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Magnetotelluric Data Across West-Central Arizona

by

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ABSTRACT

Twenty-one magnetotelluric soundings were made in June 1985 traversing the southwestern border of the Colorado Plateau from the areas of Parker to Flagstaff, Arizona. Data were obtained in single-station mode, in contrast to remote reference observations, over the frequency range of 0.002 to 12 Hz. Soundings were spaced at intervals of 10 to 20 km over most of the traverse. One-dimensional, 3-layer interpretation (conductive surface layer, resistive basement, and conductive basal layer) indicates a deepening of a basal conductor from the southwest to the northeast. Depths of 5 to 10 km are indicated near Alamo Lake in the Basin and Range province compared with depths of 25 or 30 km near Prescott in the Transition zone. The basal conductive layer appears to show an anomalously shallow upwarp (17 km depth), between Prescott and Cottonwood, Arizona. Beneath the Colorado Plateau, the basal conductor is indicated at depths of 25 to 40 km. Inasmuch as the data show effects of both surface, and deep two- or three-dimensionality, the present modeling results are tentative.

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INTRODUCTION

This report presents magnetotelluric (MT) data acquired as part of an investigation of the tectonic framework of west-central Arizona and southeastern California (fig. 1, table 1). The data compliment other geological and geophysical data being acquired by the U.S. Geological Survey under the Pacific-Arizona Crustal Experiment (PACE). The experiment is an outgrowth of intensified interest in the extensional terranes of southeastern California and their interface to the Colorado Plateau. The Universities of California, in forming a consortium (CALCRUST) to investigate parts of the Colorado River region in California by seismic reflection experiments, provided the initial impetus to the experiment.

The present MT data were obtained to define the variations of electrical conductivity in crossing the transition from the extensional terranes of the Basin and Range Province to the highlands of the Colorado Plateau.

The geological variations, as well as the large changes in topography in the study area should be treated by more sophisticated analysis than the one-dimensional modeling described here. However, the present results provide a first order picture of the variations in the crustal resistivity. These results also provide a starting point for two-dimensional modeling that can be expected to provide more accurate resolution of the horizontal layering as well as better definition of lateral variations in electrical structure.

PREVIOUS WORK

Previous MT data have been reported to the north and south of the region of Fig. 1, but no previous MT soundings are known along the current traverse.

The MT data available includes several stations near Flagstaff (Ware and O'Donnell, 1980), an east-west traverse across the northern part of the Colorado Plateau in the vicinity of the Arizona, Utah, and Nevada juncture (F. Frischknecht, U.S. Geological Survey, unpublished data), an east-west line from southeastern Colorado into Nevada (Plouff, 1966), a single sounding at Farmington New Mexico (Pederson and Hermance, 1981), and unpublished data in southern and central Arizona (Ander, 1981, Aiken and Ander, 1981).

There is also a regional geomagnetic variation study over Arizona, New Mexico, and parts of the adjacent states (Porath and Gough, 1971), and a geomagnetic variation survey in the vicinity of Flagstaff (Towle, 1984).

Bisdorf (1982) has acquired a number of DC Schlumberger soundings in the Date Creek Basin area near the current MT soundings 16 and 17 (Fig. 1).

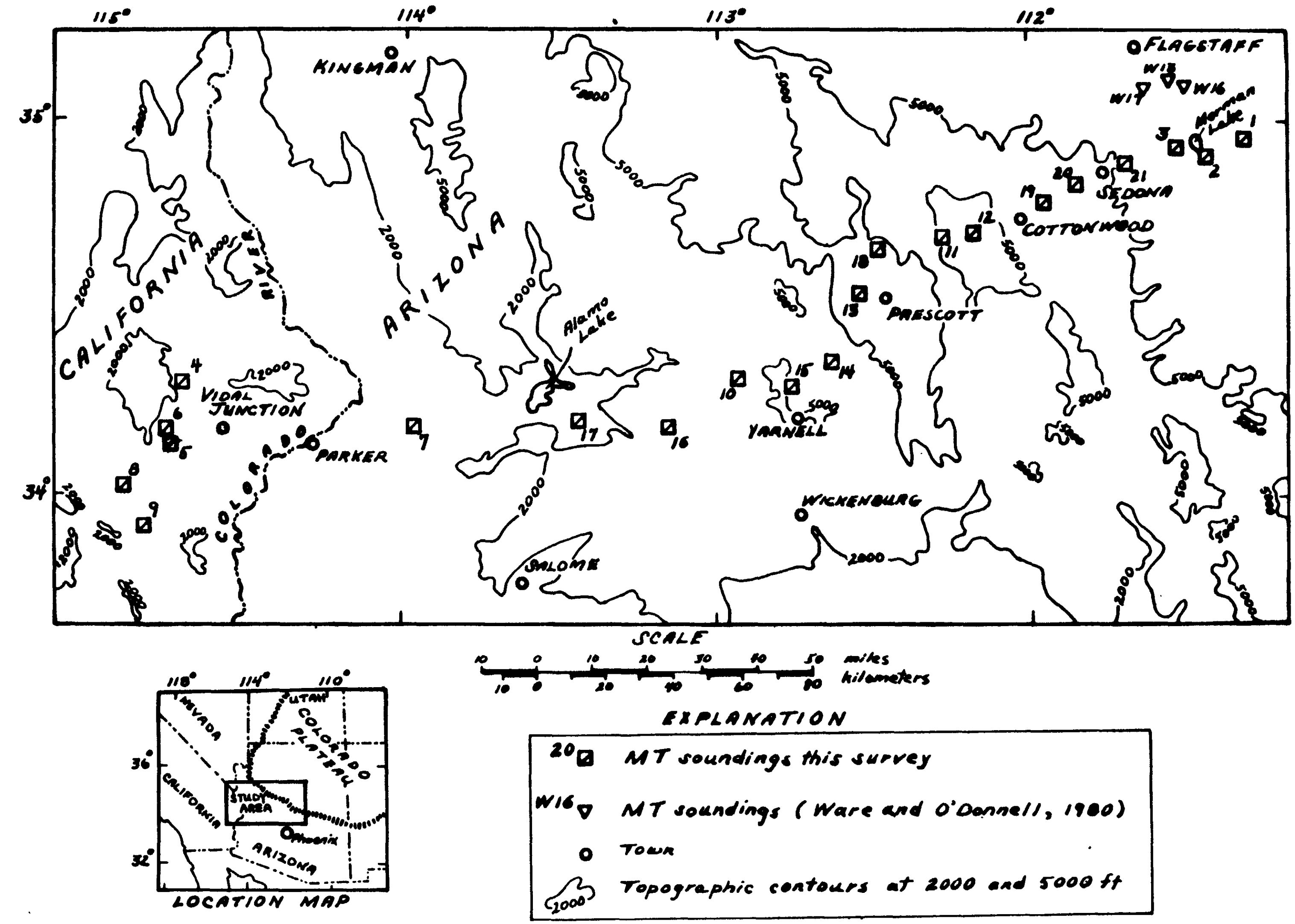


Figure 1 -- Location of MT soundings.

