Hot Sulfur Springs

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TWO-DIMENSIONAL MODELING RESULTS OF TELLURIC-MAGNETOTELLURIC DATA FROM THE TUSCARORA AREA, ELKO COUNTY, NEVADA

by

Claron E. Mackelprang

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EARTH SCIENCE LABORATORY
University of Utah Research Institute
Salt Lake City, Utah

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Prepared for
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ABSTRACT

Two-dimensional modeling of T-MT data taken at the Tuscarora Geothermal Exploration unit has shown that in this area the TM-Mode is insensitive in resolving conductivity inhomogeneities below a depth of about 2 km. Computer interpretive models showing a large conductive zone beneath the hot spring area at a depth of 2 km are compared with models in which this conductive zone is restricted to the near surface. Acceptable fits between observed apparent resistivity and calculated resistivity, within the accuracy of the field data, have also been obtained with alternate models. This non-uniqueness is inherent in the two-dimensional models themselves and is further complicated by the geologic setting where three-dimensional effects result from near-surface conductive bodies. Current channeling within the conductive sediments of Independence Valley may also limit the ability to resolve postulated, deep conductivity inhomogeneities.

Any interpretation of T-MT data, possibly leading to a deep exploration drill test, should be evaluated through a sensitivity analysis (i.e., several alternate models). Three dimensional effects should also be evaluated to the extent possible. Finally, supporting evidence derived from alternate exploration techniques should be integrated with T-MT interpretive conclusions.

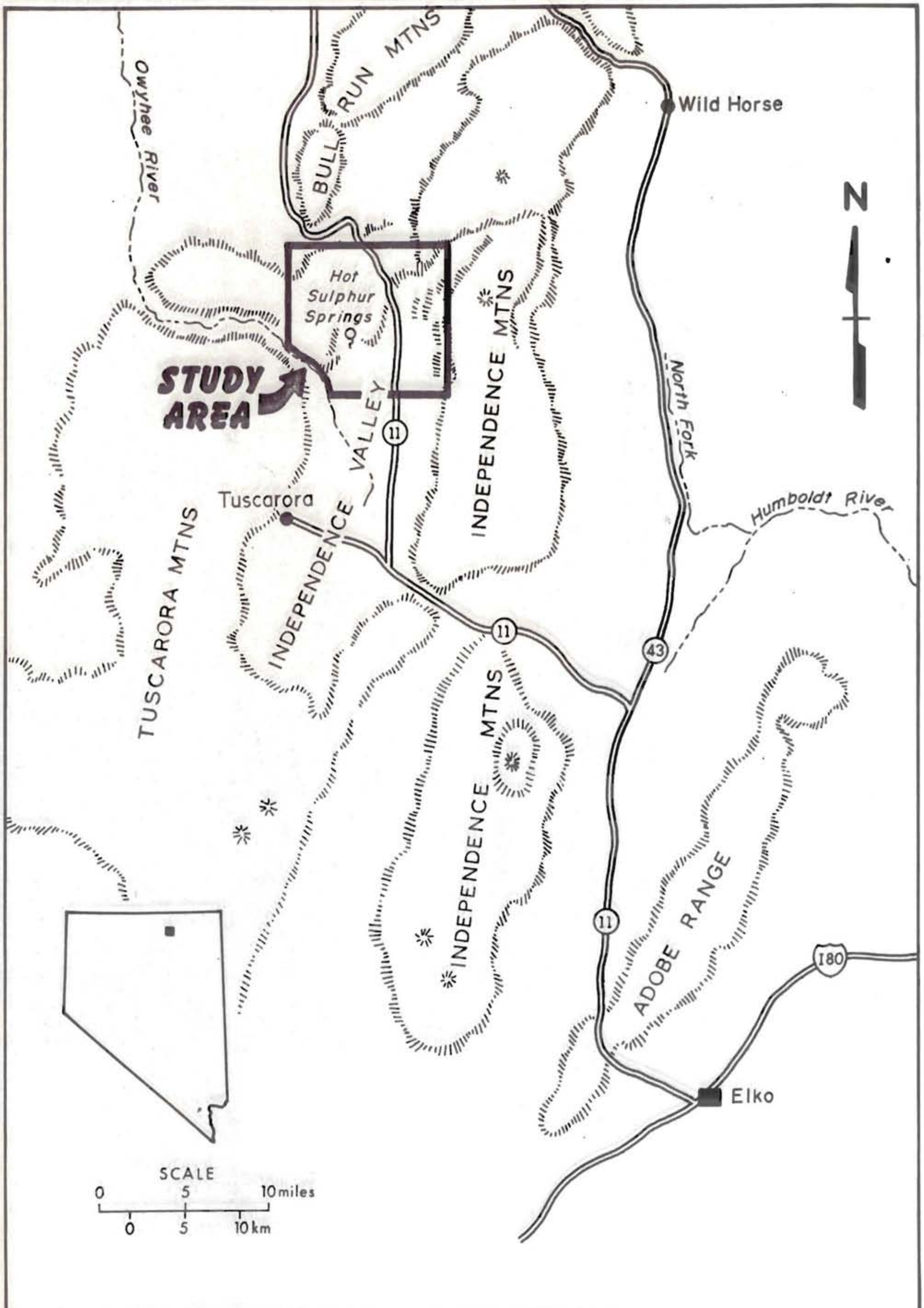


FIGURE 1. LOCATION MAP AND PHYSIOGRAPHIC SETTING OF THE TUSCARORA AREA, ELKO COUNTY, NEVADA

INTRODUCTION

The Tuscarora geothermal prospect is located approximately 90 km north-northwest of Elko, Nevada at the northern end of Independence Valley (Figure 1). This valley is a typical Basin and Range structure and is approximately 10 km wide and 30 km long. The surface manifestations of a potential geothermal resource are the thermal springs locally known as Hot Sulphur Springs.

A joint venture effort by Amax Exploration, Inc. of Denver, Earth Power Production Company of Tulsa, and Supron Energy of Dallas, has undertaken exploration of the prospect. Results of the various data sets were released to the Earth Science Laboratory Division/University of Utah Research Institute under the Department of Energy Industry Coupled Program. In addition, DOE funded detailed geologic mapping of the prospect by ESL in support of the exploration program has been published (Sibbett, 1981).

This report presents results of two-dimensional modeling of the T-MT data (TM-mode). The interpretation was enhanced by integrating the results of other pertinent data sets such as dipole-dipole resisitivity.

GENERAL GEOLOGY

Independence Valley is bordered on the east by the Independence Range and on the west by the Tuscarora Mountains (Figure 1). Figure 2 is a generalized geologic map of the geothermal prospect located at the northern end of Independence Valley (after Sibbett, 1981). The Ordovician Valmy Group quartzites and argillites are exposed in the northern Independence Mountains and form the eastern border of the prospect area. Dacitic tuff-breccia (180 m-thick) overlie the Paleozoic rocks in the area of the hot springs. The

