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HYDROLOGICAL INVESTIGATIONS NEAR SOCORRO, NEW MEXICO USING ELECTRICAL RESISTIVITY

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INTRODUCTION

Since, in the near-surface and ground-water environment of the earth, water is by far the most important factor determining the bulk electrical properties, resistivity is the most widely used geophysical method in hydrological investigations. As a portion of the U.S. Geological Survey's Southwest Alluvial Basins Study the University of New Mexico was engaged to perform resistivity tests in the middle Rio Grande valley in New Mexico. The objectives of the studies were to evaluate resistivity methods in investigating the ground-water depth, flow barriers, and water quality in selected areas. This paper presents results of these studies at two areas near Socorro, New Mexico. Complete results from other sites, including a large area west of Albuquerque, may be found in Jiracek (1982).

Our tests in the Socorro area utilized Schlumberger and equatorial resistivity arrays. An excellent discussion of these and other arrays as specifically applied to ground-water studies is included in Zohdy and others (1974). Our measurements were extended to effective spacings of many kilometers which enabled interpretations to be made to depths in excess of the water-saturated zones.

Zohdy (1969) and Zohdy and others (1969) have quantitatively interpreted the depth of the freshwater/saltwater contact in southern New Mexico and near El Paso, Texas; however, they did not hazard estimates of water-table depth, porosity values, or water salinity. Such estimates have been attempted in our study not because we possess any advanced methodology but simply to offer a comparison with known data.

RESISTIVITY METHOD IN GROUND-WATER STUDIES

Archie's Relationship

The resistivity of a water-bearing rock depends on the amount of water, the water resistivity, and its distribution in the rock framework. The resistivity is essentially independent of the rock matrix itself except where highly conductive minerals are present (such as pyrite or graphite) or where surface conduction effects are important, such as with clays.

Since the conduction of electricity in an aquifer is primarily through the water electrolyte filling the pores, not through the mineral grains, a simple relationship exists between the interstitial water resistivity (pw) and the bulk rock resistivity (pr). The relationship was empirically shown to be linear by Archie (1942) in a classical study of petroleum reservoirs. Archie defined the formation factor, F, as

F p r / p w (1)

An extension of this relationship was obtained after it was observed that the rock resistivity varies approximately as the inverse square of the water saturated porosity, 4). This has given rise to Archie's law (Keller and Frischknecht, 1966, p. 20-22)

F = ack (2) Here, a is a constant, usually near unity, and m is the so-called ce- mentation factor which is commonly two; practical limits of m are

The value of m is usually low for non-cemented, unconsolidated sediments and higher for more-cemented sediments. In our analysis, a value of porosity was estimated for strata immediately below the water table using Archie's law with published pw corrected for estimated temperature. Water-sample conductivity (the reciprocal of resistivity) is always presented at 25°C, so correction for estimated aquifer temperature must be applied. The value of pr (equation 2) was determined from the interpretation of our surface resistivity soundings. The nomogram shown in Figure 1 (Meidav, 1970) can be used to graphically correct pw for temperature, to compute formation factor, and to estimate the salinity of the formation water in parts per million of equivalent NaCl.

Pitfalls and Limitations

The evaluation of resistivity to define ground-water depth, water quality, and flow barriers in the middle Rio Grande area requires an awareness of several pitfalls and limitations in the method. Where depth or thickness is our objective we are faced with geometrical limitations, whereas the evaluation of water quality includes the geometrical problems and those associaed with the conversion of bulk formation resistivity to in situ water resistivity. Even if we assume that the true bulk formation resistivities can be determined from surface measurements, there is still no unambiguous way to derive water quality. Archie's law (equation 2) can be used to estimate the formation-water resistivity if the other variables are known. The most important variable is the porosity. Porosity information can be independently obtained using well logs, usually the formation-density logs (gamma-gamma) or sonic logs. Without such information, it is more common to use surface resistivity determinations with Archie's law to estimate the saturated porosity. This requires a knowledge of the pore-water resistivity. Tabulated values of well-water conductivity are much more available than porosity logs; however, one cannot assume with certainty that the extracted water-sample conductivity is the same as the water value in situ.

Water conductivity is usually increased when in contact with earth materials due to ionization and surface-conductivity phenomena which are most prevalent with clay minerals (Keller and Frischknecht, 1966, p. 22-23). As a result, the formation resistivities in fine-grained zones, such as shale or clay, are always much lower than expected based on either a chemical analysis of a conductivity measurement of an extracted-water sample. The interaction of pore water and mineral grains points out a failure in the linear relationship given by Archie's relation (equation 1) in so-called dirty formations (those with appreciable clay). The influence of water-mineral grain interactions on aquifer resistivities has been shown to be extremely important in one area near Albuquerque (Jiracek, 1982).

