ELECTROMAGNETIC DELINEATION OF SALINE GROUND-WATER PLUMES IN ALLUVIUM AND BEDROCK ALONG THE CANADIAN RIVER BETWEEN UTE RESERVOIR AND RANA CANYON, NEW MEXICO

by

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EXECUTIVE SUMMARY

Lake Meredith, which supplies water for domestic use to all major Texas cities on the Southern High Plains, exceeds the Texas Water Commission's standards for chloride and sulfate content (300 mg/L) as well as the U.S. Environmental Protection Agency's standard for sodium (250 mg/L). Location of the sources of these solutes is a necessary first step in any remediation effort to reduce the salinity of river waters and ultimately the salinity of Lake Meredith. Initial examination of the conductivity and salinity of Canadian River waters, which supply Lake Meredith, was completed in May 1992. The results of these analyses indicated that saline ground-water discharge areas were concentrated in the river segment between the Ute Reservoir and Rana Canyon, New Mexico, and that ground-water conductivity surveys should be focused along this part of the river.

This assessment of the distribution of saline ground-water plumes in alluvium and bedrock along the Canadian River between the Ute Reservoir and Rana Canyon, New Mexico, is an integrated geological and geophysical study that incorporates both the use of extensive ground conductivity measurements and joint measurements. These data are used to identify sites of potential ground-water discharge to the river and to suggest preferred ground-water flow paths.

Delineation of saline groundwater plumes in alluvium and bedrock along the Canadian River between the Ute Reservoir and Rana Canyon, New Mexico, is an integrated geological and geophysical study designed to identify zones of potential saline ground-water discharge to the Canadian River.

Ground conductivity surveys, consisting of more than 2,200 conductivity measurements along 7 segments of the Canadian River and its tributaries, identified 4 broad high-conductivity zones and 18 individual peaks that probably represent points of saline groundwater inflow. Each measurement represents an average conductivity between the surface and a depth of 12 m (horizontal dipole mode) or 24 m (vertical dipole mode). Surveys were completed in New

Mexico along the Canadian River from Ute Reservoir to Revuelto Creek, in the Claer well area, in the Jones well area, in the Dunes area, and near Rana Canyon. Short surveys were completed along Revuelto Creek and Rana Arroyo. Other high-conductivity zones are probably present in unsurveyed areas, particularly along Revuelto Creek, between Revuelto Creek and the Dunes area, and downstream of the Dunes area.

Three broad high-conductivity zones were located between Ute Reservoir and Revuelto Creek. Zone A, extending 1,600 m between Ute Dam and the Highway 54 bridge, contains two peaks that are each 200 m long. Zone B begins between the highway and railway bridges and ends 4,200 m downstream in the gravel pit reach. The highest conductivities—and thus the highest ground-water salinities measured during this project—were found in zone B, which contains eight conductivity peaks. Zone C, which begins a few hundred meters upstream from Revuelto Creek and continues beyond the confluence, is more than 2,000 m long and spans four conductivity peaks. Zone C probably extends farther downstream from the last point surveyed.

Apparent conductivities were high along the river in the Claer well area, but not as high as those between Ute Reservoir and Revuelto Creek. No distinct conductivity peaks were identified in this section. In the Jones well area, low conductivities were measured along a collapse feature that is bisected by the Canadian River valley.

The second longest lateral survey segment was located in the Dunes area. Low conductivities were recorded along the river near a fresh-water spring. Farther downstream, a fourth broad zone of high conductivity (zone D) extends 2,700 m along the river. Four distinct conductivity peaks, each between 140 and 260 m long, were identified in zone D.

The survey segment farthest downstream from Ute Reservoir was near Rana Canyon. Apparent conductivities were relatively low along this segment, and no peaks were found. Short segments surveyed along the tributaries of Revuelto Creek and Rana Arroyo showed that conductivities increased downstream, but no distinct conductivity peaks were identified.

Two types of electromagnetic soundings (multiple coil-spacing soundings and time-domain soundings) were completed to examine conductivity variations with depth. Multiple coil spacing soundings were completed at three sites between Ute Reservoir and Revuelto Creek and at one site in the Jones well area. At each site, a thin (0.8 to 1.8 m), low-conductivity (5 to 22 milliSiemens/m [mS/m]) surface layer was encountered. This layer represents either relatively dry alluvium or alluvium partly saturated with relatively fresh water. At the three sites between Ute Reservoir and Revuelto Creek, this layer overlies highly conductive layers that are 11 to more than 20 m thick. Conductivities in these layers, which represent alluvium saturated with highly conductive saline water, range from 577 to 1,870 mS/m. In the Jones well area, the layer that underlies the surface layer is more conductive than the surface layer, but much less conductive than correlative layers at other sites. Lower conductivities at Jones well imply lower salinities of water within the alluvium.