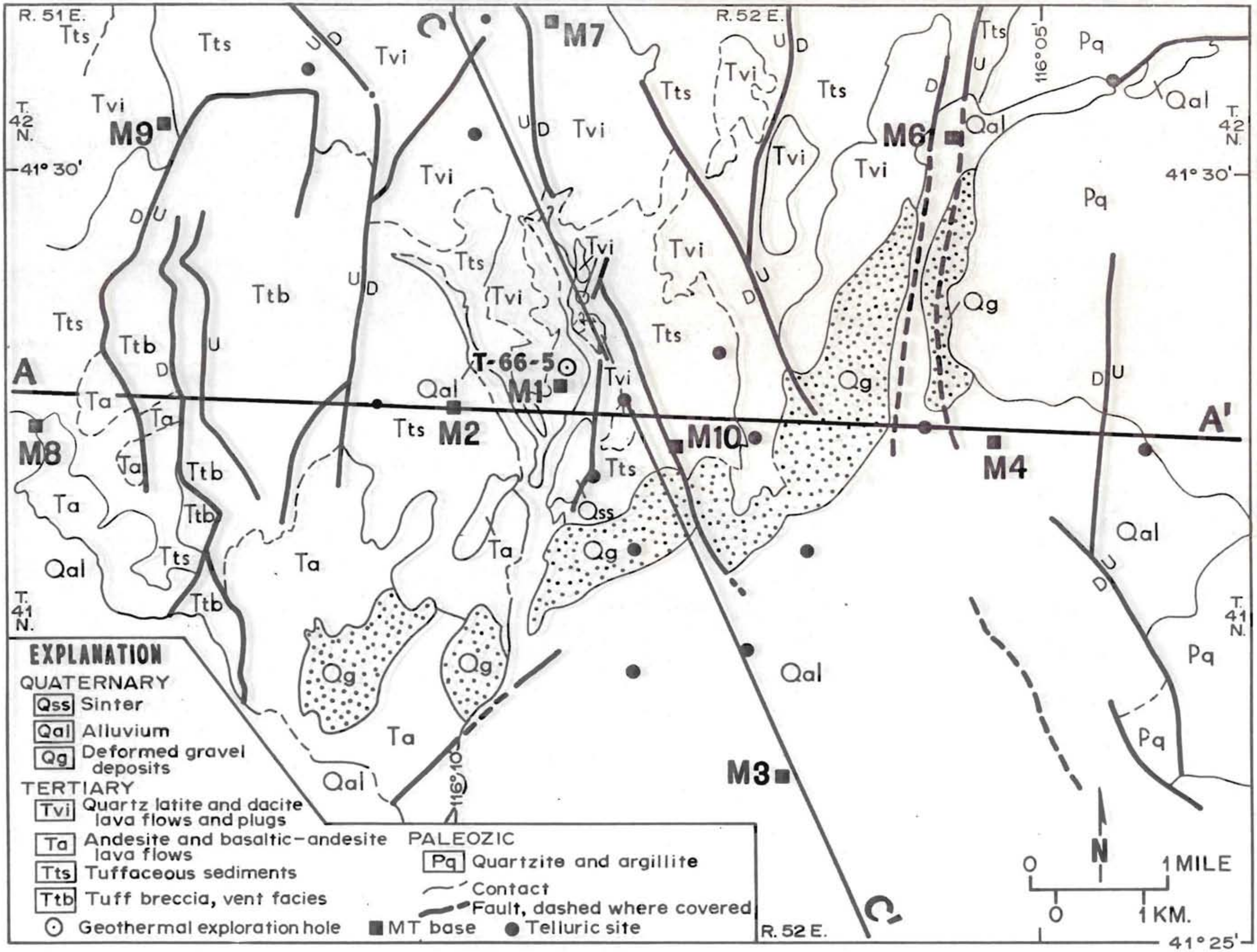


FIGURE 2. GENERALIZED GEOLOGIC MAP OF THE TUSCARORA AREA, NEVADA (AFTER SIBBETT, 1981)

tuff-breccia is exposed in its vent area three kilometers to the west. The southwest border of the study area is covered by Tertiary andesite and basaltic-andesite lava flows. Sibbett (1981) reports these flows and the tuff-breccia have been dated (K-Ar) at 38.8 ± 1.3 m.y. Overlying the tuff-breccia is approximately 320 m of tuffaceous sediments containing a rhyolite ash dated at 35.2 ± 1 m.y. (Schilling, 1965). These sediments have been partially covered to the north by Tertiary dacite and quartz-latite lava flows dated at 13.6 ± 0.7 m.y. and 16.7 ± 1.1. m.y. respectively (Sibbett, 1981).

The area is structurally complex. The Tertiary rocks have been deformed by north- and northwest-trending normal faults. These faults bound a graben between the Independence Mountains on the east and a small horst on the west (Figure 2). This horst extends from the Tuscarora Mountains northward to the Bull Run Mountains and contains the vent area for the tuff-breccia.

Another major structure trends north to north-northeast along Hot Creek. This structure, shown in greater detail in Figure 3, has controlled emplacement of several basaltic-andesite plugs and the surface expression of the geothermal system (Sibbett, 1981). This fault and the associated thermal spring along Hot Creek are centrally located within the large graben.

Numerous hot springs and an extensive opaline sinter deposit roughly 330 m wide, 1000 m long and 35 m high are present. No currently active springs issue from this sinter deposit but three springs do occur in the alluvium at the west edge of the mound. These springs are currently depositing silica. Most of the spring activity occurs in a small area 400 m upstream from the large sinter mound. The springs form a roughly triangular pattern and have temperatures of 55-95° C. The hotter springs are depositing both siliceous and calcareous sinter, sulfur, and sublimates. Several springs are boiling

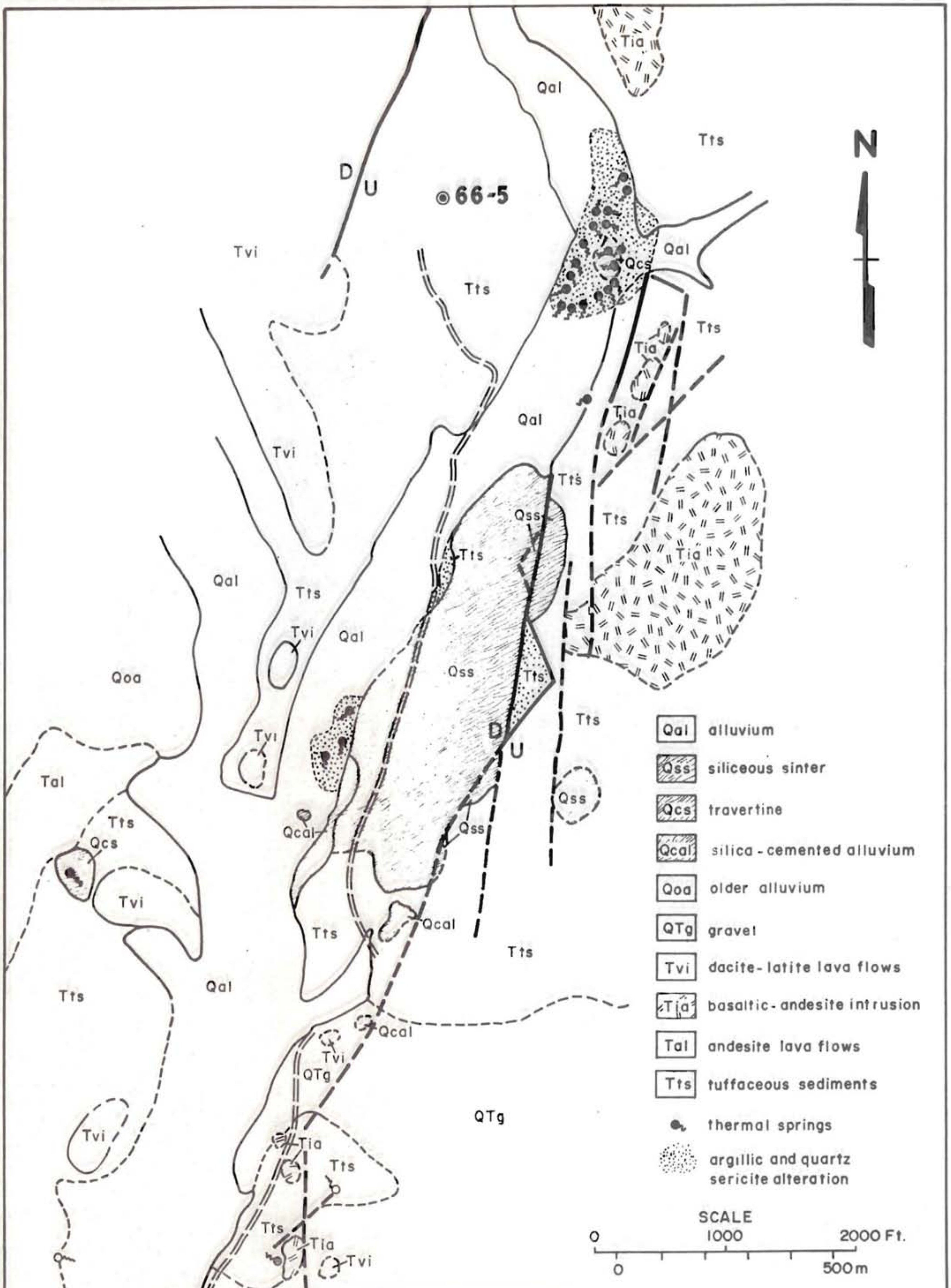


FIGURE 3. DETAILED GEOLOGY OF THE HOT SPRINGS AREA, TUSCARORA AREA, NEVADA (AFTER SIBBETT, 1981)

and one small steam vent occurs. The Na/K/Ca geothermometer indicates a - possible reservoir temperature of 181° to 228° C (Pilkington et. al., 1980).

Two geologic sections, AA' and CC', have been constructed (Sibbett, 1981) which trend east-west and northwest-southeast, respectively, across the hot spring area. These interpretative sections are shown in Figure 4. They closely parallel the T-MT profiles AA' and CC' shown in plan view on Figure 2.

