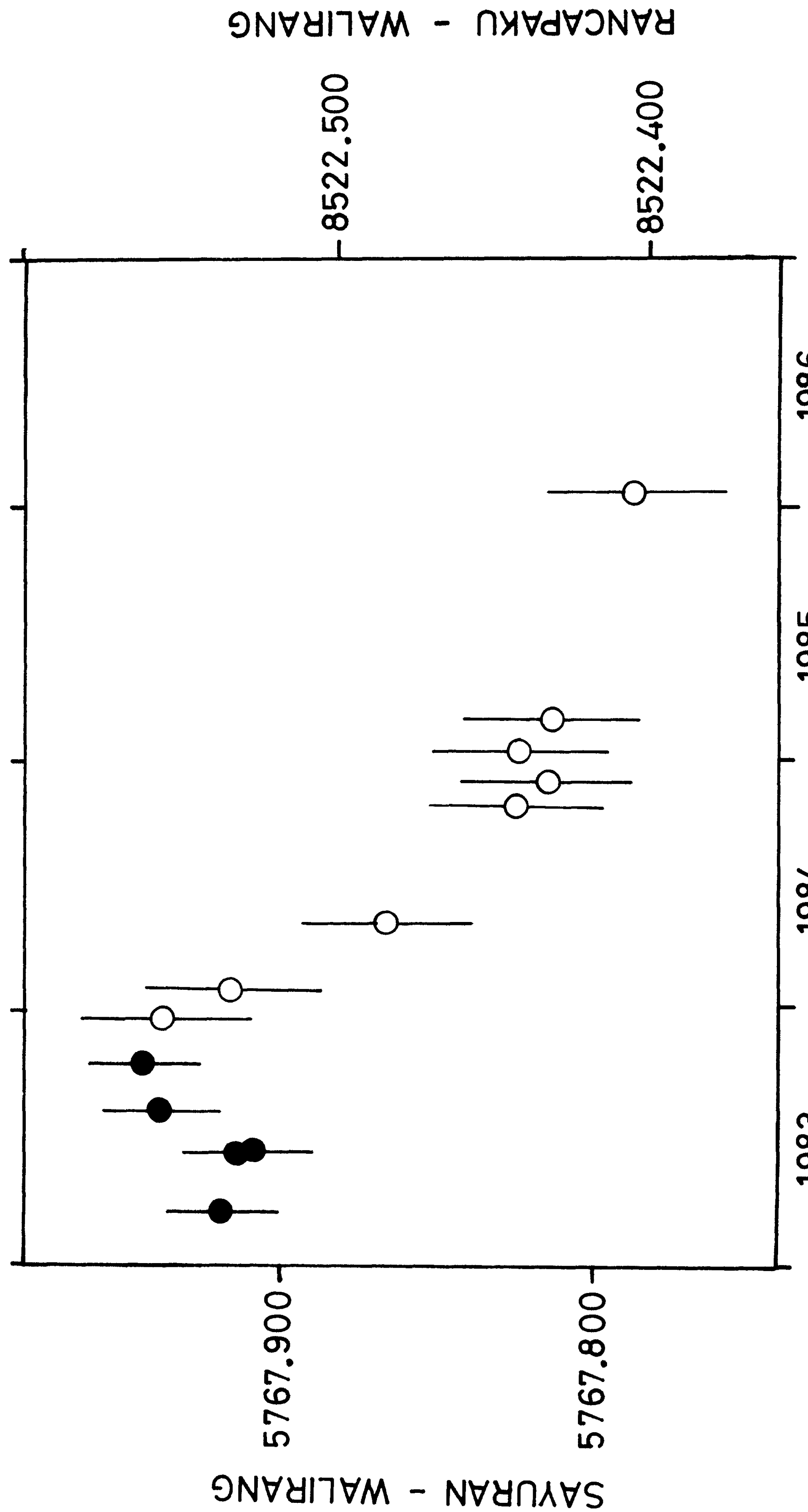

SINDANGGALIH - P. BENTANG
8385.600
8385.500
8385.400
1983
1984
1985
1986

