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Simultaneous inversion modeling of gravity and aeromagnetic data applied to a geothermal study in Utah

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ABSTRACT

Aeromagnetic and gravity surveys were conducted during 1978 in the Black Rock Desert, Utah over an area of about 2,400 km^2 between the north-trending Pavant and Cricket Mountains. Simultaneous inversion modeling of the gravity and aeromagnetic data was used to delineate subsurface geologic characteristics in an effort to evaluate the geothermal potential of the Meadow-Hatton Known Geothermal Resource Area (KGRA). The modeling technique used a weighted Gauss inversion scheme to normalize gravity and aeromagnetic data along profiles. The models indicated an extensive area of probable hydrothermal alteration in the vicinity of the KGRA and possible migration paths for hot geofluids. No evidence of a buried igneous body was identified in the models. Faulting to depths of over 4 km was modeled and is sufficient to account for the water temperatures estimated in the KGRA.

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DISCLAIMER

Permission to publish this work is dependent upon the Department of Energy who provided funding for this project. At this time, permission to publish is still pending.

INTRODUCTION

The Meadow-Hatton Known Geothermal Resource Area (KGRA) is located in the Black Rock Desert, in south-central Utah (Figure 1). The existence of hot springs and some of the youngest dated basalts and rhyolites in Utah (Luedke et al, 1978; Lipman et al, 1978) make this area an interesting geothermal prospect. The KGRA is located less than 65 km from two proven geothermal sites at Roosevelt Hot Springs (Ward et al, 1978) and Monroe, Utah (Mase et al, 1978).

In an effort to determine the geothermal potential of the KGRA, detailed gravity and aeromagnetic surveys were conducted in the KGRA and vicinity. Both the gravity and aeromagnetic data can give information about: 1) geologic structures which may control fluid migration, 2) previously undetected igneous bodies which may be related to heat sources, and 3) hydrothermally altered rock and cemented alluvium related to hot fluid migration. For this reason, it was felt that this study would provide a valuable test of our recently developed two and one-half dimensional modeling program which incorporates a simultaneous inversion of gravity and aeromagnetic data. Bodies which influence both the gravity and aeromagnetic data, particularly buried intrusive bodies, could more precisely be defined with this technique.

GENERAL GEOLOGIC SETTING

The survey area (Figure 2) lies along the eastern margin of the Sevier orogenic belt (Armstrong, 1972) in the transition zone between the Basin and Range and the Colorado Plateau provinces. The region is bounded on the east by the Pavant Range and on the west by the Cricket Mountains, both of which trend approximately north-south. Along the southern boundary lies the eastward-trending Black Rock offset which Crosby (1973) interpreted as a zone of possible right-lateral faulting.

The surface geology (Nash and Crecraft, 1979) is dominated by a zone of volcanic flows, craters, and cinder cones which trend northward through the center of the survey area. The exposed volcanics range in age from approximately 900,000 yr to less than 1,000 yr (Luedke et al, 1978; Hoover, 1974). Well and seismic data (McDonald, 1976; Dennis et al, 1946; Livingston and Maxey, 1944) suggest that the area is underlain by over 2.5 km of interbedded Neogene basalts and volcanic and fluviolacustrine sediments.

The White Mountain rhyolite dome (Figure 2) is the only exposure of silicic volcanic material in the central portion of the study area. The dome is approximately 500 m in diameter and 50 m in height. A K-Ar age of 0.4 m.y. (Lipman et al, 1978) makes it the youngest dated rhyolite dome in Utah. White et al (1971) have suggested that young rhyolite domes may be related to the high heat flow observed in some geothermal areas. Therefore, the White Mountain area is of primary interest as a geothermal prospect. Meadow Hot Springs, located approximately 6 km south of the White Mountain rhyolite dome, has water temperatures of up to 41^{o}C (Mundorff, 1970; Cleary, 1978). Older silicic volcanic rocks dated at 2.4 m.y. crop out in the extreme southwestern part of the study area (Crecraft et al, 1981).

GEOPHYSICAL DATA

The gravity data for this survey were collected 1) at stations along several east-west profiles with station spacings of approximately 0.5 km and 2) at stations that were distributed more regionally throughout the survey area. These gravity data were combined with the gravity data obtained by Isherwood (1969) and then reduced and terrain corrected to give complete Bouguer gravity anomaly values (Serpa, 1980; Serpa and Cook, 1980a,b) and contoured with a 1-mgal contour interval (Figure 3).

The aeromagnetic survey was conducted by Aerial Surveys during 1978 under contract to the Department of Geology and Geophysics, University of Utah. The survey was drape flown at a height of 305 m along north-trending flight lines spaced 0.5 km apart (Serpa and Cook, 1980a). The total magnetic field intensity residual anomaly map with a contour interval of 20 gammas is shown in Figure 4.

For the subsequent profile modeling, the gravity and aeromagnetic data were selected along two profiles. For detailed profile B-B' (Figures 3 and 4), which trends east-west, the gravity values were taken from the complete Bouguer gravity anomaly map and the magnetic values were interpolated on the aeromagnetic map to correspond with the gravity station locations along the profile. For profile A-A', which trends north-south, the values were interpolated from both the gravity and the aeromagnetic maps (Figures 3 and 4), though the values at gravity stations were used whenever possible. The geophysical models presented in this paper are assumed to extend symmetrically along strike perpendicular to the profiles. However, the actual profiles selected are not always located through the center of all the main geologic features. Therefore, some error may result from the non-symmetry. For bodies which extend at least 5 km along strike in each direction perpendicular to the profiles, the error due to non-symmetry is considered small or insignificant in the models shown.

