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Publication Date

1978-06-01

710
6/8/78

Rev: 455

LBL-7050
UC-66b

**A TELLURIC-MAGNETOTELLURIC
SURVEY AT
MT. HOOD, OREGON**
— A Preliminary Study —

by
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June 1978



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Berkeley, California

MASTER

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48.

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Printed in the United States of America

Available from

National Technical Information Service

U. S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161-7.25

Price: Printed Copy, \$ ~~6.00~~ Domestic; ~~\$12.00~~ Foreign
Microfiche, \$ 3.00 Domestic; \$ 4.50 Foreign

14.50

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MOUNT HOOD, OREGON

- A Preliminary Study -

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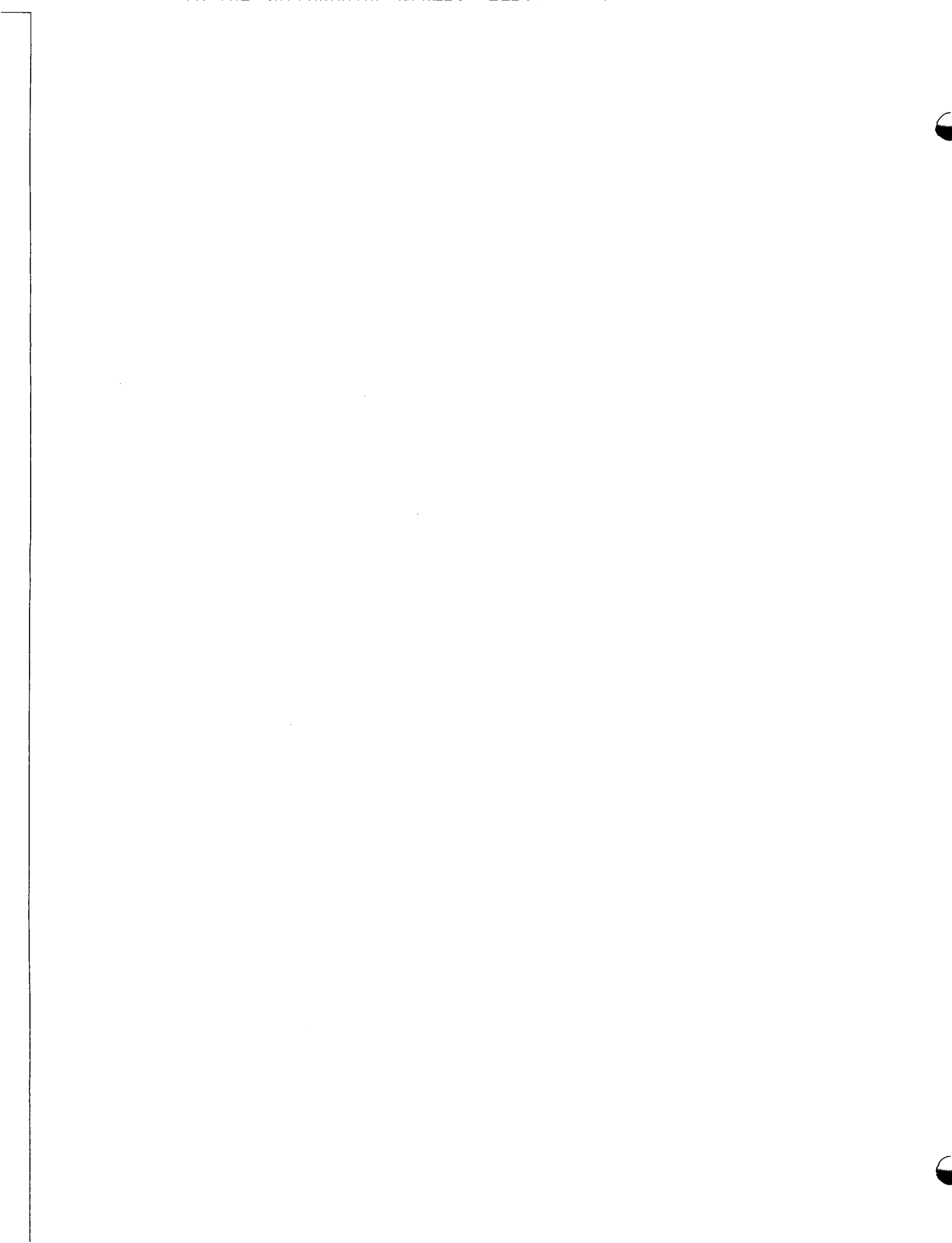
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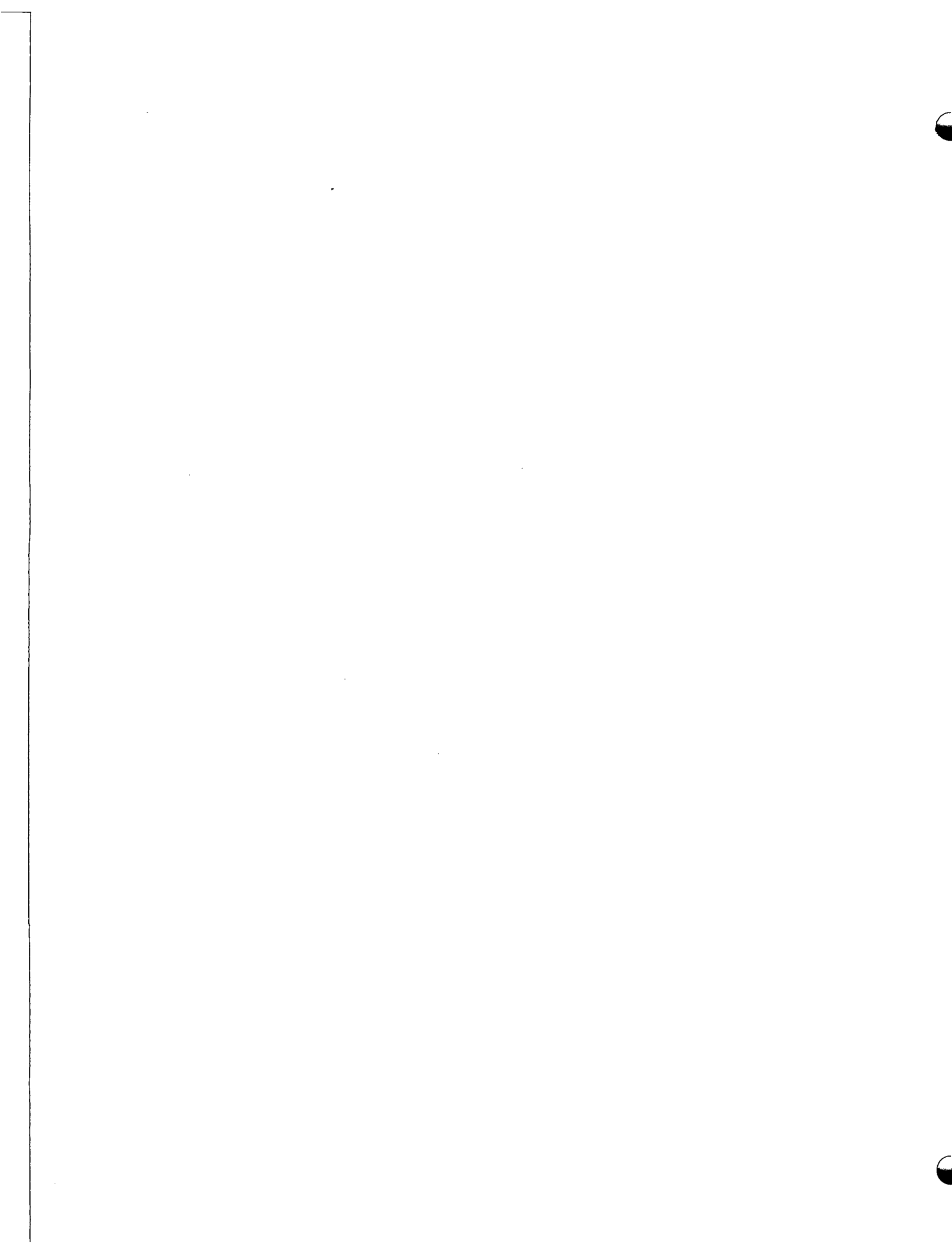
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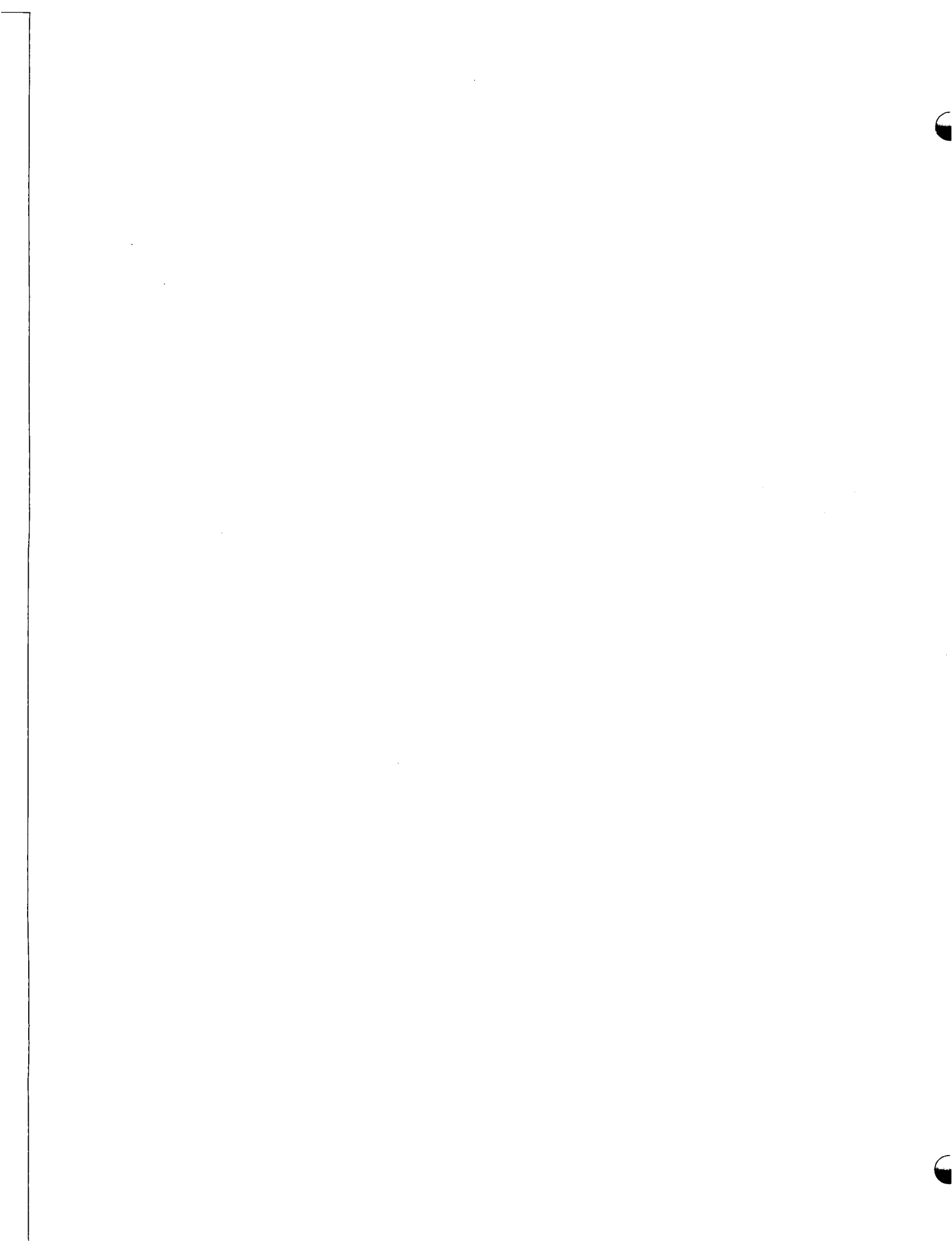
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ABSTRACT

The Lawrence Berkeley Laboratory, working with the U.S. Geological Survey, the U.S. Forest Service and the Oregon Department of Geology and Mineral Industries, was responsible for a magnetotelluric survey at Mount Hood, Oregon. The survey was conducted as part of a geothermal resource assessment study that had the overall objective of stimulating geothermal exploration near stratovolcanoes in the High Cascade Range. A telluric-magnetotelluric (T-MT) survey was chosen as the electrical resistivity technique.

Geonomics, Inc., a Berkeley geophysical company, was contracted to conduct the survey because it had a data acquisition system that would allow us to test the applicability of the T-MT method in a geologically complex area and to use a second magnetometer as a remote reference for noise rejection. Geonomics also performed the conventional MT data processing, but the reference magnetic processing is being done by the Engineering Geoscience Group, University of California.

Data were collected in overlapping bands from 0.002 to 40 Hz, although high levels of cultural noise, coupled with instrumental problems, decreased the usable high frequency response during the first phase of the two-phase field program. In the first phase a total of 29 stations in clusters, including five duplicate and two reference magnetometer stations, were occupied on the south side of the mountain below Timberline Lodge, at an elevation of 5900 feet. During the second phase 21 stations in clusters were occupied on the northeast, east, southeast and west sides of the mountain.

The apparent resistivity soundings generally show very different

characteristics from one cluster of stations to the next, and in some cases even between adjacent stations within a cluster. This is indicative of lateral discontinuities in conductivity, which are illustrated by plotting the principal resistivity directions at each station as a function of frequency. At low frequencies, less than 0.04 Hz, we find a uniform east-west structural trend at stations north, east and west of the mountain. South of the mountain the conductive strike direction changes to nearly north-south and this may show that the volcano is localized at a major structural change.

Two specific areas of interest have been identified: (a) Two anomalous near-surface low-resistivity zones occur close to the Cloud Cap eruptive center on the northeast side of the volcano. Anomalous conditions diminish away from the recent ($12,000^{\pm}$ y.B.P.) vent. The shallower zone (0.5 to 1.0 km in depth) occurs within the Mount Hood volcanic pile and its 2 ohm-m resistivity is difficult to explain. A deeper zone (2^{\pm} km), of approximately 10 ohm-m, occurs within what may be the pre-Mount Hood Yakima basalts (Miocene), and may have geothermal potential. (b) The strongly linear north-south electric field polarizations observed on the south side could be significant. Warm water emanations in the area suggest faulting, but there is neither direct evidence for faults, nor do the MT results clearly indicate anomalous resistivity conditions at depth. The MT station closest to the warm springs yielded low apparent resistivities which could be explained by conductive rock extending from surface to an undetermined depth. However, these data are incomplete and suspect, both because of severe noise and recorder malfunction at higher frequencies.

A TELLURIC-MAGNETOTELLURIC SURVEY AT MOUNT HOOD, OREGON

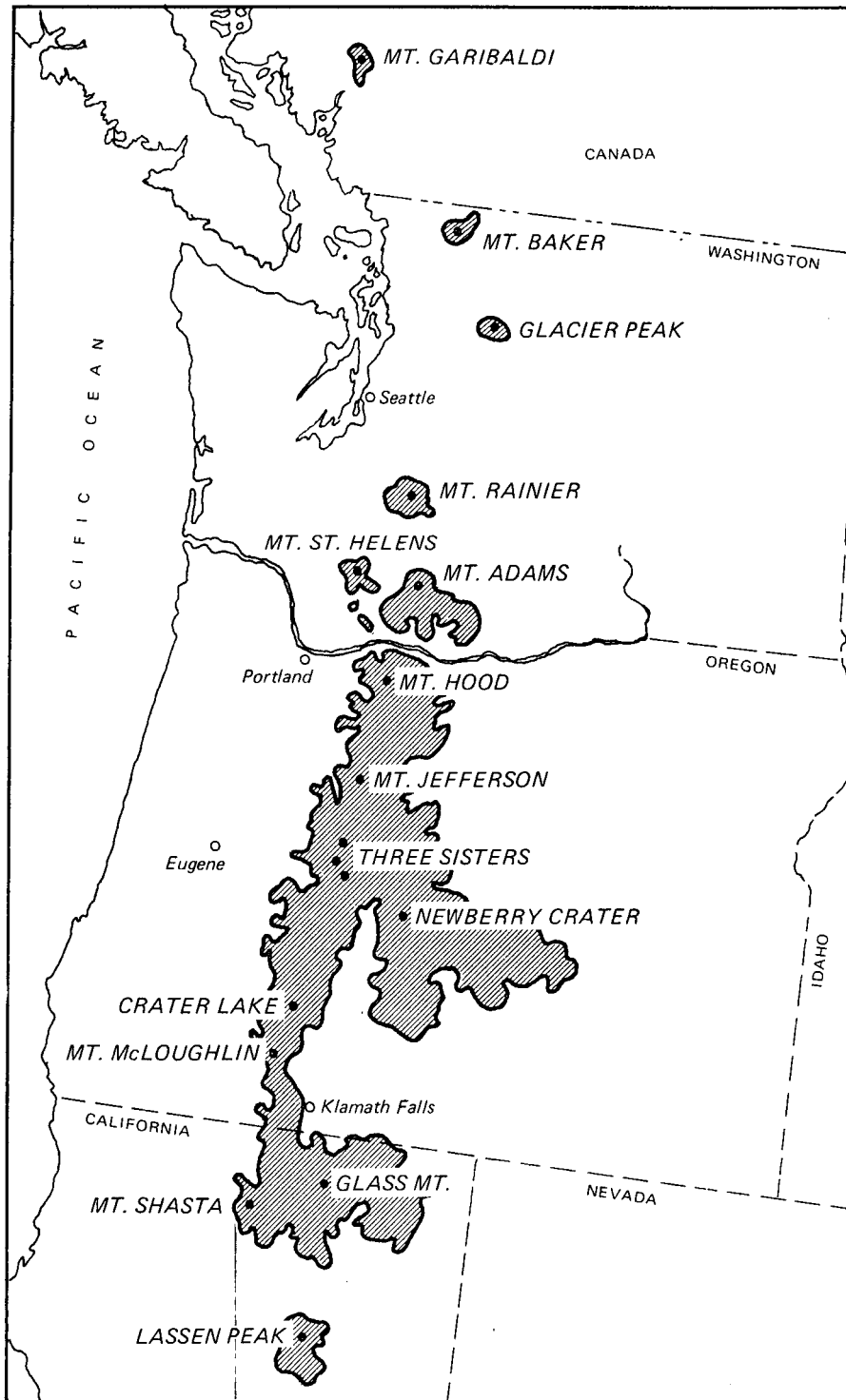
- A Preliminary Study -

INTRODUCTION

In 1977 the Department of Energy (DOE) initiated a jointly sponsored program with the U.S. Geological Survey, the U.S. Forest Service and the Department of Geology and Mineral Industries, Oregon (DOGAMI) to assess geothermal resource potential at Mount Hood, Oregon. One objective of the work is to stimulate geothermal exploration at Mount Hood, as well as at geologically similar stratovolcanoes in the High Cascade Range (Figure 1), where to date relatively little exploration work has been conducted by industry. Mount Hood was selected for this study for three principal reasons:

1. There is direct evidence for a heat source close to or within the volcanic pile, as shown by a ring of fumaroles near the summit, warm water emanations six miles south of the summit, and indications of geologically recent olivine-andesite and hornblende-dacitic eruptions near the summit and on the mountain flanks (Wise, 1977).
2. The proximity to Portland assures a major energy market, should geothermal exploitation occur.
3. There is reasonably good road access around the mountain and most of the land is controlled by the U.S. Forest Service.

As part of a national energy laboratory, LBL's Geothermal Group of the Earth Sciences Division assisted in two of many project tasks that would be needed for targeting future drill holes. These tasks were (1) sampling, chemical analyses, and geochemical interpretation of waters from springs, drill holes, and fumarole condensates, and (2) electrical resistivity investigations. This progress report deals with the electrical



XBL 784-665

Figure 1. Quaternary volcanic rocks of the High Cascades.

resistivity investigations undertaken in 1977. It is intended to document the work, to describe our method of approach and the problems encountered, and to discuss the preliminary findings.

GEOLOGY OF THE MOUNT HOOD VOLCANO

Mount Hood is the partially dissected cone of a late Pleistocene and Recent volcano (Wise, 1968 and 1969). The cone, consisting mainly of andesite flows and interlayered pyroclastic and re-worked clastic debris, rises 2500 meters above a base of Pliocene andesites and basalts of undetermined thickness (Figures 2 and 3). After the main phase of cone building, but prior to extensive glaciation, two satellitic vents over 12,000 years old developed in the north and northeast slopes (The Pinnacle and Cloud Cap, respectively) and were the sources of several olivine and andesite flows (Wise, 1968 and 1969). While glaciers were filling many of the valleys (about 12,000[±] y.B.P.), a large dome was extruded near the summit (Crandall and Rubin, 1977). Vast quantities of hot rocks and ash were expelled that mixed with the snow and ice and avalanched down the southern flank to form extensive blankets of hornblende dacite debris. After nearly 10,000 years of relative dormancy another dome erupted, producing 1.5 km³ of dacitic debris. A smaller dacitic dome may have erupted 250 to 300 y.B.P. In the historical past minor eruptions may have occurred in 1805 and 1859, but details are sketchy and these events added little new material to the volcano (Harris, 1976).

Present-day heat sources are believed to be associated with the more recent dacitic eruptions occurring within the last 300 years (Wise, 1977). A current heat source is indicated by the 20 or so fumaroles near the

summit. These occur in brecciated rock at the margin of the hornblende andesite plug-dome called Crater Rock. Hot water or steam reservoirs could exist within the cone, heated by the dacitic magma column, and/or at greater depth within fractured volcanics underlying the cone (Wise, 1977).

A minor thermal manifestation occurs six miles south of the summit at the Still Creek Campground where several orifices discharge warm waters. This has led to the speculation that there is a deep-going plumbing system bringing heated waters to the surface. However, evidence for faulting is scant there and elsewhere around the mountain. The only possible major fault is one that has been postulated to follow the north-south trending East Fork of the Hood River, bounding the volcano on the east.

Water flowing in the near surface environment is mainly meteoric, having very low dissolved solids, a pH close to neutral, and a very short residence time in the hydrologic system based on hydrogen and oxygen isotope ratios (H.A. Wollenberg, 1977, personal communication). Water of this quality would not be expected to exhibit a low resistivity, but surface conduction effects, particularly involving clay mineral surfaces within the pyroclastic interbeds, could impart a relatively low bulk apparent resistivity to the near-surface (0-1000 m) environment. Both the porosity and permeability of the flows and pyroclastics appear to be high. The flows exhibit both a platy jointing near their base, a crude columnar jointing above, and sometimes an intra-flow breccia zone (Wise, 1968 and 1969).

ELECTRICAL SURVEY PLANNING

To help plan the survey, we convened an ad hoc committee to discuss problems and make recommendations. The committee consisted of the following geophysicists:

| | |
|----------------|--|
| H.F. Morrison | Professor, University of California, Berkeley |
| Abhijit Dey | Research Geophysicist, University of California, Berkeley* |
| Thomas Gamble | Graduate Student (Physics), University of California, Berkeley |
| Charles Swift | Geophysicist, Chevron Resources, San Francisco |
| Paul Kasameyer | Geophysicist, Lawrence Livermore Laboratory, Livermore |
| Dal Stanley | Geophysicist, U.S. Geological Survey, Denver |

Various resistivity techniques were considered that might disclose the structure and thermal regime to depths of at least five kilometers. Galvanic resistivity techniques were dismissed as impractical because of the immense problems that terrain would impose on laying out and retrieving long wires. There was also concern that high contact resistances and local surface inhomogeneities would make galvanic techniques difficult to apply and the results difficult to interpret.

Audio-frequency magnetotellurics (AMT) was judged to be a possible method, having the advantage of relatively portable equipment. However, unpublished resistivity data from High Cascade Range volcanoes showed that the near-surface could be conductive. This would greatly limit the skin-depth of the AMT fields and calculations showed that the depth of exploration might be limited to only the first kilometer or so.

*Now with Chevron Resources, San Francisco

The concensus opinion was that magnetotellurics (MT) would be the most appropriate resistivity survey method, though it would not be free of problems. The obvious ones were (1) difficulty in interpreting the data if the structure were highly three-dimensional, as expected; (2) bias errors caused by electric dipoles short in length compared to the dimensions of local surface inhomogeneities; (3) difficulty in siting stations as needed due to terrain and limited access; and (4) cultural noise, mainly from power lines, cars and recreational vehicles.

The committee recommended using the telluric-magnetotelluric (T-MT) method to mitigate the access problem and to reduce per-station cost. In this method, a tensor MT station (base) is operated simultaneously with several distant telluric stations (remotes). If the magnetic field is uniform over the area of the stations, magnetic data from the base station may be combined in calculations with electric data from the remote stations to yield impedances equal to those resulting from remote tensor MT measurements. The limitation to this method is that while the incident magnetic field may be uniform over large distances, secondary magnetic fields vary considerably, particularly in geologically complex areas. Thus impedances calculated for remote sites may only approximate the true impedances. Despite this limitation, the committee felt that T-MT was still the most practical way to conduct an MT survey at Mount Hood, and felt that remote station data could be monitored by conducting the survey in a leap-frog fashion so that some of the base stations would be placed over a previous remote station to obtain results for comparison.

The committee specified that data be collected in overlapping bands covering the frequency range from 40 Hz to 0.002 Hz, and that the survey

be conducted in two phases, so that results of the first phase could be analyzed before commencing further work. For the first-phase, station spacing was to be relatively small, with stations no more than 1.5 to 2.0 km apart so that three-dimensional inhomogeneities could be identified and delineated. Variable dipole lengths, of 150 m, 300 m, and 600 m, were to be used to obtain comparative results, to determine the effect of lateral inhomogeneities on resistivity estimates. Results of this experiment are given in Appendix I, while Appendices II and III give the MT station results for Phase I and Phase II of the survey.

Because the T-MT method is best done by telemetering remote data to the base station and recording all data on a common time base, FM telemetry is needed. This requirement presents certain problems but also offers the opportunity to use a reference magnetometer in place of one remote telluric station. Therefore, the survey included a second magnetometer, located at the survey area some distance from the base stations, to serve as reference for calculating impedances in the fashion described by Gamble et al. (1977, 1978). In this procedure uncorrelated field noise, which causes serious errors in bands of low signal strength, is eliminated by using reference channel data in the calculation of impedances (see Appendix IV).

A commercial contractor was to be used for data acquisition and conventional processing while LBL, assisted by the Engineering Geoscience Group (EGG) of U.C. Berkeley, would retain responsibility for reference magnetometer processing and overall data interpretation. Graduate students in EGG had already developed a usable code for the two-dimensional scattering problem and were calculating apparent resistivities for simple

structures (Morrison, 1978). Work was in progress to develop an efficient and accurate code for three-dimensional scattering.

After several commercial MT contractors were contacted about the survey plan, contract negotiations were begun with Geonometrics, Inc. of Berkeley, the only contractor with an adequate data acquisition system available for the tasks envisioned.

PHASE I - SURVEY

Survey Plan

The Phase I Survey was limited to the south side of Mount Hood. This area was chosen for the initial study because of good road access (due to skiing and logging activities) and the warm spring emanations at Still Creek Campground. The area also provided a convenient central location for the reference magnetometer which was placed near the summit of Multorpor Mountain.

Stations extended from the Timberline Lodge, at an elevation of 5,900 feet, southward five miles to Trillium Lake, at an elevation of 3,800 feet (Figure 3). Many stations were located on the hornblende andesite debris fan whose average slope is relatively gentle. However, there are abrupt local topographic features, so stations had to be sited where roads permitted access and the surface was relatively flat.

Survey started in June 1977, when the first stations were located in the marshy ground at the base of Mount Hood. As work progressed, stations were moved to higher elevations. However, even in late June some of the minor roads above 5,000 feet were blocked by snow, and this caused some problems and delays.

Our hope was to obtain at least one long north-south line of stations, and consideration was given to putting remote telluric stations on the Palmer Glacier as high as the 8,000-foot elevation. However, severe cultural noise associated with Timberline Lodge and the ski lifts made this plan impractical. We later learned that our efforts would probably have proven futile because of the high contact resistance and strong self-potential voltages encountered on the glacier (D.B. Hoover, 1977, personal communication).

Instrumentation and Procedures

Each base station consisted of a three-component cryogenic magnetometer (S.H.E.), two orthogonal electric dipoles 150 meters in length, and a third dipole at 45° to the others that was to be used for eliminating uncorrelated noise by means of an electric reference.

Two remote telluric stations were located one to four kilometers away from each base station. Each telluric station consisted of two orthogonal dipoles, an amplifier filter box, FM telemetry equipment and batteries. The two channels of telluric data were transmitted via an FM radio telemetry link to the base station.

Rather than deploying a third remote telluric station, we chose to use a reference magnetometer, similar to the one at the base station, because it would provide reference channel data for use in impedance calculations and allow us to bypass data from the bands of low signal strength which have uncorrelated field noise. The two horizontal components were telemetered to the base station.

All together, twelve channels of data were received at the base

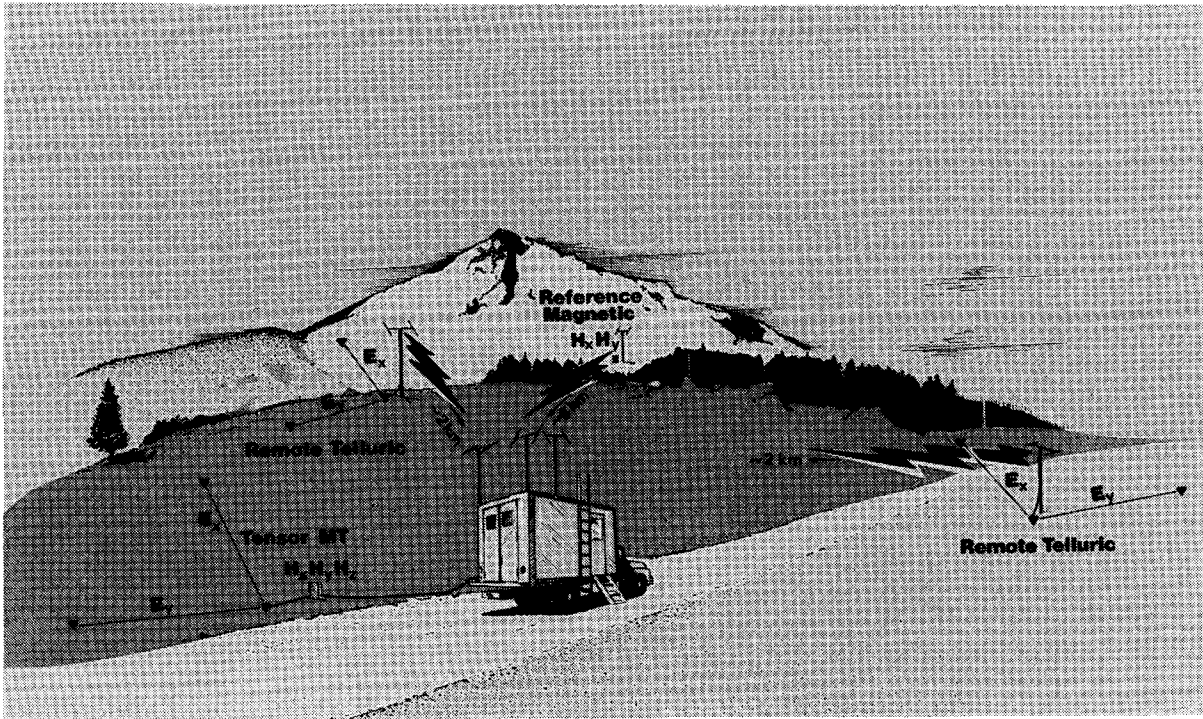
station where the signals were band-pass filtered, amplified, multiplexed, digitized and recorded on a nine-track, 800 bpi tape in a 12-bit word IBM compatible format. The analog signals from all channels were also monitored continuously by means of two Gould paper-chart recorders. Data were recorded in four or six overlapping frequency bands of those listed in Table 1. At each set-up data were recorded for a period of over 20 hours.

Table 1. Phase I - Data Recording Bands.

| BAND | FILTER BAND PASS | SCAN RATE SAMPLE/SECOND |
|------|------------------|----------------------------|
| 1 | 10 - 40 Hz | 200 |
| 2 | 0.2 - 10 | 500 |
| 3 | 0.1 - 2 | 10 |
| 4 | 0.05 - 0.2 | 1 |
| 5 | dc - 0.1 | 0.5 |
| 6 | dc - 0.016 | 0.1 |

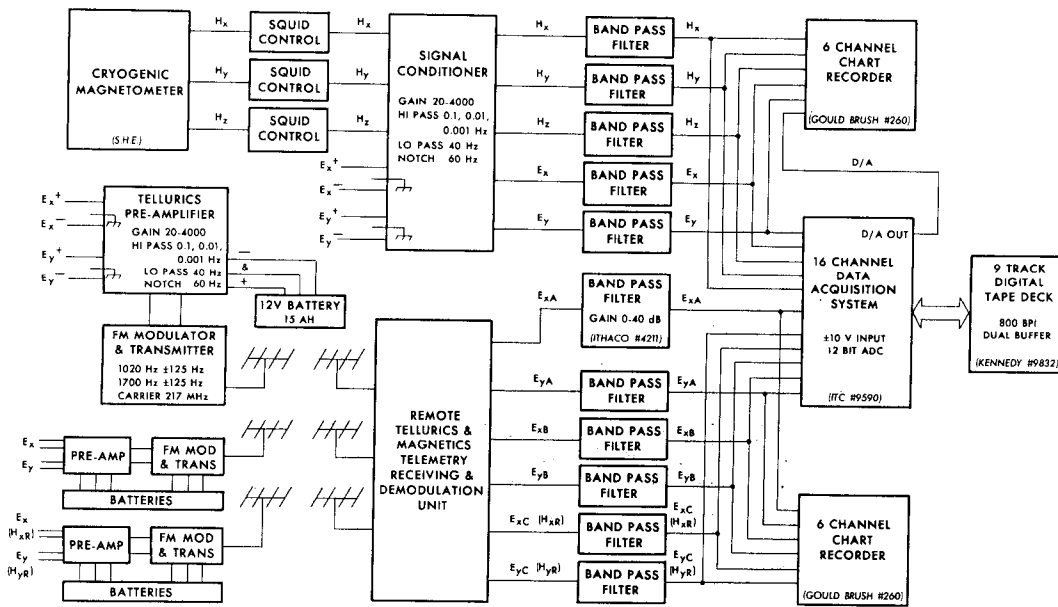
The Mount Hood T-MT field layout is shown in Figure 4a, and a block schematic of the data acquisition system is shown in Figure 4b.

Problems with telemetry were minor. Some stations, such as the reference site on Multorpor Mountain, had to be relocated to achieve line-of-sight communication. A more serious problem arose due to power-line and cultural noise, and where this occurred attempts were made to relocate the station, usually with little reduction of noise. Therefore, several stations yielded little or no usable data when processed conventionally, i.e., before remote reference processing.



(a)

CBB 770-12413



(b)

XBL 785-923

Figure 4. The field layout (a) and block schematic of the Geonometrics data acquisition system (b) for the Mt. Hood T-MT survey.

The digital data acquisition system failed during recording of the higher frequency bands at Stations 1, 6 and 8. This problem, which could not be identified in the field, resulted in the loss of important data in the > 0.10 Hz band. As a consequence, the high frequency asymptote of most sounding curves, necessary for an interpretation of the near-surface resistivities, was not obtained.

The only other instrumental problem encountered was due to the very high self-potential (SP) voltages found on the mountains. The SP bucking circuit was barely adequate to compensate for the 4-volt anomalies found at Stations 5 and 6. Later, in the Phase II survey, the SP voltages exceeded the compensation range at one station and the telluric dipoles had to be re-oriented to find a lower self-potential.

