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Magnetotelluric Study of the Thickness of Volcanic and Sedimentary Rock in the Pullman-Moscow Basin of Eastern Washington

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Abstract

Twenty-four, 4-component, magnetotelluric (MT) soundings (.03 to 10 Hz in frequency) were made in the vicinity of Pullman, Washington, and Moscow, Idaho in September, 1985 to determine the configuration of a Tertiary volcanic- and sedimentary-rock filled basin measuring about 20 km across, on the northeast edge of the Columbia Plateau Province. Data resolve the near-surface, volcanic-sedimentary layer as having a longitudinal conductance of 2.5 to 28 mhos overlaying a resistive (300-3000 ohm-m) electrical basement. Deepest rock detected is relatively conductive (about 50 ohm-m) at about 18-km depth. Drill-hole data provide control on the thickness of the volcanic-sedimentary layer near Moscow and allow interpretation of the MT data to determine variations in thickness of the volcanic-sedimentary fill elsewhere. Two-dimensional interpretation along eight profiles delineate three areas of thin (300 m or less) volcanic-sedimentary overburden that stand out in comparison to the more usual 600- to 1000-m thicknesses over much of the basin. One of the areas is a 3-km wide shelf extending east and southeast from Smoot Hill, a small butte on the west side of the area. A similarly shallow, shelf-like protrusion is interpreted on the east side of the basin extending about 2 km beyond pre-Tertiary-rock outcrop north of Moscow. The third area of shallow basement is to the southwest of the basin, about 8 km west-southwest of Pullman, where there is no nearby outcrop of rock. This latter area is associated with nearby gravity and aeromagnetic highs which lead to an alternate interpretation of a dike swarm. Data on the west-southwest edge of the study area suggest an increase in depth to electrical basement to about 2 or 3 km.

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A MAGNETOTELLURIC STUDY OF THE THICKNESS OF VOLCANIC AND SEDIMENTARY ROCK IN THE PULLMAN-MOSCOW BASIN OF EASTERN WASHINGTON

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Introduction

Twenty four magnetotelluric soundings in the area of Moscow, Idaho and Pullman, Washington (fig.1) provide data to map the thickness of the basaltic lava flows and sedimentary and volcaniclastic interbeds that cover pre-Tertiary igneous and metamorphic basement. The work supports a hydrologic study being carried out by the Water Resources Division of the U.S. Geological Survey. Constraints on the thickness of the water-bearing, volcanic-sedimentary layer are required for a numerical model of the dynamic characteristics of the Pullman-Moscow basin ground-water flow system.

Magnetotelluric data consist of measurements of time-variations of orthogonal, horizontal electric and magnetic fields, reduced to the frequency domain (.03 - 10.5 Hz) and combined into smoothed transfer functions of apparent resisitivity and phase that define the electromagnetic response of the Earth (Vozoff, 1972). Instrumentation and field procedures are described by Stanley and Frederick (1979), and Stanley and Tinkler (1982).

There are numerous drill holes in the study area, but only two of these penetrate the pre-Tertiary basement; both are on the east side of the study area in the vicinity of Moscow, Idaho (fig. 1). The basement depth in these holes is about 400 m below the surface. Geological reasoning has placed the pre-Tertiary basement at maximum depths of approximately 1 to 2 km (Bill Lum, U.S. Geological Survey, Water Resources Division, Tacoma, Washington, personal communication, 1985). Direct-current Schlumberger-array soundings (Jackson, 1975; D. Jackson and Gregory, 1975) along an east-west line passing through Pullman and Moscow do not clearly delineate the electrical basement. The Schlumberger data indicate a inhomogeneous volcanic-sedimentary layer to depths of 1 km or more; they also indicate inhomogeneity in the upper part of the pre-Tertiary basement, and the possibility that the interface between the volcanic-sedimentary layer and underlying pre-Tertiary is poorly defined electrically.

The frequencies of the present magnetotelluric data are too low to define in detail the response of the surface layer, thus the data are primarily sensitive to the longitudinal (horizontal) electrical conductance of the surface layer, defined as the integrated thickness over resistivity (Keller and Frischknecht, 1966, p. 35). Inasmuch as the soundings within the basin do not resolve either the thickness or resistivity of the surface layer separately, it is necessary to obtain additional data to constrain the contrast between the surface layer and the electrical basement, and to establish an average longitudinal resistivity value for the surface layer. A sounding east of the basin identifies the magnetotelluric response of the pre-Tertiary basement. A sounding near the drill holes on the outskirts of Moscow constrains the electrical resistivity of the volcanic-sedimentary layer at a location where the depth to pre-Tertiary basement is known. These data provide estimates of resistivity values for both the volcanic sedimentary layer and the electrical basement and thus, form the basis for subsequent interpretation of data throughout the study area.

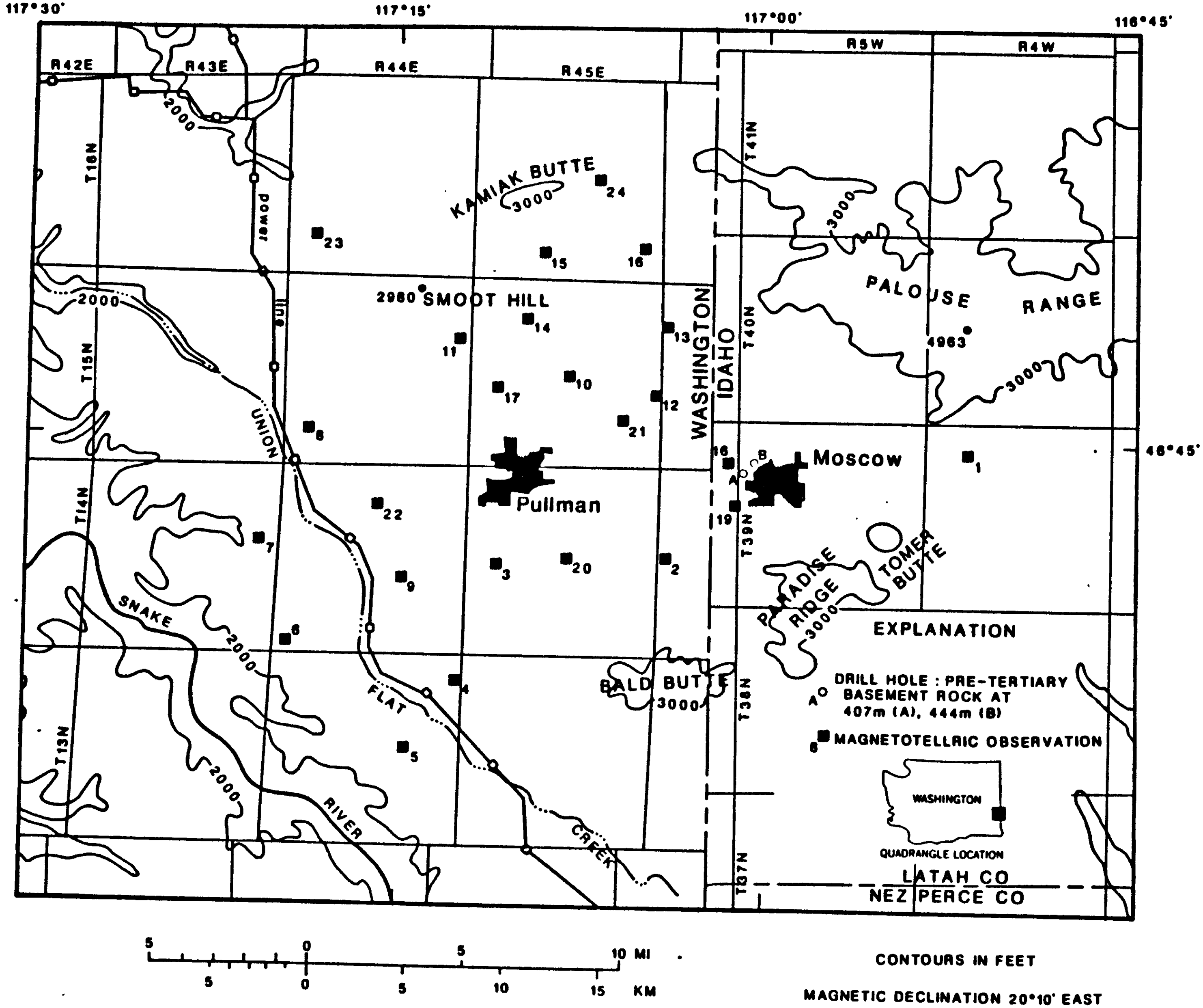

Figure 1. Map showing the location of magnetotelluric observations.

One dimensional modeling of the data provides first-order, point estimates of the thickness of the volcanic-sedimentary layer. Two-dimensional analysis provided additional information on the lateral variations in thickness of this layer.

Magnetotelluric data at the lower and more deeply penetrating frequencies contain information on the resistivities of the Earth's crust to depths of about 20 km, however, the implications of this part of the data are of secondary importance to the present report.

Characteristics of the Data

Observed sounding data are shown in fig. 2 along with theoretical sounding curves for distributions of Earth resistivity that vary only in the vertical direction (one-dimensional models). The observed data consist of two curves rotated minimize the Zxx and Zyy elements of the magnetotelluric response function (Zij) given by:

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

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

The response elements (Zij) are transformed into units of apparent resistivity (Rij) by the relationship:

$$Rij = (1/af)|Z_{ij}|^2$$

where $a=8\pi^2 10^{-7}$ and f is frequency (Hz). The phase is the arctangent of the imaginary part divided by the real part of Zij for each frequency. In fig. 2, triangles show the observed Rxy and its phase, squares show observed Ryx and its phase and solid lines show theoretical one-dimensional responses for the models listed in Table 1.

The azimuth of rotation for Rxy is within 15^o of magnetic north-south for all data. However, there is a mathematical ambiguety of 90^o in the derived azimuths. Observations are made in geomagnetic azimuths of 0^o (for x) and 90^o (for y); geomagnetic declination in the area is about 20^o east.

Uncertainty in the observed data is about 0.1 to 0.2 log-cycle (base 10 logarithm). "Uncertainty" is used qualitatively to define the noise (scatter) in the data, but it is believed to roughly correspond to the "standard error" of the mean sounding curve (a 68-percent confidence level). Coherences of the data (fig. 2 solid (Rxy) and dashed (Ryx) lines at the top of each sounding curve) provide quantitative estimates of the signal correlations for Ex:Hy and Ey:Hx at observed frequencies. Thus, data reliability is indicated directly by the coherency; lower noise levels are present when coherency is higher.

Uncertainty associated with noise in the data affects the modeling at all stages. In one-dimensional analysis, an 0.1 to 0.2 log-cycle uncertainty in the data can be shown to result into roughly 20- to 30-percent uncertainty in the determination of the surface layer conductance, and a larger uncertainty in the parameters of deeper layers. Such error bounds can also be expected in the results of two- or three-dimensional modeling.

