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INTERPRETATION OF A TELLURIC-MAGNETOTELLURIC SURVEY AT THE TUSCARORA GEOTHERMAL EXPLORATION UNIT, ELKO COUNTY, NEVADA

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ABSTRACT

Two-dimensional modeling of T-MT data taken at the Tuscarora Geothermal Exploration Unit has shown that here 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 below 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 been obtained with alternate models. This ambiguity is inherent in the two-dimensional models themselves, and is further complicated by the complex geologic setting wherein three-dimensional effects result from near-surface conductive bodies. Current channeling within the conductive sediments of Independence Valley may also have a significant impact upon the resolution of the deep, postulated conductivity structure.

We recommend that any interpretation of T-MT data, possibly leading to a deep exploration drill test, 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.

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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., Earth Power Productive Company and Supron Energy has under taken a comprehensive 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.

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

GENERAL GEOLOGY

Independence Valley is bordered on the east by the Independence Range and on the west by the Tuscarora Mountains (Figure 2). Figure 3 is a generalized geologic map of the geothermal prospect located at the northern end of Independence Valley. 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 (180m-thick) overlie the Paleozoic rocks in the area of the hot springs. The 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. These flows and the tuff-breccia have been dated (K-Ar) at 38.8 ± 1.3 m.y. (Evans, 1981). 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 (Pilkington, 1980; Evans, 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 (Fig. 3). 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 4, 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 sinter deposit roughly 330 m wide, 1000 m long and 35 m high are present. No currently active springs issue from the 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 springs 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 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 as Figures 5 and 6. They closely parallel the T-MT profiles AA' and CC' shown in plan view on Figure 3.

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 Heramance and Thayer (1975). It combines quantitative magnetotelluric measurements at a base site with telluric measurements at a number of remote sites. Combining the two methods minimizes the time required, and thereby the cost, of completing a given survey. Paramount to the T-MT method, however, is the implicit assumption of spatial uniformity of the horizontal magnetic field.

Stodt, et al. (1979) conducted a study of the lateral variation of the electrical and magnetic fields in the vicinity of two-dimensional and three-dimensional conductivity inhomogeneities to assess the applicability of the T-MT method. Magnetic and electric fields which are nearly uniform laterally are produced at the surface of a one-dimensional earth by a plane-wave source of arbitrary incidence. Stodt et al. (1979) in their computer model studies have shown, however, that the assumption of spatial uniformity of the horizontal magnetic field is not always valid. 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, this spatial variation of the horizontal magnetic field is not as great but they conclude that the variation can contribute significantly to impedance magnitude and phase over shallow inhomogenities at higher frequencies.

There is no space charge present for the 2-D, TE-mode. The electric field vector is always aligned parallel to interfaces of differing conductivity. Since no component of current flows normal to these interfaces, no space charge is developed. Hence, induction is the only process producing lateral variation in the horizontal field components for this mode.

Space charges are always present for 3-D conductivity inhomogeneities regardless of incident field polarization. As a result there probably is no TE-mode in a 3-D environment (Ting and Hohmann, 1981). Space charges are present, however, in the 2-D TM-mode response because current flows transverse to the strike of any conductivity inhomogeneity.

SURVEY PROCEDURE

The T-MT survey was conducted by Terraphysics. Rotated tensor data were obtained at 11 base stations and 19 remote sites (Figure 7). 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. Both the magnetic and electric field data were processed using standard procedures. Utilizing the average cross 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 8 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 3-D effects are present and have a strong contribution to the 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 2-dimensional and more likely 3-dimensional. Several authors (Swift, 1967; Wannamaker, et al., 1980; Stodt, et al., 1981; Ting and Hohmann, 1981) have suggested modeling of selected T-MT and MT field data from a 3-D area using a 2-D TM algorithm. This appears to give more accurate conductivity cross-sections than those obtained with a TE algorithm. A two-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- amd TM-mode problems (Stodt, 1978). This program was used to model the T-MT (TM-mode data.

MODEL RESULTS

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 stitched together 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 9 through 12.

INTERPRETATION

The 2-D TM-mode model (Figure 9) for profile AA' shows a general decrease in near-surface resistivity from west to east. Hot Creek and the attendant structure, from which the hot springs issue, occurs between stations M1 and B1. The resistivity discontinuity shown on the model between these stations is thought to be indicative of this fault. The low (5 Ω m) resistivity material indicated near surface beneath station M1 is also evident on the dipole-dipole model and is thought to be related to hot fluids within shallow volcanic aquifers. Station B1 is located very near the larger intrusive plug shown on the geologic section (Figure 5). The resistive (500 Ω m) material shown on the model beneath station B1 is very likely this same intrusion. Similarly the resistive material shown at depth between stations M8 and B2 is representative of the tuff-breccia vent area and the postulated underlying intrusion. The conductive material shown beneath station B10 in all likelihood represents the nearby volcanic sediments of the valley. Similarly, the South Fork of the Owyhee River and its related conductive sediments is also thought to have an effect upon the sounding at station A8.

The conductive zone (1 Ω m) which is shown to have a large depth extent rising to 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 5 is the equivalent geologic cross-section. Good agreement is seen between the two portrayals. The resistive bodies shown on the MT model coincide with intrusions on the geologic section whereas the shallow more moderate resistivities are associated with Tertiary volcanics and sediments.

A geothermal reservoir occuring at a depth of 2 km has major economic significance. It is understood that this model (Figure 9) is non-unique, and refinements can be made for a better overall fit to the observed data. Profile AA' is not two-dimensional. The presence of Independence Valley with its conductive volcanic sediments lying immediately south of the profile causes additional concern. Theoretical MT model results are not available for comparison, for a geologic setting similar to Tuscarora. The interpretation of the model therefore became suspect. Consequently, it was necessary to test the sensitivity of the MT model shown in Figure 9.

Figure 10 shows another calculated MT model for profile AA'. Its primary difference is the removal of the conductive (1 Ω m) body. The geothermal reservoir at a depth of 2 km is of lesser contrast, 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.

Figure 11 shows the MT model for the observed data along Profile CC'. This profile extends into Independence Valley south of the hot springs. The Hot Creek structure is again 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 resistivity (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) mateial at depth on the southeast end of the profile is thought to be Paleozoic sediments beneath Independence Valley and the intrusion beneath 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 within the horst.

The most significant feature shown by this model is the very conductive (1 Ω m) zone 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 the geothermal reservoir. Figure 6 is the corresponding geological section. Good agreement is seen between the MT model and the geologic section. A sensitivity test was performed upon the MT model shown as Figure 11. Figure 12 shows the results of an alternate model having a less conductive (50 Ω m) body beneath the hot spring area. Note the strong similarity between the computed resistivity values (Figures 11 and 12). Both figures show acceptable fits to the observed data. We have since revised this model to limit the depth extent of the 50 Ω m body to 1.5 kilometers. The only significant change to Figure 12 occured at 0.01 Hz with stations B1, and A1 and M10. Calculated resistivities for these stations, at this frequency, changed to 19, 21 and 21 Ω m. No relatively conductive body extending to great depths is therefore required to fit the observed data.

A test hole was drilled 300 meters north of station M1 to a depth of 1663 meters. Its temperature log was disturbed, however, by invading waters of approximately 115°C at about 600 meters depth. The resistivity log of this well (Figure 13) is compared with resistivities deduced from dipole-dipole modeling, the 2-D MT modeling and the TE-mode 1-D inversion at Station M1, supplied by the contractor. These compare well with the resistivity log, and confirm that at 1663 meters the drill had not fully penetrated the zone of intermediate resistivity.