An intrusive is inferred beneath the horst on the west end of section AA' because the vent area for the tuff-breccia is uplifted relative to the rest of the horst, and the bounding faults, where well exposed, are convex upward. This and massive quartz veins within the vent and along some of the bounding faults all suggest an intrusion at depth (Sibbett, 1981).

TELLURIC-MAGNETOTELLURIC METHOD

The telluric-magnetotelluric (T-MT) method is described by Hermance and Thayer (1975). It combines magnetotelluric measurements at a few base sites with telluric measurements at a number of remote sites. This combination minimizes the time required, and thereby the cost, of completing a given survey.

Crucial to the T-MT method is the implicit assumption of spatial uniformity of the horizontal magnetic field. Stodt et al. (1981), however, in their computer model studies have shown that this assumption is not always valid in the vicinity of two-dimensional (2-D) and three-dimensional (3-D) resistivity inhomogeneities. They show, for a 2-D case, that the TE-mode horizontal magnetic field can vary by as much as a factor of three over a distance of five kilometers. For a three-dimensional (3-D) case, spatial variation of the horizontal magnetic field is not as great, but they conclude

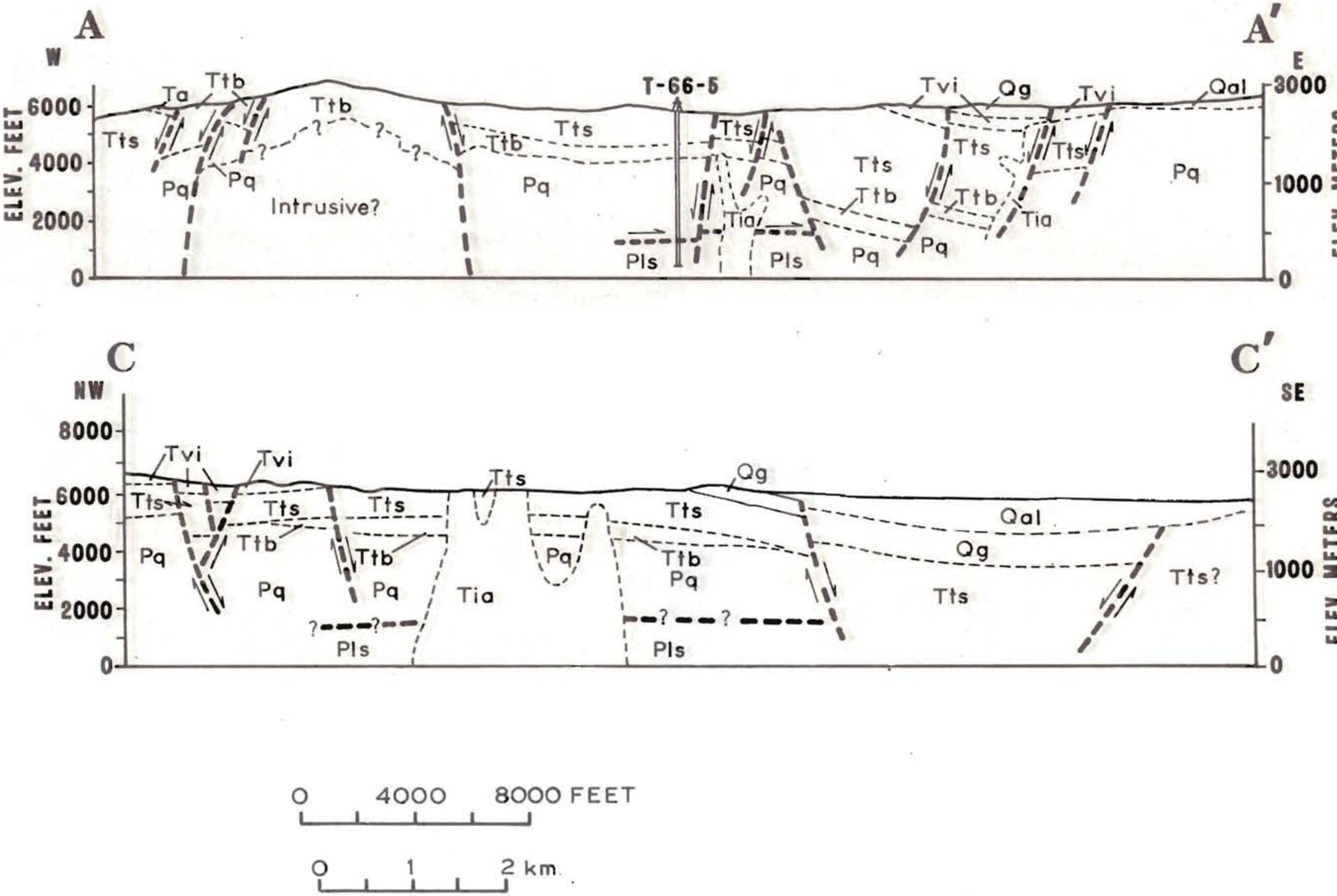


FIGURE 4. GEOLOGIC CROSS SECTIONS OF THE TUSCARORA AREA, NEVADA (AFTER SIBBETT, 1981)

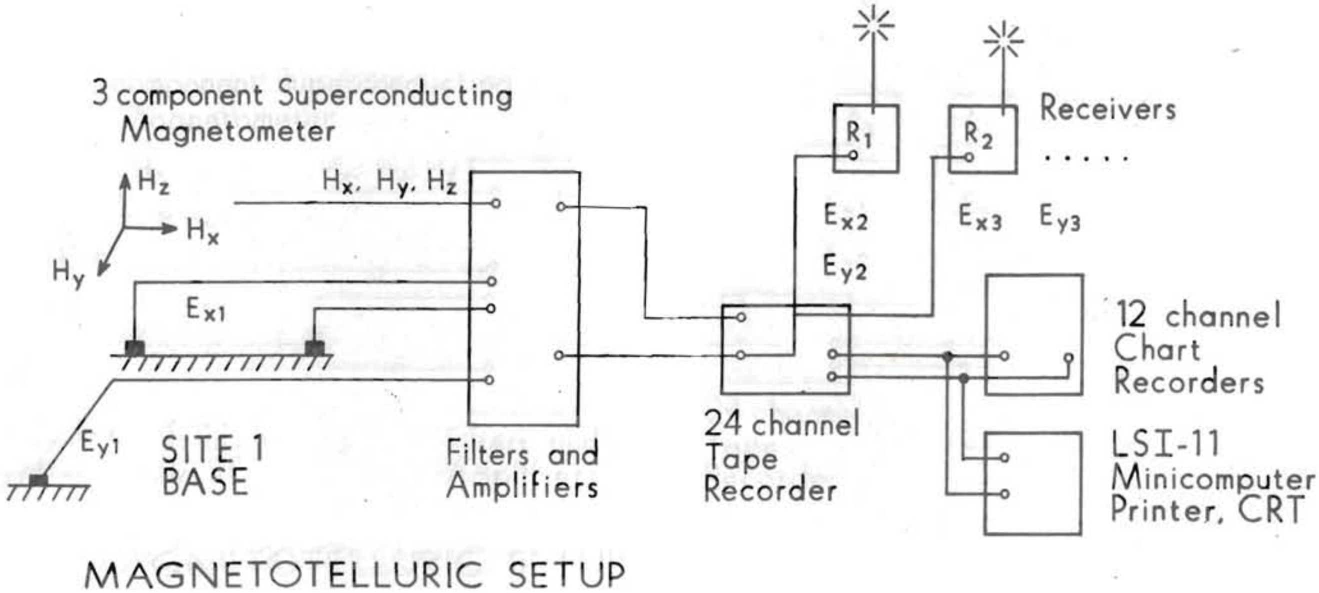
that the variation can contribute significantly to impedance magnitude and phase over shallow inhomogenities at higher frequencies.

SURVEY PROCEDURE

The T-MT survey was conducted by Terraphysics (Mazzella, 1979). Rotated tensor data were obtained at 11 base stations and 22 remote sites (Figure 2). Typical distances between base and remote sites are one to two kilometers. Telluric dipoles were 200 meters long and were oriented north-south and east-west. Figure 5 shows the recording setup for both base and remote sites. Both the magnetic and electric field data were processed using a technique described by Gambel et al. (1979). Utilizing the estimated spectral powers, the impedance, principle axis direction, rotated apparent resistivity, skewness, impedance phase, tipper and tipper strike direction were calculated. These data were then plotted as a function of frequency from 10 to 0.01 Hz. Figure 6 shows the data for Station B1. Note that the data are highly variable, by a factor of 2 in places, in the frequency range of 1.0 to 0.1 Hz. This implies anisotropy is present and has a strong influence on the observed data.

