UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Tiltmeter and magnetometer measurements at Mount St. Helens, Washington: 1980-1981

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ABSTRACT

The tilt and magnetic records obtained from telemetered instruments during the initial eleven months of magmatic eruptions at Mount St. Helens are presented in this report. These records cover the catastrophic eruption on May 18, 1980, and the sequence of lesser intensity explosive and dome-building eruptions up to February 1981.

A steady rate of change in both the ground tilt and the magnetic field intensity was indicated by these instruments beginning at the time of installation in early May 1980 and continuing to mid-June 1980. Following this period, the tilt and magnetic curves both reversed and changed at lesser rates.

No short-term tilt or magnetic changes immediately preceded the eruption on May 18, 1980. However, changes in ground deformation and in magnetic field intensity were recorded during this eruption and the following two eruptions on May 25-26, 1980, and June 12-13, 1980. During the later, less intense, eruptive episodes between July 1980 and February 1981, tilt and magnetic changes were below the detectable limit of our instruments located five kilometers from the volcano.

We propose a scenario for the sequence of eruptive events at Mount St. Helens based on the tilt and magnetic records, on the changing seismic pattern, and on gas emission rates. We suggest that a magmatic body was emplaced within a few kilometers beneath Mount St. Helens during the spring of 1980 and that this emplacement was essentially completed by mid-June 1980. The post-June 1980 eruptive activity has been the result of the thermal evolution of this body which results in a continuation of a series of extrusions which do not involve the addition of material from a greater depth.

INTRODUCTION

The recent eruptions of Mount St. Helens, Washington, which began in late March 1980, were the first volcanic eruptions to occur in the contiguous United States since the 1914-1921 activity at Lassen Peak, California. The sequence of events at Mount St. Helens were closely monitored by a variety of techniques. This report presents the results of two such techniques designed to remotely monitor volcanic activity. These techniques concern measuring changes in ground deformation and in magnetic field intensity associated with eruptive activity. Preliminary results of tilt and magnetic data collected during 1980 were given by Dvorak et al. (1981) and Johnston et al. (1981).

A summary of the volcanic activity at Mount St. Helens from March 1980 to February 1981 will first be presented followed by a description of the instrument installation. The major portion of this report will discuss both long-term variations in our measurements, spanning an eleven month period beginning two weeks prior to the cataclysmic eruption on May 18, 1980, and short-term variations recorded immediately before, during, and after major eruptions from May 1980 to February 1981. Our interpretation of the sequence of events observed during the first eleven months of eruptive activity at Mount St. Helens will be given in the final section.

SUMMARY OF RECENT VOLCANIC ACTIVITY

Mount St. Helens is a volcanic cone lying in the northern half of the Cascade Range eighty kilometers north of the metropolitan area of Portland, Oregon. The eruptive history of this volcano and the potential hazards which might accompany future eruptions were described by Crandell and Mullineaux (1978).

A summary of the recent eruptive sequence at Mount St. Helens, extending from the initial recognition of a buildup in seismic activity in late March 1980 to the short dome growth event in February 1981, is given in table I. A more detailed account of the initial activity is provided by the collection of papers edited by Lipman and Mullineaux (1981). The timing of each major explosive event, expressed in Universal time (UTC), is listed in table I along with the maximum height of the convective portion of each eruptive column and the duration of increased seismic activity. The numbers in parentheses are the durations in hours of the highest amplitude tremor recorded during the two initial magmatic events.

The 1980 and early-1981 eruptive sequence (table I) was preceded by at least one week of shallow earthquake activity which itself may have been preceded by several days of microseismic activity (Endo et al., 1981). This shallow earthquake activity continued up to the large eruption on May 18, 1980.

The initial eruptive activity occurred on March 27 as a phreatic explosion which formed a new summit crater and an arcuate east-west trending graben crossing the summit (Christiansen and Peterson, 1981). Similar, though smaller, phreatic bursts continued intermittently throughout the next seven weeks. Coincident with the onset of this phreatic activity, a major bulge encompassing much of the north side of the volcano was formed and probably continued to enlarge from the time of its initial formation in late March up to the May 18, 1980 eruption (Lipman et al., 1981). Prior to May 18, the net volume increase of the volcano resulting from movement of the north flank was approximately 0.1 cubic kilometers (Moore and Albee, 1981).

The first magmatic material was erupted at the onset of eruptive activity at 15:32 UTC on May 18, 1980. A shallow earthquake, comparable in magnitude to several events which had occurred over the past few weeks, initiated a large landslide of the north-side of the volcano. This landsliding triggered a rapid series of events culminating in devastation of an area 30 kilometers west to east and 20 kilometers north of the volcano and in creation of a breached crater 1.5 by 3 kilometers across (Christiansen and Peterson, 1981). All subsequent eruptive activity has originated from the center of this breached crater.

Immediately following the onset of activity on May 18, seismic activity remained high for several minutes probably resulting from a combination of multiple earthquakes, of the mechanics of the landslide, and of the blast induced by the sudden unloading of the magmatic column (Malone et al., 1981). During the next three hours, harmonic tremor remained at a moderate amplitude. The main magmatic phase and production of pyroclastic flows probably began at about 18:17 UTC based on a rapid increase in tremor amplitude and a change in color of the eruptive column. Five hours later, the amplitude of harmonic tremor noticeably decreased, though it remained at a detectable level through early June 1980. During this decrease in amplitude, a swarm of high-frequency earthquakes located 5 to 20 kilometers beneath the volcano were first identified. A swarm of earthquakes also began along north-northwest and south-southeast trends away from the volcano and continued at a decreasing rate for many months (Weaver et al., 1981).

On May 25, 1980, the second magmatic eruption of Mount St. Helens was preceded by a rapid rise and drop in tremor amplitude a few hours prior to the main eruptive phase. In general, the explosivity of Mount St. Helens, as measured by the amplitude and duration of the seismicity associated with each eruptive period, has decreased since May 18.

Several hours of increasing tremor amplitude preceded the next eruption on June 12-13, 1980. This eruptive episode deposited the largest volume of pyroclastic material of any post-May 18 eruption (Rowley et al., 1981) and resulted in the emplacement of the first lava dome. A few days prior to this June eruption, the sulfur dioxide emission rose dramatically from 30-200 tons/day to 600-1200 tons/day (Casadevall et al., 1981). In addition, sulfur encrustatons were much more apparent at rootless fumeroles on the surface of the June 1980 pyroclastic flows than on flows deposited by the two earlier magmatic eruptions (Casadevall and Greenland, 1981).

The July 22 eruption, preceded by several hours of shallow earthquakes, consisted of three major explosive events, each accompanied by small pyroclastic flows. The increased level of seismic activity associated with the initial two bursts lasted no more than several minutes; however, the last explosive event was followed by several hours of harmonic tremor which slowly decreased in amplitude. The explosions associated with this eruption destroyed part of the lava dome emplaced during the previous month. This has been the only post-June 1980 eruption which did not result in emplacement of an extruded lobe.

On August 7, an increase in tremor amplitude once again preceded the occurrence of two major eruptive pulses each resulting in production of new pyroclastic flows. The initial explosion lasted only several minutes; the second major explosion initiated a two hour period of low level harmonic tremor and resulted in the emplacement of a very small dome.

The last significant explosive eruptions occurred in mid-October 1980. During a forty-eight hour period, five short duration, relatively small, explosive events produced at least two small pyroclastic flows culminating in the growth of a lava dome larger than the August extrusion, though smaller than the initial lava dome formed in June 1980.

The eruptive events in December 1980 and February 1981 were both preceded by an almost identical buildup of small shallow earthquakes resulting in additional extruded lobes to the October 1980 lava dome. The December eruption was also accompanied by a very small ash explosion.

INSTRUMENTATION

An initial network of automatic tiltmeters and magnetometers was installed around Mount St. Helens in late April and early May 1980. Several additional instruments were installed during the summer of 1980 to replace those destroyed at the onset of eruptive activity on May 18, 1980. The installation date for each instrument is listed in table II. The location of instrument sites on the volcano are indicated in figure 1. The locations of instruments installed at later dates were specifically chosen to be on the lower, gentler slopes of the volcano in an attempt to increase their potential for surviving possible snow avalanching during winter months and continuing volcanic activity.

Data from each site were transmitted at approximately ten minute intervals to a receiving station located seventy kilometers to the south in Vancouver, Washington. Here they were recorded in digital form on paper tape and manually entered onto the UNIX 11/70 computer system located at the University of Washington in Seattle, Washington.

The tiltmeters were Kinemetrics bubble instruments whose field installation was similar to that used at sites along the San Andreas fault system in California (Mortensen et al., 1977) and on Kilauea and Mauna Loa volcanoes in Hawaii. Platform instruments were anchored onto a rigid circular base cemented on bedrock in a lava tube; borehole instruments were positioned two meters beneath the surface in pre-1980 ash deposits. The amplifiers and recording system were adjusted to record changes in tilt ranging between 0.07 and 100 microradians along two perpendicular horizontal directions. However, owing to site instablity and wet winter conditions, long-term changes have been determined, at best, to an accuracy of only ten microradians.

The magnetometers were Geometrics proton precession instruments which record the total magnetic field intensity to a sensitivity of 0.25 nanotesla. The installation techniques were identical to those used at similar sites along the San Andreas fault in California (Mueller et al., 1981).

LONG-TERM VARIATIONS

Tilt vectors determined by fitting linear trends to data received from the telemetered tiltmeters between May 6 and the onset of activity on May 18 are indicated in figure 1. The instrument nearest the active vent, East Dome, recorded a downward deflection toward the volcano. This movement was probably related to the growth of the east-west summit graben. Two tiltmeters positioned five kilometers from the volcano, Timberline and Ape Cave North, both indicated inflation of the volcano. The tilt change from these two instruments may more accurately reflect the broader scale deformation pattern taking place at Mount St. Helens during this time period. From March 30 to April 30, measurements made at a spirit-level tilt station located near the Timberline tiltmeter on the northeast side of the volcano indicated a net tilt down to the northeast (i.e., away from the volcano) at an average rate of two microradians per day (Lipman et al., 1981). However, frequent measurements at this tilt station also revealed transient tilt changes of as much as 50 microradians occurring at this locality over a time span of a few hours. Diurnal variations in the tiltmeter record have inhibited attempts to further identify the occurrence of these transient tilt changes.

The most distant tiltmeters, Ape Cave and Ape Cave South, located more than eight kilometers south of the volcano, did not record any significant change during the days immediately prior to May 18.

Long-term tilt changes, representing daily averages of hourly values, are plotted in figure 2 for the first eleven months of eruptive activity. The recorded east-west and north-south tilt components have been rotated to a cylindrical coordinate system with the origin positioned at the geometric center of the volcano. A positive radial tilt change denotes a downward motion of the ground directed away from the volcano and usually indicates inflation of the volcano; a positive concentric tilt denotes a downward motion directed in a clockwise sense about the center of the volcano.

These records are derived from the average daily tilt on the Ape Cave North instrument prior to June 20, 1980 and from the June Lake instrument afterwards. A change in reference instrument was necessary in late June 1980, when the Ape Cave North instrument began to record occasional erratic tilt changes, probably related to rockfalls from the ceiling of the lava tube in which this instrument was installed. The June Lake borehole instrument remained free of daily excursions in excess of three microradians up to October 1980. The large tilt changes beginning in November 1980 are possibly the result of rainfall.

The timing of major eruptions of Mount St. Helens did not result in sudden changes in tilt rate (figure 2). However, the tilt pattern does suggest that a steady inflation of the region around the volcano may have begun prior to the operation of the tiltmeter network. In mid-June 1980, the radial tilt component in figure 2 suggests the beginning of a gradual subsidence trend which continued for at least three months. Horizontal distance measurements also indicated a slight subsidence of Mount St. Helens during June and July, 1980 (Swanson et al., 1981). During most of the period of initial increase in tilt indicated in figure 2, only the Ape Cave North instrument was operating. In view of this, it is not possible to completely rule out environmental factors, such as earlier rockfalls within the lava tube containing this instrument, as responsible for the initial steady tilt rate.

Long-term magnetic changes were computed by averaging all data received during each twenty-four hour period beginning at midnight local time. Effects of magnetic storms were not taken into account in determining these averages.

The variation in magnetic field intensity recorded by the only magnetometer near Mount St. Helens to survive the May 18 eruption is plotted in the upper diagram in figure 3. The difference in field intensity recorded between this station and an instrument installed near Mount St. Helens during the summer of 1980 is also presented.

Though permanent offsets in the difference in the magnetic field intensity between Mount St. Helens and Victoria, B. C., were identified by Johnston et al. (1981), these offsets are not apparent in the total field data. The general character of these total field data show a rapid change up to mid-June followed by a reversal in trend and in rate, a pattern similar to the radial tilt curve shown in figure 2. The difference in the magnetic fields measured near Mount St. Helens, shown in the bottom diagram of figure 3, suggests a gradual, local change in magnetic field intensity continuing into late-1980 and 1981. Transient changes coincident with the May 18, May 25, and June 12 eruptions are a combination of regional magnetic storm activity and local magnetic changes probably related to explosive events of Mount St. Helens. The details of these short-term changes are examined in a later section which discusses data recorded during each eruption.

To better illustrate possible similarities in radial tilt and magnetic field intensity, these data have been replotted in figure 4. Since different physical quantities are sensed by these two types of instruments, the general similarities of these two curves are probably not coincidental. One possible explanation for anticipating a relation between tilt measurements and magnetic field changes is the piezomagnetic effect which has been calculated by Stacey et al. (1965) for a volcano similar to Mount St. Helens, and which has been observed under laboratory conditions (Nagata, 1970). Different stress conditions applied to magnetic minerals alter both the magnetic remanence and susceptibility. This change in susceptibility is revealed as a change in the magnetic field external to the sample. In active volcanic areas, changes in local stress conditions at depth are anticipated to give rise to surface displacements and to variations in the magnetic field (Johnston and Stacey, 1969). Figure 4 suggests that at Mount St. Helens, a change in tilt of one microradian at a distance of five kilometers from the active vent may be related to a magnetic change of one to two nanotesla.

SHORT-TERM VARIATIONS

Episodes of eruptive activity at Mount St. Helens were of short duration lasting no more than several hours and always less than a few days. Because of these short durations, telemetered instrumentaton was a primary means to record changes taking place during eruptive activity.

May 18-19, 1980

Tilt and magnetic changes recorded on May 18-19, 1980, by instruments nearest to Mount St. Helens which survived this eruption are shown in figures 5 to 7. All tilt data displayed in this paper have been rotated to the cylindrical coordinate system described in the previous section. In these and the following figures, the onset of major explosive events are indicated by vertical arrows and the time periods of increased seismic activity are denoted by a horizontal line.