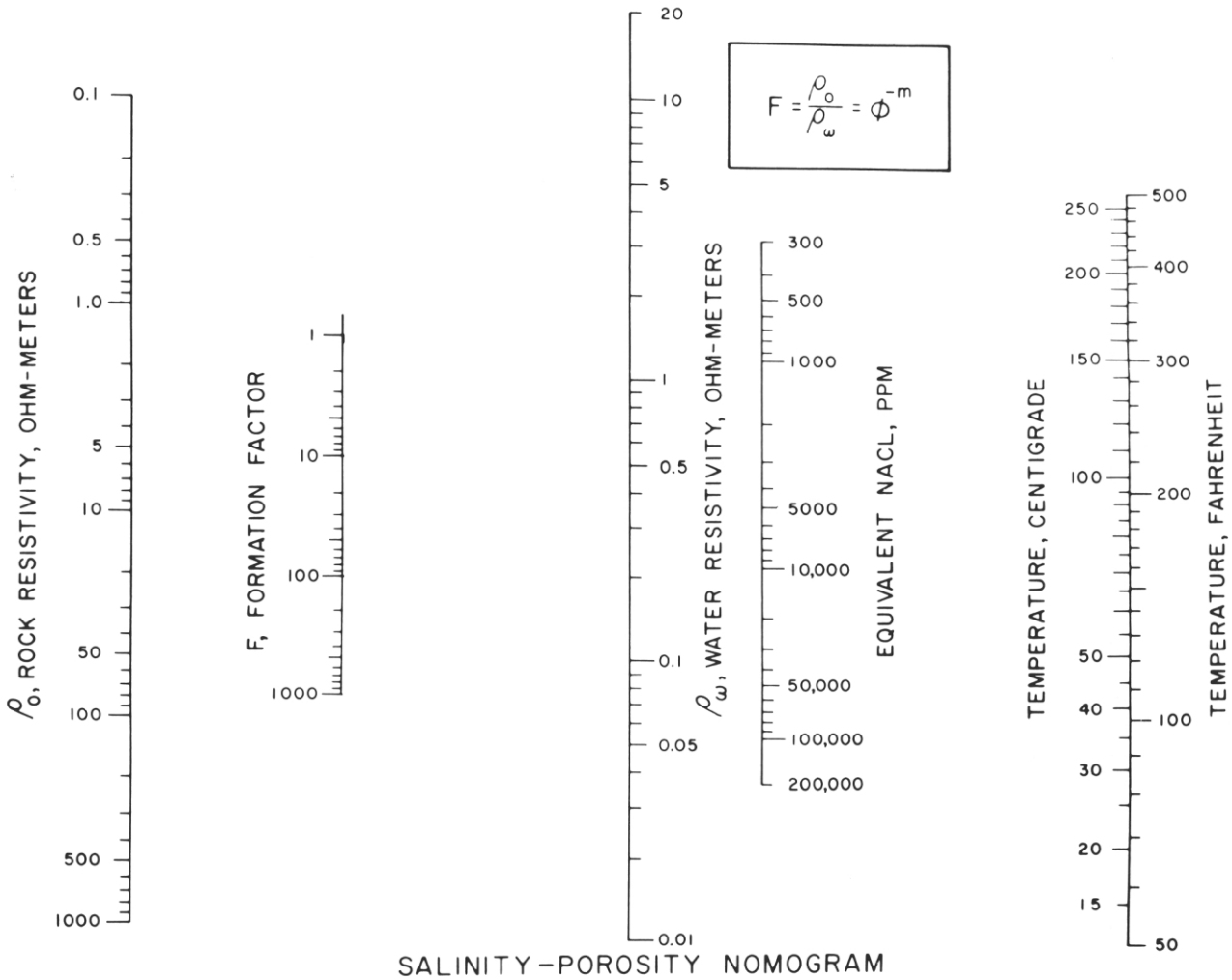

Figure 1. Nomogram relating resistivity, formation factor, salinity, and temperature. Any one of these parameters may be determined if the other three are known (after Meidav, 1970).

To estimate water quality (in ppm equivalent NaC1 concentration) at each site, the formation factor computed for the layer directly below the water table has been assumed for all subsequent layers of the saturated zone. Because there is reason to believe that the formation factor would increase with depth, such estimates would represent lower than actual in situ salinity values. Increased formation factor with depth would be due to lower water resistivity and to an expected decrease in porosity.