Figure 8



RANCAPAKU - WALIRANG
8522.500
8522.400
1983
1984
1985
1986
5767.900
5767.800
SAYURAN - WALIRANG

Figure 9

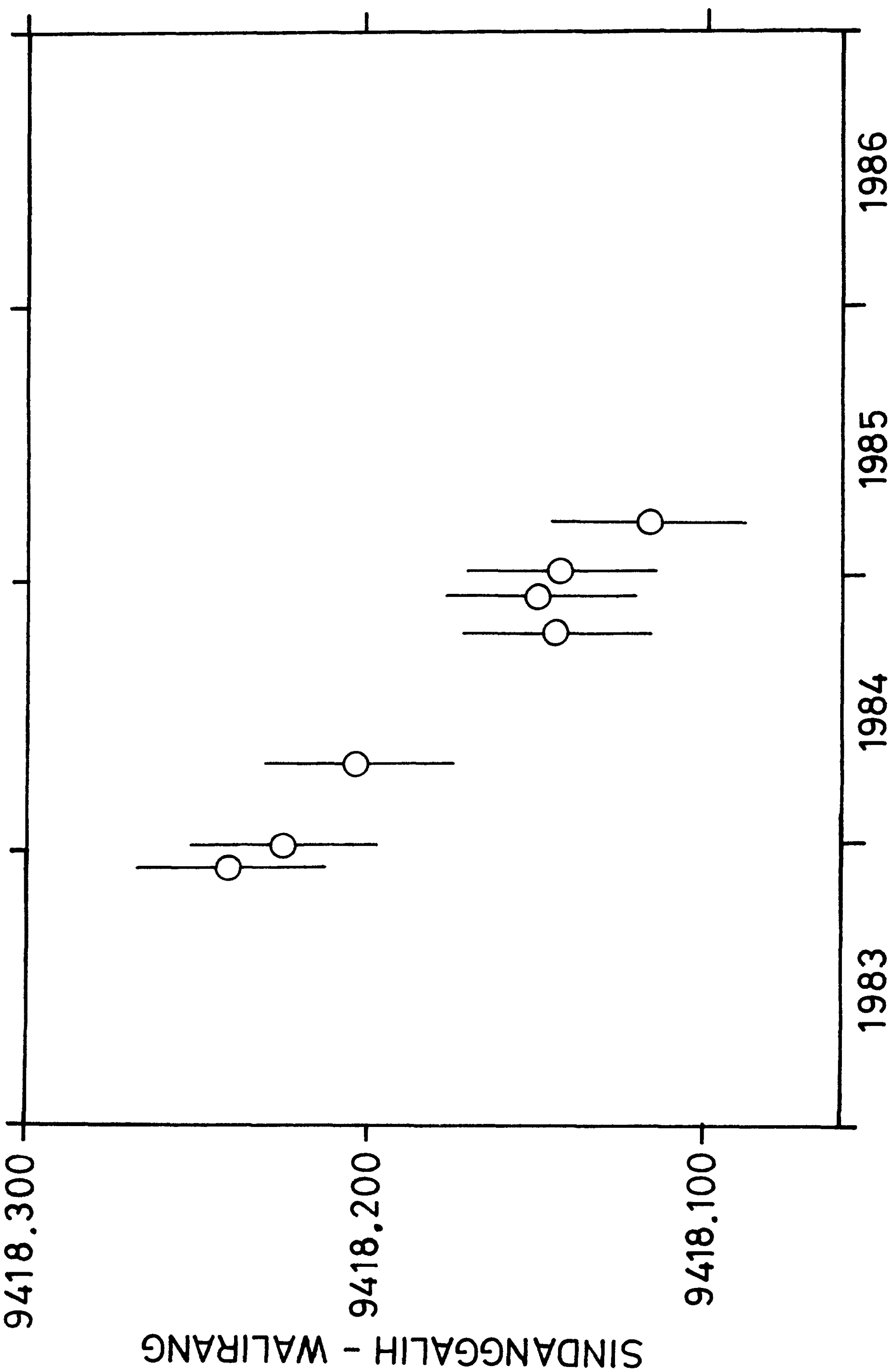
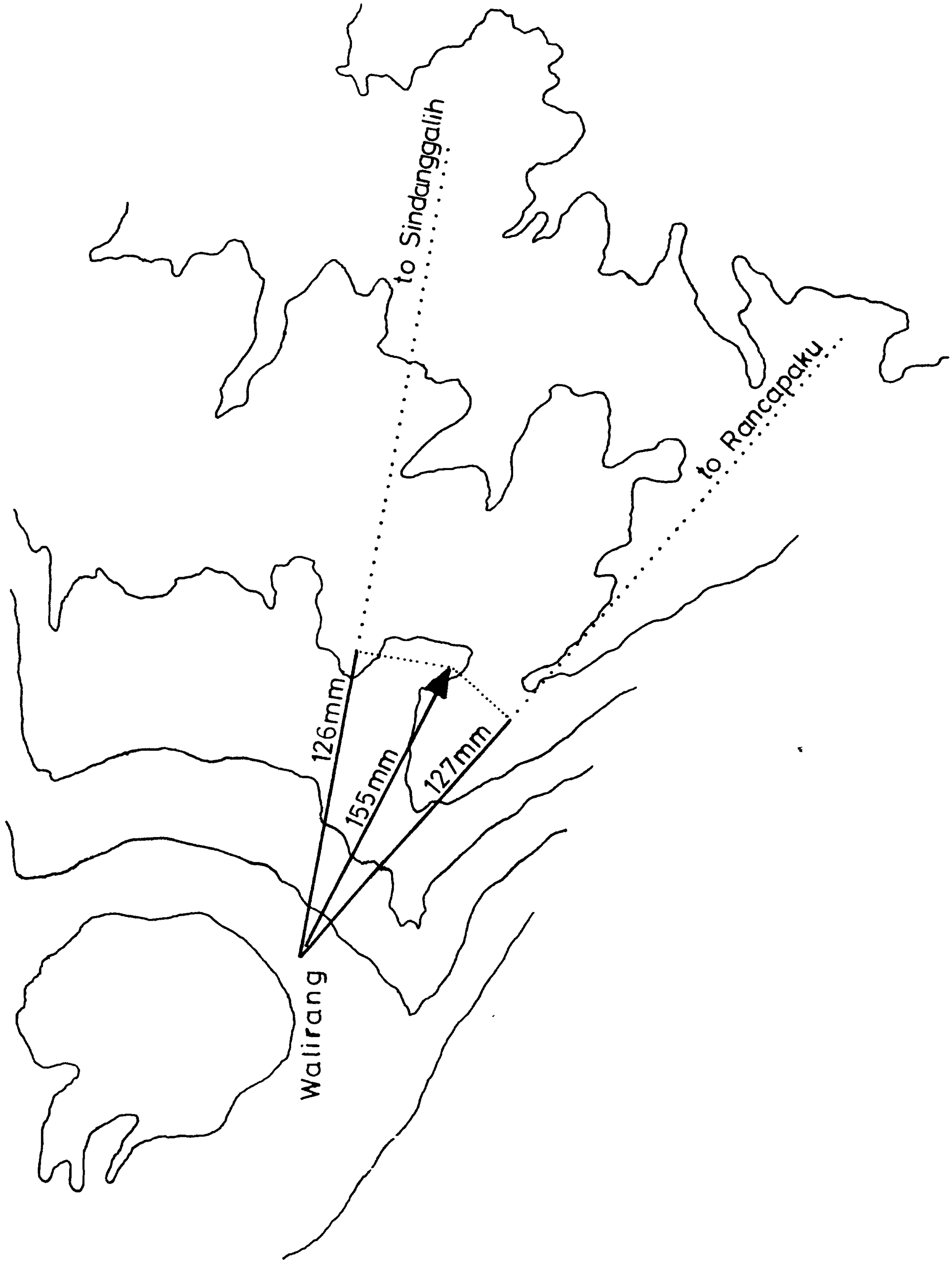
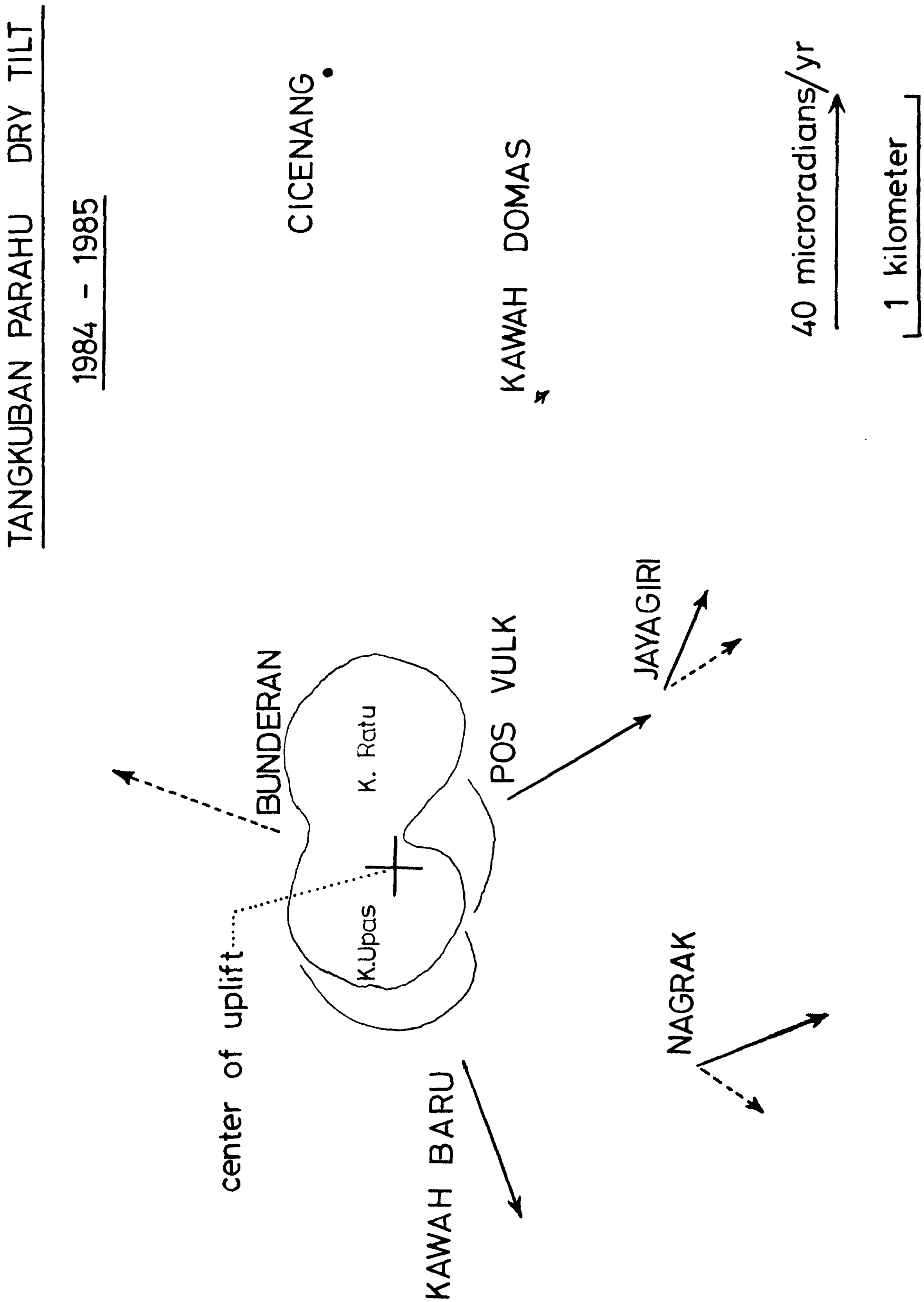