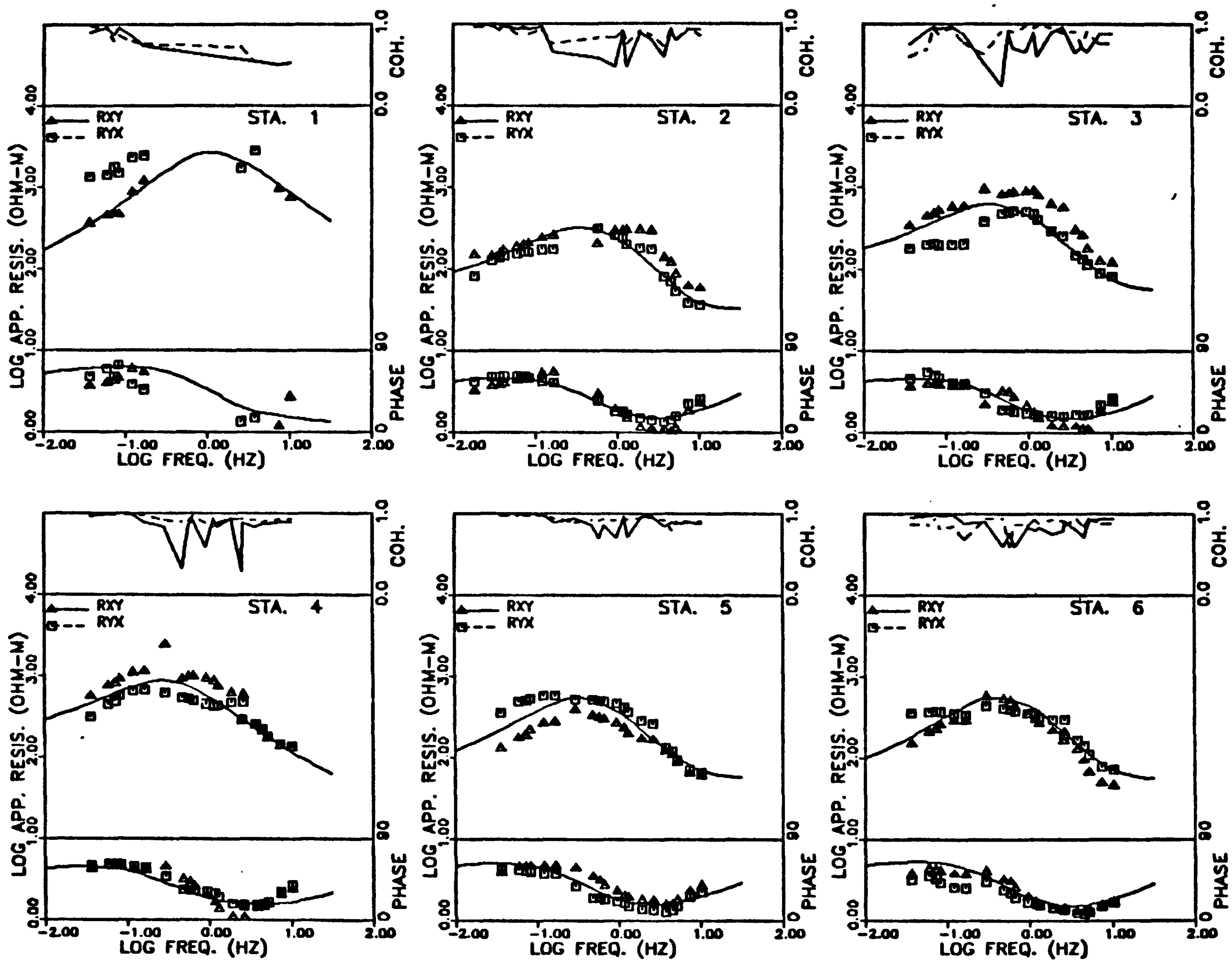

Figure 2. (soundings 1-6) Magnetotelluric sounding data and one-dimensional model responses. Triangles and squares show the observed sounding data as labeled, with coherency, apparent resistivity, and phase on the top middle, and bottom portion of each plot respectively. Modeled responses are shown by the solid lines for apparent resistivity and phase. The models correspond to those listed on Table 1.