Concerning the depth and thickness calculations from resistivity soundings we must consider limitations inherent in resolving a stratified structure as well as the effects of lateral variations. Assuming that the geoelectric section is stratified (one-dimensional) leads us to the consequence of anisotropy and the principles of equivalence and suppression. Good discussions of these aspects appear in Keller and Frischknecht (1966, p. 158-171) and Kunetz (1966, p. 56-61).

The most common form of anisotropy is when the resistivity of a bed measured parallel (lateral) to bedding (pi) differs from that measured perpendicular (transverse) to the layering (R). This type of anisotropy is termed microanisotropy (Zohdy, 1965) because it is typically due to small-scale phenomena such as platey minerals (clays). In this case, surface measurements see the anisotropic layer as equivalent to one of resistivity equal toρ_{pi} and of thickness equal to $(WR)^{1/2}$ times the actual thickness. In the layered case R is always greater than pi; therefore, this common anisotropy results in an overestimation of layer thickness and corresponding depths.

Definition of the water table from resistivity in our study area invariably suffers from the principle of suppression. This occurs in our situation because the top layer of the water-saturated zone has a resistivity intermediate to the values above and below it. Such a bed, which is thin compared to the surrounding beds, has very little influence on the resistivity sounding curve. It is, therefore, poorly resolved or may not be detected at all. In our case, the overlying unsaturated zone has higher resistivity and lower strata typically have lower resistivity due to higher salinity water.

The principle of equivalence, in our application, concerns the definition of a conductive bed with higher resistivity zones on either side. The so-called bowl-type sounding curve is thus produced by the highly saline, conductive strata at the bottom of the saturated zone which overlies more resistive electrical basement. It can be shown that sounding curves in this situation are virtually indistinguishable when a variable conductive layer's thickness divided by resistivity is constant, provided the thickness and resistivity of the layer are small compared to the neighboring layers. This means that the resistivity of this conductive layer, and consequently the salinity estimate, is poorly resolved. It is coupled with poor definition of the conductive layer thickness; hence, the total depth to resistive basement is ill-determined. This adversely affects depth estimates to resistive ground-water barriers.

To evaluate the effects of lateral resistivity variations (either two- or three-dimensional) we performed crossed soundings with common center points at most sites. Agreement or disagreement between these

perpendicular sounding curves gives a qualitative estimate of the layered assumption. Equatorial soundings on either side of current sources are much more sensitive to lateral resistivity variations such as a dipping contact than are crossed Schlumberger soundings. This has been evident from our results in the Socorro area.

Equipment and Field Procedures

Resistivity soundings at each location were made with a combination of standard and inverse Schlumberger, together with equatorial soundings. First, a commercial low-power resistivity unit (Bison Model 2350) was used to perform standard Schlumberger soundings from an effective spacing of 1 m to typically 50-60 m. Effective spacing is herein defined as one-half the outer array spacing (AB/2) for the Schlumberger array. Next, a 50 kw (1200 V maximum) resistivity unit fabricated by an Albuquerque engineer, Tom Summers, Sr., for the University of New Mexico, was employed for inverse Schlumberger points out to AB/2 = 1,000 m. Current levels were digitally presented and recorded to three significant digits. After obtaining the inverse Schlumberger data, equatorial sounding points out to effective spacings (the slant distance between A or B and the center of the voltage dipole) of more than 5,000 m were occupied using a current source bipole of 2,000 m. The 2 km AB wire already in place for the final inverse Schlumberger voltage measurement was converted to a current carrying bipole. Equatorial apparent resistivity values corresponding to the above definition of effective spacing are identical to Schlumberger values corresponding to AB/2 for a horizontally stratified, laterally homogeneous, isotropic earth (Zohdy, 1969).

The electrical resistivity voltage-measurement system utilized standard Cu-CuSO4 porous-pot electrodes, locally fabricated self-potential nulling and low-pass (below 1 Hz) amplifiers, and Simpson Model 2745 battery-operated portable potentiometric chart recorders.

SAN ACACIA AREA

Introduction

The small farming community of San Acacia, New Mexico (fig. 2), is located on the west side of the Rio Grande 20 km north of Socorro., This is at the southern termination of the Albuquerque basin in what has been termed the Socorro constriction (Kelley, 1952; Kelley, 1977). The constriction of the basin is formed by a southward convergence of the bordering mountains (Ladron Mountains on the west and Los Pinos Mountains on the east) and faults within the basin (Kelley, 1977). Although a 20-km-wide graben filled with Santa Fe rift-fill sediments is described by Kelley (1977) between the Ladron and Joyita Precambrian horst blocks, gravity observations clearly expose a basement high centered beneath San Acacia (Sanford, 1978). The gravity high is manifested as a near-perfect saddle approximately 10 km in north-south extent and 5 km wide east-west. It is approximately 25 mGal higher than deeper portions of the Albuquerque basin to the north and more than 10 mGal higher than the Socorro trough immediately to the south. The precise thickness of the Rio Grande aquifer overlying this basement uplift has been an unknown factor that is required for evaluation of the hydrologic effects of the constriction. Consequently, our objective in the San Acacia area was to determine the basement depth and the overlying aquifer characteristics.