The geologic interpretation presented by McDonald (1976) was used extensively as a basis for the models presented in this study. The Black Rock Desert was included in a comprehensive study by McDonald in which he used reflection seismic profiles and well data. Two of McDonald's seismic profiles lie within the study area (Figure 2) and a third lies just north of the study area near Delta, Utah (not shown in Figure 2). All three profiles were converted to depth sections using an average velocity of 4 km/s for the interpreted Cenozoic sedimentary rocks and alluvium. These depth sections were then used as the basis for the initial guess required for modeling (see Appendix A for a description of the modeling technique).

To prepare the initial guess models, the values of the rock parameters used were based on 1) the density measurements made by Carrier (1979) for rocks in an area immediately adjacent to the study area and 2) the density and magnetic susceptibility measurements made by Serpa (1980) for rocks in the study area. These values were not allowed to vary significantly during subsequent iterations on the models.

MODELING

Two profiles (A-A' and B-B') were selected for simultaneous modeling of the gravity and aeromagnetic data (Figures 3 and 4). During the modeling process, the vertices (of the polygons)_/ and, to a lesser extent, the density and magnetic susceptibility contrasts were allowed to vary about an initial guess using the inversion scheme described in Appendix A. At no time was any vertex allowed to vary greatly from the initial model.

During the modeling, it was found that the inversion technique worked very well if only a few vertices were allowed to vary during any given iteration. Efforts to invert on the entire model at once resulted in erratic variations in the model and generally worsened the fit to the observed data. Additionally, inversions of the density and magnetic susceptibility contrasts proved to become unstable during repeated iterations. These effects were attributed to the ambiguity inherent in potential field data and were avoided by making several runs of the inversion program while varing only a few parameters at a time. The final models for profile A-A' and B-B' are shown in Figures 5 and 6, respectively, and both give a good fit to the data. The models were held fixed or allowed only minor variation where seismic data were available, and the vertices at the surface were constrained on the

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_/ In this paper, the use of the words "vertex" or "vertices" applies to the polygon (or polygons) in the Talwani modeling technique (Talwani et al, 1959).

basis of the surface geology. Somewhat greater variation was allowed for the thickness of volcanic bodies and the extent of hydrothermal alteration as these parameters were not well determined in any of the available data.

It was anticipated that the presence of a buried igneous body might be detected by identifying anomalies in either, or both, data sets which could not be accounted for by the basic model. The model was allowed to vary to obtain the best fit to both data sets during the inversion phase of the modeling, and the resulting fit was sufficiently good that the presence of buried igneous bodies could not be interpreted along these profiles.

GEOLOGIC INTERPRETATION

Profile A-A'

Profile A-A' (Figure 5) extends approximately 50 km north-south across the center of the study area. The area of geothermal interest lies within the southern 20 km of the profile where a nearly 10 km long body of hydrothermally altered alluvium and rocks has been modeled. To the north, basalt flows with an average thickness of 200 m have been modeled to represent the Tabernacle, Pavant, and Ice Springs volcanic fields. It is believed that these volcanic fields may reach greater depths and probably consist of thin layers of basalt interbedded with Neogene rocks.

In the extreme southern end of profile A-A' lie the Kanosh cinder cones which have been modeled to depths of up to 700 m. In the model, the cinder cones are assumed to be underlain by a thin layer of sedimentary rocks which, in turn, overlie a wedge of rocks probably related to the Pavant Mountains.

Throughout this profile the upper approximately 3 km of material is believed to be Cenozoic sedimentary rocks and alluvium overlying rocks of higher density which are believed to be pre-Tertiary in age. Within the upper 3 km, two tear faults have been interpreted to correspond with east-west trends in the gravity and aeromagnetic maps (Figures 3 and 4). These faults are believed to be the result of differential motion between blocks of normally faulted material.

Profile B-B'

Profile B-B' (Figure 6) extends approximately 50 km east-west across the center of the survey area. An approximately 10 km wide body of volcanic material corresponding to the Ice Springs and Tabernacle volcanic fields is modeled near the center of the profile. The volcanics and the underlying Cenozoic rocks are cut by numerous faults which have been interpreted as listric normal faults. These faults are believed to curve into and terminate along a west-dipping detachment plane separating the Tertiary sedimentary rocks from the pre-Tertiary rocks. The curvature of these faults could not be proven with either the gravity or the aeromagnetic data, but this interpretation appears reasonable from the seismic data presented by McDonald (1976). A wedge of rocks with density and magnetic susceptibility lying between those of the surrounding Tertiary and pre-Tertiary rocks was modeled in the western 10 km of profile B-B'. McDonald (1976) has interpreted this material as pre-Tertiary and it may represent material related to the Cricket Mountains to the west.

CONCLUSIONS

The use of the simultaneous inversion modeling technique has provided a reasonable geologic interpretation of the subsurface which corresponds well with all of the data available. The absence of any identifiable buried igneous body along either of the two profiles may indicate that the source of the hot springs in the area is from the circulation of fluids along faults. The heat flow in this region has been shown to be typical for the Basin and Range province (Carrier, 1979; Carrier and Chapman, 1980) with a geothermal gradient of 50° C/km. Fluids circulating to a depth of 4 km along faults in this area would be heated to temperatures of 200° C which is in the range of temperatures estimated by Cleary (1978) for the Meadow Hot Springs. This depth of circulation and resulting temperature of hot springs associated with faults in the Basin and Range province are compatible with the results obtained elsewhere in similar geologic settings (Halliday and Cook, 1970; Cook et al, 1980; Pe and Cook, 1980; Clement, 1980).