MODELING PROCEDURE

Only a cursory examination of the T-MT data and geologic setting is needed to see that the Tuscarora geothermal prospect is at least two-dimensional and more likely three-dimensional. Several authors (Wannamaker et al., 1980; Stodt et al., 1981; Ting and Hohmann, 1981) have suggested modeling selected T-MT and MT field data from a 3-D area showing preferred structural trends with a 2-D TM algorithm. This approach generally gives more accurate conductivity cross sections than those obtained with a TE algorithm. A two-



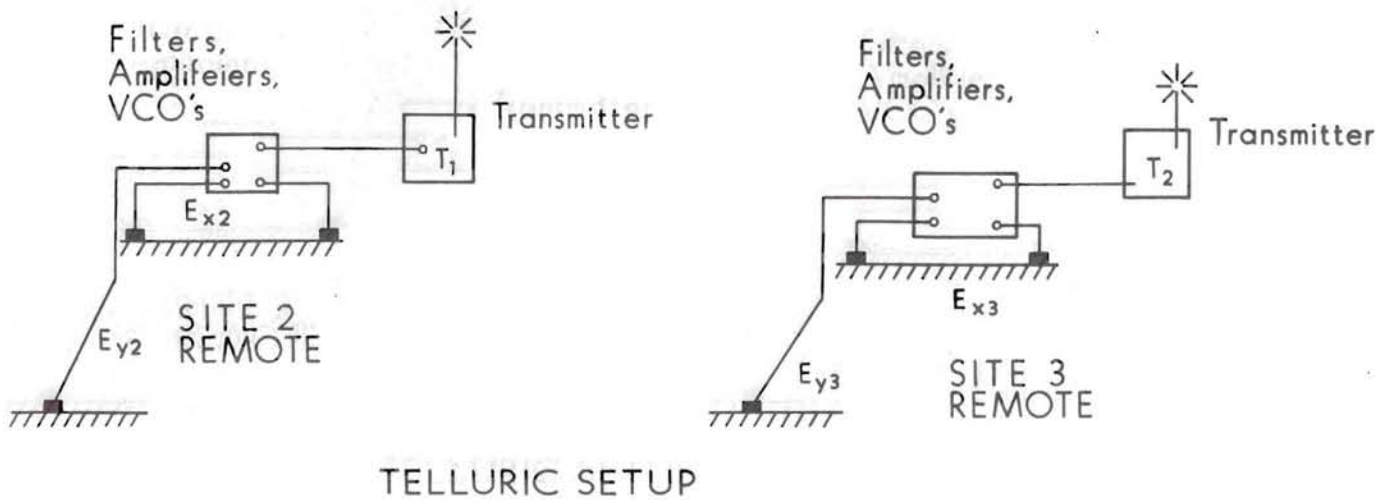


FIGURE 5. TELLURIC-MAGNETOTELLURIC DATA RECORDING SETUP, TUSCARORA AREA, NEVADA (FROM MAZZELLA, 1979)