Resistivity Sounding

Figure 2 contains the location of a Schlumberger-equatorial sounding centered 2 km northeast of the village of San Acacia. The location is on a terrace deposit (Santa Fe Group) 2 km southwest of where the Rio Salado enters the Rio Grande. An outcrop of Tertiary basaltic andesite, known locally as Indian Hill, protrudes near the western end of the Schlumberger sounding (fig. 2).

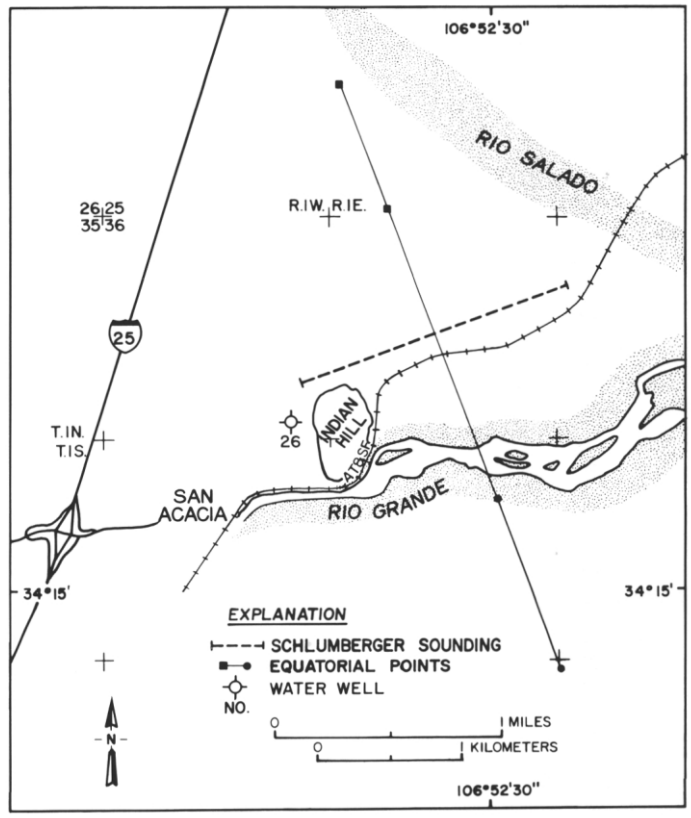

Figure 2. Base map of San Acacia study area.

The Schlumberger expansion was increased from AB/2 of 1 m to 1,000 m in directions 70° and 250° from true north. Four additional equatorial points were measured in directions of 160° and 340° to effective spacings of 2,811 and 2,209 m, respectively. The 160° equatorial points crossed the Rio Grande while the 340° end point was located in the dry bed of the Rio Salado (fig. 2).

Figure 3 plots the Schlumberger and equatorial apparent resistivity field results as circles and squares. The Zohdy (1973) inversion routine was performed on the smoothed version of the field data closely described by the curve in Figure 3. The solid triangles are the computer-generated values derived from the interpreted layer resistivity and depth results given in Figure 3.

Resistivity Interpretations

The near surface (1-11.5 m) at this site is highly resistive and represents the unsaturated section above the water table. The modeled transition from 210 ohm-m to 30 ohm-m (fig. 3) is interpreted to represent the water table at 11.5 m. This is consistent with the elevation of the sounding above the Rio Grande (9 m). The zone from 11.5 to 47 m depth is interpreted to be water-filled alluvium of highest water quality. The section from 47 m to 399 m of low resistivities ohm-m) is deeper strata with significantly deteriorated water quality. Relatively resistive basement (23 ohm-m) is sensed below 399 m. This basement may be exposed in the Joyita Hills about 5 km to the east. Westward-tilted Paleozoic strata make up the western side of the hills; the formations are faulted down to the west and may bear small quantities of water (Spiegel, 1955).

Hydrologically, the resistivity sounding near San Acacia is significant in the interpretation of a higher quality ground water from 11.5 to 47 m depth and an underlying poor-quality aquifer extending to 399 m. A quantitative estimate of water quality based on resistivity analysis and nearby water wells remains to be done.