Data were reduced by Geomatics and the results are shown in Figures I-1 through I-3 of Appendix I and Figures II-1 through II-19 of Appendix II. The method of data reduction as described in the contractor's report was as follows:

Data ... (were) edited for analysis using analog chart records obtained during recording. Data segments of 2048, 1024, or 512 points per channel, free from extraneous visible noise, (were) selected for processing. If any one of the two horizontal magnetic field components were 'noisy', analysis for both remote telluric sites, as well as for the base station, were not performed. Data from satellite telluric stations (were) treated the same as the base magnetotelluric fields, using base magnetometer data. Magnetic and telluric field data (were) rotated in the time domain into geographical N-S, E-W coordinates) and power and cross-power spectra were computed using fast Fourier transform. The raw spectral estimates were smoothed using variable Q filters. For each frequency band, several such smoothed estimates were stacked to minimize cross power noise terms.

Least square estimates of the elements of the horizontal impedance tensor (Z_{xx}, Z_{xy}, Z_{yx} and Z_{yy}) are obtained by using magnetic field components as independent variables. For example, the least square estimate for Z_{xy} is written as:

$$Z_{xy} = \frac{\begin{pmatrix} H & H \\ x & x \end{pmatrix} \begin{pmatrix} E & H \\ x & y \end{pmatrix} - \begin{pmatrix} H & H \\ x & y \end{pmatrix} \begin{pmatrix} E & H \\ x & x \end{pmatrix}}{\begin{pmatrix} H & H \\ x & x \end{pmatrix} \begin{pmatrix} H & H \\ y & y \end{pmatrix} - \begin{pmatrix} H & H \\ x & y \end{pmatrix} \begin{pmatrix} H & H \\ y & x \end{pmatrix}}$$

where $E_x H_y$ represents the smoothed cross power spectral estimate.

From the horizontal impedances, principal directions (1 and 2) are obtained by maximizing $Z_{xy}^2 + Z_{yx}^2$ with respect to rotation angle in the horizontal plane. Power and cross power spectral estimates are rotated into the principal direction, and tensor impedances, multiple coherencies, skew and ellipticity index are computed in the principal direction (1 and 2). Ninety-five percent confidence bands for multiple coherencies and complex tensor impedances are computed using the techniques described by Bendat and Piersol (1971), and Reddy et al. (1976).

Reliable vertical magnetic field data were obtained for long period bands in most instances. Vertical magnetic field is used to determine the strike direction. Ratio of vertical to horizontal magnetic field or "Tipper," which gives information on the resistivity contrast across a discontinuity and the location of the discontinuity with respect to the field station, was computed. Several other parameters, such as ordinary coherencies, partial coherencies and field polarization, were also obtained.

Tensor apparent resistivities along principal directions were plotted as a function of square root of period for multiple coherency square greater than 0.8, and the directions of maximum resistivity principal direction, skew and geologic strike direction computed from vertical magnetic field and tipper values are shown in Appendices I, II and III.

Survey Results

Phase I station locations are shown in Figures 2 and 3 and the orientation of the telluric and magnetic axes are listed in Table 2. Twenty-nine stations, of which five were duplicates and two were reference magnetometer stations, were occupied. Base stations are designated by a number (1, 2, etc.) and the corresponding telluric remotes are designated in alphanumeric form (1A, 1B, or 2A, 2B, etc.).

Several base-over-remotes were planned, but man-made noise, principally 60-Hz power line noise and switching transients, limited the

number to one: base station 7 and remote station 4A. Apparent resistivity curves for these stations have similar shapes, but differ in absolute values by as much as 100 percent. The cause of this may be bias error introduced by noise, and this will be investigated by means of remote magnetometer processing. Two remote telluric stations, 2B and 7A (Figures II-6 and II-15), were also located at the same site. They showed very similar results to each other, differing only by 25 to 30 percent over the bandwidth covered even though the two magnetometer stations were 2.4 km apart.

At Station 1, the T-MT data were first recorded using 150-meter dipoles and then the measurements were repeated using 150-, 300- and 600-meter dipoles simultaneously (Figures I-1, I-2, I-3 of Appendix I). The longer dipoles were used to determine the effect of lateral inhomogeneities on the resistivity estimates. The particular site was chosen because of flat terrain and easy access, but it should be noted that these results cannot be transferred to all stations because of station-to-station variations in near-surface geology. Although these results have limited value, the following observations can be made:

- (1) The 150- and 300-meter dipoles give very similar results, but 300-meter curves show more scatter and some of the resistivities appear to be biased downward. This may be due, in part, to electrochemical noise from an electrode on the 300-meter spread.
- (2) Compared to the two shorter spreads, the 600-meter dipoles give a similar resistivity curve shape, but all the resistivity values are biased upward. This could be due to bias errors induced by changing noise characteristics over the several days involved in data acquisition.

Table 2. Orientation of Telluric and Magnetic Axes at Phase I Stations
(Degrees Measured Clockwise from Geographical North).

| STATION | E_x | E_y | H_x | H_y | H_{xr} | H_{yr} |
|---------|-------|-------|-------|-------|----------|----------|
| 1 | 30° | 120° | 30° | 300° | 30° | 120° |
| 1A | 175° | 265° | - | - | - | - |
| 1B | 235° | 325° | - | - | - | - |
| 2 | 240° | 330° | 240° | 150° | 30° | 120° |
| 2A | 320° | 50° | - | - | - | - |
| 2B (7A) | 240° | 330° | - | - | - | - |
| 3 | 270° | 0° | 270° | 180° | 270° | 0° |
| 3A | 0° | 90° | - | - | - | - |
| 3B | 240° | 330° | - | - | - | - |
| 4 | 51° | 141° | 51° | 321° | 51° | 140° |
| 4A (7) | 15° | 105° | - | - | - | - |
| 4B | 16° | 106° | - | - | - | - |
| 5 | 230° | 320° | 230° | 140° | 230° | 320° |
| 5A | 355° | 85° | - | - | - | - |
| 5B | 55° | 145° | - | - | - | - |
| 6 | 180° | 270° | 180° | 90° | 270° | 0° |
| 6A | 230° | 320° | - | - | - | - |
| 6B | 180° | 270° | - | - | - | - |
| 7 (4A) | 30° | 120° | 30° | 300° | 30° | 120° |
| 7A (2B) | 240° | 330° | - | - | - | - |
| 7B | 110° | 200° | - | - | - | - |
| 8 | 295° | 25° | 295° | 205° | - | - |
| 8A | 35° | 125° | - | - | - | - |
| 8B | 275° | 5° | - | - | - | - |
| 8C | 220° | 310° | - | - | - | - |

At stations where broad-band coverage was obtained (Stations 4 and 4A, for example), the resistivity curves show a number of similar characteristics: (1) extreme apparent anisotropy, (2) a conductive near-surface layer of 10-20 ohm-m grading downward into (3) an apparently resistive layer on the R_{12} component, and (4) a second conductive region that may occur in the upper mantle but whose depth and resistivity cannot be estimated from these data by means of one-dimensional inversions. Geologic strikes based on tensor rotations and vertical magnetics are very close to north-south [0° and 180° for θ (max) and H_z strike].

Station 1A was located over the only thermal manifestation in the region of investigation: the Still Creek Campground (see Geology section). Over the limited bandwidth obtained, the results show uniformly low resistivities. This could be due to more conductive rocks near the surface and extending to some undetermined depth. However, cultural noise and equipment problems place the credibility of the results in question.

PHASE II - SURVEY

Survey Plan

After the results of the first survey were obtained, it was decided that regional data had to be collected in Phase II. Four new areas around the mountain were selected for study, and it was hoped that several of the Phase I stations for which data were incomplete could be reoccupied. At each of the four new areas the survey plan was to make two set-ups, with each set-up consisting of a base tensor MT station, two remote telluric stations and a reference magnetometer station. After the first set-up, the base MT station would be moved to one of the previous remote telluric

stations, and thus provide a base-over-remote check on the accuracy of the MT results obtained from remote stations in the cluster. For the second set-up two new remote telluric stations would be occupied, and, terrain permitting, the reference magnetometer would remain where it was. In this fashion we planned to obtain a total of five T-MT stations per cluster, one of which would be a base-over-remote. The station separations were planned to be between one and three kilometers.

The following areas were selected for study:

Cluster 1, Cloud Cap: The Cloud Cap area on the northeast side of the mountain was selected because of access and elevation, and because we wanted stations over what was supposed to have been a fairly recent (12,000 \pm y.B.P.) side-vent eruption.

Cluster 2, East Hood River-Hood River Meadows: These stations run in an east-west trending line on the southeast side of the mountain, and straddle the East Hood River. This cluster was included to test whether the north-south East Hood River, believed to be a fault zone, would offer MT evidence for a major fault. Older Tertiary (Miocene) Yakima basalts occur immediately east of the river near the Robinhood Campground (Sec. 5, T.3 S., R. 10 E.) leading some to believe that the Mount Hood block has been down-dropped relative to the pre-Mount Hood andesites which overlie the Yakima basalt and cover the highlands east of the river (Figure 3).

Cluster 3, White River: A cluster of stations in the White River area on the south side of the mountain was planned to fill the gap between Phase I stations and Cluster 2 stations, and to help discern whether a major north-south structural break occurs in the area.

Cluster 4, Old Maid Flat: This cluster west of the mountain in the Sandy River drainage was included to take advantage of the temporary opening of the Bull Run Watershed Area to public use, and because Northwest National Gas was drilling a geothermal exploration well there.

Surveys commenced in late September 1977 and continued until early November. The start-up was delayed a month for repairs to the digital acquisition system and scheduling conflicts with other surveys.

Realizing that worsening weather conditions would be encountered, we began work at the highest elevations (Cluster 1, Cloud Cap) and progressed downward to Old Maid Flat. Rain, heavy at many times, and snow showers occurred for all but a one-week period during the survey.

Instrumentation and Procedures

Instrumentation and procedures were very much the same as for the Phase I survey. The major differences were the elimination of the 45° electric dipole at base stations and a modification in the recording bands (Table 3). Use of an extra electric dipole was discontinued after it was determined that the reference magnetometer processing appeared to be yielding unbiased impedance results.

Table 3. Phase II - Recording Bands.

| Band | Filter Band Pass | Scan Rate (Samples/sec) |
|------|---------------------|----------------------------|
| 1 | 1 - 50 Hz | 200 |
| 2 | 0.1 - 10 | 50 |
| 3 | 0.1 - 3.15 | 10 |
| 4 | dc - 0.315 | 1 |
| 5 | dc - 0.02 | 0.5 |

The largest difference between field procedures in Phases I and II was in the siting of the reference magnetometer. Whereas the reference magnetometer could be left on Multorpor Mountain for the entire Phase I survey, it had to be moved once or twice with each cluster of stations

in Phase II. Moreover, there was the attendant problem of finding a suitable site for the reference magnetometer, which required a location secure and free of traffic, yet accessible by road and on a promontory where the radio telemetry would work. Because satisfactory sites were hard to find, the reference magnetometer was usually installed at a remote telluric site. This provided an additional tensor MT station.

The initial data processing was done by Geonometrics as described in Phase I with the exception that Dr. I.K Reddy's iterative bias reduction scheme was used on the Phase II data. The results are shown in Figures III-1 through III-20 of Appendix III.

Survey Results

Phase II station locations are shown in Figures 2 and 3 and the orientations of the telluric and magnetic axes are listed in Table 4. Twenty-one telluric-magnetotelluric stations were occupied, of which two stations were duplicated as base-MT-over-remote-telluric sites. Base MT and remote telluric sites are designated in the same manner as the Phase I stations, i.e., by number and by alphanumerics, respectively. At most sites, data were recorded over the frequency band from 40 Hz to 0.003-0.002 Hz.

The Cloud Cap cluster (Cluster 1) containing MT base stations 1, 2, and remote telluric stations 1A, 1B, 2A, 2B, and the White River Cluster (Cluster 3) containing MT base stations 5, 6, and remote telluric stations 5A, 5B, 6A, 6B were recorded as planned. The survey procedure along the profile between Lookout Mountain and the eastern flank of Mt. Hood (Cluster 2) was modified from the original scheme. In order to obtain

Table 4. Orientation of Telluric and Magnetic Axes in Degrees
(Measured from Geographical North - Phase II).

| STATION | E_x | E_y | H_x | H_y | H_{xr} | H_{yr} |
|---------|-------|-------|-------|-------|----------|----------|
| 1 | 40 | 130 | 40 | 310 | 40 | 130 |
| 1A | 210 | 300 | - | - | - | - |
| 1B | 265 | 355 | - | - | - | - |
| 2 | 265 | 355 | 265 | 175 | 65 | 355 |
| 2A | 125 | 215 | - | - | - | - |
| 2B | 210 | 300 | - | - | - | - |
| 3 | 90 | 180 | 90 | 0 | 90 | 180 |
| 3A | 90 | 180 | - | - | - | - |
| 3B | 90 | 180 | - | - | - | - |
| 4 | 180 | 270 | 180 | 90 | 180 | 270 |
| 4A | 180 | 90 | - | - | - | - |
| 4B | 180 | 270 | - | - | - | - |
| 5 | 0 | 270 | 0 | 270 | 0 | 90 |
| 5A | 0 | 270 | - | - | - | - |
| 5B | 0 | 90 | - | - | - | - |
| 6 | 180 | 270 | 180 | 90 | 180 | 270 |
| 6A | 0 | 270 | - | - | - | - |
| 6B | 180 | 270 | - | - | - | - |
| 7 | 320 | 230 | 320 | 230 | - | - |
| 7A | 320 | 50 | - | - | - | - |
| 7B | 320 | 50 | - | - | - | - |
| 7C | 130 | 220 | - | - | - | - |

as broad an areal coverage as possible in this region, the base-MT-over-remote-telluric measurements were deleted here. In Cluster 4 only one base MT station, 7, with remote telluric stations 7A, 7B and 7C, was recorded. The reference magnetic measurements were deleted due to a malfunction in the reference magnetometer. Processing problems encountered by Geonometrics during data manipulation prevented the initial presentation of resistivity estimates at Station 7C. Due to inclement weather, the project was terminated after Stations 7, 7A, 7B, 7C were recorded. The second set-up in Cluster 4 and repeat measurements at selected Phase I stations were not done.

An evaluation of the accuracy of the information obtained via the remote telluric-magnetotelluric (T-MT) method in a complex geologic environment was one objective of the study. The Phase II survey provided two sets of base-over-remote station data to evaluate this method. The first set was the T-MT site (2, 1B) in the Cloud Cap cluster. The resulting apparent resistivity soundings are shown in Appendix III. In this example the data are quite similar, with the greatest deviation occurring in band 2 (between 0.1-10 Hz). The low signal levels in this band may be responsible for the departure in the two estimates. The second base-MT-over-remote-telluric pair was located in the White River cluster, Stations 5 and 6A. The apparent resistivities from these data sets are somewhat similar in shape; however, there are some disturbing differences. At the higher frequencies (greater than 1.0 Hz), the apparent resistivities differ by 20 to 50 percent and at lower frequencies (less than 0.04 Hz) the deviations are from 20 to 100 percent.

The reasons for these differences are not clear. There was one

possibly important difference between the first case above, which provided a fairly good correlation between the remote and base resistivity estimates, and the second case where the differences were appreciable. At Cloud Cap (T-MT site 2, 1B) the environmental conditions (temperature and moisture) under which both sets of data were recorded were very similar. In the second test case (T-MT site 5, 6A) the data sets were recorded under quite different conditions. The data at Station 5 were recorded during a period of mild temperatures and dry weather. The remote telluric data for the same location were recorded a week later during a period of freezing temperatures and with several inches of snow on the ground. These adverse conditions may have increased the noise in some field components, thus biasing the resistivity estimates. If the differences in the resistivity estimates are due to bias errors, the differences should decrease when reprocessing procedures are used.

A further check on the accuracy of the remote site estimates of resistivity will be obtained when the data are reprocessed. The remote magnetics in three clusters were located at remote telluric sites. These data sets may be processed as both MT estimates as well as T-MT estimates of resistivity at each of these locations (sites 2A, 3A, 4A, 5A).

PRELIMINARY INTERPRETATION

The apparent resistivity soundings generally have very different characteristics from one cluster of stations to the next and even between adjacent stations within a cluster in many cases. These major spatial changes in apparent resistivity as a function of frequency indicate major lateral discontinuities in conductivity throughout the region of investigation.

Two notable examples would be the Lookout Mountain-Hood River cluster (Figures III-7 through III-12) and the White River cluster (Figures III-13 through III-18). Lateral changes in conductivities cause the principal resistivity estimates R_{12} and R_2 to diverge and may bias both sounding curves to the extent that simple, one-dimensional (layered earth) interpretations would be in error.

Confronted by this apparently complex conductivity distribution, we took the following approach toward the interpretation. The principal axes of rotation of the two components of apparent resistivity (designated as Θ in the Appendices) and the strike direction obtained by means of the vertical magnetic field measurements (designated as Strike in the Appendices) were studied as to (1) uniformity with respect to frequency, and (2) spatial correlation at various frequencies. Three frequencies were chosen to represent the data: 8 Hz, 0.04 Hz and 0.01 Hz. The rotations at these three frequencies are shown in Figures 5, 6, and 7, respectively. Comparing the variations in rotation directions as a function of frequency, we see that rotations of both principal axes and strike directions were nearly the same from 0.003 to 0.04 Hz at most stations. The rotations at 8 Hz were similar in many cases, with only two notable changes in strike at Stations 4 and 5. However, in general the rotations for both resistivity and strike were not smooth functions of frequency at around 1.0 Hz.

The second point of interest is the spatial relationships between various rotations throughout the region of study. For frequencies below 0.04 Hz the region may be divided into two sections. In the regions north, east, and west of Mount Hood strikes range between 90° and 120°

(azimuths are clockwise from geographic north), indicating a dominantly east-west structural trend. To the south of Mount Hood, we find a very strong rotation for both the resistivity and vertical magnetic data into a north-south strike direction. Rotations are fairly uniform at low frequencies and are consistent throughout the area. The data suggest deep conductive structures in the vicinity of the northern sector of Mount Hood, striking 120° , and a structural change occurring south of Mount Hood where the conductive strike direction becomes more north-south.

Two specific areas of interest have been identified from the MT results. MT station 1 (Phase II), situated a short distance down-slope from a concealed vent in the Cloud Cap area from which large flows of olivine andesite extruded $12,000 \pm$ y.B.P., provided an anomalous sounding. This station also produced the only sounding curves that are "similar" to those for a one-dimensional response (Figure III-1). A one-dimensional inversion of the two components of apparent resistivity is shown in Figure 8. Notably, there is an unusually conductive zone 400 to 500 meters thick at a depth of 600-700 meters. This region has a resistivity on the order of 2 ohm-m and may correspond to a zone of water-saturated clay and ash within the Mount Hood volcanics. Considering the apparently high porosity-permeability and the active groundwater flow within units of the Mount Hood volcanics, it is difficult to imagine how this conductive zone is a manifestation of heat retained in the rocks since the last Cloud Cap eruption. It is equally difficult to reconcile a 2 ohm-m resistivity solely with surface conduction effects due to clays in rocks saturated by cold meteoric water. The low resistivity value may be stratigraphic, enhanced by a structural boundary, but the possibility of a hot water reservoir being replenished from below cannot be ruled out.

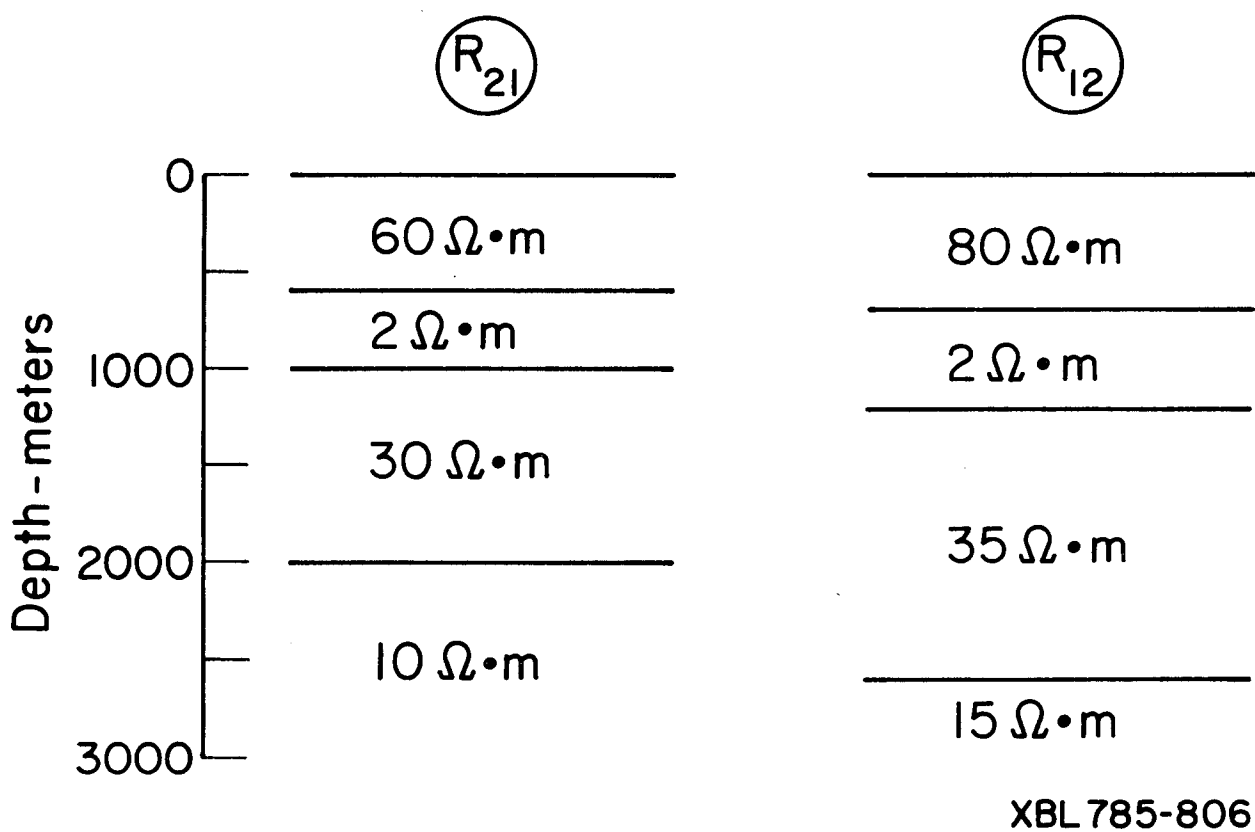
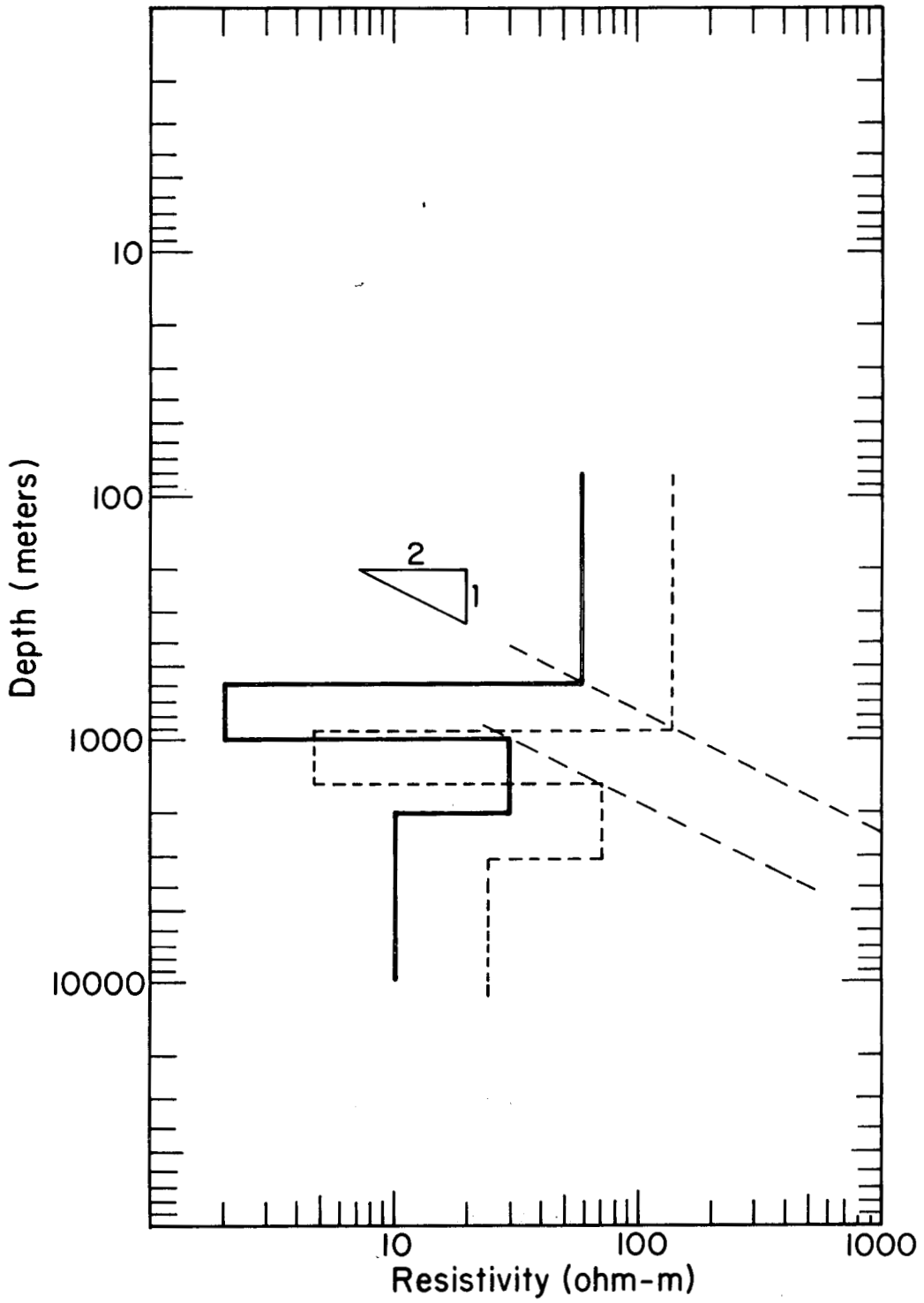


Figure 8. One-dimensional interpretation of MT data from Station 1, Phase II, Cloud Cap.

The second feature of interest at this station is a deeper conductive zone (10 ohm-m) at a depth of 2000⁺ meters, probably located within the pre-Hood andesites. This zone may indicate fractured and porous rocks which could serve as a geothermal reservoir. However, a note of warning is necessary: the accuracy of the inversion model is in question because the apparent resistivity curves do not strictly correspond to a one-dimensional geology. Although the two apparent resistivity curves have the same shape, there is a dc shift of 80 to 150 ohm-m between them at the higher frequencies. This indicates that there could be near-surface inhomogeneities at this location which would influence the inversion model. If so, we have a highly ambiguous situation, and the lack of information about the near-surface structure allows interpretation of changes in resistivity versus depth only in a relative sense, not in an absolute sense (Bostick, 1978). If one plots layer resistivities versus depth on a log-log scale, the family of acceptable models is given, to a reasonable approximation, by sliding the model up or down along a straight line with a slope of $-1/2$ (see Figure 9).

Both conductive zones become less anomalous at stations farther away from the vent area. The deeper zone shows a departure from one-dimensionality with increasing distance from the vent, suggesting the influence of a structural boundary.

Another region of specific interest is the area investigated during Phase I. In this region, the prevalent data characteristic observed was the high degree of nearly linear, north-south polarization of the electric fields. The vertical magnetic strike direction and the principal axes of the apparent resistivity were nearly coincident. The strong polarization



XBL 785-805

Figure 9. Family of acceptable solutions for Station 1, Phase II, Cloud Cap.

causes the amplitudes of the two modes of apparent resistivity to diverge, and at some stations the separation of the two modes at low frequencies is up to two orders of magnitude. It is likely that this response is due to a large, relatively shallow conductivity contrast, striking north-south in this vicinity. The general electrical strike in the region was later confirmed by the strike directions provided by Phase II, stations 5 and 6, at low frequencies (below 0.025 Hz). However, at this time we are not able to tell exactly where this structure is located, nor can we infer what significance it bears to the geothermal resource potential. It may be worth noting that the warm springs at the Still Creek Campground lie within this region. Station 1A, closest to the springs, yielded anomalously low resistivities, but these results must be viewed with extreme caution because of the limited bandwidth and questionable data quality due to severe noise levels.

CONCLUSIONS

The MT survey verified one of the initial suppositions, namely, that the results would indicate a complex, three-dimensional geometry and would therefore not be amenable to interpretation by means of layered or, perhaps, even simple two-dimensional models. In places the apparent resistivity soundings obtained show very different characteristics over distances as short as three or four kilometers.

To illustrate major structural features, plots were made showing the two principal resistivity directions, one determined from tensor rotation and one from vertical magnetic field information, at 8, 0.04 and 0.01 Hz. Below 0.04 Hz these directions tend to be relatively constant at most

stations, and show that the region has two electrical trends. On the north, east and west flanks of Mount Hood the principal direction is approximately east-west, azimuths varying between 90° and 120° relative to north. However, resistivities at stations on the south flank show a pronounced north-south principal direction. This contrast suggests that the volcano may be localized by the intersection of north-south structural trend paralleling the High Cascades, and an east-west structure.

Although it was not possible to put stations close to the summit, the most obvious focus of thermal activity, observations were made in the areas of secondary interest: Cloud Cap, a $12,000^{\pm}$ y.B.P. eruptive center on the northeast side of the volcano and Still Creek Campground, a site of numerous warm water orifices six miles south of the summit.

Of all the stations occupied, the one closest to Cloud Cap (Station 1, Phase II) provided the most encouraging results. Despite our reservations about using one-dimensional interpretations, sounding curves in the principal directions were so similar that a layered earth interpretation was made. It shows a surprisingly conductive zone (resistivity of 2 ohm-m) at a depth interval of about 0.5 to 1.0 km, and a deeper conductive zone (~ 10 ohm-m) at a depth of 2^+ km, extending downward for an undetermined distance before disappearing into a region of increasing resistivity. The shallower conductor probably occurs within the Mount Hood volcanic pile, and whether it is related to thermal waters is problematic. Cold groundwaters moving down-slope in the active hydrologic regime close to surface should have carried away the heat from the Cloud Cap eruption unless a hot water reservoir is being replenished from below. Unless one invokes

the presence of either thermal or saline cold water it is difficult to account for rock resistivities of only 2 ohm-meters. The deeper conductive zone occurs in what are likely to be pre-Mount Hood Yakima basalts (Miocene) and this zone also has geothermal potential. The actual depths to both zones cannot be accurately determined from the MT results. In addition to the fundamental uncertainty of a one-dimensional inversion, local inhomogeneities near the surface (e.g., uneven topography) can bias depth and resistivity estimates. It is interesting that both zones show diminishing definition with increasing distance from the eruptive center.

In the second area of interest, the station closest to the warm springs at the Still Creek Campground (Station 1A, Phase I) gave uniformly low apparent resistivities, orders of magnitude lower than at stations nearby. However, owing to severe man-made noise and loss of data due to a recorder malfunction, these results are suspect. Regarding a cause for the warm water emanations, the strongly linear north-south electric field polarizations observed could signify faulting, but there is no direct evidence for faults.

Until the data are reprocessed utilizing the reference magnetometer data to suppress uncorrelated noise and remove possible biases in the sounding curves, it is difficult to make an adequate appraisal of the telluric-magnetotelluric method in this complex geologic setting. At sites where we have both a remote telluric station and a conventional tensor station the resulting sets of sounding curves have similar shapes but differ in apparent resistivity by 20 percent and more. Whether these differences are due to a non-uniform magnetic field related to local geology or due to biasing effects caused by noise is yet to be determined.

RECOMMENDATIONS FOR FUTURE WORK

When unbiased impedance estimates are obtained, the results will be interpreted, initially, in terms of two-dimensional structures using, as a directional basis, the tipper rotations and the principal resistivity directions. Each cluster will be considered as a separate two-dimensional situation, a fairly good initial model because the rotations and strikes are fairly consistent within each cluster of stations. Following this, three-dimensional modeling will be attempted using computer codes now under development. This will provide a spatial tie between the five clusters that surround the volcano.

In order to achieve better control on the depth estimates and position of lateral discontinuities we must obtain detailed information about the conductivity distribution near the surface. From this information we may also possibly estimate the magnitude of the geologic bias that appears in most of the sounding curves. This information may be obtained from a high-density audio-magnetotelluric (AMT) survey in the vicinity of each MT cluster, thus helping to define the high frequency asymptotes on the apparent resistivity curves and the positions of lateral conductivity changes near the surface. Similar data could also be obtained by means of dc resistivity or an active electromagnetic system.

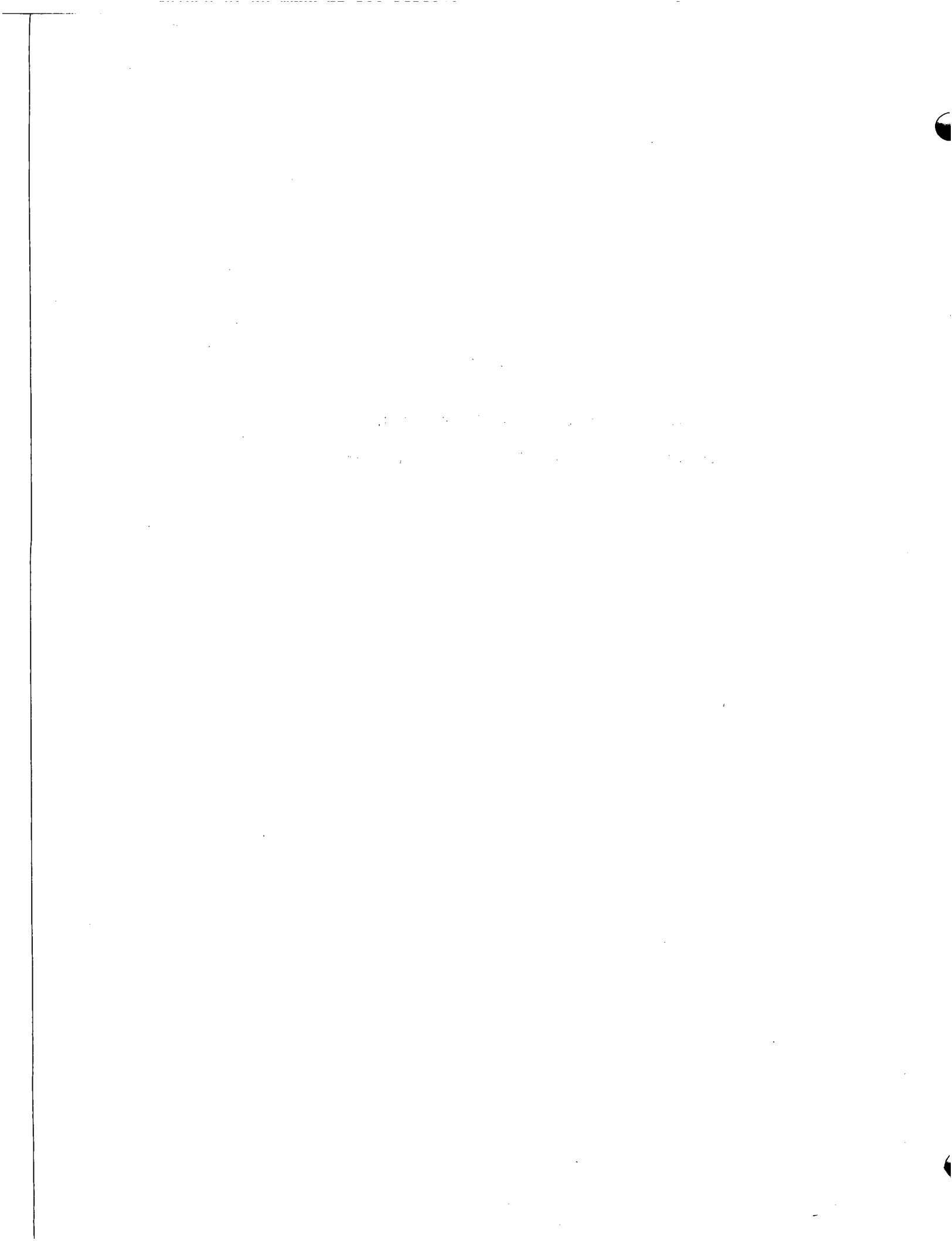
We are presently developing an AMT system and an active loop source sounding system with which we hope to obtain the required data during the summer of 1978.