Tilt values received from the Ape Cave North instrument did not indicate any sudden or unusual changes taking place immediately prior to the onset of eruptive activity on May 18, 1980 (figure 5). Within the ten minute time resolution of this instrument, a change of four microradians in an inflationary sense was coincident with the onset of this eruption. A steady, deflationary tilt of several hours duration immediately followed the initiation of eruptive activity. Two later, brief periods of increased deflation rate and recovery began at about 18:15 UTC on May 18 and 04:45 UTC on May 19. These brief transient changes are similar in appearance to tilt changes recorded during prolonged eruptive phases on May 25 and June 13. The rapid tilt changes detected along the concentric component may be related to very short periods of increased seismic activity.

The sudden tilt change at the onset of eruptive activity on May 18 was probably the result of the elastic response of the crust to landsliding of material at the onset of this eruption. A displaced volume of 2.7 cubic kilometers (Moore and Albee, 1981) having an average density of 2600 kilograms per cubic meter and an assumed value of 6x10**11 dynes/cm**2 for the rigidity of the crust will result in the observed four microradian tilt change at the distance of the Ape Cave North instrument.

The steady deflationary trend recorded at the Ape Cave North site, continuing three hours after the onset of eruptive activity, is possibly the result of the shallow upward movement of material shortly after the onset of activity.

At the Ape Cave North station, rapid transient changes occurred along both radial and concentric tilt components near the end of the period of high amplitude tremor.

At a distance of ten kilometers from the volcano, the Ape Cave tiltmeter did not record a tilt change coincident with the onset of activity (figure 6). However, this instrument did indicate an abrupt tilt change during the period of high amplitude tremor (22:40 UTC).

The magnetic record from the surviving magnetometer at Mount St. Helens, Blue Lake, has been differenced with the magnetic record obtained from a synchronized magnetometer at the Victoria Geomagnetic Observatory located in Victoria, B. C. The purpose of examining magnetic field differences is to reduce effects of diurnal variations and other magnetopheric disturbances. Immediately prior to the onset of eruptive activity on May 18 (figure 7), no change is apparent in the magnetic field. However, oscillations did accompany the initial few hours of eruptive activity. A more gradual, permanent change in the field intensity occurred during the period of highest amplitude harmonic tremor. We suggest that the early oscillations are the result of the initial disturbance of the upper atmosphere and ionosphere by the eruptive column. The permanent offset of nine nanotesla which occurred during the period of highest amplitude tremor has been suggested to be related to the elastic strain released by this event (Johnston et al., 1981).

May 25-26, 1980

Tilt data for the May 25 eruption (figure 8) show considerably less variation during this eruption than data recorded on May 18-19. At the time of the initial explosive burst and the start of the period of high amplitude tremor, tilt values indicated subsidence of the volcano followed by gradual recovery to approximately the pre-eruption level. This pattern is very similar to tilt changes measured during the explosive 1979 eruptions of Usu Volcano in HokKaido, Japan (I. Yokoyama, 1981, personal communication). No tilt changes were recorded by the Ape Cave tiltmeter during this eruption (figure 9).

Magnetic data related to the second magmatic eruption indicate variations in the field intensity of more than one hundred nanoteslas over a time scale of less than one hour. The largest magnetic variations occurred during the five hours of highest amplitude tremor (figure 10).

June 12-13, 1980

A tilt pattern similar in appearance, though smaller in magnitude, to that recorded on May 25-26 also accompanied the period of high amplitude tremor during the June 12-13 eruption (figure 11). No noticeable offset in local magnetic field intensity is apparent during this eruption (figure 12), though, as noted by Johnston et al.(1981), diurnal variations in the amplitude of the magnetic field intensity during this eruption were much higher than during noneruptive periods.

Later Eruptions (July 1980 through February 1981)

Based on the level of seismicity, the post-June 1980 eruptions of Mount St. Helens have been less in intensity and in duration than the initial three magmatic eruptions. At the five kilometer distance of our nearest instruments, no tilt or magnetic changes could be attributed to later eruptive activity (figures 13 to 24). Variations in the tilt records presented in these figures may be related to periods of heavy rainfall. Diurnal variations exhibited in the total field magnetic data are typical patterns of global extent induced in the earth's magnetophere and ionosphere (e.g., figure 20).

DISCUSSION

The episodes of recent eruptive activity at Mount St. Helens are viewed as part of an evolving sequence which resulted from the vertical migration of a magmatic body to the surface. We regard the individual eruptive events as only one aspect of the processes involved in this evolution. The depth at which this material resided at the time of the initial seismic activity in March 1980 is undetermined. However, a comparison of the broadbased studies begun shortly after the onset of intense seismic activity allows a scenario to be constructed from the sequence of observed events. Before presenting our interpretation, we will first highlight several observations considered important in understanding the sequence of volcanic activity which began in the spring of 1980 at Mount St. Helens.

Prior to the catastrophic eruption on May 18, seismic activity was limited to a swarm of shallow earthquakes less than four kilometers beneath the surface (Endo et al., 1981). Also during this time period, several short episodes of harmonic tremor, unrelated to eruptive activity, were recorded at stations more than a hundred kilometers from the volcano. The process giving rise to these tremor episodes may be analogous to the rapid movement of material proposed to occur beneath Kilauea Volcano, Hawaii, during episodes of deep volcanic tremor (Aki and Koyanagi, 1981). On May 18, very high amplitude harmonic tremor was not recorded until three hours after the onset of eruptive activity. This tremor episode lasted five hours and began to subside at about 00:30 UTC on May 19. High frequency, deep earthquakes, located 5 to 20 kilometers beneath the volcano and along a linear zone extending up to twenty kilometers north-northwest and south-southeast of the volcano (Weaver et al., 1981), were first recognized during this decrease in tremor amplitude. Harmonic tremor recorded throughout the next three weeks rose in amplitude several hours prior to eruptions on May 25-26 and June 12-13. Since mid-June 1980, seismic activity at Mount St. Helens has been limited to increases in harmonic tremor amplitude or to a buildup of shallow earthquakes several hours to perhaps as much as a few weeks prior to each post-June 1980 eruption (Malone et al., 1981).

Tilt changes recorded by automatic instruments suggest continual inflation of the volcano up to mid-June 1980. The cessation of an inflationary trend approximately coincides in time with the June 12-13 eruption and the appearance of the first lava dome. The steady inflationary trend was not recorded by horizontal distance measurements because poor weather conditions and continued eruptive activity inhibited these surveys (Lipman et al., 1981). However, horizontal distance measurements (Swanson et al., 1981) and telemetered tilt data (figure 2) both indicate a slow subsidence of the volcano during the summer of 1980.

Long-term changes in the magnetic field intensity were similar to the tilt pattern (figure 4). Prior to mid-June 1980, the magnetic field intensity changed rapidly. Since mid-June, the field intensity reversed its trend and changed at a lesser rate.

A few days prior to the June 1980 eruption, the emission rate of sulfur dioxide increased dramatically and remained at a higher, though gradually decreasing, level for the next several months (Casadevall et al., 1981). In addition to this change in emission rate, numerous small patches of sulfur encrustations were observed at rootless fumeroles on pyroclastic flows deposited by the June 1980 eruption (Keith et al., 1981; Casadevall and Greenland, 1981).

The sequence of observations outlined above and the proposed related processes are outlined in table III. Events from late-March to mid-June 1980 are considered to be the result of the continual, upward movement of a body of magma.

The coincident occurrence of the initial eruptive activity and appearance of the north-side bulge in March 1980 probably resulted from a sudden surge of material to a position very near the surface. The steady growth of this feature implies continual supply from depth. The immediate source for the shallow intrusion is proposed to be a much larger body a few kilometers beneath the surface. The existence of this larger body is suggested by the continued tilt and magnetic changes after May 18 at a distance of five kilometers and the occurrence of later eruptive episodes.

The upward movement of the main body was essentially uninterrupted by eruptive activity on May 18 and 25. This movement is indicated by the steady rate in the tilt and the magnetic curves whose long-term trends were only slightly disturbed by the large eruptions on May 18 and May 25.

In our view, the initial magmatic eruption on May 18 was premature. It did not directly result from the continued formation and propagation of cracks and the concurrent migration of the main body to the surface but probably involved a limited mass of material supplied from depth and emplaced very near the surface. The May 18 eruption was initiated by the structural collapse of the north-side of the volcano and did not immediately result in establishing a well-defined vent, as is suggested by the delay in the maximum sulfur emission until June 4 (Casadevall et al., 1981). Simultaneous changes in the tilt and the magnetic curves, cessation of continuous seismic activity, and appearance of the first lava dome, in mid-June 1980, further suggest that the final vertical migration of the main magmatic body did not take place at the time of the May 18 eruption but was delayed until several weeks later.

The lesser intensity of the post-June 1980 eruptions, the decrease in seismic activity, the deflationary tilt pattern and the slight extension indicated by the horizontal distance measurements, the slower magnetic changes, and the apparent decline in sulfur emission since June 1980 all indicate that this magmatic body is now residing in a much more stable position within the crust. The upper portion of this body may now have appeared on the surface as the present lava dome complex. At the present time, this body is continuing to extrude in a series of episodic, relatively minor, non-explosive events.

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TABLE I

SUMMARY OF ERUPTIVE ACTIVITY

Mount St. Helens: March 1980 - February 1981

DATE	TIME (UTC)	MAXIMUM HEIGHT OF ERUPTIVE COLUMN	DURATION	COMMENTS
20 March 1980	23:47			first 4+ earthquake
27 March	20:36	2 km (?)		first steam explosion
28 March to late-May				intermittent steam explosions
18 May	15:32	20 km	15 min	first magmatic eruption
	18:17	20	72 hrs (5)	main eruptive phase
25 May	05:30 (?)		10 min	possible short eruptive burst
	09:36	12 km	20 hrs (3)	main eruptive phase
13 June	02:26	10 km	5 min	appearance of first lava (first sighted 15 June) (4×10^6 m^3)
	04:11	15	6 hrs	
23 July	00:14	12 km	6 min	
	01:25	18	22	
	02:01	12	3 hrs	
7 August	23:36	12 km	2 min	lava dome ($< 10^6$ m^3)
8 August	05:32	--	2 hrs	
17 October	04:58	12 km	5 min	lava dome (2×10^6 m^3)
	16:28	13	4 min	
18 October	04:12	12	5 min	
	19:35	6	5 min	
	21:28	5	3 min	
26 December		volcanic earthquake swarm		lava dome ($\sim 5 \times 10^6$ m^3)
5 February 1981		volcanic earthquake swarm		lava dome ($\sim 5 \times 10^6$ m^3)

TABLE II

INSTRUMENT INSTALLATION DATES

TILTMETERS

*Timberline (P)	7 April 1980
*East Dome (P)	13 April 1980
Ape Cave (P)	19 April 1980
Ape Cave North (P)	1 May 1980
Ape Cave South (P)	12 May 1980
Blue Lake (B)	11 June 1980
June Lake (B)	15 June 1980

MAGNETOMETERS

*Timberline	7 May 1980
*East Dome	8 May 1980
Blue Lake	9 May 1980
Ape Cave North	26 Aug 1980

*destroyed on May 18, 1980

(P) platform instrument

(B) borehole instrument

TABLE III

MAJOR OBSERVATIONS AND INTERPRETATIONS

Mount St. Helens 1980-1981

dates	observations	interpretation
20-26 Mar 1980	major buildup of shallow volcanic earthquake swarm	continual crack growth and possible deep intrusion of material
27-28 Mar 1980	large initial phreatic explosions, first apparent surface disruption; continuation of earthquake activity	sudden surge of material to a position very near the surface
29 Mar - 17 May 1980	continuation of earthquake swarm; large-scale, continuous displacement of north flank of the volcano	steady, near-surface intrusion
18 May 1980 (15:32 UTC)	structural failure of north slope; formation of blast deposit	sudden release of pressure allowed rapid expansion of shallow, intruded material
18 May (15:33-18:16 UTC)	continuous, moderate amplitude harmonic tremor; possible deflation indicated by distant tiltmeter	rapid, upward migration of material
18 May (18:17 UTC) - 19 May (00:30) 1980	high amplitude harmonic tremor; rapid ground tilt changes; color change of eruptive column	main Plinian phase of eruption; extrusion of most of the eruptive products during May 18-19
19 May - late May 1980	deep, high-frequency earthquakes centered both beneath the volcano and along a linear trend NNW-SSE of the volcano	stress adjustment to rapid transport and extrusion of material during eruption

TABLE III (continued)

dates	observations	interpretations
19 May - early June 1980	continuous harmonic tremor; continual tilt and magnetic changes; two explosive eruptions	continual upward migration of large volume of material beneath the volcano
mid-June 1980	cessation of seismic activity and of tilt and magnetic changes; sudden increase in sulfur emission; appearance of first lava dome	completion of the opening of the vent from the main magmatic body to the surface allowing rapid gas emission and extrusion of material en masse
late-June 1980 - 1981	very slow subsidence; partial recovery of magnetic changes; brief periods of minor seismic activity; occasional short-duration eruptive episodes steadily decreasing in explosive intensity; decreasing sulfur emission rate	thermal evolution of large magmatic body emplaced near the surface which is episodically being extruded

Figure 1. Location of tiltmeter and magnetometer sites around Mount St. Helens. Tilt changes recorded between May 6 and May 18, 1980 are indicated. Timberline and East Dome instruments were destroyed at the onset of eruptive activity on May 18, 1980. Outlines correspond to the 4000 foot contour at Mount St Helens which approximates the pre-1980 timberline.

Figure 2. Daily tilt pattern recorded five kilometers south of Mount St. Helens from May 1980 to March 1981. In this and following figures, the recorded north-south and east-west tilt components have been rotated to a cylindrical coordinate system centered on the volcano. A positive radial tilt is a downward deflection of the ground directed radially away from the volcano; a positive concentric tilt is a downward deflection of the ground in a clockwise sense concentric with the center of the volcano.

Figure 3. Daily values of the magnetic field intensity recorded by stations five kilometers from Mount St. Helens. In the upper plot are daily averages of magnetic data received from the Blue Lake magnetometer. In the lower plot are daily averages of the difference in the magnetic field intensity recorded between instruments located five kilometers west and south of the volcano.

Figure 4. Comparison of daily values of tilt and magnetic field intensity from May to October 1980.

Figure 5. Tilt changes recorded by the Ape Cave North tiltmeter during the forty-eight hour period spanning the May 18-19, 1980 eruption. In this and following figures, the onset of major eruptive bursts and periods of the highest amplitude harmonic tremor recorded during each eruption are indicated by a vertical arrow and a solid horizontal line, respectively.

Figure 6. Tilt changes recorded by the Ape Cave tiltmeter during the May 18-19, 1980 eruption.

Figure 7. Differences in magnetic field intensity recorded by an instrument located near Victoria, B. C., and by the Blue Lake magnetometer located five kilometers west of Mount St. Helens during the May 18-19, 1980 eruption.

Figure 8. Tilt changes recorded by the Ape Cave North tiltmeter during the May 25-26, 1980 eruption.

Figure 9. Tilt changes recorded by the Ape Cave tiltmeter during the May 25-26, 1980 eruption.