Well number 1 of Clark and Summers (1971) appears to be coincident

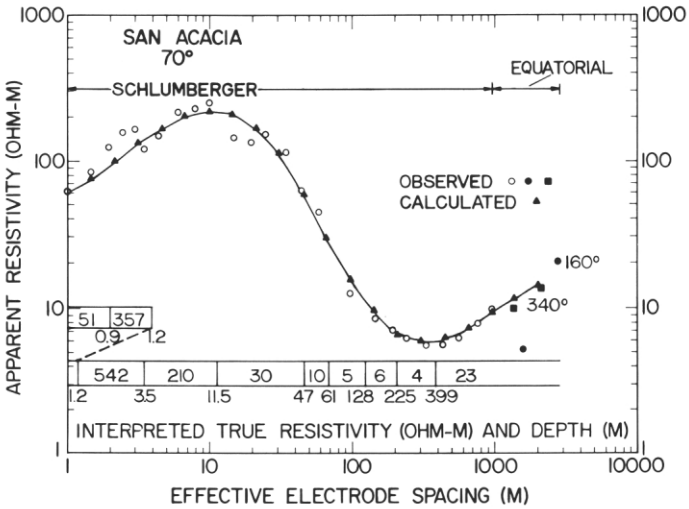

Figure 3. Observed and calculated combined Schlumberger-equatorial sounding San Acacia 70° and interpreted ten-layer resistivity model.

with our Schlumberger spread; however, no chemical analysis of this well was presented. A more recent study by Wierenga and others (1979) provides chemical and specific conductivity results from more than 30 shallow water wells in the San Acacia area. The wells were sampled on approximately a tri-weekly basis in 1977-78 to observe the correlation between shallow water-quality variations and irrigation.

Observation well number 26 of Wierenga and others (1979) is near our Schlumberger sounding (fig. 2). It yielded a water-resistivity value of 3.3 ohm-m in July, 1977, the same month our resistivity measurements were made in 1979. Using an estimated geothermal gradient of 33°C/km, the 3.3 ohm-m water at the reported standard temperature of 25°C is corrected (fig. 1) to the average temperature of 17°C in the shallow aquifer. This yields 4 ohm-m for the in situ water resistivity. Coupled with the 30 ohm-m bulk reservoir resistivity, this defines a formation factor of 7.5. Assuming that this information factor is constant below the water table (11.5 m) and using 1.6-m---c.2.4 in equation 2, a porosity range of 28 to 43 percent is calculated for the saturated zone above 47 m. Porosity would presumably decrease with increasing depth.

Salinity estimates may be obtained using the nomogram (fig. 1) provided by Meidav (1970). Equivalent NaCl concentration estimated in this fashion yields a salinity of 1,500 ppm from 11.5 to 47 m depth and 8,000 ppm from 61 to 399 m. Salinities of more than 8,000 ppm have been previously encountered in wells in Socorro County (Spiegel, 1955).

SOCORRO AREA

Introduction

Resistivity soundings in the Socorro area were located between the New Mexico Institute of Mining and Technology campus and Socorro Peak (fig. 4). The entire area in Figure 4 is within the Socorro Peak KGRA (Known Geothermal Resource Area) which encompasses approximately 360 km'. Our studies in this area were motivated by the geothermal aspects and the known occurrence of appreciable shallow ground water flowing southward, east of Socorro Peak.

Resistivity soundings S 1 and S2 (fig. 4) were centered at approximately 1,450 m elevation on the piedmont-slope deposits beneath 2,208-m-high Socorro Peak. The peak itself is composed primarily of 10-12-my-old silicic volcanic rocks which overlie fanglomerate and playa deposits of the Popotosa Formation (Miocene). A complete description of the Tertiary structure and stratigraphy in the Socorro area has been given by Chapin and others (1978) and Chamberlin (1981). The Popotosa Formation buried the 33-my-old Socorro cauldron and lies under our study area beneath an unknown thickness of piedmont-slope deposits and axial-river sands of the ancestral Rio Grande. The depth of these Quaternary sands has been estimated to be between 600 and 1,200 m using seismic and gravity data (A. R. Sanford, 1978, personal commun.). The sands provide an important aquifer for the town of Socorro (Chapin and others, 1978). A 400- to 800-m-thick aquitard is expected in the upper Popotosa Formation beneath the axial-river sands (Sanford and Schlue, 1981). The lower Popotosa has little primary porosity but appears to have good fracture permeability along fault zones. This is apparent from a series of fault-controlled springs issuing from this unit where is has been uplifted along the western boundary of Socorro (fig. 5). A possible deep aquifer in the lower Popotosa Formation beneath Socorro is considered a prime geothermal target (Sanford and Schlue, 1981).