CONCLUSIONS AND RECOMMENDATIONS

The heat source and reservoir for the thermal springs occuring 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 paper has presented results of a telluric-magnetotelluric survey enhanced through two-dimensional computer modeling. Near-surface conductive zones shown by the MT models have also been indicated by dipole-dipole resistivity data.

The results of the TM-mode modeling are not conclusive. The sensitivity of the 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 conductive zones lying within 1 km of the surface. We attribute this lack of resolution to ambiguity inherent in 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 conclusions drawn from the data.

The T-MT method with its potential for aquiring 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 interpretative algorithms currently applied must therefore be viewed with caution. No general 3-D interpretative algorithms are currently available. Therefore, we recommend that, until 3-D interpretative aids are developed, emphasis should be placed upon the application of the T-MT method where geology is likely 1-D or 2-D and results can be interpreted. Sensitivity analysis of any interpretive model is of utmost importance and cannot be omitted. We further recommend that supporting evidence from alternate exploration techniques be obtained before deep, expensive, drill tests are undertaken on postulated geothermal reservoirs derived from T-MT surveys using present day interpretative aids.

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FIGURE CAPTIONS

Figure 1. Location map Tuscarora Area, Nevada.

Figure 2. Physiographic setting Tuscarora Area, Nevada.

Figure 3. Generalized geologic map Tuscarora Area, Nevada.

Figure 4. Detailed geologic map of Hot Spring Area Tuscarora, Area, Nevada.

Figure 5. Geologic cross-section profile AA' Tuscarora Area, Nevada.

Figure 6. Geologic cross-section profile CC' Tuscarora Area, Nevada.

Figure 7. T-MT station locations Tuscarora Area, Nevada.

Figure 8. Station B1 data Tuscarora Area, Nevada.

Figure 9. Profile AA' theoretical model 1 2-D TM-mode Tuscarora, Area, Nevada.

Figure 10. Profile AA' theoretical model 2 2-D TM-mode Tuscarora Area, Nevada.

Figure 11. Profile CC' theoretical model 1 2-D TM-mode Tuscarora Area, Nevada.

Figure 12. Profile CC' theoretical model 2 2-D TM-mode Tuscarora Area, Nevada.

Figure 13. Well 66-5 resistivity log compared with dipole-dipole and MT (1-D TE-mode, 2-D TM-mode) calculated resistivity, Tuscarora Area, Nevada.

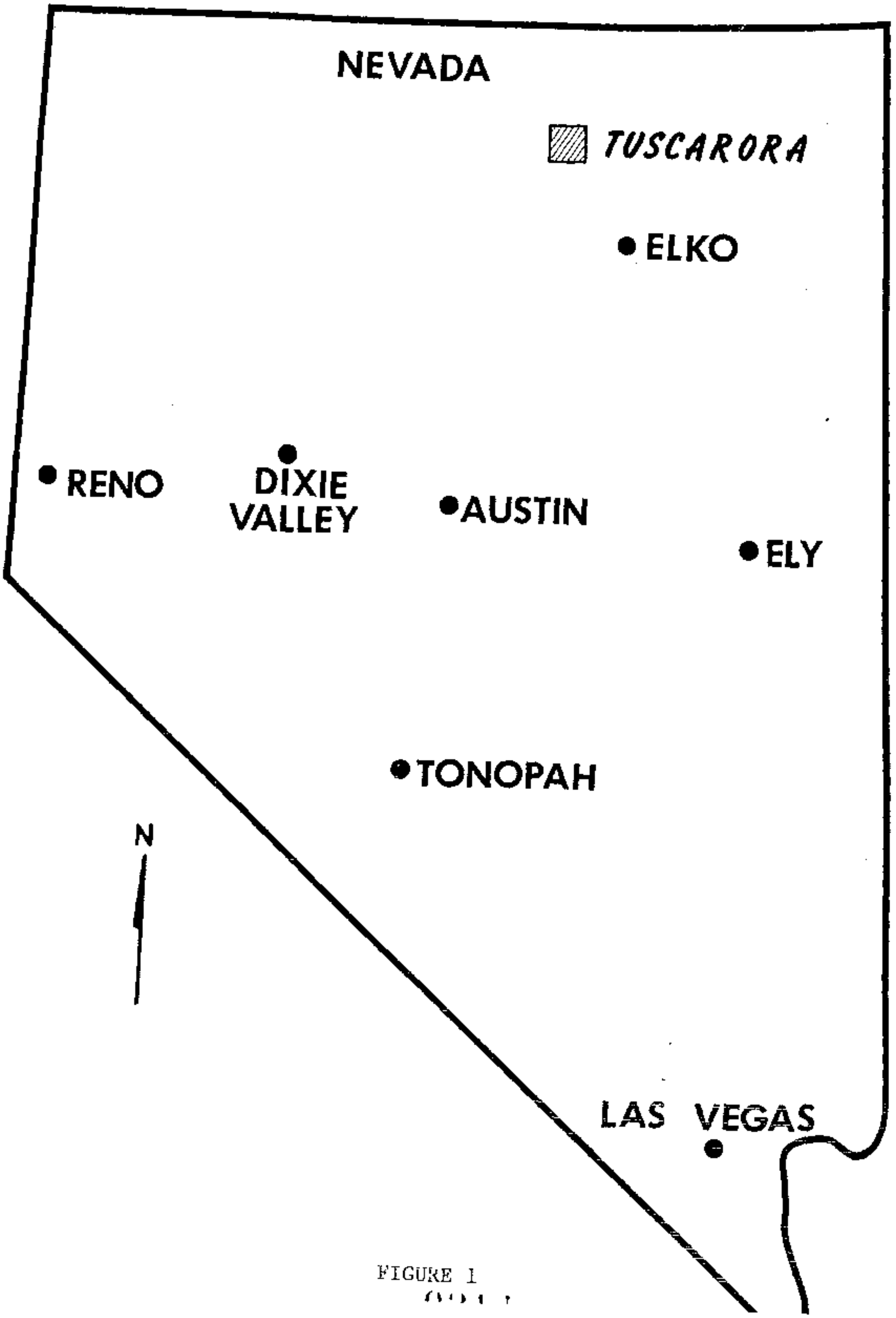

NEVADA
TUSCARORA
ELKO
RENO
DIXIE VALLEY
AUSTIN
ELY
TONOPAH
N
LAS VEGAS

FIGURE 1

[illegible]