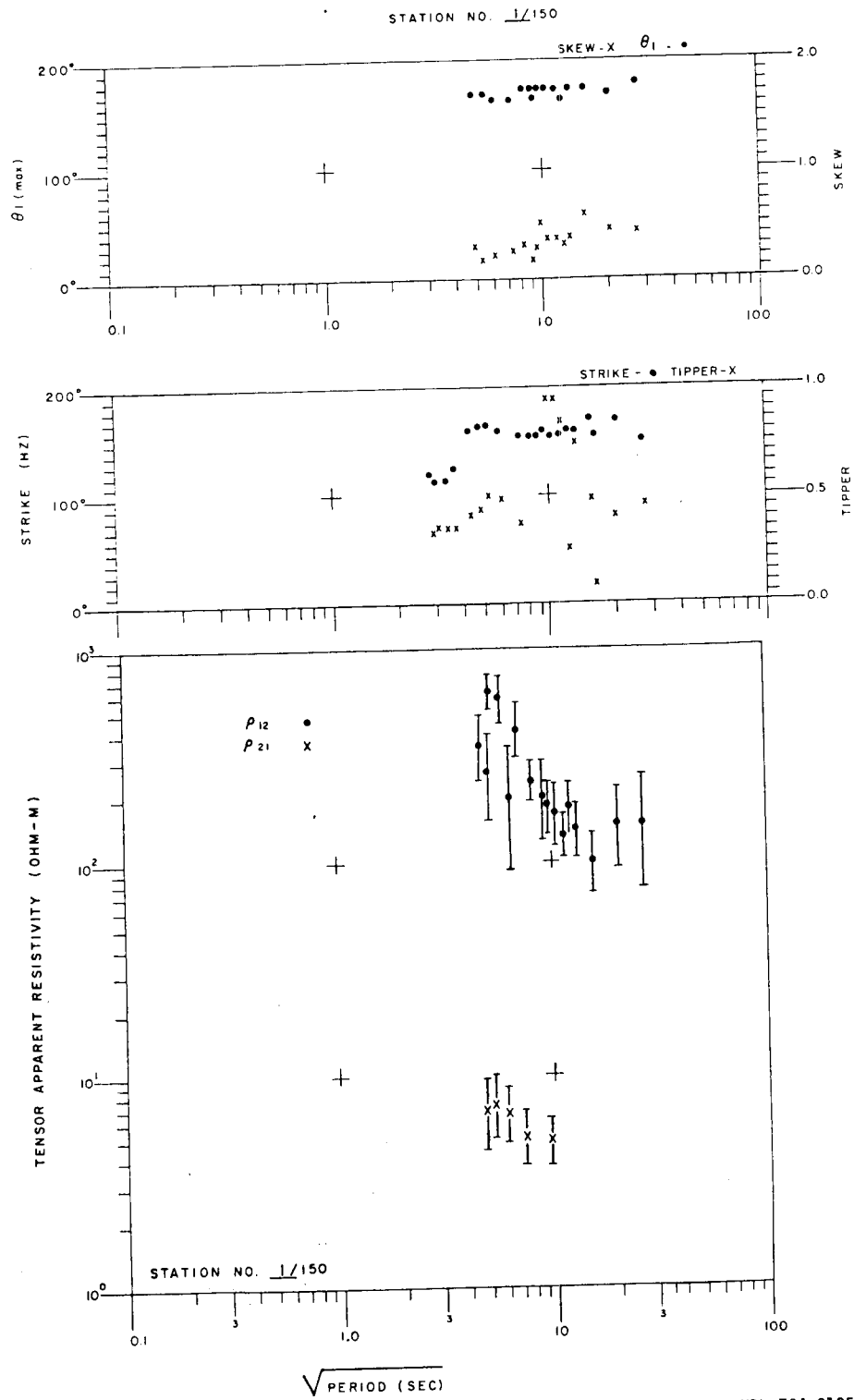
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APPENDIX I

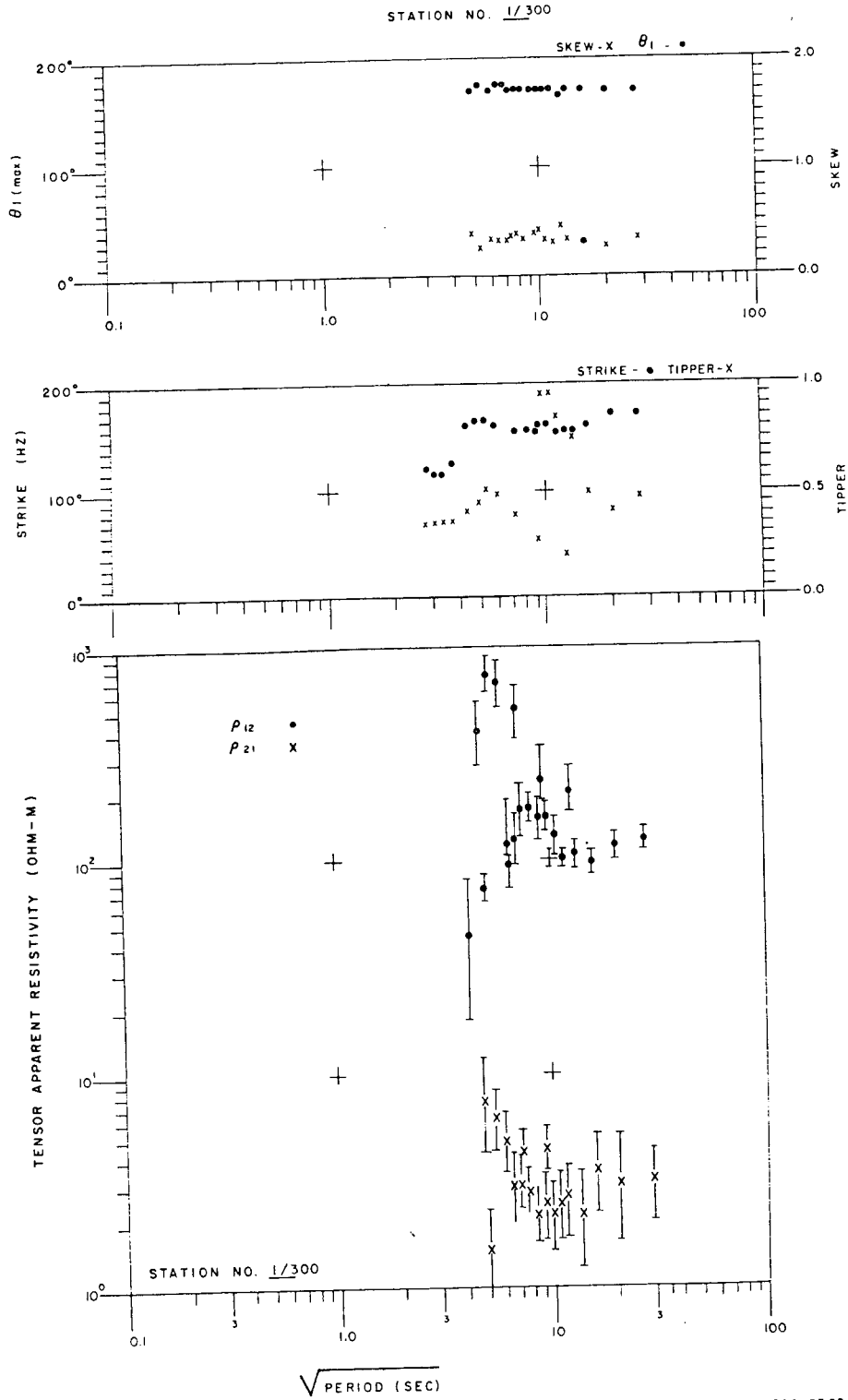
VARIABLE DIPOLE LENGTH EXPERIMENT:
ELECTRIC DIPOLES AT 150 m, 300 m and 600 m





XBL 784-8125

Fig. I-1



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Fig. I-2

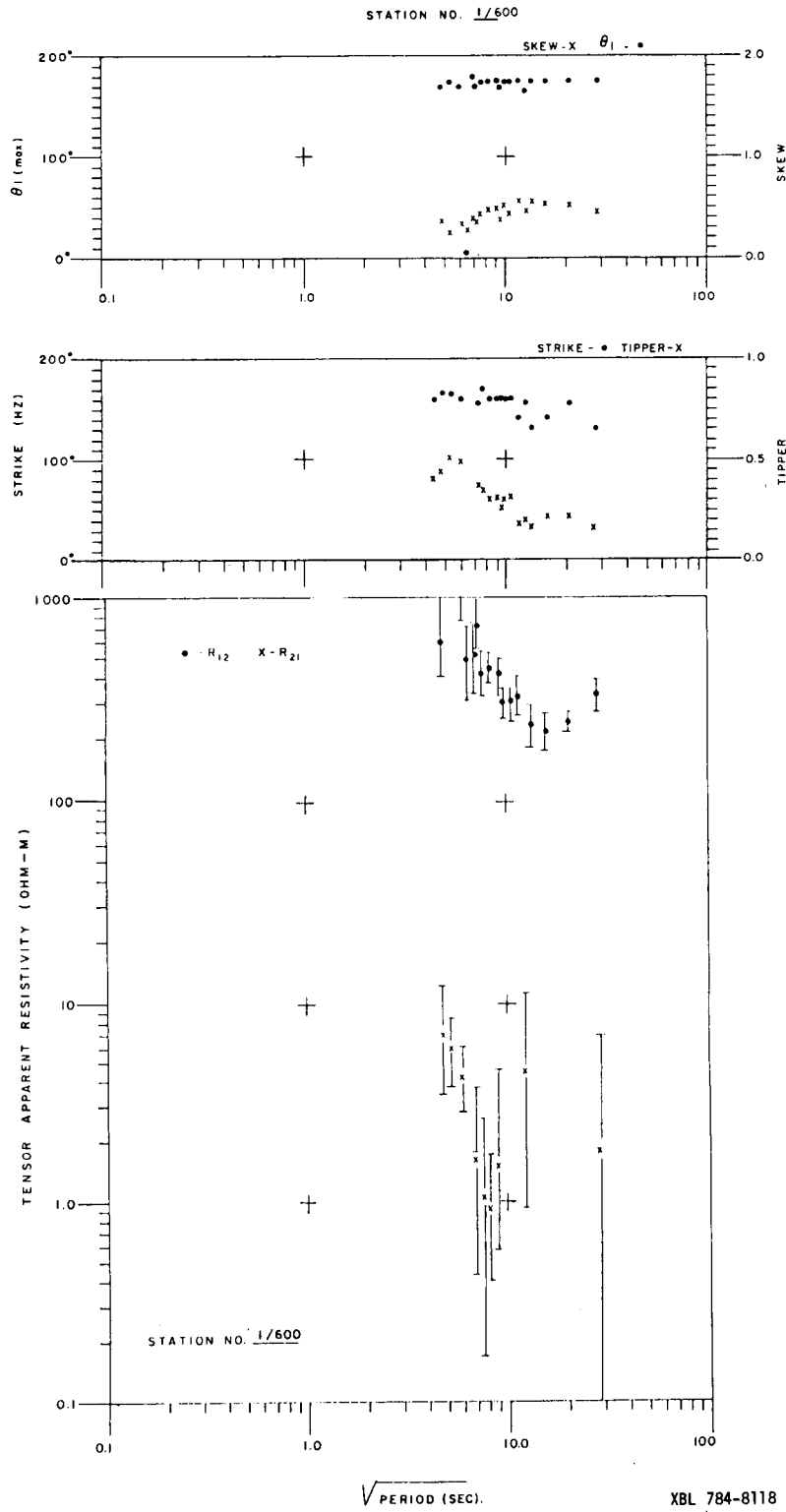
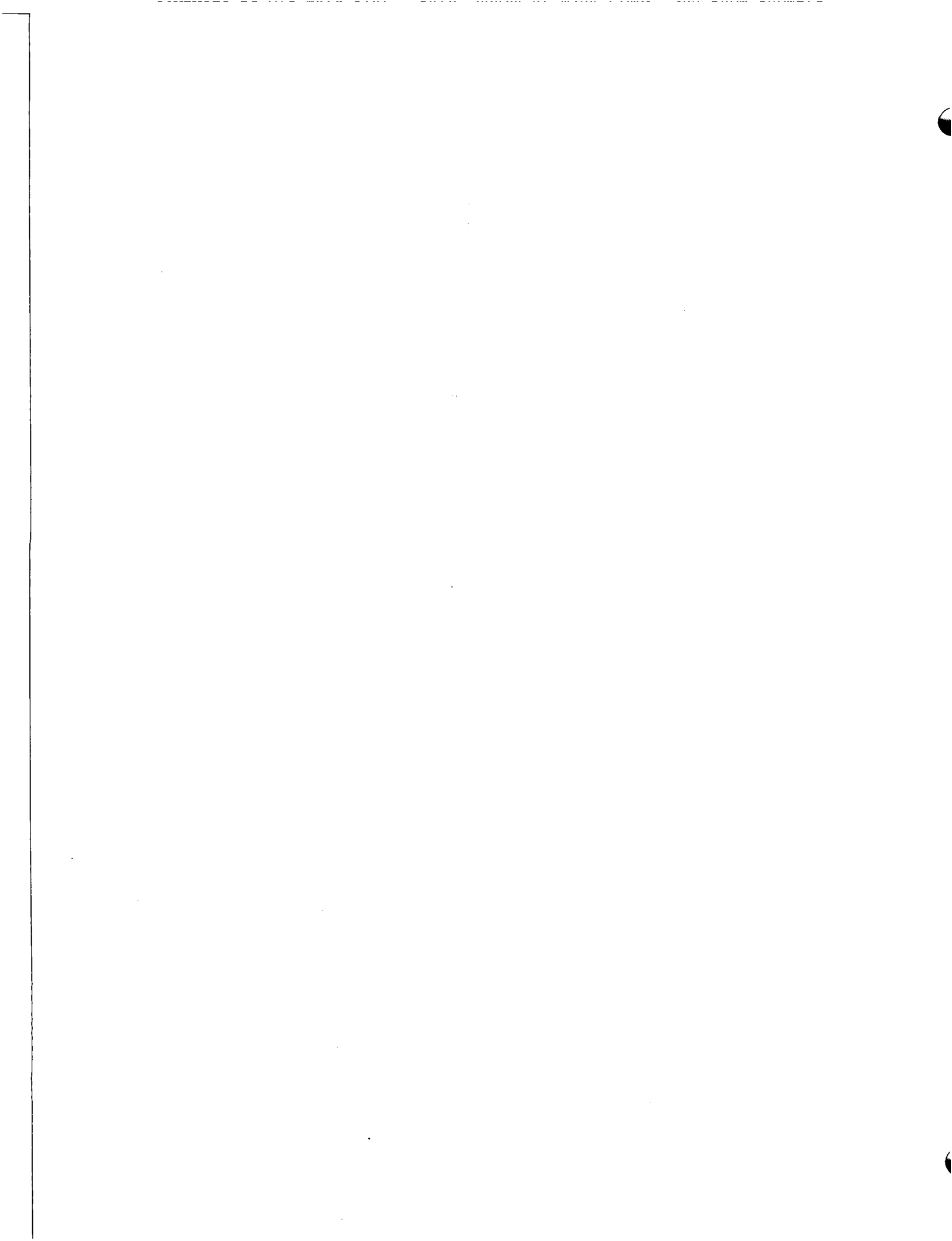
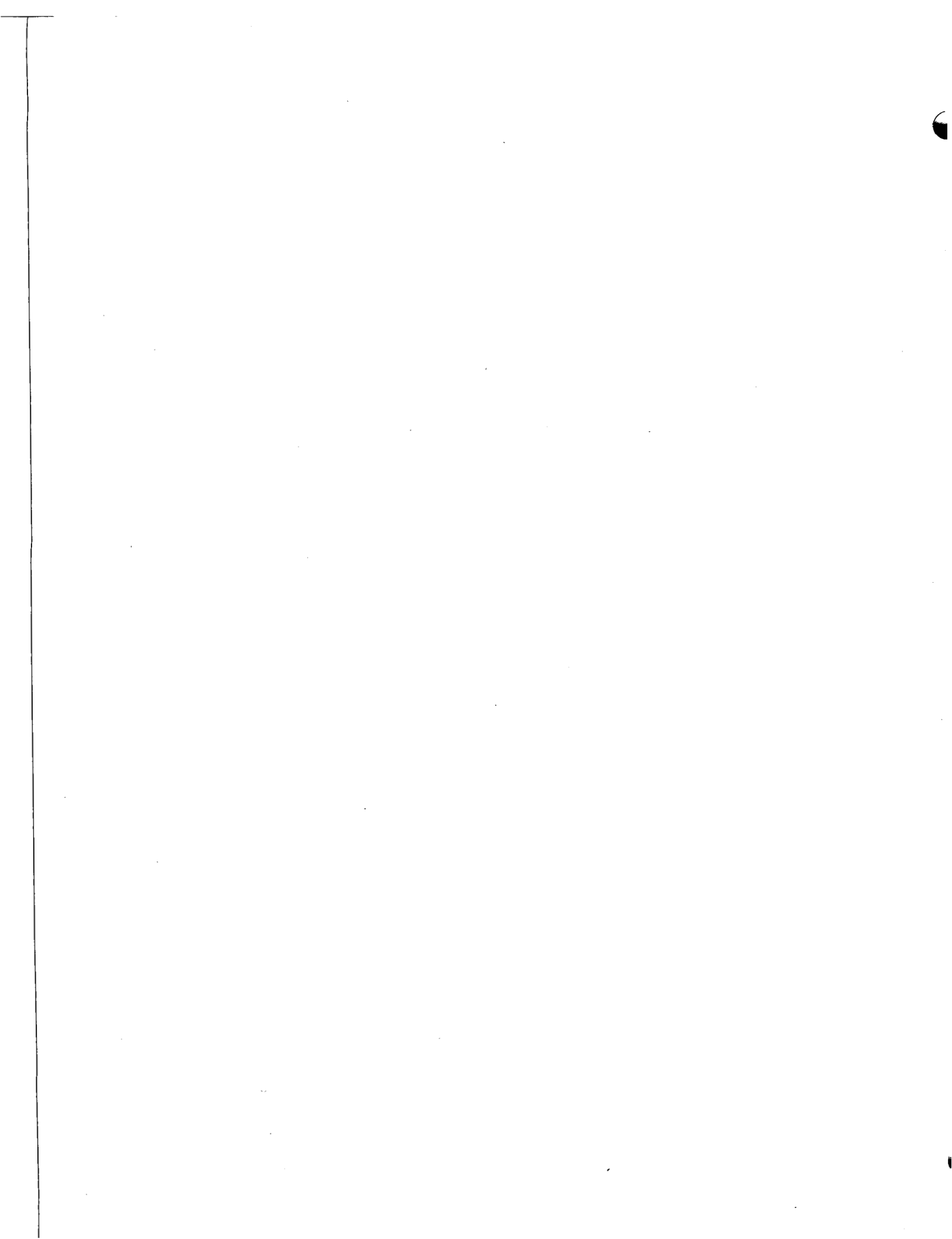


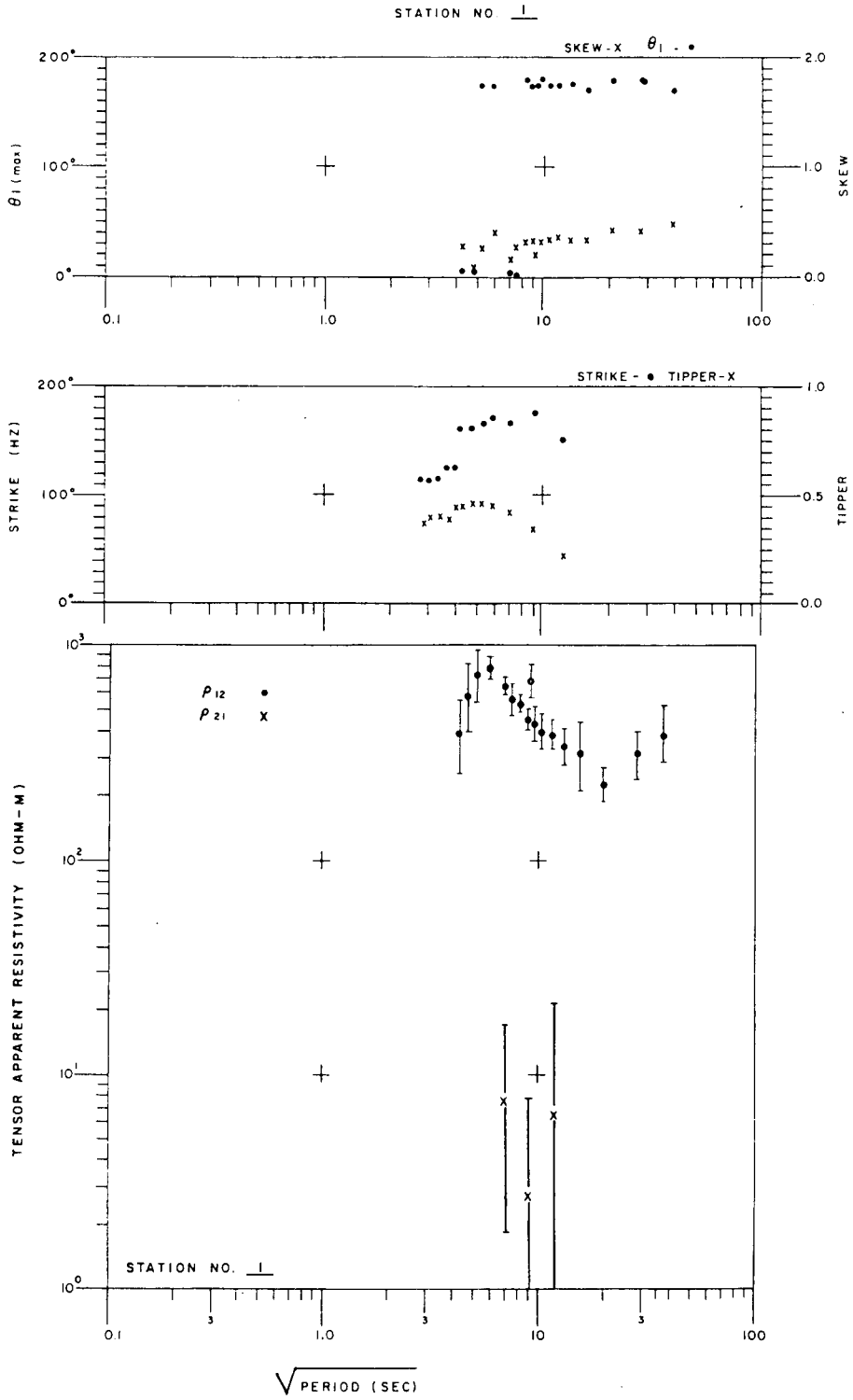
Fig. I-3



APPENDIX II

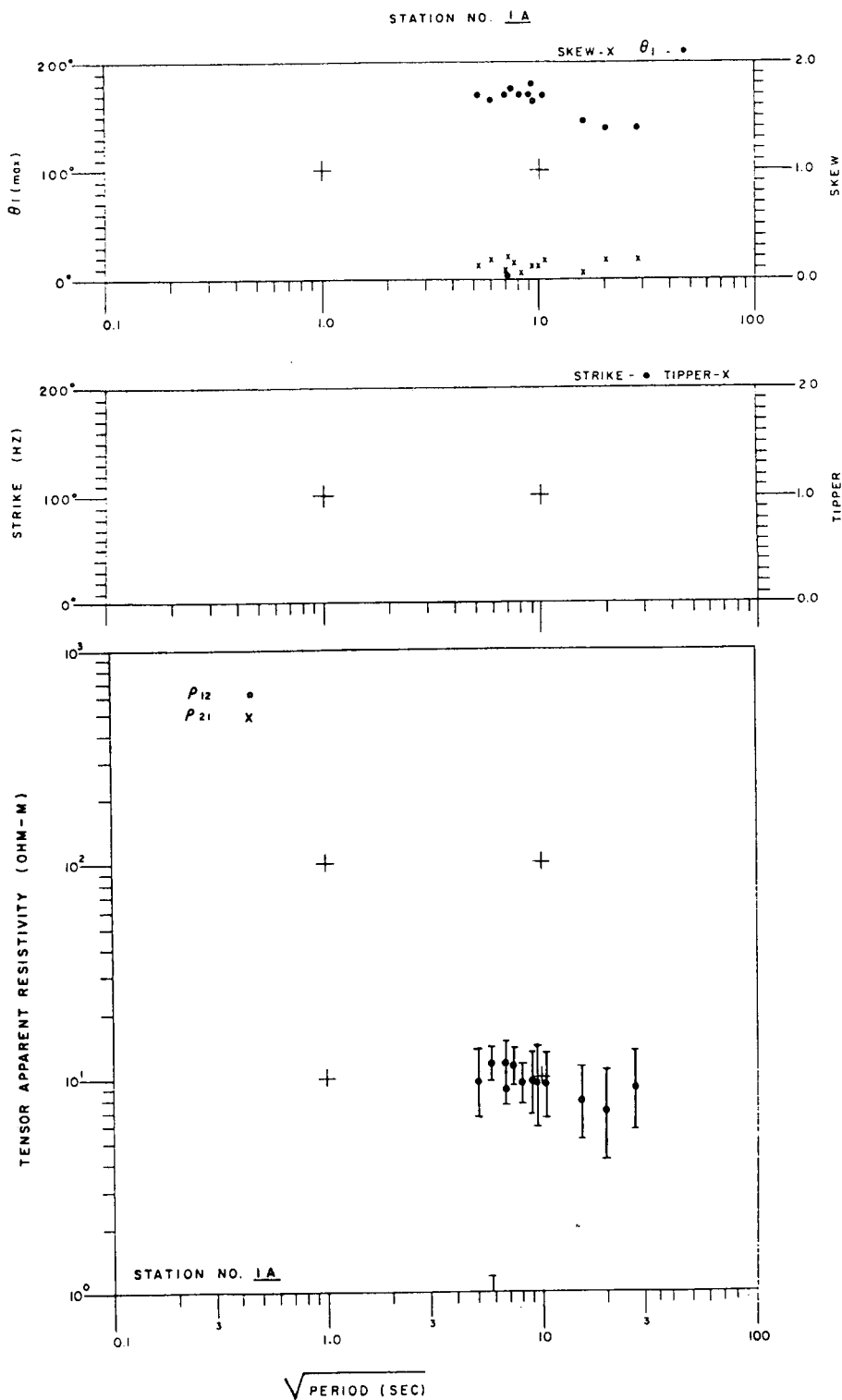
PHASE I, MT STATION RESULTS





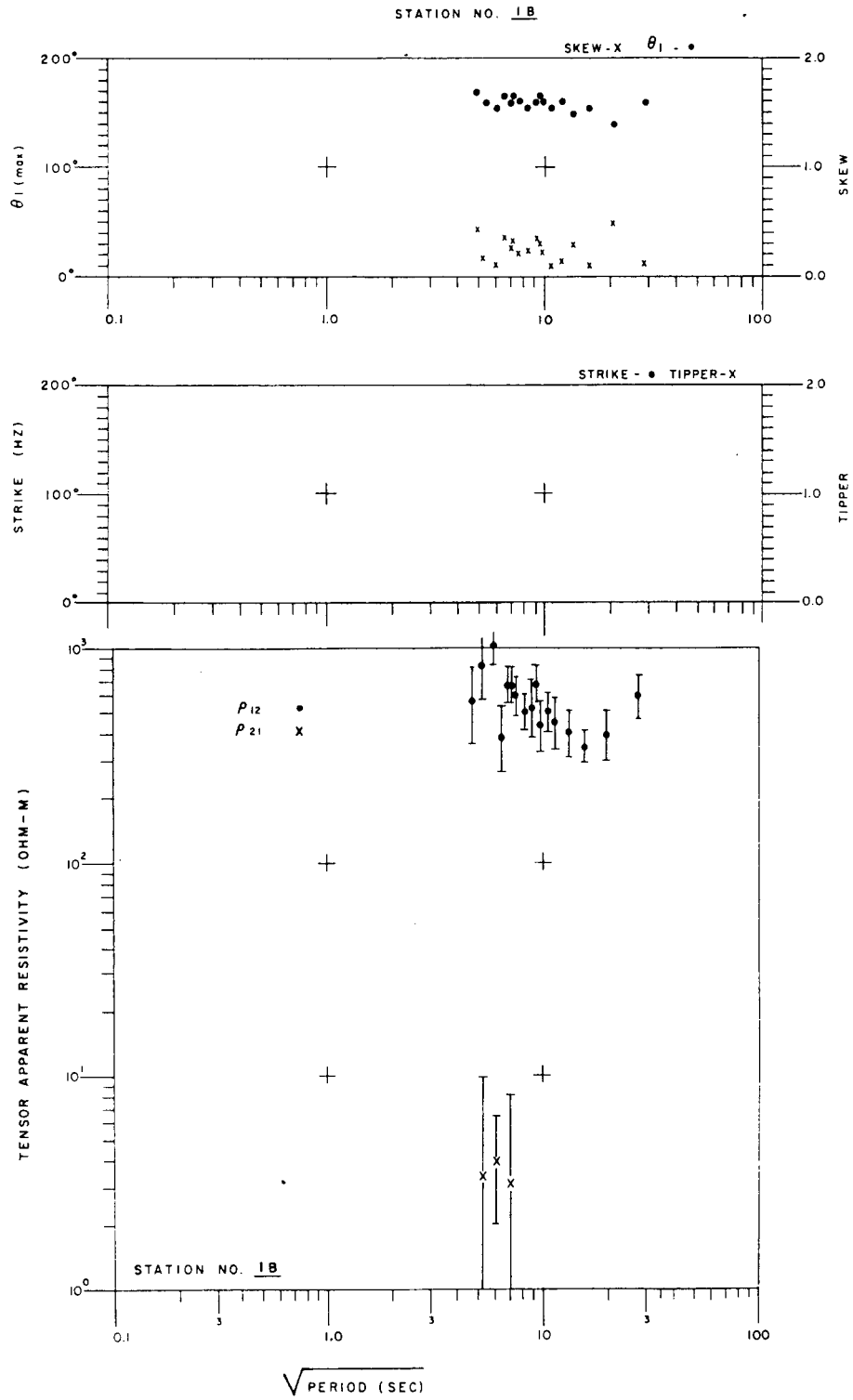
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Fig. II-1



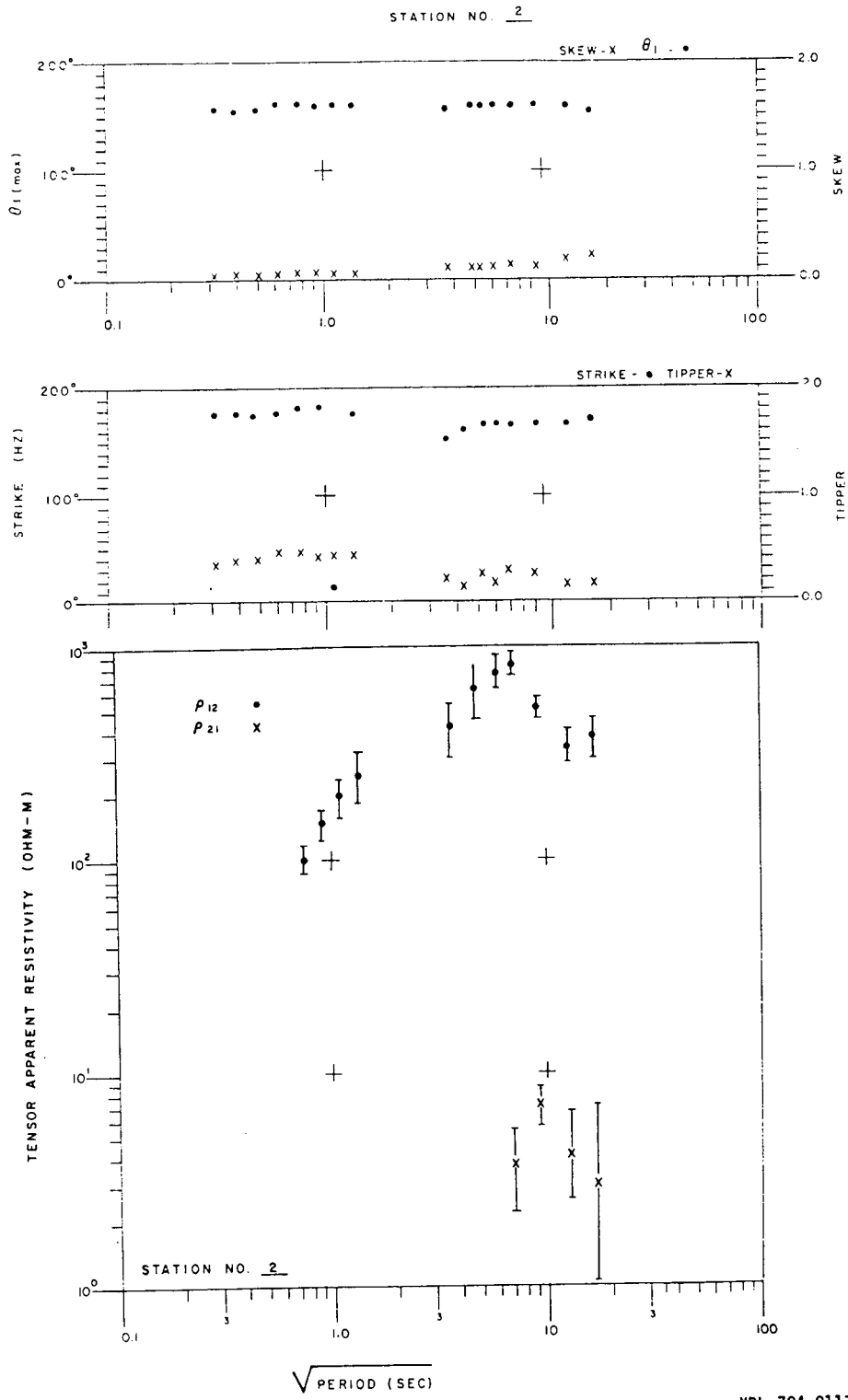
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Fig. II-2