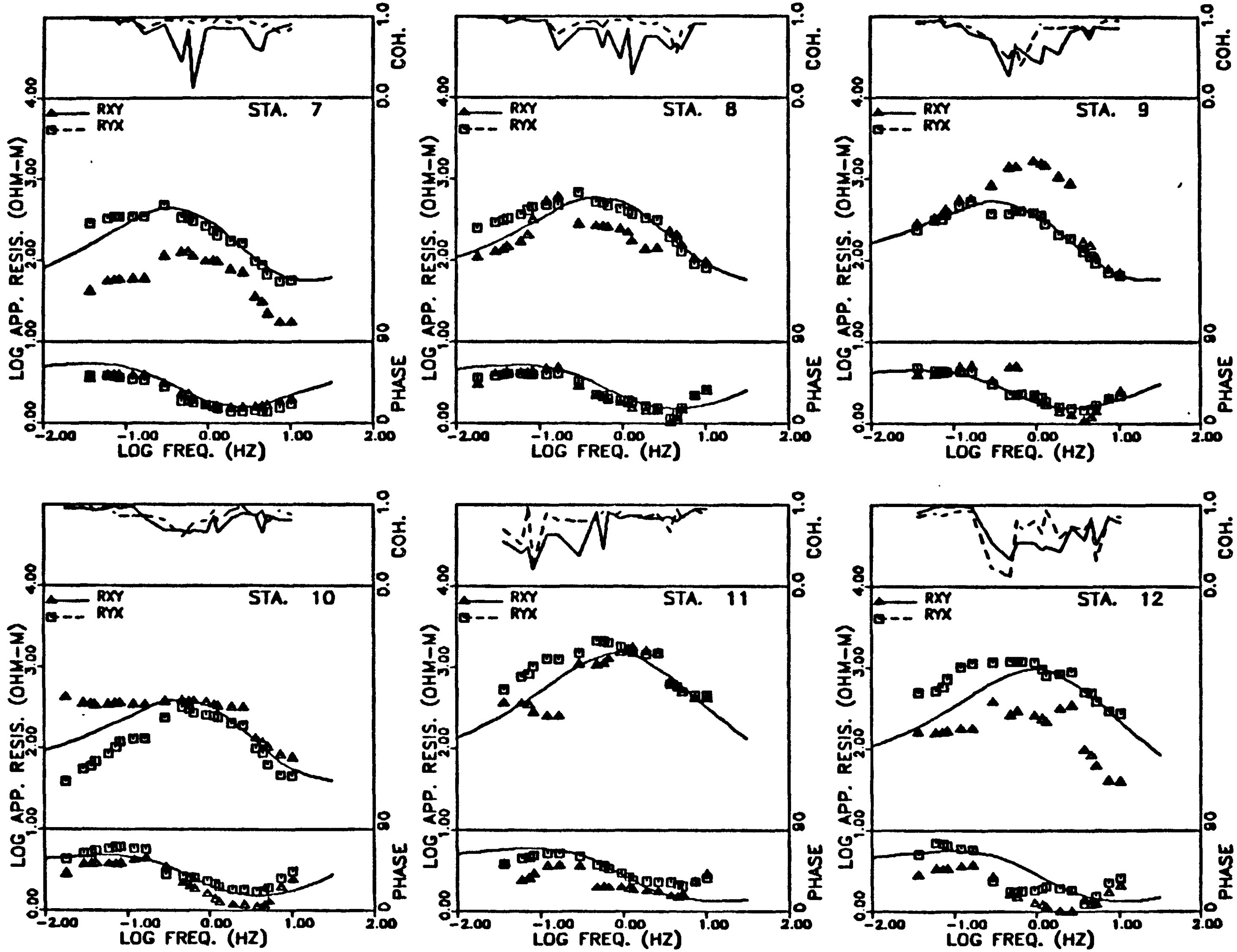

Figure 2 (continued) soundings 7-12

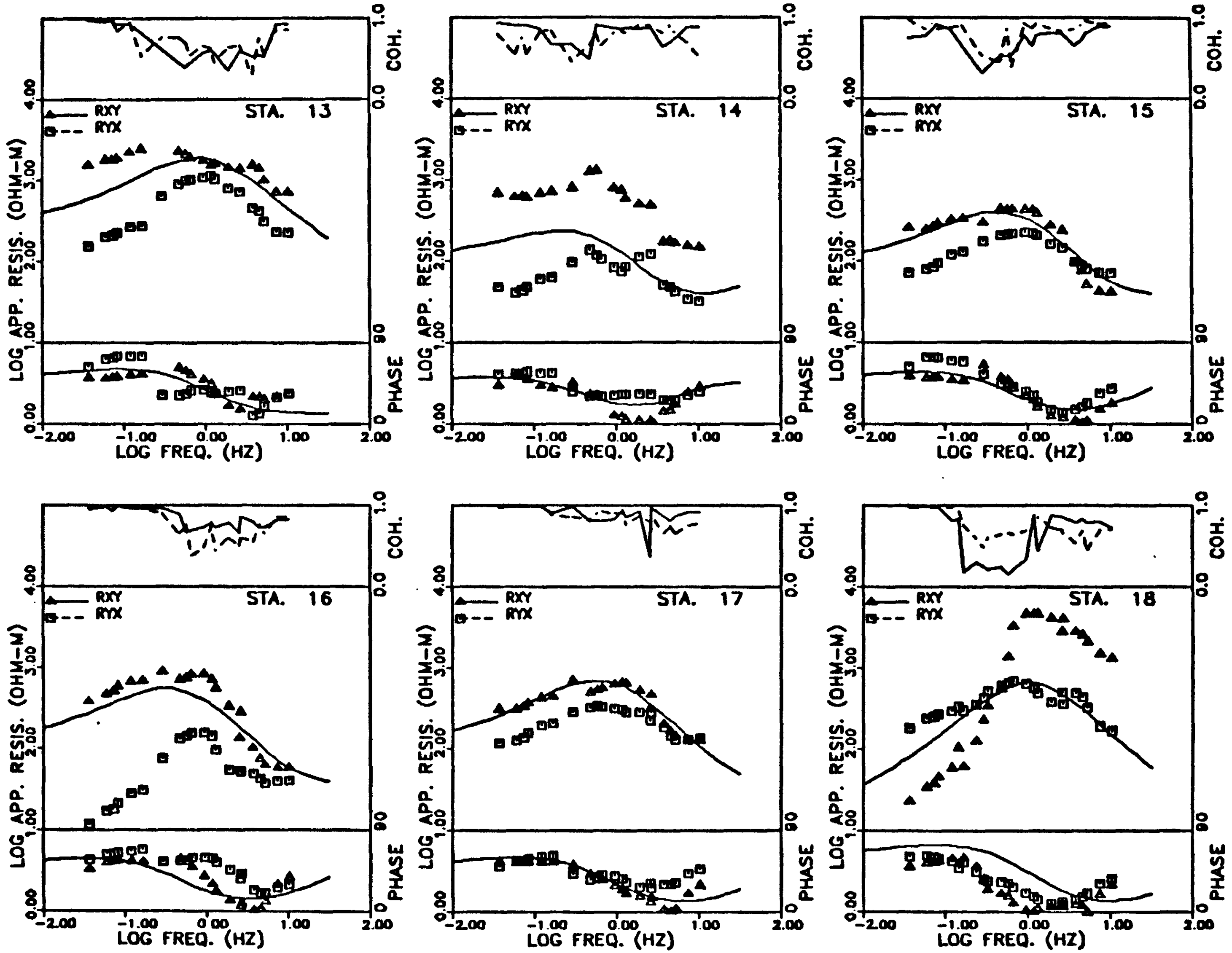

Figure 2 (continued) soundings 13-18

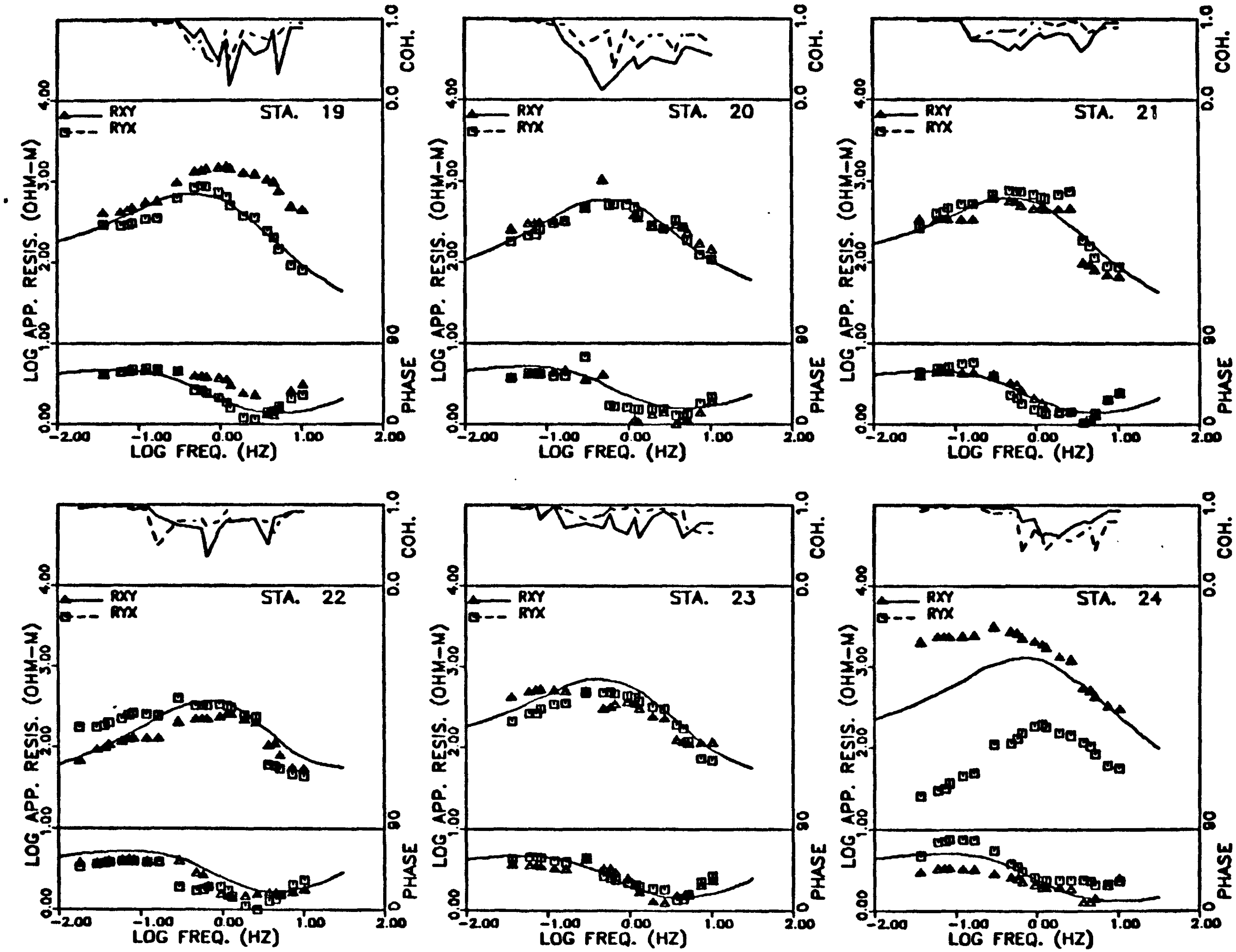

Figure 2 (continued) soundings 19–24

All soundings show response characteristics of a low resistivity layer near the surface, high resistivity in an intermediate-depth layer, and low-resistivity in the deepest rock detected. This is indicated by the descending apparent resistivity values at the higher and lower frequencies. One-dimensional (3-layer) analysis of the data indicates a surface layer conductance (thickness over resistivity) of about 11 mho as the median, an intermediate-depth layer of high resisitivity (3,000 to 5,000 ohm-m was used, but values approaching 1,000 ohm-m would suffice), and a conductive basal layer (typically 30 to 100 ohm-m) at 10 to 25 km depth. This information is summarized in table 1.

Table 1 also shows the range of logarithmic-separation (shift) between Rxy and Ryx apparent resistivities. This is referred to as distortion (Berdichevsky and Dmitriev, 1976) because it reflects a departure from a one-dimensional response where there would be no shift. Distortion usually indicates lateral changes in resistivity, but it can also be caused by cultural electromagnetic sources or cultural features that realign the natural electromagnetic fields. Distortion causes uncertainty in one-dimensional modeling. Eight of the soundings have distortions less than 0.3 log-cycle; these data can be modeled using one-dimensional resistivity distributions with reasonable confidence.

One-dimensional modeling of distorted response data can be improved by interpretative modeling, where the theoretical response is not matched to either Rxy or Ryx exclusively. For distortions caused by near-surface inhomogeneity, one-dimensional modeling can be improved when the theoretical response is weighted toward the effective H-polarization mode (TM, or H-parallel to the most influential lateral contrast) in the higher frequencies and toward the E-polarization mode (TE, or E-parallel to the most influential lateral contrast) in the lower frequencies (Berdichevsky and Dmitriev, 1976). This approach is used for the one-dimensional modeling of the present data. It is assumed in the one-dimensional modeling that the lateral changes in conductance are related to variations in thickness of the volcanic-sedimentary layer, with Rxy representing the effective E-polarization (E-parallel) mode and Ryx representing the effective H-polarization (E-normal) mode.

The 2-dimensional profile analysis reveals that the initially assumed effective polarization modes were inconsistent for several stations. Observed data do not include measurements of vertical magnetic field variations, which would have served to resolve this earlier. Also, the results of one-dimensional analysis show correlations between the derived surface layer conductances and the depths and resistivities of the basal layer. This indicates that 2- or 3-dimensional distortions due to near-surface inhomogeneities were inadequately accounted for. The profile analysis further shows that lateral resistivity variations in the deep part of the Earth are not required.

Final selection of the effective E- and H-polarization modes is based on a comparative analysis of all Rxy and Ryx curves. The effective E-polarization curves were chosen (from Rxy or Ryx) to minimize the spread among the low-frequency, descending branches of this mode. Figure 3 shows the smoothed data for all stations plotted according to the selected mode. The plots are further divided according to strongly distorted data, and (for the less distorted data) by distance from outcrop. This figure illustrates how the E-polarization mode data tends to cluster at the lower frequencies, and how the H-polarization data is distorted (shifted) throughout the whole

Table 1 -- Summary of magnetotelluric data and one-dimensional modeling results. Each layer is specified by resistivity (ρ, ohm-m) and thickness (T, m), with the longitudinal conductance (T/ρ, mhos) also shown for layer 1. Sounding curve distortion is shown as the range of logarithmic separations over the frequency range of the data. The TM (effective E-perpendicular mode, see text) is the signed (+/-), logarithmic shift of the TM mode relative to the TE (effective E-parallel mode) at the descending, low frequencies.

	ONE-DIMENSIONAL MODELS					
STATION	LAYER 1 ρ_1; T_1	CONDUCTANCE	LAYER 2 ρ_2; T_2	LAYER 3 ρ_3	SOUNDING CURVE DISTORTION IN LOG-CYCLE MIN-MAX	TM MODE SHIFT IN LOG-CYCLE S
1	20; 50	2.5	5,000; 24,000	60	0.1-0.7	+.43
2	40; 800	20.	5,000; 12,000	50	0.1-0.3	-.10
3	70; 950	13.6	5,000; 17,000	100	0.2-0.3	+.30
4	70; 650	9.3	2,000; 25,000	150	0. -0.2	+.21
5	70; 1,000	14.3	2,000; 18,000	50	0. -0.6	+.39
6	70; 1,000	14.3	5,000; 16,000	40	0.2-0.4	+.19
7	70; 1,250	17.9	5,000; 15,000	30	0.5-1.0	-.76
8	70; 800	11.4	3,000; 15,000	50	0.1-0.4	+.38
9	70; 1,100	15.7	5,000; 16,000	90	0. -0.8	+.08
10	50; 800	16.	5,000; 12,000	50	0.2-1.2	-.26
11	50; 250	5.	5,000; 20,000	50	0. -0.3	+.39
12	50; 330	6.6	5,000; 15,000	50	0.8-1.0	+.68
13	50; 200	4.0	5,000; 22,000	250	0.5-1.3	+.93
14	50; 1,400	28.	5,000; 10,000	100	0.6-1.4	-1.03
15	50; 800	16.	5,000; 12,000	80	0.2-0.5	-0.42
16	50; 750	15.	5,000; 17,000	100	0.3-1.8	-1.40
17	50; 500	10.	5,000; 15,000	100	0. -0.4	-0.37
18	50; 420	8.4	5,000; 12,000	10	0. -1.0	+0.82
19	50; 550	11.	5,000; 17,000	100	0.2-0.8	-0.16
20	70; 700	10.	2,000; 15,000	50	0.1-0.1	-0.10
21	50; 570	11.4	5,000; 15,000	100	0.2-0.2	-0.11
22	70; 1,000	14.3	5,000; 10,000	30	0.1-0.4	-0.25
23	70; 800	11.4	5,000; 17,000	100	0.2-0.3	+0.23
24	50; 300	6.0	5,000; 20,000	120	0.8-2.0	-1.69

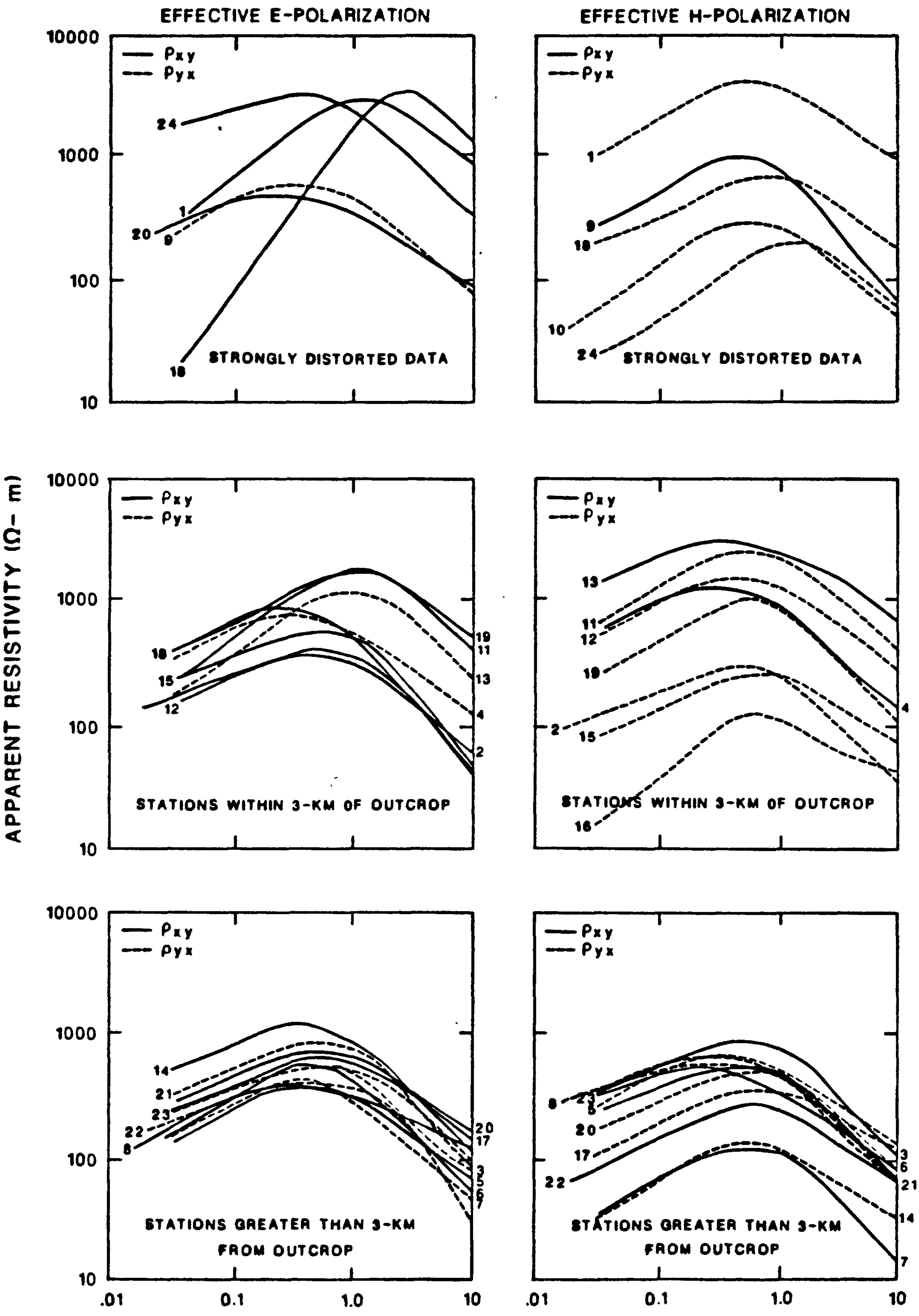

Figure 3. Magnetotelluric apparent-resistivity sounding curves separated into effective E- and H-polarization modes. The dashed curves are Ryx data; the continuous curves are Rxy data.

frequency range. These features are characteristic of data influenced by lateral heterogeneity in near-surface resistivities.

Table 1 lists the observed shifts (S) between the inferred polarization modes. This is similiar to the distortion parameter, except the logarithmic average is taken only for the low-frequency part of the curve. The sign indicates the direction of shift of the H-polarization mode (along the apparent resistivity ordinate) with respect to the E-polarization mode. Positive values indicate that the H-polarization is shifted upward, negative values indicate the H-polarization is shifted downward. This is referred as the S shift, and has primary significance in the 2-dimensional analysis.

Geoelectric characteristics of the strata

Station 1 (fig.1) is located in an area of mapped, pre-Tertiary-rock outcrop, although the observation was actually on loess. The sounding provides evidence that the bulk of pre-Tertiary rock has high resistivity, at least 1,000 ohm-m. Apparent resistivities for the higher frequencies at station 1 are consistent with shallow cover (50 m) of conductive (20 ohm-m) sediment, but also allow the possibility that part of the upper, pre-Tertiary rock has fairly low resistivity.

If the upper part of the pre-Tertiary rock contains conductive zones, such as might be associated with metamorphic lithologies (phyllite or mica shist for examples), or associated with weathering and alteration prior to the deposition of sediments, then this conductive zone may be integrated into the surface layer as the modeling technique utilizes step changes in resistivity (in contrast to gradational changes). This factor contributes to ambiguity in interpreting the geological interface in terms of the geoelectric model.