Figure 10. Differences in magnetic field intensity recorded

between Victoria, B. C., and the Blue lake magnetometers near Mount St. Helens during the May 25-26, 1980 eruption.

Figure 11. Tilt changes recorded by the Ape Cave North tiltmeter during the June 12-13, 1980 eruption.

Figure 12. Differences in the magnetic field intensity recorded between Victoria, B. C., and the Blue Lake magnetometers during the June 12-13, 1980 eruption.

Figure 13. Tilt changes recorded by the Ape Cave North tiltmeter during the July 22-23, 1980 eruption.

Figure 14. Tilt changes recorded by the Ape Cave North tiltmeter during the August 7-8, 1980 eruption.

Figure 15. Tilt changes recorded by the June Lake tiltmeter during the August 7-8, 1980 eruption.

Figure 16. Tilt changes recorded by the June Lake tiltmeter during the October 1980 eruption.

Figure 17. Hourly tilt changes recorded by the Ape Cave North tiltmeter during a ten day period spanning the December 1980 eruption. The time period of the earthquake swarm and the first sighting of the new extrusion are indicated.

Figure 18. Hourly tilt changes recorded by the June Lake tiltmeter during the December 1980 eruption.

Figure 19. Hourly tilt changes recorded by the Blue Lake tiltmeter during the December 1980 eruption.

Figure 20. Ten minute magnetic data from Blue Lake magnetometer and differences in the field intensity measured between Ape Cave North and Blue Lake magnetometers during the December 1980 eruption.

Figure 21. Hourly tilt changes recorded by the Ape Cave North tiltmeter during the February 1981 eruption.

Figure 22. Hourly tilt changes recorded by the June Lake tiltmeter during the February 1981 eruption.

Figure 23. Hourly tilt changes recorded by the Blue Lake tiltmeter during the February 1981 eruption.

Figure 24. Ten minute magnetic data from the Blue Lake magnetometer and differences in the field intensity measured between Ape Cave North and Blue Lake magnetometers during the February 1981 eruption.

Figure 1

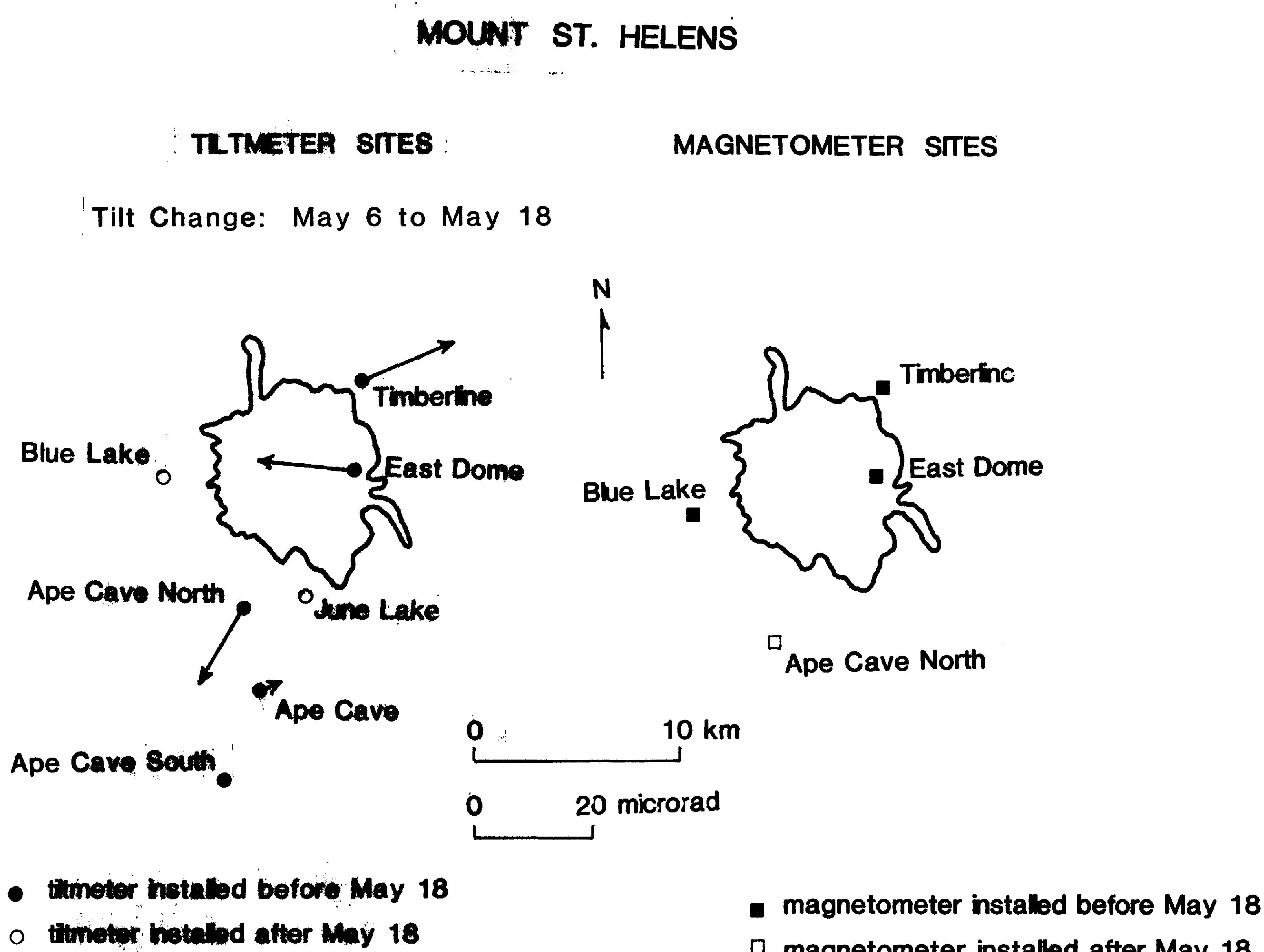

MOUNT ST. HELENS
TILTMETER SITES
Tilt Change: May 6 to May 18
MAGNETOMETER SITES
N
Timberline
East Dome
Blue Lake
Ape Cave North
June Lake
Ape Cave
Ape Cave South
Timberlinc
East Dome
Blue Lake
Ape Cave North
0
10 km
0
20 microrad
tiltmeter installed before May 18
tiltmeter installed after May 18
magnetometer installed before May 18
magnetometer installed after May 18

Figure 3

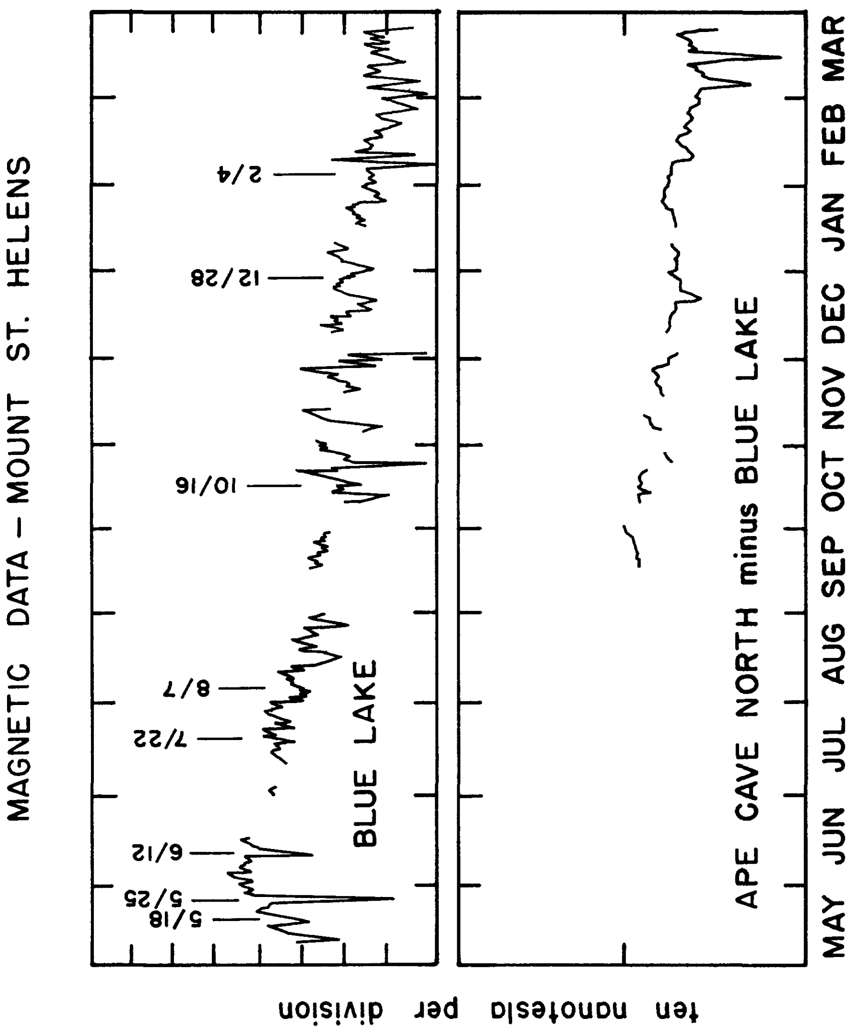
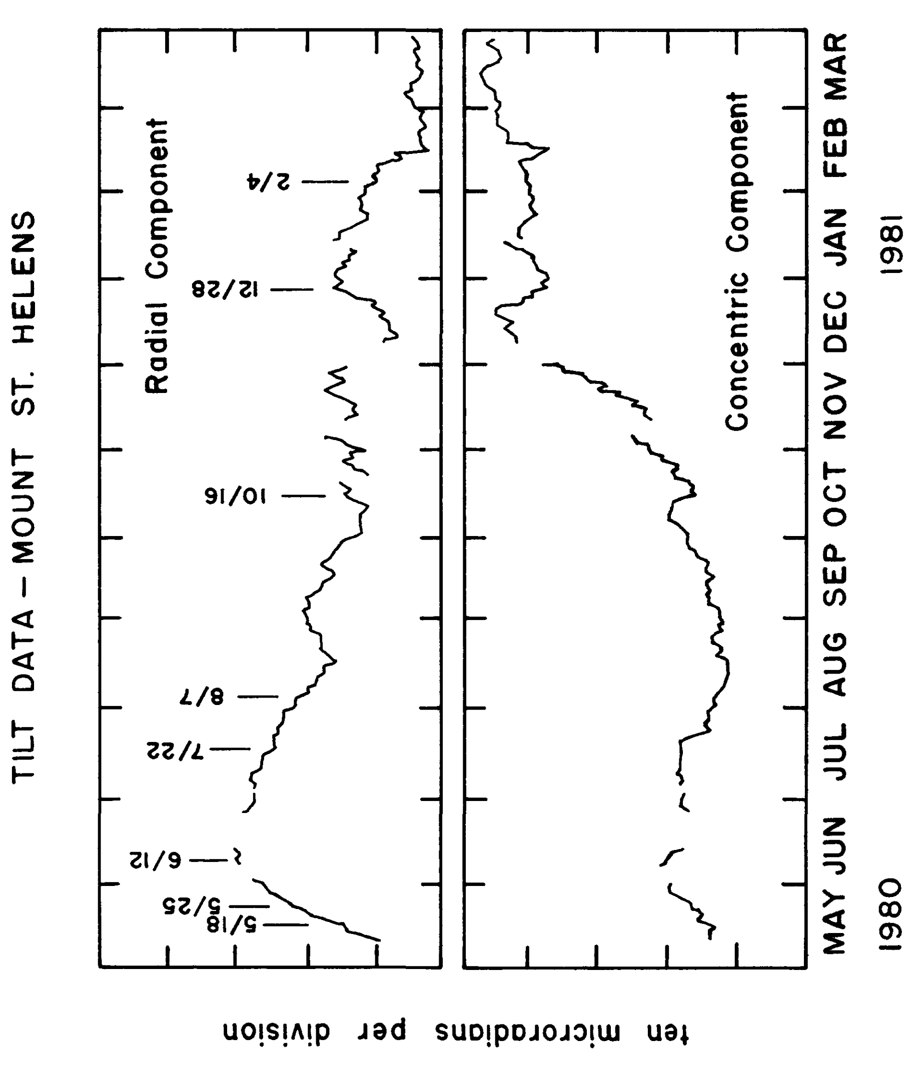

MAGNETIC DATA – MOUNT ST. HELENS
BLUE LAKE
5/18
5/25
6/12
7/22
8/7
10/16
12/28
2/4
APE CAVE NORTH minus BLUE LAKE
ten nanotesla per division
MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR
1980
1981

Figure 2


TILT DATA - MOUNT ST. HELENS
Radial Component
5/18
5/25
6/12
7/22
8/7
10/16
12/28
2/4
Concentric Component
MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR
1980
1981
ten microradians per division