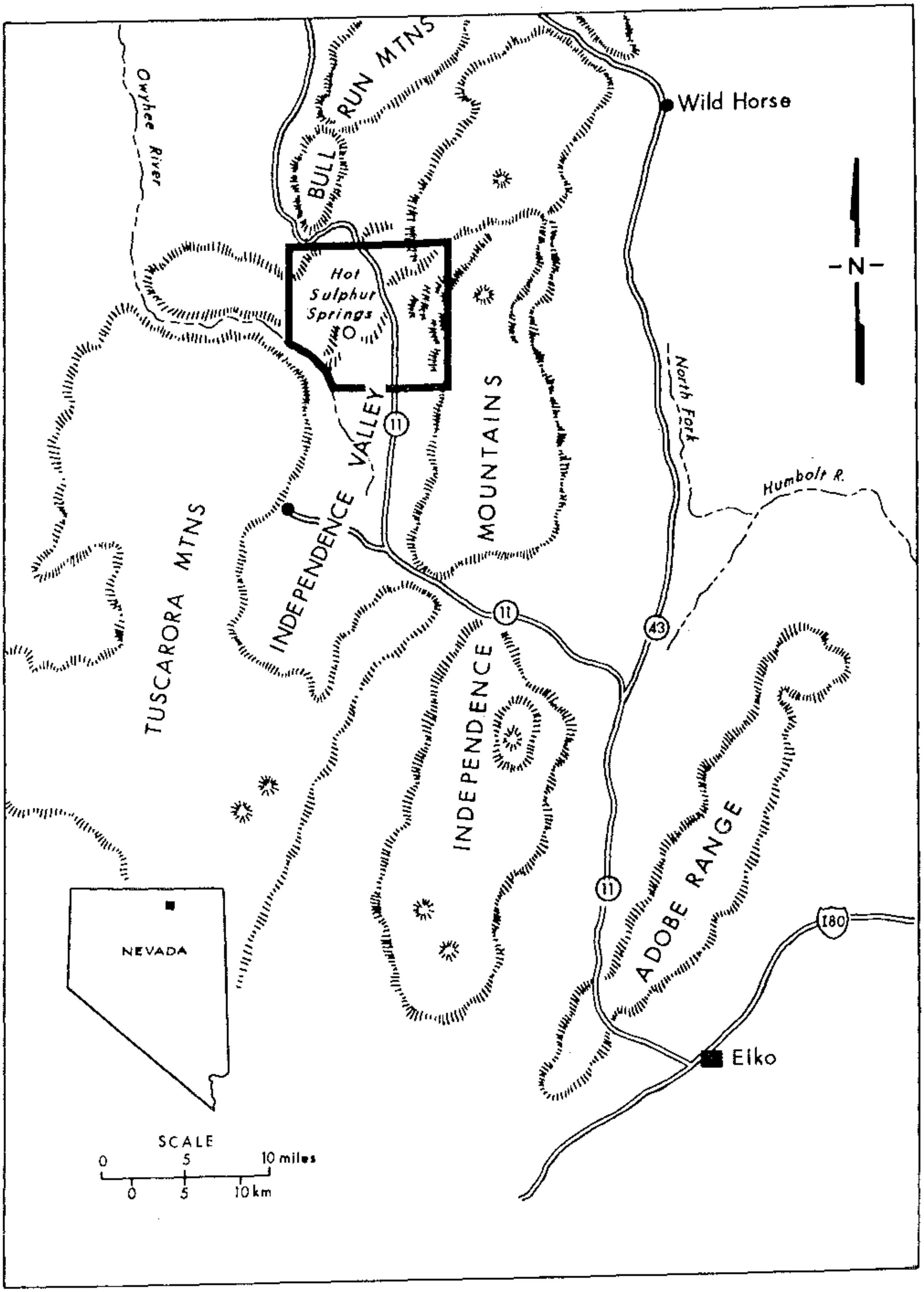

BULL RUN MTNS
Owyhee River
Wild Horse
Hot Sulphur Springs
N
North Fork
INDEPENDENCE VALLEY
MOUNTAINS
11
Humbolt R.
TUSCARORA MTNS
INDEPENDENCE
43
INDEPENDENCE
ADOBE RANGE
11
180
NEVADA
Elko
SCALE
0
5
10 miles
0
5
10 km

FIGURE 2

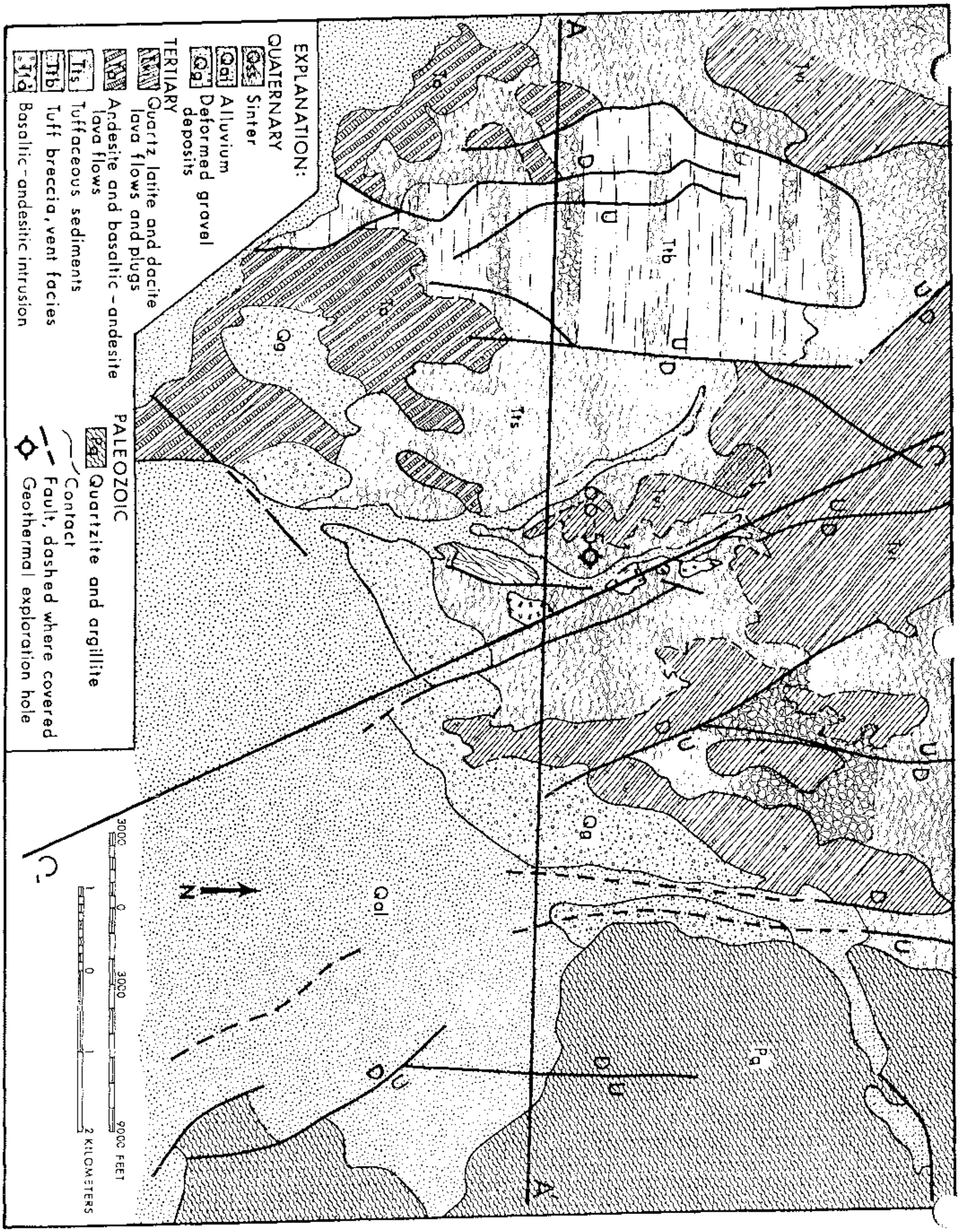

EXPLANATION:
QUATERNARY
Qss Sinter
Qal Alluvium
Qg Deformed gravel deposits
TERTIARY
Tql Quartz latite and dacite lava flows and plugs
Ta Andesite and basaltic-andesite lava flows
Tts Tuffaceous sediments
Ttb Tuff breccia, vent facies
Tia Basaltic-andesitic intrusion
PALEOZOIC
Pq Quartzite and argillite
Contact
Fault, dashed where covered
Geothermal exploration hole
3000 0 3000 9000 FEET
1 0 1 2 KILOMETERS
N
A
A'
U
D
Ttb
Tts
Ta
Qg
Qal
Pq