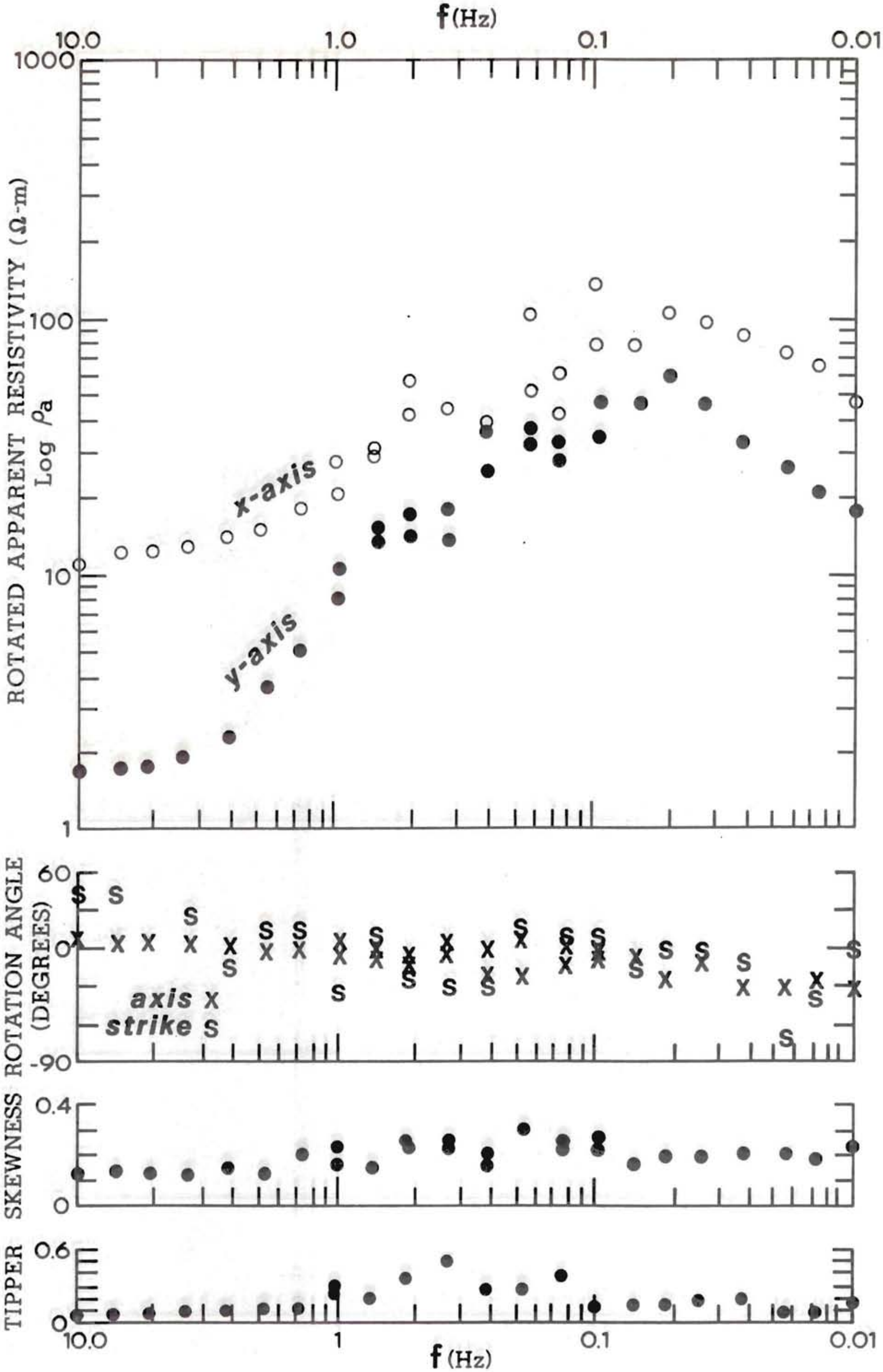


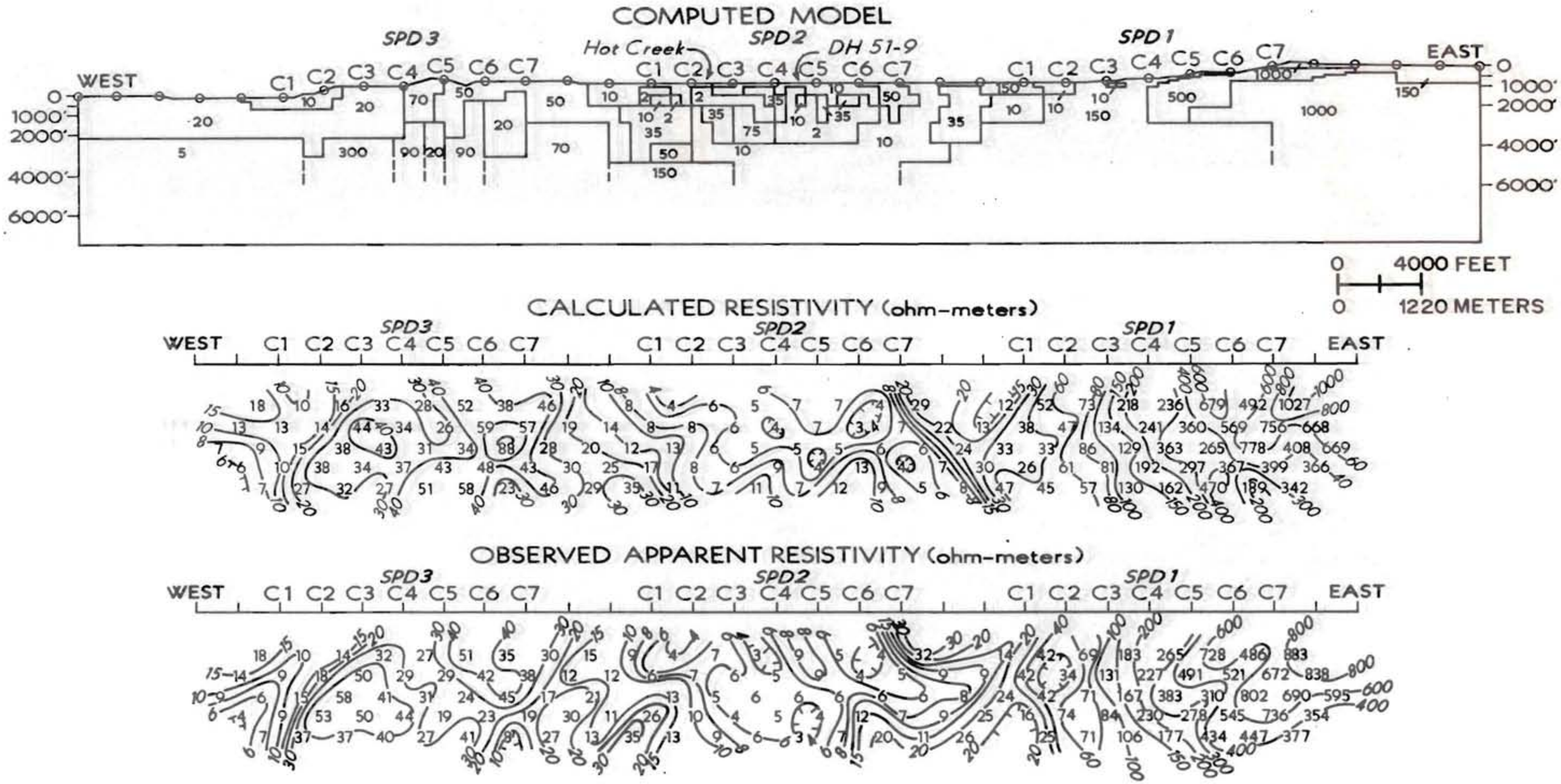
FIGURE 6. STATION B1 DATA, TUSCARORA AREA, NEVADA

dimensional finite element program developed at the University of Utah (Rijo, 1977) has been modified and consolidated into a single program to handle the 2-D magnetotelluric TE- and TM-mode problems (Stodt, 1978). This program was used to model the T-MT (TM- mode) data.

T-MT stations aligned along general east-west and northwest-southeast directions were used to construct two profiles labeled AA' and CC' respectively. These profiles intersect one another in close proximity to Hot Sulphur Springs. Rotated apparent resistivities determined at each station along the profiles at 4 frequencies (10.0 - 0.01 Hz), a decade apart, were compiled to form observed data pseudosections. A finite element mesh was then designed for each profile. Interpreted intrinsic resistivity values, closely approximating those obtained from modeling 610 m dipole-dipole data taken over the same general profile, were then assigned to the MT model. MT models showing acceptable fits to the observed data, through an iterative process, were then obtained as shown in Figures 8 through 12.

INTERPRETATION

Figure 7 shows a calculated dipole-dipole model (Mackelprang, 1981), determined to be a good fit to the observed data and which closely parallels T-MT profile AA'. The interpreted resistivities shown in the upper 1 km of T-MT model AA' (Figure 8) have been generalized from this dipole-dipole model. Both the 2-D TM-mode and dipole-dipole models for profile AA' show conductive near-surface material in the vicinity of the hot springs. Hot Creek and the attendant structure, from which the hot springs issue, occur between T-MT stations M1 and B1 and dipole-dipole stations C2 and C3, spread 2. This low resistivity (< 10 ohm-meter) is thought to be partially caused by hot fluids within shallow volcanic aquifers. The more resistive (100-500 Ω m) material



LINE 9 - DIPOLE-DIPOLE DATA

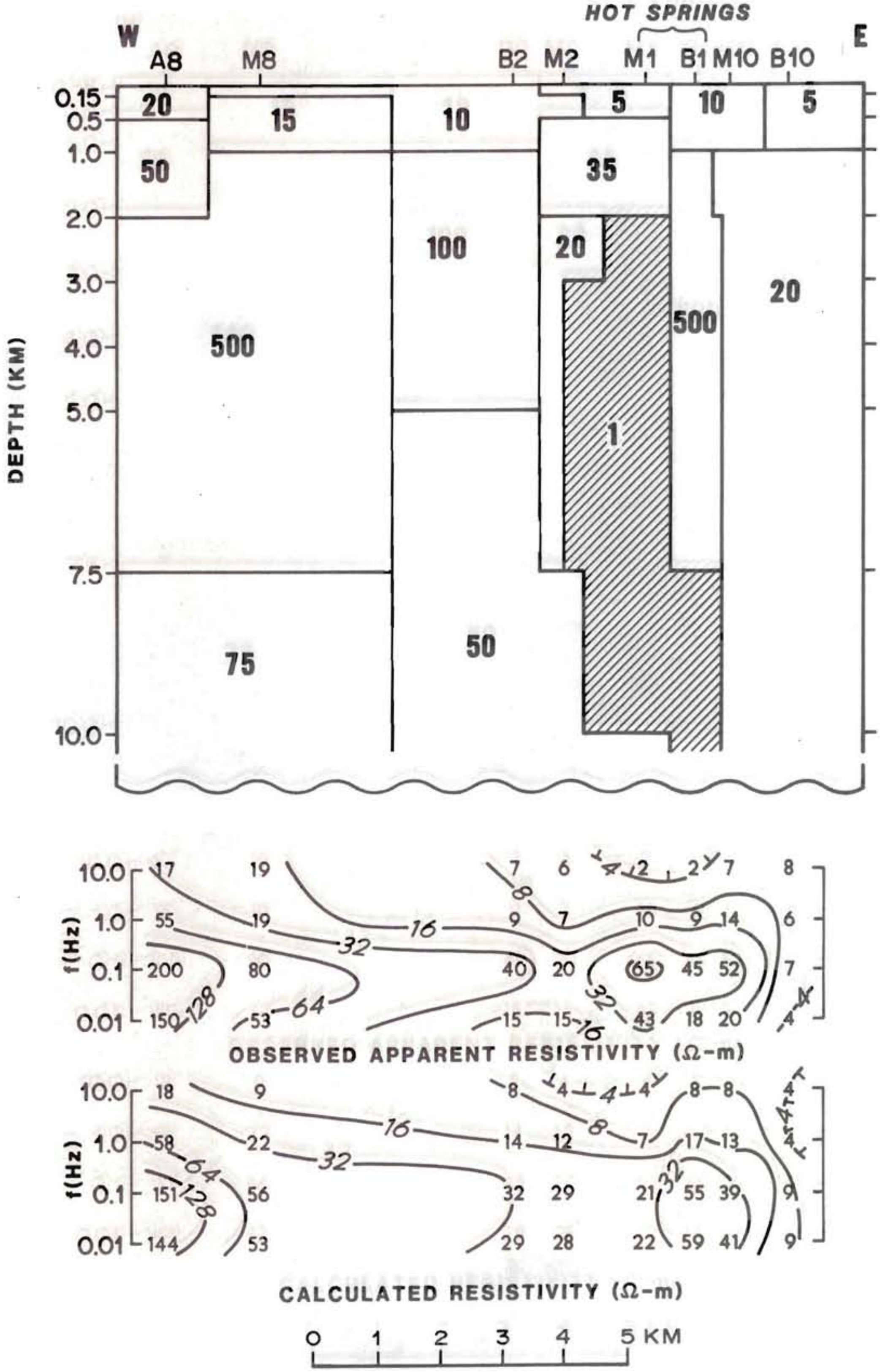
TUSCARORA PROJECT

ELKO COUNTY, NEVADA

FIGURE 7

FIGURE 8

MODEL 1
TUSCARORA AREA, NEVADA
T-MT PROFILE AA'



occuring at depth between stations M8 and B2 coincides with the horst and vent area for the Tertiary tuff-breccia.