COMPARISON OF TILT AND MAGNETIC DATA

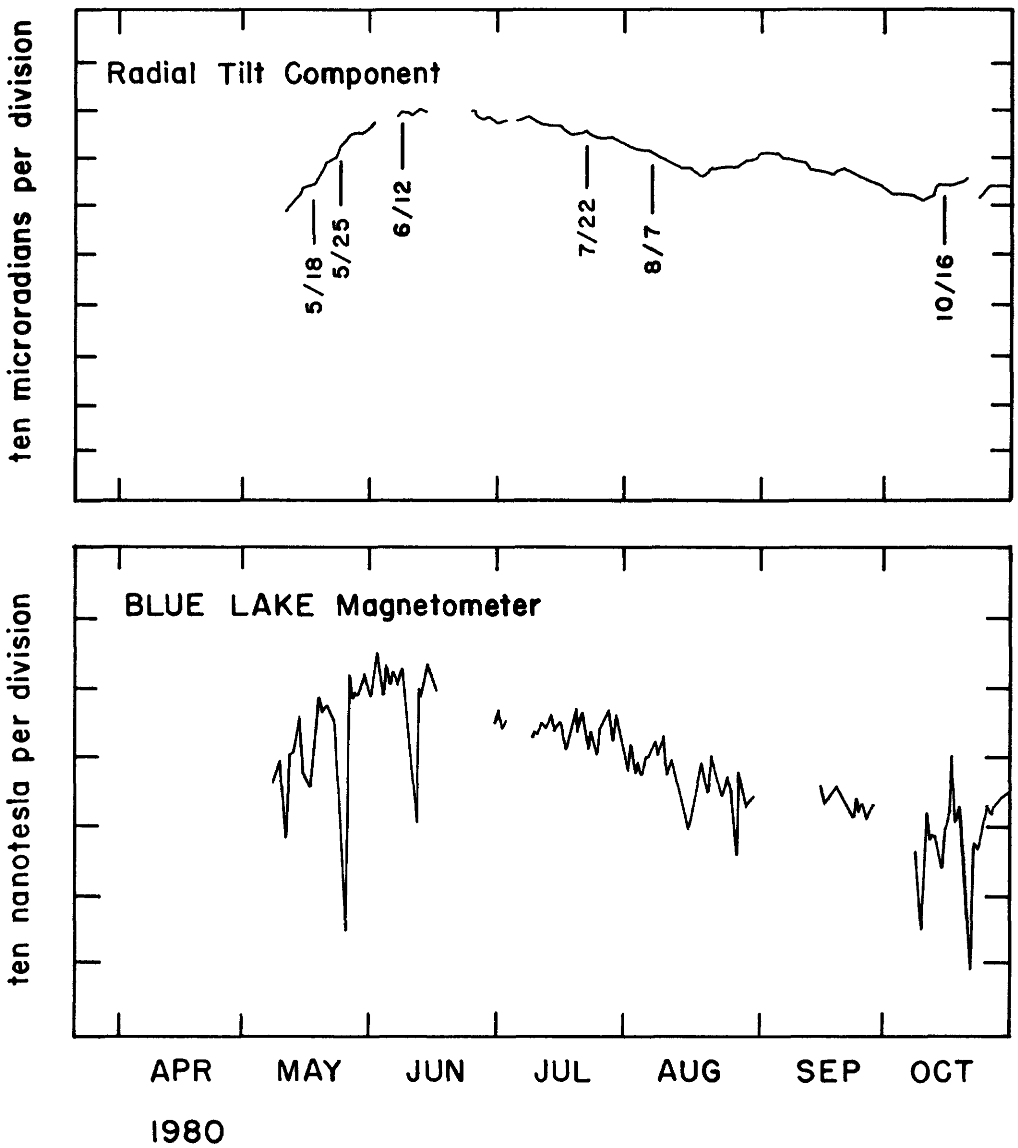
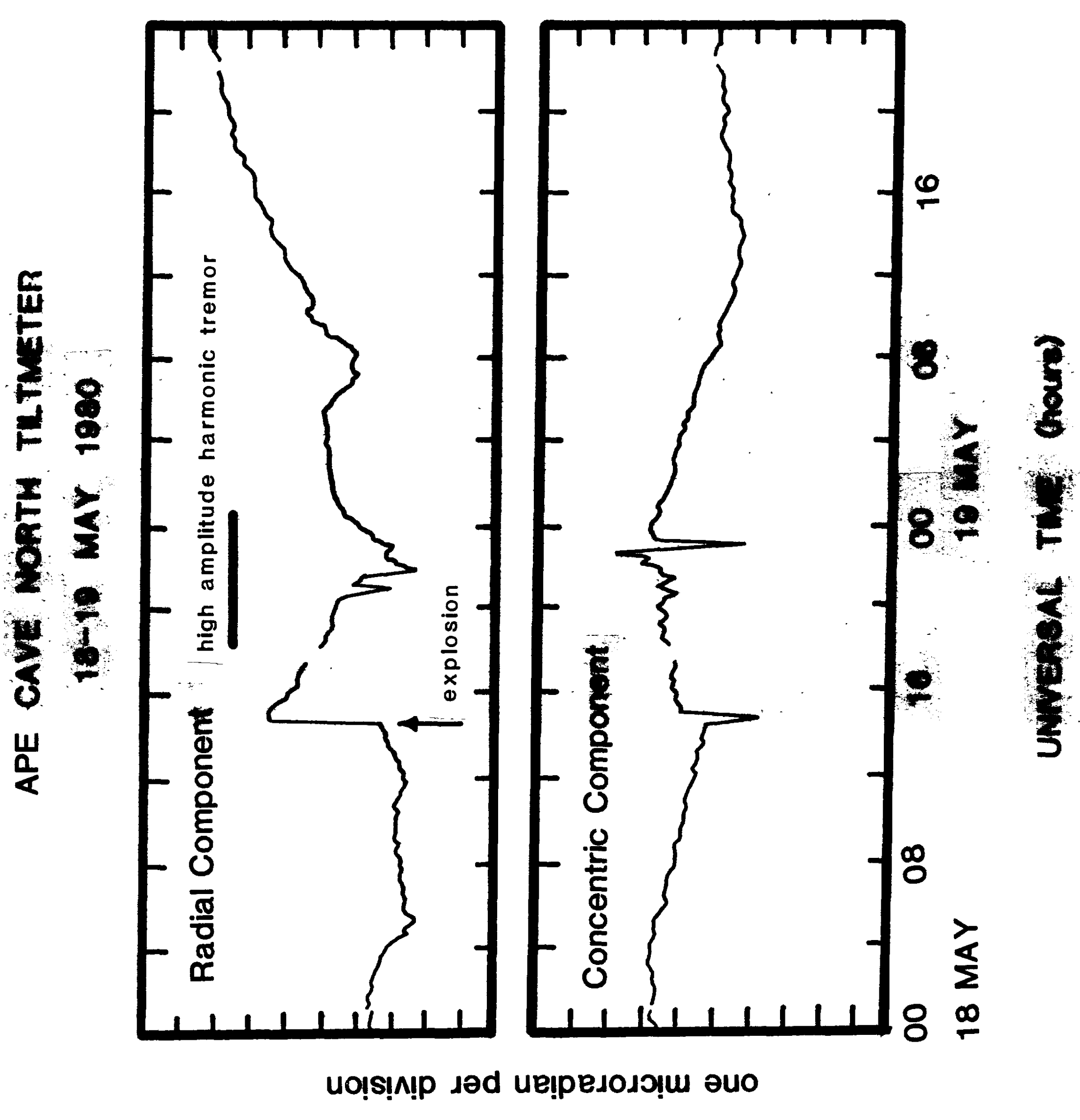


Figure 5


APE CAVE NORTH TILTMETER
18–19 MAY 1980
Radial Component
high amplitude harmonic tremor
explosion
Concentric Component
one microradian per division
00
08
16
00
08
16
18 MAY
19 MAY
UNIVERSAL TIME (hours)

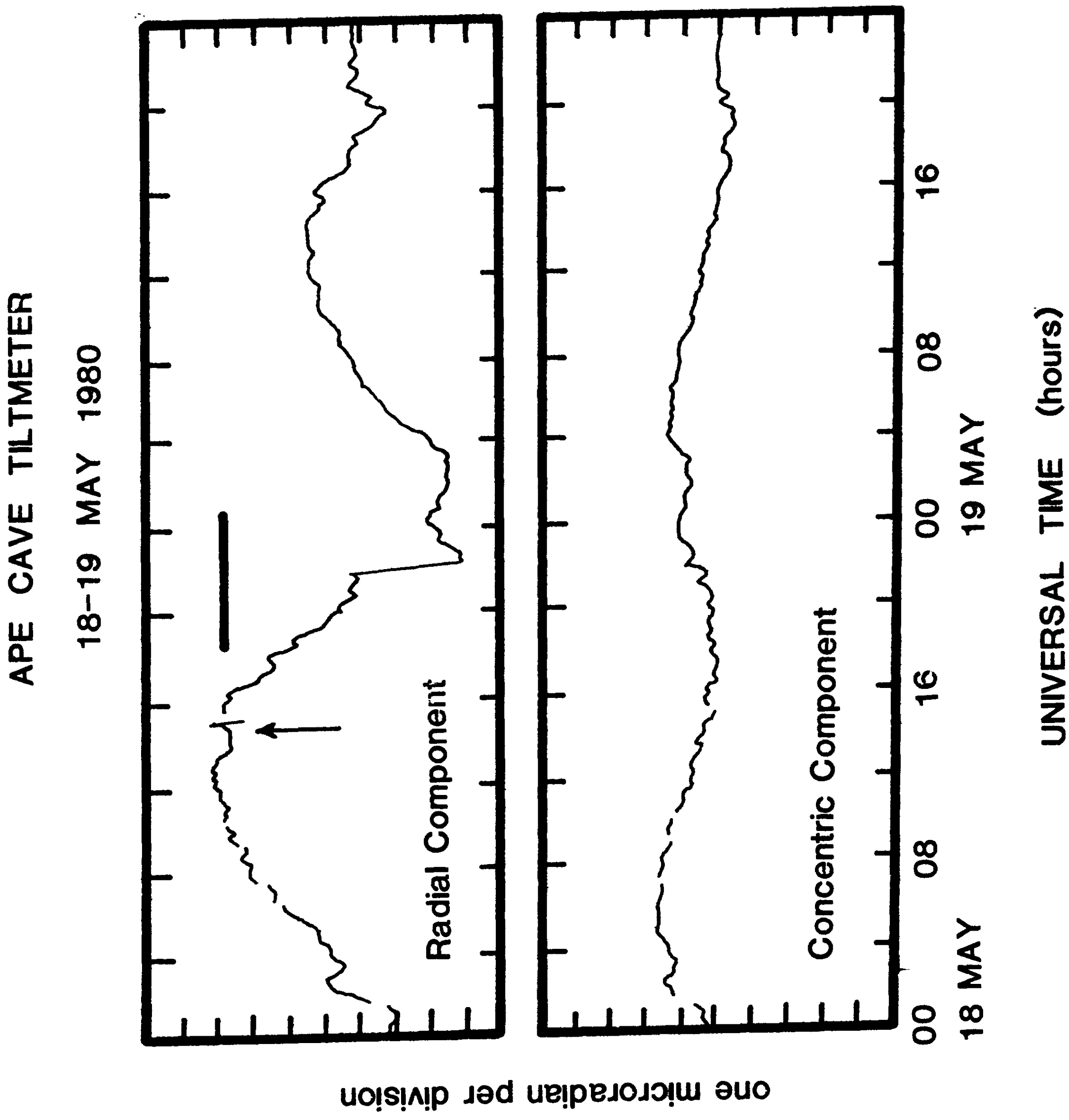
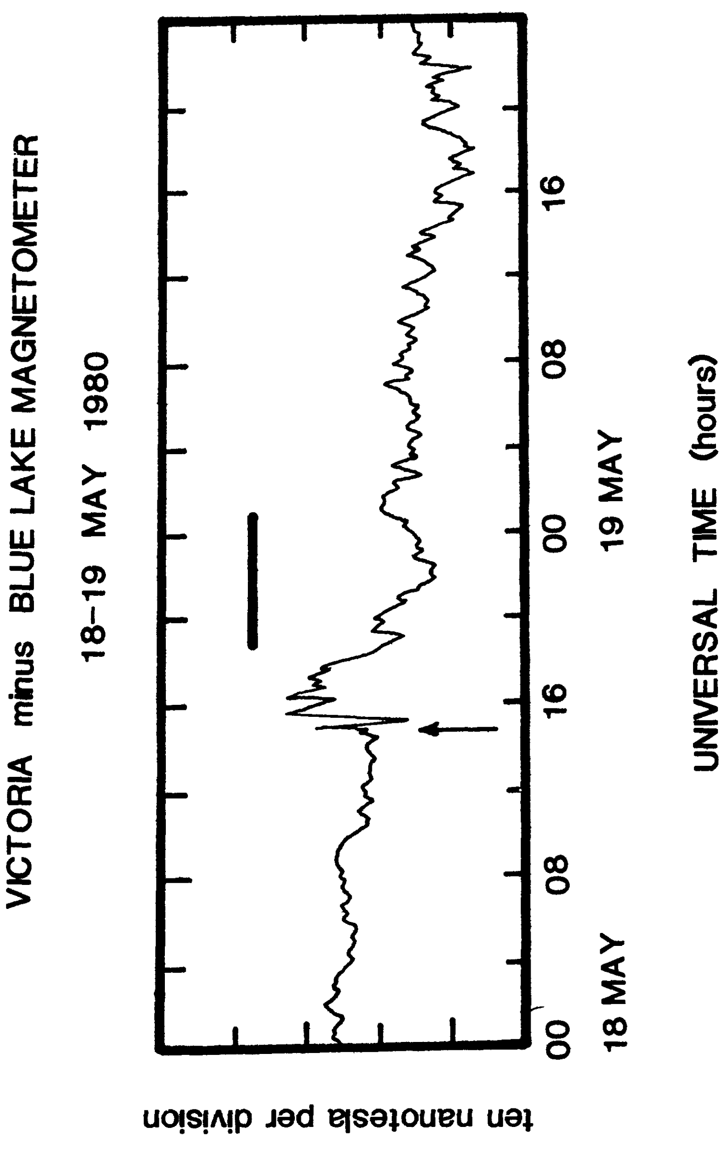
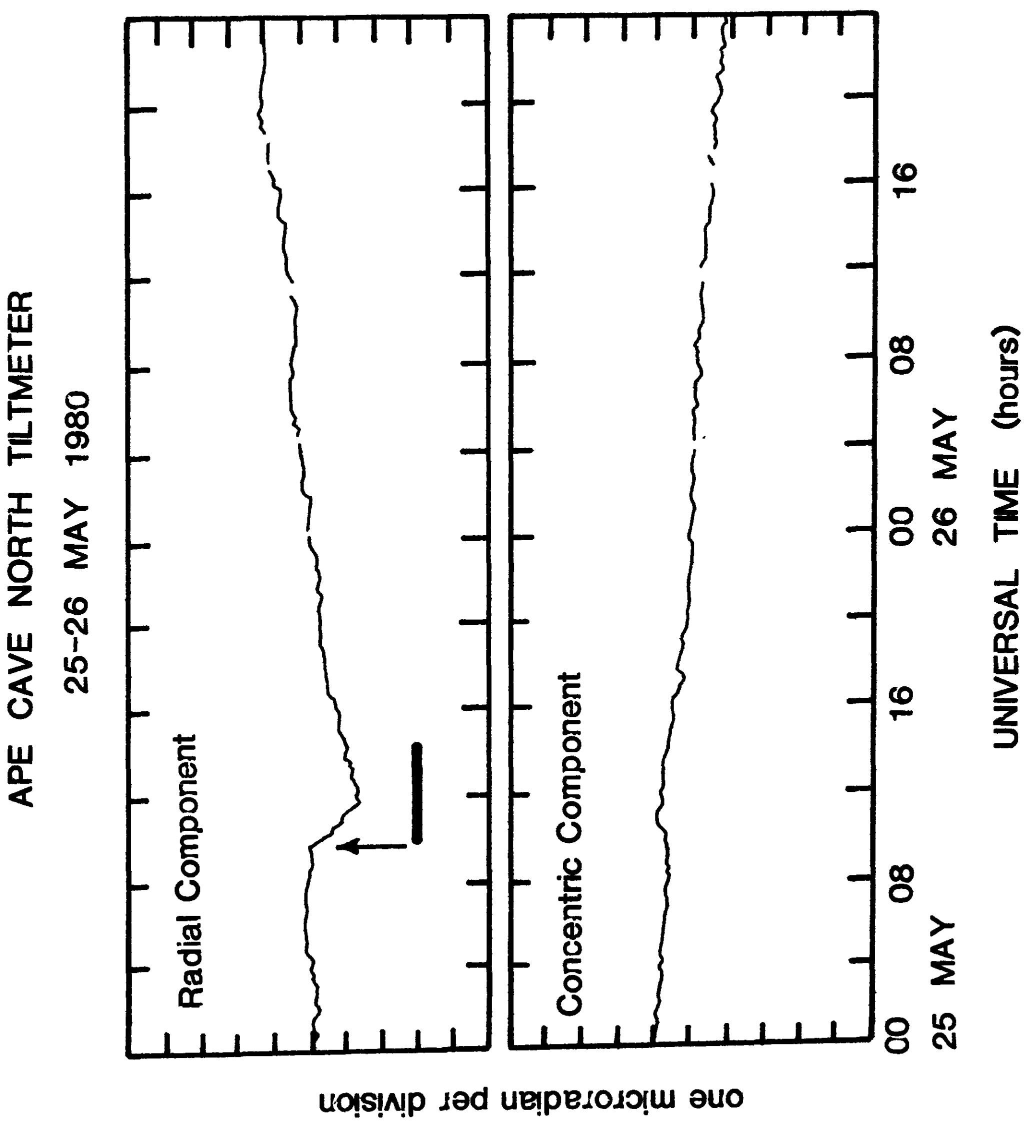
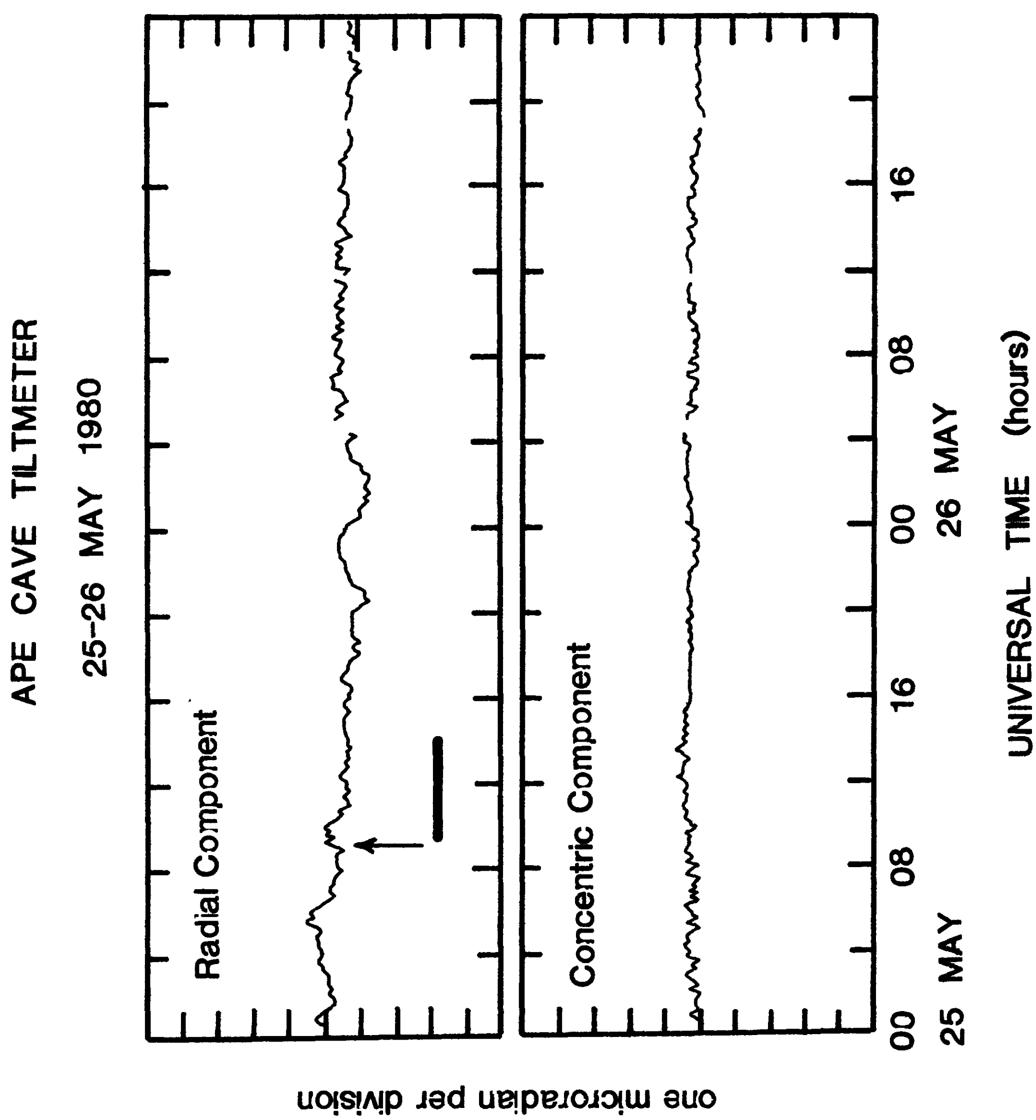
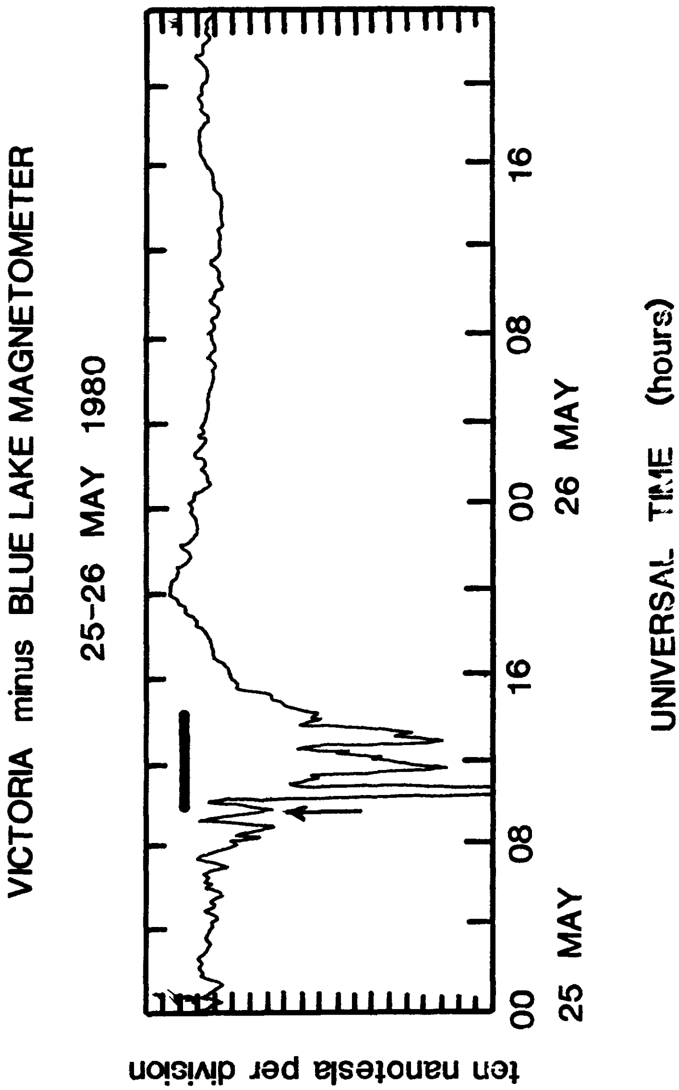