9418.300
9418.200
9418.100
1983
1984
1985
1986
SINDANGGALIH - WALIRANG

Figure 10

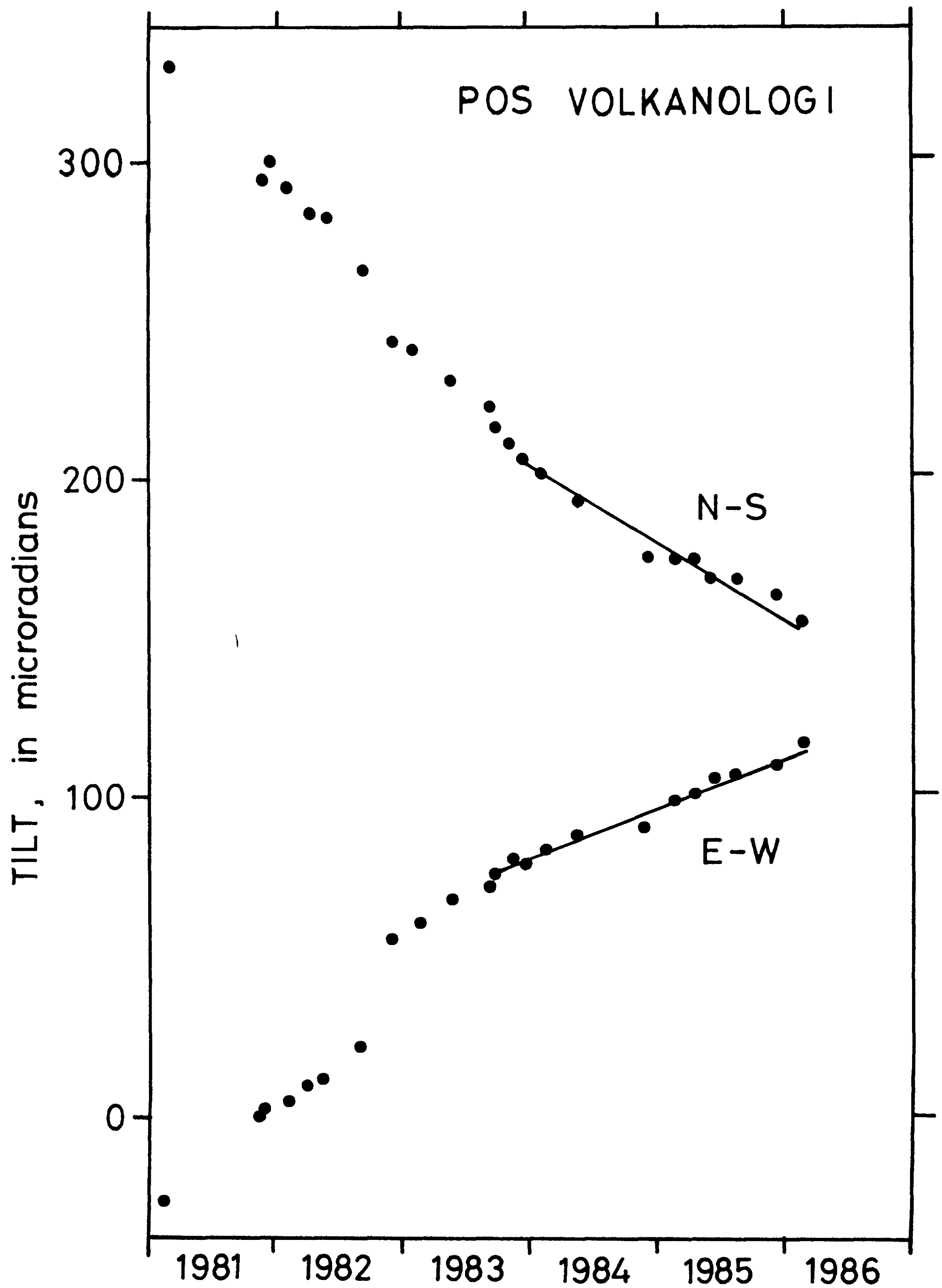


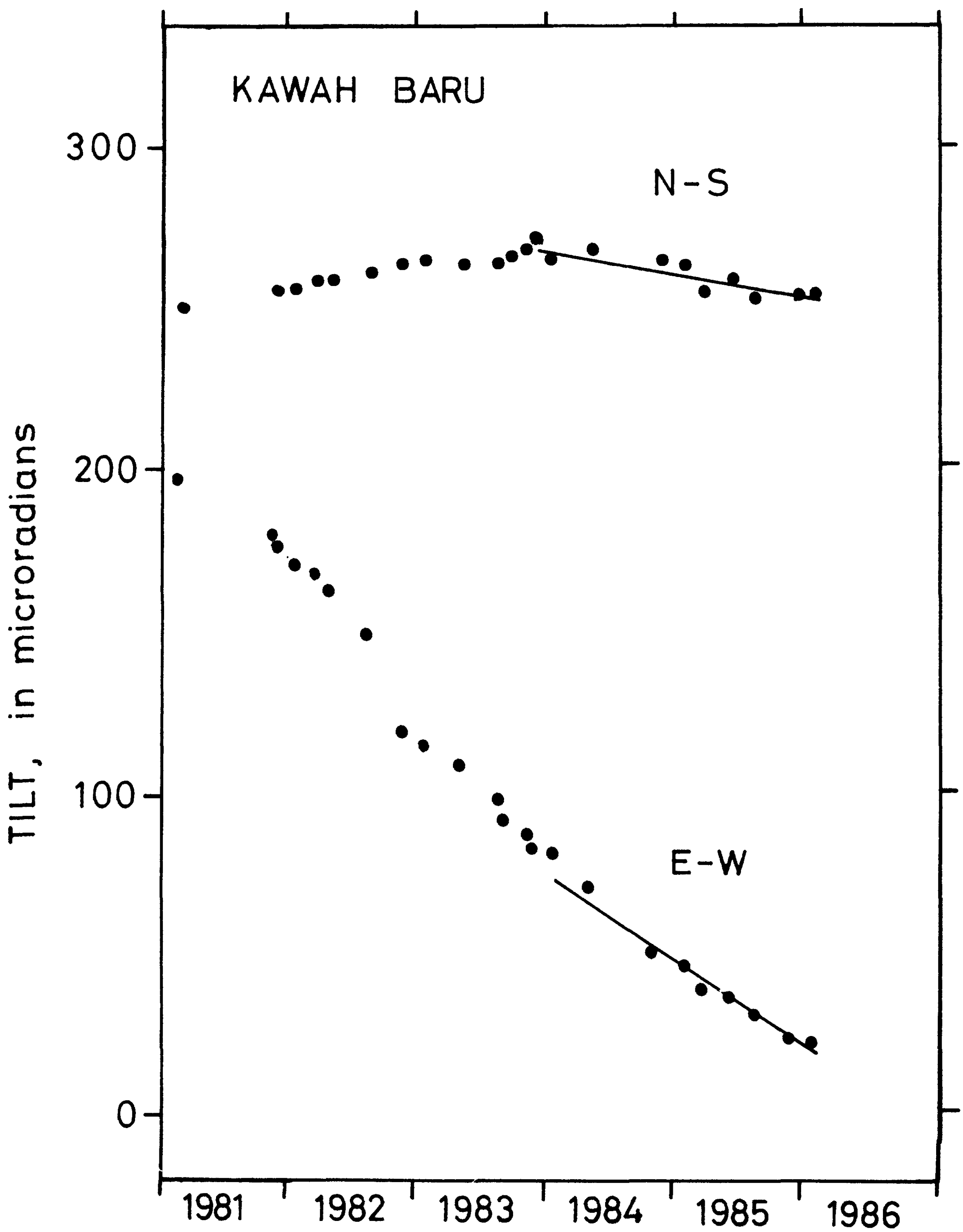
11

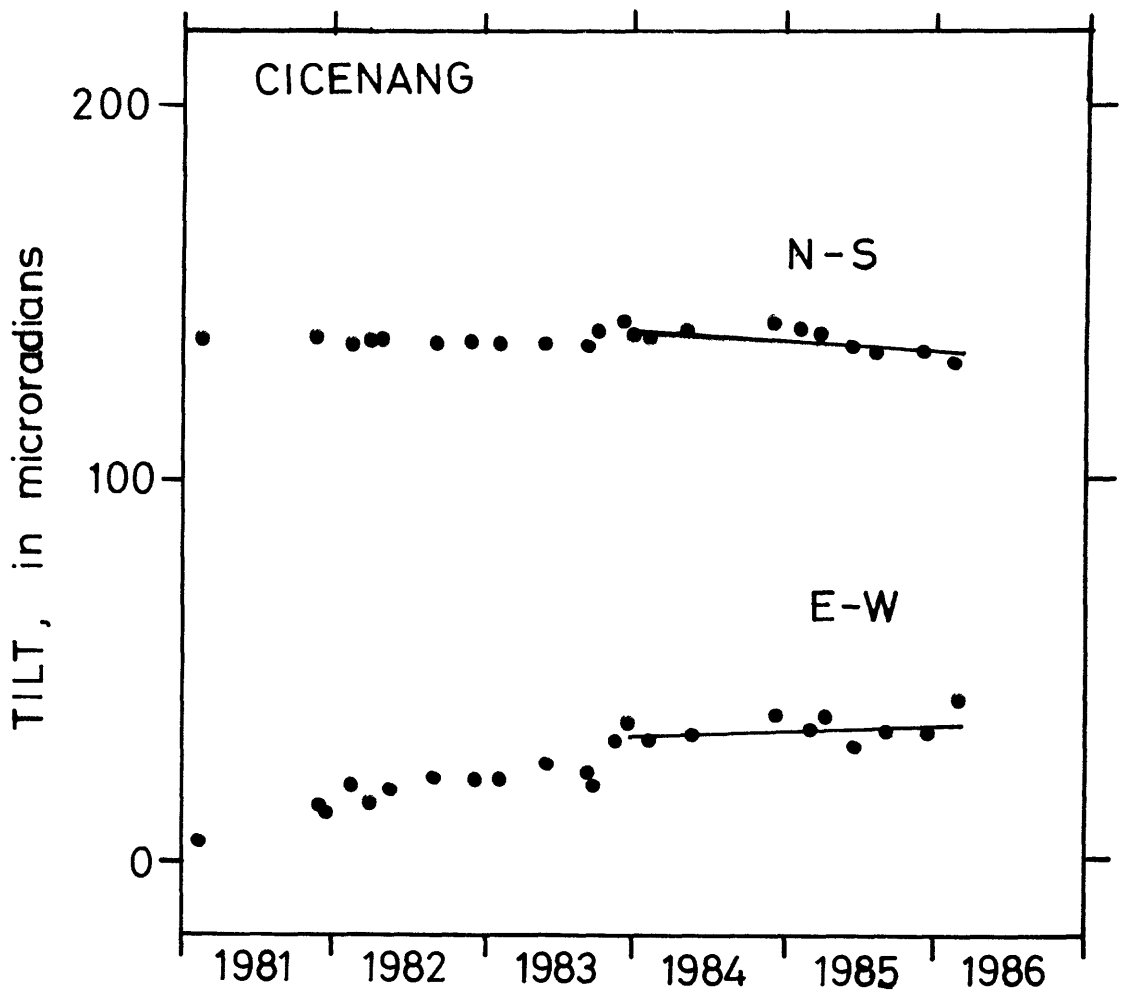