Modeling of potential field data is non-unique. However, the simultaneous modeling of the gravity and aeromagnetic data, coupled with seismic reflection information (McDonald, 1976), has significantly reduced the ambiguity. The models presented in this paper provide the "best fit" to three different types of geophysical data combined with information about the surface geology (Nash and Crecraft, 1979) and well data (McDonald, 1976; Dennis et al, 1946; Livingston and Maxey, 1944). Although various parts of the models were derived from the individual data sources, only the use of all the available information can provide a reasonable model of the subsurface geology. As additional data become available, these models can be refined or modified as needed to improve our understanding of this geothermal system.

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APPENDIX A

DESCRIPTION OF THE SIMULTANEOUS MODELING PROGRAM (JOINT)

A number of computer programs are available (Snow, 1978) which use inversion techniques to model either gravity or aeromagnetic data. JOINT was initially a combination of two of these programs (namely MAGINV and G2HINV) written by Snow (1978) and still bears a number of similarities to these programs. However, it was found that the use of a Marquardt step did not significantly improve the stability of the joint inversion and therefore a Gauss method (Beck and Arnold, 1977) was used for the inversion scheme.

JOINT uses a 2 1/2 dimensional modeling technique (Talwani et al, 1959) which incorporates the Talwani method and end corrections for polygons of finite strike length (Cady, 1977, 1980; Shuey and Pasquale, 1973). The forward problem is given as:

$$g_j = K \sum_{i=1}^{N} \Delta\rho_i \sum_{k=1}^{M} f(x_{ijk}, y_j, z_{ijk}) \qquad (1)$$

where g_j is the theoretical value of gravity or magnetics that would be observed at the j'th point on, or above, the surface. K is a constant which depends on the type of data (gravity or magnetic) being calculated. $\Delta\rho_i$ is the density contrast, for the gravity data, and the magnetic susceptibility contrast, for the magnetic data, of the i'th polygon. x, y, and z are the vertices of the i'th polygon measured from the j'th station.

To combine the two data sets, it is necessary to standardize the data. It is assumed that some knowledge of the error in each data set is available, and therefore an objective function was chosen to utilize this information and standardize the data in a manner suggested by Jackson (1973). JOINT is designed to find those parameters which minimize a chi-squared objective function:

$$S_{\chi^2} = \sum_{j=1}^{M} \left(\frac{g_j{}^\circ - g_j}{\sigma_j}\right)^2 \qquad (2)$$

where g_j° is the observed value and g_j is the predicted value at the j'th station and σ_j is the estimated variance for either the gravity or aeromagnetic data represented by g_j°. Rewriting equation (2) in matrix notation gives:

$$s = [\bar{g}^\circ - \bar{g}(\bar{p})]^T \bar{\bar{W}} [\bar{g}^\circ - \bar{g}(\bar{p})] \qquad (3)$$

$$\bar{\bar{W}} = \begin{matrix} 1/\sigma_{ij}^2 & \text{for } i=j \\ 0 & \text{elsewhere} \end{matrix}$$

To minimize s, the matrix derivative of s is set equal to zero.

$$\nabla_\rho s = \bar{\bar{A}}^T(\hat{p}) \bar{\bar{W}} [\bar{g}^\circ - \bar{g}(\hat{p})] = 0 \qquad (4)$$

where $\bar{\bar{A}}(\hat{p}) = \nabla_\rho \bar{g}(\hat{p})$ and $\nabla_\rho = \left[\frac{\partial}{\partial P_1}, \ldots, \frac{\partial}{\partial P_k}\right]^T$

Because $\bar{g}(\hat{p})$ is generally non-linear with respect to the parameters $\hat{p}$, a truncated Taylor expansion about some $\hat{p}'$ is used to find the estimated $\hat{p}$. This gives (Beck and Arnold, 1977);

$$\bar{\bar{A}}^T(\hat{p}')\bar{\bar{W}}[\bar{g}^\circ-\bar{g}(\hat{p}')-\bar{\bar{A}}(\hat{p}')\Delta\bar{p}] \approx 0 \quad (5a)$$

$$\Delta\bar{p} = \hat{p} - \hat{p}'$$

or

$$\bar{\bar{A}}^T\bar{\bar{W}}\bar{\bar{A}}\Delta\bar{p} = \bar{\bar{A}}^T\bar{\bar{W}}\bar{e} \quad (5b)$$

$$\bar{e} = \bar{g}^\circ - \bar{g}$$

Solving equation (5b) iteratively to find the best estimate of p for the k'th iteration gives:

$$\bar{p}^{k+1} = \bar{p}^k + (\bar{\bar{A}}^T\bar{\bar{W}}\bar{\bar{A}})^{-1}\bar{\bar{A}}^T\bar{\bar{W}}\bar{e}. \quad (6)$$

A listing of the computer program JOINT is given in Serpa (1980). This program was written for use on a UNIVAC 1108 but could readily be modified for use on any standard computer.

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LIST OF FIGURES

Table 1. -- Geophysical parameters and interpreted geologic units modeled for bodies shown in profiles AA' (Figure 5) and BB' (Figure 6).