APE CAVE TILTMETER
18-19 MAY 1980
Radial Component
Concentric Component
00
08
16
00
08
16
18 MAY
19 MAY
UNIVERSAL TIME (hours)
one microradian per division

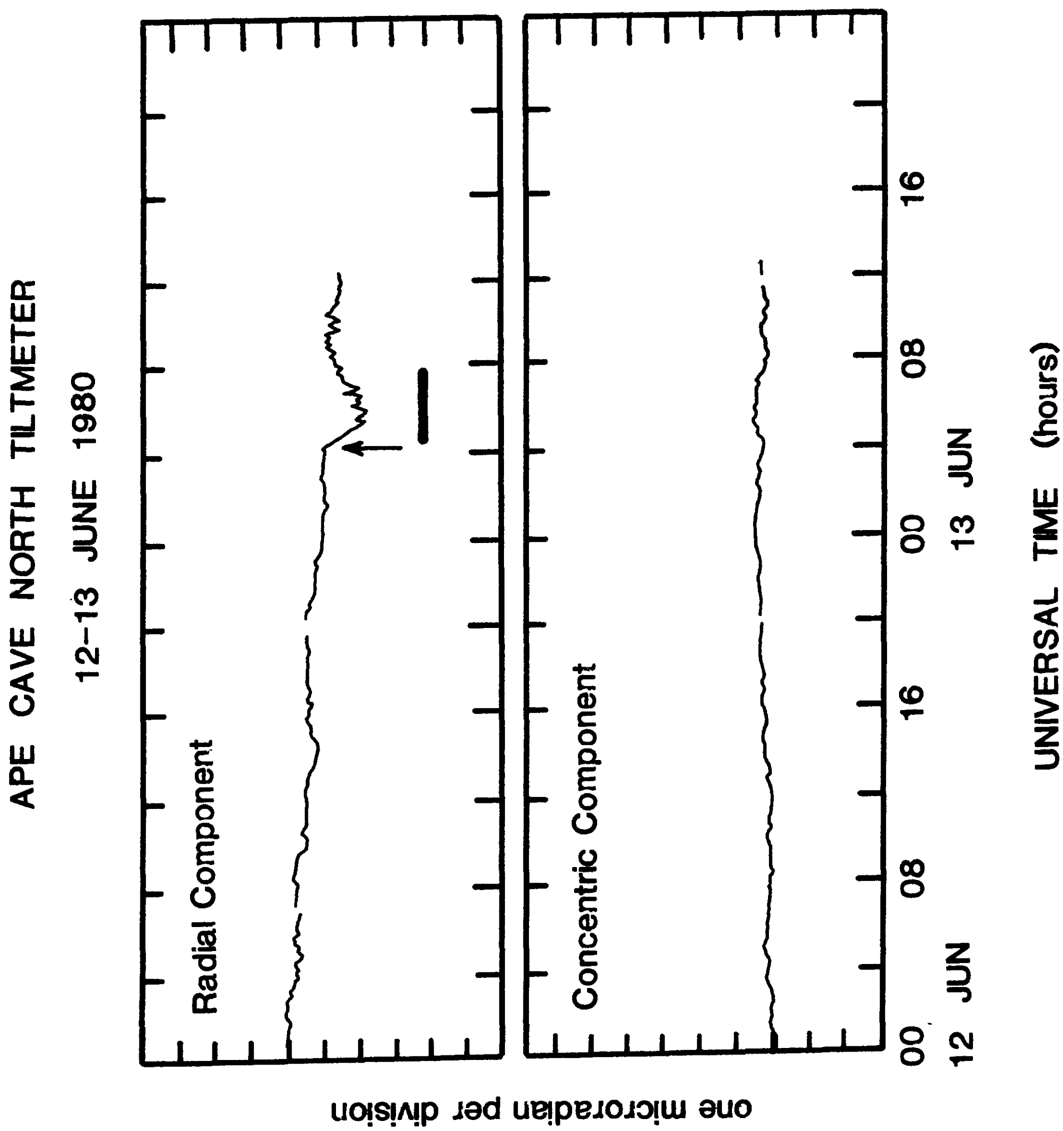
Figure 7


VICTORIA minus BLUE LAKE MAGNETOMETER
18-19 MAY 1980
00
08
16
00
08
16
18 MAY
19 MAY
UNIVERSAL TIME (hours)
ten nanotesla per division


APE CAVE NORTH TILTMETER
25-26 MAY 1980
Radial Component
Concentric Component
one microradian per division
00
08
16
00
08
16
25 MAY
26 MAY
UNIVERSAL TIME (hours)


APE CAVE TILTMETER
25-26 MAY 1980
Radial Component
Concentric Component
00
08
16
00
08
16
25 MAY
26 MAY
UNIVERSAL TIME (hours)
one microradian per division


VICTORIA minus BLUE LAKE MAGNETOMETER
25-26 MAY 1980
00
08
16
00
08
16
25 MAY
26 MAY
UNIVERSAL TIME (hours)
ten nanotesla per division


APE CAVE NORTH TILTMETER
12-13 JUNE 1980
Radial Component
Concentric Component
00
08
16
00
08
16
12 JUN
13 JUN
UNIVERSAL TIME (hours)
one microradian per division