Figure 11

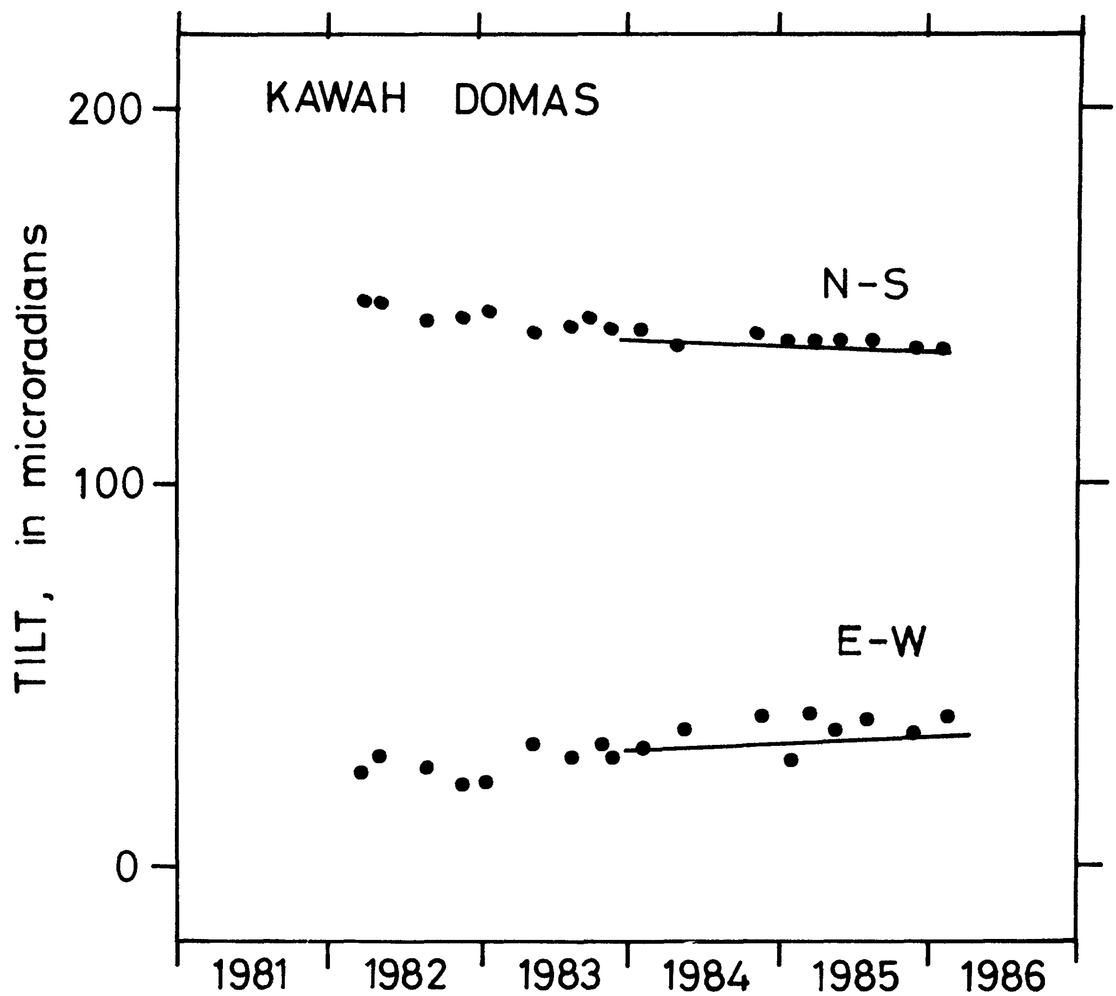


TANGKUBAN PARAHU DRY TILT
1984 - 1985
CICENANG
KAWAH DOMAS
40 microradians/yr
1 kilometer
BUNDERAN
K. Ratu
K.Upas
center of uplift
POS VULK
JAYAGIRI
NAGRAK
KAWAH BARU