Resistivity Soundings

Figure 4 shows the two sites of Schlumberger soundings in the Socorro areas as S1 and S2. At location Sl, crossed Schlumberger soundings were made out to AB/2 spacings of 1,000 m in directions of 55° and 145° from true north. Using the 2-km source in the 55° directions, equatorial soundings were added to effective spacings of 5,466 m and 2,092 m in the 145° and 325° directions, respectively. Similarly, employing the 145° source, equatorial points out to effective spacings of 5,148 m and 1,632 m were measured in directions 55° and 235°, respectively. The rugged terrain of Blue Canyon (fig. 4) prevented extension in the 235° direction beyond a single point.

Figures 5 and 6 contain the multilayered Zohdy (1973) inversion results for the crossed Schlumberger-equatorial soundings at S 1 . The similar shapes of the sounding curves out to about 1,000 m spacing and the general compatibility of corresponding layered models is evident. However, it is clear from the equatorial points located in Figure 4 that stations in the 235° and 325° directions are sensing the upthrown resistive block of Socorro Peak to the west. The companion equatorial points in 145° and 55° directions are over a thicker sequence of conductive rift fill to the east. Under these circumstances, modeling the contrasting equatorial branches in Figure 5 and 6 probably gives a reasonable range (1,372 to 1,690 m) for the depth to electrical basement (>30 ohm-m) in the area of the S1 soundings.

Schlumberger sounding S2 in the Socorro area (fig. 4) was expanded

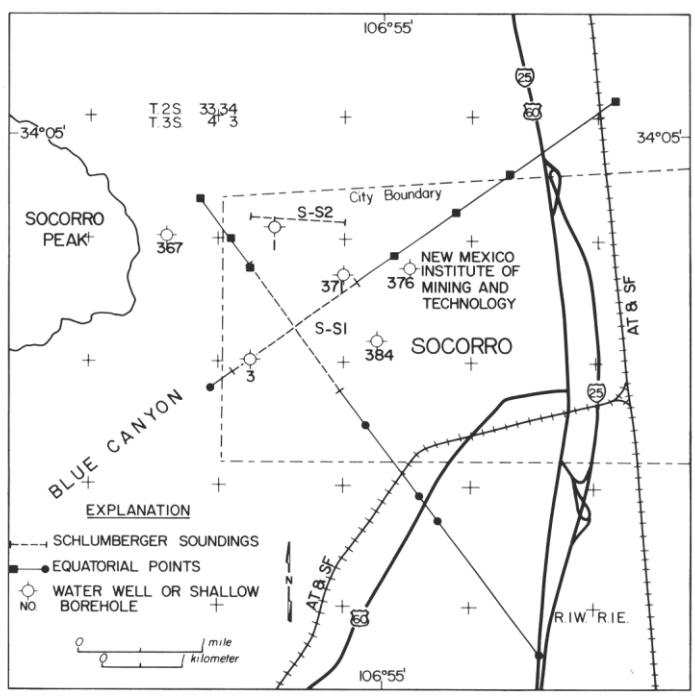

Figure 4. Base map of Socorro study area.

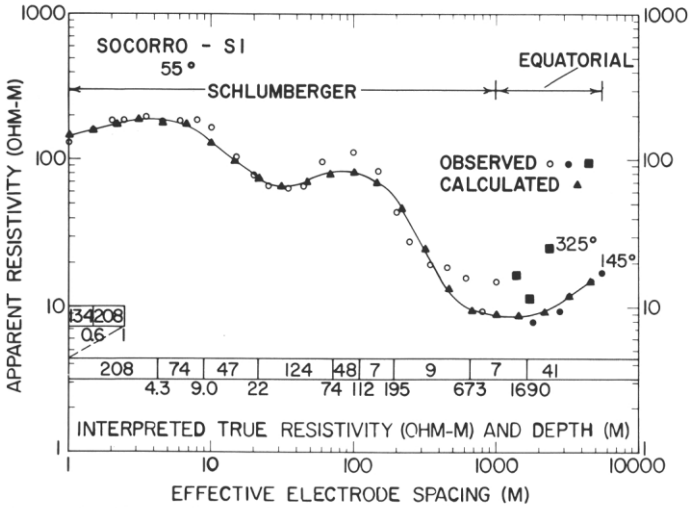

Figure 5. Observed and calculated combined Schlumberger-equatorial sounding S1–55° in Socorro area and interpreted ten-layer resistivity model.

to an AB/2 spacing of 600 m. The eight-layered resistivity section computed from this single sounding is presented in Figure 7.