Table 1. - MT sounding locations

Sounding	Date (1985)	Latitude N	Longitude W	Elevation (m)	1:100,000 Quadrangle (Arizona)
1	June 1	34° 57.00′	111° 17.63′	2,140	Sedona
2	June 2	34° 54.68′	111° 25.43′	2,260	Sedona
3	June 2	34° 56.40′	111° 30.98′	2,300	Sedona
4	June 4	34° 19.80′	114° 42.90′	600	Parker
5	June 6	34° 9.00′	114° 43.95′	450	Parker
6	June 6	34° 10.80′	114° 44.85′	500	Parker
7	June 7	34° 12.08′	113° 58.35′	470	Alamo Lake
8	June 8	34° 1.70′	114° 52.80′	250	Parker
9	June 8	33° 54.80′	114° 49.20′	200	Blythe, (California)
10	June 9	34° 19.70′	112° 55.88′	1,100	Bradshaw Mts
11	June 10	34° 41.48′	112° 16.80′	1,530	Prescott
12	June 10	34° 42.90′	112° 10.58′	2,200	Prescott
13	June 12	34° 32.63′	112° 32.63′	1,820	Prescott
14	June 13	34° 21.90′	112° 38.40′	1,300	Bradshaw Mts
15	June 14	34° 17.78′	112° 45.75′	1,380	Bradshaw Mts
16	June 15	34° 11.10′	113° 8.78′	790	Alamo Lake
17	June 17	34° 13.35′	113° 26.48′	490	Alamo Lake
18	June 18	34° 40.05′	112° 29.55′	1,560	Prescott
19	June 19	34° 46.65′	111° 57.45′	1,180	Sedona
20	June 20	34° 50.10′	111° 51.00′	1,270	Sedona
21	June 21	34° 53.55′	111° 40.80′	1,960	Sedona

DATA ACQUISITION

Data were acquired with a truck-mounted MT system designed and constructed by the U.S. Geological Survey. Except for the magnetic sensors, and refinements in the data acquisition programs, the system is similar to that described by Stanley and Frederick (1979).

The horizontal magnetic field sensors consist of two 60-inch long by 4-inch diameter (48,000 turns) permalloy-core induction coils. Response curves for the permalloy-core coils are shown in fig. 2 (Stanley and Tinkler, 1982). The vertical magnetic field is sensed by a 96-turn, 100-ft (30.48-m) circumference air coil. Because of uncertainty in the response of the air-coil, the vertical magnetic field results are not used in this report.

Electric field sensors consist of lead-lead-chloride, plaster-of-Paris electrodes, (Petiau and Dupuis, 1980), configured in an L-spread, dipole pair with orthogonal 150-m (496-ft) legs. The corner of the L-spread is an electrode common to each of the legs. The spread was always oriented magnetic north-south and east-west, as were the horizontal magnetic-field coils. Magnetic declination in the survey area varies from 13° to 14° East.

Electrodes were set in shallow (3- to 6-inch) holes wetted with tap water. The horizontal coils were laid on elongate sandbags and covered by a low-profile plywood and styrofoam wind-and-sun shield.

Signals from the sensors were fed into preamplifiers at the sensor site, and then through a 150-ft (30.5-m) shielded cable to the data acquisition system mounted in the truck. The preamplifier gains were 2,600 for the magnetic fields, and 83 (Ey, east-west) to 85 (Ex, north-south) for the electric field. The preamplifiers and their 12-VDC battery power supply were housed in a styrofoam box to stabilize them against ambient temperature changes.

The data-acquisition system includes matched, adjustable-gain amplifiers and adjustable-response filters for each of the channels. Amplifier gains can be varied from 2 to 1000 in increments having decade multipliers of 2, 5, and 10. After amplification and filtering, the data are recorded on a strip chart recorder for inspection, and converted to digital format for processing and storage. Resolution of the digital conversion is 1:4096 (12-bit).

Observations are made in four frequency bands using sample intervals of 4, 1, .0625, and 0.016 sec. These are labeled L, M, H, and S respectively on fig. 3, which shows the frequency response curves for the various filter settings.

The digital part of the acquisition system is controlled by a 16-bit microcomputer, which also allows field processing of the data. Except for the sensors and their preamplifiers, the system is powered by a portable 4.5 kw generator and housed in an air-conditioned camper.

The digital system provides the options of storage of time series, or of real-time processing and storage of the Fourier co-spectral estimates. The latter option provides full MT tensor analysis and the display of results during data acquisition. However, when real-time processing is used at sample