FIGURE 3

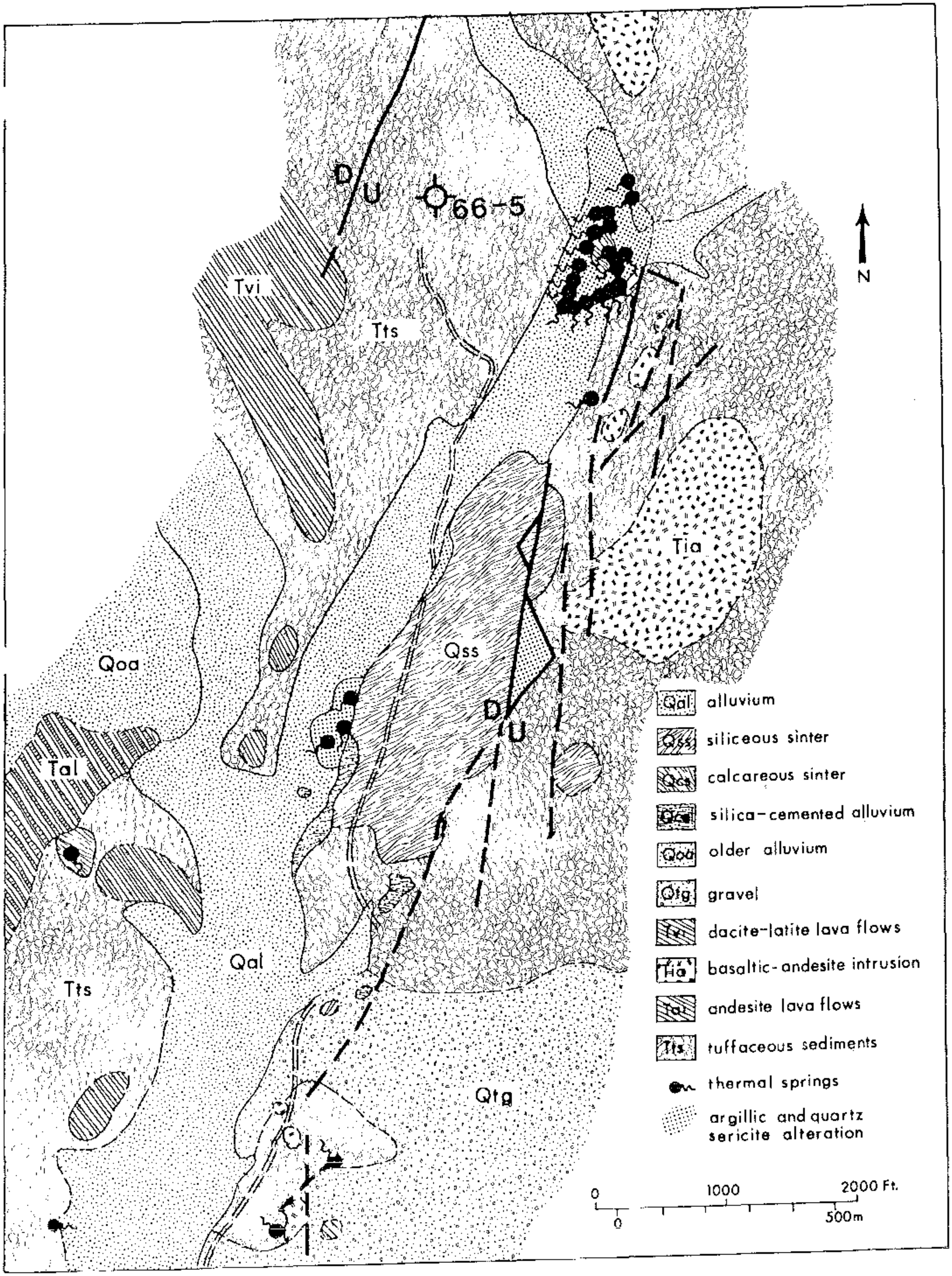
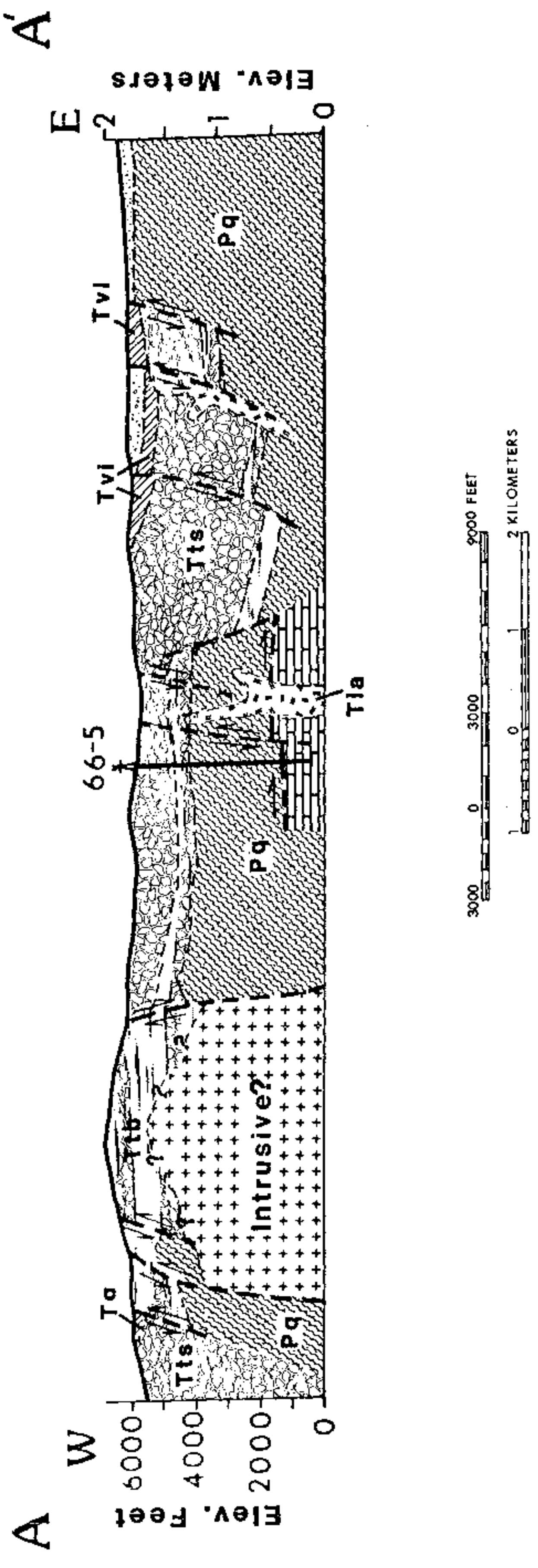

66-5
D
U
Tvi
Tts
N
Tia
Qss
Qoa
D
U
Tal
Qal
Tts
Qtg
Qal alluvium
Qss siliceous sinter
Qcs calcareous sinter
Qca silica-cemented alluvium
Qoa older alluvium
Qtg gravel
Tv dacite-latite lava flows
Tia basaltic-andesite intrusion
Tal andesite lava flows
Tts tuffaceous sediments
thermal springs
argillic and quartz sericite alteration
0
1000
2000 Ft.
0
500m