Resistivity Interpretations

A resistivity-depth estimate at site S1 must consider a combination of the crossed soundings. The unsaturated zone is estimated to be above 74 m. It, however, exhibits considerable resistivity variation and some clearly nonlayered sections, such as the 55° sounding results near AB/2 = 50 m. The water-table depth is estimated at 74 m and the freshwater zone may extend to a range of 112 to 160 m depth. Water-table depths measured at nearby water wells (fig. 4) are 45 and 56 m at Clark and Summers' (1971) wells numbers 371 and 384; it is greater than 71.3 m at heat-flow hole number 3 (Sanford, 1977).

Resistivity modeling of the deeper section at S1 is ambiguous because of the known geologic complexities which invalidate a layered assumption. Equatorial directions of 55° and 145° would be expected to yield less-distorted results. However, distant 55° results, beyond 3,000 m, have an ascending slope greater than 45° which is theoretically impossible for horizontally layered strata. Hence, we have placed more credibility on the S1-55° results using the 145° equatorial points (fig. 5). Based on the averaged modeling results, the electrical basement at

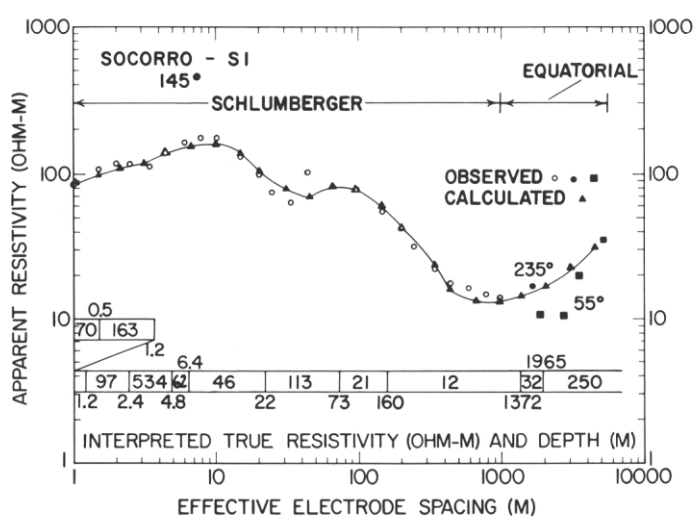

Figure 6. Observed and calculated combined Schlumberger-equatorial sounding S1–145° in Socorro area and interpreted eleven-layer resistivity model.

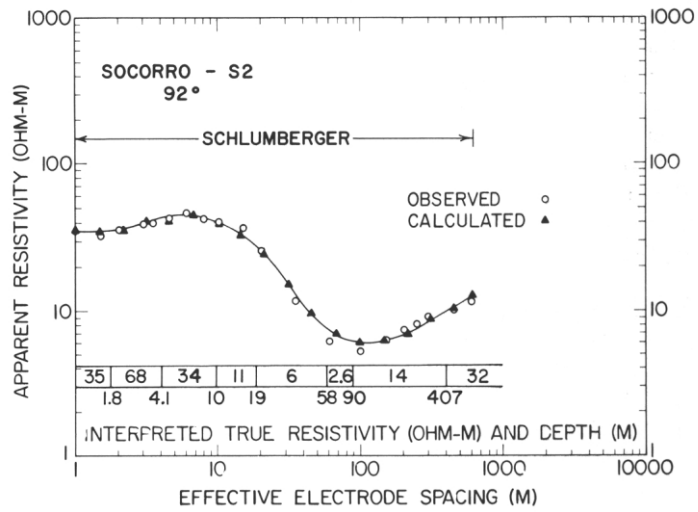

Figure 7. Observed and calculated combined Schlumberger sounding S2–92° in Socorro area and interpreted eight-layer resistivity model.

Si is estimated as 37 ohm-m beginning at 1,531 m depth (averages of 32 and 41 ohm-m; 1,372 and 1,690 m; figs. 5 and 6).

To estimate porosity and salinity values, we have used the nearest reported water-sample conductivity (1,150 micromhos/cm) at Clark and Summers' (1971) well number 376 (fig. 4). This conductivity value was corrected for temperature (fig. 1) by using the gradient of 40.6°C/km reported by Sanford (1977) from heat-flow hole number 3 (fig. 4). The resulting water resistivity in the 74-112 m zone (fig. 5) is estimated to be 9.0 ohm-m with a corresponding formation factor of 5.3. Applying Archie's law (equation 2), one obtains an estimated porosity range of 35 to 50 percent. This range would be 59 to 71 percent if we had chosen 21 ohm-m from Figure 6 as representative of the shallowest aquifer. This value is unrealistically high; however, our decision to use the 48 ohm-m value from Figure 5 rests on an accepted value of in situ water resistivity of 9.0 ohm-m. The uncertainty of this assumption based on a nearby water sample analysis is discussed under the section on Pitfalls and Limitations.