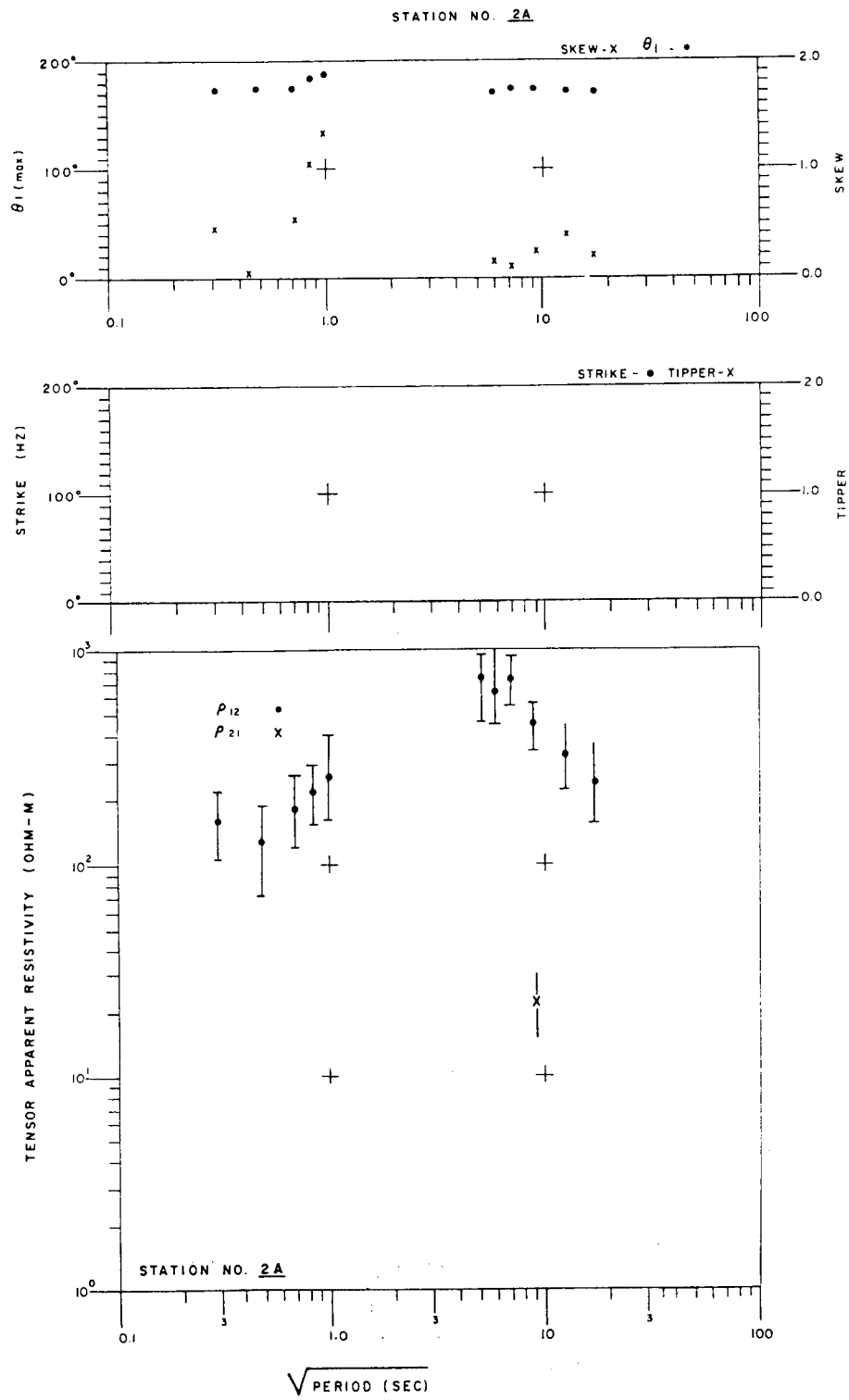
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Fig. II-3



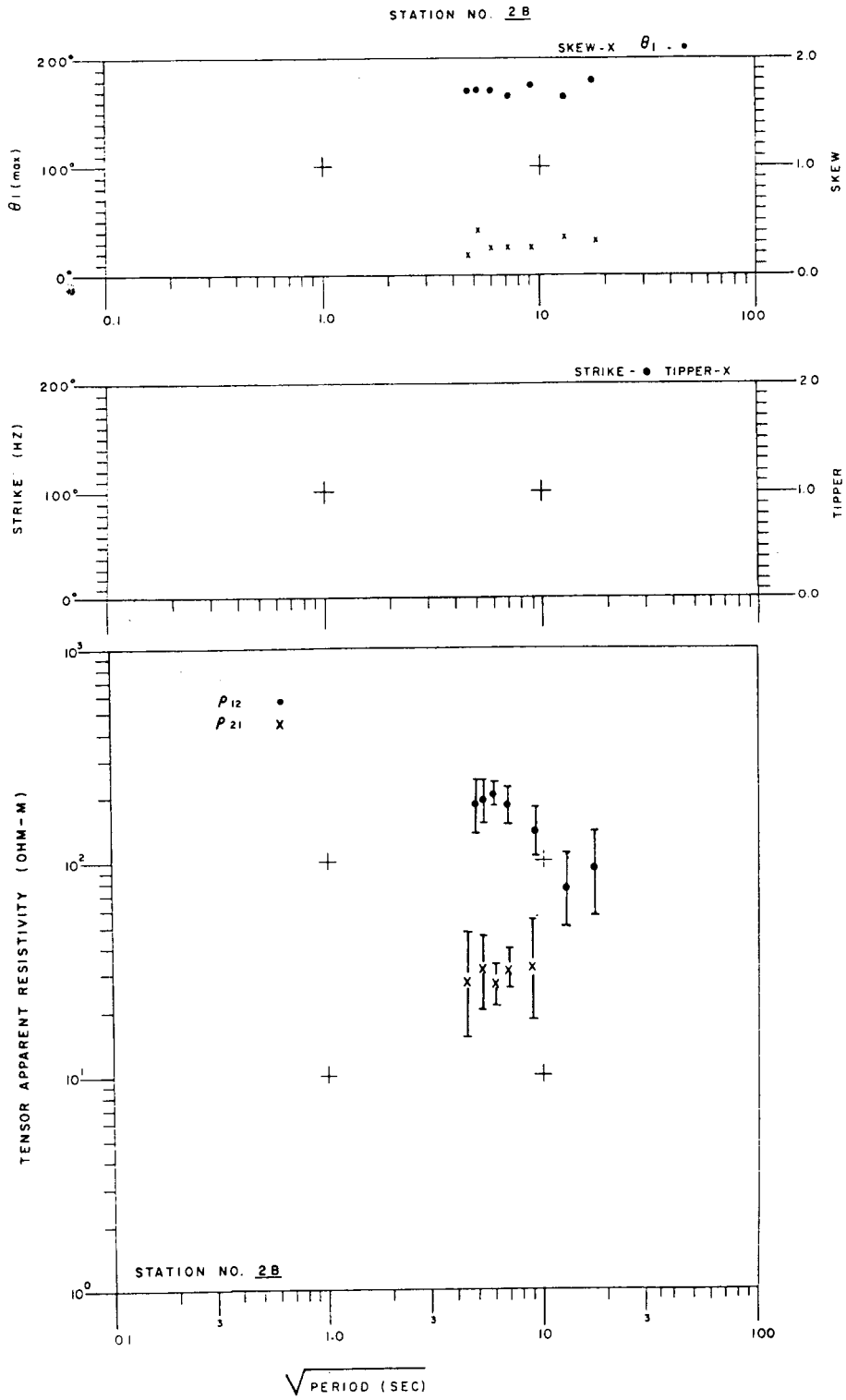
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Fig. II-4



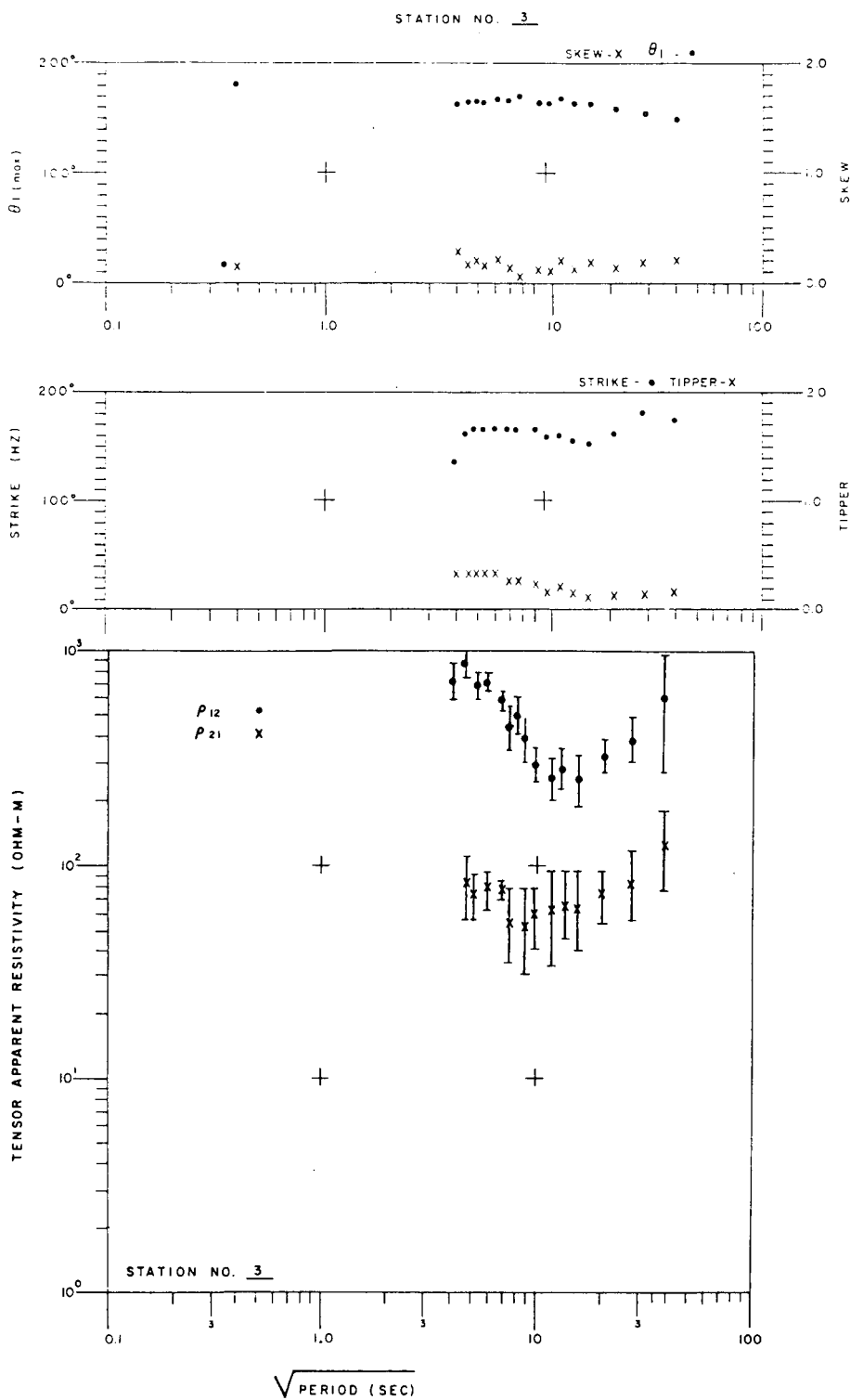
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Fig. II-5



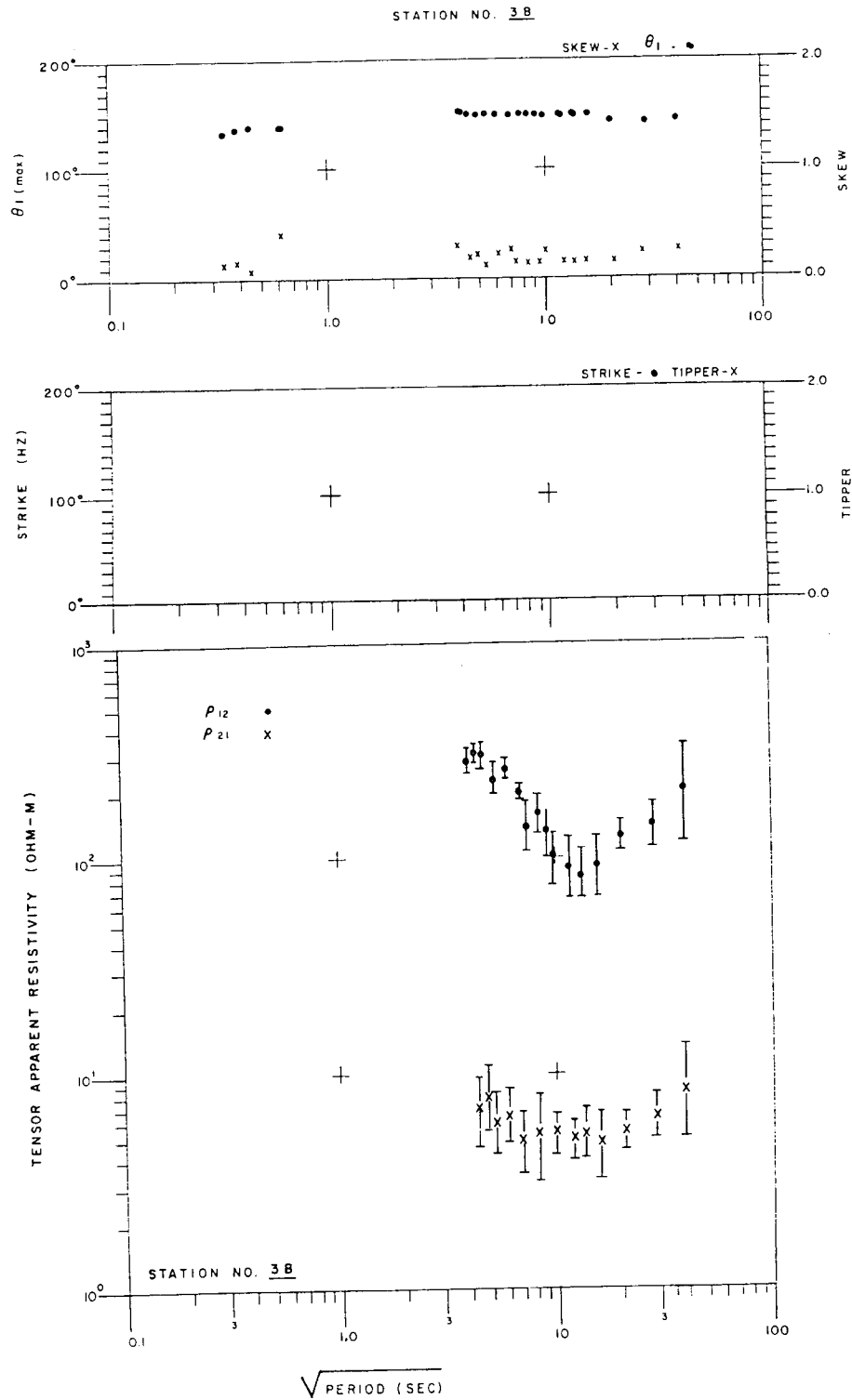
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Fig. II-6



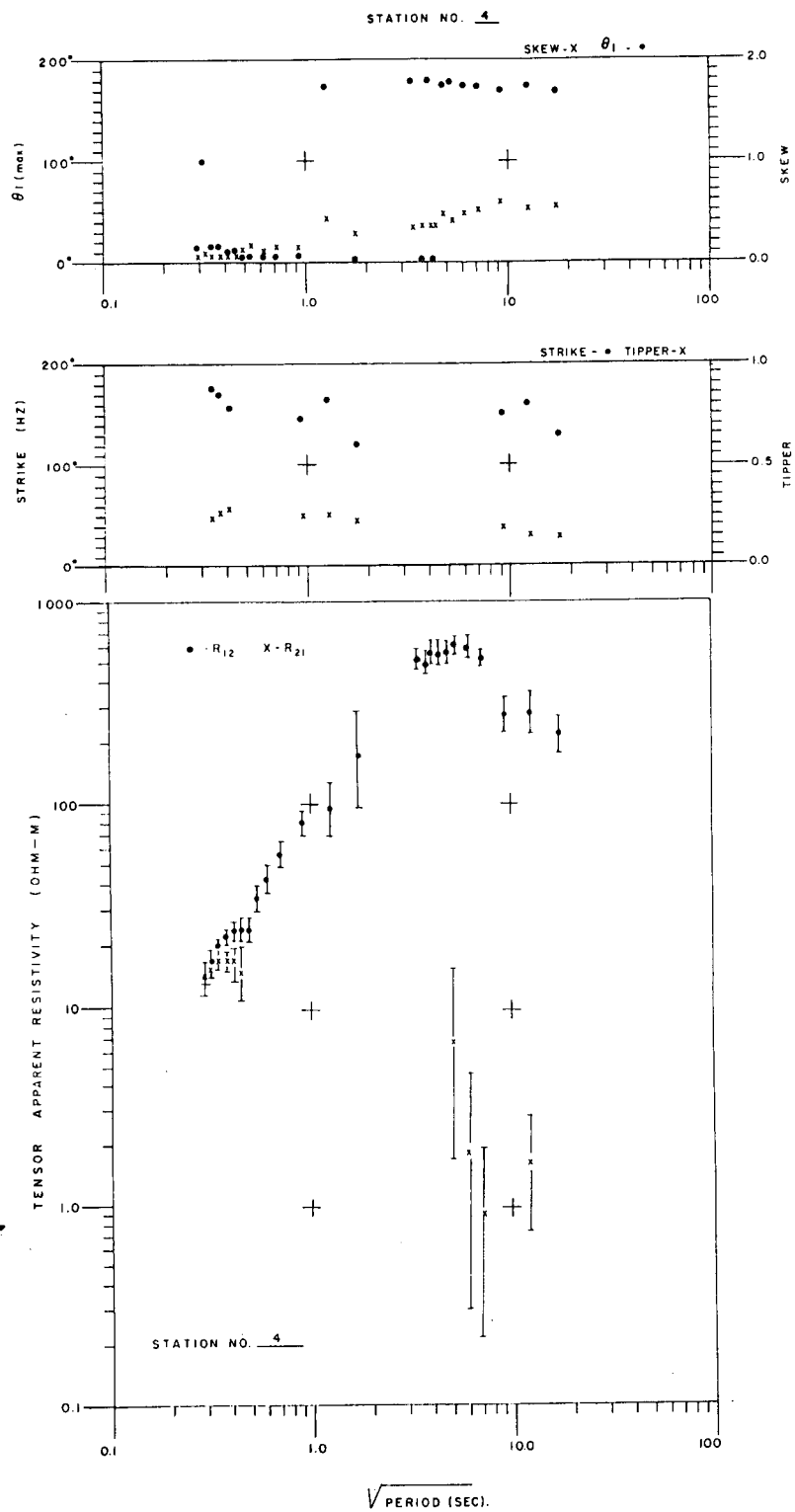
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Fig. II-7



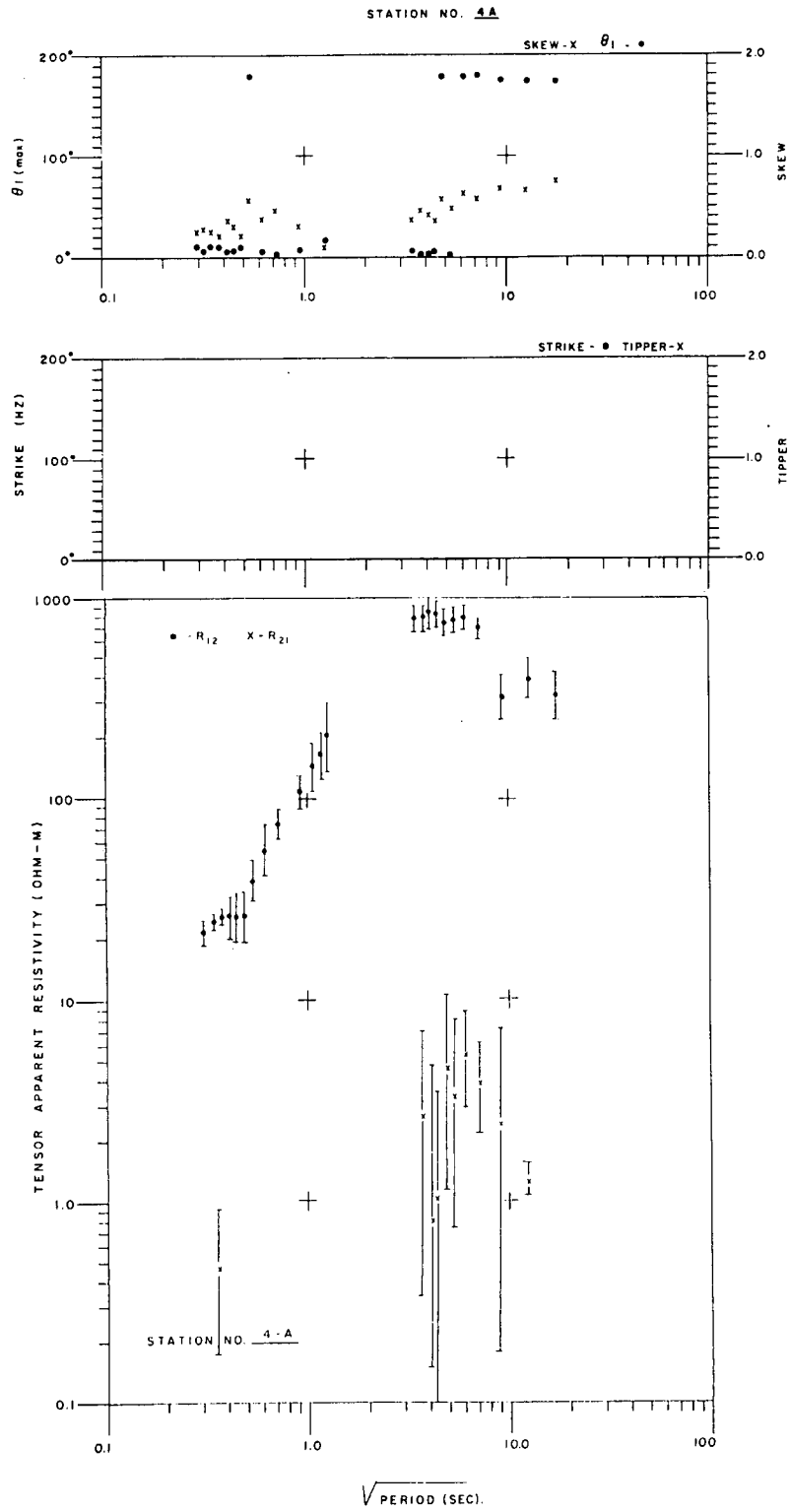
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Fig. II-8



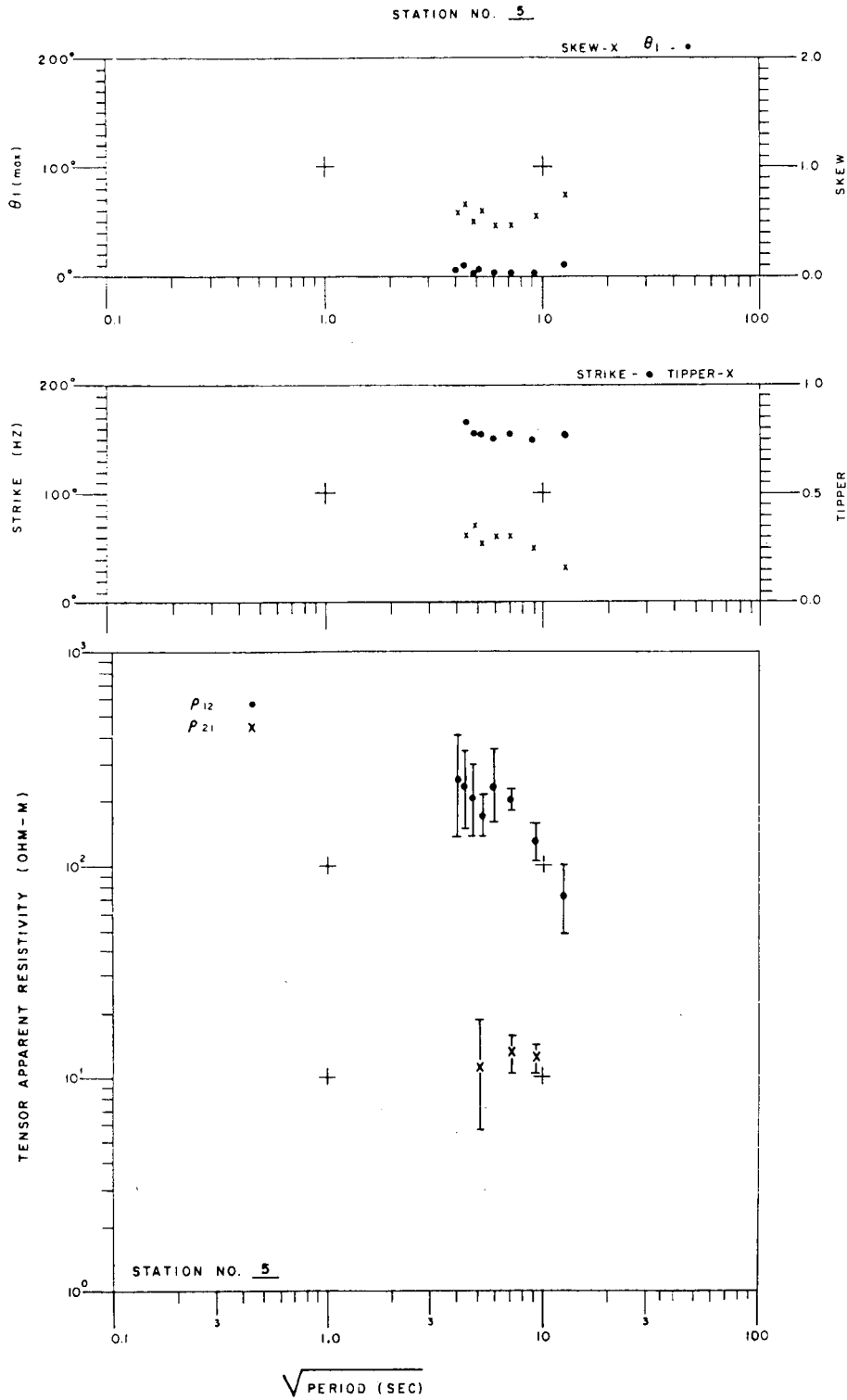
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Fig. II-9



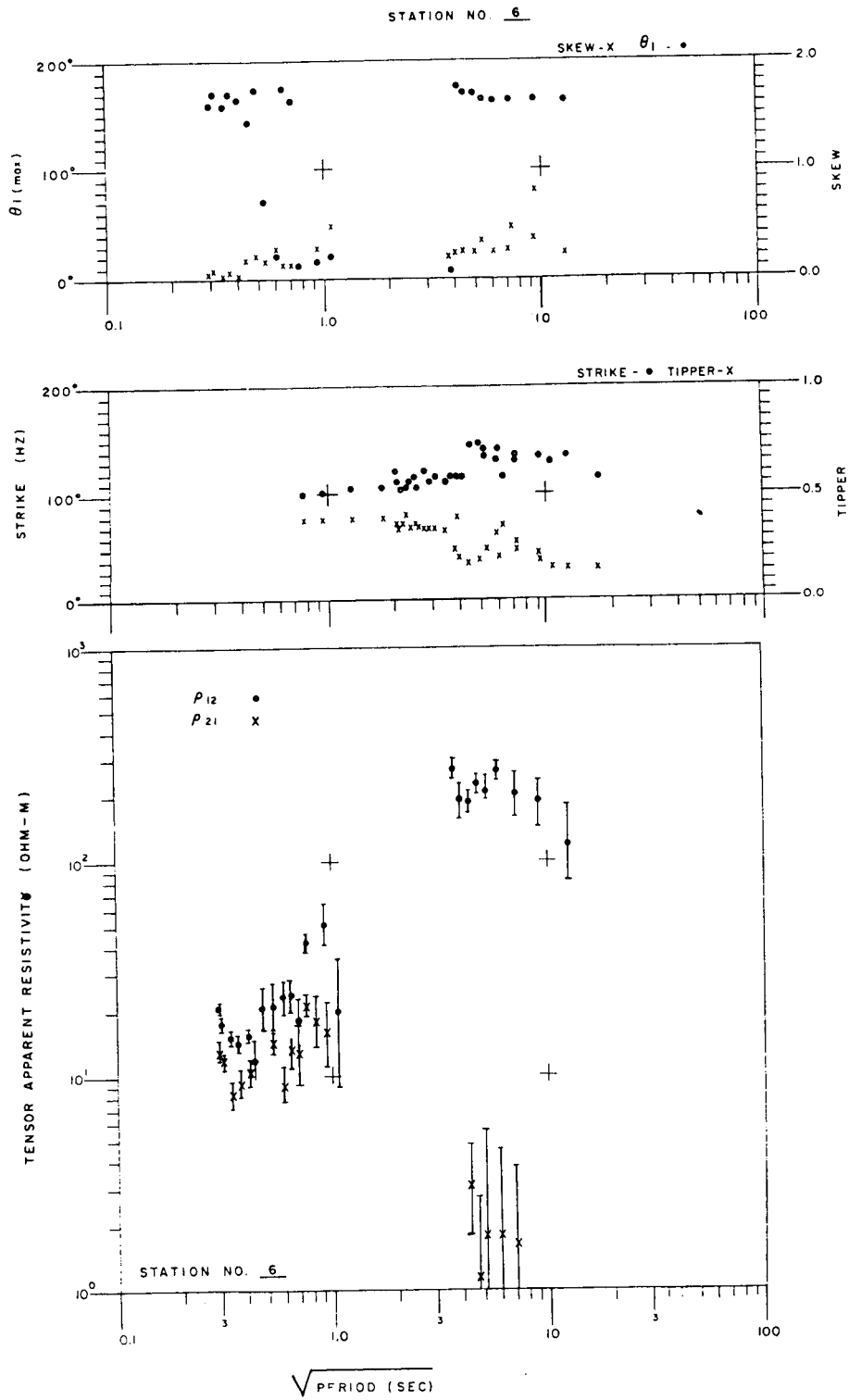
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Fig. II-10



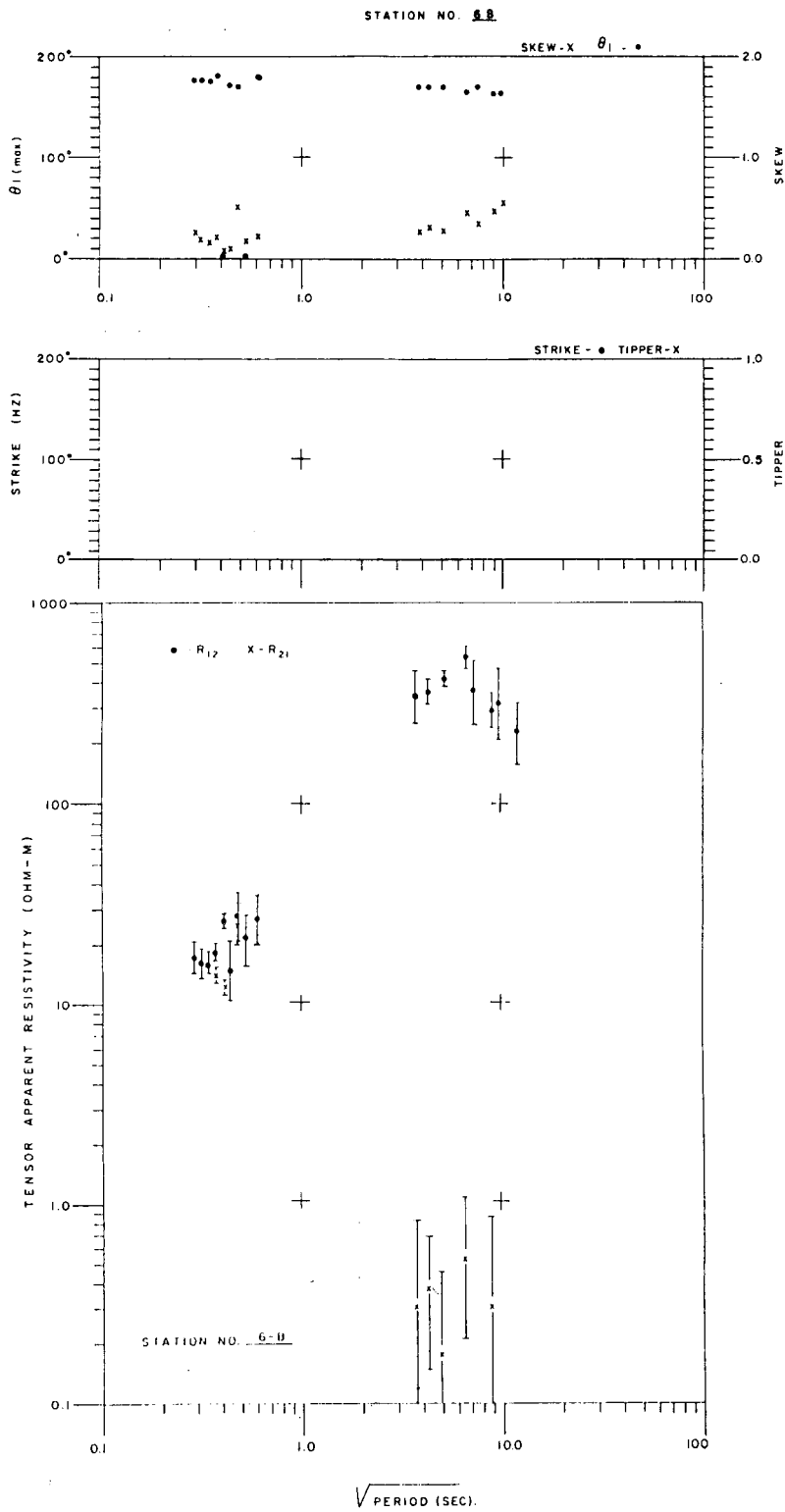
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Fig. II-11



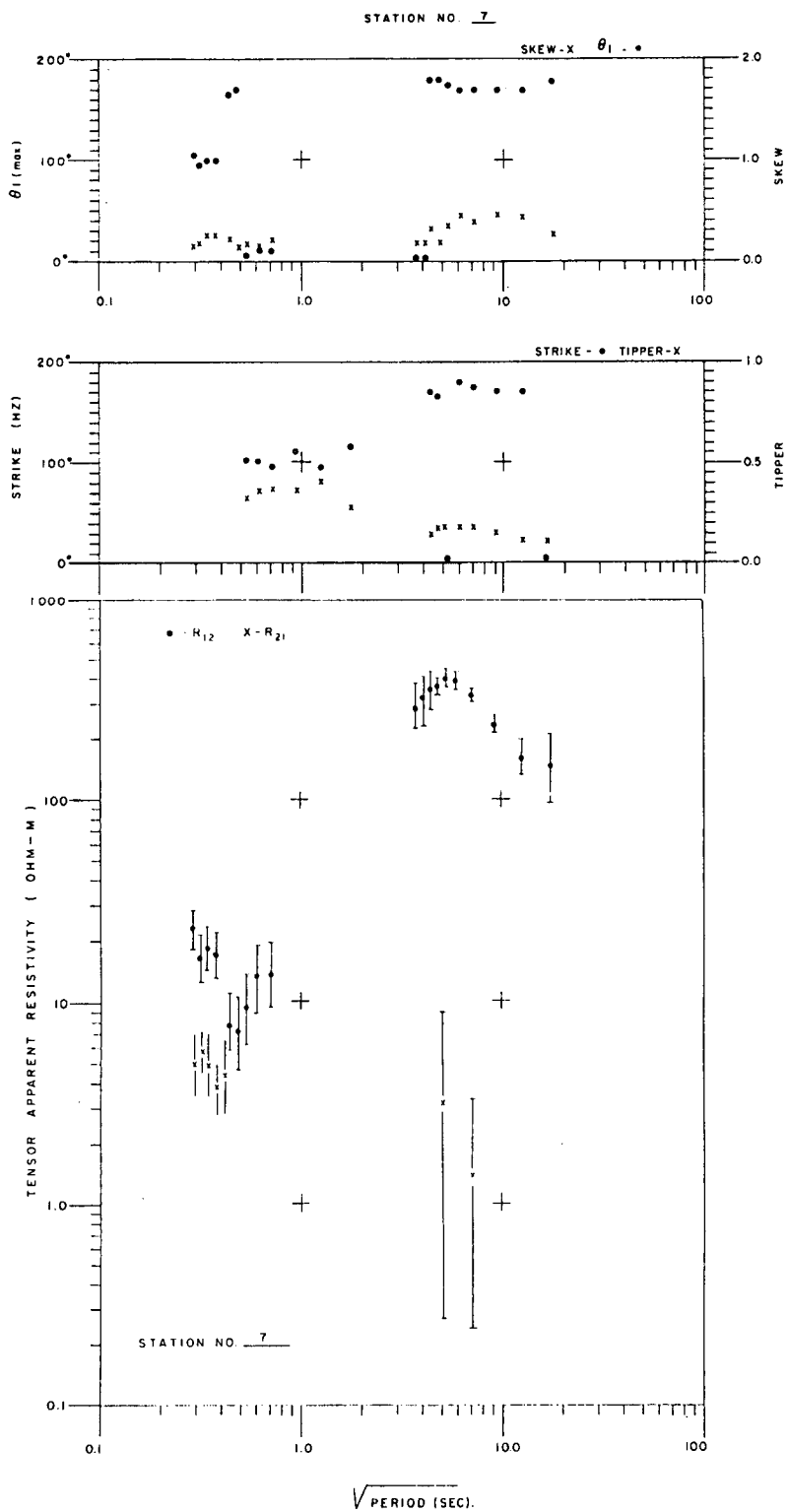
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Fig. II-12