Body No.	Density (gm/cc)	Magnetic Susceptibility (cgs units)	Half-length Profile AA'	(km) Profiles BB'	Interpreted Geologic Units
1	2.78	0.0004	---	---	Pre-Tertiary basement rocks
2	2.58	0.0011	100	100	Tertiary (?) sedimentary rocks
3	2.38	0.0011	100	100	Neogene sedimentary rocks
4	2.67	0.0007	---	100	Uncertain
5	2.50	0.0036-0.0039	5.0-8.0	6.0	Quaternary basalt flows
6	2.38	0.0036-0.0042	0.5-1.0	---	Quaternary cinder cones
7	2.53	0.0000	4.0	---	Zone of Quaternary hydrothermal alteration

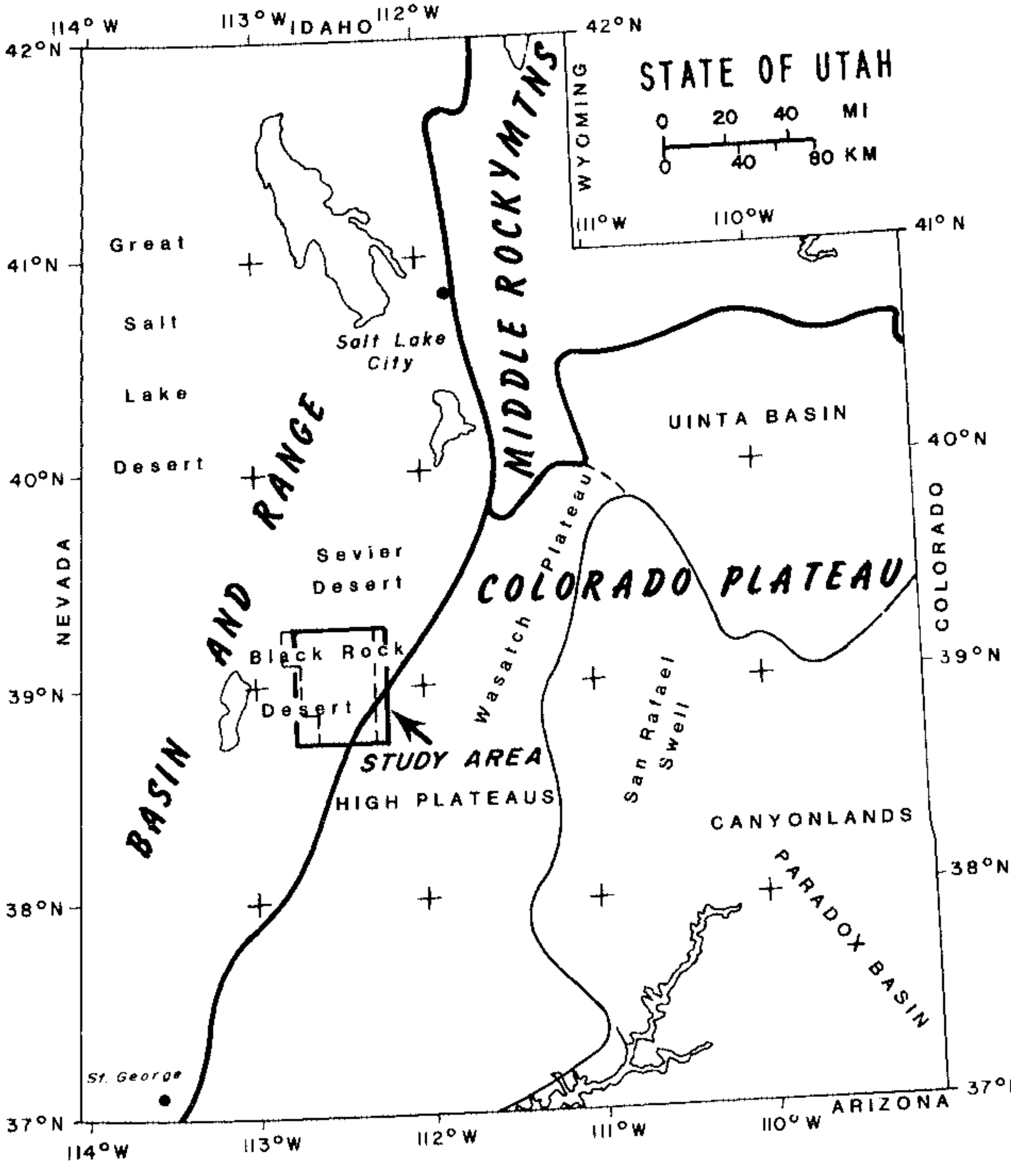

STATE OF UTAH
0 20 40 MI
0 40 80 KM
IDAHO
WYOMING
NEVADA
COLORADO
ARIZONA
114° W
113° W
112° W
111° W
110° W
42° N
41° N
40° N
39° N
38° N
37° N
MIDDLE ROCKY MTNS
Great Salt Lake Desert
Salt Lake City
BASIN AND RANGE
Sevier Desert
Black Rock Desert
STUDY AREA
HIGH PLATEAUS
Wasatch Plateau
COLORADO PLATEAU
UINTA BASIN
San Rafael Swell
CANYONLANDS
PARADOX BASIN
St. George