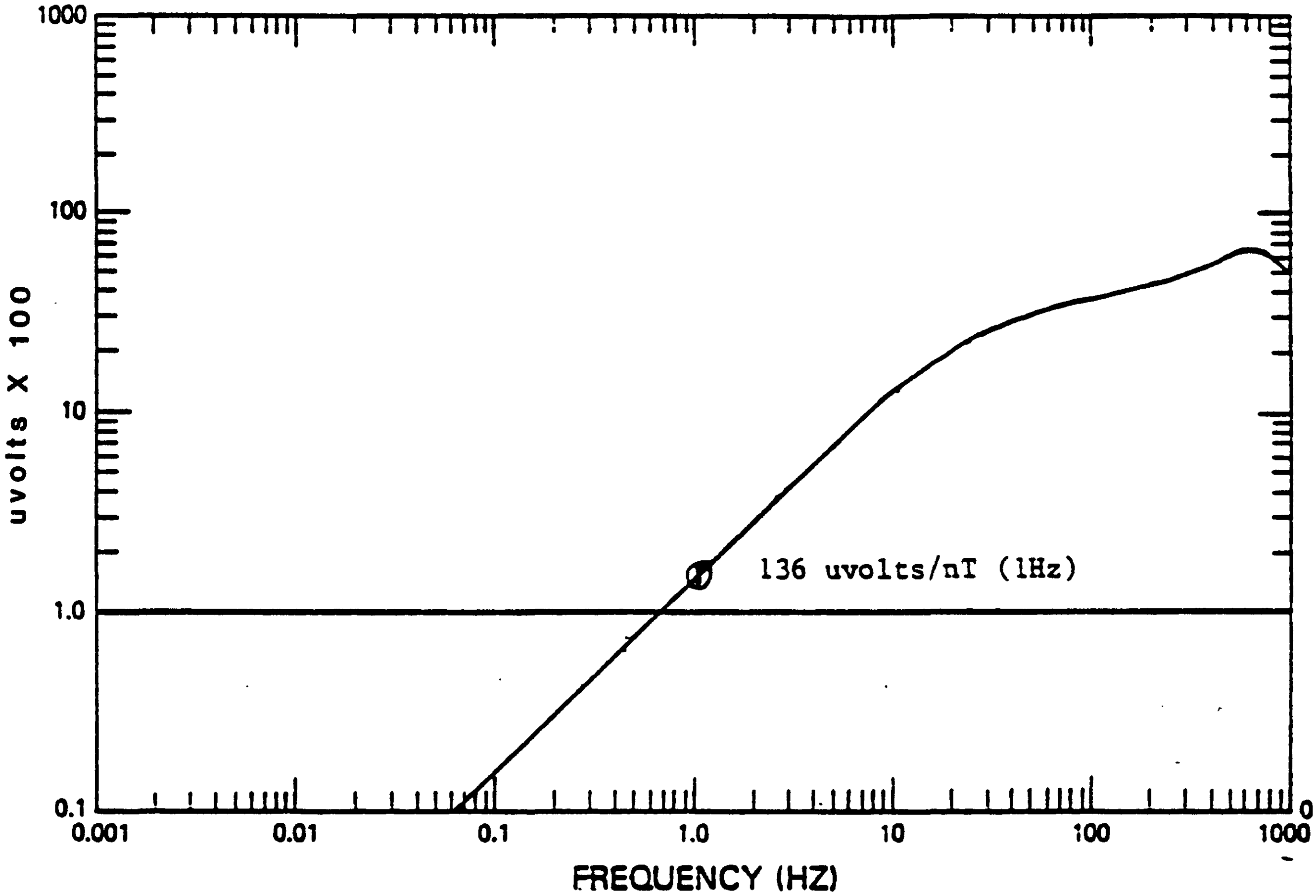


Figure 2 -- Response of induction coils (Stanley and Tinkler, 1982).

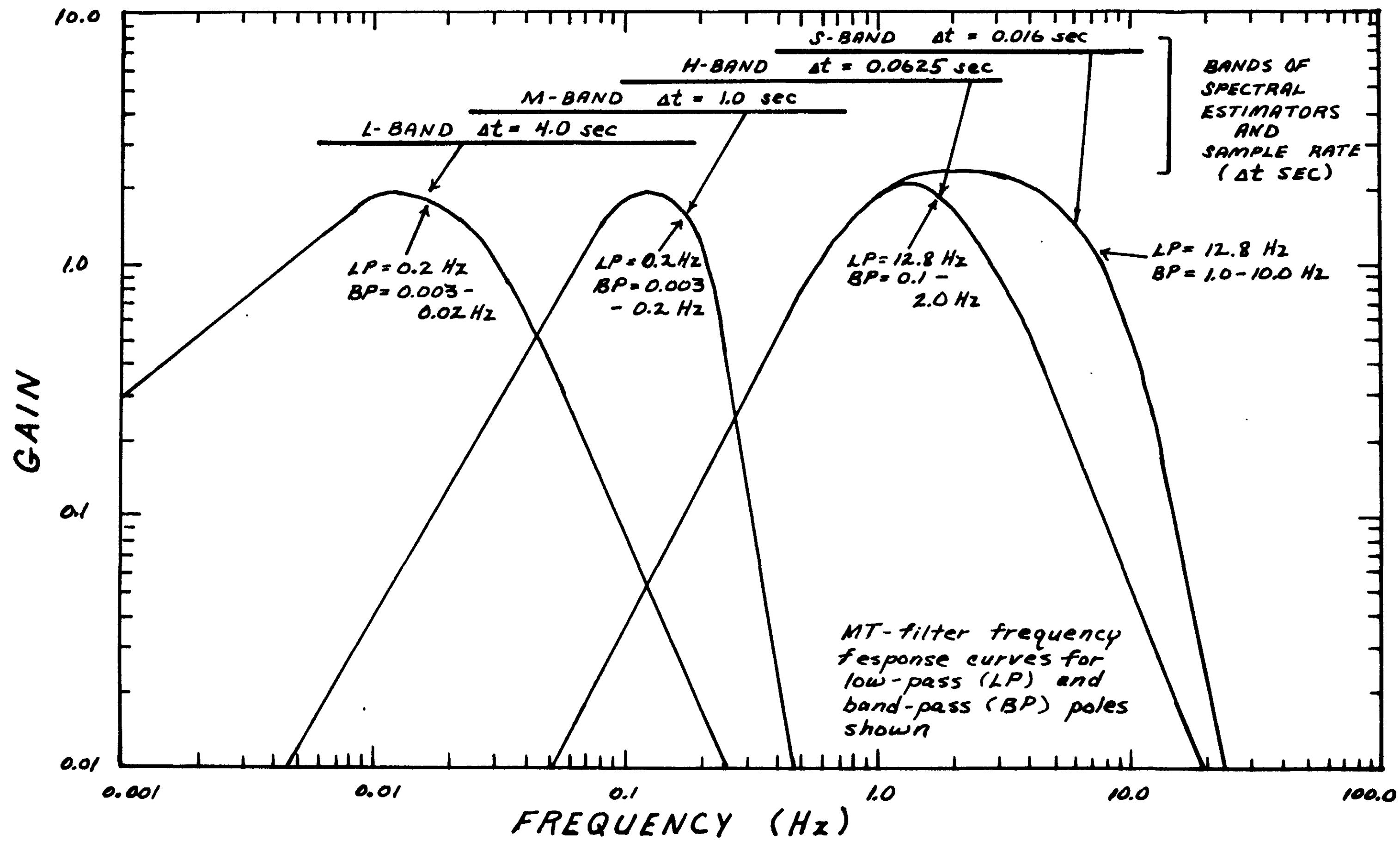


Figure 3 -- Response of the filter system. Shown is the total filter response for the various bands defined by the low-pass (LP) and band-pass (BP) poles of the analog filter system (excluding the pre-amplifiers). Also shown are the data sampling intervals used for each of the bands.

rates higher than 1-Hz, there are gaps in the time series caused by the fact that data acquisition is faster than data processing.