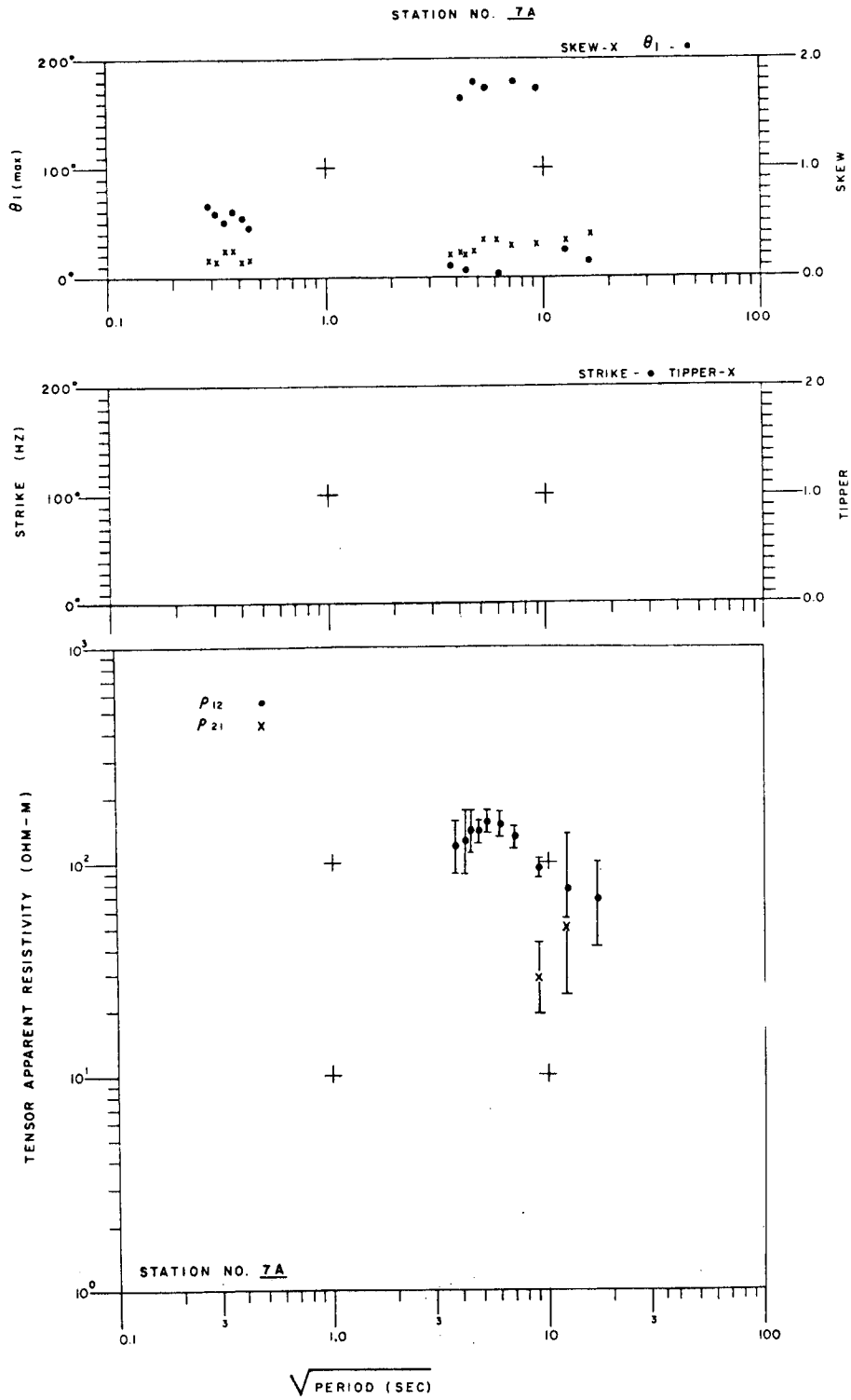
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Fig. II-13



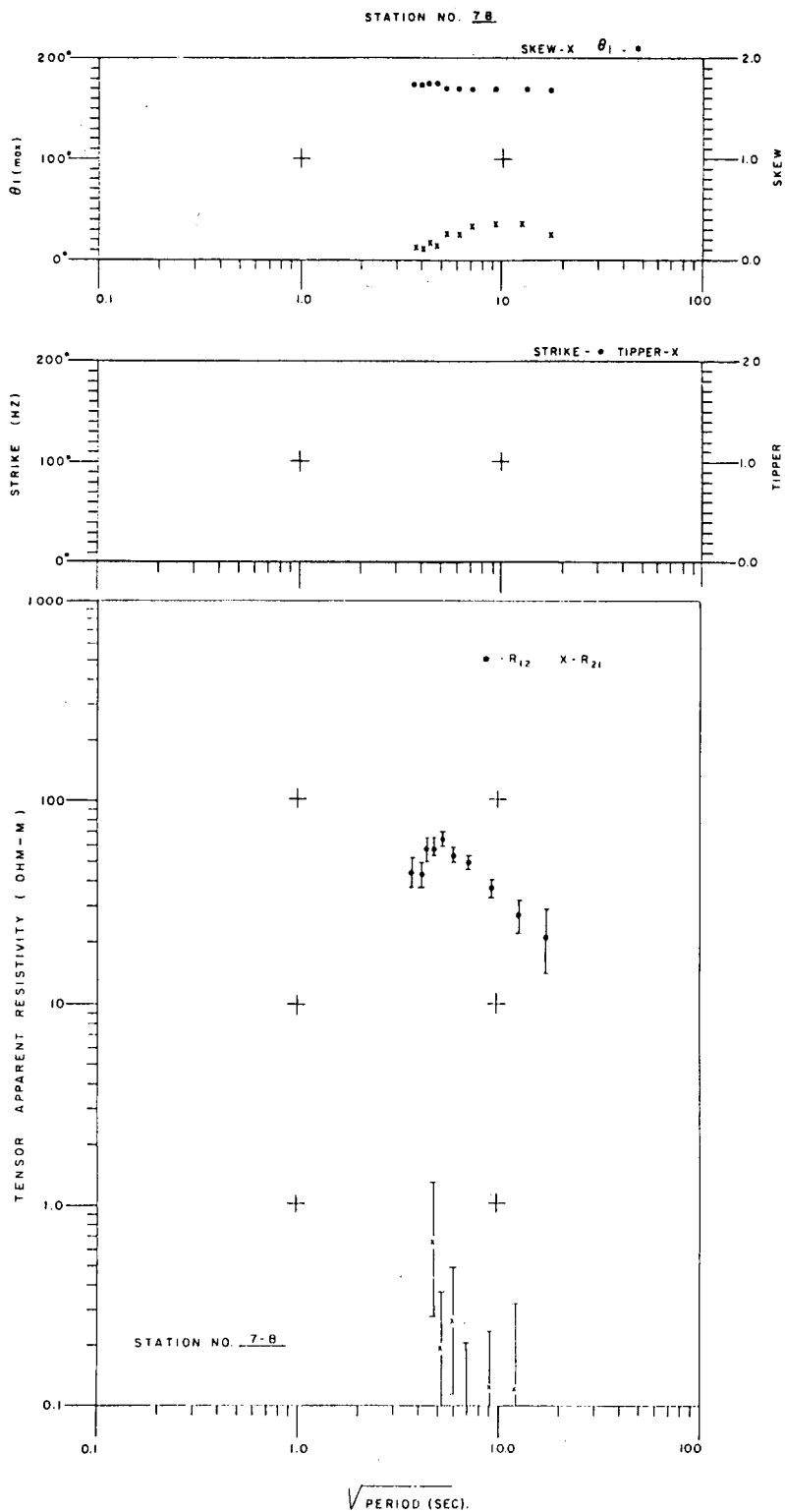
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Fig. II-14



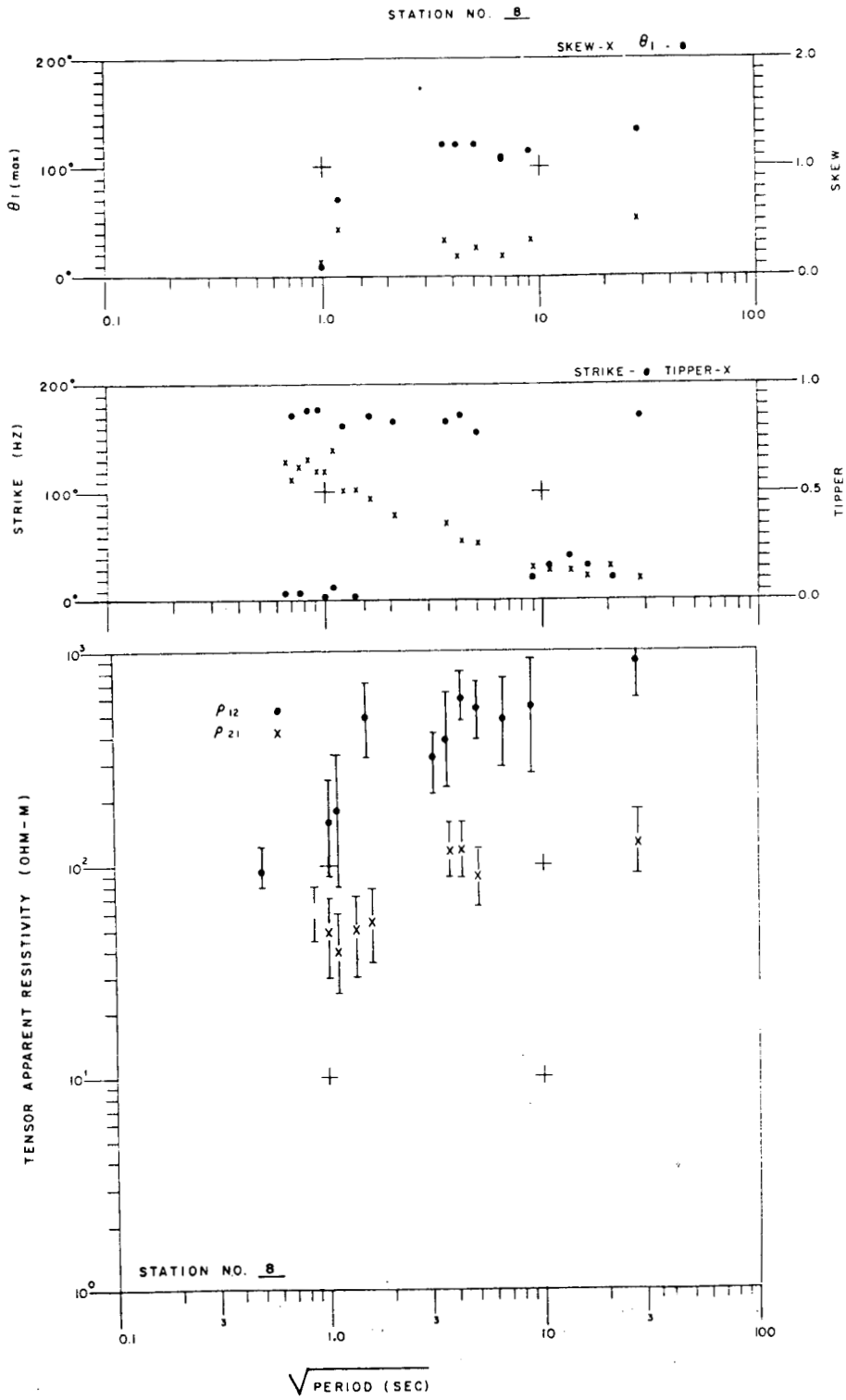
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Fig. II-15



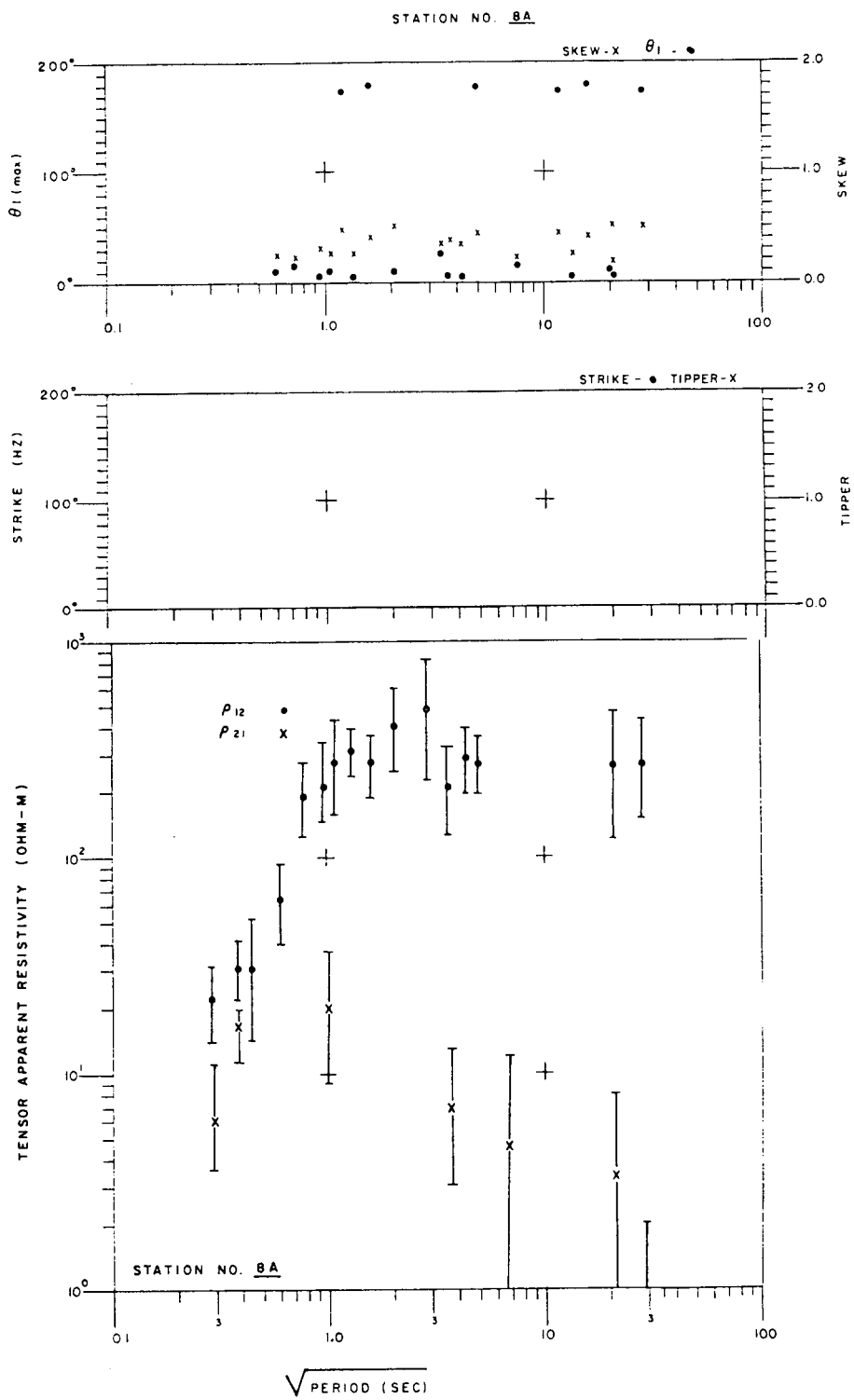
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Fig. II-16



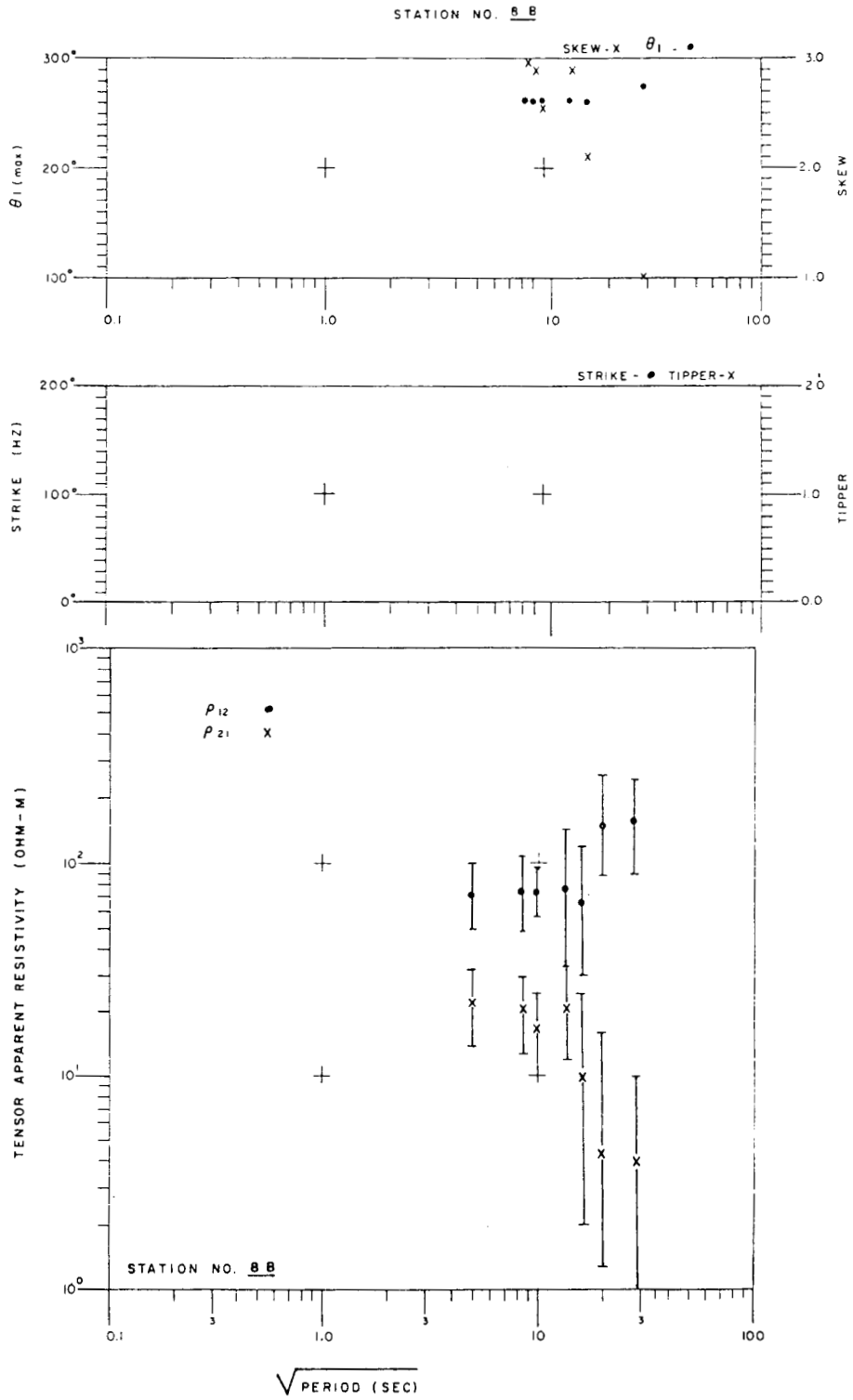
XBL 784-8122

Fig. II-17



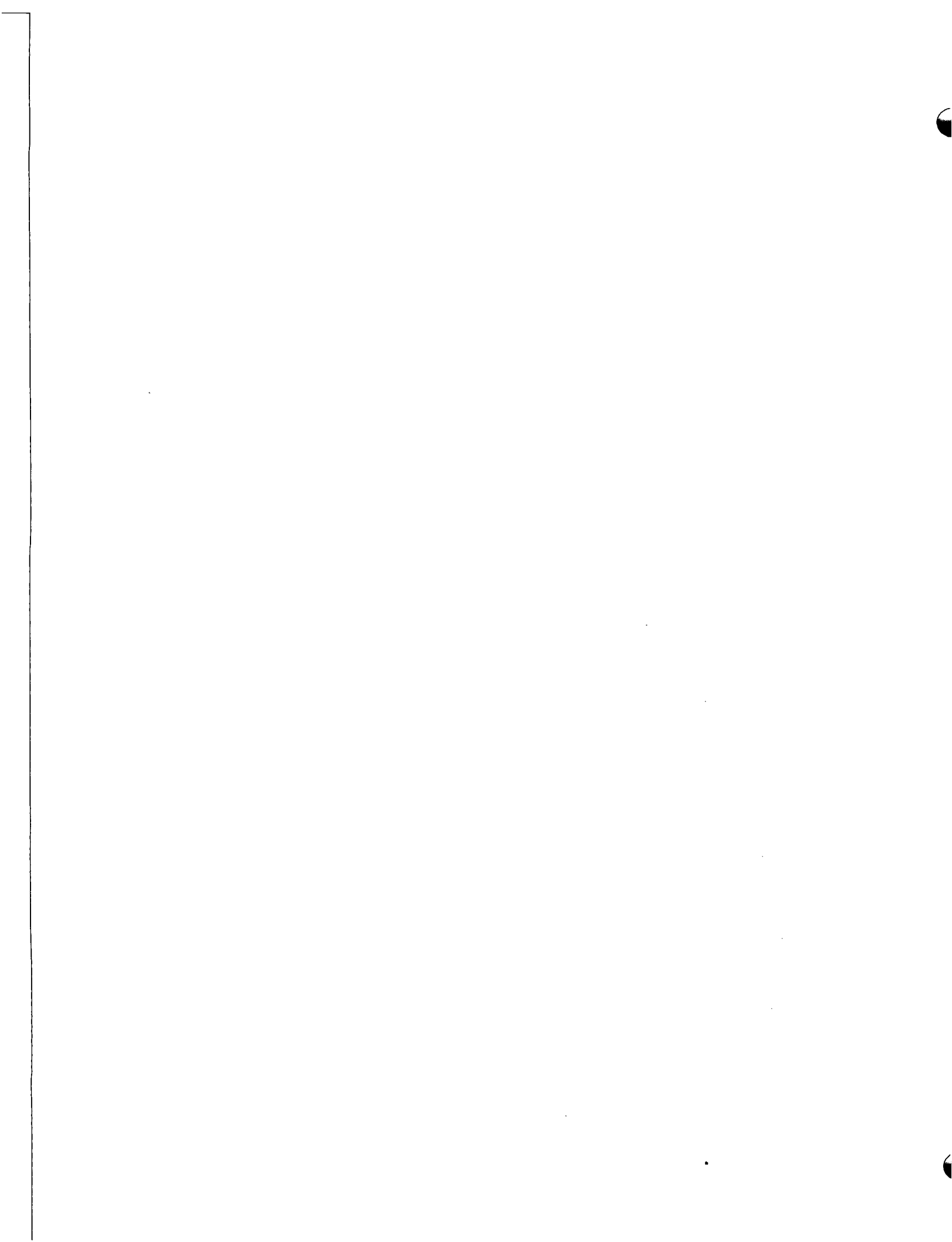
XBL 784-8131

Fig. II-18



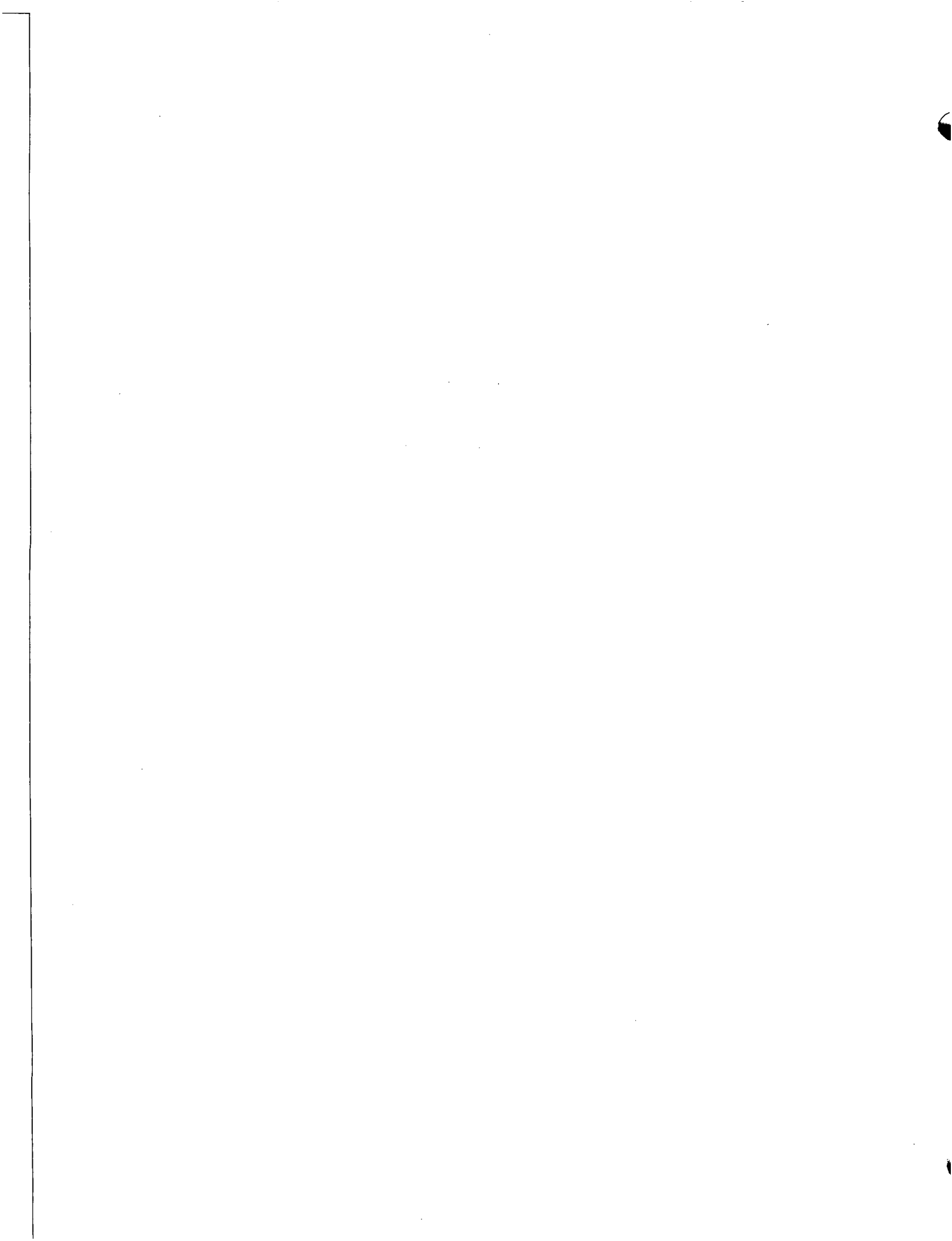
XBL 784-8123

Fig. II-19

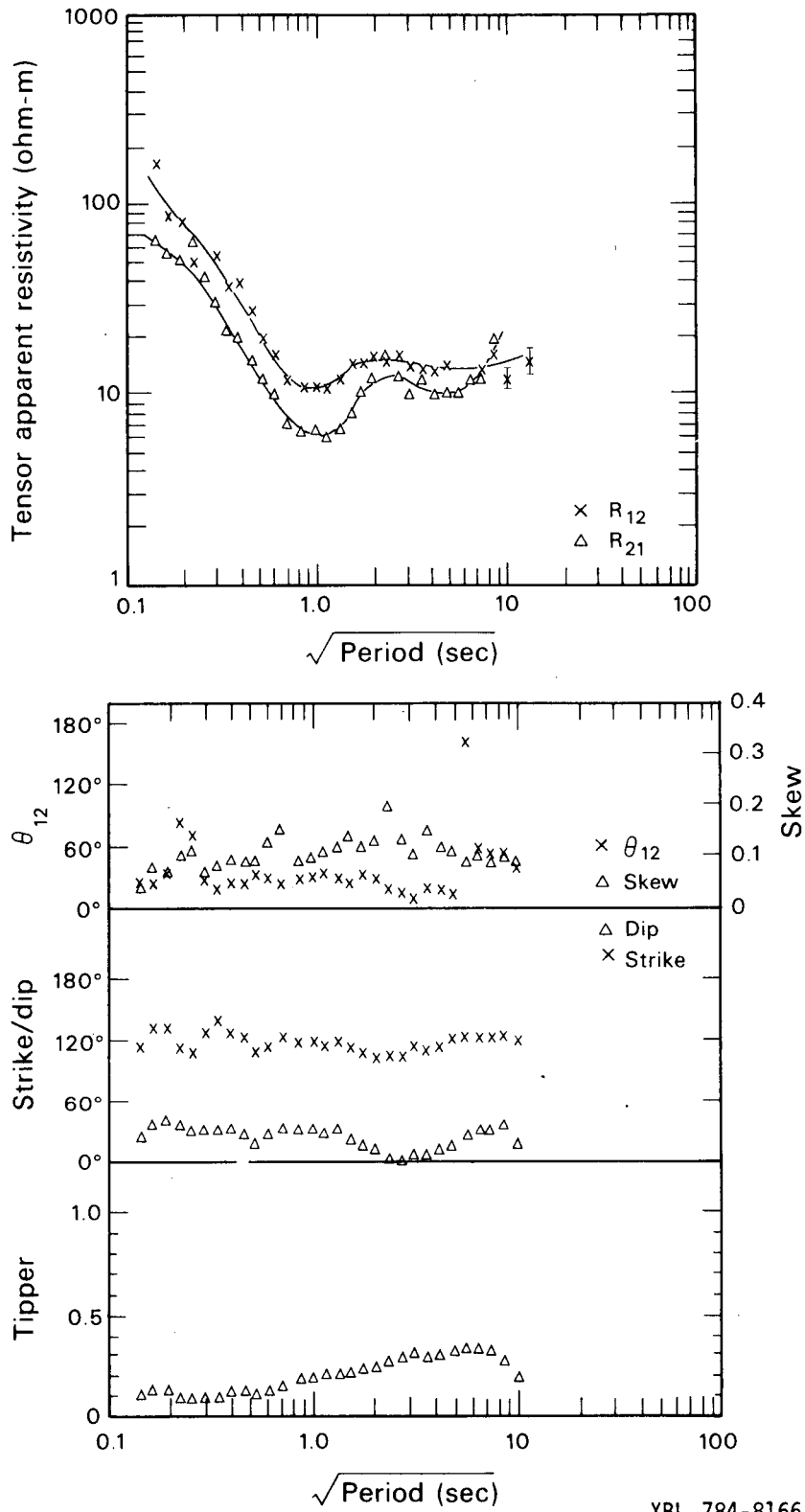


APPENDIX III

PHASE II, MT STATION RESULTS



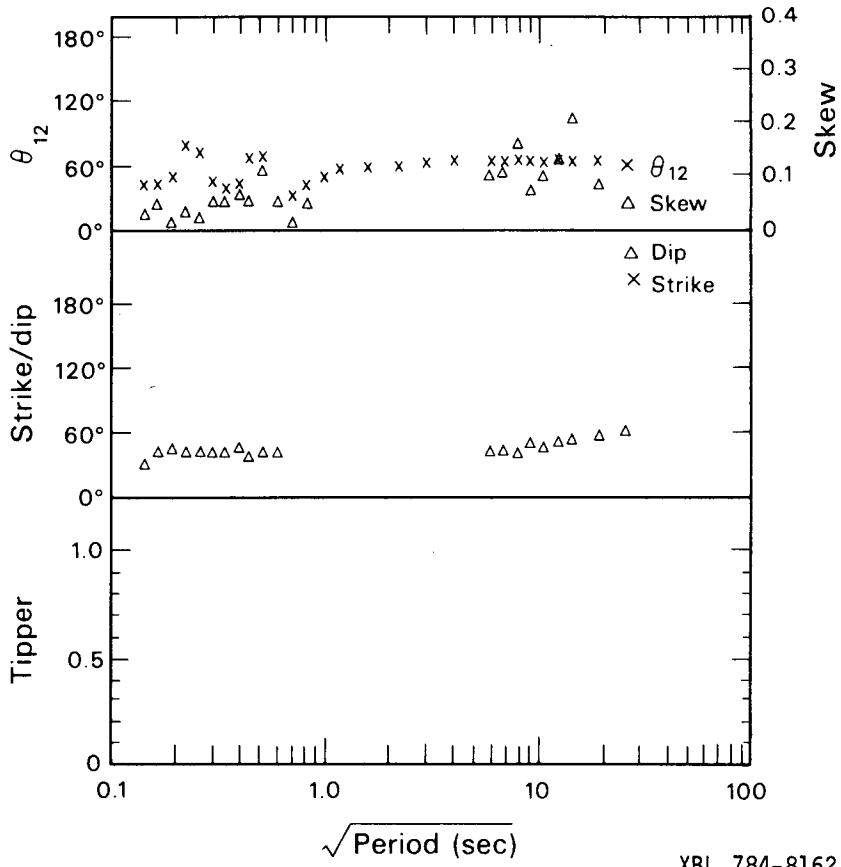
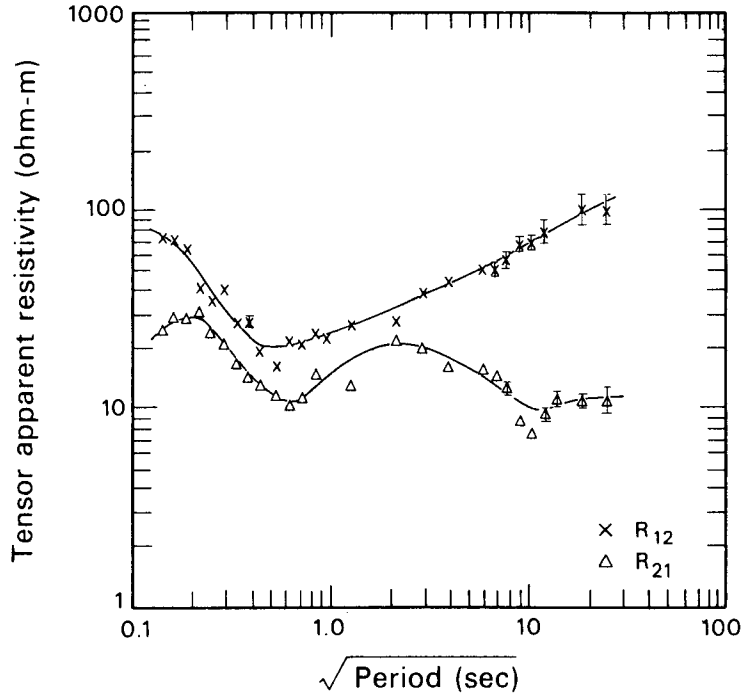
STATION I