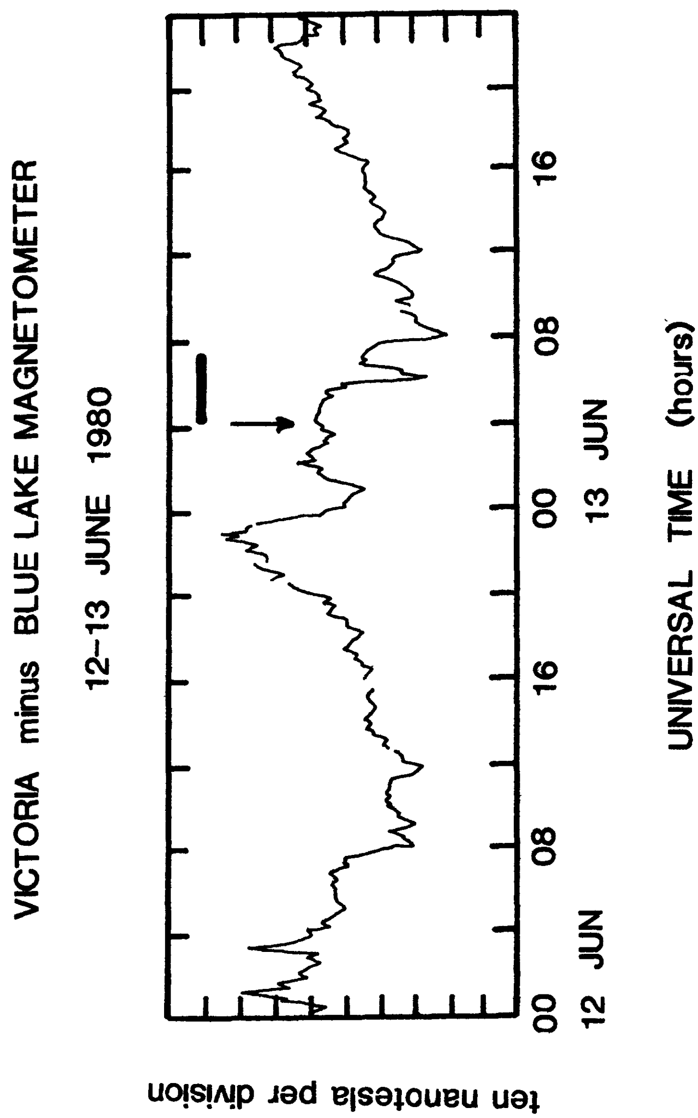
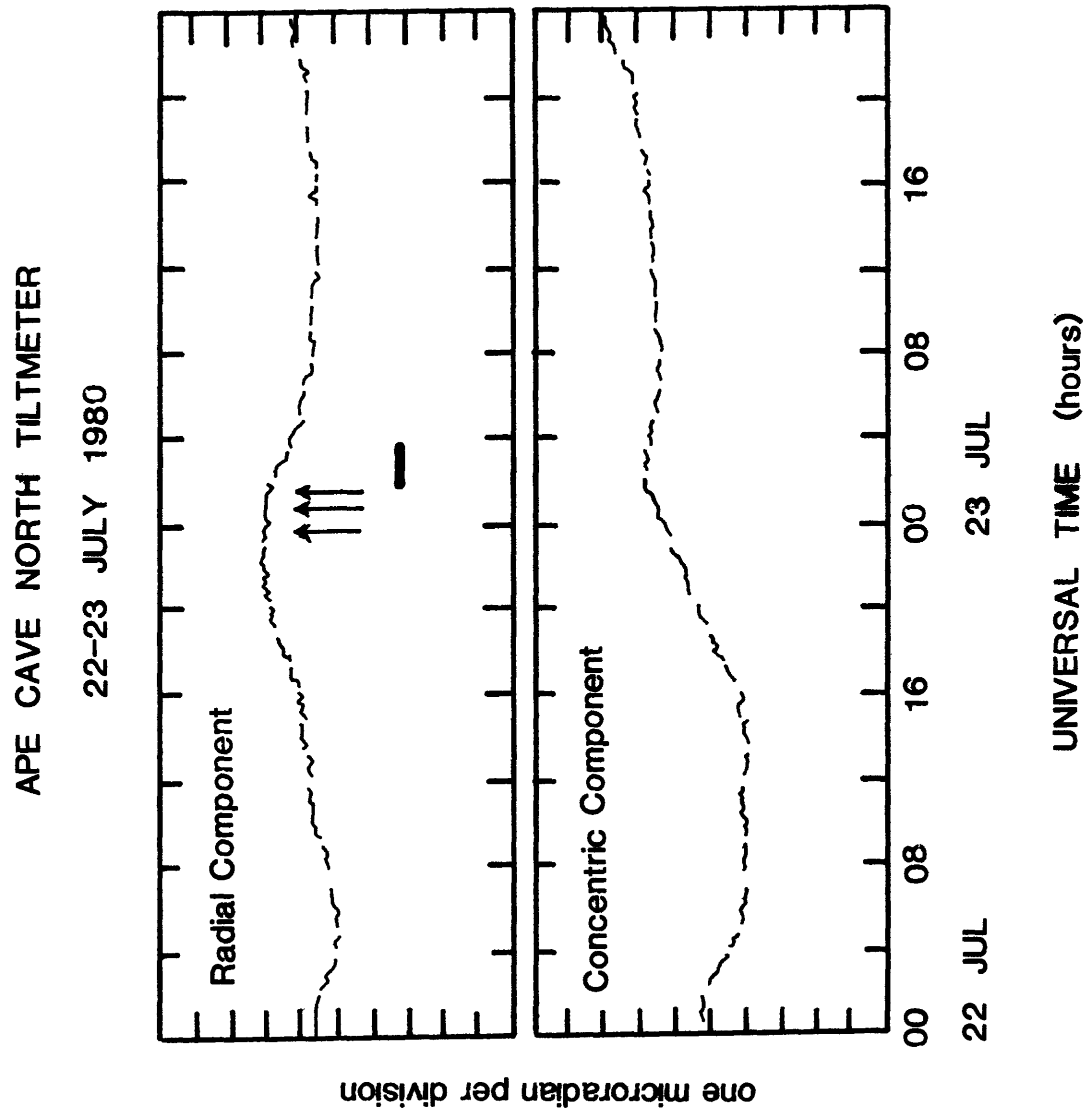
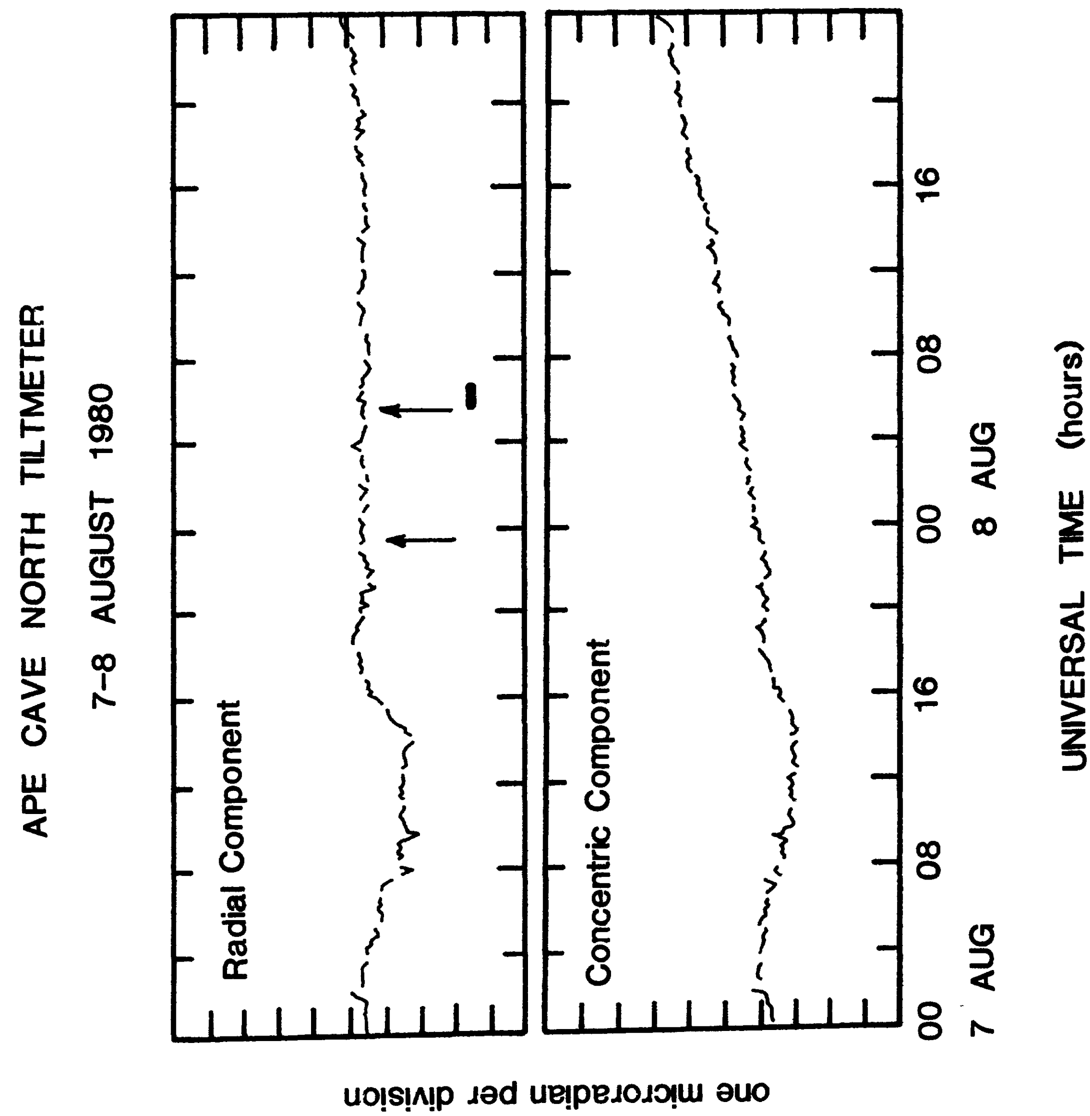
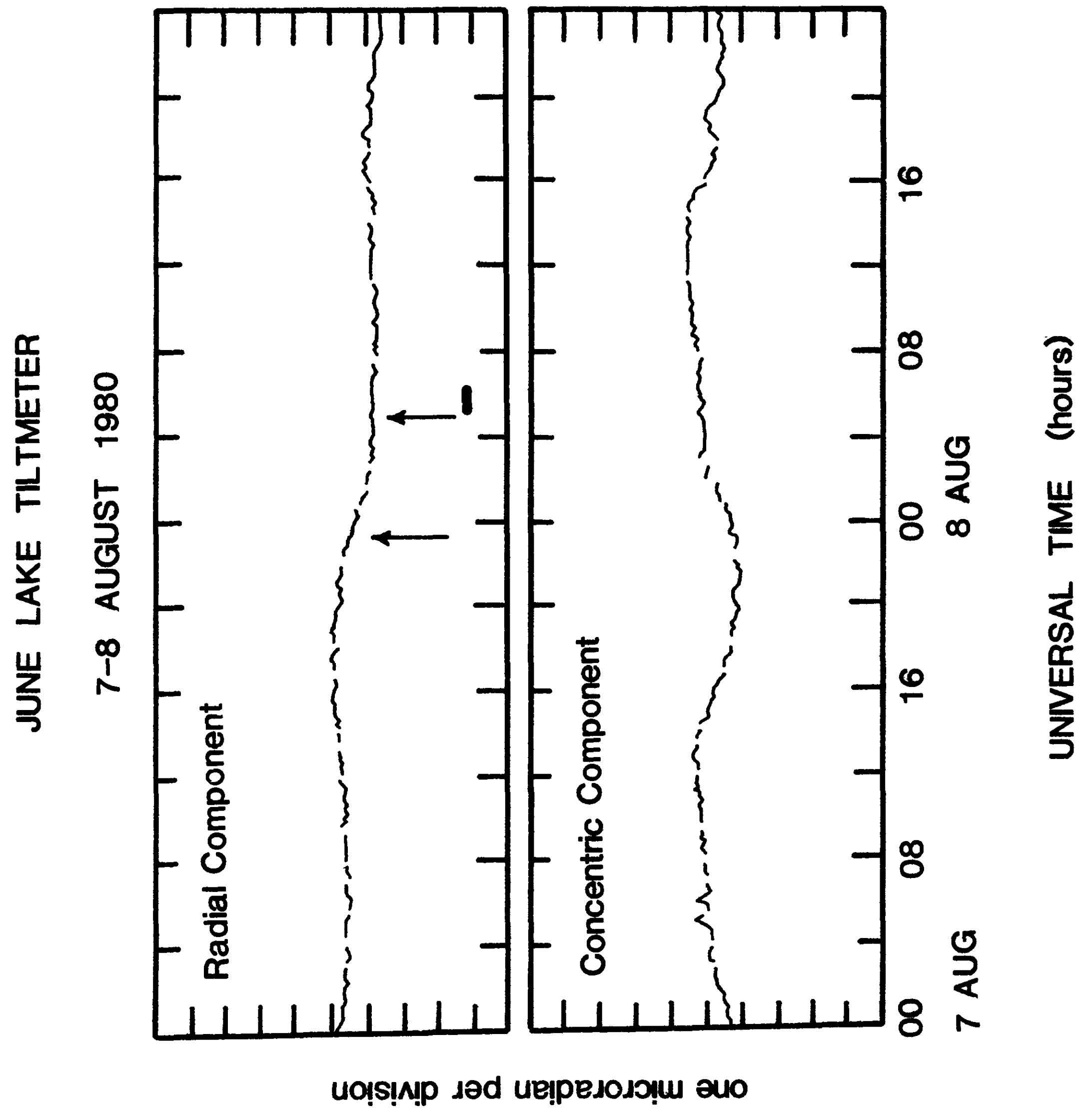

VICTORIA minus BLUE LAKE MAGNETOMETER
12-13 JUNE 1980
ten nanotesla per division
00
08
16
00
08
16
12 JUN
13 JUN
UNIVERSAL TIME (hours)

Figure 13


APE CAVE NORTH TILTMETER
22-23 JULY 1980
Radial Component
Concentric Component
one microradian per division
00
08
16
00
08
16
22 JUL
23 JUL
UNIVERSAL TIME (hours)


APE CAVE NORTH TILTMETER
7–8 AUGUST 1980
Radial Component
Concentric Component
one microradian per division
00
7 AUG
08
16
00
8 AUG
08
16
UNIVERSAL TIME (hours)


JUNE LAKE TILTMETER
7-8 AUGUST 1980
Radial Component
Concentric Component
00
08
16
00
08
16
7 AUG
8 AUG
UNIVERSAL TIME (hours)
one microradian per division

