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1983, pp. 133-136. https://doi.org/10.56577/FFC-34.133

in:

Socorro Region II, Chapin, C. E.; Callender, J. F.; [eds.], New Mexico Geological Society 34 th Annual Fall Field Conference Guidebook, 344 p. https://doi.org/10.56577/FFC-34

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MAGNETOTELLURIC SOUNDINGS ALONG THE COCORP SEISMIC PROFILE IN THE CENTRAL RIO GRANDE RIFT

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INTRODUCTION

Geophysical probing of the earth's crust and upper mantle has been accomplished primarily by seismic methods although important complementary information has been supplied by gravity, magnetic, and heat flow studies. Magnetotelluric (MT) soundings have more recently contributed to our understanding of the lithosphere by defining its electrical resistivity. The resistivity of earth materials in the subterranean environment is extremely sensitive to the prevailing temperature and moisture conditions. Indeed, the distribution with depth of electrically conducting zones may provide an effective measure of the temperature distribution in the earth (Adam, 1978; Shankland and Ander, 1981).

In 1977 and 1979, a total of 27 magnetotelluric stations were occupied in the region of the Rio Grande rift of central New Mexico (fig. 1). This paper presents the results of two-dimensional (2-D) modeling of 10 of those stations. Most of the 10 stations were located along the 1975-1976 Consortium for Continental Reflection Profiling (COCORP) seismic lines 1 and la (S-S in figs. 1 and 2). Therefore, the MT stations form a profile across the southern Albuquerque-Belen Basin of the Rio Grande rift. The profile is more than 100 km long, stretching from the Sierra Lucero in the west to the Estancia Basin in the east. Major objectives of the study were: (1) to compare the MT interpretations with the COCORP findings, and (2) to investigate the rift's crust and upper mantle transitional boundaries with the Basin and Range and the Great Plains tectonic provinces, to the west and east, respectively.

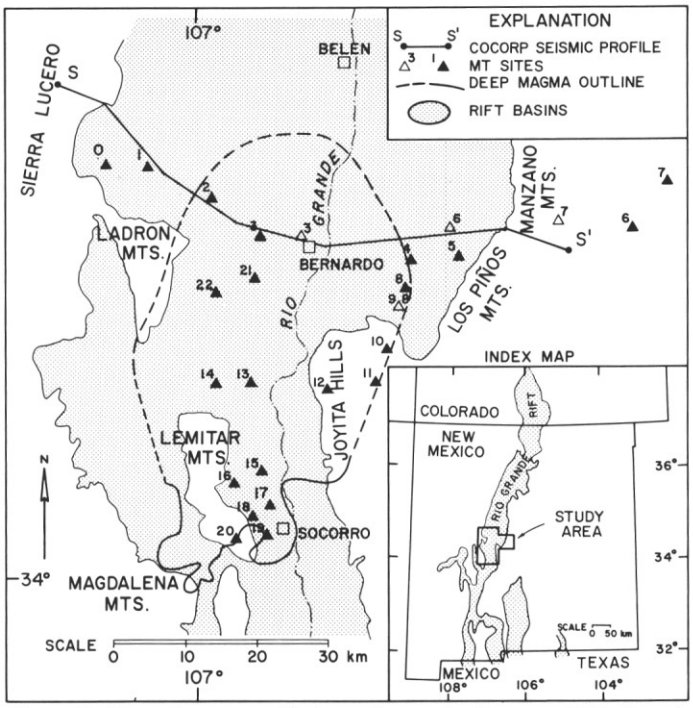

Figure 1. Map of magnetotelluric study area in the central Rio Grande rift. Location of COCORP seismic profile S-S', outline of deep magma body (dashed where uncertain), rift basins, and MT stations occupied are indicated. Solid triangles mark 1979 MT sites; open triangles are 1977 MT locations (after Jiracek and others, 1983).

PREVIOUS STUDIES

In the past 20 years, the Rio Grande rift has become an area of intense geological and geophysical study. A variety of studies of the rift in New Mexico have been summarized by Woodward and others (1975), Kelley (1977), Cordell (1978), and Ander (1981). The result is an excellent regional overview of the rift's geometry and structure. This provides information that is useful in constructing geologically realistic geoelectric models to be used in the magnetotelluric interpretations. Specifically, the studies were used to constrain such model variables as basin geometry and structure, deep crustal structure, and resistivities of the earth materials present.