The procedure followed for this survey was to collect and store time-domain data when the sample rate exceeded 0.25 Hz. Three or four segments of 2048 samples each were collected for the .0625 and 0.16 sec sample rates, and one or two segments for the 1-sec rate. The 0.25-Hz sample rate (L-Band) was run for 640-samples using real-time processing.

Typical time on station, including setup, data acquisition, and partial analysis, was about 3-hours. Travel time between sites, station selection, and electronic problems caused by mid-day ambient temperatures usually limited data acquisition to 1 station per day. At the time of the survey, ambient temperatures in Colorado River area near Parker were often between 100 and 120°F, and the inside of the air-conditioned camper typically showed temperatures exceeding 96°F by mid-day. The high temperatures caused problems with the digital system (primarily unreliable operation of the disk drives). Significant artificial transients in the magnetic field signal were also observed, which are believed to be related to heating expansion effects on the coils. Observations with obvious manifestations of such transients were repeated.

DATA PROCESSING

Fourier transformation of the time series to the frequency domain is performed on a data length consisting of a 128-points. Sixteen consecutive 128 point series totaling 2048 samples comprises the largest data set acquired. Successive decimations of the basic data series by 2, 4, and 8 sample intervals provide data at lower frequencies (Wight and others, 1977, Stanley and Frederick, 1979). Anti-aliasing filtering is performed prior to decimation.

Band averaging of the Fourier spectral components across frequency is performed over 8-harmonics, starting at harmonic 3, and overlapping adjacent bands by 2 harmonics at each end. This provides 4 cospectral estimates across a bandwidth of 0.6 decade of frequency. At each successive decimation, giving series lengths 128, 256, 512, and 1024 times the sample interval, the bandwidth increases by 0.3 decade. Thus the total bandwidth obtained with decimation by 8 is 1.5 decade.

The horizontal lines on fig. 3 show the bandwidths of data for each sample interval, assuming a full decimation by 8 within each band. There is overlap among estimates both within each band for the different decimation levels, and between different bands, which allows an evaluation of data consistency.

For this report, most time series are processed only through the first 640-samples. For several cases studied, it appears that the sounding curves will not be substantially modified by full processing.

The MT impedances are calculated using the formulas presented by Vozoff (1972). The basic data consist of the Earth response functions (Rij) for each frequency, scaled to units of resistivity (referred to as apparent resistivity). The functions Rij relate the electric field (Ei) to the corresponding perpendicular magnetic field (Hj) at specific frequencies (f). There are two components (curves or modes) for each sounding corresponding to 2-pairs of orthogonal directions observed, the Ex/Hy (Rxy) and Ey/Hx (Ryx) responses. The formulas are based on the relationships given below:

$$Ex = Zxx\ Hy + Zxy\ Hx$$

$$Ey = Zyx\ Hx + Zyy\ Hy$$

$$Rij = \frac{0.2}{f} Z_{ij}^2$$

where the units are nT (1nT = 1 gamma) for Hi, mV/km for Ei, and Ohm-m for Rij. All elements are functions of frequency (f) in Hertz, and the response elements are complex hence the data includes amplitude and phase.

Observations are north-south and east-west, but the two components are rotated in the analysis to maximize the $¢Rxy¢^2+¢Ryx¢^2$ amplitudes. The rotation converts one of the responses (Rxy or Ryx) so the rotated Ex is parallel to the effective strike of geological structure, and the other to the perpendicular direction. The mathematical rotation is ambiguous by 90°.

The analysis method provides data at closely spaced frequency intervals by sacrificing statistical stability at any given frequency. Thus, scatter of the data provides a qualitative estimate of data reliability, rather than error bars (usually large and not shown) on individual estimates.

Inspection of the various data segments collected allowed the selection of the best data set for each band based on coherence and consistency between bands.

The complete sounding curve is generated by merging the selected data from the various bands, and averaging the response parameters (Rij and phase of Zij) across the estimates at repeat frequencies within and among the bands. Data processing procedures are identical whether done in real time or on stored data. The complete sounding curves are shown in fig. 4.

PRELIMINARY ANALYSIS

Apparent resistivity curves have been interpreted based on 1-dimensional forward modeling. The resulting models provide a preliminary view of the resistivity variations, and provide a framework to consider the influences of 2- or 3-dimensionality, as well as the noise characteristics of the data.

Eight of the soundings show separations of the orthogonal sounding curves of 0.5 log-cycle or more (curves 1, 4, 8, 9, 10, 14, 20, and 21) which indicates important multi-dimensionality in the surface layer. This is expected from the fact that the study area is a composite of low-resistivity, alluvial basins, and relatively higher resistivity ranges.

One-dimensional modeling follows an approach based on the asymptotic behavior of TM and TE curves in the presence of near-surface, lateral, inhomogeneity (Berdichevskiy and Dimitriev, 1976). The higher frequency part of the sounding curve, always ascending to higher apparent resistivities in the mid-frequency range of the present data, is modeled to fit the Ryx data. This component (Ryx) is assumed to represent the effective E-perpendicular to strike (TM mode). The lower frequency data, always descending to lower