FIGURE 4


A
A′
W
E
Elev. Feet
Elev. Meters
6000
4000
2000
0
2
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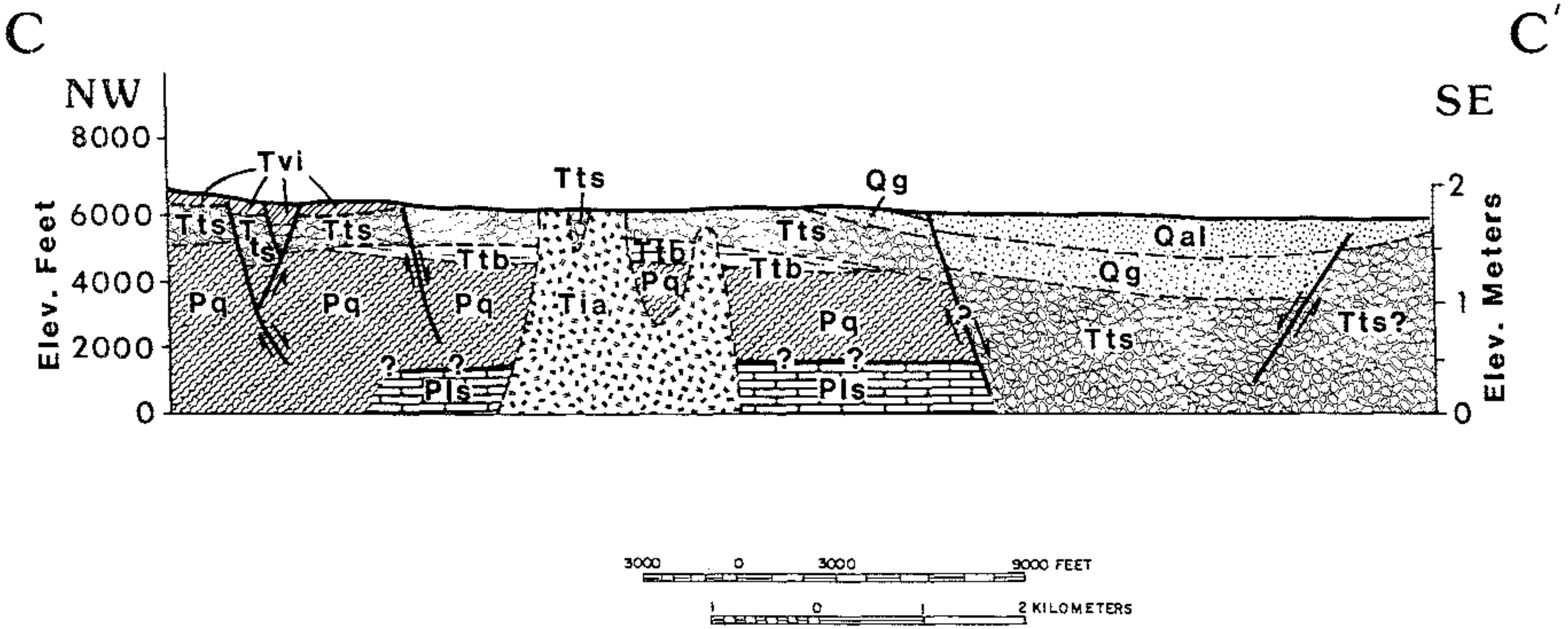
Ta
Tts
Pq
Ttb
Intrusive?
66-5
Tla
Tvl
Tvl
3000
0
3000
9000 FEET
1
0
1
2 KILOMETERS

FIGURE 5


C
C′
NW
SE
8000
6000
4000
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2
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Tts
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Ts
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Qg
Tts
Qal
Qg
Ttb
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Ttb
Pq
Pq
Pq
Pq
Pq
Tia
Tts
Tts?
?
Pls
Pls
3000 0 3000 9000 FEET
1 0 1 2 KILOMETERS

FIGURE 6

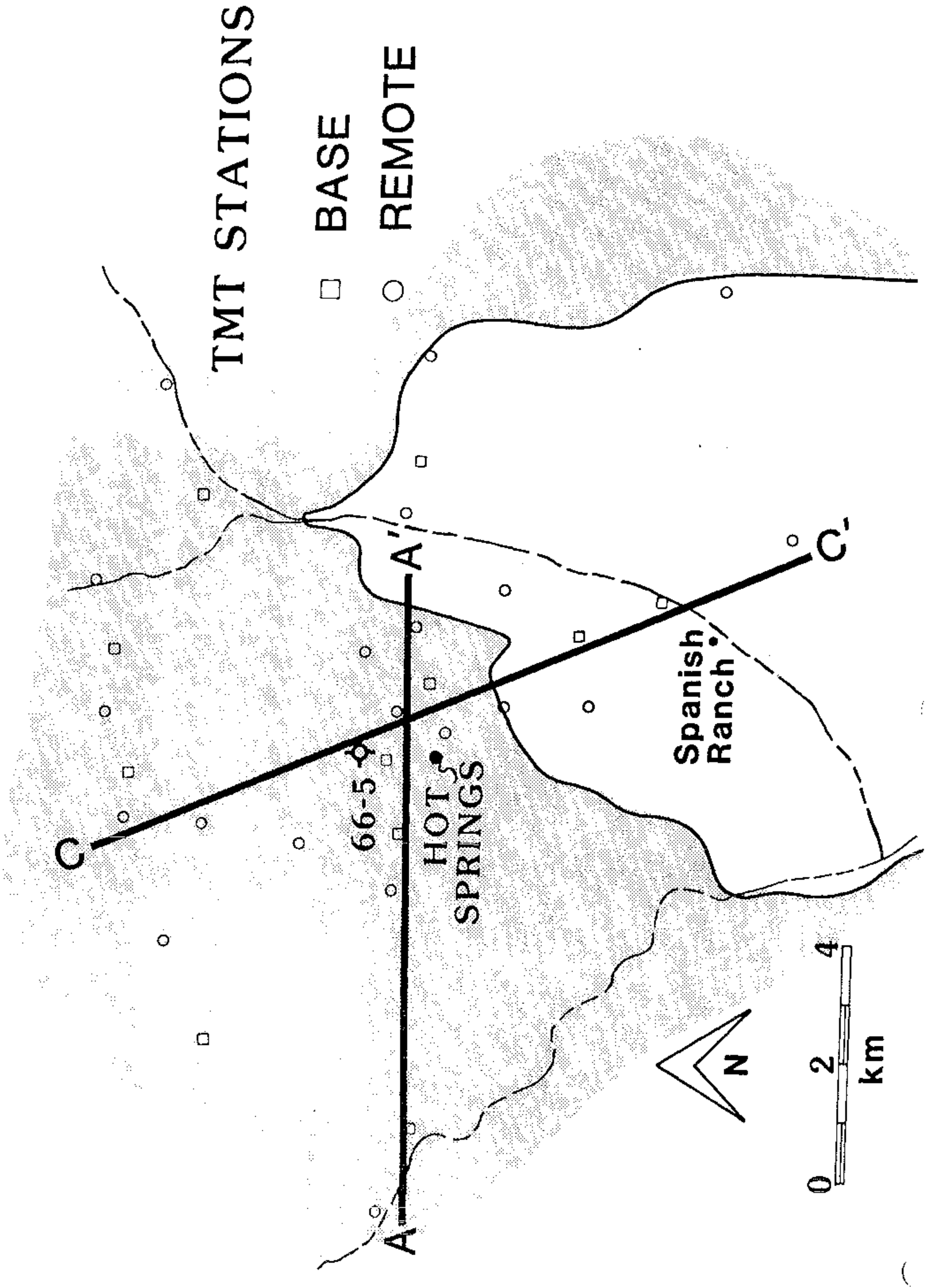
TMT STATIONS
□ BASE
○ REMOTE
A
A'
C
C'
66-5
HOT SPRINGS
Spanish Ranch
N
0
2
4
km