Brown and others (1980) summarized the findings of the 1975-1976 COCORP program of seismic investigation of the central Rio Grande rift. The results of high resolution reflection data along line S-S' (fig. 1) are schematically shown in Figure 2. They reveal a predominance of normal faulting beneath the 0-4-km-thick Cenozoic fill of the Albuquerque-Belen Basin (fig. 2). Also depicted in Figure 2 is a buried horst block, unmistakeably connected with the Sierra Ladron. To the east, the Hubbell-Joyita bench is clearly defined beneath a thin veneer of sediments. Within the basement, numerous transport zones and dis-

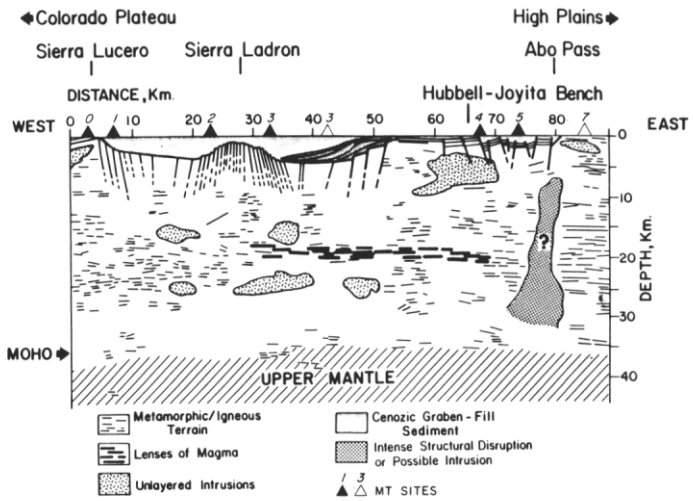

Figure 2. Schematic cross section of the COCORP seismic profile S-S', summarizing salient features (after Brown and others, 1980). Triangles are approximate locations of the MT stations.

continuous reflectors suggest a highly deformed and intruded Precambrian metamorphic terrane. Most interesting though is the COCORP perception of crustal magma lenses at a depth of approximately 20 km. Brown and others (1980) suggest that a midcrustal discontinuity is preventing further upward migration of the magma and hence its present sill-like form. The total areal extent of the magma (outlined in fig. 1) is thought to be more than 1700 km' (Rinehart and others, 1979).

DATA ACQUISITION AND ANALYSIS

Two magnetotelluric systems were used to acquire the data. The systems were supplied by the California Institute of Technology and by Woodward-Clyde Consultants. The station locations occupied by the Cal Tech system are shown as open triangles in Figure 1; stations occupied by the Woodward-Clyde system are indicated by the closed triangles.

The Cal Tech system recorded a single station of magnetotelluric data per equipment setup. In constrast, the Woodward-Clyde system was able to record two stations of MT data per equipment setup. The ability of the Woodward-Clyde system to record two stations simultaneously allowed the application of the remote referencing technique of noise bias reduction. This combined with an ability to process data in the field greatly improved the quality of the information recorded by the Woodward-Clyde system compared to that acquired by Cal Tech.

After the data were processed, each of the magnetotelluric stations were analyzed to identify the geometry of the earth's subsurface (one-dimensional, two-dimensional, or three-dimensional). The computer modeling algorithm which we used for interpreting the data assumes that the earth's geometry is two-dimensional. Data which are representative of three-dimensional structures can be modeled, in some instances, using a two-dimensional technique.

Three MT parameters (skew, rotation angle, and tipper strike) were utilized to estimate the complexity of the earth at each station. For a perfectly two-dimensional earth, the skew index is zero (Vozoff, 1972) and the tipper strikes and rotation angles are invariant with sounding frequency. In this study, the earth was considered two-dimensional at periods where the skew values were less than or equal to 0.3 and the tipper strikes and rotation angles were relatively stable. The three-dimensional MT modeling studies of Ting and Hohmann (1981) clearly show that these criteria are not totally adequate.

In addition, a fourth criterion of comparing rotation angles and tipper strikes between adjacent stations was utilized. Ideal two-dimensional data has only one strike direction that is consistent from station to station for all frequencies of the soundings. Stability of these parameters between stations at different frequencies is required for two-dimensionality.

The reliability of the data was determined by comparing the predicted electric and magnetic fields to their observed counterparts. This measure of stability (termed predictability or coherency) should ideally equal 1.0 (Vozoff, 1972). In this study, predictabilities of 0.7, or greater, indicated data of adequate reliability. Some data with coherencies of less than 0.7 were used for computer modeling.