The observed resistivity data at station B1 are poorly matched at the lower frequencies. This is attributed to lateral and 3-D effects arising from the larger intrusive plug occurring south of station B1. A modification to the geometry of the 500 Ω m body beneath this station is required to fit the observed data.

The conductive zone (1 Ω m), which is shown on Figure 8 to have a large depth extent beginning within about 2 km of the surface beneath the hot spring area (station M1), is of particular interest. It is tempting to infer that this conductive zone is the signature of a geothermal reservoir. Figure 9 shows another calculated MT model for profile AA'. The primary divergence from Figure 8 is the modification in the geometry of the conductive (1 Ω m) body. The intrinsic resistivity was increased by a factor of 20, yet the overall fit to the observed data is essentially equal to that for the model with the 1 Ω m conductor. Although numerical differences occur, they are, for the most part, well within the accuracy of the field data.

It is understood that models for profile AA' are non-unique, and refinements can be made for a better overall fit to the observed data. Profile AA' is also not two-dimensional (Figure 2). The presence of Independence Valley with its conductive volcanic sediments lying immediately south of the profile causes additional concern. Theoretical MT model studies demonstrating the applicability of 2-D interpretation approaches in a geologic setting similar to Tuscarora are not available. The veracity of models for profile AA' is therefore uncertain.

FIGURE 9

MODEL 2
TUSCARORA AREA, NEVADA
T-MT PROFILE AA'

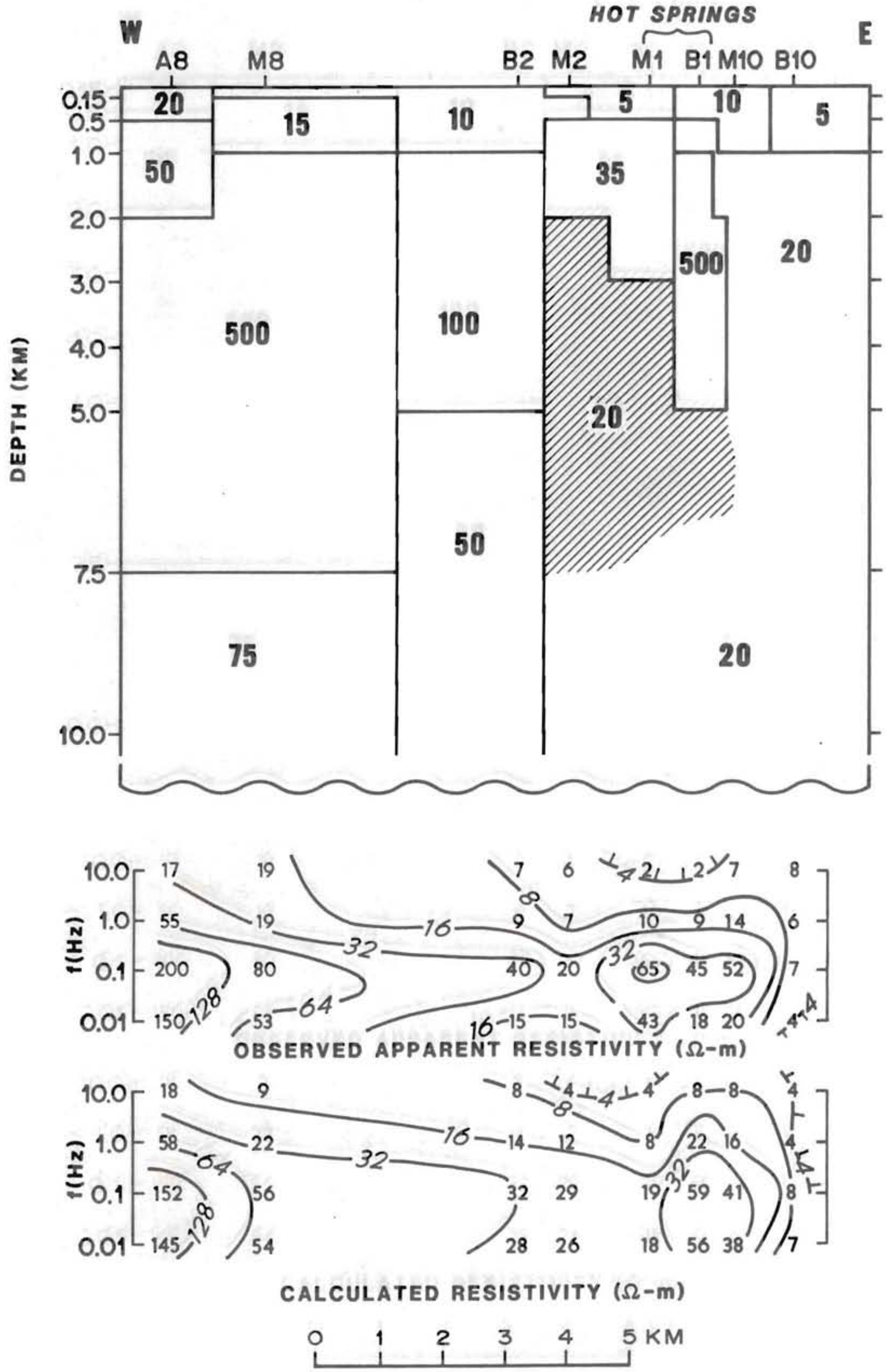
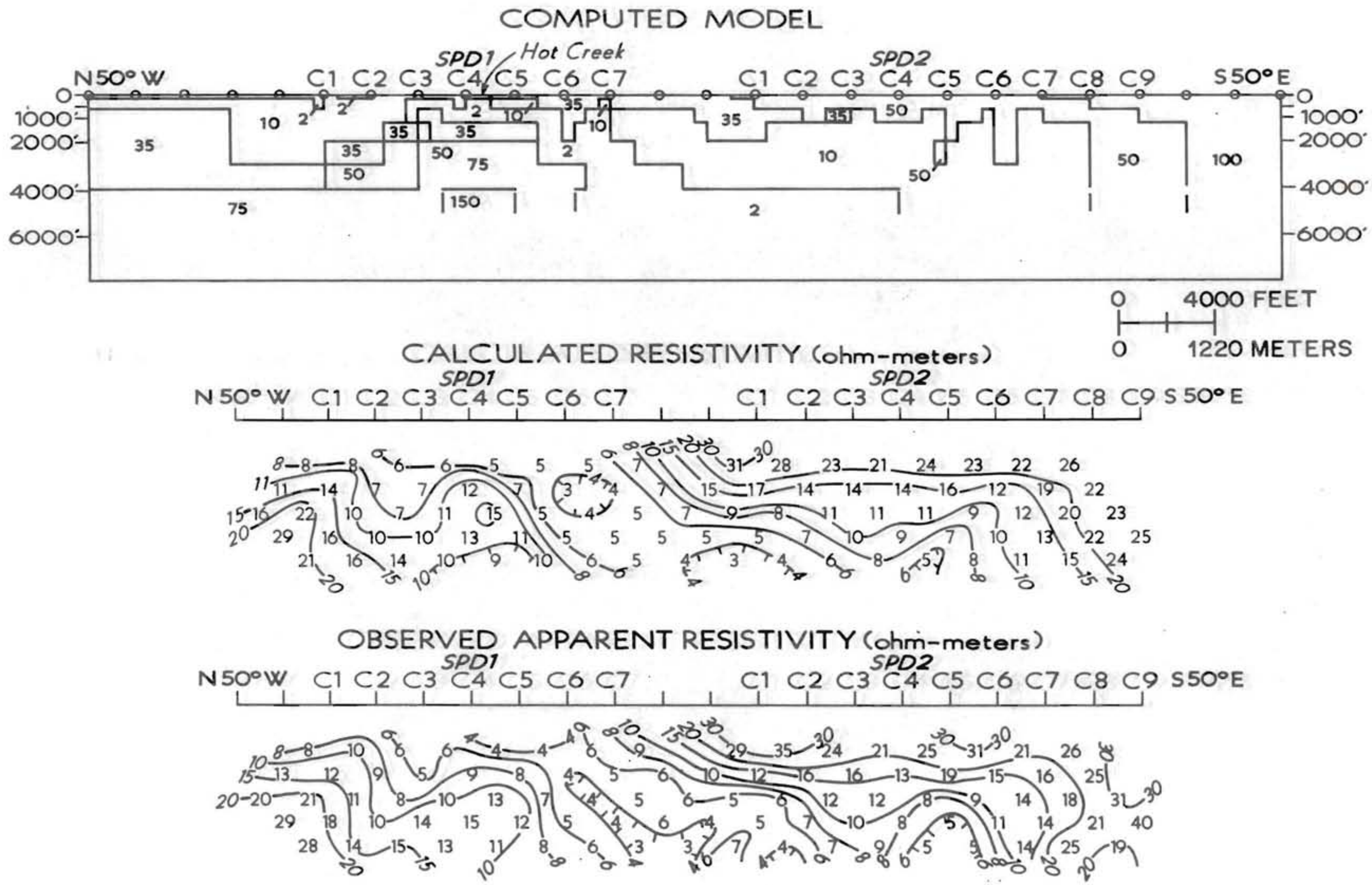