XBL 784-8166

Fig. III-1

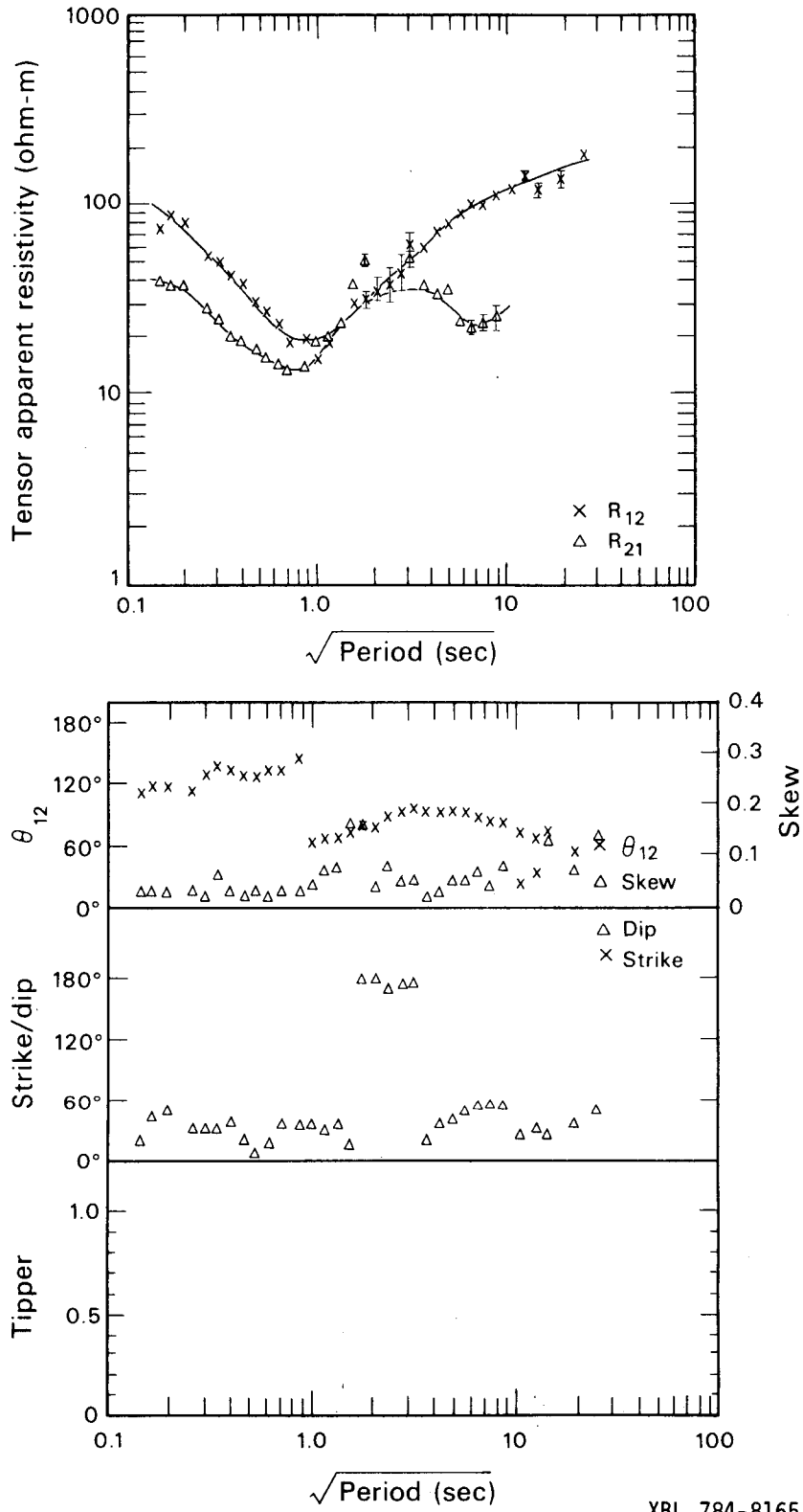
STATION 1A



XBL 784-8162

Fig. III-2

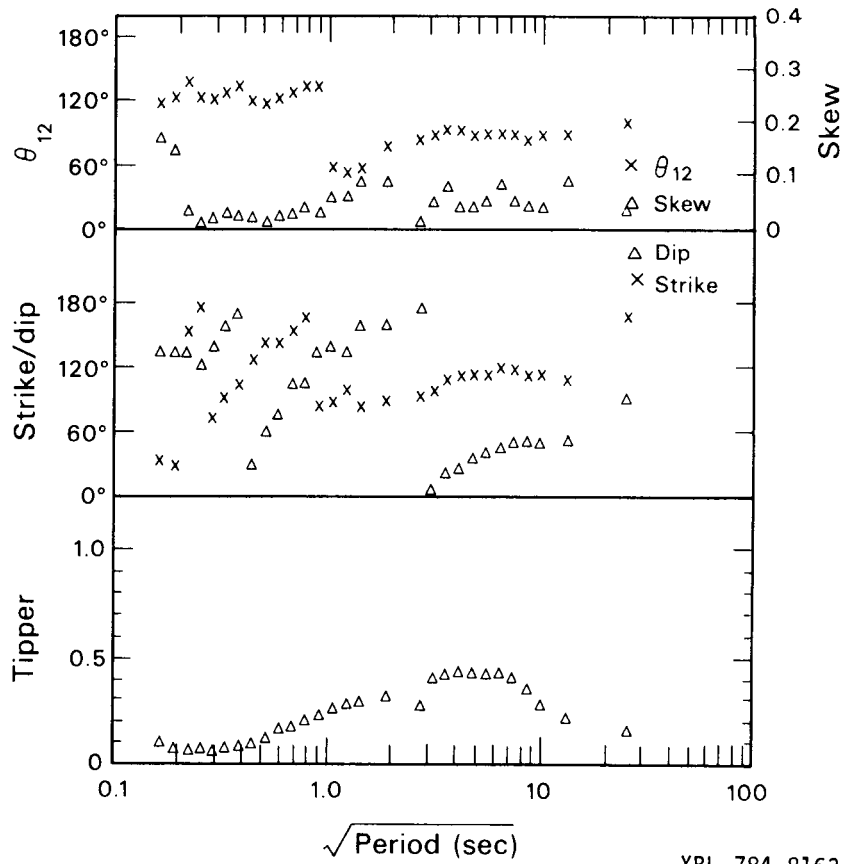
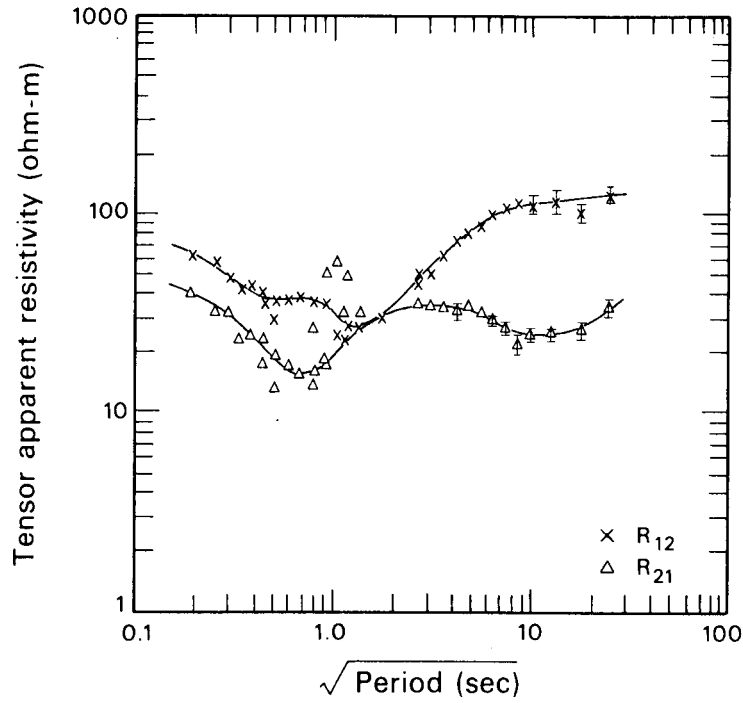
STATION 1B



XBL 784-8165

Fig. III-3

STATION 2



XBL 784-8163

Fig. III-4

STATION 2A

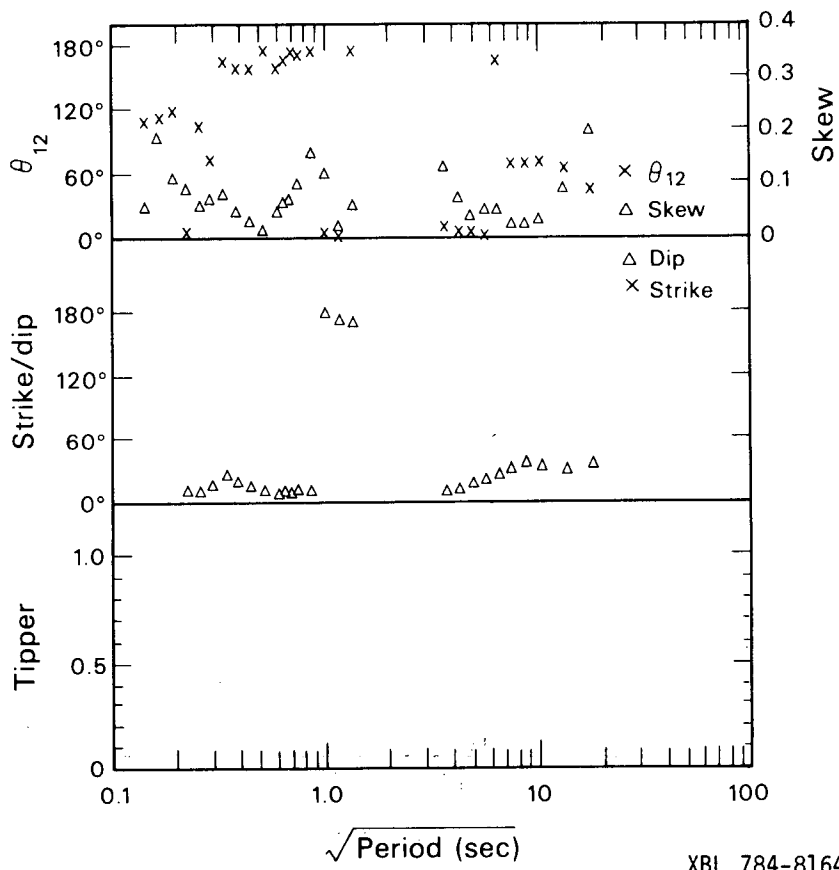
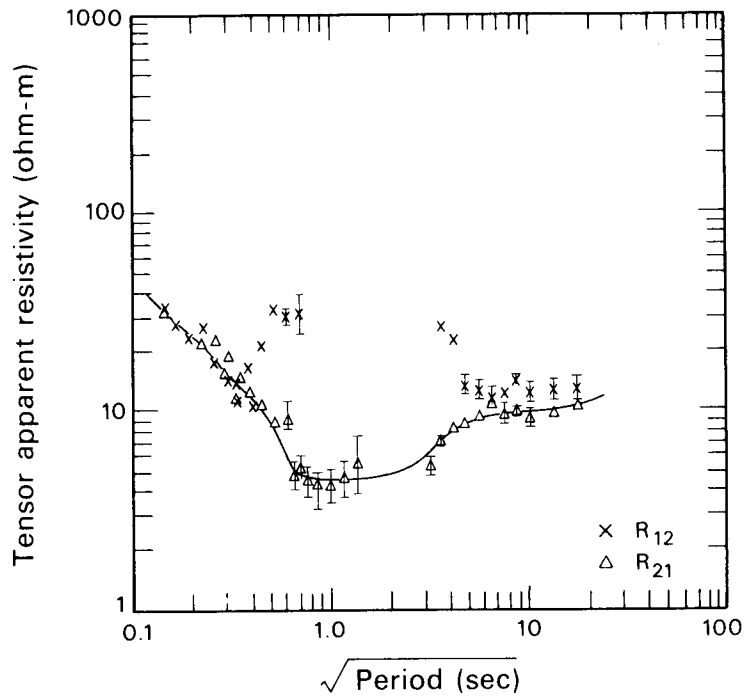
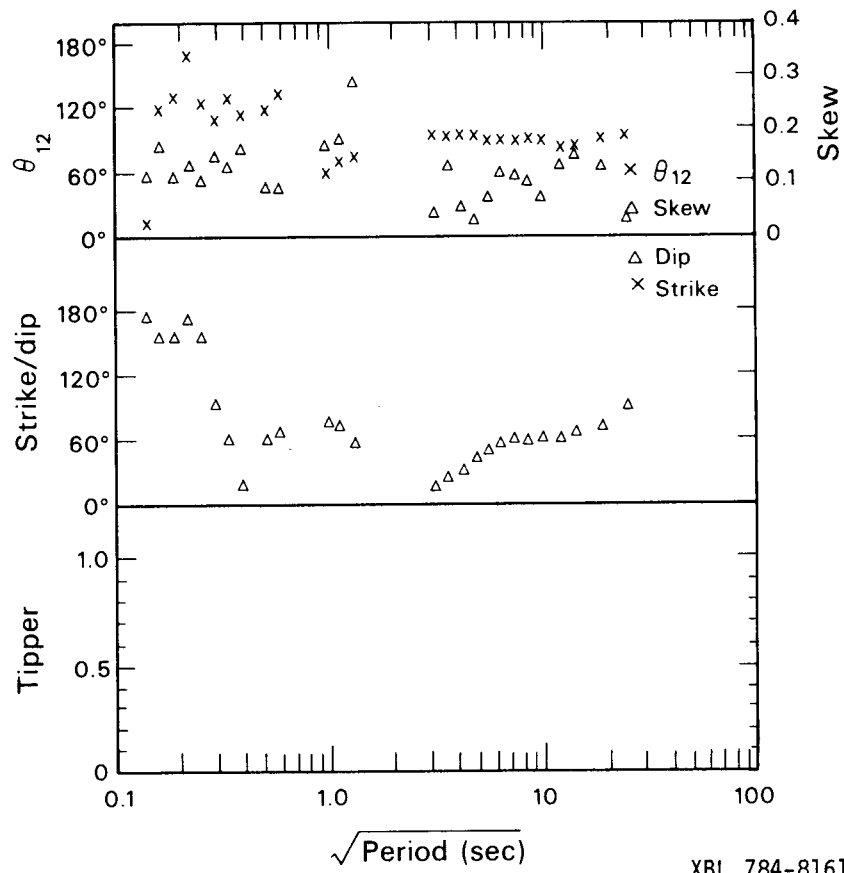
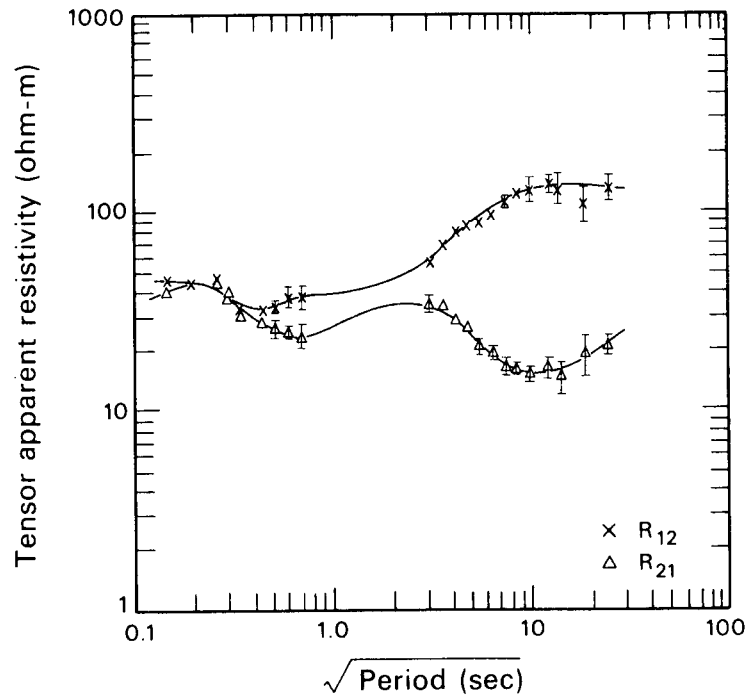


Fig. III-5

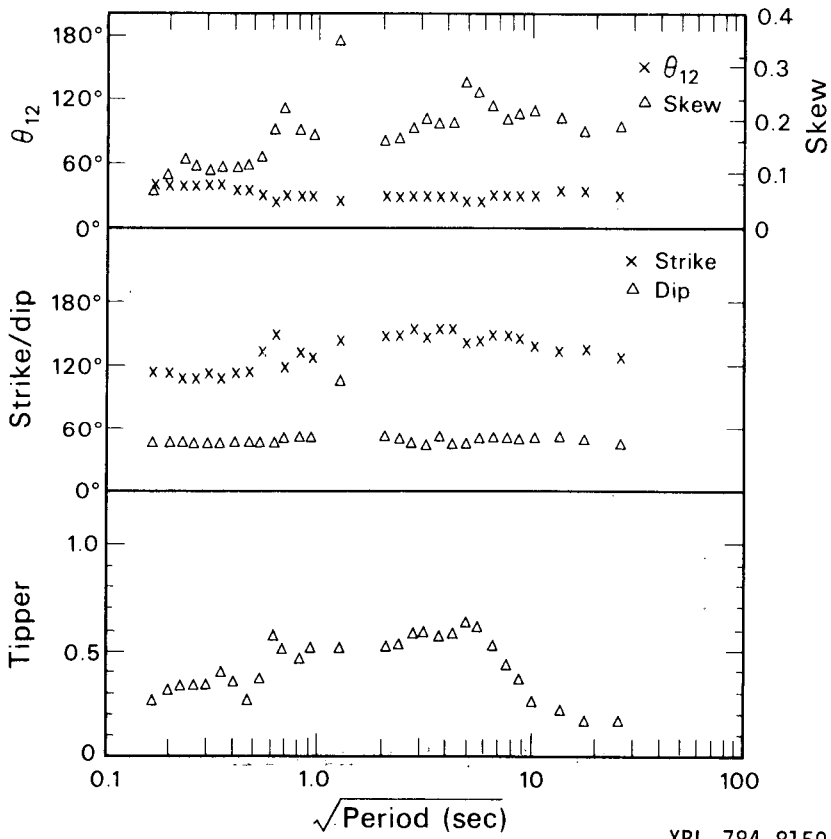
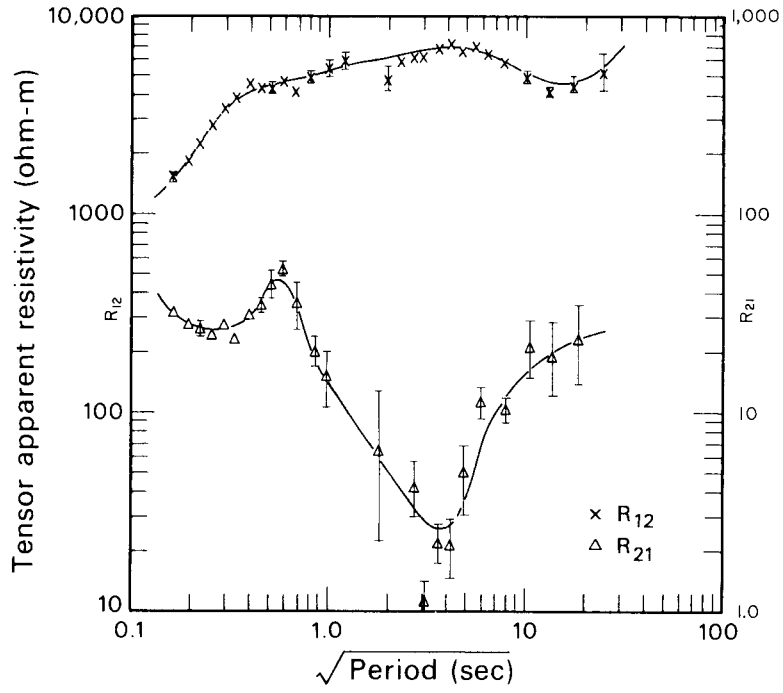
STATION 2B



XBL 784-8161

Fig. III-6

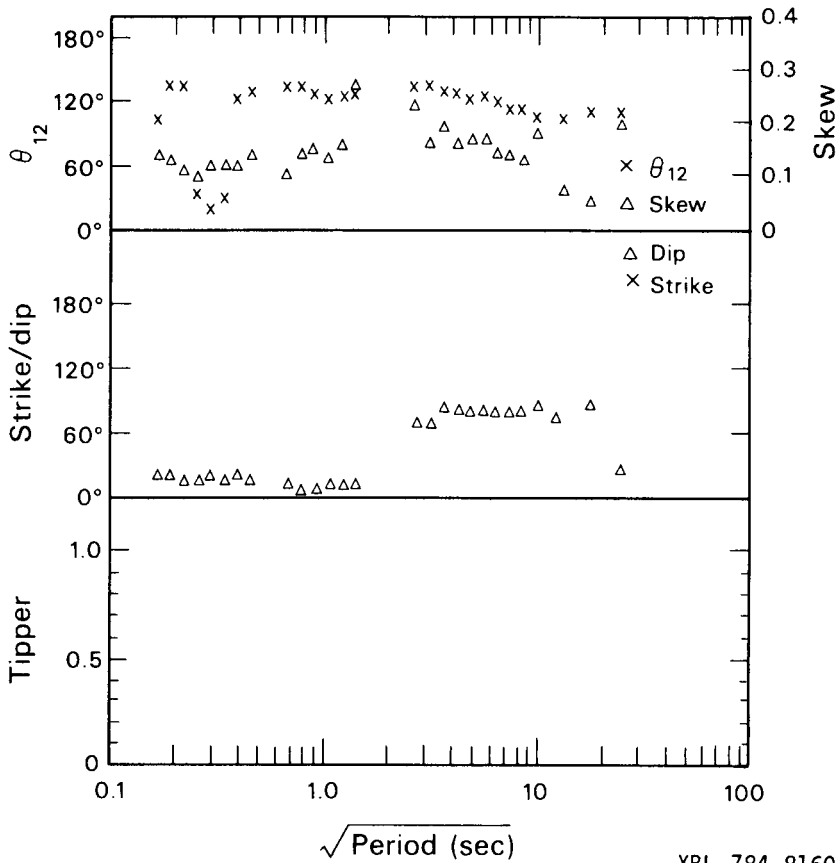
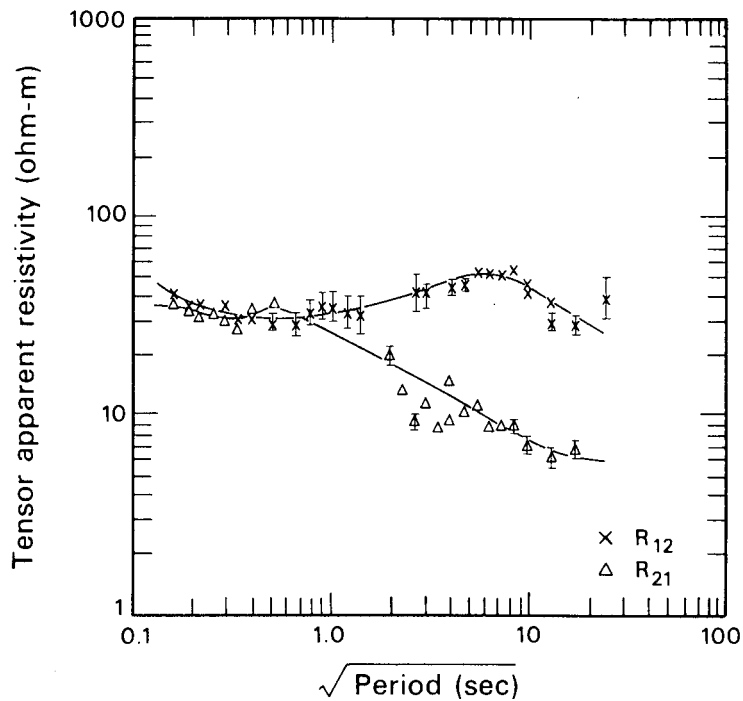
STATION 3



XBL 784-8159

Fig. III-7

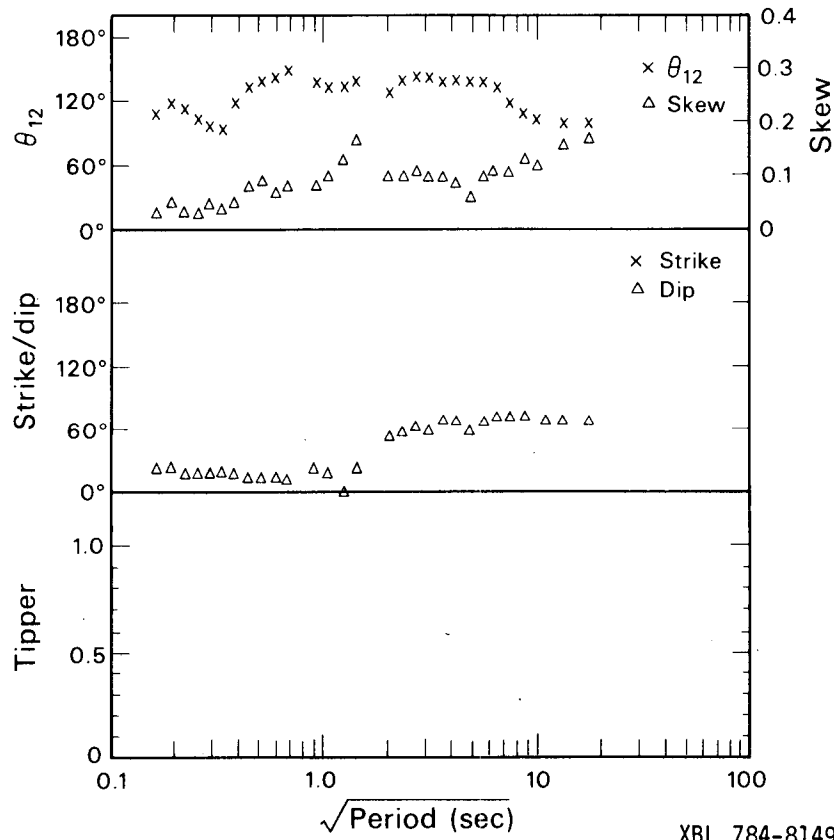
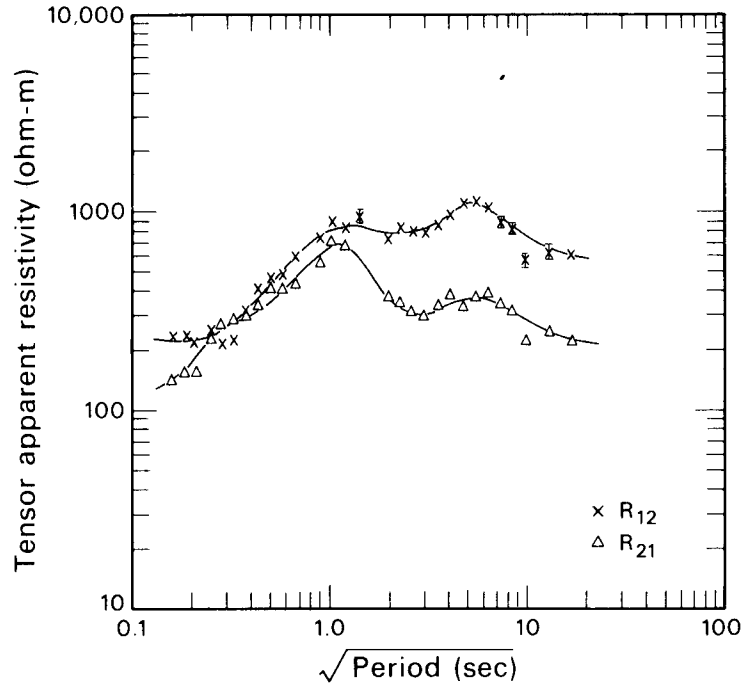
STATION 3A



XBL 784-8160

Fig. III-8

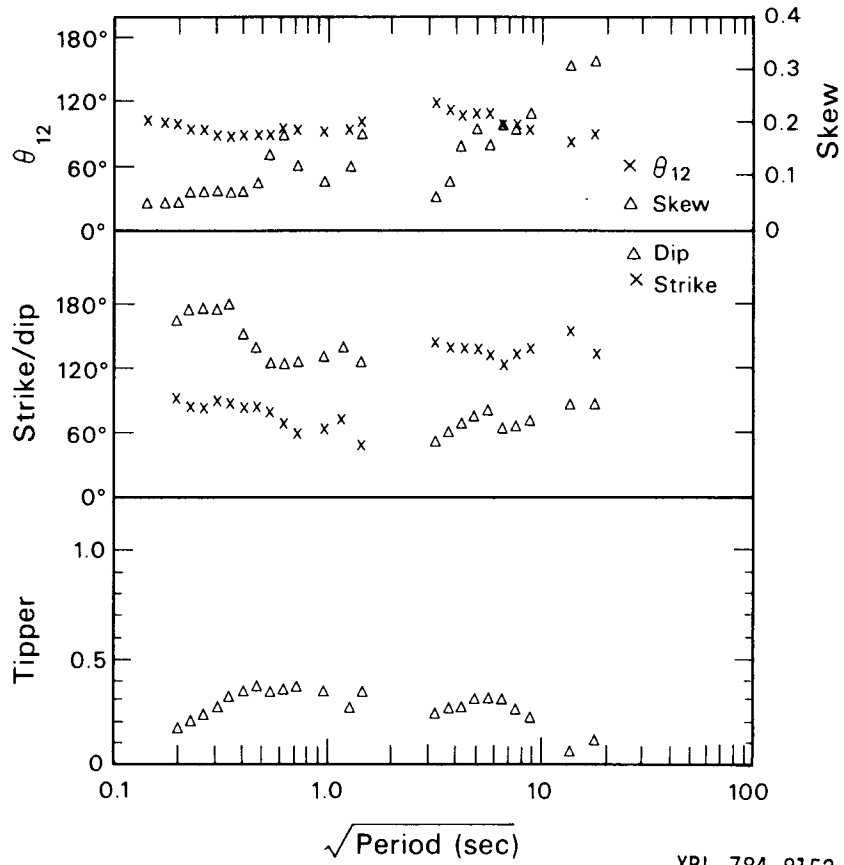
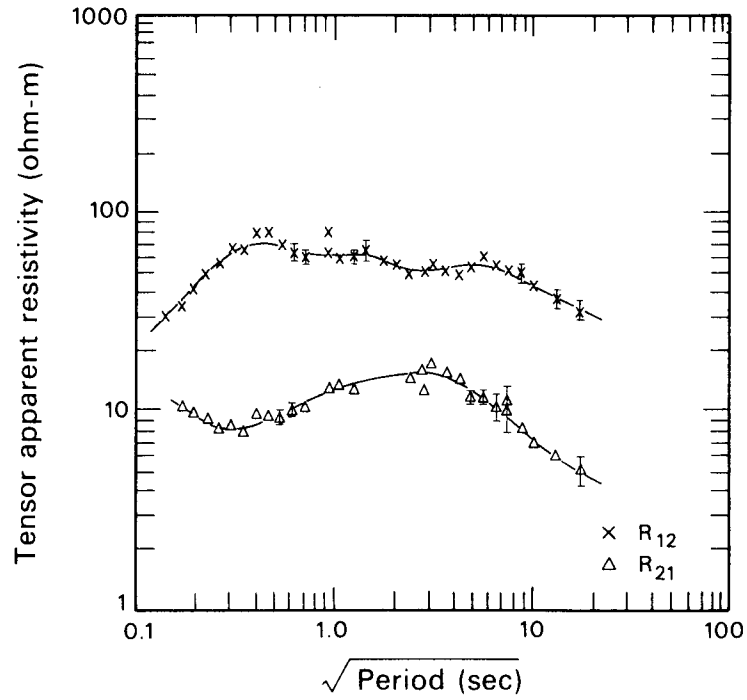
STATION 3B



XBL 784-8149

Fig. III-9

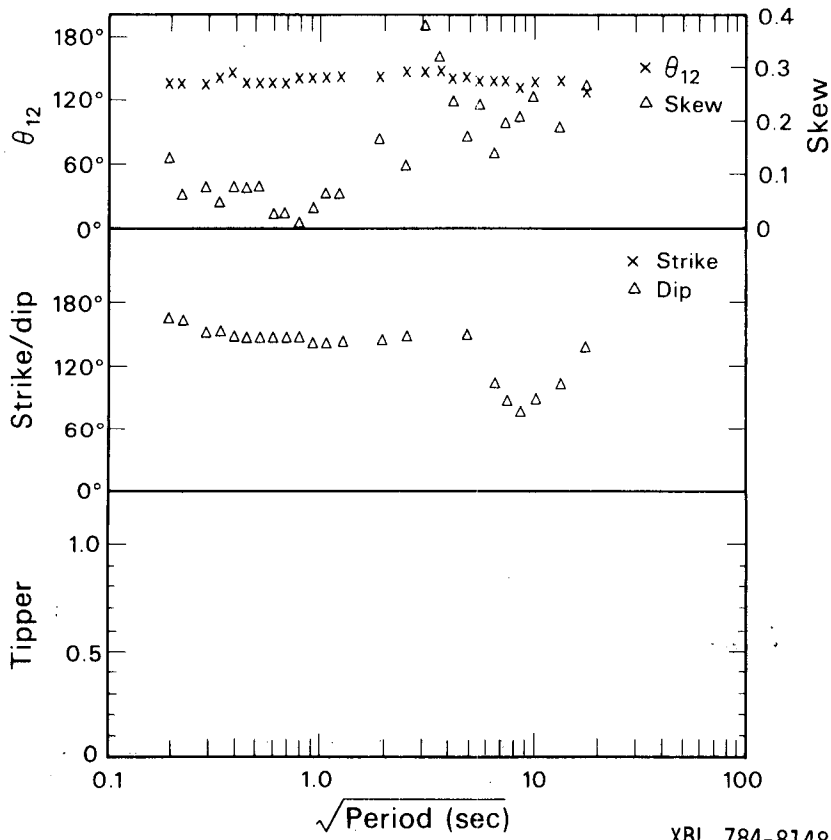
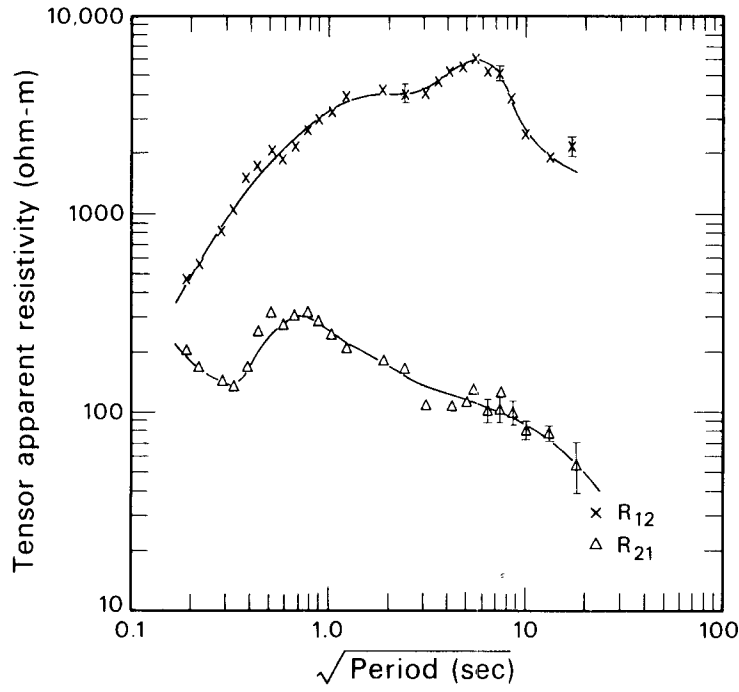
STATION 4