Station 18 (fig. 1) provides an estimate of the electrical resistivity of the volcanic-sedimentary layer; this station is within about 1 km of two drill holes that penetrated pre-Tertiary basement rock. Based on the known depth to the pre-Tertiary basement, the resistivity of the volcanic-sedimentary surface layer is estimated at 50 to 70 ohm-m.

Schlumberger data (D. Jackson, 1975) show that resistivity variations within the volcanic-sedimentary layer range from 10 ohm-m to values of several 100 ohm-m. The lower resistivities may represent clayey sedimentary beds or altered volcanic rock; the higher resistivities are characteristic of massive basalt flows.

The volcanic-sedimentary layer is generally covered by loess. The thickness of the loess, based on shallow drill hole information, can be as great as 70 m (230 ft); but is more commonly less than 30 m (100 ft). Schlumberger data (D. Jackson, 1975) indicates resistivities of 10- to 40-ohm-m for the loess layer.

The present interpretation must assume a value for the average longitudinal resistivity for all units that comprise the low-resistivity, near-surface zone which includes the loess and the volcanic-sedimentary rocks. This value is constrained only near the drill holes on the eastern side of the basin. Lateral lithological changes in the near-surface layer may be mistaken as variations in thickness, which adds another element of error in the current interpretation.

Thickness of the volcanic-sedimentary layer

Method

Observed magnetotelluric data are analyzed along the profiles shown in figure 4. The analysis is based on 2-dimensional, numerical modeling using the method described by Madden and Swift (1969) and Swift (1971). Figure 4 also shows the inferred changes in surface-layer thickness derived by the analyses. One-dimensional modeling results are shown for stations 6 and 19 which are the only stations excluded from a profile. The method utilizes horizontal and vertical step changes in resistivity, thus, the results should be considered as an available solution to possible gradational variations in resistivity, or sloping interfaces between rocks of different resistivity.

Constraints in modeling the surface layer are provided by the high-frequency, H-polarization data that define the conductance of the near-surface zone beneath the station, and by the S shifts that define lateral inhomogeneities. The latter is assumed to be related to the thickness of the surface layer. The sign of the S shift indicates whether the observation is on the resistive side of an inhomogeneity (+), or on the conductive side (-). Inhomogeneity should be located laterally in the direction perpendicular to the azimuth of the effective E-polarization.

Constraints on the deeper part of the Earth are provided by the E-polarization data at low frequencies. These data define the depth to, and the resistivity of the basal layer. Preliminary 2-dimensional modeling trials indicated that it is not required to incorporate the variations in the resistivity and depth to the basal layer derived in the one-dimensional analysis. The median depth to the basal low-resistivity zone (table 1) is about 18 km; the logarithmic median of the resistivity of this layer is about 50 ohm-m. These values are generally appropriate for the 2-dimensional models.

Computed 2-dimensional response curves are compared to observed apparent resistivities and phases selected at intervals of roughly 1/3 to 1/2 decade in frequency. This corresponds to the theoretical 2-dimensional response data calculated on 0.5-decade intervals in frequency. The continuous theoretical curves displayed are interpolated between calculated points using a spline curve.

Results are presented as cross sections showing the modeled resistivity distribution together with the theoretical response and observed data for each sounding on the profile. Cross-sections are plotted linearly in the horizontal direction and logarithmically in the vertical direction. Upper parts of the model, usually the upper 100 m, are not shown but are identical in resistivity to the shallowest level displayed. All observations are assumed to be on a plane surface at zero depth.

Cross-section interpretations

In the discussion below, terminology is used in the context of the assumptions of the interpretation. The geoelectrical basement is considered synonomous with the pre-Tertiary basement. It is considered to be represented by the first resistive unit below the relatively low-resistivity surface layer. The surface geoelectric layer, unless specified, is assumed to represent the volcanic-sedimentary layer.

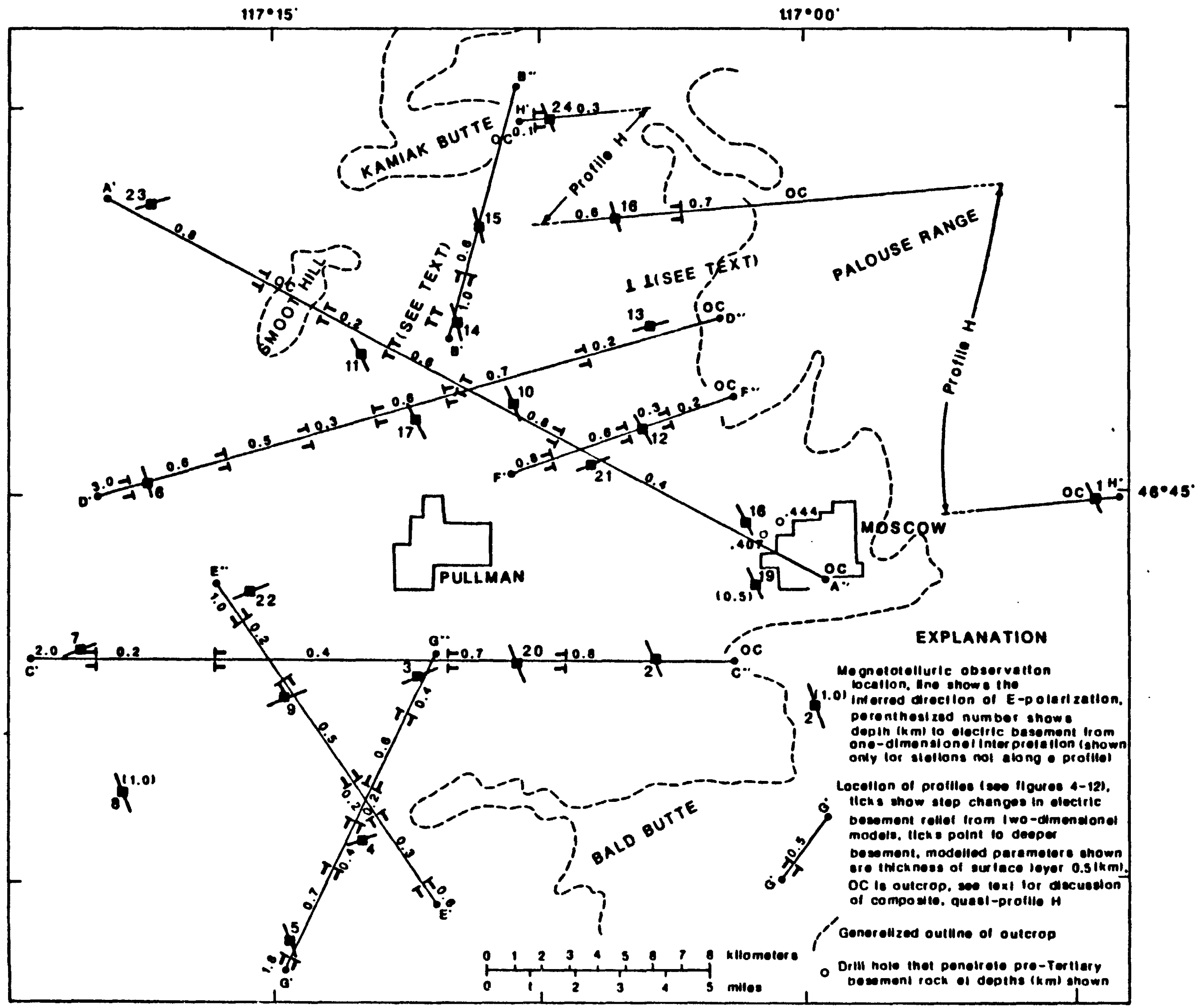

Figure 4. Profile locations showing sounding locations and depths to resistive basement inferred from two-dimensional analysis.

Profile A′-A′′

Profile A′-A′′ (fig. 5) crosses the central part of Pullman Basin in a southeast direction from station 23, northwest of Smoot Hill to the area of Moscow. The low-resistivity layer beneath Smoot Hill accounts for 3-dimensional electric "flow-around" associated with a resistive body in a conductive layer. This layer is an artifact of the 2-dimensional method, and it is not considered to represent vertical resistivity changes.

A shallow, high-resistivity basement shelf is indicated southeast of Smoot Hill beneath station 11. The model shows the resistive basement at about 200-m depth and extending eastward about 3 km from the outcrop. This feature is controlled by the observed data at station 11.

Misfit between observed and theoretical data along profile A′-A′′ is seen at station 23 at the lower frequencies where the S shift has the wrong sense, and at 18 where the E-polarization (TE) data cannot be fitted. There is also a misfit at station 10 where the small observed S shift near 1 Hz is not consistent with the larger shift at the lower and higher frequency. The misfit at station 23 is within in the data uncertainty, but suggests an additional deepening of the volcanic-sedimentary layer to the northwest. At station 18, the E-polarization data is beleived to be distorted by cultural electrical noise in the vicinity of Moscow, and is not used in fitting the data.

On the southeast edge of the profile, pre-Tertiary rock associated with outcrop requires resistivities less than about 300 ohm-m to fit the observed S shifts. Similiar results are found for all profiles that extended to the eastern edge of the basin; this suggests an upper zone within the pre-Tertiary rock where the longitudinal resistivity is significantly lower than the average for the upper-crustal, basement rocks. Schlumberger data also indicate that parts of the pre-Tertiary basement rocks had relatively low resistivity (Jackson and Gregory, 1975).

Profile B′-B′′

Profile B′-B′′ (fig. 6) extends northward from the central part of the basin, to Kaimiak Butte (stations 15 and 14). This profile is analyzed to investigate the one-dimensional result, derived at station 14, which suggests an anomalously thick section of volcanic-sedimentary rock (table 1). Azimuths of E-polarizations on this profile are approximately parallel to the profile. Inasmuch as the E-polarization azimuth is assumed to represent the effective strike of resistivity contrasts, the modeled contrasts for this profile may represent contrasts lateral to the profile rather than along the profile. Furthermore, the distribution of outcrop indicates that three-dimensional effects also may have a major influence on the magnetotelluric response in this area. Nevertheless, 2-dimensional modeling provides information on the magnitude of resistivity contrasts responsible for the observed S shift, particularly at station 14 where the S shift is larger than one decade of apparent resistivity. The sounding was obtained at a location where there was no obvious source of cultural distortion.

The modeling demonstrates that station 14 requires a significant, near-surface resistivity contrast within a distance of about 1 km. This contrast, which is modeled as "outcrop" 0.2 km south of 14, is believed to represent the effect of shallow basement east of Smoot Hill. This shelf is also detected by