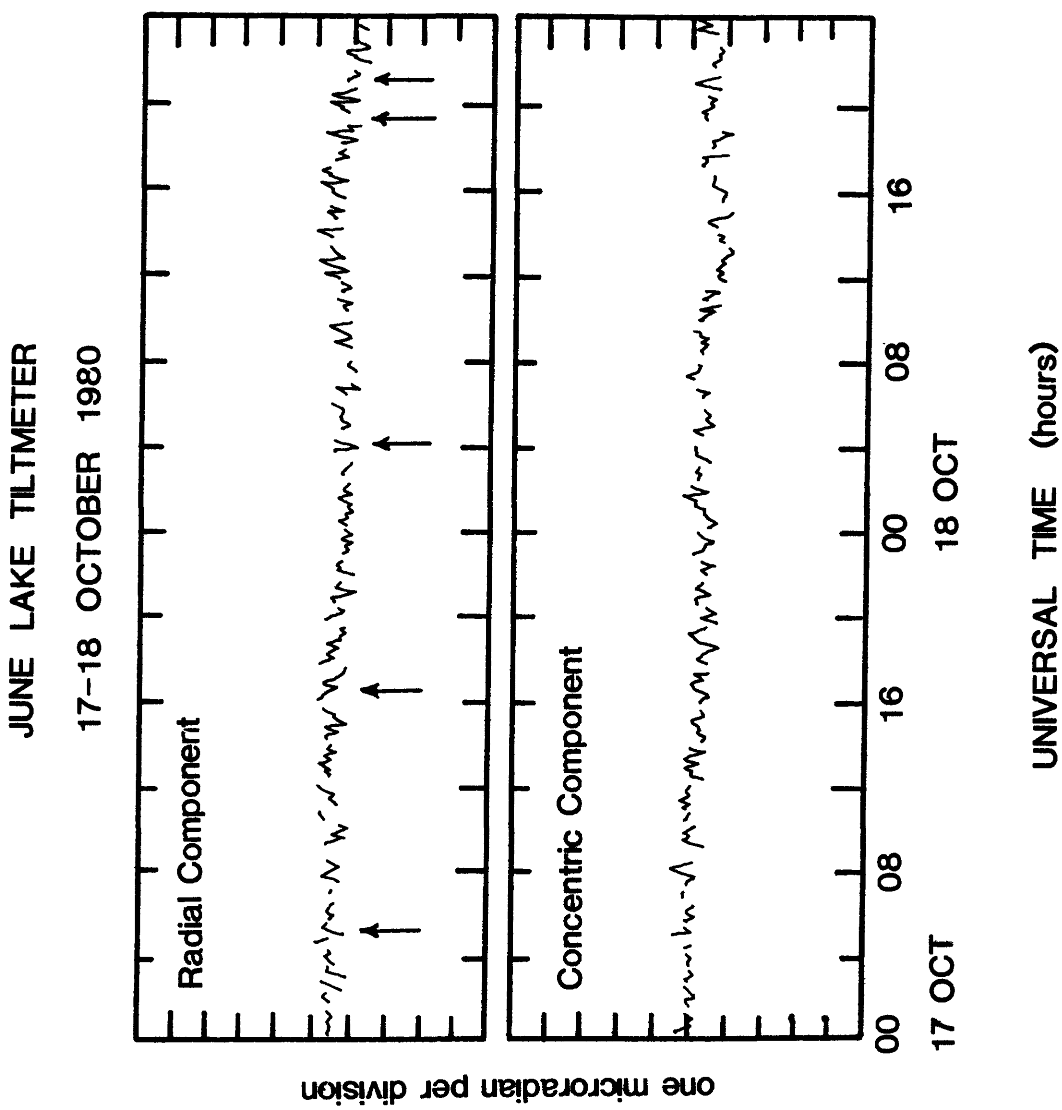
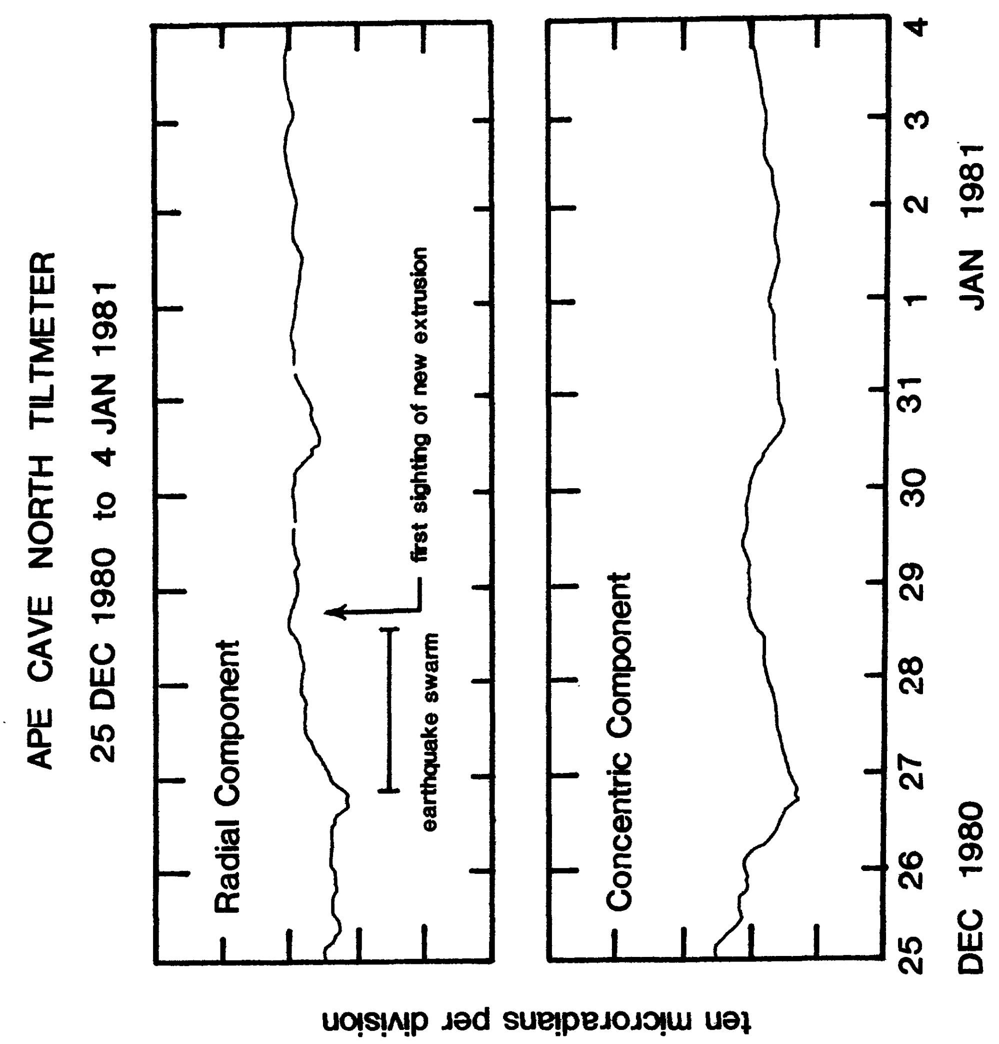
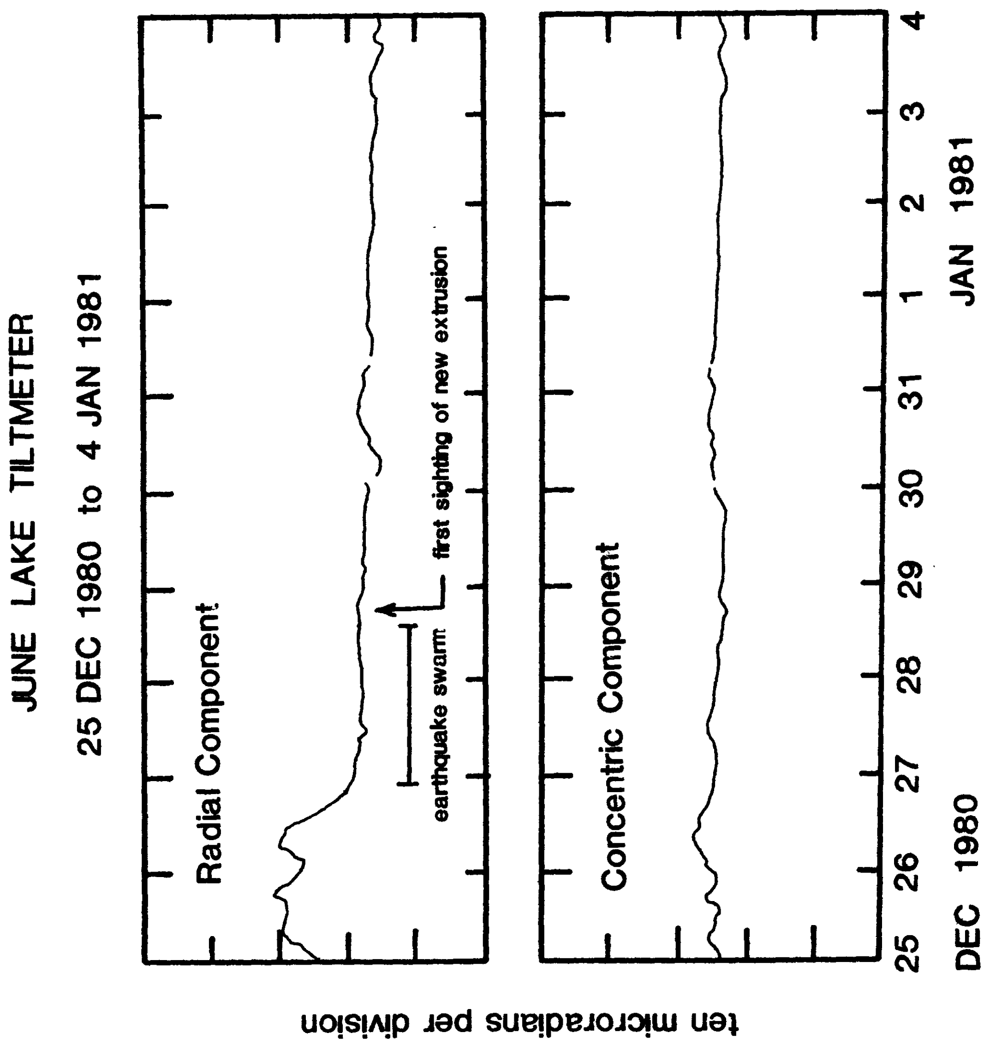
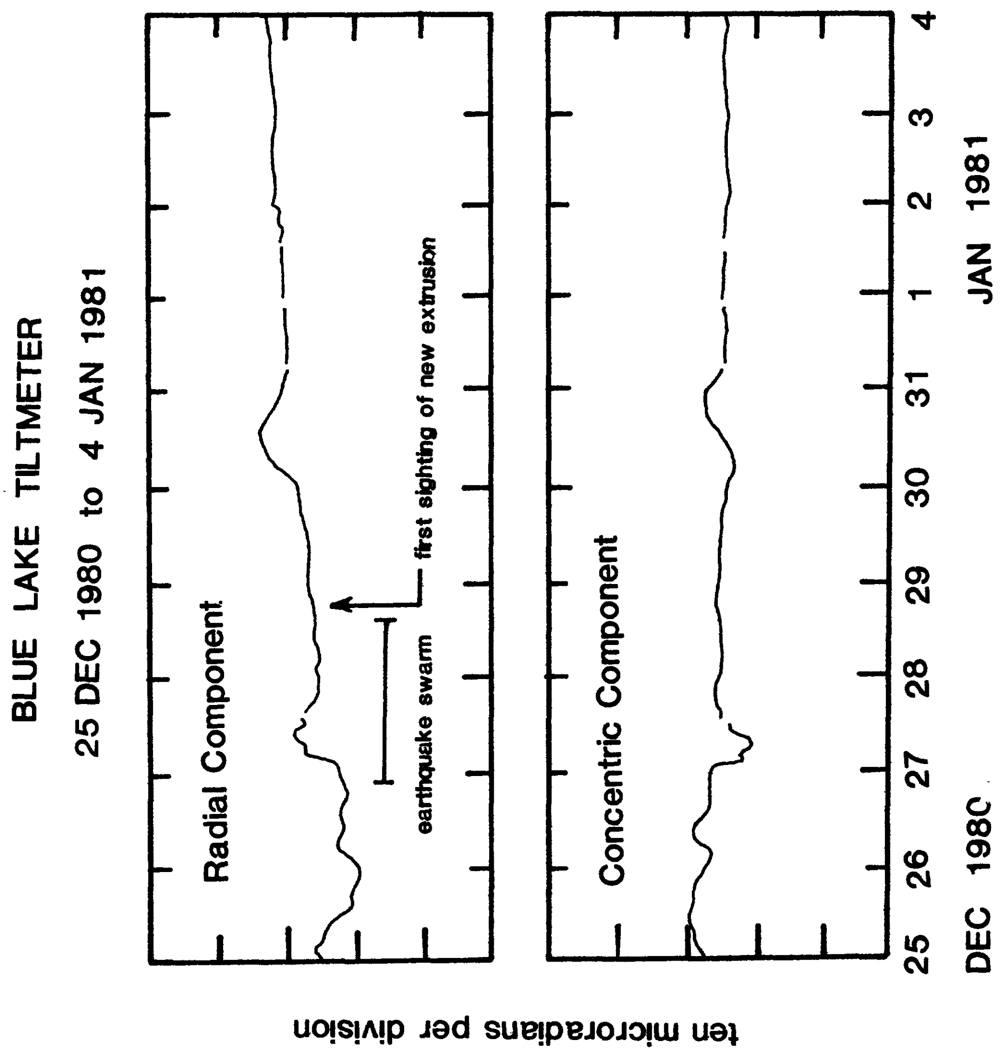

JUNE LAKE TILTMETER
17–18 OCTOBER 1980
Radial Component
Concentric Component
00
08
16
00
08
16
17 OCT
18 OCT
UNIVERSAL TIME (hours)
one microradian per division

Figure 17


APE CAVE NORTH TILTMETER
25 DEC 1980 to 4 JAN 1981
Radial Component
earthquake swarm
first sighting of new extrusion
Concentric Component
25
26
27
28
29
30
31
1
2
3
4
DEC 1980
JAN 1981
ten microradians per division


JUNE LAKE TILTMETER
25 DEC 1980 to 4 JAN 1981
Radial Component
earthquake swarm
first sighting of new extrusion
Concentric Component
25
26
27
28
29
30
31
1
2
3
4
DEC 1980
JAN 1981
ten microradians per division


BLUE LAKE TILTMETER
25 DEC 1980 to 4 JAN 1981
Radial Component
earthquake swarm
first sighting of new extrusion
Concentric Component
25
26
27
28
29
30
31
1
2
3
4
DEC 1980
JAN 1981
ten microradians per division

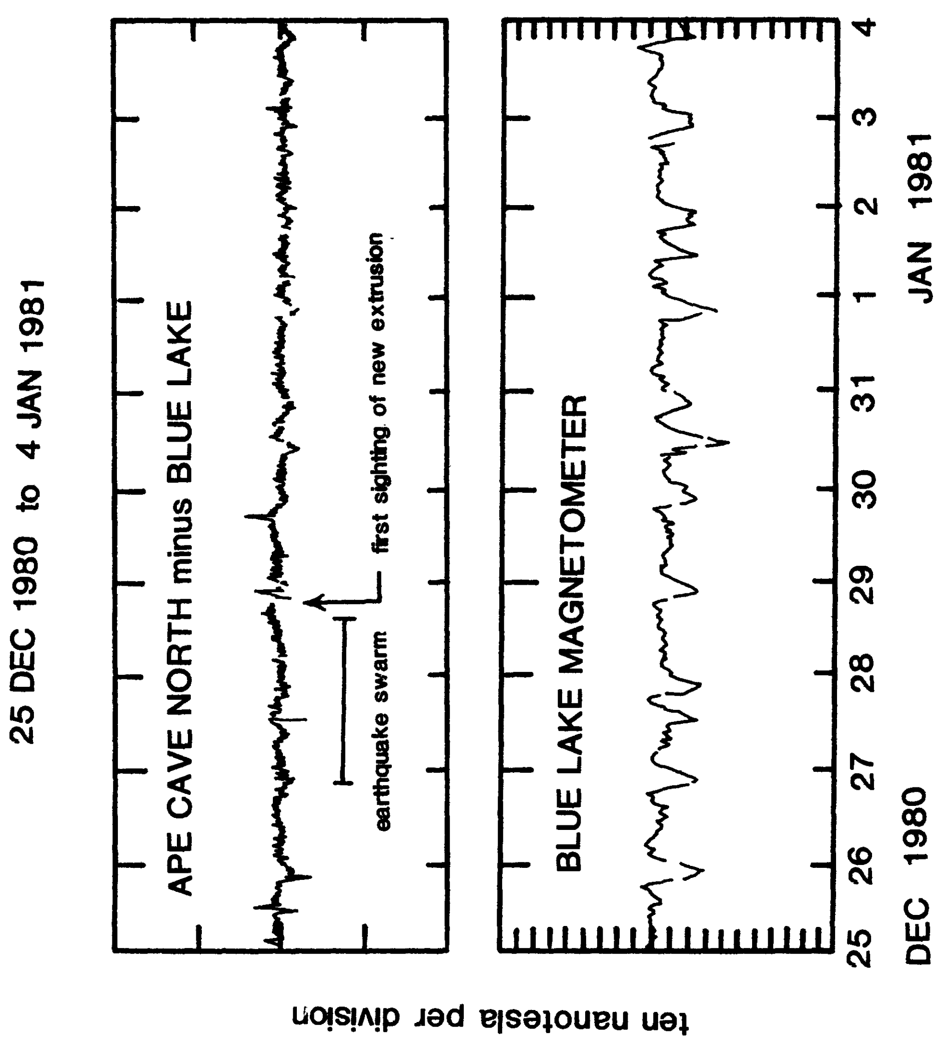

25 DEC 1980 to 4 JAN 1981
APE CAVE NORTH minus BLUE LAKE
earthquake swarm
first sighting of new extrusion
BLUE LAKE MAGNETOMETER
25
26
27
28
29
30
31
1
2
3
4
DEC 1980
JAN 1981
ten nanotesla per division