Figure 10 shows the dipole-dipole model that roughly parallels T-MT profile CC'. Hot Creek is crossed by spread 1 between stations C4 and C5. The resistivity section from this dipole-dipole model was again generalized and used for the upper 1 km on the MT profile. Figure 11 shows the MT model fit to the observed TM-mode data along profile CC'. This profile extends into Independence Valley south of the hot springs. The Hot Creek structure is located between stations M1 and M10. The conductive (5 Ω m) material at the surface is apparently alluvium and volcanic sediments, possibly containing clay, which may be saturated with thermal waters. The slightly more resistive (10-25 Ω m) material at the surface on the southeast end of the profile is perhaps best explained by relatively dry sediments above the water table. The resistive (500 Ω m) material at depth on the southeast end of the profile is thought to be a combination of Paleozoic sediments beneath Independence Valley and the intrusion near station B1. The 50 -500 Ω m material at depth on the northwest end of the profile is thought to represent Tertiary volcanics and Paleozoic sediments.

The most significant feature shown by this model is again the very conductive zone (1 Ω m) at depth in the central portion of the profile which rises to within about 2 km of the surface between stations M1 and M10. This zone is roughly centered on the Hot Creek fault and appears to extend downward for a considerable depth then laterally into Independence Valley and the buried Paleozoics (?). It is again tempting to interpret this zone as an indication of the geothermal reservoir. T-MT profile CC' appears more nearly two-dimensional than profile AA', and therefore a sensitivity test has been performed upon the MT model shown as Figure 11. Figure 12 shows the results of this alternate model which has a less conductive (50 Ω m) body beneath the hot spring area. Note the strong similarity between the computed resistivity



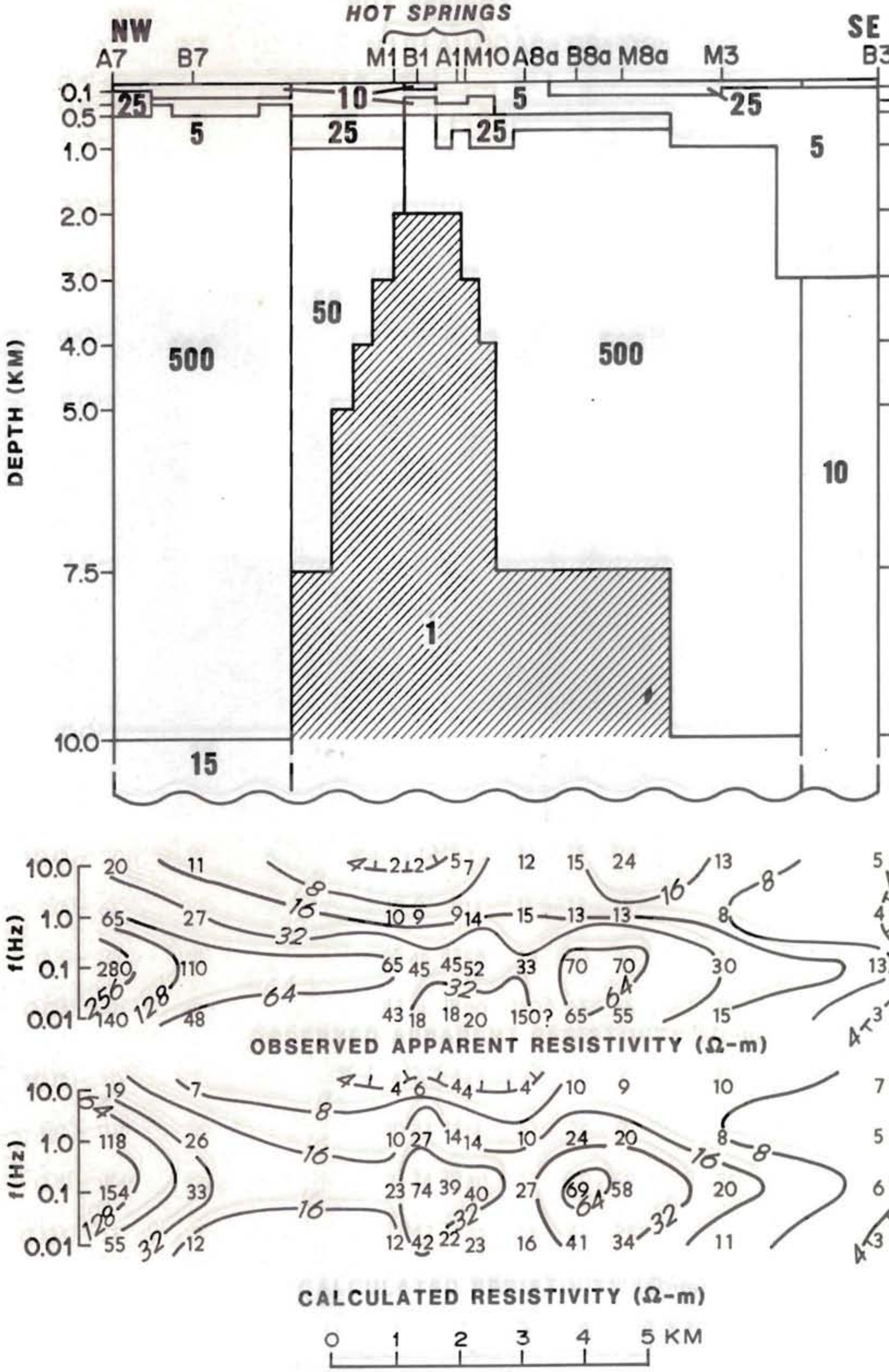
LINE 16 - DIPOLE-DIPOLE DATA

TUSCARORA PROJECT
ELKO COUNTY, NEVADA

FIGURE 10

FIGURE 11

MODEL 1
TUSCARORA AREA, NEVADA
T-MT PROFILE CC′



values for the two models (Figures 11 and 12). Both figures show acceptable fits to the observed data. This model (Figure 12) was further revised to limit the depth extent of the 50 Ω m body to 1.5 kilometers. This depth and moderate resistivity agree well with results of a resistivity log from a test hole (66-5) drilled 300 meters north of station M1. The only significant change resulting from this modification as shown by Figure 13 occurred at 0.01 Hz with stations B1, A1, and M10. Calculated resistivities for these stations at this frequency actually agree more closely with the observed data than do the calculations using the previous two models. No conductive body at great depths is therefore required to fit the observed data.