FIGURE 7

TUSCARORA PROSPECT, NEVADA

Station B1

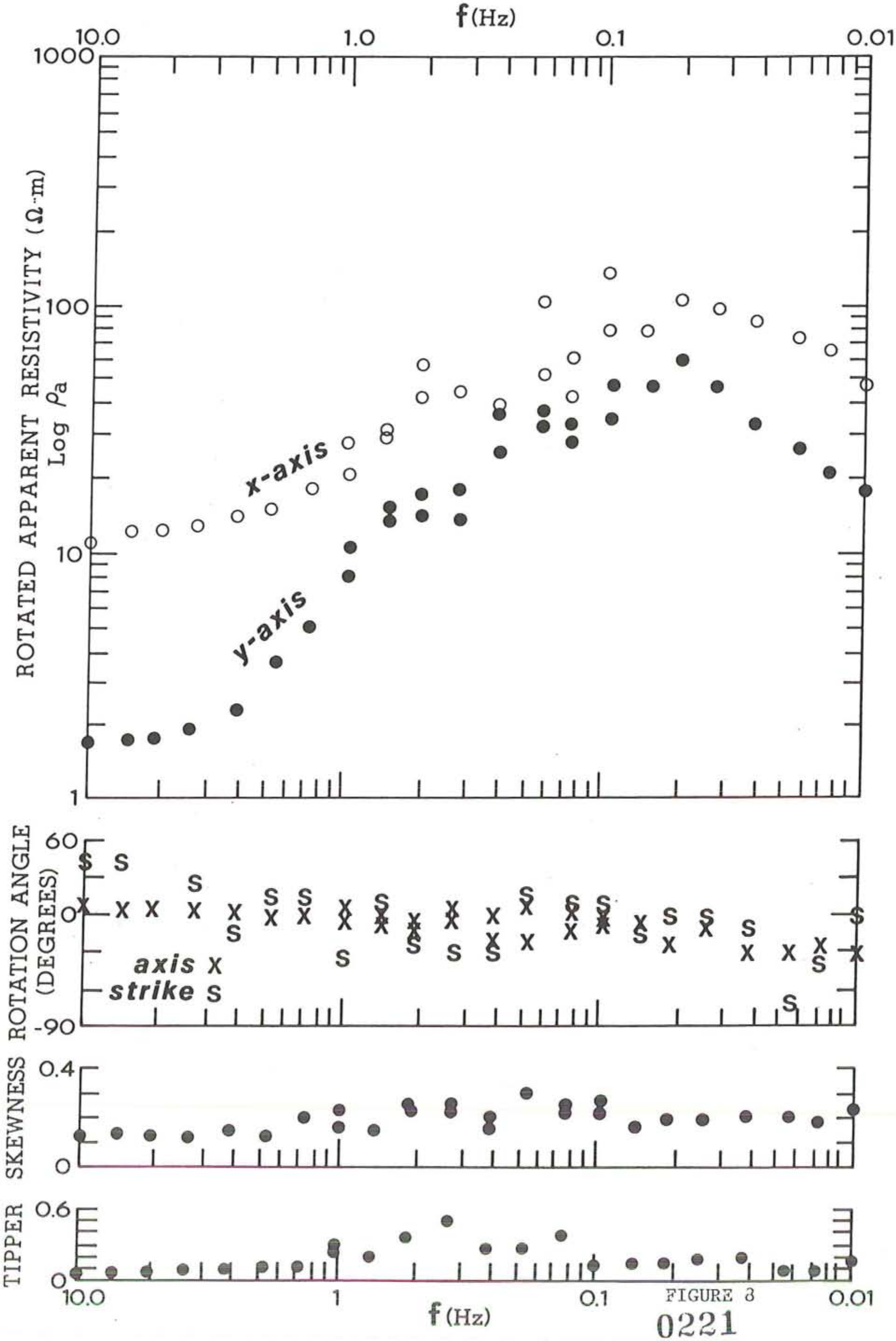

FIGURE 3

TUSCARORA AREA, NEVADA
T-MT PROFILE AA'

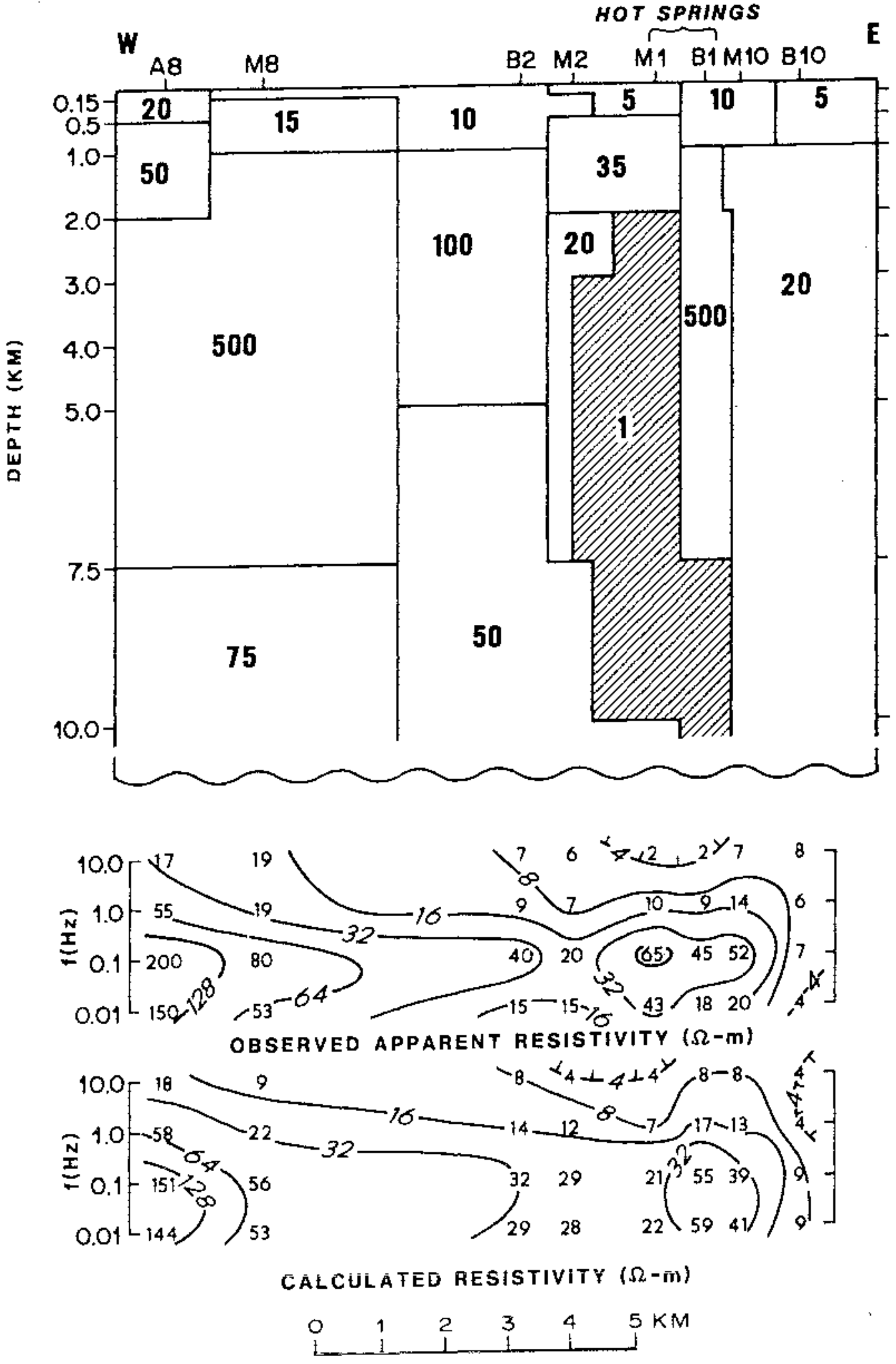

FIGURE 9

TUSCARORA AREA, NEVADA
T-MT PROFILE AA'