INTERPRETATION

The apparent resistivity data for each station were forward modeled using a computer algorithm that calculates the electromagnetic fields over two-dimensional resistivity and topographic structures. The program is limited by its inability to model sloping interfaces. Therefore, lateral contacts must be modeled as vertical interfaces, giving a stepped appearance to the geoelectric models. Detailed explanations of the computer technique can be found in Swift (1971), with practical application discussed by Madden (1973).

There is considerable variability in the degree to which our trial an error modeling has produced synthetic MT soundings that match till observed data. This is in part due to the simple models required by till computer program. Also, several of the MT stations indicate three dimensional distortions which are not included in the 2-D algorithm Despite these limitations, and with a full realization of the nonunique ness of the model solutions (Jiracek and others, 1983), we believe tha the gross features indicated by the geoelectric models are consisten with the data. The following discussion is based on this premise. Thos(readers desiring to assess the validity of our 2-D modeling are directec to Jiracek and others (1983) and Mitchell (1983). The latter referenc■ to Jiracek and others (1983) and Mitchell (1983). The latter referenc■ contains all field data and complete model results.

The final modeled results appear in Figures 3 and 4. Figure 3 is flu geoelectric model of the western Rio Grande rift. It extends from th(Sierra Lucero to east of the Rio Grande. Figure 4 is the geoelectrn model for the eastern rift and western Great Plains tectonic province It extends from the Hubbell-Joyita bench to the Estancia Basin. Ti facilitate the comparison between these models and the COCORP pro file, the locations of the MT stations have been projected onto flu seismic line in Figure 2.

In a gross sense, the geoelectric models agree well with the COCORI seismic results. Figure 3 clearly illustrates the rift basins and the in tragraben Sierra Ladron horst. To the east, the Hubbell-Joyita bend with a small overlying basin (fig. 4) is in agreement with the COCORI findings (fig. 2). The rift's underlying basement, to a depth of 10 km is modeled as a homogeneous, resistive layer of 200 ohm-m (figs. 2 and 4). This is correlative with the Precambrian metamorphic terranc of the COCORP profile (fig. 2). The 1500 ohm-m block beneath thc Manzano Mountains corresponds to a zone of possible intrusion showr at 80 km distance from the west end of profile S-S' in Figure 2. Beyonc 80 km in Figure 2 the upper crust appears more coherent than beneatt the rift basins. The coherent reflectors indicate a crust that is not extensively faulted or intruded. Such a crust would not allow fluid circulation through deep fractures. In addition, heat flow measurement

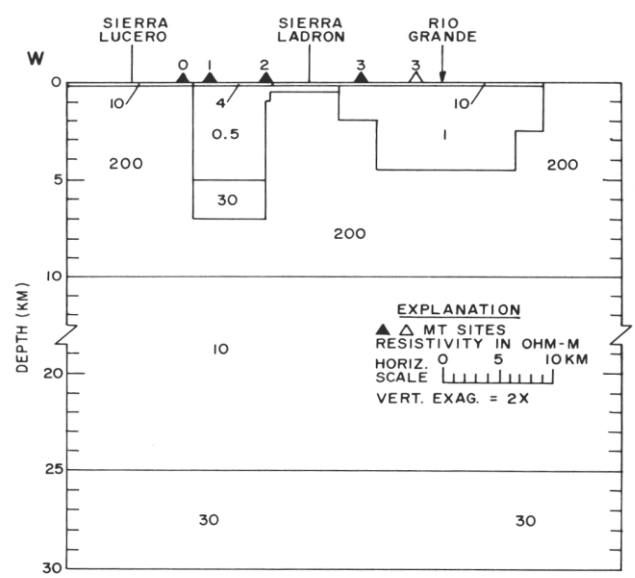

Figure 3. Two-dimensional geoelectric model of the western Rio Grande rift with triangles marking MT station locations. Depth scale broken from 12 to 19 km.

by Reiter and others (1975) show decreasing values to the east. Thesc

observations suggest that deep earth resistivities would be higher in this direction in agreement with our modeling (figs. 3 and 4). Deep in the crust (10 to 25 km) the geoelectric models show a conductive zone of 10 ohm-m. Comparatively, the center of the COCORP profile (fig. 2) indicates lenses of magma at approximately 20 km depth. Below 25 km in the western portion of the geoelectric section (figs. 3 and 4) the resistivity increases to 30 ohm-m. This is a reasonable value for a zone of interfingered partial melt. Such an interpretation has been hypothesized by Brown and others (1980) for the COCORP events recorded from 30-35 km depth.