POS VOLKANOLOGI
N-S
E-W
TILT, in microradians
300
200
100
0
1981
1982
1983
1984
1985
1986


KAWAH BARU
N-S
E-W
300
200
100
0
TILT, in microradians
1981
1982
1983
1984
1985
1986


CICENANG
N-S
E-W
TILT, in microradians
200
100
0
1981
1982
1983
1984
1985
1986


KAWAH DOMAS
N-S
E-W
200
100
0
TILT, in microradians
1981
1982
1983
1984
1985
1986

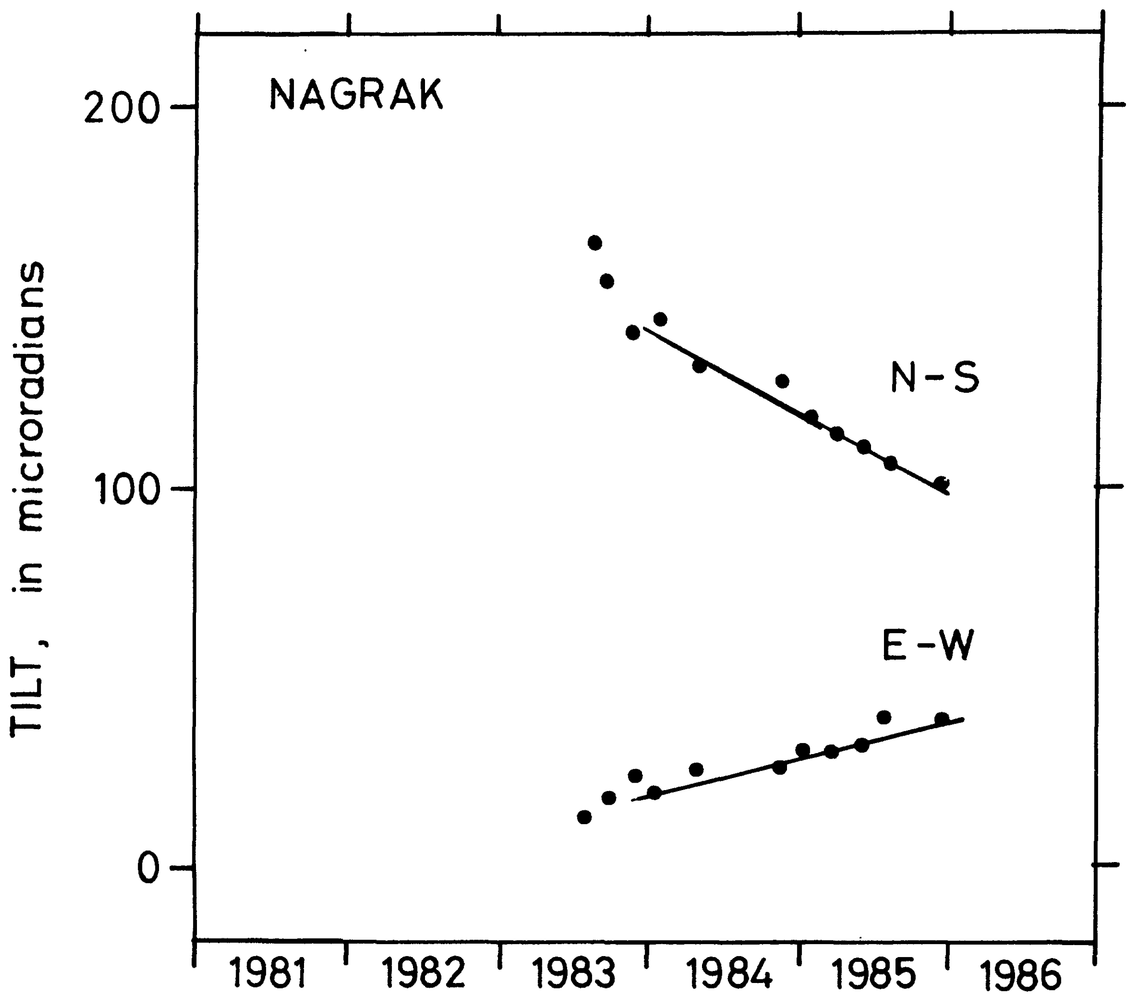
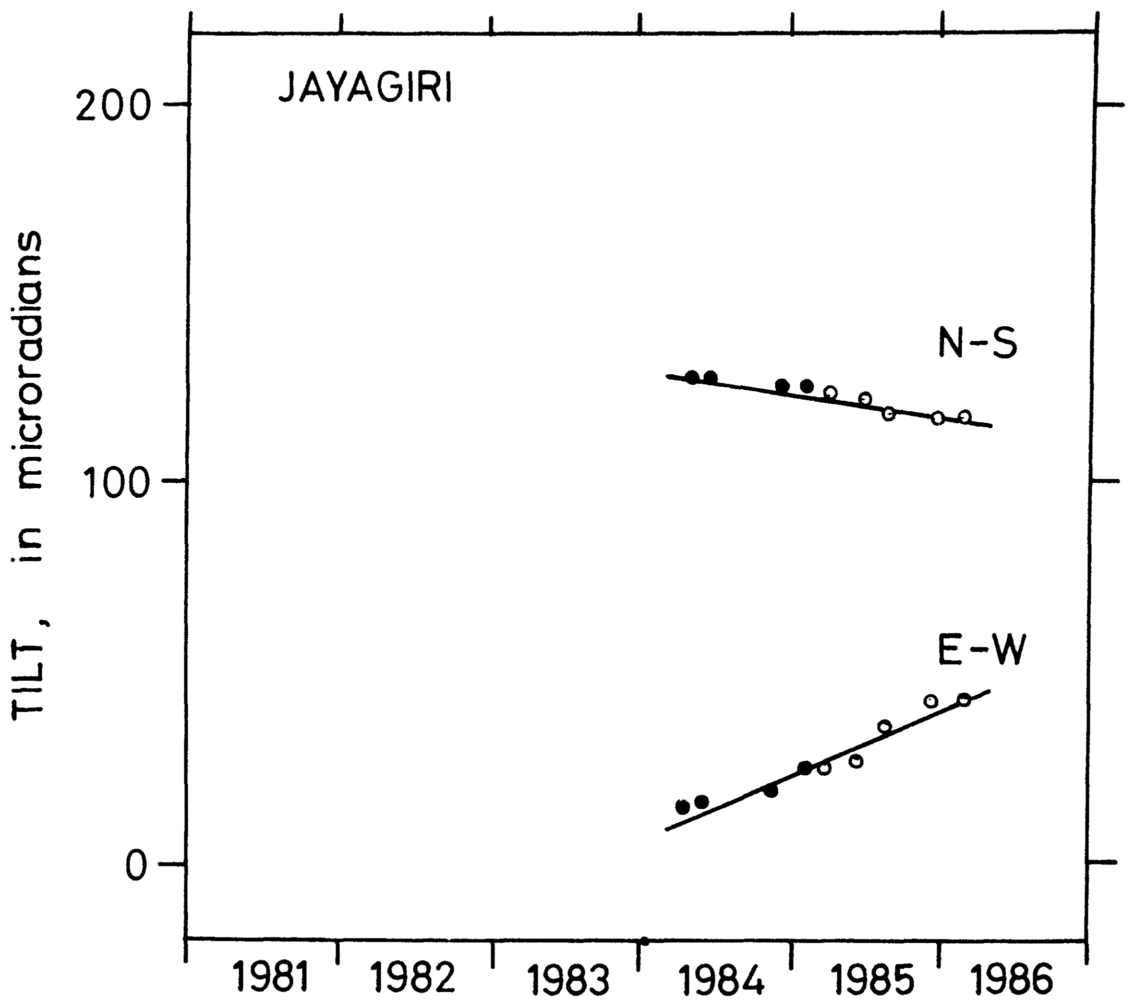