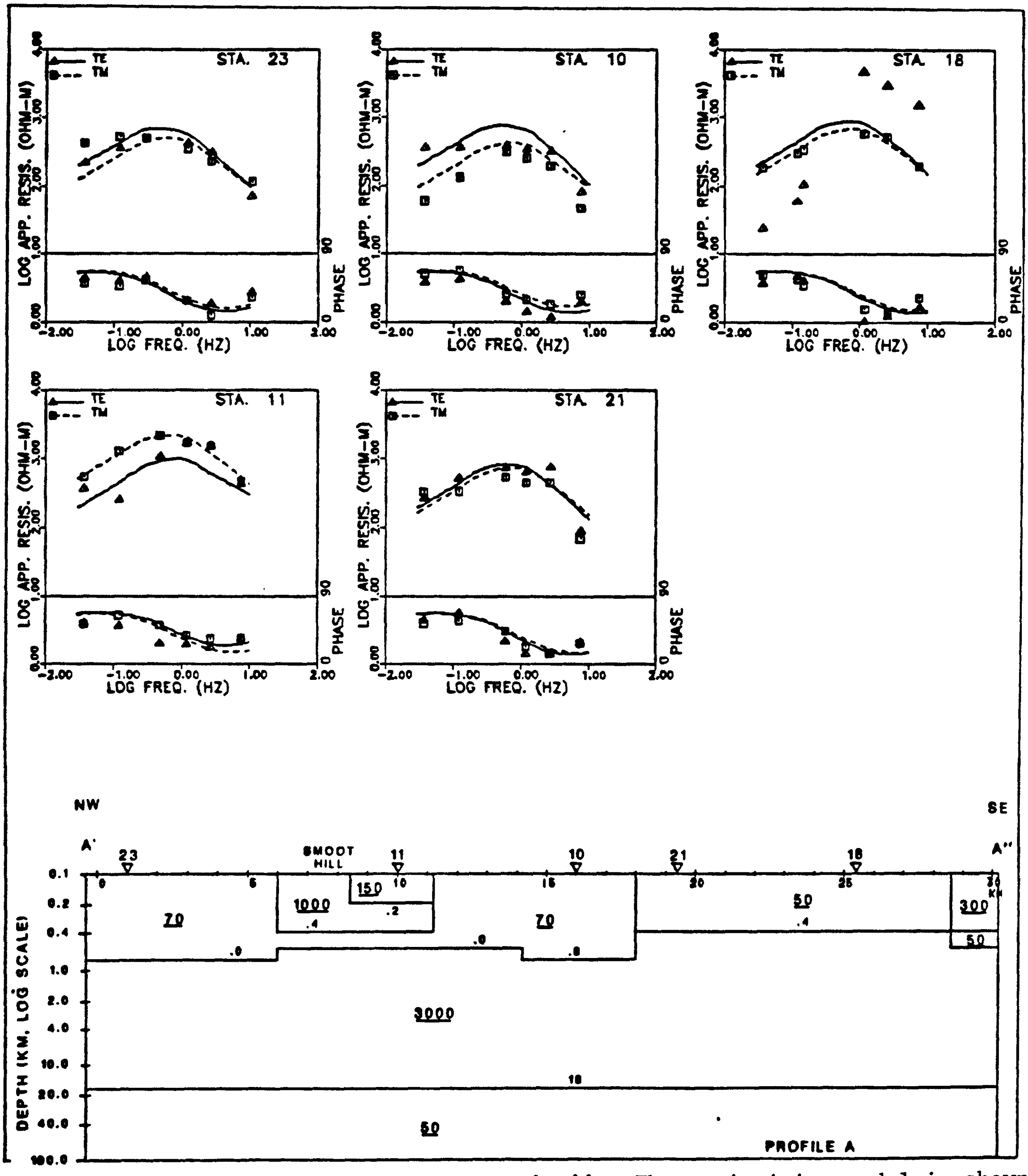

Figure 5. Magnetotelluric model of Profile A'-A''. The resistivity model is shown on the bottom of the figure, with linear horizontal distances and logarithmic depths. Model resistivities (ohm-m) are underlined; depths are in km; responses are calculated at horizontal locations shown by triangles and sounding number. Distances along the profile are ticked in km. Calculated and observed responses are shown above the model; continuous and dashed lines are calculated TE (E-polarization) and TM (H-polarization) modes respectively. Triangles and squares are observed TE and TM modes respectively.

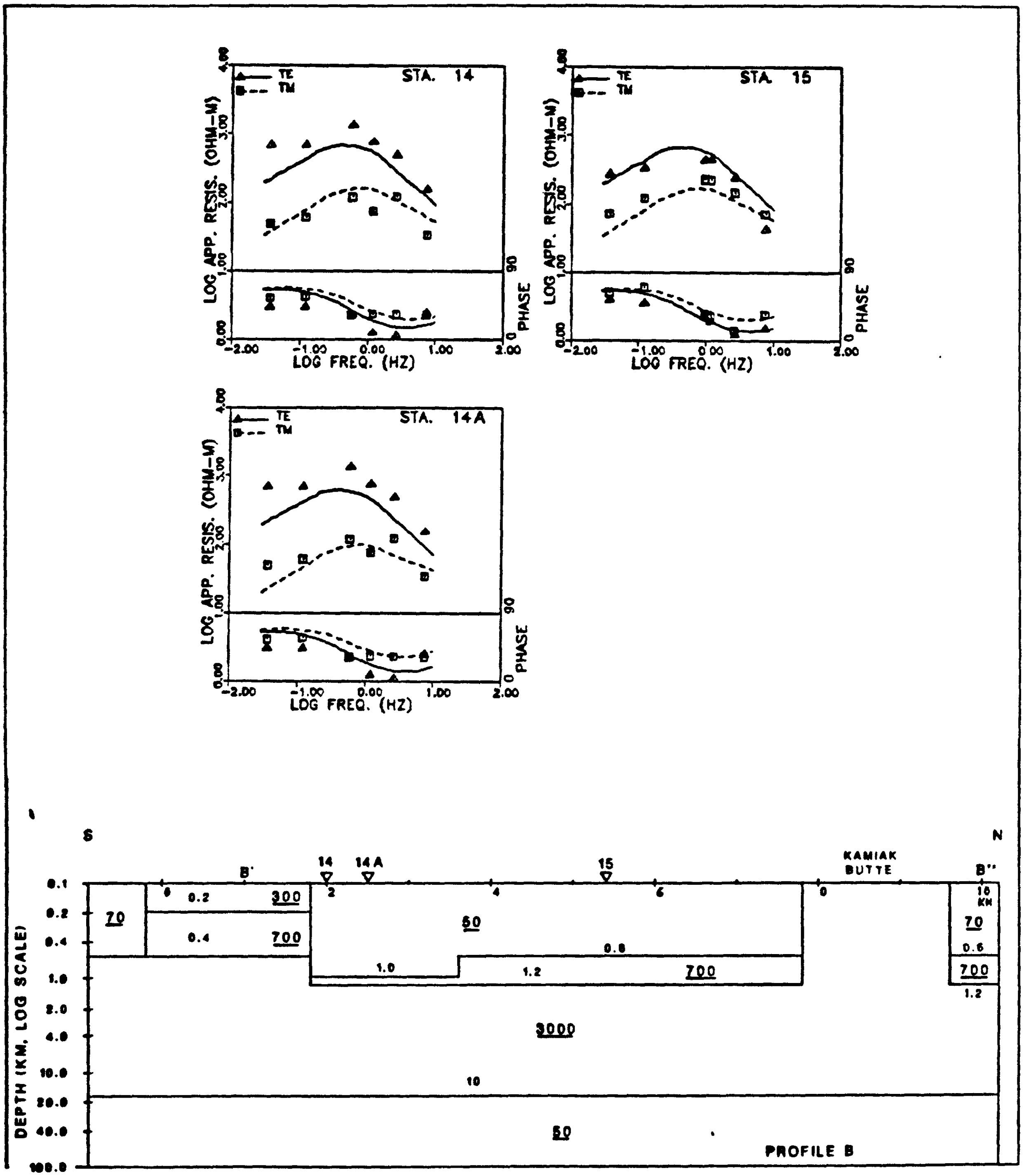

Figure 6. Magnetotelluric model for profile B'-B''. See fig. 5 for explanation. 14A is an alternate position considered for station 14 to show the influence of distance from nearest interface.

station 11 (profile A′-A′′), and thus may trend north roughly parallel to profile B, and approach within 1 km of station 14. There is probably a step in the pre-Tertiary basement relief just west of 14, dropping from about 200-m depth on the shelf to about 800- to 1000-m depth in the vicinity of station 14. No 2-dimensional model was found that would reproduce the magnitude of the S shift, and fit the E-polarization mode for station 14. The observed data are believed to be indicating a concentration of electric current caused by the 3-dimensional distribution of near surface resistivities.

The resistivity contrast caused by outcrop north of station 15, corresponding to Kamiak Butte, controls the computed S shift at station 15. However, based on the azimuth of the E-polarization data at station 15, the S shift is equally consistent with shallow basement west (or east) of 15. The configuration of outcrop (fig. 4) suggests that Smoot Hill may be connected to Kaimiak Butte by a ridge of basement. Data at stations 14 and 15 are consistent with such basement being within 100- or 200-m of the surface.

Profile C′-C′′

Profile C′-C′′ (fig. 7) crosses the southern part of the basin about 2 km south of Pullman, extending east from station 7 to station 2. Stations 3 and 7 have an inappropriate E-polarization azimuth for the direction of this profile. Station 3 is analyzed more appropriately on profile G, but retained here for reference. Station 7 is retained to gain some insight into the magnitude of resistivity contrast required for the observed S shift; this station is far enough from other stations on the profile so that the effect of the required contrast should not have a major effect on the response at the remaining stations. The resistivity structure midway between stations 20 and 7 is modeled by profiles E and G.

Sounding 7 requires a major resistivity increase within about 0.5 km. Based on the azimuth of the E-polarization, this contrast could be either to the northwest or to the southeast. The southeast position is more consistent with profile E.

The eastern part of profile C′-C′′ is characterized by relatively low resistivity in the surface layer and in the electrical basement rock. An alternative would be to infer a thicker volcanic-sedimentary layer. Either alternative requires a small contrast where outcrop is mapped.

Profile D′-D′′

Profile D′-D′′ (fig. 8), north of Pullman, extends from the west side of the study area (station 8), northeastward across the Pullman-Moscow basin to outcrop on the east near station 13. Station 13 has an E-polarization parallel to the profile, thus the model fitting was weighted toward sounding 10 rather than 13. Station 11 is projected into this profile for reference because its′ E-polarization direction is well suited to the orientation of this profile. Station 11 is also analyzed on profile A′-A′′.

The resistivity contrast west of station 8 (lower resistivities or deeper pre-Tertiary basement) is required by the data at this station. The solution presented shows a fault in the basement (2.2 km throw), however, an alternate solution (not shown) that had an equivalent fit decreased the throw to 1.0 km by having an outcropping contrast in the surface layer (50 ohm-m to a depth of 1.8 km) to the west. This alternative is disconcerting, but points out the importance of S-shift enhancement when contrasts are brought to the surface as outcrop.

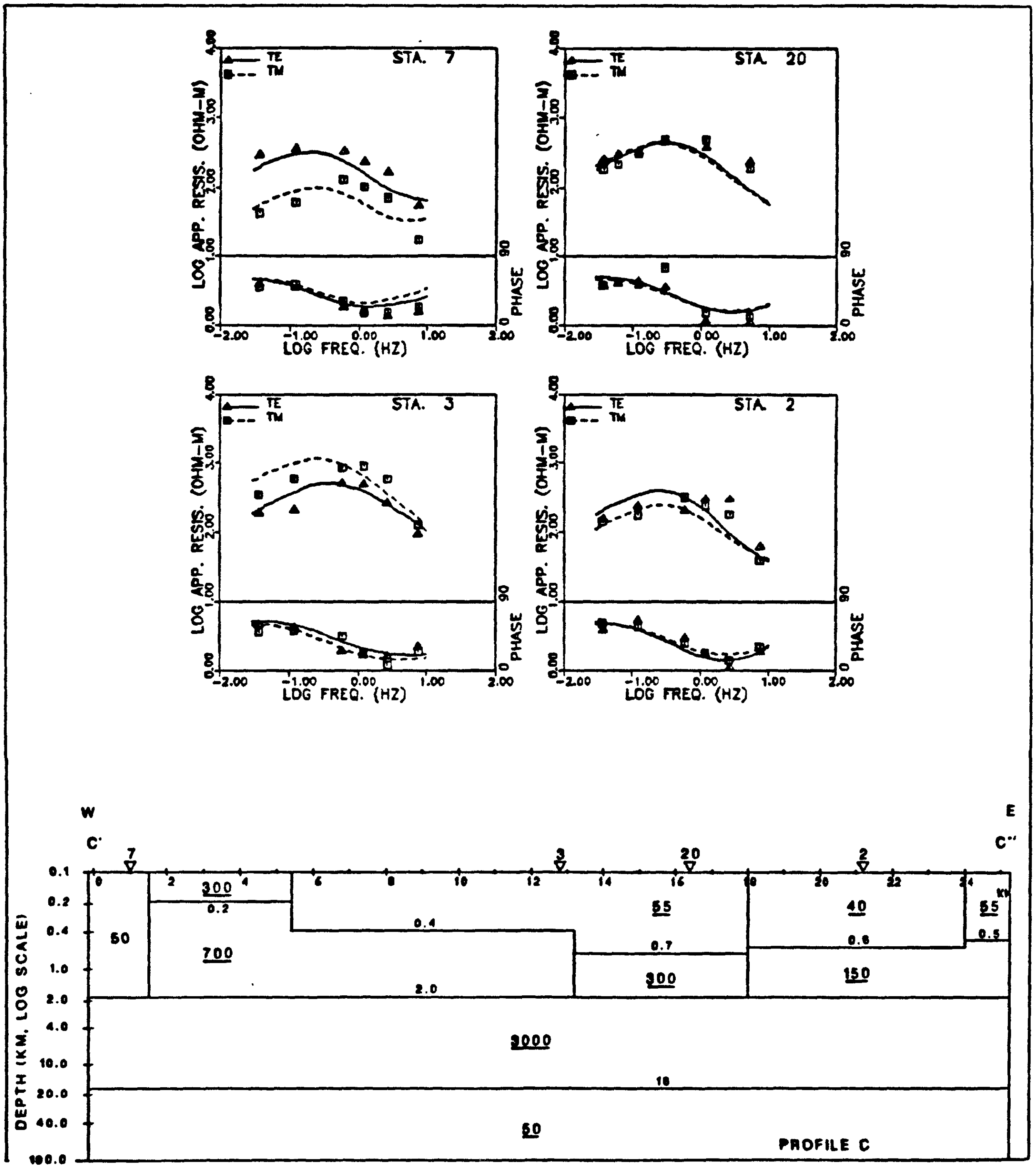

Figure 7. Magnetotelluric model for profile C'-C''. See fig. 5 for explanation.