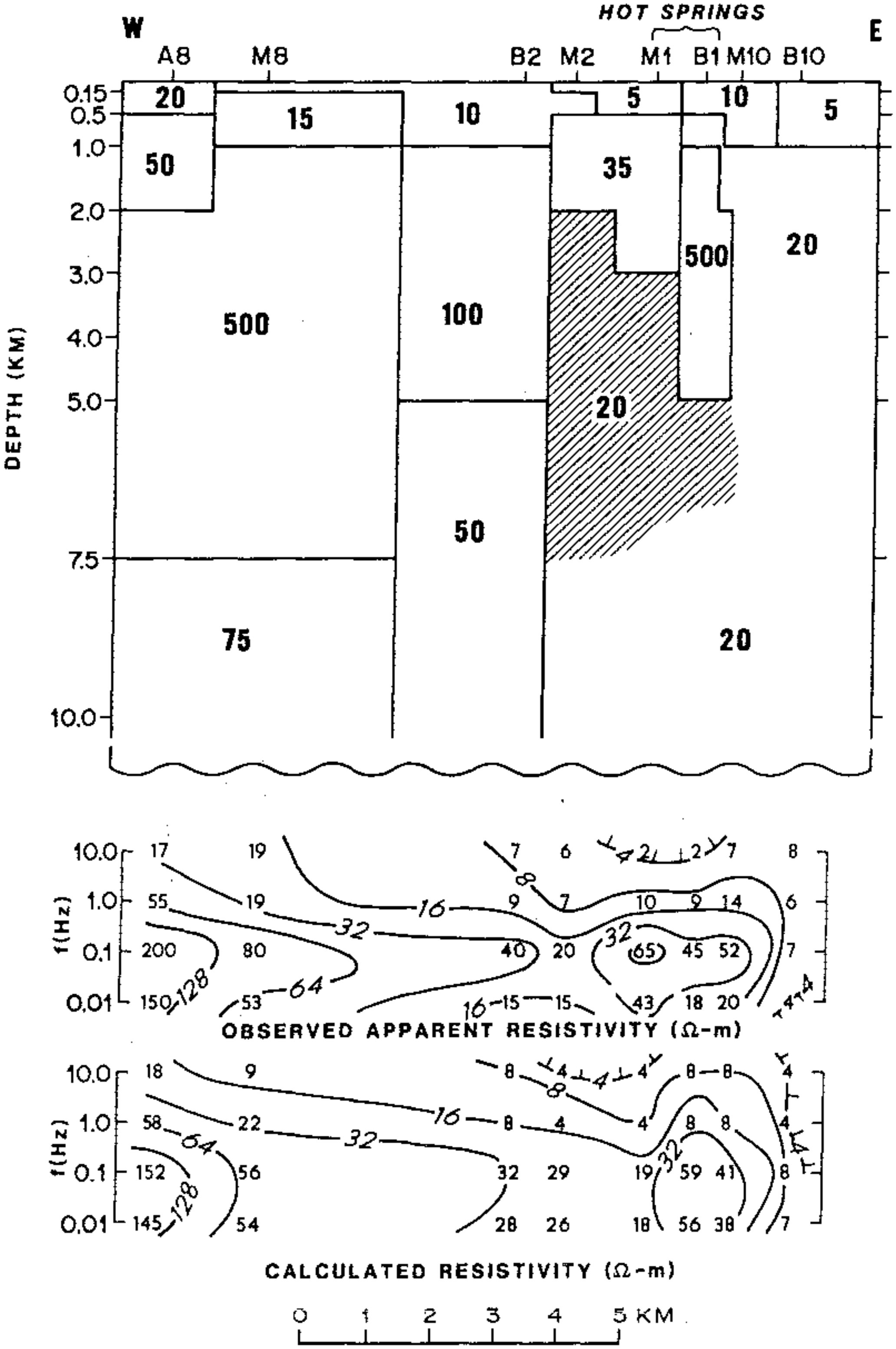

FIGURE 10

TUSCARORA AREA, NEVADA
T-MT PROFILE CC′

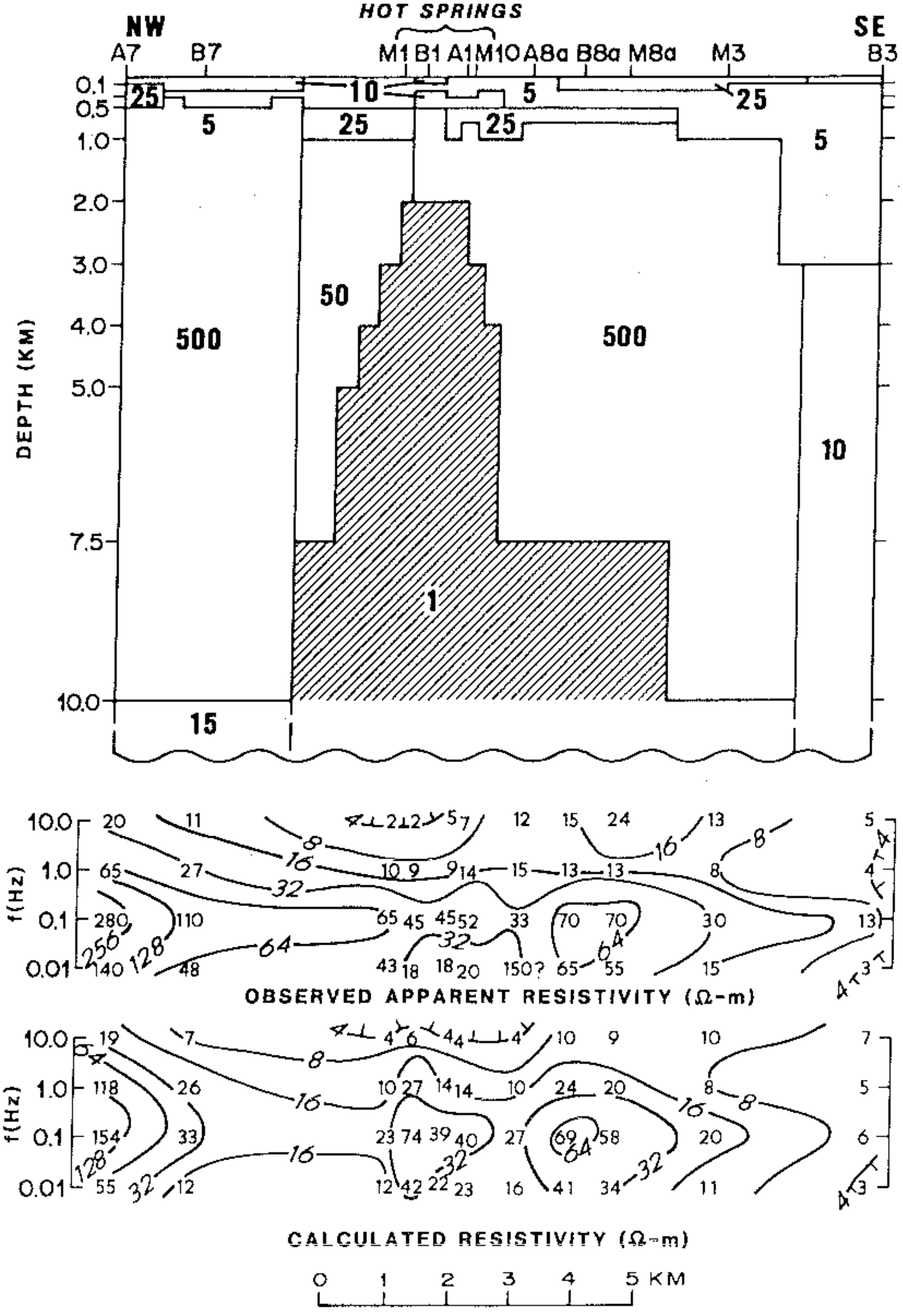

FIGURE 11

TUSCARORA AREA, NEVADA