The depth to electrical basement (200 ohm-m), within each of the basins (fig. 3) agrees closely with corresponding seismic data. The 4.5 km depth of the major rift basin (fig. 3) is in excellent agreement with the seismic data. The depth of 5 km for the western basin is 1 km greater than that determined by COCORP (fig. 2). The 30 ohm-m bottom layer of this basin is probably Precambrian basement (not basin fill) that has been sufficiently disrupted to allow water to penetrate into the fractures and lower its resistivity. Under any circumstances, such a layer is poorly resolved by MT since it is intermediate in resistivity and thin compared to layers above and below it.

The electrical homogeneity of the basins in Figures 3 and 4 belies the complexity of the actual sedimentary section. Recent reinterpretation of the shallow COCORP seismic data (upper 6 km) by Cape and others (1983) indicates that the basins contain discernible layers of Quaternary-Tertiary fill, Tertiary volcanic rocks, and Tertiary, Mesozoic, and Paleozic sedimentary rocks. The Quaternary basin fill is correlative with the 200 m thick, 4 to 10 ohm-m surface layer (fig. 3). This grossly represents the upper ground-water environment of the sedimentary sequence. The remaining basin fill is modeled by the 0.5 and 1 ohm-m blocks. These are extremely low resistivities considering that sea water is 0.25 ohm-m. However, Hiss and others (1975) report water resis- tivities of 1.06 ohm-m (after correction to 25°C) at approximately 3 km depth near Albuquerque. Actual in situ water

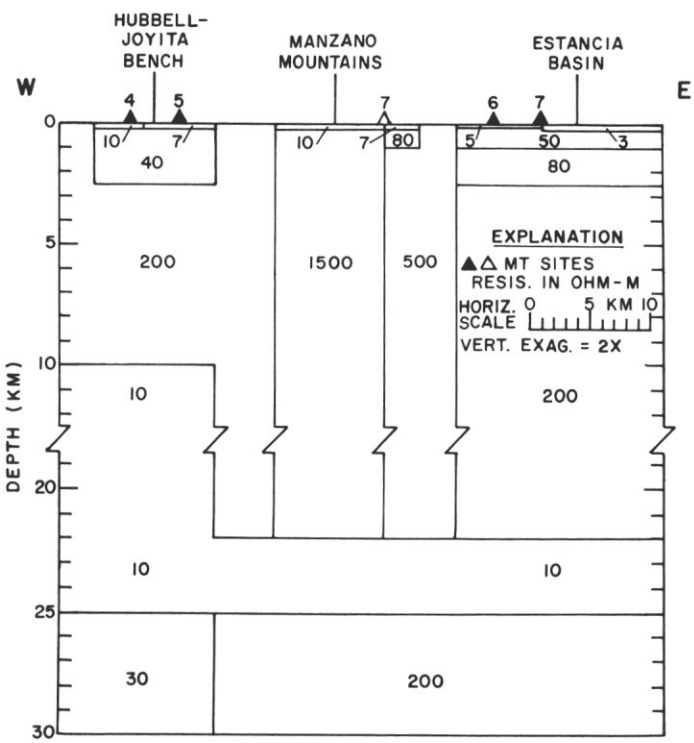

Figure 4. Two-dimensional geoelectric model of the eastern Rio Grande rift and western Great Plains tectonic province with triangles marking MT station locations. Depth scale broken from 12 to 19 km.

values would be less
than 1 ohm-m. DC resistivity soundings at MT station 3-79 indicate a 1.5 ohm-m layer at about 1 km depth (Jiracek, 1982). Therefore, bulk resistivities of 0.5 and 1 ohm-m are plausible values for the basins since they are obviously saturated with highly saline ground water.

There are some noteworthy discrepancies between the geoelectric models and the COCORP findings. First, the dimensions of the rift basins and the Ladron block in Figures 2 and 3 are quite different. These discrepancies are due to the different orientations and station densities of the MT and seismic surveys. The COCORP seismic line crosses the western embayment at an oblique angle (fig. 1). Therefore, the seismic profile indicates an exaggerated width for the basin. By comparison, the MT stations cross the embayment nearly perpendicular to its western margin. In addition, the lateral differences can also be attributed to poorly constrained contacts. The widely separated MT stations make it difficult to accurately locate boundaries.