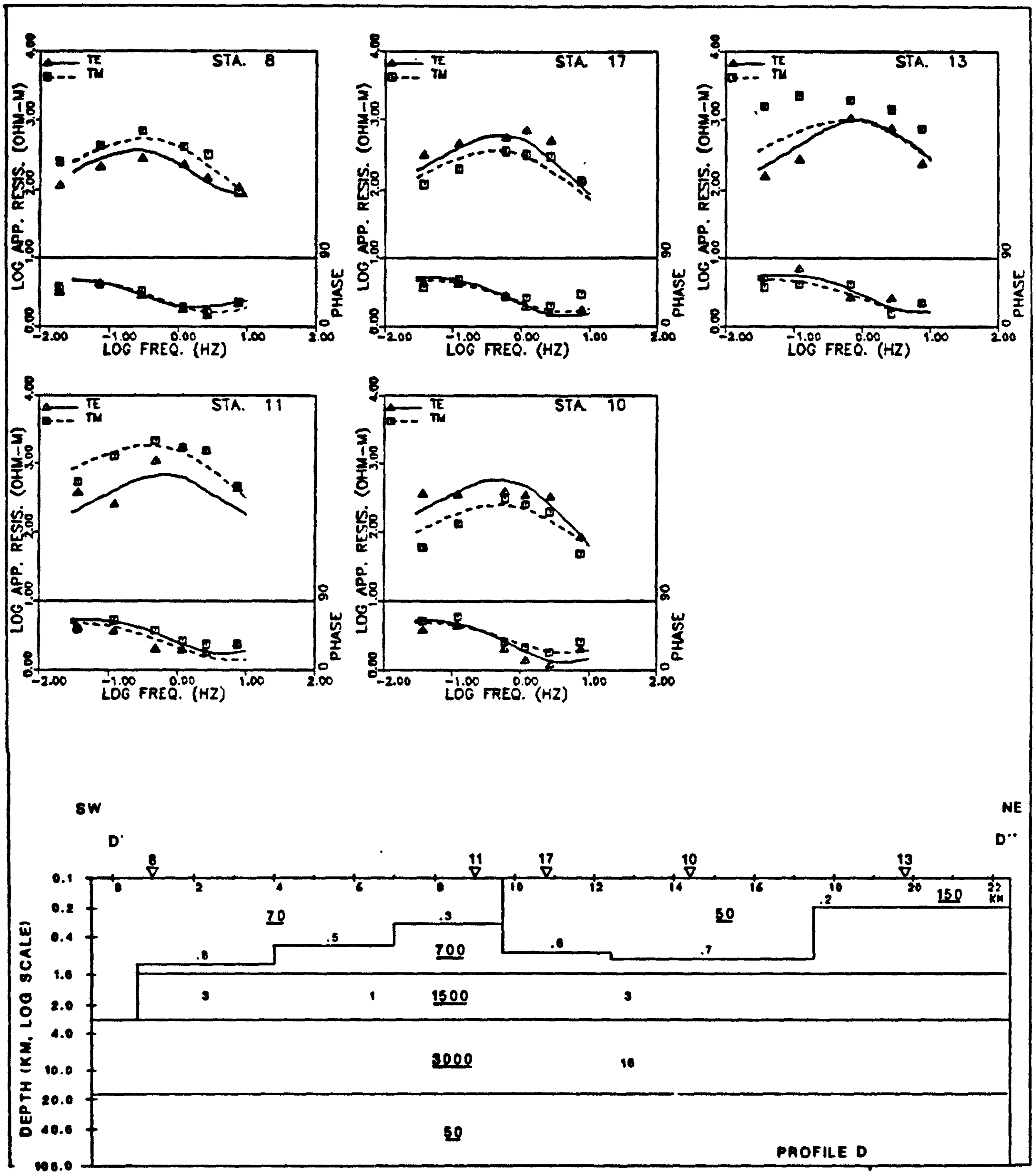

Figure 8. Magnetotelluric model for profile D'-D''. See fig. 5 for explanation.

The shallow basement (under projected station 11) is required for the response at station 17; however, the configuration of the basement deepening between stations 8 and 17 is not well controlled.

A wide (about 3 km) shelf on the east side of the basin is indicated by the observed response at stations 10 and 13. Station 10, on the conductive side, requires a step within a distance of 2 to 3 km. Station 13, on the resistive side, requires a step within about 1 km. The model uses the requirements indicated by station 10. A solution might have been found that satisfied both stations by using a two-step model between stations 10 and 13, but the E-polarization azimuth at 13 suggests that the response at this station is largely affected by an interface to the north or south (rather than along profile). Thus, there is evidence that the shelf is limited in north-south extent. Based on the data at station 12 (profile F), it is believed that this shelf is truncated north of station 13.

Profile E′-E′′

Profile E′-E′′ (fig. 9) is located southwest of Pullman, extending northwest from the vicinity of station 4 to the area of station 22. E-polarization data are well oriented with respect to the profile. H-polarization data (TM) at station 9 are suspect because of a large upward shift in a limited frequency band from 0.7 to 1.3 Hz. This portion of the data is believed to be distorted by cultural distortion and is not weighted in the fit. A north-south, grounded steel fence located about 100-m west of this station is a source of data distortion.

A relatively shallow basement is indicated across the whole profile. The shallow resistivity anomaly southeast of station 22 is required for the negative S shift at this station. Such an anomaly northwest of station 22 would not be consistent with the data at station 8 (profile D′-D′′).

Sounding 4 requires a relatively shallow basement, such as a ridge of pre-Tertiary rock extending west from the protrusion of outcrop associated with Bald Butte (fig. 4).

Sounding 6 (fig. 2, not analyzed on a profile; see also fig. 4) is consistent with an increasing thickness of the volcanic-sedimentary layer from north of station 9, to about 1-km southwest of 6, where an abrupt increase in surface-layer conductance (interpreted as a fault in the pre-Tertiary basement) may be postulated.

Profile F′-F′′

Profile F′-F′′ (fig. 10) crosses the eastern edge of the basin to provide further information on the westward-extending, shallow basement (see profile D). The E-polarization azimuth at station 21 is parallel to this profile, but the data for the station are nearly 1-dimensional in character (table 1), thus, the inferred azimuth is not critical. Station 10 is projected about 2.5 km, but its′ inclusion in the profile is instructive in showing that this sounding is more sensitive to the shallowing of resistive basement toward outcrop rather than to buried shelf (or ridge) on the west (see profile D).

The S shift at station 12 requires a shallow, resistive basement extending outwards about 3 km from the mapped outcrop. This data suggests a southward continuation of the shallow electrical basement inferred on profile D. The cause of the misfit of the E-polarization (TE) mode between the model

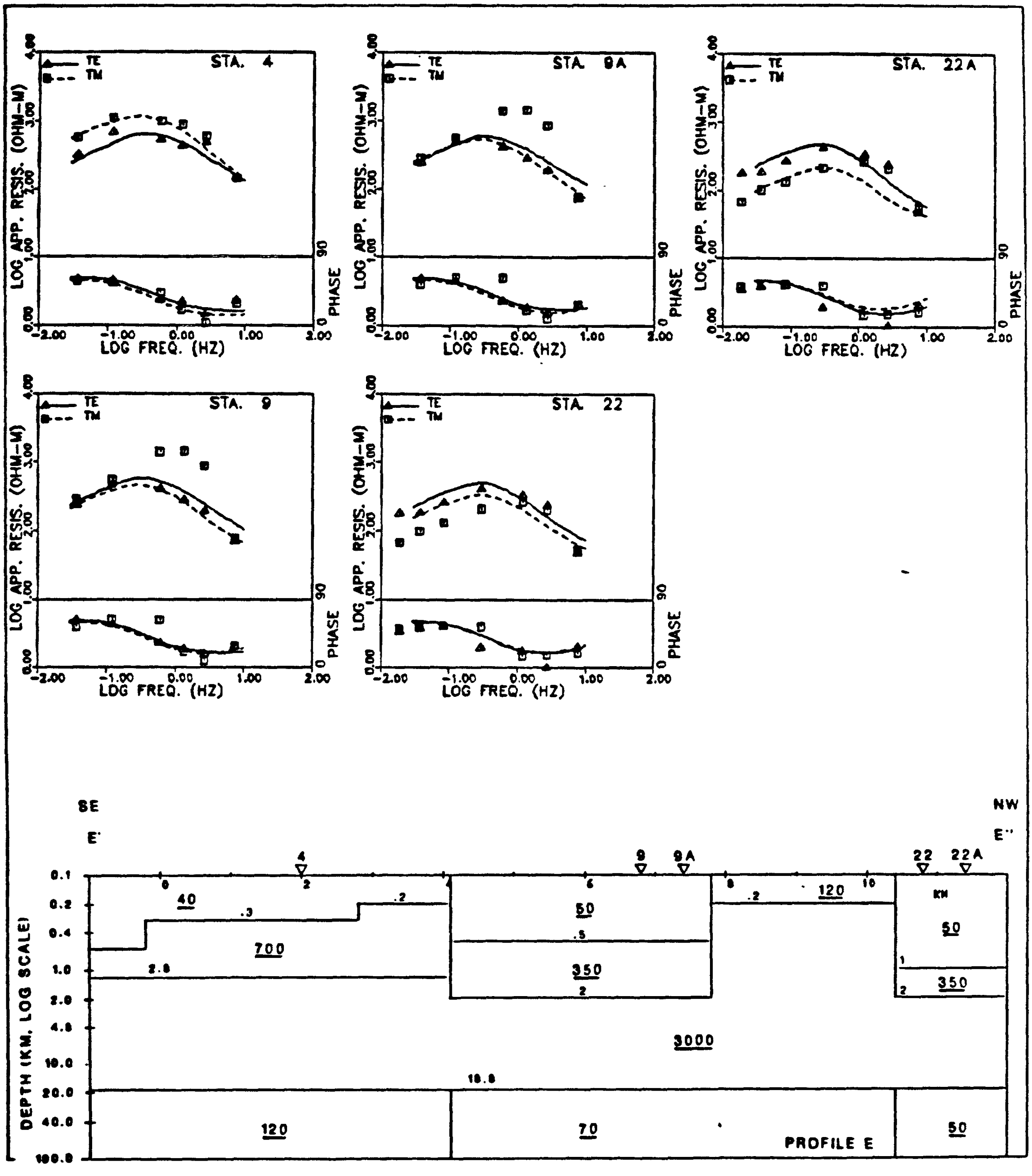

Figure 9. Magnetotelluric model for profile E'-E''. See fig. 5 for explanation. 9A and 22A are alternate positions considered for stations 9 and 22 to show the influence of distance from the nearest interface.