Bedrock was probably encountered at two of the four sites. Between Ute Dam and the Highway 54 bridge, layer conductivity decreases from 577 to 150 mS/m at a depth of 12 m. The boundary between these layers is probably the bedrock-alluvium contact. At the Jones well site, where conductivity increases from 19 to 106 mS/m at a calculated depth of 19 m, the low-conductivity layer above the bedrock contact may represent alluvium saturated with saline ground water that has been diluted with fresh water.

Time-domain electromagnetic soundings, with a maximum penetration depth of about 100 m, were completed at two sites on the upland near Ute Reservoir, four sites within the Canadian River valley between Ute Reservoir and Revuelto Creek, one site along Revuelto Creek, and six sites along the Canadian River in the Dunes area. Vertical conductivity profiles computed from the time-domain data indicate that (1) a high conductivity layer that may represent the top of the postulated "brine aquifer" was found at a depth of 44 m on the upland south of the river and at a depth of 84 m north of the river; (2) subsurface conductivities are higher along the Canadian River between Ute Reservoir and Revuelto Creek than they are at Revuelto Creek, farther downstream in the Dunes area, and on the upland;

and (3) subsurface conductivities in the Dunes area vary from relatively resistive profiles near a fresh water spring to relatively conductive profiles within high conductivity zone D.

Analyses of joints in Dockum Group strata show that these natural rock fractures are grouped and not evenly distributed. Furthermore, primary joints, which are through-going and oriented roughly east-west, show evidence of dilation at the surface, in contrast to secondary joints, which are not open and terminate against primary joints. Primary joints, therefore, may be preferred pathways for ground-water flow in the subsurface. If preferred flow paths are present, then borehole placement, which would control the number of joints the well bore intersects and therefore the well production rate, may be critical to the success of a mitigation program designed to reduce saline water discharge to the Canadian River by lowering the local potentiometric surface. For example, it is possible for the screened interval of a conventional vertical well to end up in a block of Dockum strata without intersecting any joints.

Horizontal drilling may be a useful alternative to conventional drilling (Morgan, 1992) for environments like the Canadian River. Horizontal wells are drilled with conventional drilling rigs and consist of an initial vertical section to reach planned depth, a short curved section where the borehole is deflected to horizontal, and a horizontal section of varying length. Drilling of the curved and horizontal sections is accomplished using a downhole rotary motor powered by drilling fluid pumped through flexible drill pipe. Several significant advantages can be expected over the use of conventional vertical wells. Properly oriented horizontal drilling in Dockum strata would intersect numerous vertical primary joints, and the horizontal screened section of production wells could be placed at relatively shallow depths beneath the Canadian River.

INTRODUCTION

Problem, Purpose, and Objectives

Lake Meredith, which supplies water to all major cities on the Southern High Plains in Texas, has high salinity levels that are primarily due to discharge of subsurface brines into the eastern New Mexico segment of its source, the Canadian River (Gustavson and others, 1980). Subsurface dissolution of Permian salt (NaCl) and anhydrite ($CaSO_4 \cdot H_2O$) supplies as much as 53,000 metric tons (58,400 tons) of solutes per year to the Canadian River. Salinity of Lake Meredith has doubled over the past 10 years. Analyses in 1991 showed concentrations of chloride as great as 430 mg/L and sulfate greater than 300 mg/L (John Williams, Manager, Canadian River Municipal Water Authority [CRMWA], personal communication), which exceed chloride and sulfate standards of 300 mg/L set by the Texas Water Commission (TWC). To reduce the salinity of Lake Meredith water to TWC standards for domestic consumption, these communities must pump large volumes of low-salinity water from the Ogallala aquifer.

Locating saline ground-water plumes in alluvium or bedrock is the critical first step in any remediation process designed to reduce salinity levels in Lake Meredith. This report describes electromagnetic (EM) surveys and geologic investigations in the Canadian River valley in eastern New Mexico that were designed to identify variations in ground conductivities and to locate sources of naturally occurring waters with high Na^+, Ca^{++}, Cl^-, and SO_4^{--} loads that pollute the Canadian River and Lake Meredith. The spatial distribution of joints in Dockum Group strata was also examined because joints are potentially important preferred pathways for ground-water flow. Recognition of the distribution of preferred flow paths is also important if natural salt pollution of the Canadian River is to be mitigated by pumping of shallow saline ground water to draw down the local hydrostatic head.