T-MT PROFILE CC′

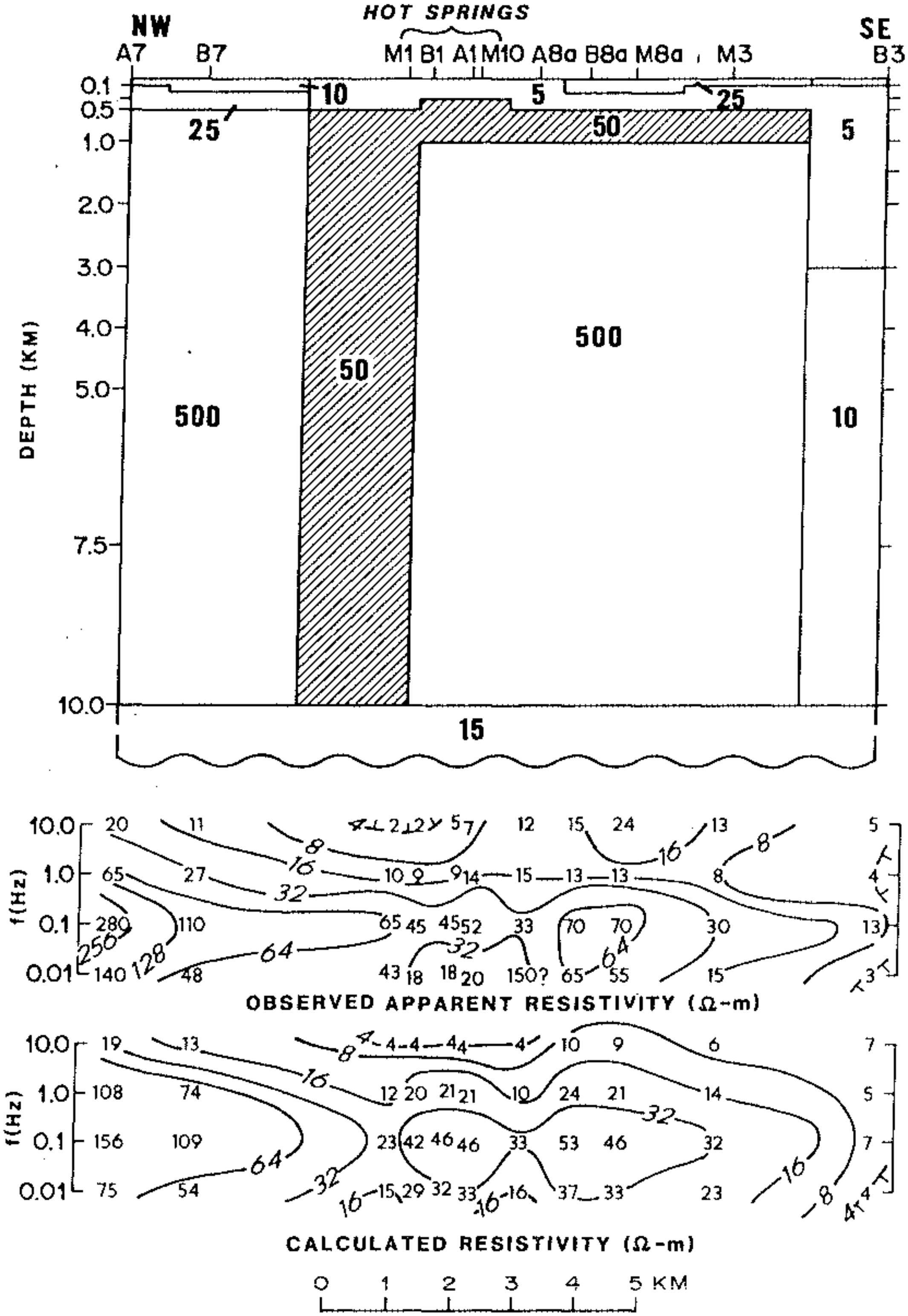

FIGURE 12

WELL 66-5 RESISTIVITY
(DUAL IND. LATEROLOG)

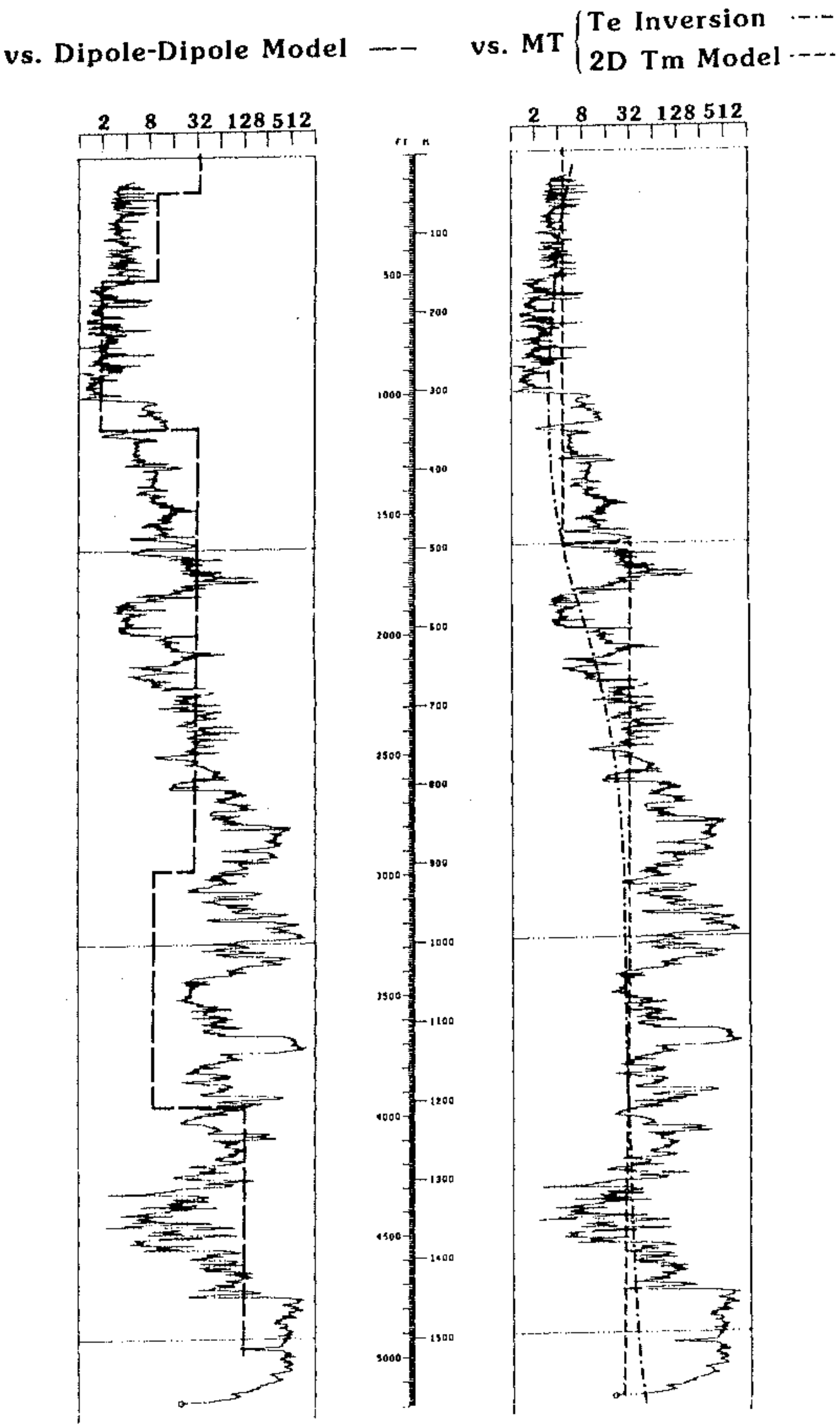

FIGURE 13