NAGRAK
N-S
E-W
TILT, in microradians
200
100
0
1981
1982
1983
1984
1985
1986

Figure 17



JAYAGIRI
200
100
0
TILT, in microradians
N-S
E-W
1981
1982
1983
1984
1985
1986

Figure 18

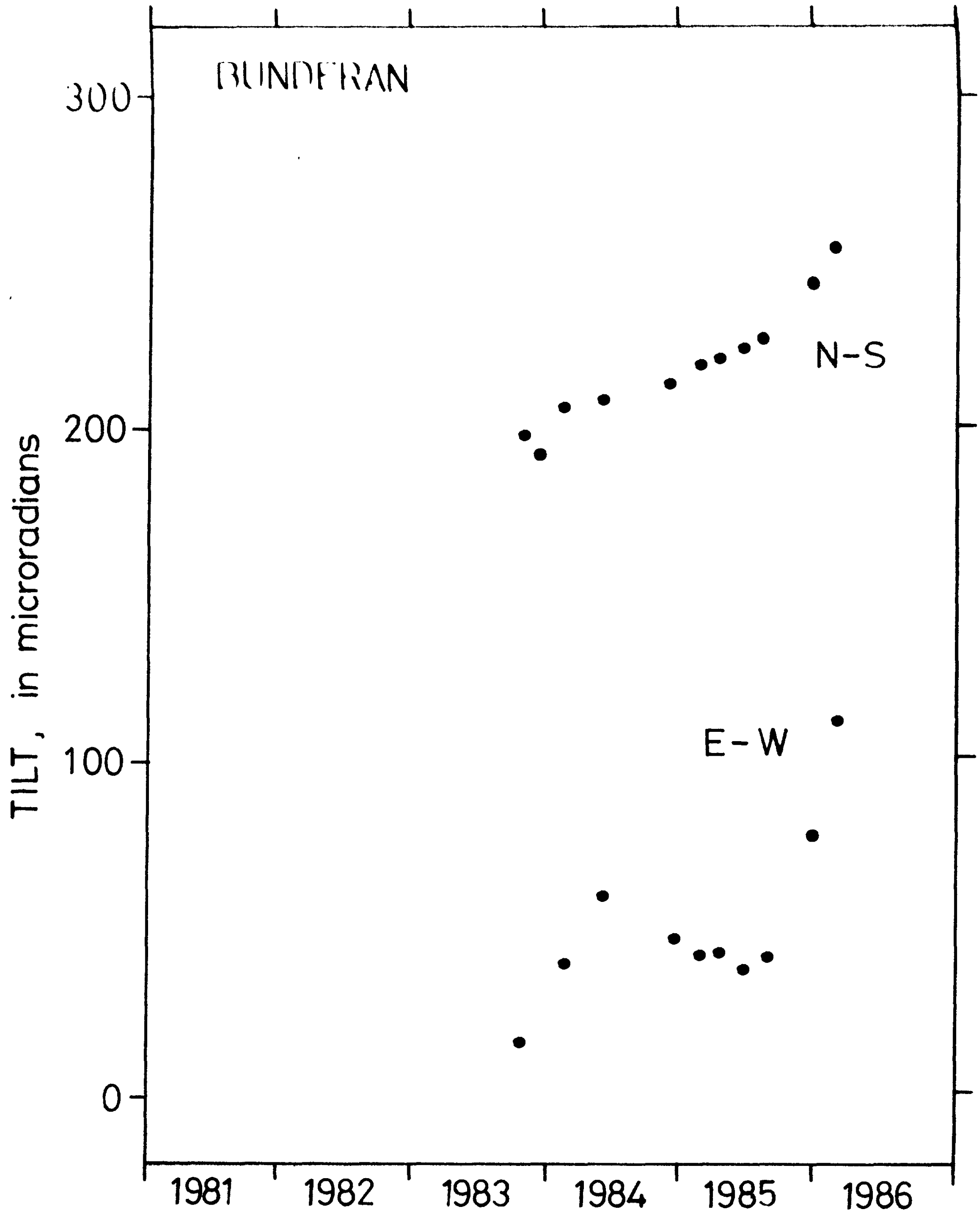
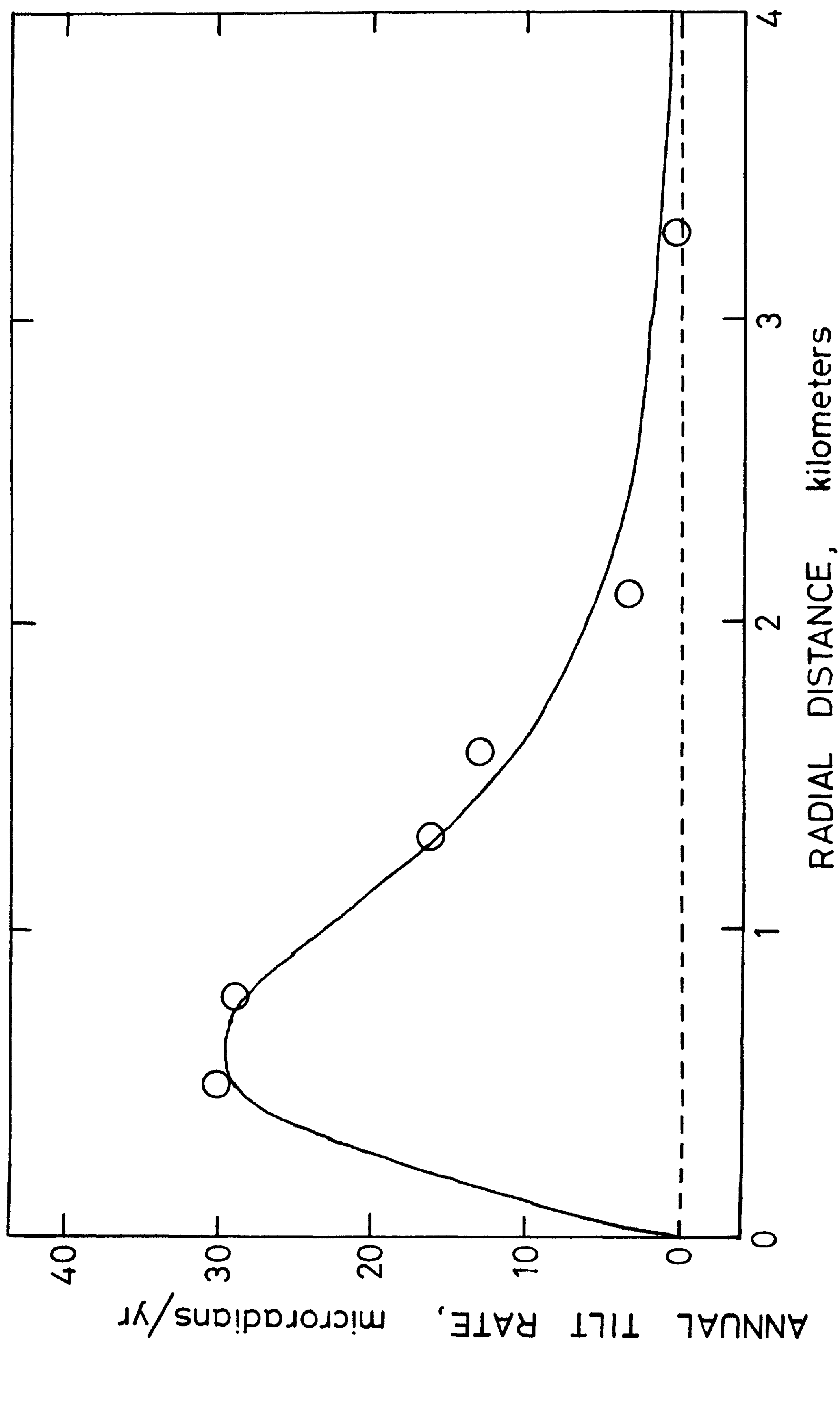

BUNDERAN
300
200
100
0
TILT, in microradians
N-S
E-W
1981
1982
1983
1984
1985
1986

Figure 19


ANNUAL TILT RATE, microradians/yr
RADIAL DISTANCE, kilometers
0
10
20
30
40
0
1
2
3
4