XBL 784-8152

Fig. III-10

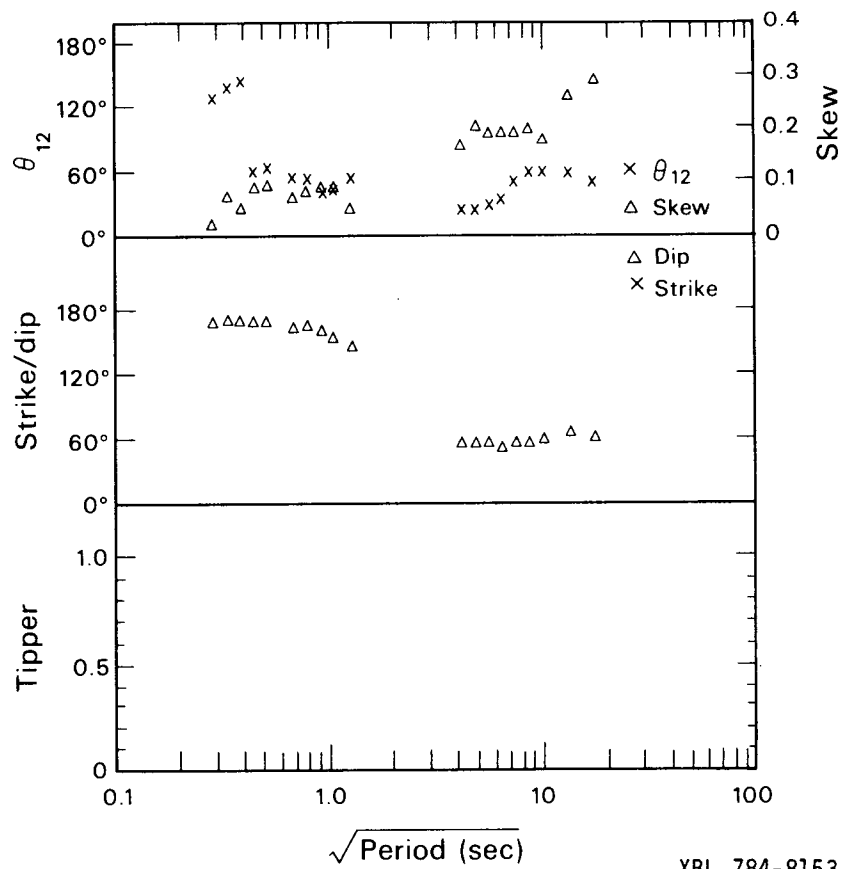
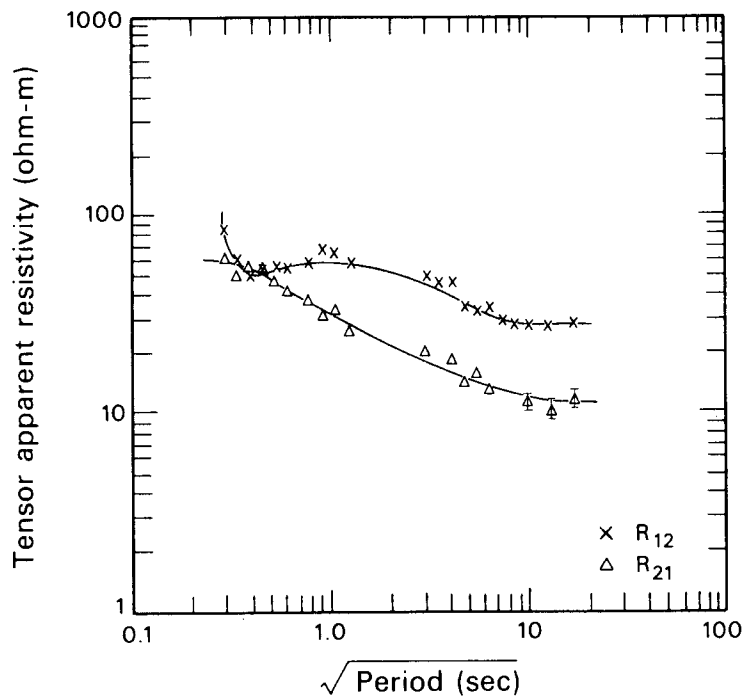
STATION 4A



XBL 784-8148

Fig. III-11

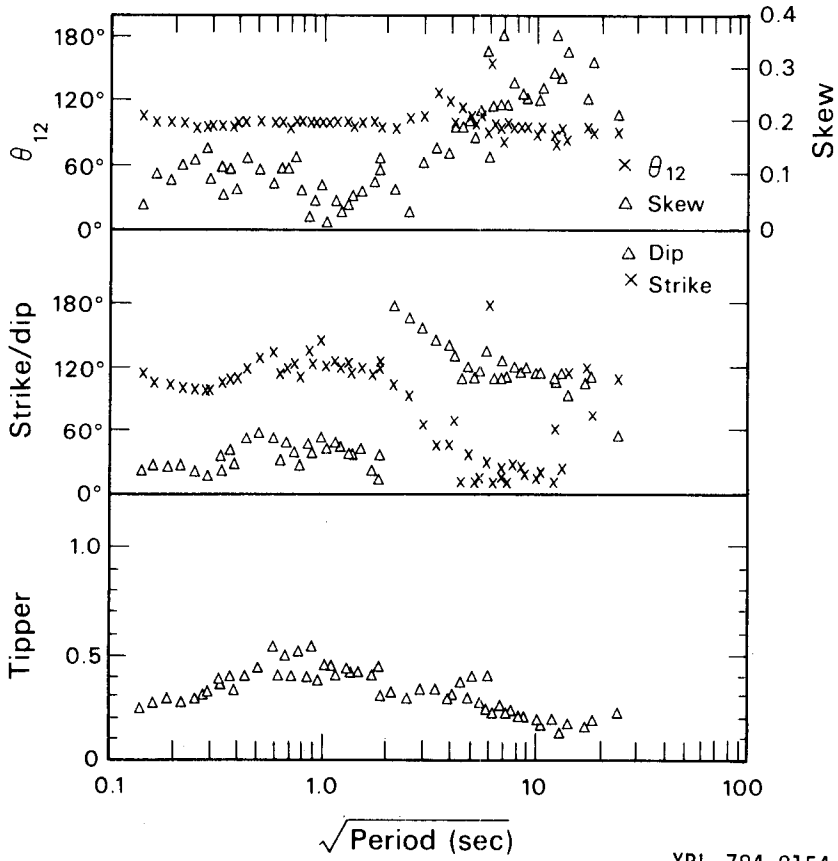
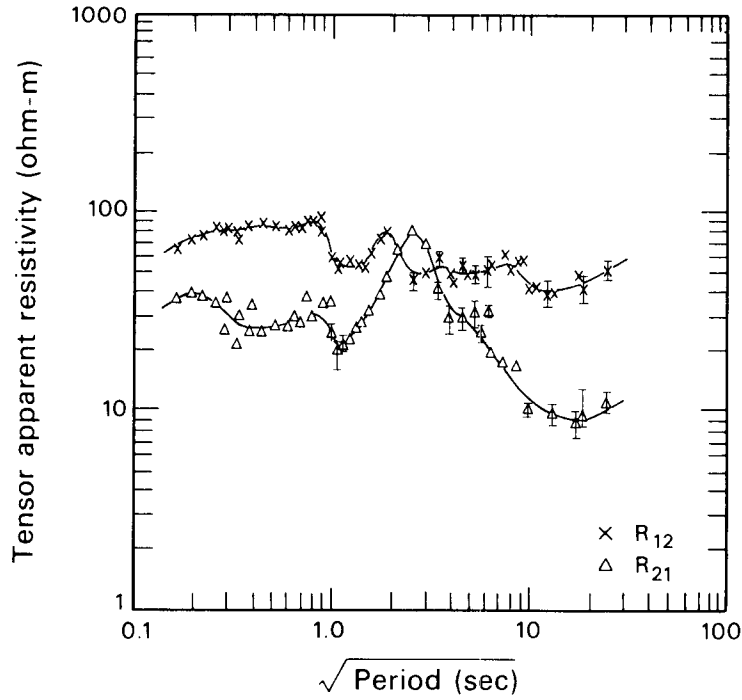
STATION 4B



XBL 784-8153

Fig. III-12

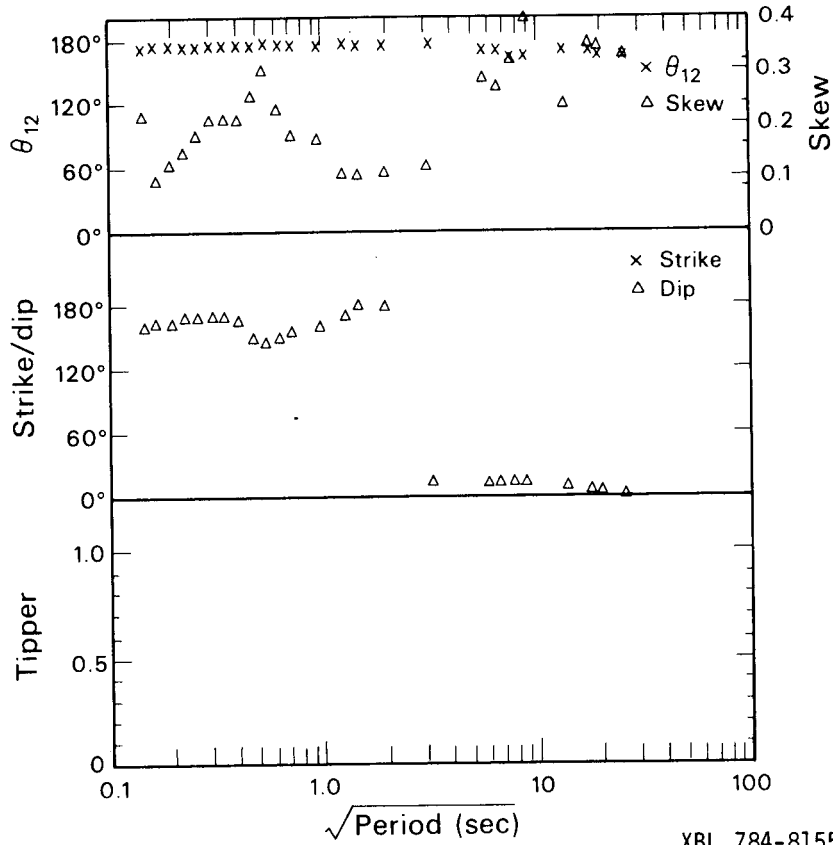
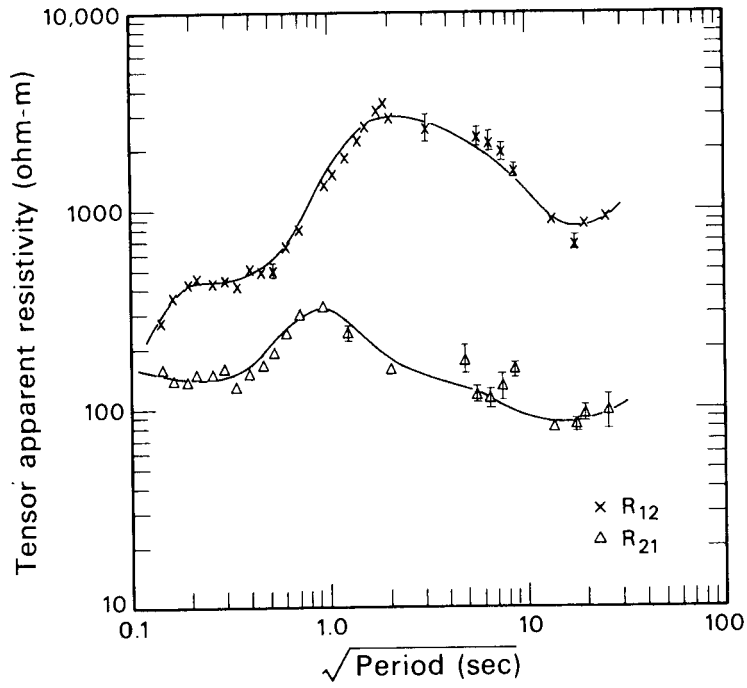
STATION 5



XBL 784-8154

Fig. III-13

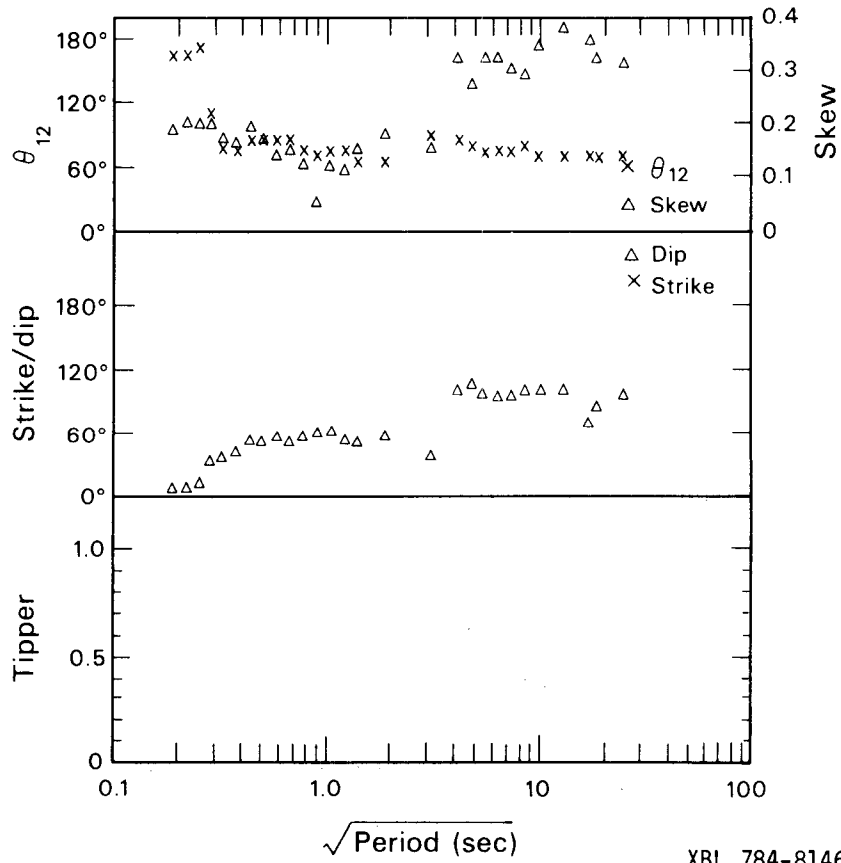
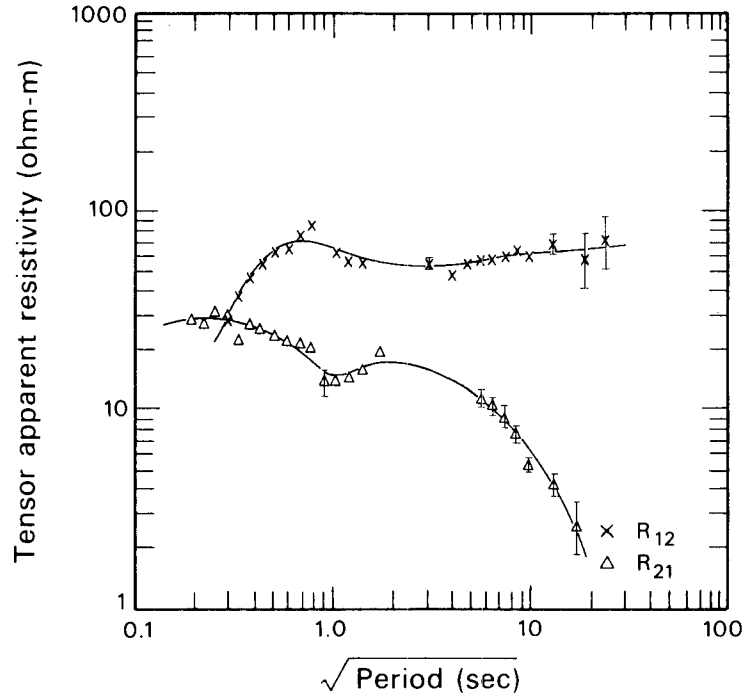
76
STATION 5A



XBL 784-8155

Fig. III-14

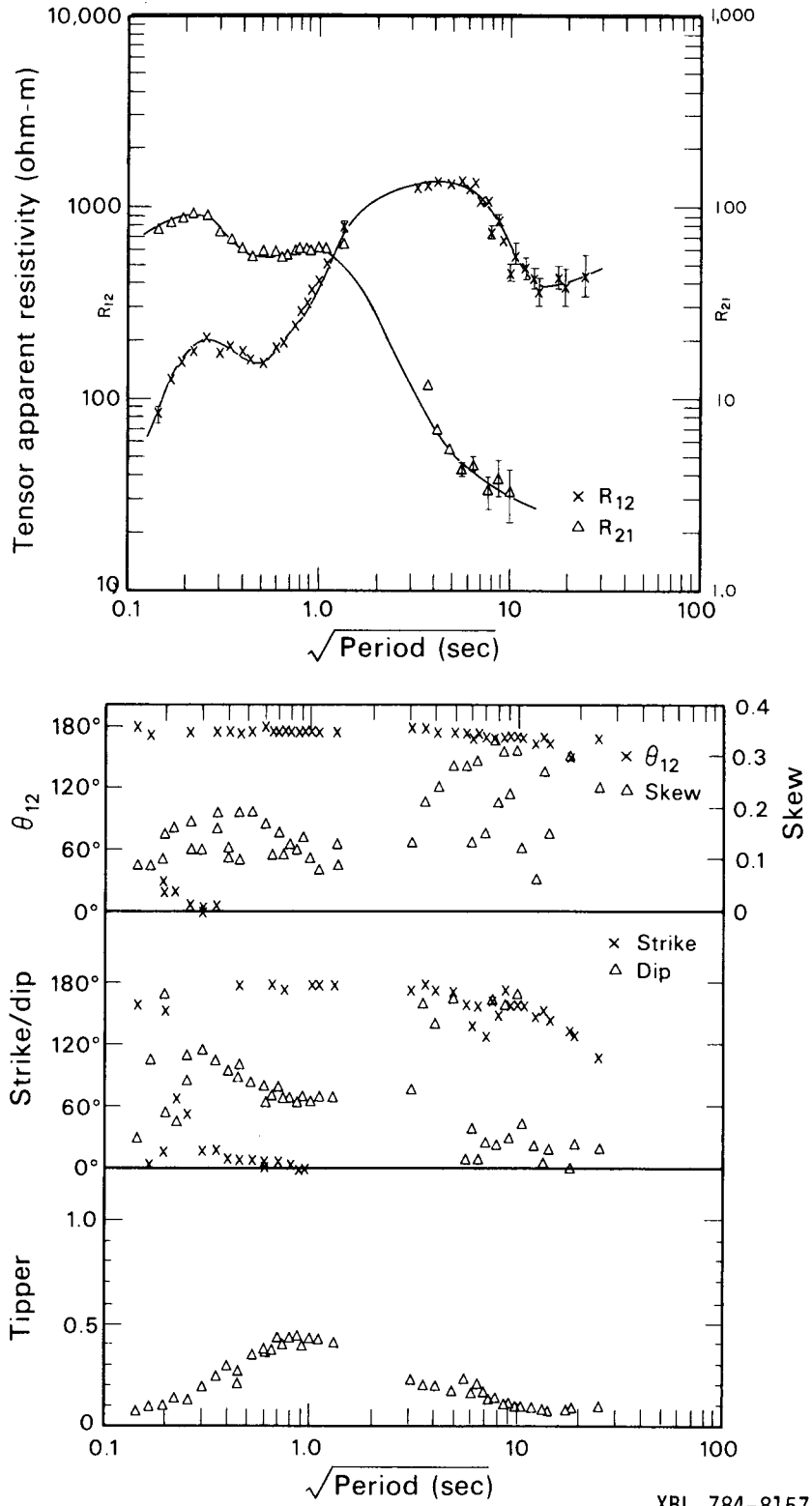
STATION 5B



XBL 784-8146

Fig. III-15

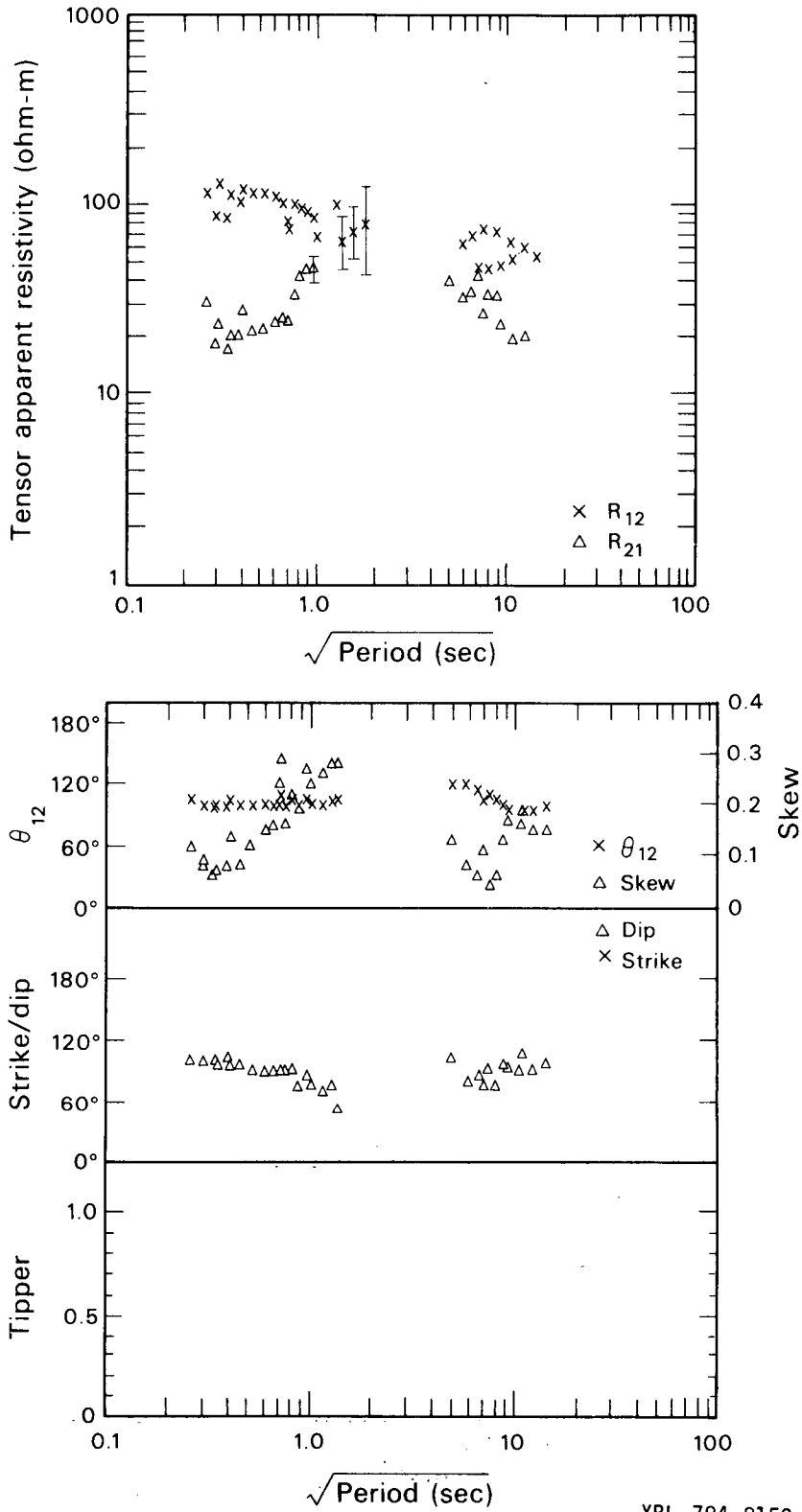
STATION 6



XBL 784-8157

Fig. III-16

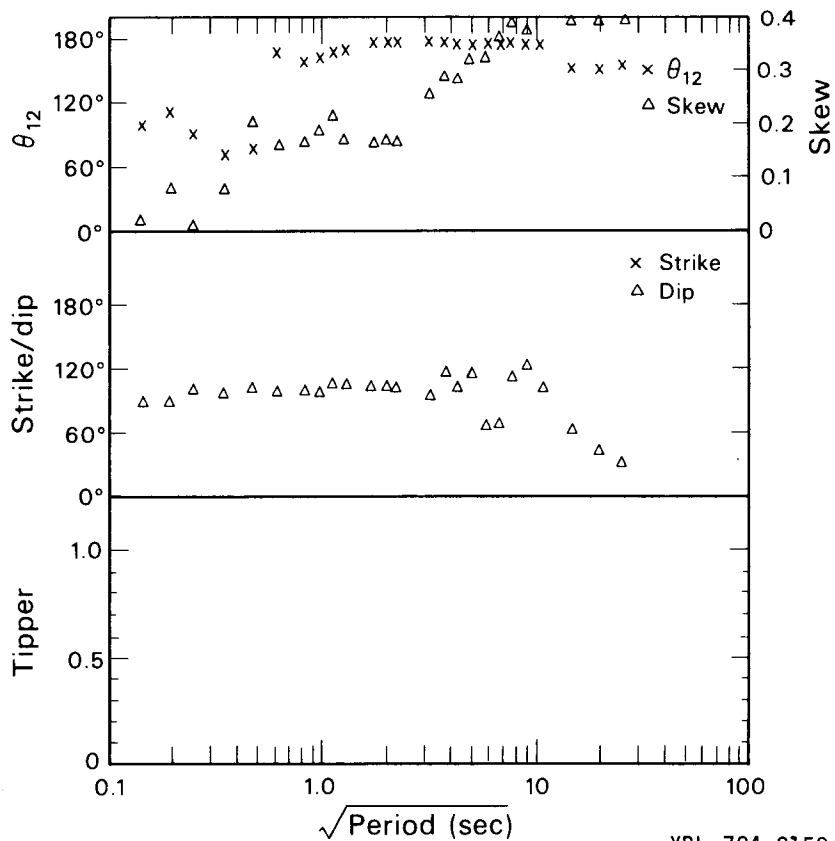
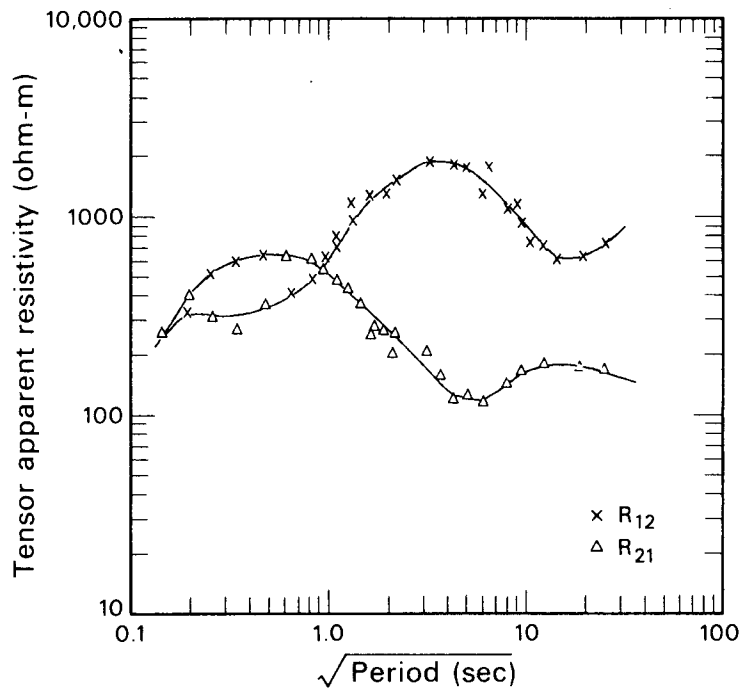
STATION 6A



XBL 784-8150

Fig. III-17

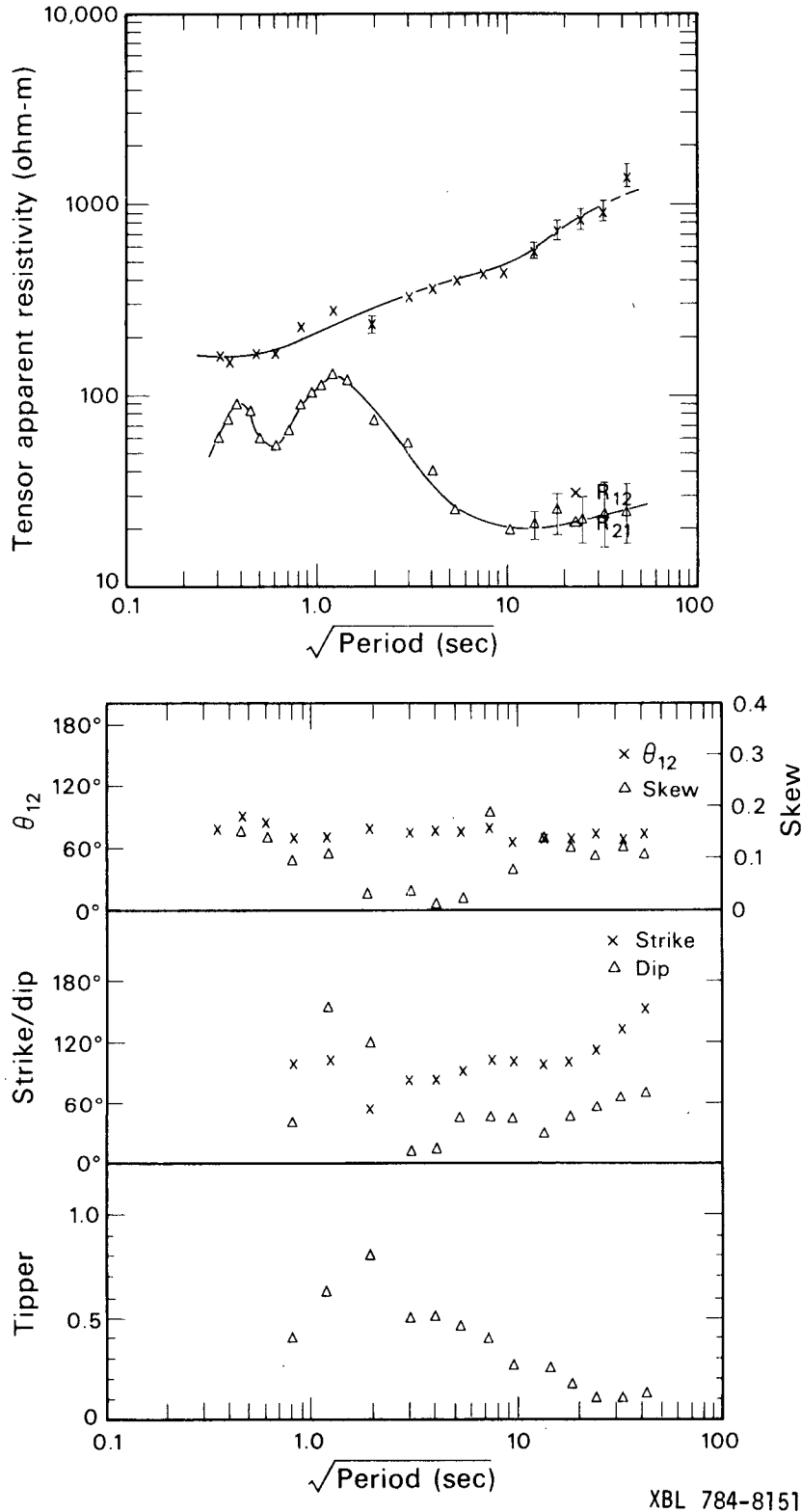
STATION 6B



XBL 784-8158

Fig. III-18

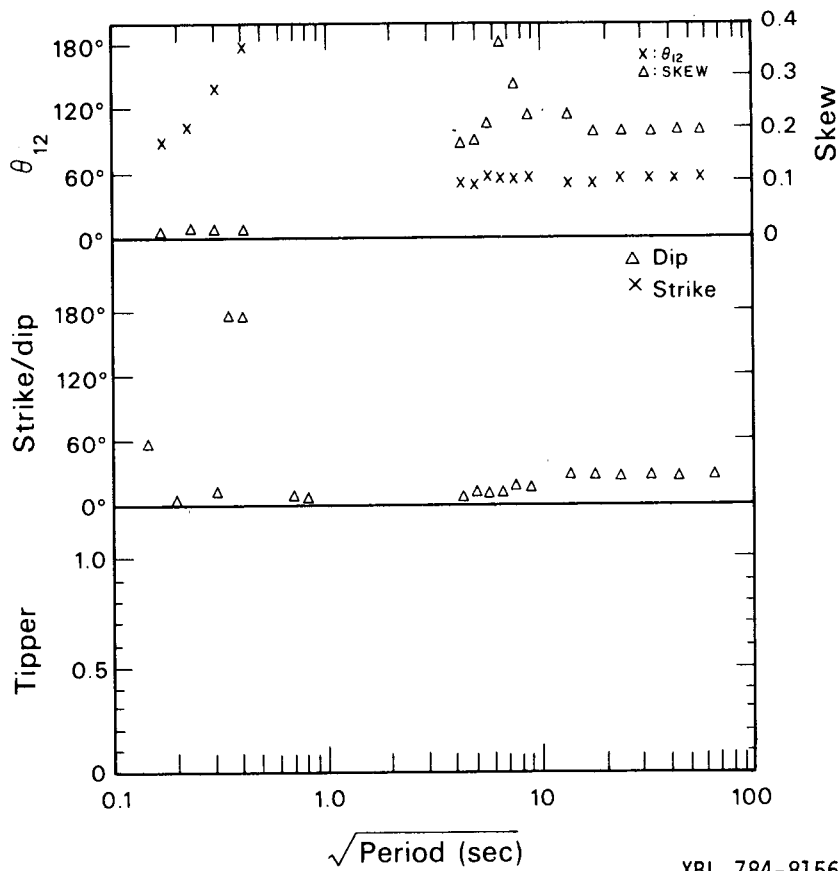
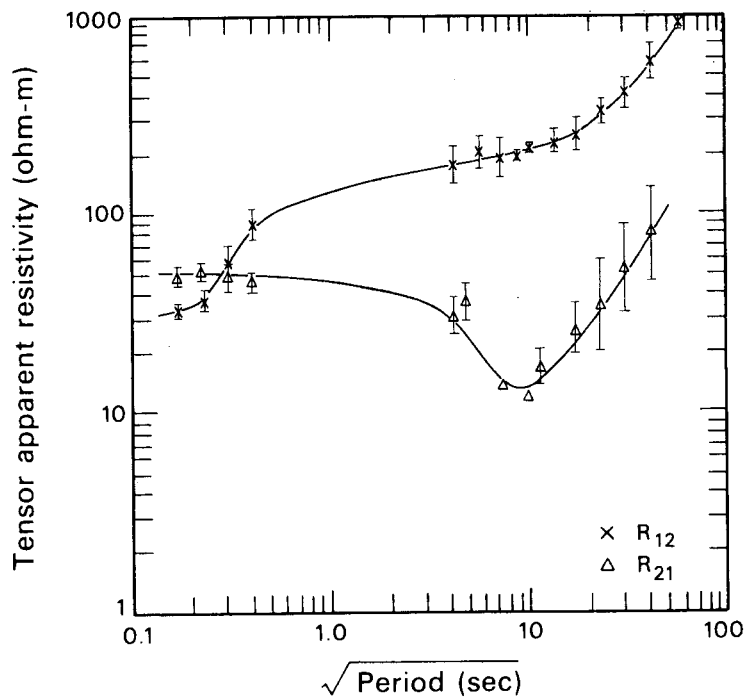
STATION 7