Electromagnetic induction methods were used to measure apparent ground conductivity, which is a direct measure of ground-water conductivity and an indirect measure of salinity. Field studies were focused in five segments of the river and two segments of tributaries between Ute Dam and the Texas–New Mexico state line (figs. 1 and 2), in probable or potential saline-water inflow areas. The segments include (A) an 11.4-km reach from Ute Dam to approximately 1.5 km downstream from Revuelto Creek and a 0.3-km reach at the end of Revuelto Creek, (B) a 1.5-km reach in the vicinity of Claer well, (C) a 1.9-km reach in the vicinity of Jones well, (D) a 4.8-km reach in the area of the originally proposed "Dunes" dam and reservoir, and (E) a 1.3-km reach in the vicinity of Rana Canyon and a 0.3-km reach at the end of Rana Arroyo (table 1).

Previous Studies

The existence of artesian conditions in Permian strata and of saline springs and seeps issuing from those rocks along the Canadian River in the western part of the Texas Panhandle was noted in early studies by Gould (1907) and Baker (1915). Fink (1963) noted that ground water in Triassic rocks in the northern part of the Southern High Plains is also generally under artesian conditions.

Preliminary studies completed in 1960 recognized that the quality of water in the segment of the Canadian River that would supply Lake Meredith is marginal and that during critical periods of low flow and reservoir evaporation salinity of water held in Lake Meredith would increase beyond tolerable limits (U.S. Bureau of Reclamation, 1985). A streamflow–water quality survey completed in 1970 by the Texas Water Quality Board confirmed that most of the salt load was entering the river between Ute Dam and the New Mexico–Texas state line (U.S. Bureau of Reclamation, 1985). Studies completed in 1972 concluded that inflow of poor quality water from bedrock beneath the riverbed directly into the alluvium (not appearing at the surface before entering the river) was the likely source of natural salt pollution (U.S. Bureau of Reclamation, 1979). Streamflow measurements and analyses of waters in riverbed alluvium in 1974 suggested that the greatest amount of subsurface inflow of saline water (as much as 1/3 of

Table 1. Number of lateral conductivity measurements taken and distance covered during October 1992, November 1992, and February 1993 lateral conductivity surveys of the Canadian River and its tributaries. Spacings and distances in m.

				Oct. 19–23, 1993		Nov. 16–20, 1992		Feb. 1–5, 1993		Total	
Area	Dipole orientation	Station spacing	Coil spacing	Sites	Distance surveyed	Sites	Distance surveyed	Sites	Distance surveyed	Sites	Distance surveyed
A. Ute Reservoir to	Vertical	10	20	76	760	0	0	0	0	76	760
beyond Revuelto Creek	Vertical	20	20	434	8,680	149	2,980	231	4,620	814	16,280[1]
(11.4 km [6.8 mi])	Horizontal	20	20	0	0	149	2,980	231	4,620	380	7,600
Revuelto Creek	Vertical	20	20	16	320	13	260	0	0	29	580[1]
(0.3 km [0.2 mi])	Horizontal	20	20	0	0	13	260	0	0	13	260
B. Claer Well	Vertical	20	20	0	0	0	0	75	1,500	75	1,500
(1.5 km [0.9 mi])	Horizontal	20	20	0	0	0	0	75	1,500	75	1,500
C. Jones Well	Vertical	20	20	0	0	0	0	93	1,860	93	1,860
(1.9 km [1.1 mi])	Horizontal	20	20	0	0	0	0	93	1,860	93	1,860
D. Dunes	Vertical	20	20	238	4,760	0	0	0	0	238	4,760
(4.8 km [2.9 mi])	Horizontal	20	20	238	4,760	0	0	0	0	238	4,760
E. Near Rana Canyon	Vertical	20	20	50	1,000	0	0	0	0	50	1,000
(1.0 km [0.6 mi])	Horizontal	20	20	50	1,000	0	0	0	0	50	1,000
Rana Arroyo	Vertical	20	20	17	340	0	0	0	0	17	340
(0.3 km [0.2 mi])	Horizontal	20	20	17	340	0	0	0	0	17	340