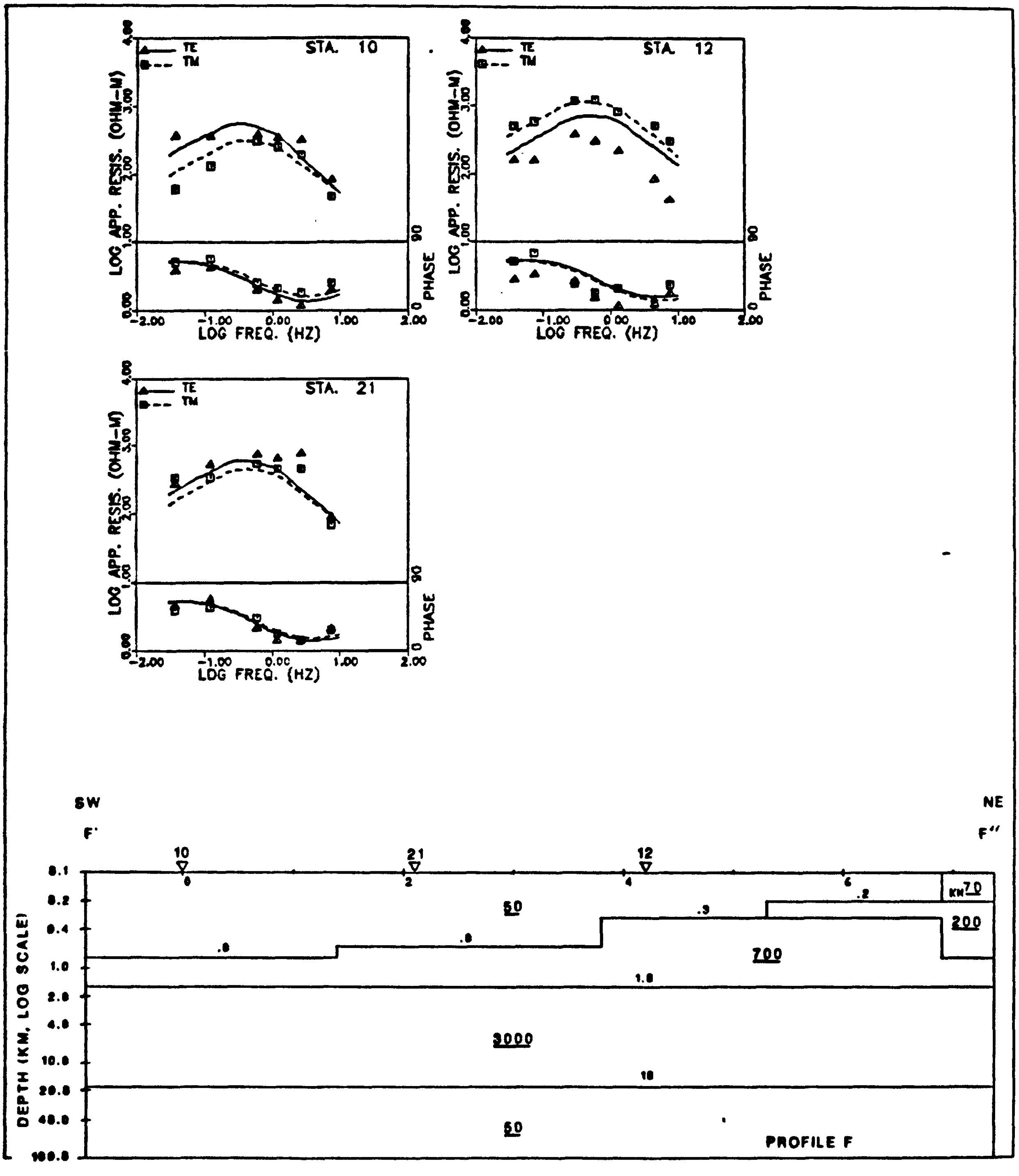

Figure 10. Magnetotelluric model for profile F'-F''. See fig. 5 for explanation.

and data for station 12 could not be resolved by 2-dimensional modeling. The observed E-polarization data have anomalously low amplitudes (figs. 2 and 3) that may result from cultural or (and) 3-dimensional distortion. The sign of the S shift, however, requires a model fundamentally like that shown on fig. 10.

Profile G′-G′′

Profile G′-G′′ (fig. 11), located south of Pullman, extends north end from station 5 to station 3. The profile provides an alternate view of the resistivity structures responsible for the responses at soundings 3 (profile C) and 4 (profile E).

Shallow resistive basement in the vicinity of station 3 on the north end of the profile is consistent with the model of profile C. Inasmuch as the E-polarization at station 3 is oriented at roughly 45^{o} to both profile C and profile G, the location of the lateral resistivity contrast on both profile models is misplaced. The preferred location of the contrast is southeast of station 3, consistent with E-polarization azimuth at station 3, and with the overall configuration of models for both profiles.

The resistivity structure near station 4 is essentially that discussed with profile E. The vertical step south of station 5 is consistent with the requirements of the S shift at this station, but does not rule out a resistivity contrast associated with a lithology variation rather than with a fault.

Profile H′-H′′

Profile H′-H′′ (fig. 12) is a composite of non-aligned soundings that traverses station 24 near Kamiak Butte, then is offset to the south to station 16, and is offset again to station 1. The model is valid to qualitatively indicate some isolated characteristics for each of the stations shown. The reason for this is that each sounding response is dominated by the effect of the nearest outcrop. Various models showed that the effects of buried resistivity contrasts more than 4-km east of station 24 have a minor effect on the response at 24; similarly, the effects of buried resistivity contrasts more than 3-km west of station 16 have a minor effect at 16.

This model indicates that the one-dimensional modelling results are consistent with a 2-dimensional view for stations 16 and 24. The resistivity values used to derive depths to basement of 300 m and 600 m for stations 24 and 16 respectively are thought to be reasonable; lower values of resistivity (10 ohm-m is considered the minimum allowable) would result in depth to basement as shallow as 75 m and 150 m (for stations 24 and 16 respectively).

No 2-dimensional model was found that fit the large S shift at station 24. Three dimensionality and(or) cultural effects are apparently affecting the data.

Relatively low resistivity for the pre-Tertiary basement in the near-surface zone on the east side of the basin (between stations 16 and 1) is consistent with models found for other profiles.

Inconsistency between observed data and model results at station 1 is with respect to the observed S shift. Profile H shows that the observed S shift is not explainable solely by the basin boundary as defined by outcrop 4

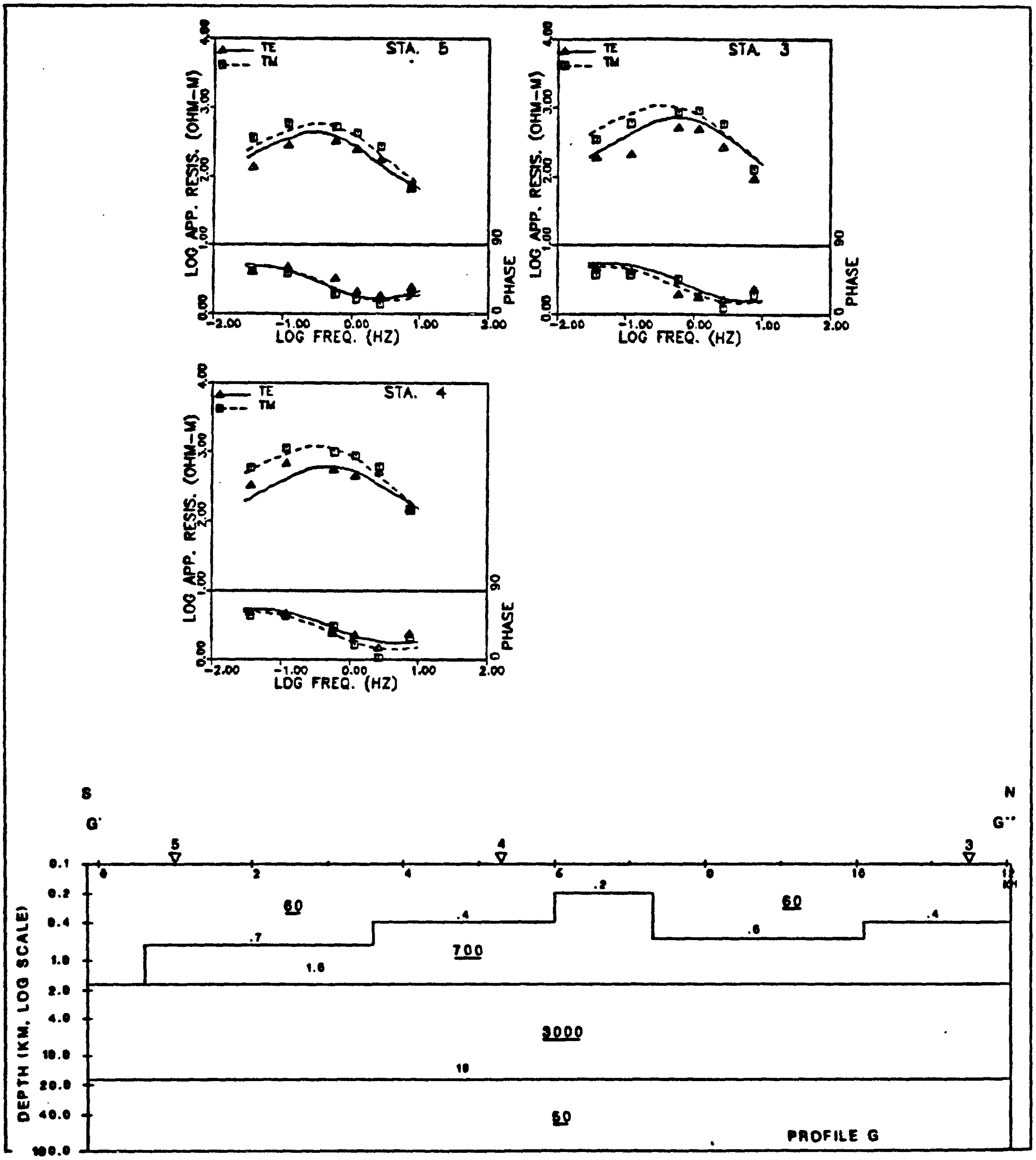

Figure 11. Magnetotelluric model for profile G'-G''. See fig. 5 for explanation.

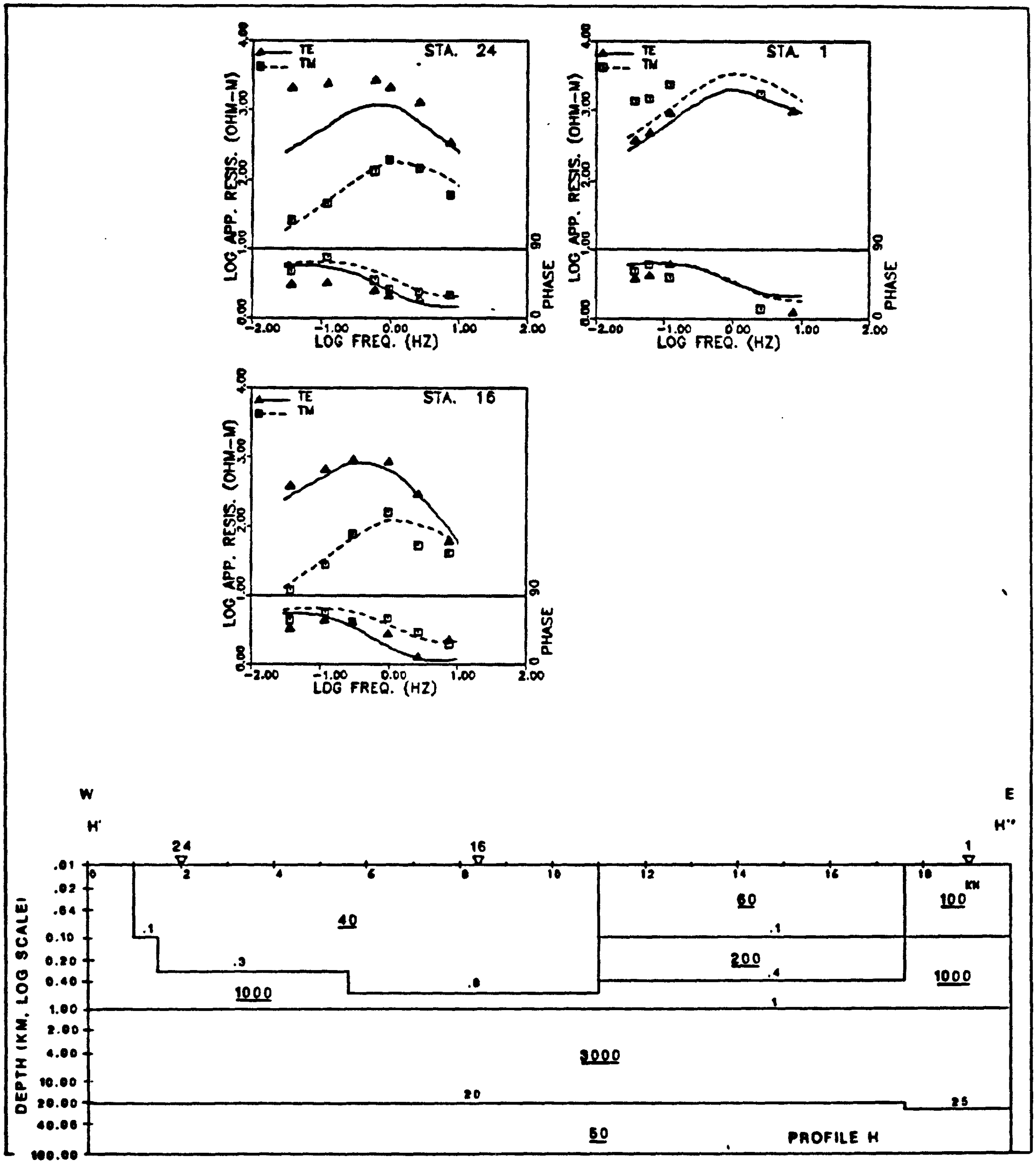

Figure 12. Magnetotelluric model for profile H'-H''. See fig. 5 for explanation. This is a composite section (see fig. 4 and text) to investigate the order of magnitude contrasts required for the observed S shifts.

km to the west. This sounding shows abnormal scatter and poor coherency compared to other soundings in the survey. It is thought that the observed S shift is partly a result of cultural noise. Topographic effects and inhomogeneity in the upper part of the pre-Tertiary basement could also be responsible.