FIGURE 12

MODEL 2
TUSCARORA AREA, NEVADA
T-MT PROFILE CC′

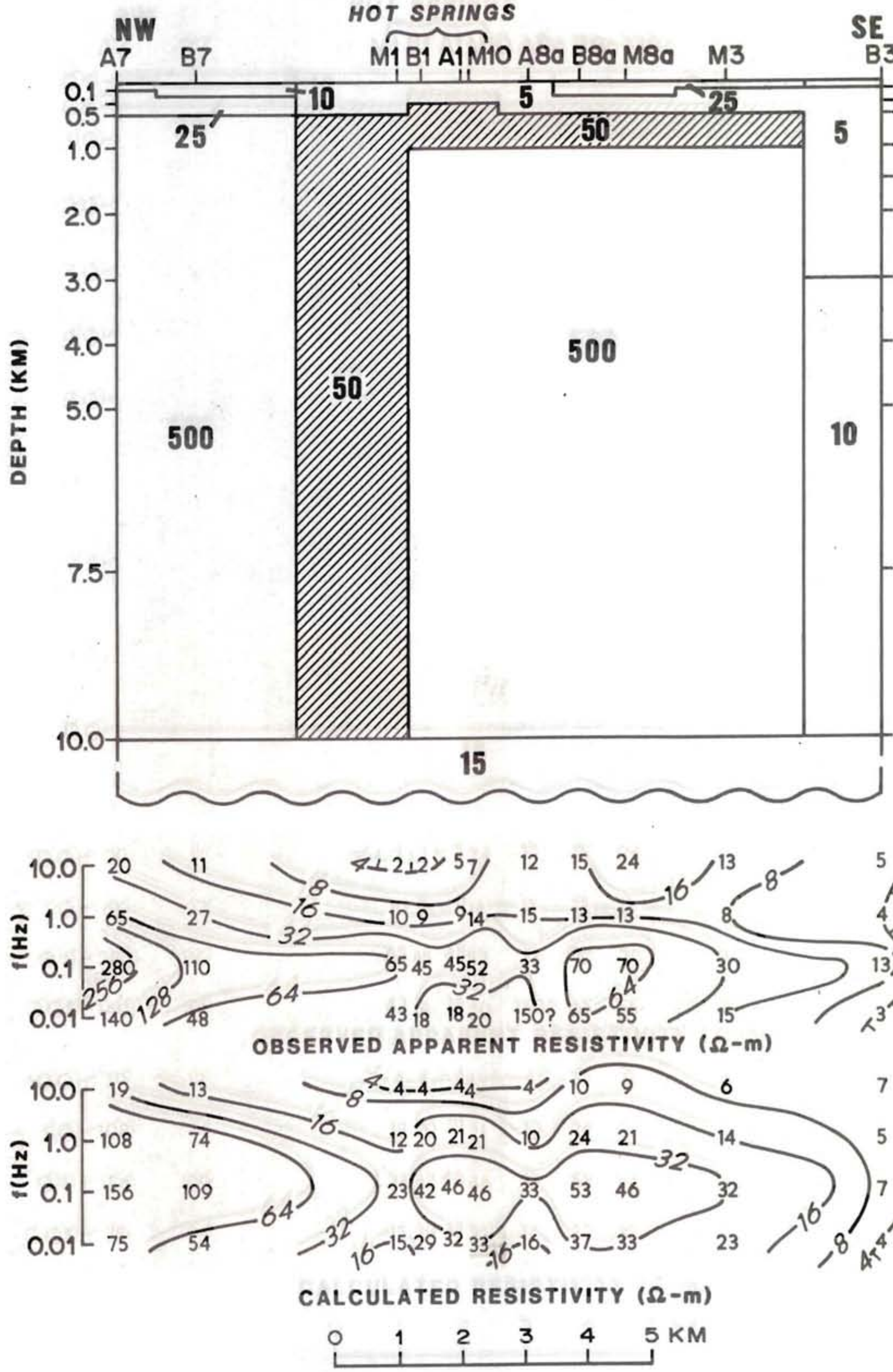
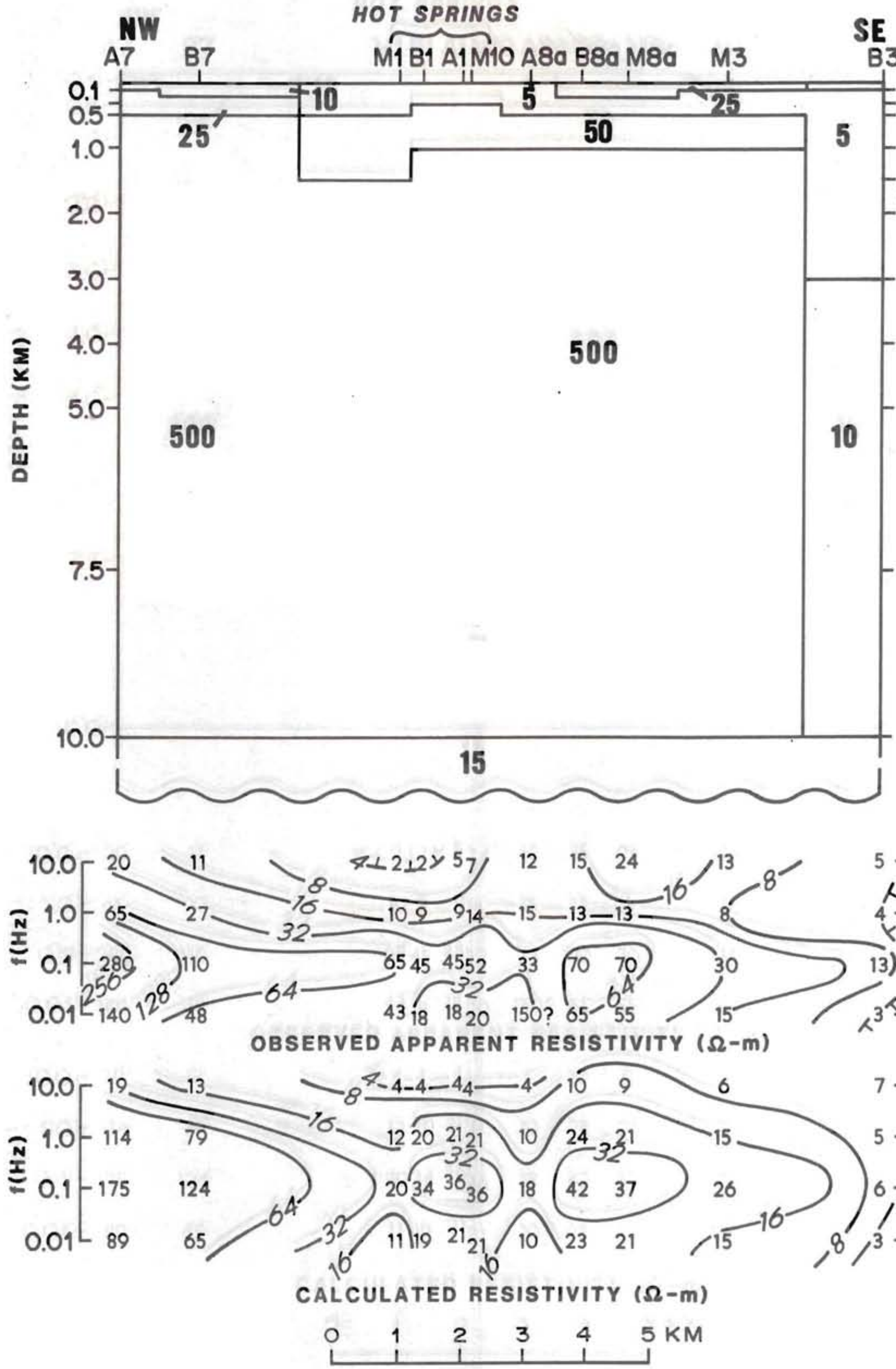


FIGURE 13

MODEL 3

TUSCARORA AREA, NEVADA

T-MT PROFILE CC′



CONCLUSIONS AND RECOMMENDATIONS

The heat source and reservoir for the thermal springs occurring on the Tuscarora Geothermal Exploration unit have been an elusive target. Geologic mapping has shown the prospect to be structurally complex. Several geophysical techniques have been applied - each offering tidbits of information. This report has presented results of a telluric-magnetotelluric survey modeled with a computer using a two-dimensional algorithm. The geometry of the near-surface conductive zones shown by the MT models was guided by two-dimensional dipole-dipole resistivity model results which had previously shown similar zones.

The results of this T-MT modeling are not conclusive. The sensitivity of the TM-mode, in this geologic environment, appears to be very low below depths of about 2 km. A conductive zone may exist beneath the hot springs at a depth of approximately 2 km, but the observed resistivity data can be explained equally well by the conductive zones lying within 1 km of the surface. This lack of resolution is attributed to ambiguity inherent in the geometry of the 2-D models themselves and is further complicated by a complex geologic setting. Three-dimensional effects combined with those resulting from near-surface conductive bodies appear to dominate any interpretive models drawn from the data.

The T-MT method with its potential for acquiring deep electrical soundings has become increasingly popular with geothermal contractors and industry in recent years. Geothermal environments in the Basin and Range Province have, at best, geometries that are two-dimensional and more likely three-dimensional. The 1-D and 2-D interpretation algorithms currently applied must therefore be used with caution. No general 3-D interpretative algorithms are currently available. Until practical 3-D interpretative aids are developed, the T-MT method should be employed primarily where the geology is likely 1-D or 2-D and the results can be reasonably interpreted. Sensitivity analysis of any interpretive model is of utmost importance and should not be omitted. Supporting evidence from alternate exploration techniques should also be evaluated before deep, expensive, drill tests are undertaken on geothermal reservoirs postulated solely from T-MT surveys using present interpretative aids.

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