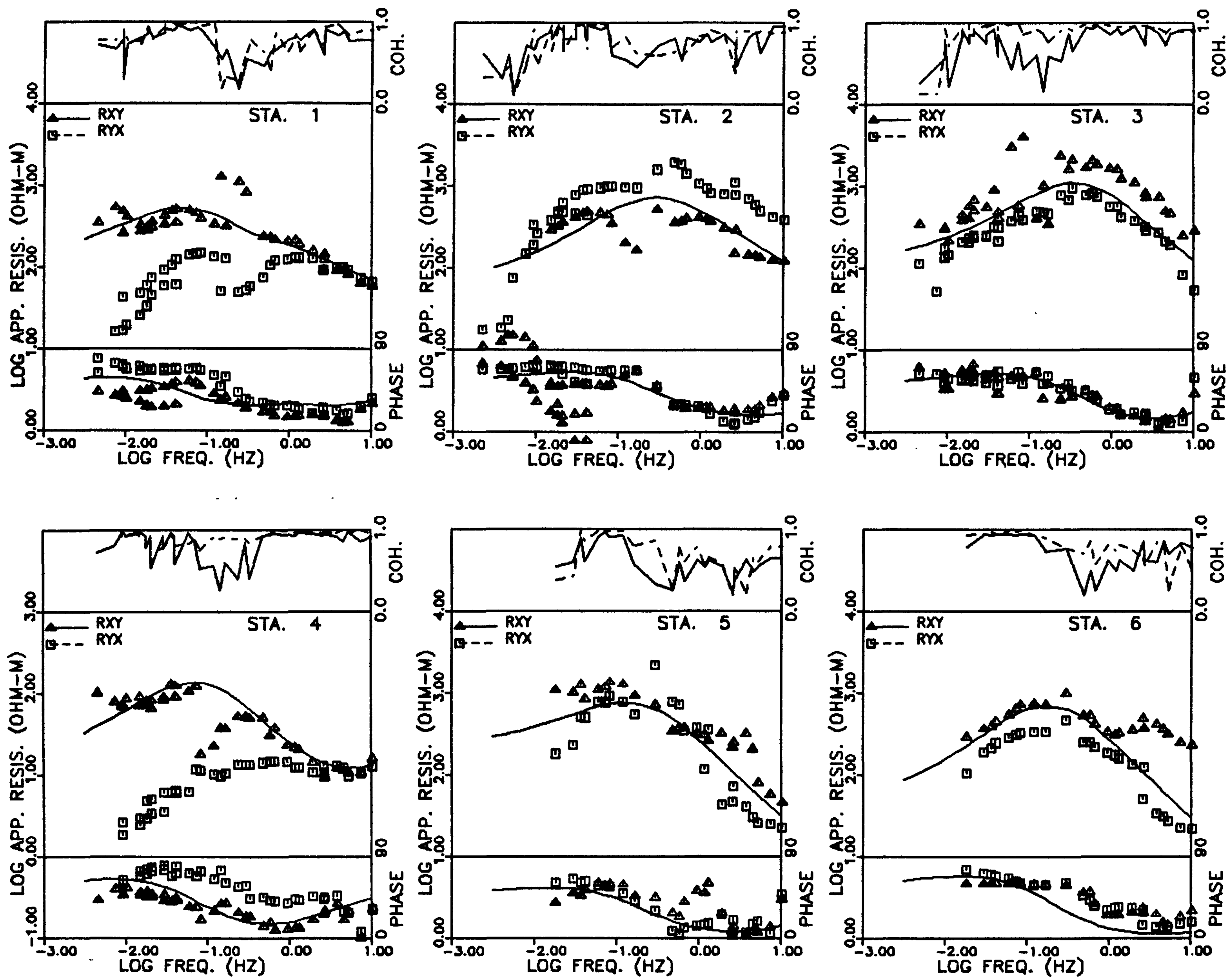
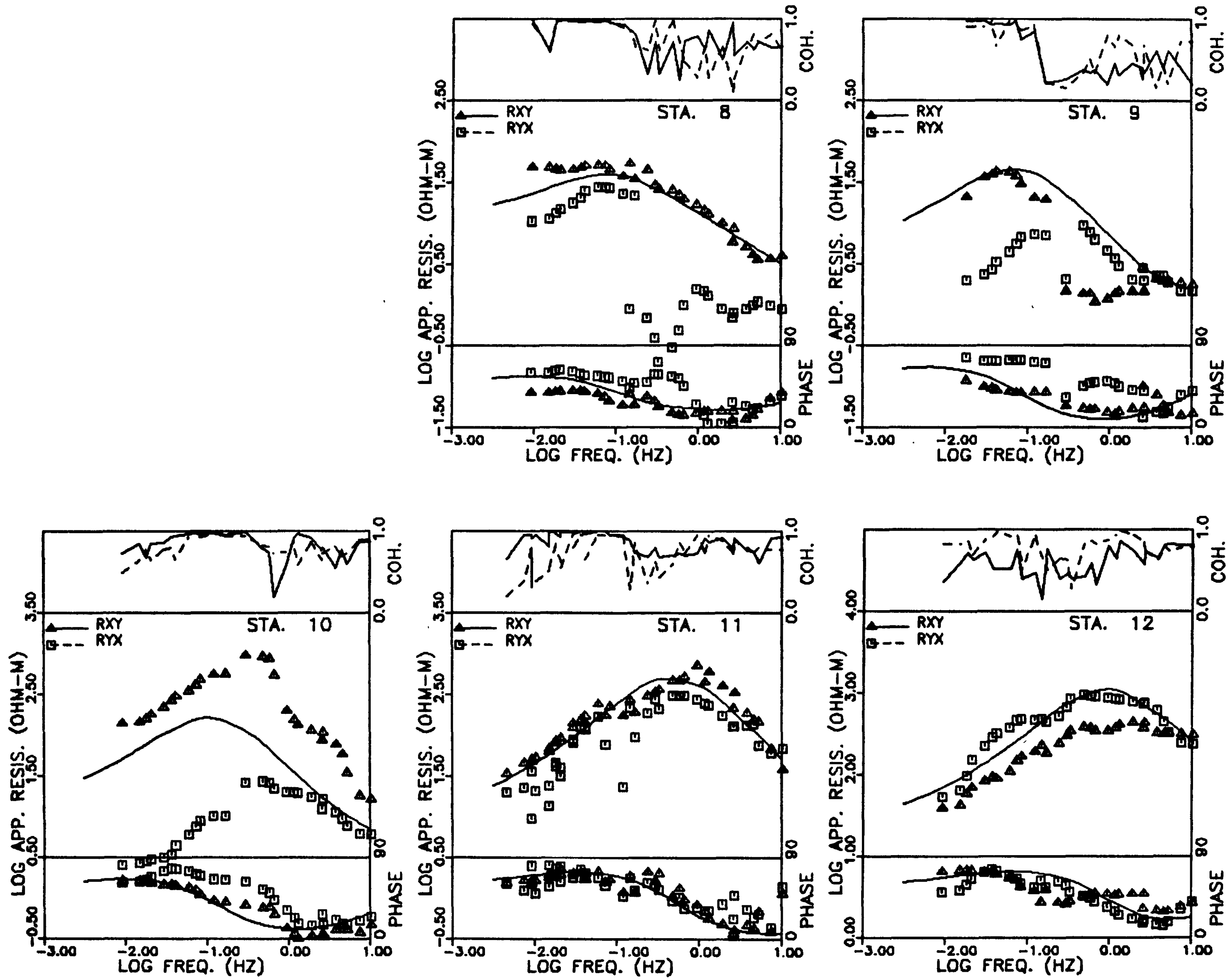


Figure 4 -- MT sounding curves. Shown are the estimates of coherency, top (solid for Rxy and dashed for Ryx), logarithmic apparent resistivities, middle, and phases (0 to 90 degrees), bottom. Rxy and Ryx data are shown by triangles and squares respectively. The solid lines shown with the apparent resistivities and phases are the modeled response curves for one dimensional models listed in table 2.