Figure 21

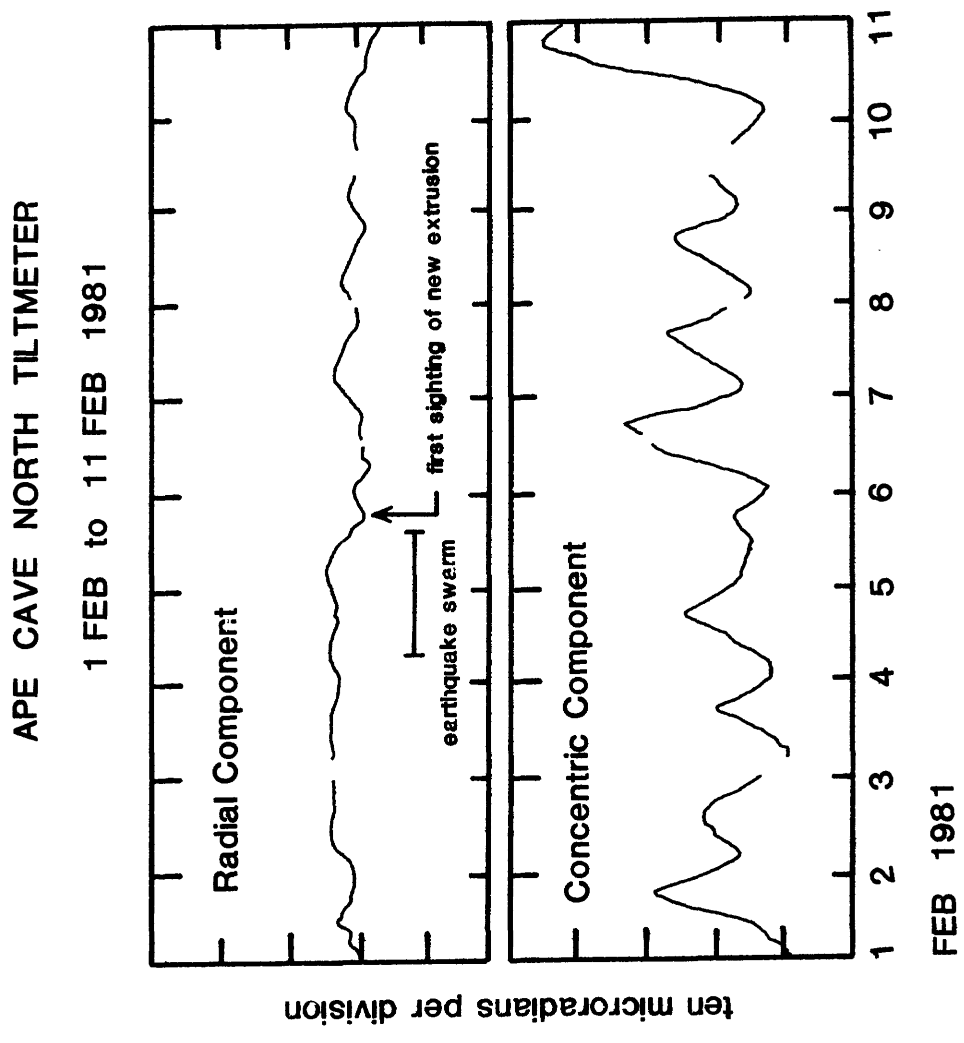
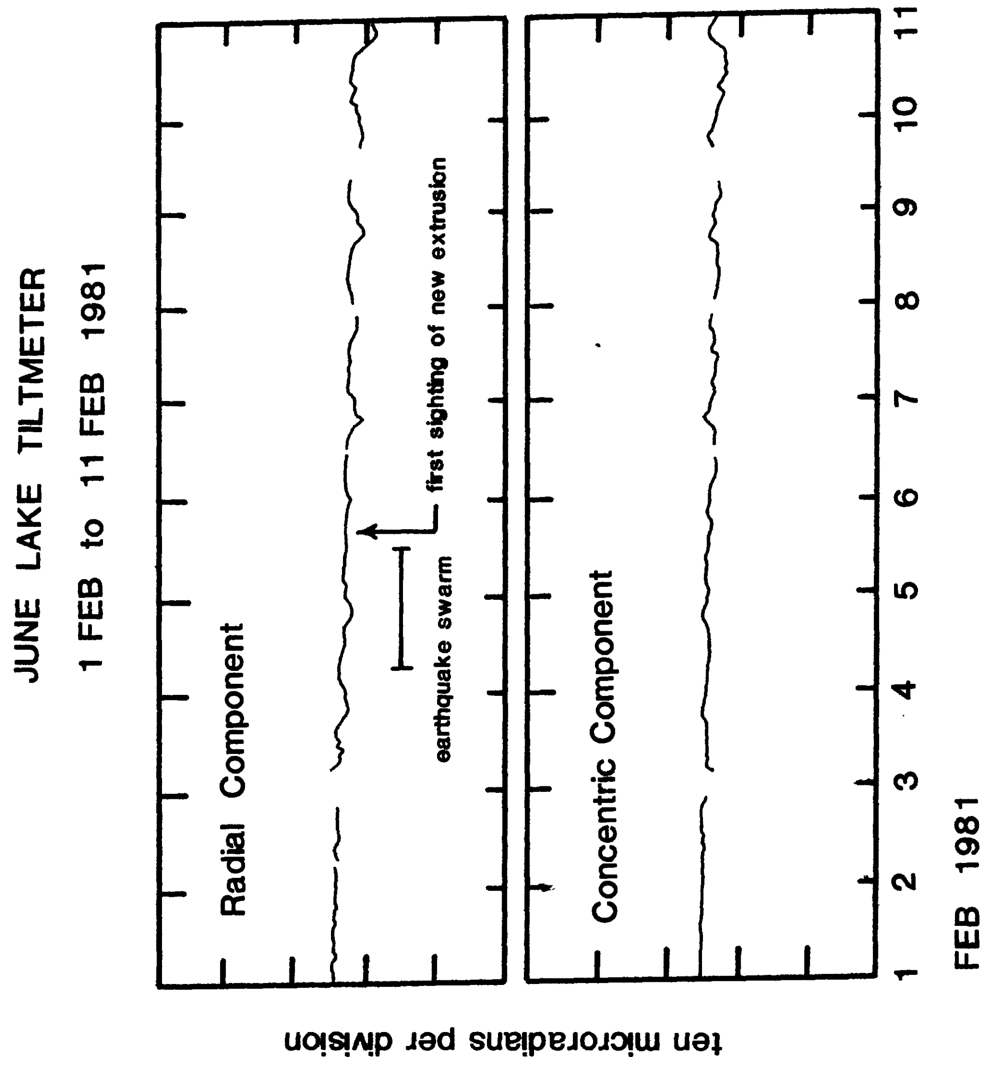
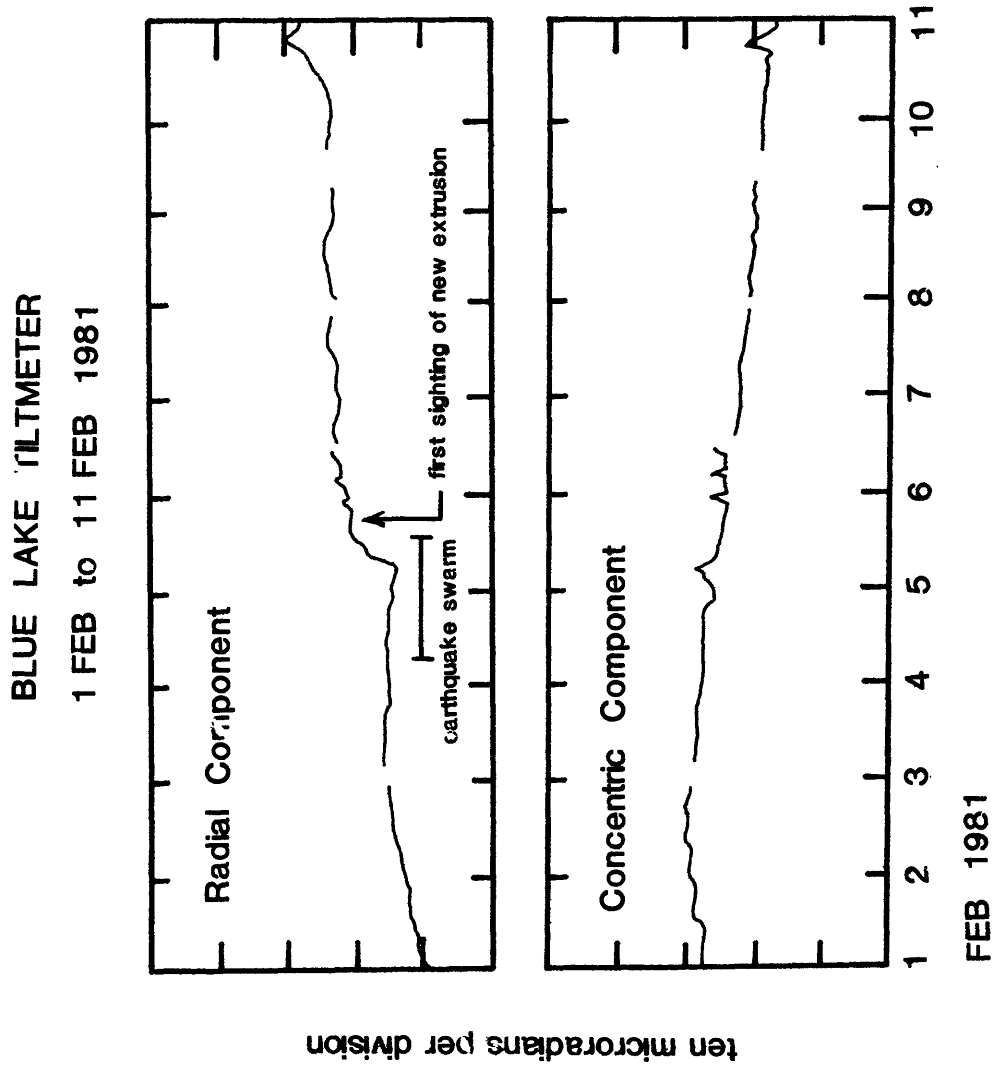
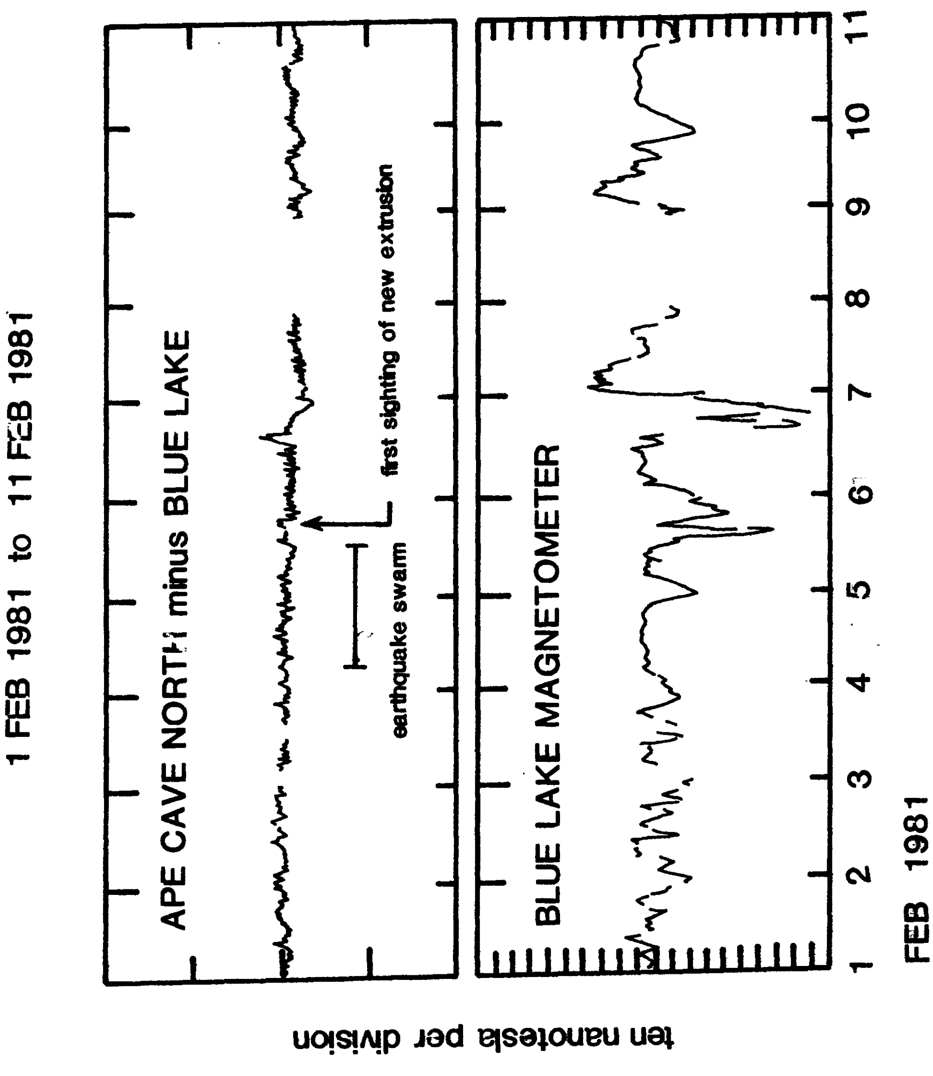

APE CAVE NORTH TILTMETER
1 FEB to 11 FEB 1981
Radial Component
earthquake swarm
first sighting of new extrusion
Concentric Component
1 2 3 4 5 6 7 8 9 10 11
FEB 1981
ten microradians per division

Figure 22


JUNE LAKE TILTMETER
1 FEB to 11 FEB 1981
Radial Component
earthquake swarm
first sighting of new extrusion
Concentric Component
1
2
3
4
5
6
7
8
9
10
11
FEB 1981
ten microradians per division


BLUE LAKE TILTMETER
1 FEB to 11 FEB 1981
Radial Component
first sighting of new extrusion
earthquake swarm
Concentric Component
1
2
3
4
5
6
7
8
9
10
11
FEB 1981
ten microradians per division


1 FEB 1981 to 11 FEB 1981
APE CAVE NORTH minus BLUE LAKE
earthquake swarm
first sighting of new extrusion
BLUE LAKE MAGNETOMETER
ten nanotesla per division
1 2 3 4 5 6 7 8 9 10 11
FEB 1981