XBL 784-8151

Fig. III-19

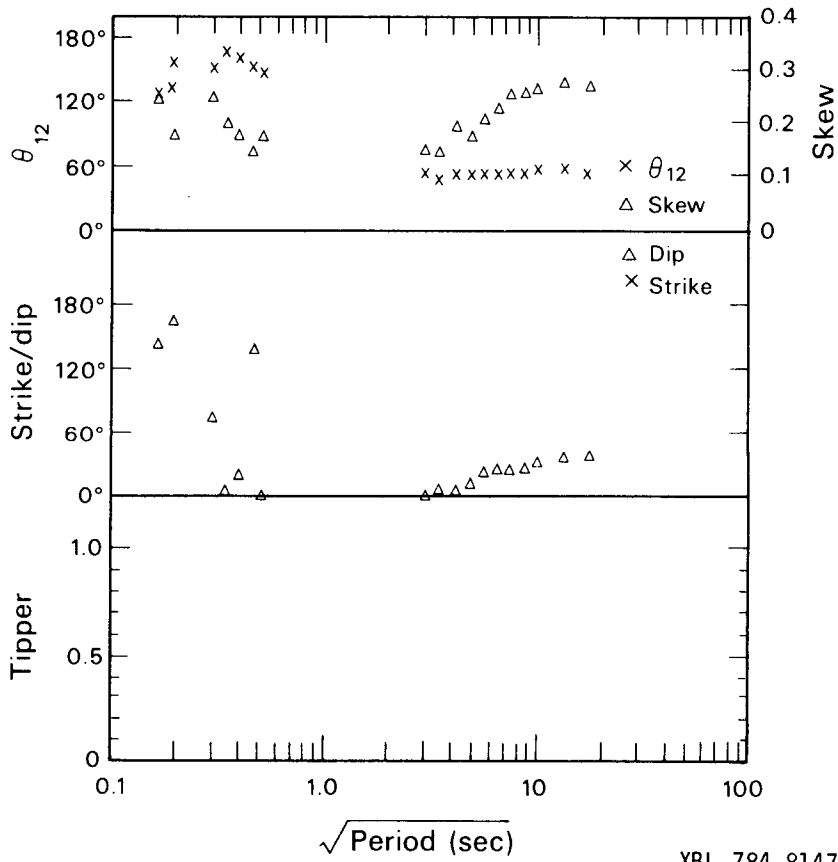
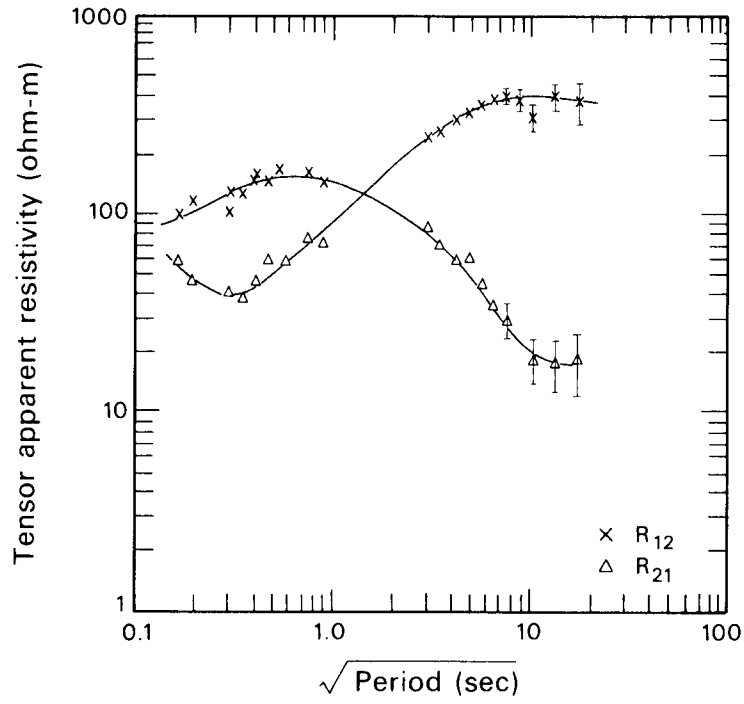
STATION 7A



XBL 784-8156

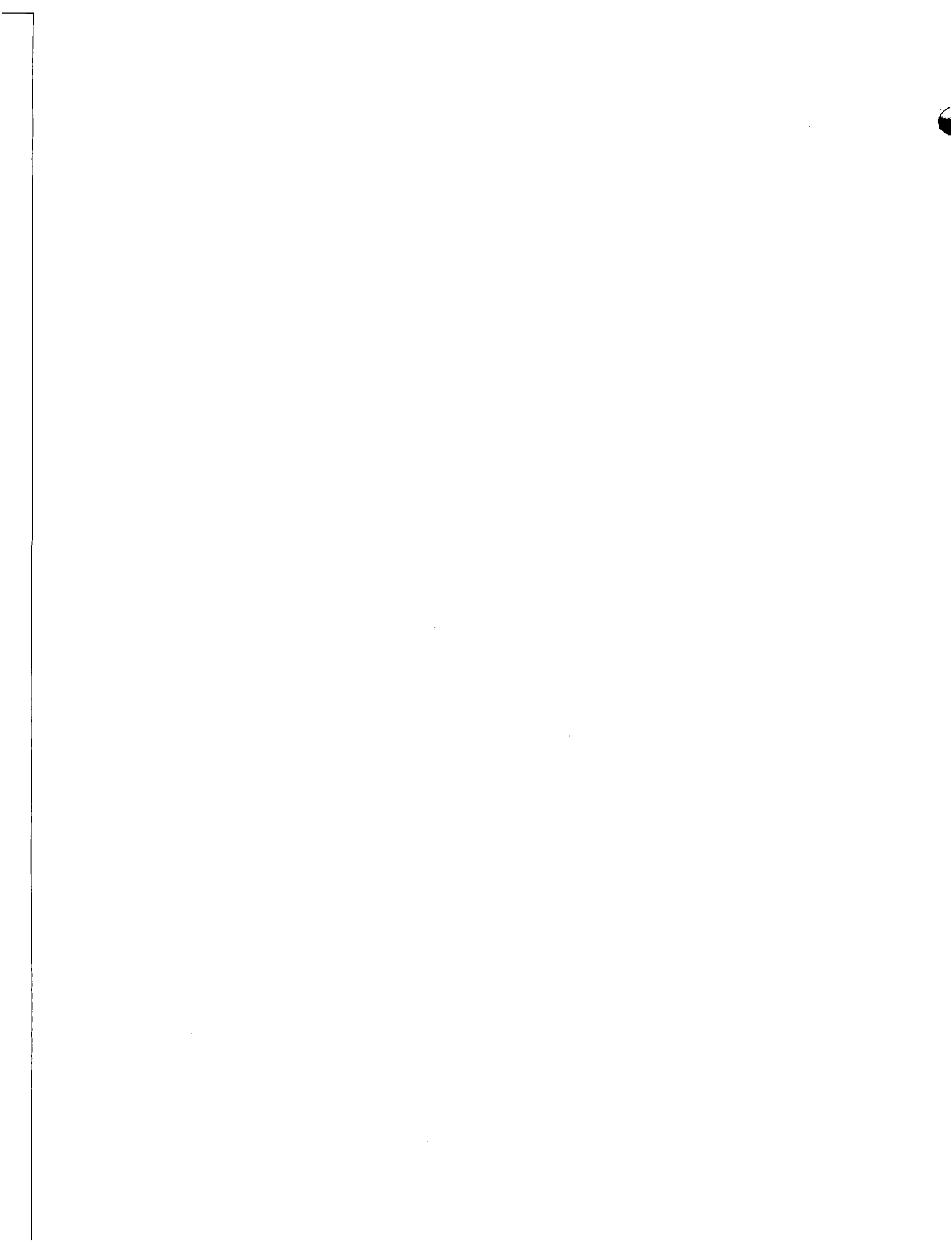
Fig. III-20

STATION 7B

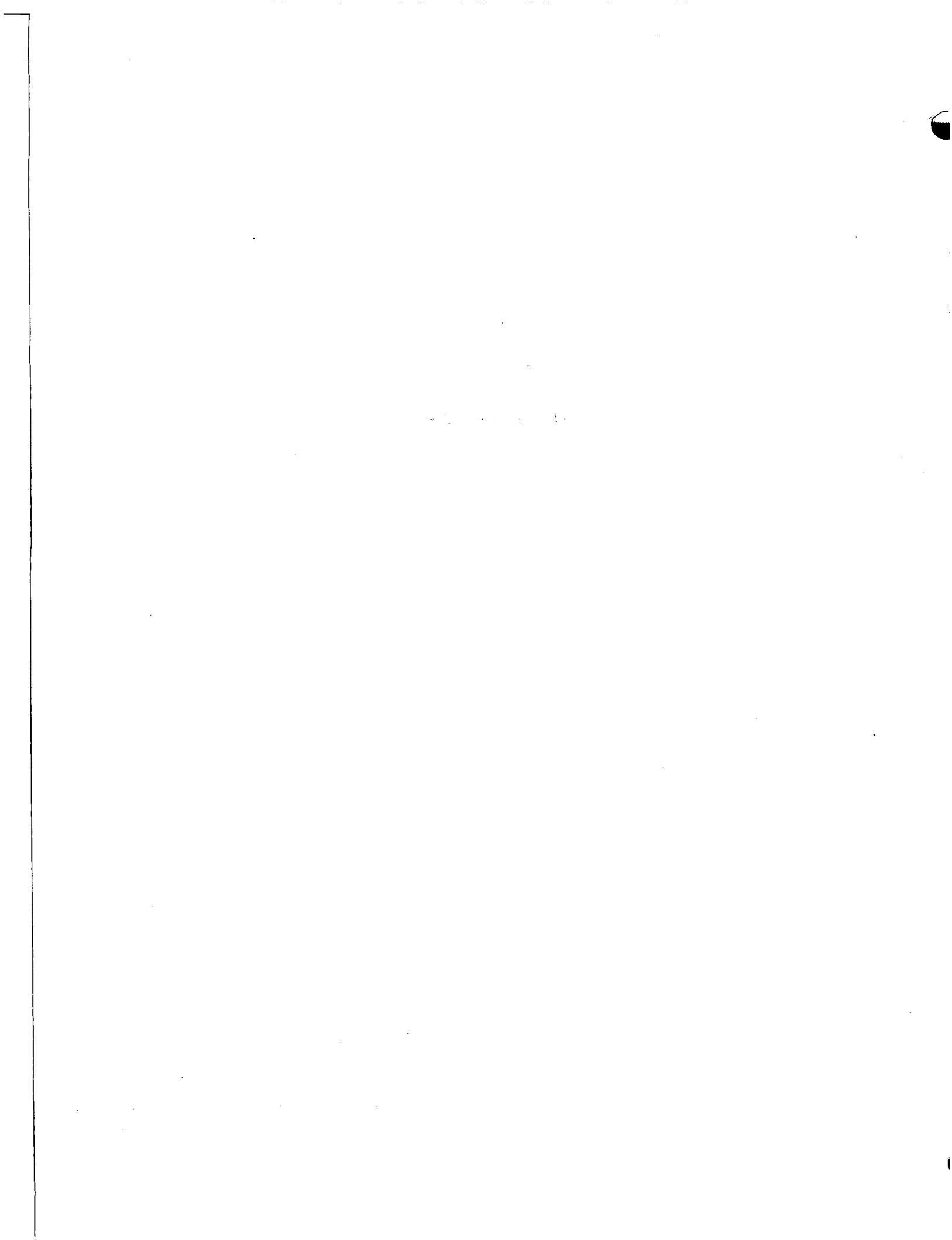


XBL 784-8147

Fig. III-21



APPENDIX IV
REPROCESSING PROCEDURES



APPENDIX IV: REPROCESSING PROCEDURES

The data are presently being reprocessed using magnetic data at remote stations to remove the bias caused by noise at base stations. The method summarized below was developed and described in detail by Gamble et al. (1978).

The initial processing step is the same as in standard MT analysis. The eleven channels of data per site are Fourier-transformed using a tapered time window containing 1024 or 2048 data points per channel. The Fourier coefficients are rotated to obtain geographic north and east components and all necessary system correction functions are applied. The various crosspower and autopower estimates are calculated and averaged over a set of constant Q windows. These average spectral estimates are stored as input for the second phase of analysis.

A second program calculates the following parameters from the crosspower and autopower estimates: (1) rotated apparent resistivities, (2) tippers and (3) various coherencies. The tensor impedances are calculated by multiplying the following set of linear equations for each frequency window,

$$E_x = Z_{xx}H_x + Z_{xy}H_y$$

$$E_y = Z_{yx}H_x + Z_{yy}H_y ,$$

by the complex conjugate of the two components of the reference fields from a remote site. This provides four equations, from which one may solve for the four unknown impedance terms:

$$Z_{xx} = (\langle E_x R_x \rangle \langle H_y R_y \rangle - \langle E_y R_x \rangle \langle E_x R_x \rangle) / D ,$$

$$Z_{xy} = (\langle E_x R_y \rangle \langle H_x R_x \rangle - \langle E_x R_x \rangle \langle H_x R_y \rangle) / D ,$$

$$Z_{yx} = (\langle E_y R_x \rangle \langle H_y R_y \rangle - \langle E_y R_y \rangle \langle H_y R_x \rangle) / D ,$$

$$Z_{yy} = (\langle E_y R_y \rangle \langle H_x R_x \rangle - \langle E_y R_x \rangle \langle H_x R_y \rangle) / D ,$$

$$\text{where } D = \langle H_x R_x \rangle \langle H_y R_y \rangle - \langle H_x R_y \rangle \langle H_y R_x \rangle .$$

The complex conjugate of the k^{th} component of the remote reference is designated by R_k and the symbol $\langle \rangle$ denotes an average estimate. If the noise in the remote reference signals is uncorrelated with respect to that in the MT base field measurements, the impedances calculated will provide unbiased estimates. It is a property of the technique that the values Z_{ij} are independent of reference field magnitude and phase, and therefore one needs no precise knowledge of gains and phase shifts in the telemetry link. An experiment using a reference magnetometer in MT surveys has indicated that consistent apparent resistivities can be obtained in bands of low coherency, even for data where the E-observed to E-predicted coherencies are as low as 0.1 (Gamble et al., 1978).

The unbiased tipper calculations, which are based on the following relationship between the horizontal and vertical magnetic components,

$$H_z = AH_x + BH_y ,$$

are carried out in the same manner as the impedances. Multiplying this equation by the complex conjugates of the two reference field components provides two equations which are then solved for the two unknown constants,

A and B. The tipper expressions are rotated to find the angle for which B is a minimum. This angle plus 90° gives the direction of geologic strike in two dimensions. A measure of the three-dimensionality of an area may be obtained by comparing the magnitudes of A and B after rotation, as well as the variability of strike direction over the area. The phase of the tipper provides information as to the relative position of conductive and resistive structures.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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LBL-7050
MAP SUPPLEMENT
Figures, 2, 3, 5, 6 and 7

**A TELLURIC-MAGNETOTELLURIC
SURVEY AT
MT. HOOD, OREGON**
— A Preliminary Study —

by
Norman E. Goldstein
Earth Sciences Division
Lawrence Berkeley Laboratory

Edward Mozley
Engineering Geoscience
University of California, Berkeley

June 1978



Lawrence Berkeley Laboratory
University of California
Berkeley, California

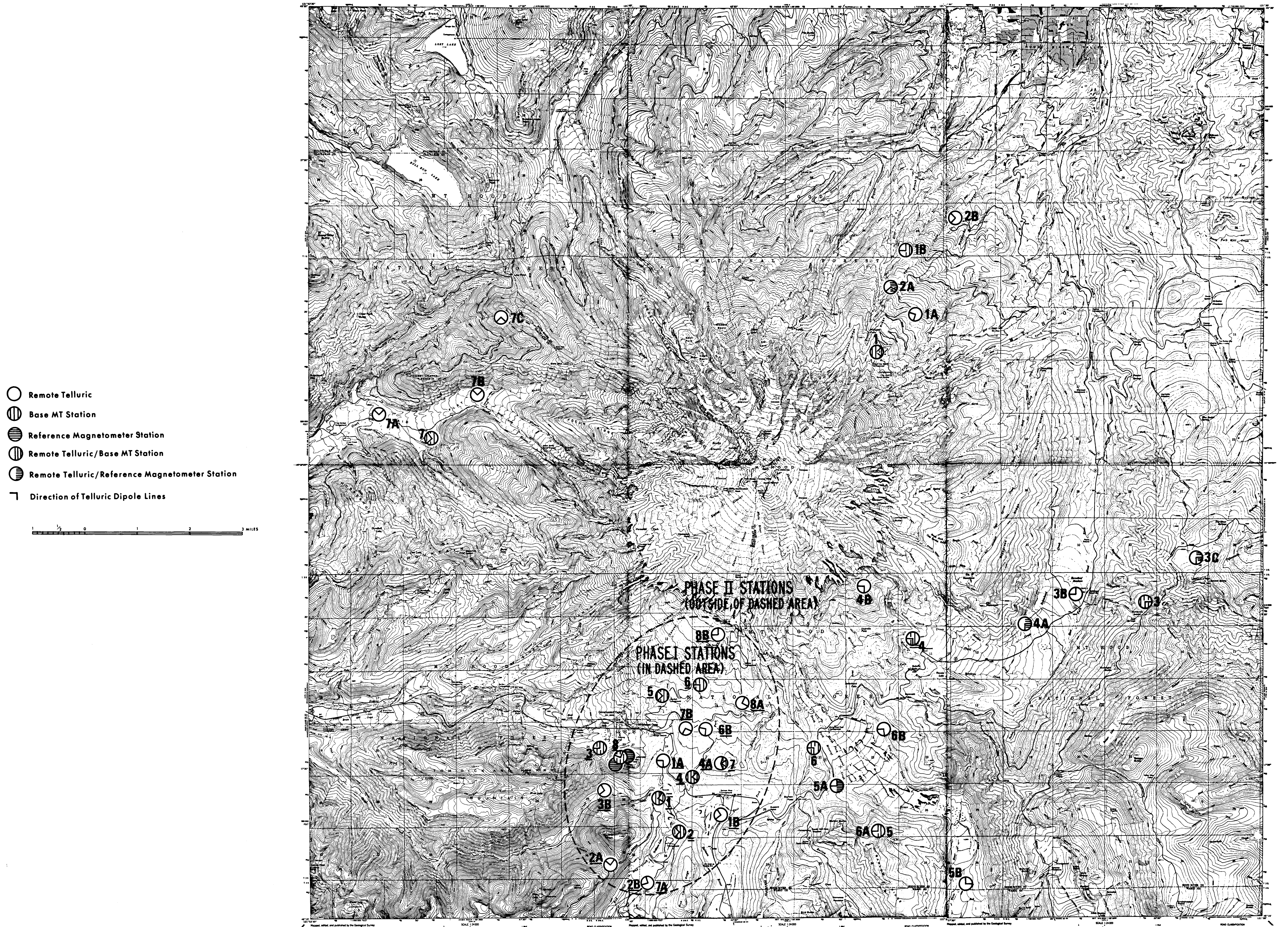
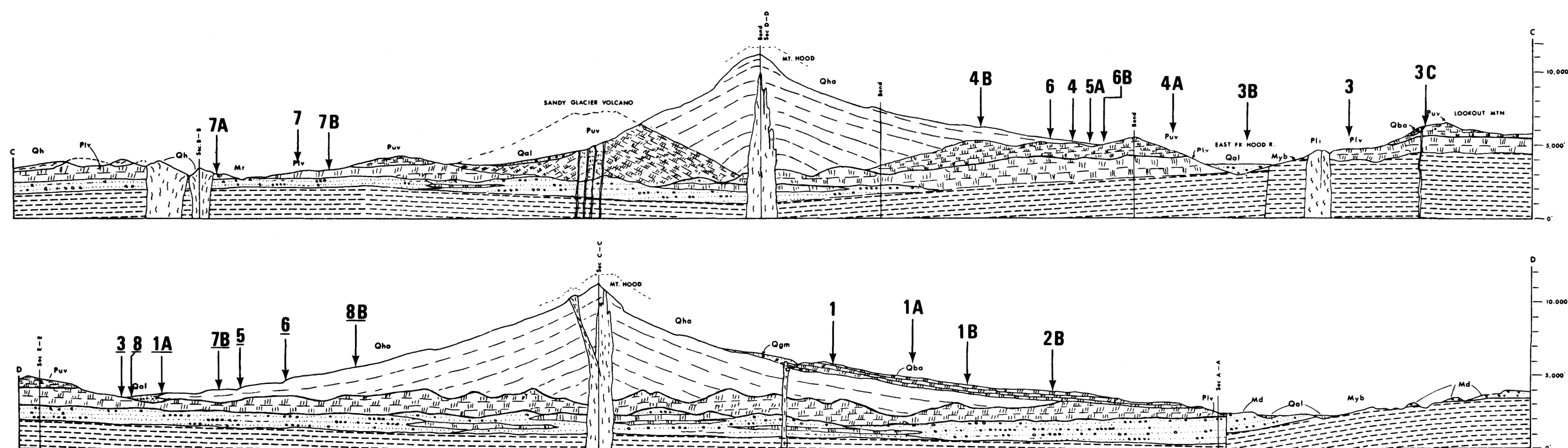
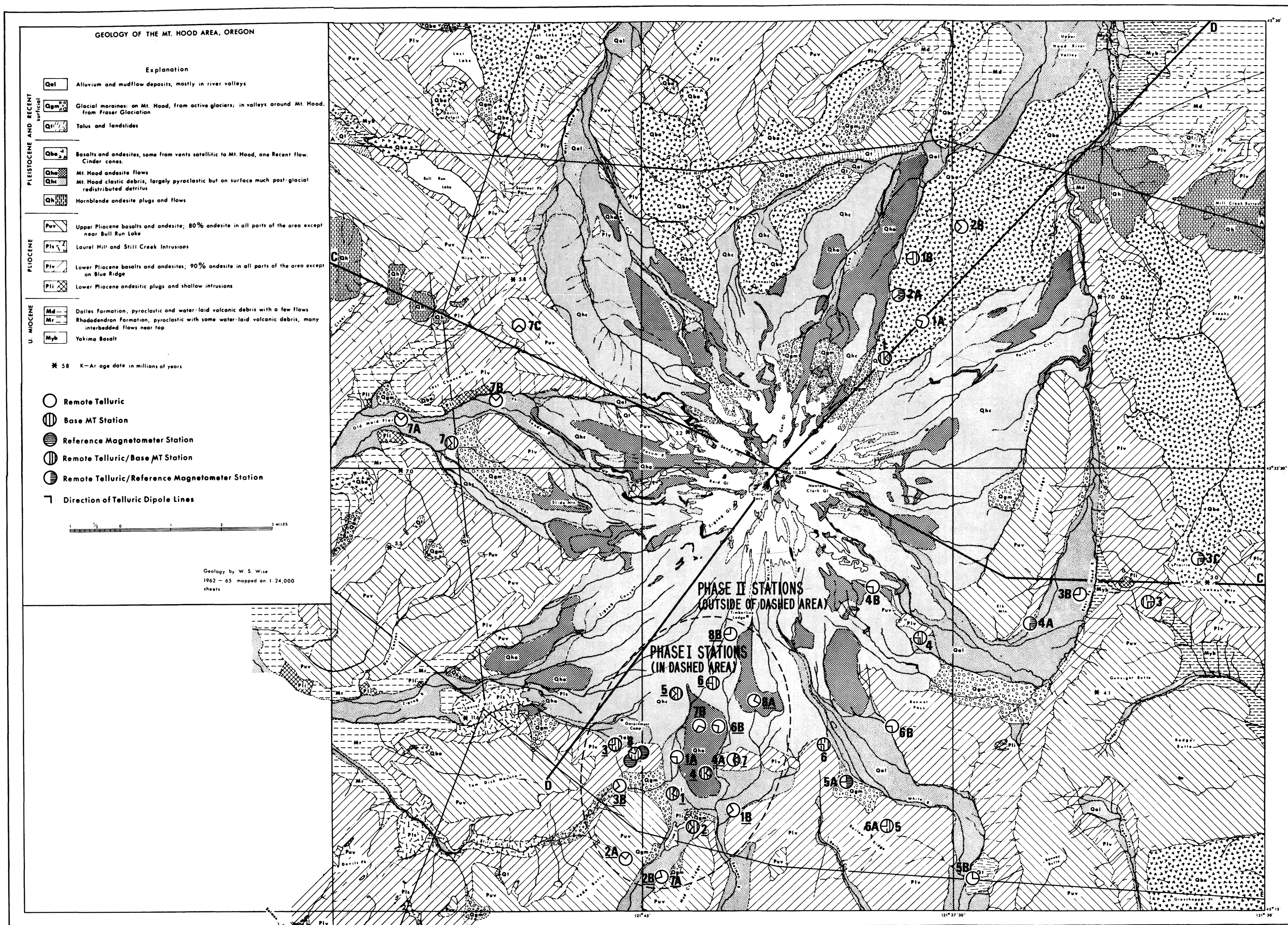
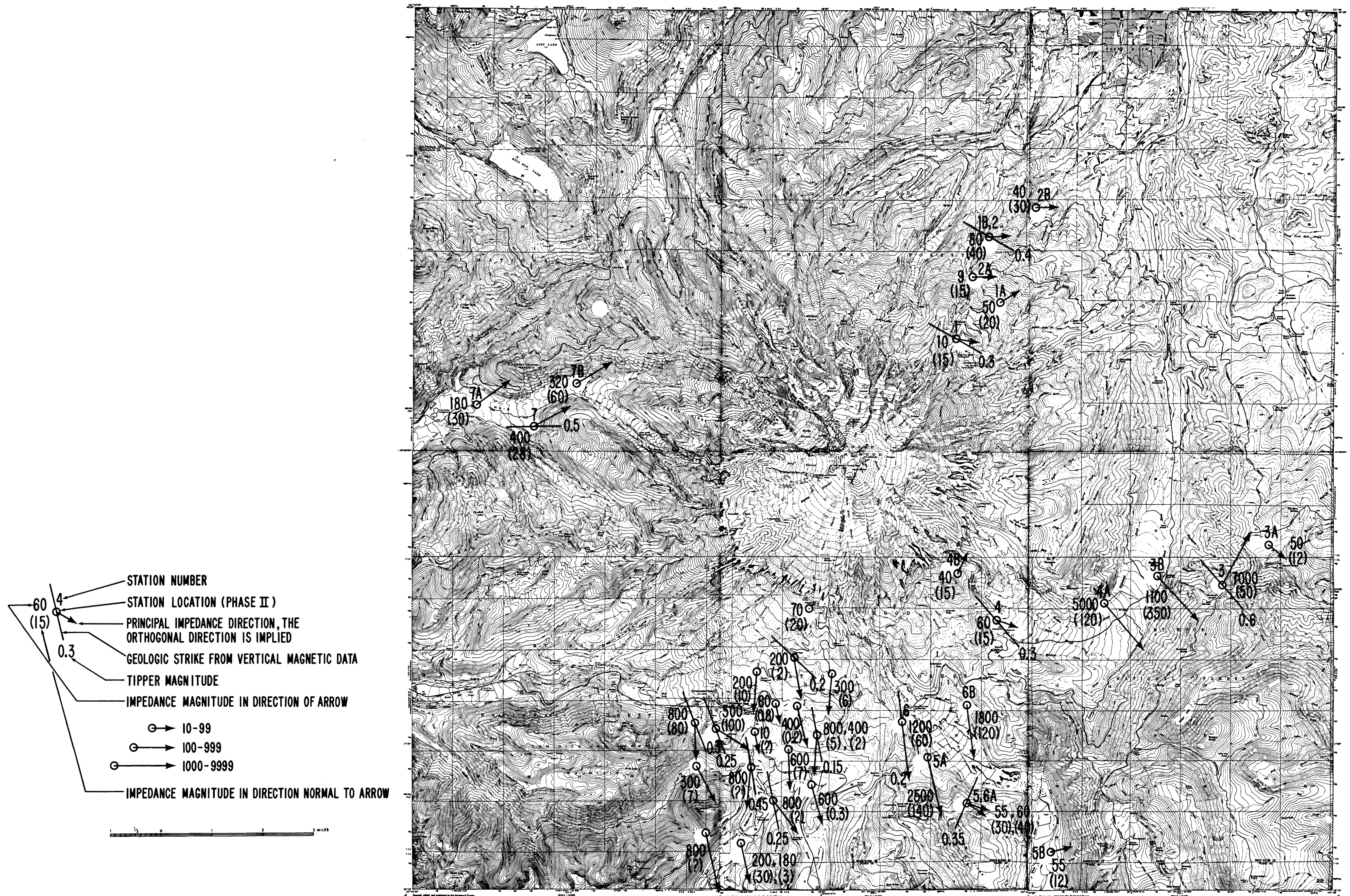


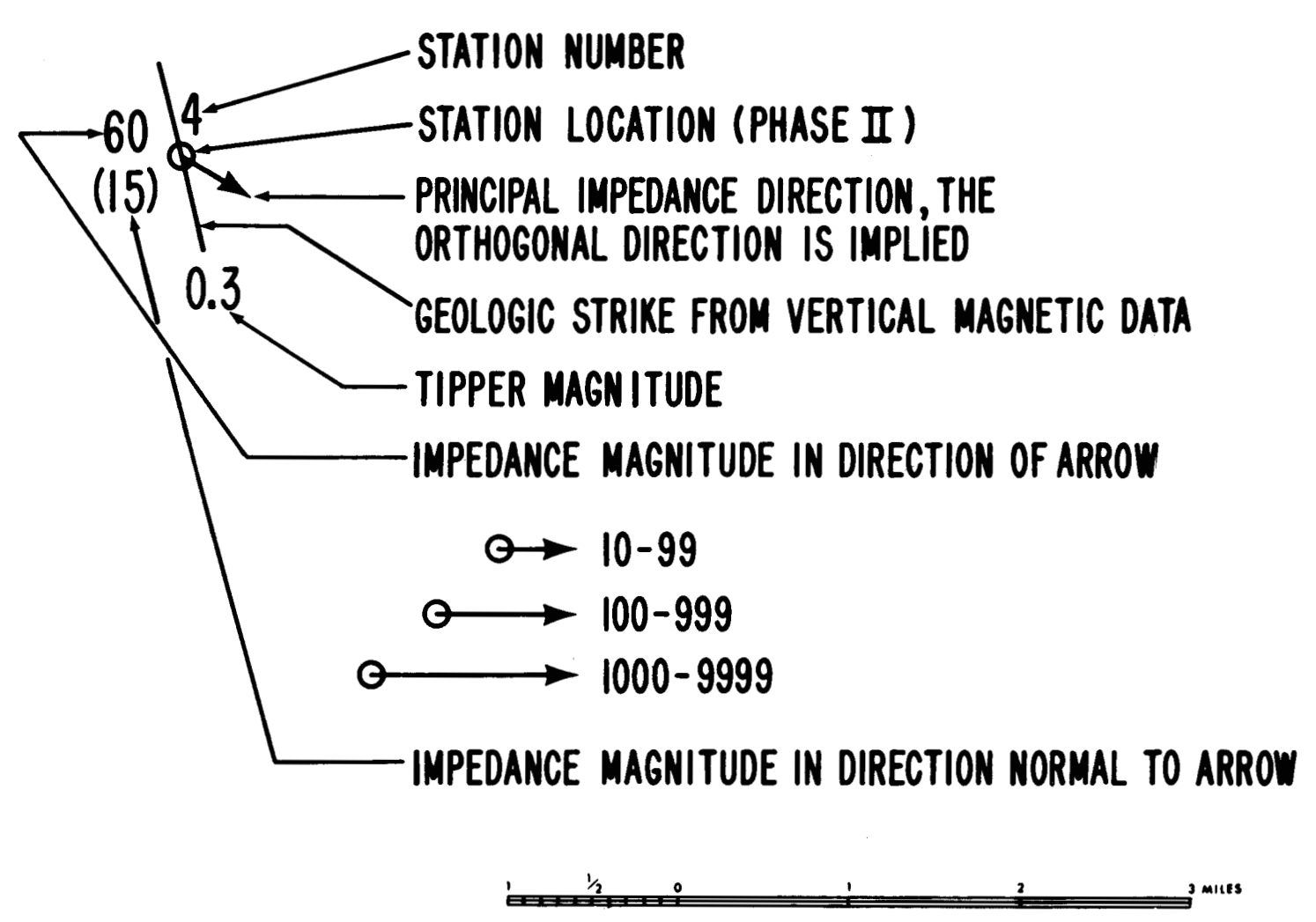
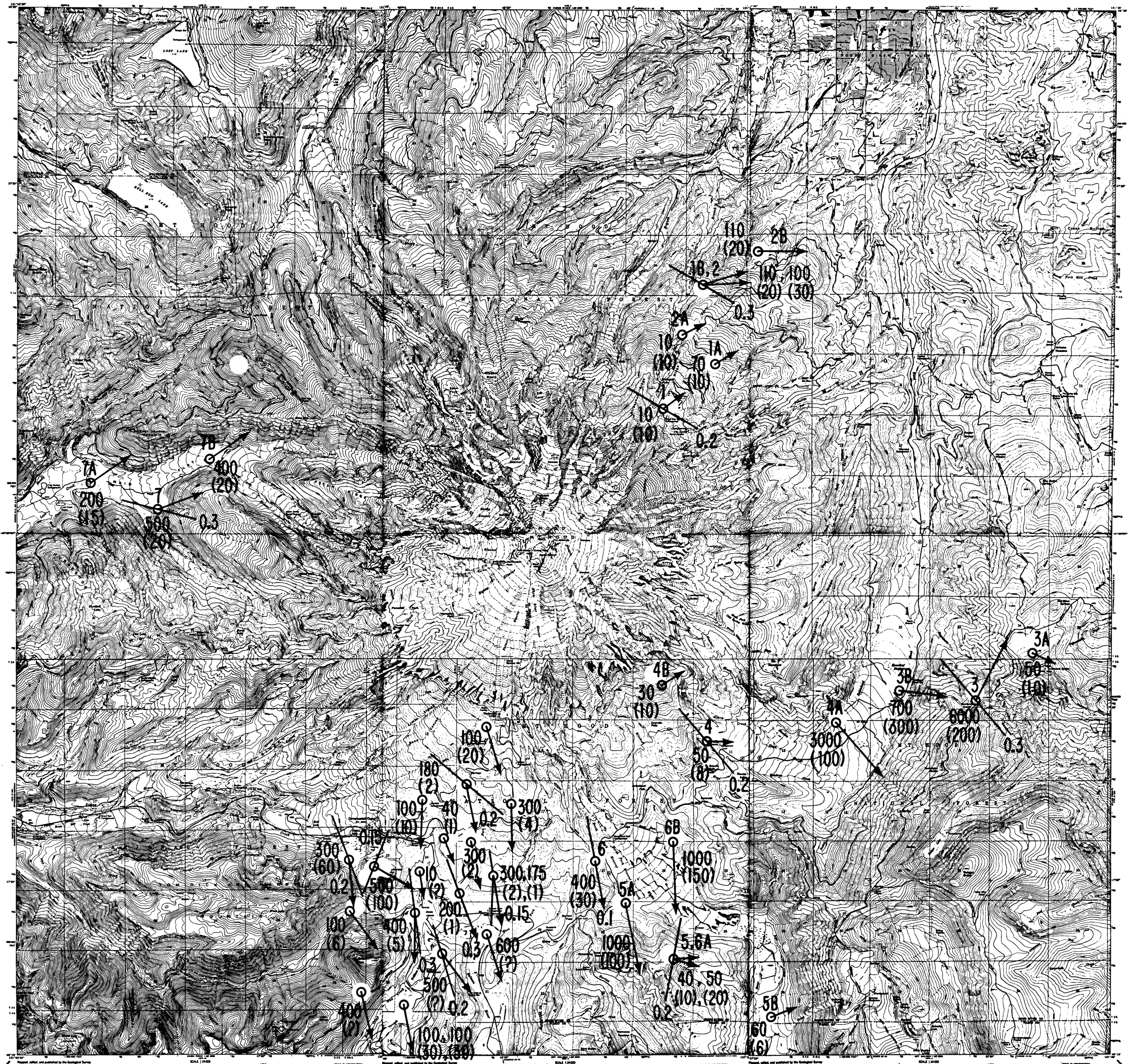
Figure 2. Topographic map of the Mt. Hood area showing T-MT station locations.



XBL 785-8848A

Figure 3. Geologic map and cross sections of the Mt. Hood area (after Wise, 1968), showing T-MT station locations.





XBB 785-6431A

Figure 7. Rotation vectors and principal direction resistivities at 0.01 Hz.