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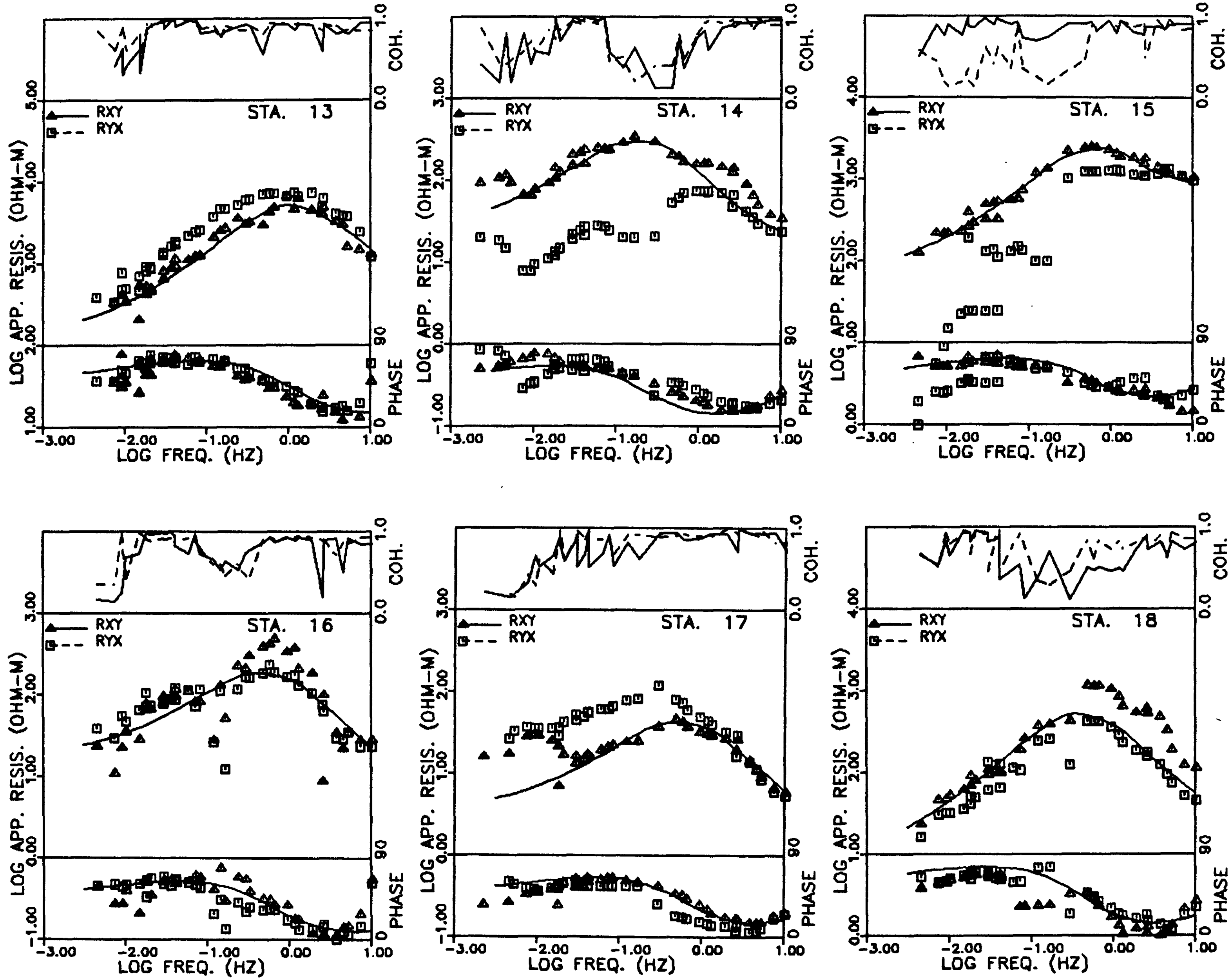

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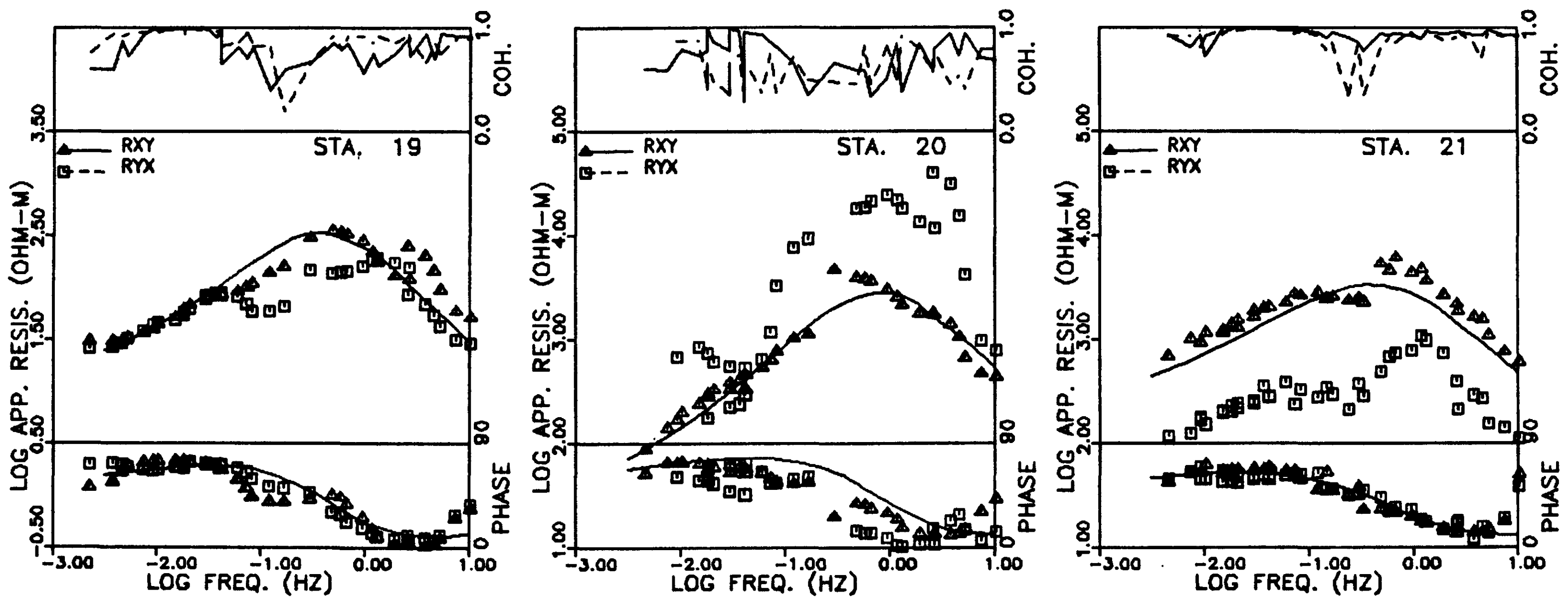