To the east, the Hubbell-Joyita bench in Figures 3 and 4 is 2 km smaller in width than seismically defined in Figure 2. This difference can be attributed again to poor constraints on the locations of lateral boundaries due to the limited number of MT stations. Cape and others (1983) have identified a 3-km-thick sequence of sedimentary rocks capping the Precambrian basement of the bench. Geoelectrically the 7 to 10 ohm-m surface layers (fig. 4) are probably the Quaternary alluvium. The 40 ohm-m layer may be sedimentary rocks of late Cenozoic to middle Paleozoic age. The 200 ohm-m block rising to the surface west of station 4-79 (figs. 3 and 4), corresponds to a seismically defined portion of the bench (fig. 2).

The most significant contrast between the seismic and geoelectric models concerns the 10 ohm-m conductive zone at 10-25 km depth shown in Figures 3 and 4. The COCORP results identify a discontinuous band of magma lenses at roughly 20 km depth beneath the central rift. Microseismic studies by Rinehart and others (1979) indicate that no magma lies above this level along profile S-S' (fig. 1). The thick conductive zone, therefore, cannot be due to magma. In addition, the decrease in resistivity cannot be accounted for by electronic conduction since crustal temperatures are not of sufficient magnitude at this depth. Jiracek and others (1983) suggest that the electrically conductive zone may result from the entrapment of high-pressure pore fluids beneath an impermeable ductile cap. The cap would be formed by a low viscosity layer at the base (-10 km depth) of the brittle upper crust. The trapped pore fluids may be derived from mineral dehydration at greater depth or from injected magma. Dramatic reduction of earthquake focal depths below 13 km in the central Rio Grande rift (Sanford and others, 1979) supports a change from brittle to ductile deformation in the upper crust.

The 12-km increase in depth to the 10 ohm-m crustal conductor in Figure 4, may indicate the transition between the Rio Grande rift and the eastern Great Plains tectonic province. The crust to the east of this interface has a higher resistivity overall. The 30 ohm-m layer at 25 km depth beneath the central rift models at 200 ohm-m to the east. This increase in resistivity may correspond to a possible sharp increase in the depth of the asthenosphere at about 30-40 km east of the rift axis (Ander, 1981). The eastward decline in heat flow values from a maximum along the western rift margin also supports this contention. The eastward continuity of the deep electrical conductor has some supporting evidence from the refraction studies of Olsen and others (1979). The more pervasive westward continuity of the deep electrical conductor suggests that the central rift's middle to lower crustal features may be closely tied to those of the Basin and Range province. This description is in agreement with a hypothesis presented by Ander (1981). The region to the west is usually considered to be a portion of the Colorado Plateau (fig. 2).

MT stations 6-79 and 7-79 (fig. 4) are located beyond the eastern end of the COCORP seismic line (fig. 2). The 2.5-km depth to electrical

basement (200 ohm-m) is 1 km greater than that estimated by Birch (1982) using gravity and well-log data. Therefore, the 1-km-thick 80 ohm-m layer may be Precambrian basement with water-filled fractures. The near surface 500 ohm-m block to the west of station 6-79, may be correlative with a large igneous dike swarm of Tertiary or Cretaceous age (Woodward and others, 1975).

CONCLUSIONS

The MT geoelectric models of the southern Albuquerque-Belen Basin for the upper 6 km or so agree well with the COCORP seismic results. Minor differences in near-surface structure are primarily due to inherent dissimilarities between the surveys; in particular, the MT station density is insufficient in several areas. Some disparity between MT and COCORP results is expected since each is sensing a different physical property-electrical and elastic parameters, respectively. For example, the deep structure is significantly different. A 15-km-thick conductive zone beginning at 10-km depth beneath the central rift in the geoelectric models has no counterpart in the COCORP soundings. Its high conductivity may result from pore fluids trapped beneath a ductile cap. The zone appears to be continuous westward beyond our MT survey. An abrupt eastward deepening and thinning of the conductive horizon is modeled along with a general enhancement in crustal resistivities. This possibly indicates that the transition with the Great Plains tectonic province is sharp and occurs at the rift's eastern margin, and not further to the east. In contrast, the deep crustal structure of the western rift margin appears to continue uninterrupted into what seems to be the Basin and Range province.

ACKNOWLEDGMENTS

We wish to thank the magnetotelluric crew and supporting personnel of Woodward-Clyde Consultants for their diligent collection and processing of the magnetotelluric field data. Able field assistance was also provided by M. E. Ander of Los Alamos National Laboratory, B. R. Lienert of the California Institute of Technology, and several students from the University of New Mexico. Permission to occupy many of our sites in the Sevilleta National Wildlife Refuge is appreciated. In addition, we are indebted to D. Salzbuch of the San Diego State University Computer Center. The research was supported by the National Science Foundation Grants EAR-7813684 and EAR-8021517.

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