Summary and discussion

Results are summarized in fig. 13, showing a generalized map of the interpreted thickness of the volcanic-sedimentary layer in the Pullman-Moscow basin. Control points are based on the 2-dimensional analysis, and are shown as fault symbols that are taken from the resistivity contrasts shown in figures 4-12. Contours of isothickness are drawn to be roughly consistent with these control points, but also to show a 3-dimensional view of the basin that smooths the step changes inherent in the modeling process. The zero contour corresponds with the edge of outcrop. Contours are dashed in areas of no control.

The main features inferred are: 1) a shallow shelf of pre-Tertiary basement east of Smoot Hill; 2) a protrusion of shallow pre-Tertiary basement on the east side of the basin near stations 12 and 13; 3) a relatively shallow (.2 to .4 km) electrical basement a few km west-southwest of Pullman; 4) a relatively sharp escarpment along a line associated with stations 5, 6 and 7 on the southwest edge of the survey area; and 5) the location of the probable deepest part of the basin north of Pullman and east of station 14.

Inasmuch as 3-dimensionality is clearly present, the two-dimensional models are qualitative in many aspects. However, they provide insight unavailable from one-dimensional modeling.

Corroborative evidence for the conclusions of this study is sparse. Previous Schlumberger data showed no consistent signature of the pre-Tertiary basement to interpreted depths of about 1000 m. An aeromagnetic map of the area, fig. 14, shows lows over most areas where the present analysis indicates thin volcanic-sedimentary cover. This is consistent with granitic basement rock at relatively shallow depth. One of the aeromagnetic anomalies is a high to the south and southwest of Pullman, near where the present data indicates shallow resistive rock (shown by the stippled area on fig. 14). Gravity data, fig. 14, also show relative lows over most areas where the present analysis indicates shallow basement. This too is consistent with granitic pre-Tertiary rock in contrast to more dense basaltic surface material. The exception, as with the aeromagnetic map, is a gravity high to the southwest of Pullman.

In view of the gravity and aeromagnetic data, the high-resistivity area to the southwest of Pullman may be the site of a lithological anomaly, such as dike intrusions or massive, unaltered basalt, rather than being a pre-Tertiary basement high. The anomaly may indicate a volcanic source area. An igneous source area would most likely be characterized by a gravity and an aeromagnetic high. The inexact correlation of the gravity, aeromagnetic and resistivity data may be due to the fact that different methods respond to different physical properties, or it may be due to different distributions of data coverage. The magnetotelluric anomaly, for instance, is defined by only 3 soundings; and the data are primarily reflecting resistivity changes in the upper volcanic-sedimentary layer. If the resistivity anomaly is related to a dike swarm, the swarm would probably have hydrological characteristics that would retard the flow of ground water.

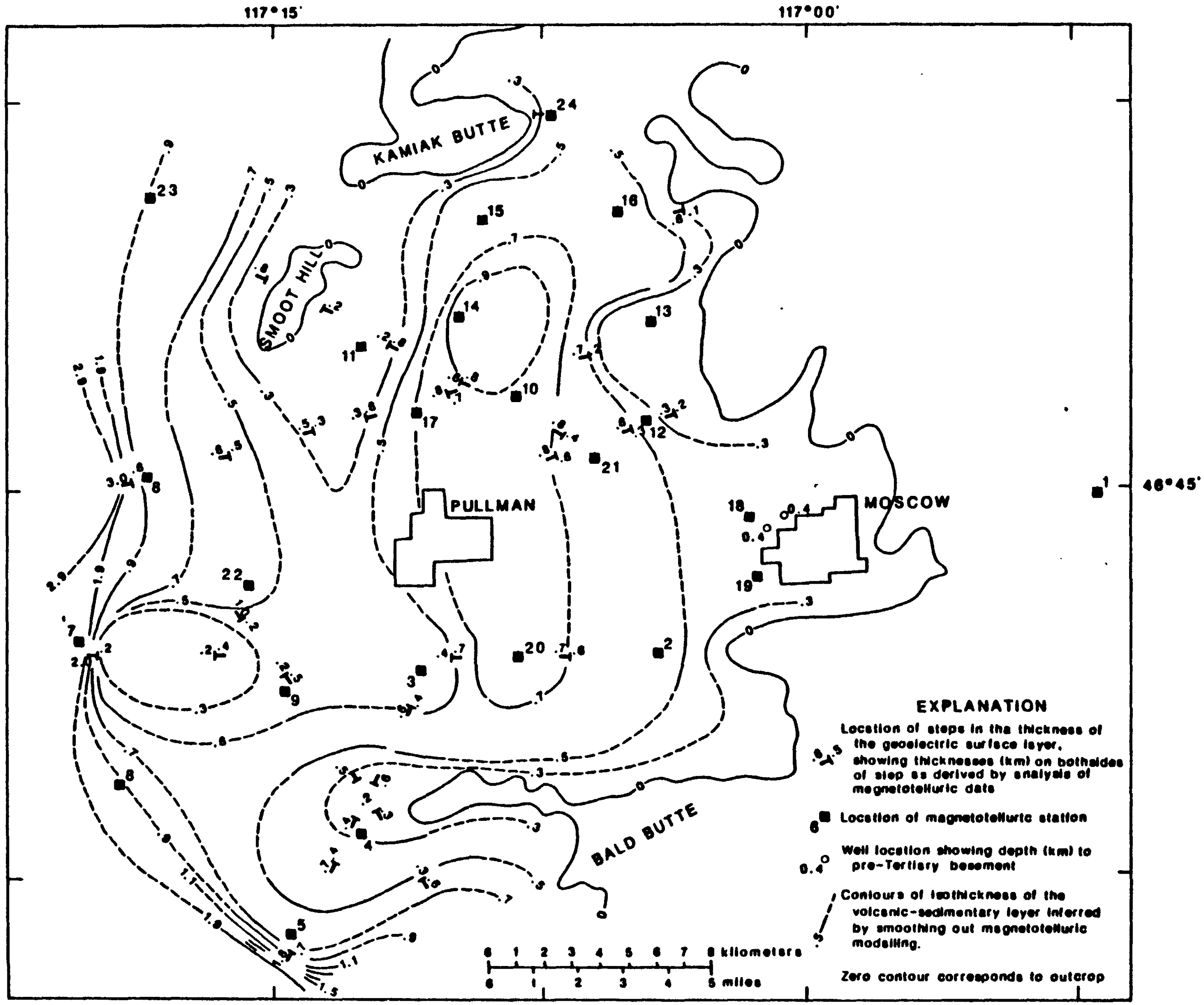

Figure 13. Generalized map of the interpreted thickness of the volcanic-sedimentary layer based on 2-dimensional analyses.

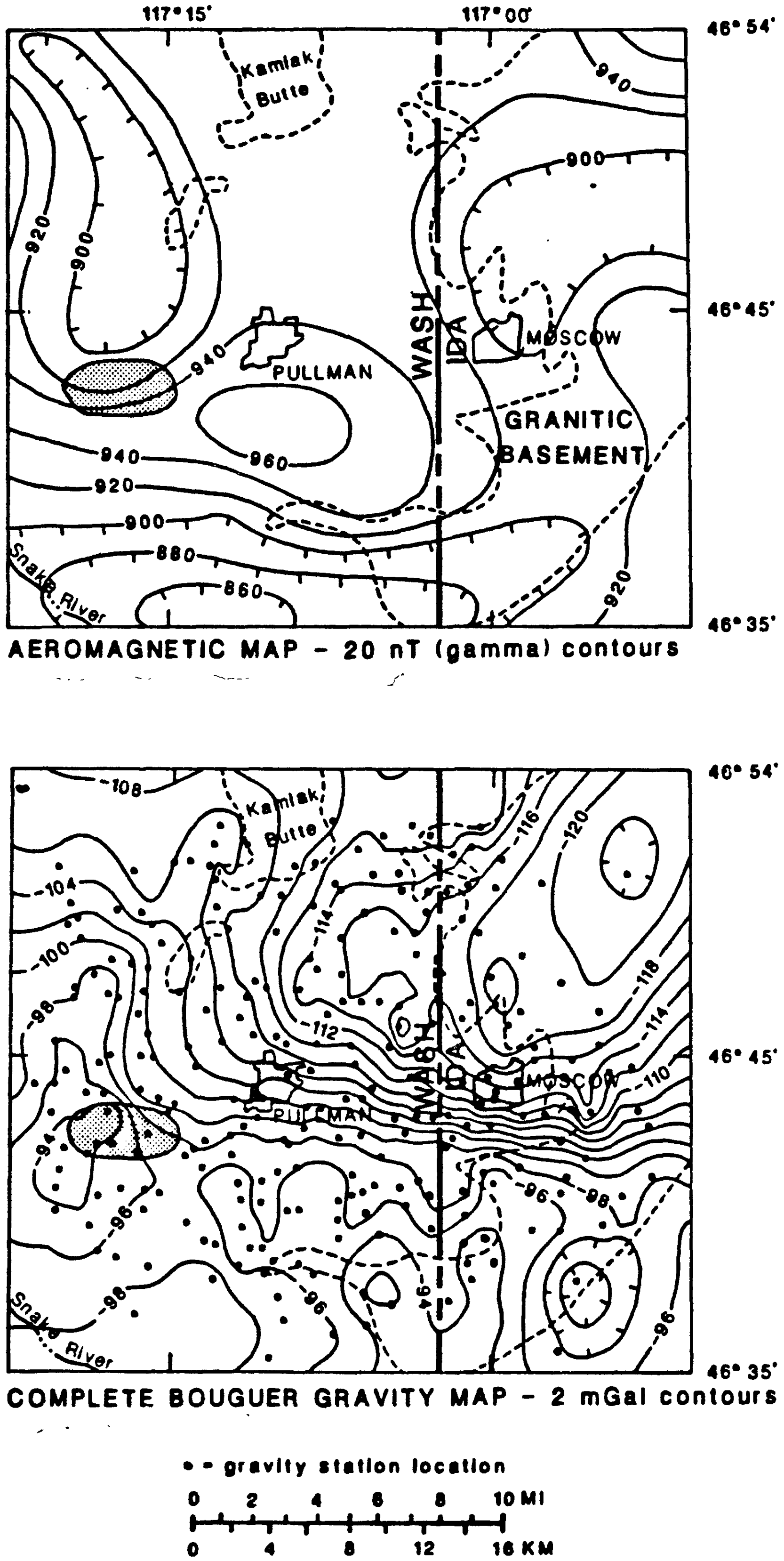

Figure 14. Aeromagnetic map (Zeitz and others, 1971) and complete Bouguer anomaly map (Finn, 1984) over the study area. The stippled areas refer to an area of inferred high-resistivity based on the interpretation of magnetotelluric data of this report. Dots on the gravity map show gravity station locations (see also Jackson and others, 1976; Gregory and Jackson, 1976).

Areas that could benefit from further investigation are those surrounding Smoot Hill and Kamiak Butte. Natural-source electrical methods, particularly at low frequency such as the present study, are strongly affected by the three dimensionality of outcrop in this area. Therefore, controlled source electrical methods, which employ relatively short wavelength source fields, would be recommended for additional study. More information is needed in the vicinity of Pullman, but cultural electromagnetic sources make this area difficult to survey using electrical methods.

Acknowledgements

Data obtained for this report were obtained with the cooperation of the farm families throughout the vicinity of the Pullman-Basin area. We gratefully acknowledge the assistance from these many landowners who gave us permission to work on their property, and provided information on the local terrain. The University of Idaho at Moscow, Geological Sciences Department, provided an additional vehicle used in this survey. This was of assistance in allowing site reconnaissance while our main trucks were stationary for data acquisition. Jay Sampson (U.S. Geological Survey, Denver) assisted in setting up the numerical models for the 2-dimensional analysis.

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