Fig. 1

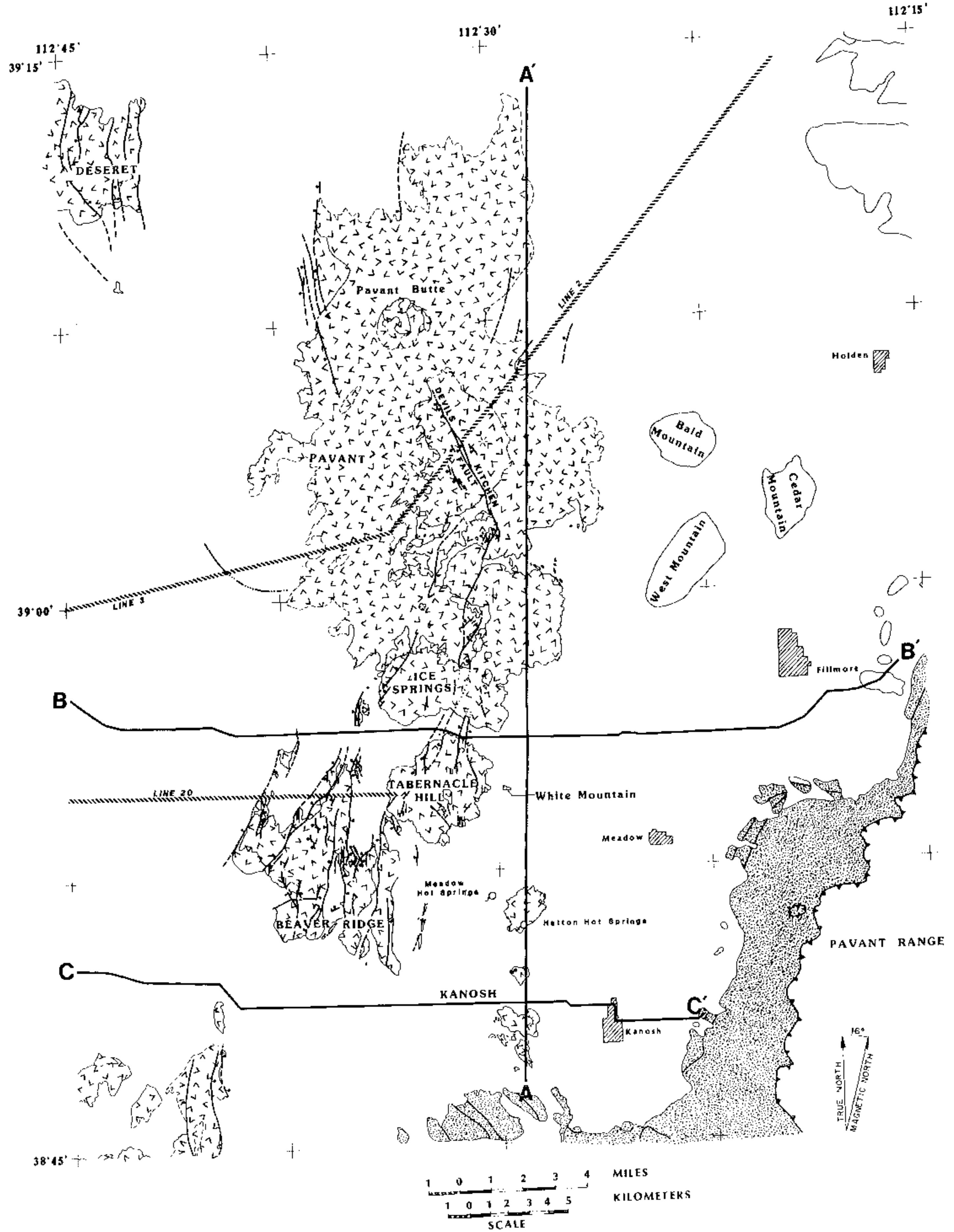
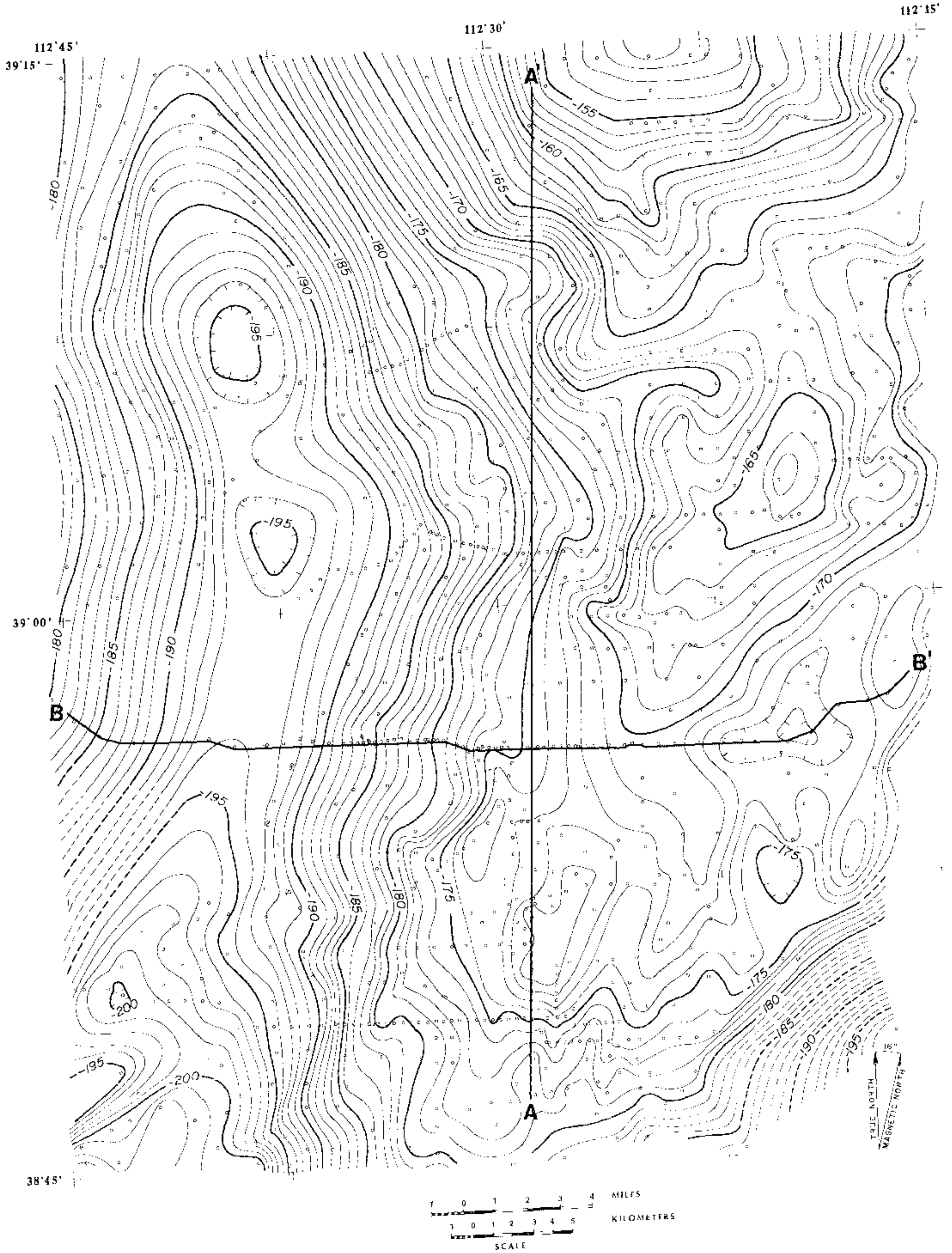