Figure 4 -- continued

apparent resistivities at lower frequencies in the present data, are modeled to fit the Rxy which is assumed to represent the E-parallel to strike (TE mode). Uncertainties in the assumed effective E-parallel or E-perpendicular modes will be resolved with 2-dimensional analysis at a latter date.

Three layer models were employed for all stations except 1, 2, and 21. This first-order modeling provides an estimate of depth to the deepest low-resistivity layer detected. The major source of possible modeling error is associated with the arbitrary choice of curves for the effective E-parallel and E-perpendicular modes.

The critical parameters derived in the present modeling are the conductance (thickness over resistivity) of the top layer, the thickness of the middle layer, and the resistivity of the bottom layer. One-dimensional models for the frequencies used are not strongly sensitive to individual variations in the thickness or resistivity of the top layer, nor are they strongly sensitive to the resistivity of the middle layer, as long as it is large (about 1,000 ohm-m or more).

Results of one-dimensional modelling are shown in fig. 5. Traverse A-A′, on the right, runs from Morman Lake (sounding 1) near Flagstaff southwest across the Colorado Plateau transition to the area of Alamo Lake (sounding 17). The shorter traverse B-B′, on the left, runs from the Turtle Mountains on the north (sounding 4) south to the middle of Rice Valley (sounding 9).

The top diagram on fig. 5 shows the changes in elevation among the stations with a vertical exaggeration of 20. The bottom diagram shows the main features of the modeling as listed in Table 2 and has no vertical exaggeration.

DISCUSSION

One common feature among all MT data acquired in this survey is the low resistivity (typically 3 to 50 ohm-m) detected at the lowest frequencies observed. This low-resistivity zone is assumed to be in the deepest part of the Earth sampled in the survey; none of the data indicate the thickness of this zone. Based on one-dimensional modeling, the top of the zone is usually below the sedimentary rocks at depths of a few km to a few tens of km.

MT studies in other areas have also interpreted a low resistivity zone within the basement rocks, typically at depths of about 10 km to 40 km (for example Mitchell and Landisman, 1971, Rankin and Reddy, 1973, Jiracek and others, 1979, Stanley and others, 1977). Laboratory measurements indicate that "dry" granite rocks do not exhibit low (about 10 Ohm-m or less) resistivities at temperatures typically inferred for the mid-crust (Olhoeft, 1981). Thus, mid-crustal low resistivities have been attributed to anomalously high thermal gradients, hydrated crustal rocks, partial melting of "wet" granitic rocks, or conductive, metamorphic or altered rocks (Feldman, 1976, Stanley and others, 1977). There is no general agreement that these mid-crustal low resistivities are widespread, or actually present as interpreted in some cases because lateral changes in resistivity rather than vertical changes may offer an alternate interpretation (Porath, 1971, Edwards and others, 1981).