Equivalent NaC1 salinity of the assumed 9 ohm-m water in the shallow aquifer is determined from Meidav's (1970) nomogram (fig. 1) to be 530 ppm. Assuming a constant formation factor throughout the saturated zone, lower quality waters with salinity averaging about 1,600 ppm are estimated at depth. Our data in Figures 5 and 6 cannot resolve separate conductive layers below 112 m, so we have averaged the 55° and 145° soundings to estimate 10 ohm-m above electrical basement. An averaged basement resistivity of 37 ohm-m is low for crystalline rock. This could be a deep aquifer with fracture porosity, possibly the lower Popotosa Formation. Higher resistivity of about 250 ohm-m (fig. 6) would be more representative of tight, buried volcanic rocks of the Socorro cauldron.

Seismic reflections have been recorded in the area (fig. 4) from depths of 1,200 to 2,200 m by Sanford and Schlue (1981). However, they believe these reflections do not exhibit sufficient dips to correspond to those expected in the upper Popotosa Formation (10-20'). Thus, they suggest a depth of over 2,200 m to this horizon. The resistivity results in Figure 6 indicate resistive basement at approximately this depth; deeper horizons have not been resolved.

Even though wells 1 and 371, very near Schlumberger sounding S2 in the Socorro area (fig. 4), have water-table depths reported to be 43 and 45 m, respectively (Clark and Summers, 1971; Sanford, 1977), we have interpreted the S2 value as 19 m from Figure 7. Without the well data, one would normally select an even shallower horizon (34 or 11 ohm-m zones) to represent the upper zone of saturation. Ground

water at this location is evidently very conductive and saline; resistivity of a water sample from well number 367 (fig. 4) from Clark and Summers (1971) measures 2.9 ohm-m at 25°C. This is probably not as low as waters below sounding S2 since Archie's relation using p, = 2.9 ohm-m would indicate a low formation factor (2.2) and corresponding high values of porosity (>60 percent). Using a formation factor of 5.3 (identical to that calculated at Si) gives a temperature-corrected water resistivity of 1.1 to 1.2 ohm-m. Estimated temperature with depth used a gradient of 54.7°C/km listed by Sanford (1977). Assuming the same formation factor for Si and S2 soundings necessarily yields identical porosity estimates (equation 2). Salinity estimates using Figure 1 reach over 9,000 ppm; however, it is interesting that the resistivity interpretation suggests a higher water-quality zone or very significant porosity decrease between 90 and 407 m depth. The large thickness of this zone and the high quality of the computer fit in Figure 7 tends to confirm the existence of this aquifer. Electrical basement at S2 is interpreted at 407 m depth; therefore, location S2 appears to be on a structural bench or fault block since basement is estimated to be about 1 km higher than at the Si site.

CONCLUSIONS

Assuming layered resistivity sequences in the subsurface beneath two areas near Socorro, New Mexico, we have used surface resistivity measurements to estimate water-table depths, thicknesses of the underlying fresh and saline water-saturated zones, and depths to electrically resistive basement. Archie's law has been evoked to estimate aquifer porosities and water salinities.

The calculations are consistent with a water-table depth of 11.5 m near San Acacia with an underlying fresher water (-1,500 ppm NaC1) aquifer of 28-43% porosity extending to near 50 m depth. Water quality below this level is markedly deteriorated; salinity of 8,000 ppm (or greater) is likely above electrical basement, here estimated to be at approximately 400 m depth.

At two sites on the west side of Socorro, two distinct levels of water table (-20 and 70 m) and corresponding depths to electrical basement (-400 and 1,500 m) are estimated. The site of the shallow depths evidently has very saline shallow ground water (>9,000 ppm NaC1); however, a fresher zone may occur from roughly 90 to 400 m depth. The shallowest aquifer, where the water table is estimated to be at 70 m, appears to have very good quality water (about 500 ppm NaC1) to roughly 100 m depth. Below 100 m the aquifer salinity is estimted to be more than 1,600 ppm.

Even if the earth approximates a one-dimensional or layered geometry as we assumed in our calculations, problems associated with anisotropy and practical limitations due to the principles of suppression and equivalence can be severe. We cannot estimate these effects in our electrical soundings near Socorro; however, comparison with municipal water-well logs in Albuquerque indicates overestimation of depths by a factor of two where clay or shaley formations are prevalent. General agreement with known water-table depths close by our soundings in Socorro and San Acacia would tend to discount such an error in the measurements at these locales.

Estimates of porosity using Archie's law and aquifer water quality are hampered by the above geometrical limitations as well as by the uncertainty regarding the in situ resistivity of the pore water. Where this problem exists our scheme would tend to overestimate the porosity and underestimate the salinity.

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