112°45'
39°15'
112°30'
112°15'
A'
DESERET
Pavant Butte
LINE 2
Holden
Bald Mountain
Cedar Mountain
West Mountain
DEVILS KITCHEN FAULT
PAVANT
LINE 3
39°00'
B'
Fillmore
ICE SPRINGS
B
LINE 20
TABERNACLE HILL
White Mountain
Meadow
Meadow Hot Springs
Hatton Hot Springs
BEAVER RIDGE
PAVANT RANGE
C
KANOSH
C'
Kanosh
16°
TRUE NORTH
MAGNETIC NORTH
A
38°45'
1 0 1 2 3 4
MILES
1 0 1 2 3 4 5
KILOMETERS
SCALE

Fig. 2



112°45'
112°30'
112°15'
39°15'
39°00'
38°45'
A'
A
B
B'
MILES
KILOMETERS
SCALE
TRUE NORTH
MAGNETIC NORTH

Fig. 3

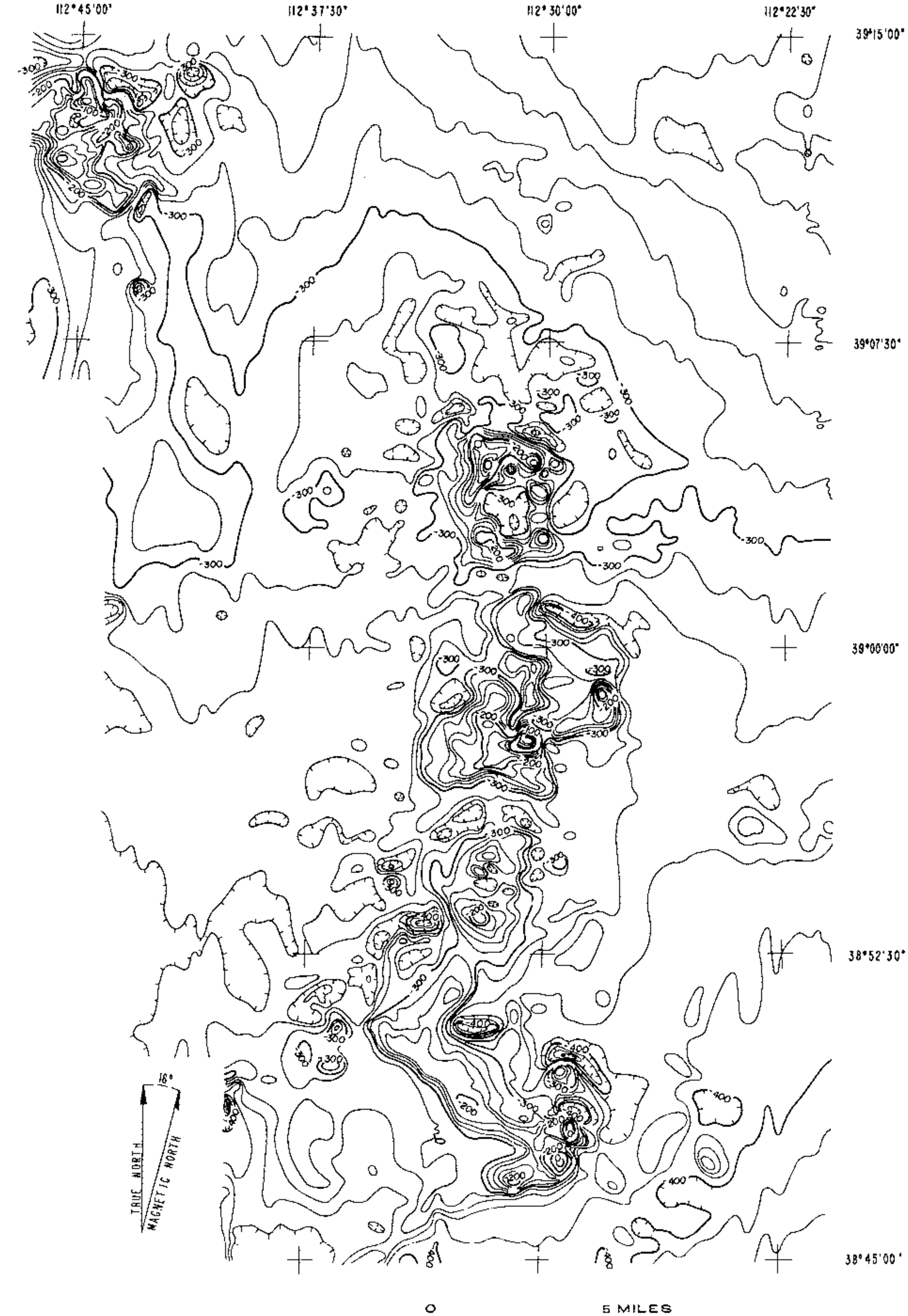
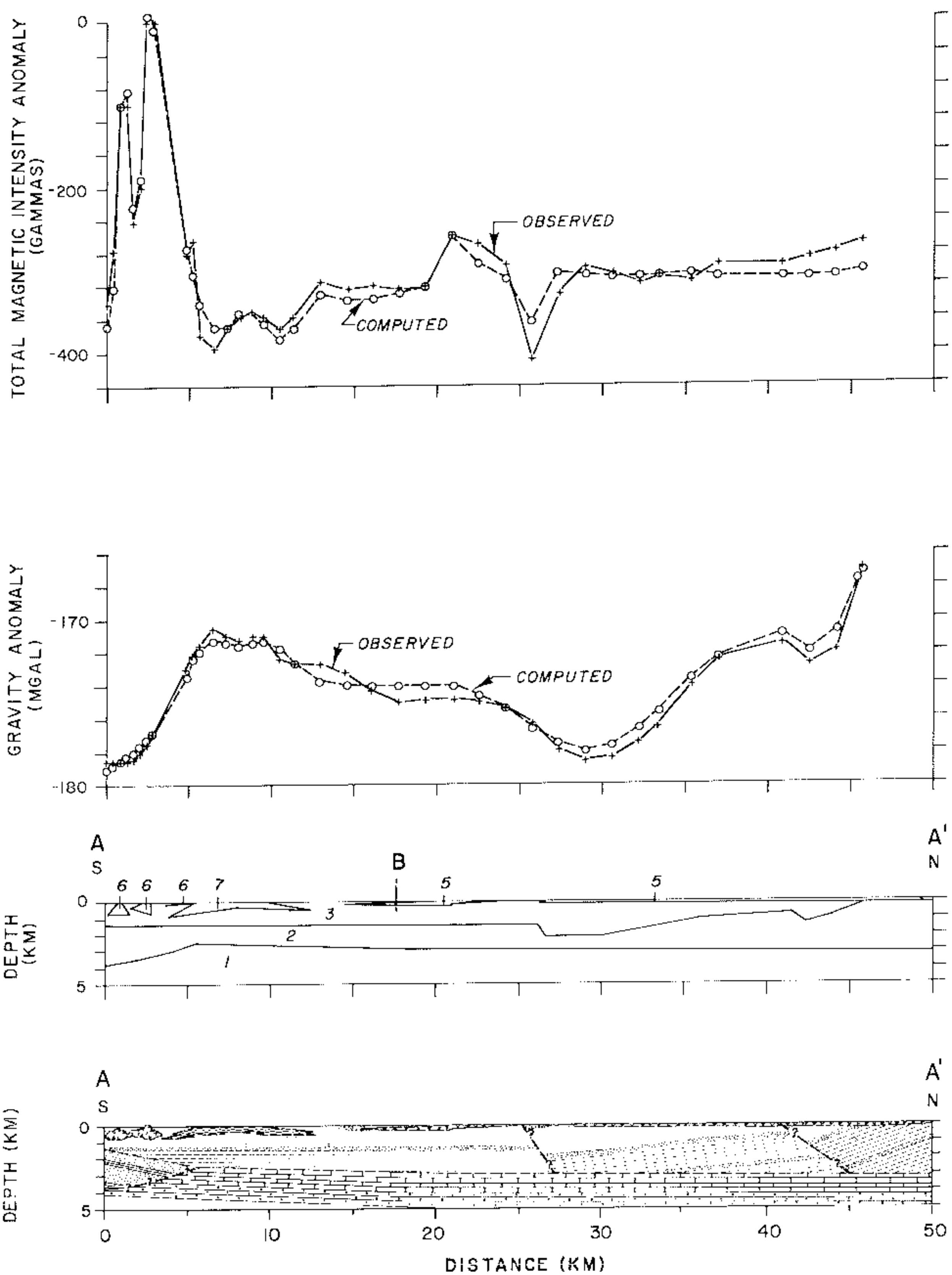