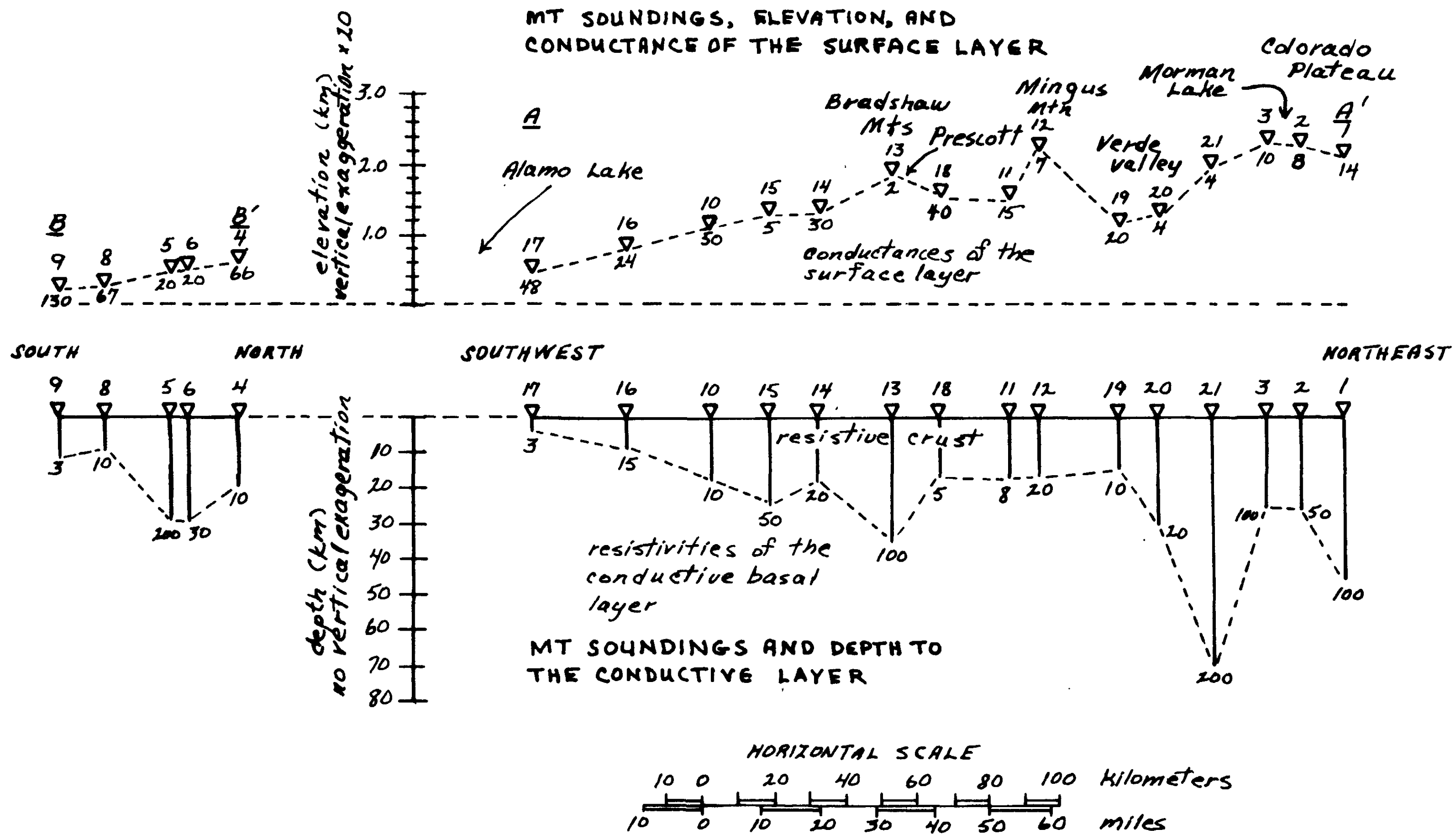

Figure 5 -- Profile of one-dimensional MT results. Shown are the elevations, surface-layer conductances (mhos), and depths to the lowermost conductor defined by one-dimensional modeling of the sounding curves. The parameters plotted are also listed on Table 2.

Table 2. - One-dimensional models. Conductance (mho, thickness over resistivity) is shown for the top layer; resistivity (R) and Thickness (T) are shown for the top and intermediate layers; resistivity (R) and depth (D), neglecting the surface layer, is shown for the basal layer. Data from sounding 7 was lost due to failure of a disk drive.

	Top Layer			Intermediate Layer(s)		Basal Layer	
Sounding	Conductance (mho)	R (ohm-m)	T (km)	R (ohm-m)	T (km)	R (ohm)	D (km)
1	14	70	1.0	(2) 500	20	100	45
				(3) 9,000	25		
2	8	50	0.4	(2) 1,000	7	50	26
				(3) 5,000	7.		
				(4) 500	12.		
3	10	100	1.0	5,000	25.	100	25
4	66	15	1.0	700	20	10	20
5	20	20	0.4	10,000	30	200	30
6	20	8	0.16	10,000	30	30	30
8	67	3	0.2	70	10	10	10
9	130	2	0.26	1,000	12	3	12
10	50	8	0.4	1,000	18	10	18
11	15	10	0.15	10,000	16	8	16
12	7	200	1.4	5,000	16	20	16
13	2	100	0.2	10,000	35	100	35
14	30	30	0.9	5,000	18	20	18
15	5	1,000	5.0	5,000	25	50	25
16	24	8	0.2	10,000	9	15	9
17	48	5	0.24	1,000	4	3	4
18	20	50	0.8	5,000	17	5	17
19	20	15	0.3	5,000	14	10	14
20	4	100	0.4	9,000	30	20	30
21	4	70	0.3	(2)10,000	40	200	70
				(3) 500	30		

The existence, and geometry of a relatively conductive zone in the crustal rocks of the present survey area will have to be verified by further analysis of the data. At present, the fact that such a zone is evident in data from numerous soundings in different local geological settings of west-central Arizona is taken as evidence that the low resistivity layer exists at depth, rather than being a misinterpretation due to lateral variations resistivity.

The preliminary interpretation (fig. 5) shows a deeping of the lower-most conductor in traversing from the Basin-and-Range Province into the Colorado Plateau area. The depth to the basal conductor varies from less than 10-km at the southwestern-most soundings to 30-km (up to 50-km) at the northeastern-most soundings. This variation in depth shows up consistently in the models from sounding 17 through 13, and suggests an electrical interface dipping northeast at about 15 degrees. The models also suggest, with less certainty, an associated increase in resistivity of the lower-most conductor to the northeast along this dip.

Northeast of sounding 13, between Prescott and Cottonwood, the lower-most, conductive layer appears to be upwarped. The models for soundings 18, 11, 12, and 19 show a depth of roughly 17 km to the top of the lower-most conductive layer. Soundings 18 and 11 are in the Chino Valley, 12 is on Mingus Mountain, and 19 is in the Verde Valley. Although there exists major topographic and surficial geology variations among these soundings, all show consistency in the deep electrical structure as modeled.

Northeast of station 19, there is again a deepening of the lower-most conductive layer. Station 21 is just a kilometer or so northeast of the rim of the Colorado Plateau (fig. 5, top). The deeping of the basal conductor between the Verde Valley and the high Colorado Plateau appears to be about 10 km based on the average of depths from soundings 11, 12, and 19 and the average of depths from sounding 20, and 1-3.

The anomalously deep interface (about 70-km) to the conductor modelled at sounding 21 is not considered reliable. The data at sounding 21 (fig. 4) has fair coherency and consistency among impedance estimates, however, there is a range of probable error associated with modeling data that has strongly divergent orthogonal sounding curves (Rxy and Ryx). The sounding curve at station 21 shows a full decade shift for all frequencies which indicates the influence of nearby lateral resistivity change. The lateral resistivity change is probably related to a combination of the topographic escarpment located about 1.5-km to the southwest and to lateral contrasts in near surface geology. Sounding 21 is near the edge of outcrop of volcanic rocks of the San Francisco volcanic field, and the interface between the volcanic rocks and the Mesozoic and Paleozoic rocks may be shallow and have variable relief.

There is a relatively shallow depth to the basal conductor at sounding 3 and 2 compared with adjoining soundings. These data cross an area marked by a chain of lakes, including Morman Lake and the Lake Mary chain, which extend linearly north toward the San Francisco volcanic field. This conductivity anomaly may be an expression of a crustal fault zone, or of a graben filled with volcanic and sedimentary rocks.

Data on profile B-B´ are generally consistent with that in the Basin-and-Range Province section of profile A-A´, in that relatively shallow depths to the basal conductor are modeled. The data at all these soundings, except 4, show poor coherence and large scatter among the impedance estimates. This signal degradation may be the effect of cultural electromagnetic signals, or temperature noise in the sensors. The temperatures in the area were generally exceeding the specifications of the instrumentation, and the area contains numerous major power lines. New data have been obtained in this area as well as further south, therefore the discussion of profile B-B´ will not be carried further at the present.

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