112°45'00"
112°37'30"
112°30'00"
112°22'30"
39°15'00"
39°07'30"
39°00'00"
38°52'30"
38°45'00"
16°
TRUE NORTH
MAGNETIC NORTH
0 5 MILES
0 5 KM

Fig. 4



TOTAL MAGNETIC INTENSITY ANOMALY (GAMMAS)
0
-200
-400
OBSERVED
COMPUTED
GRAVITY ANOMALY (MGAL)
-170
-180
OBSERVED
COMPUTED
A
S
B
A'
N
6
6
6
7
5
5
3
2
1
DEPTH (KM)
0
5
A
S
A'
N
DEPTH (KM)
0
5
0
10
20
30
40
50
DISTANCE (KM)

Fig. 5

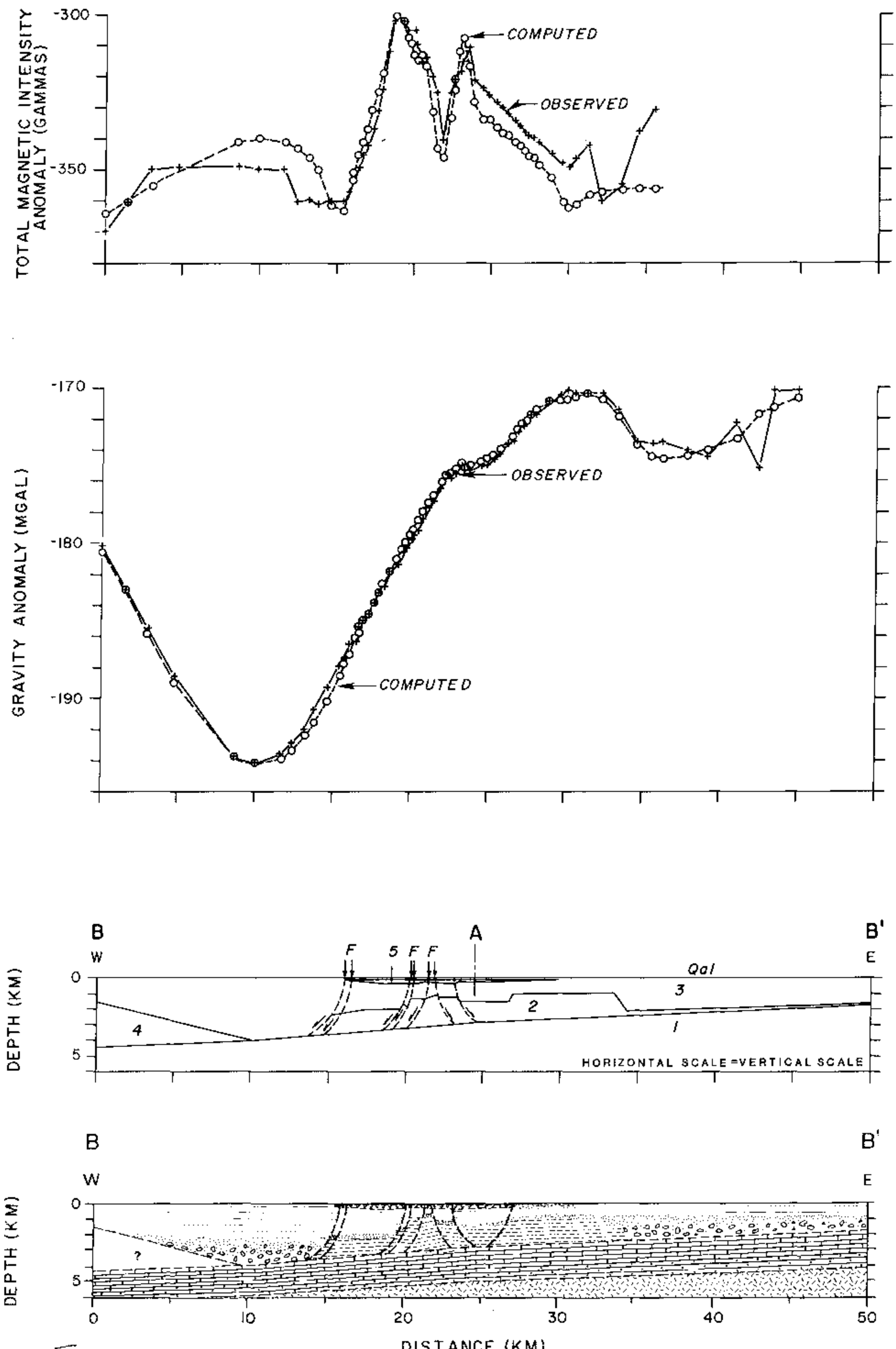

TOTAL MAGNETIC INTENSITY ANOMALY (GAMMAS)
-300
-350
COMPUTED
OBSERVED
GRAVITY ANOMALY (MGAL)
-170
-180
-190
OBSERVED
COMPUTED
B
A
B'
W
E
F
5
F
F
Qal
3
2
4
1
DEPTH (KM)
0
5
HORIZONTAL SCALE=VERTICAL SCALE
B
B'
W
E
?
DEPTH (KM)
0
5
0
10
20
30
40
50
DISTANCE (KM)

Fig 6