[1]Total distance surveyed includes repeat of some segments

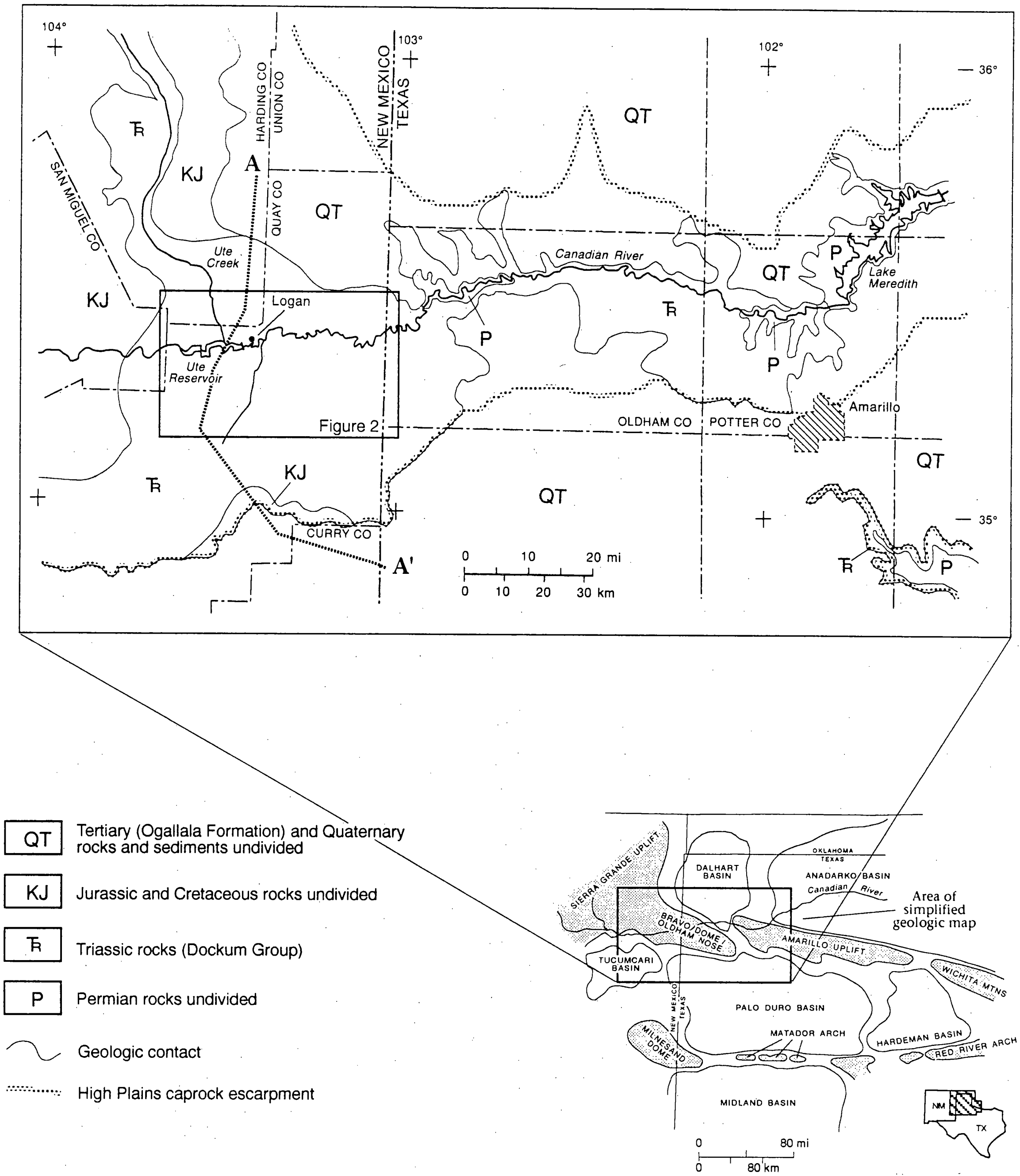

Figure 1. Regional structural elements and simplified geologic map of the Canadian River valley in eastern New Mexico and Texas Panhandle; cross section along line A-A' is shown in figure 3 (compiled from Nicholson, 1960, fig. 1; Berkstresser and Mourant, 1966, plate 2; Eifler, 1969; Eifler and others, 1983; Suleiman and Keller, 1985, figs. 6 and 7; and Gustavson and others, 1992, fig. 1).

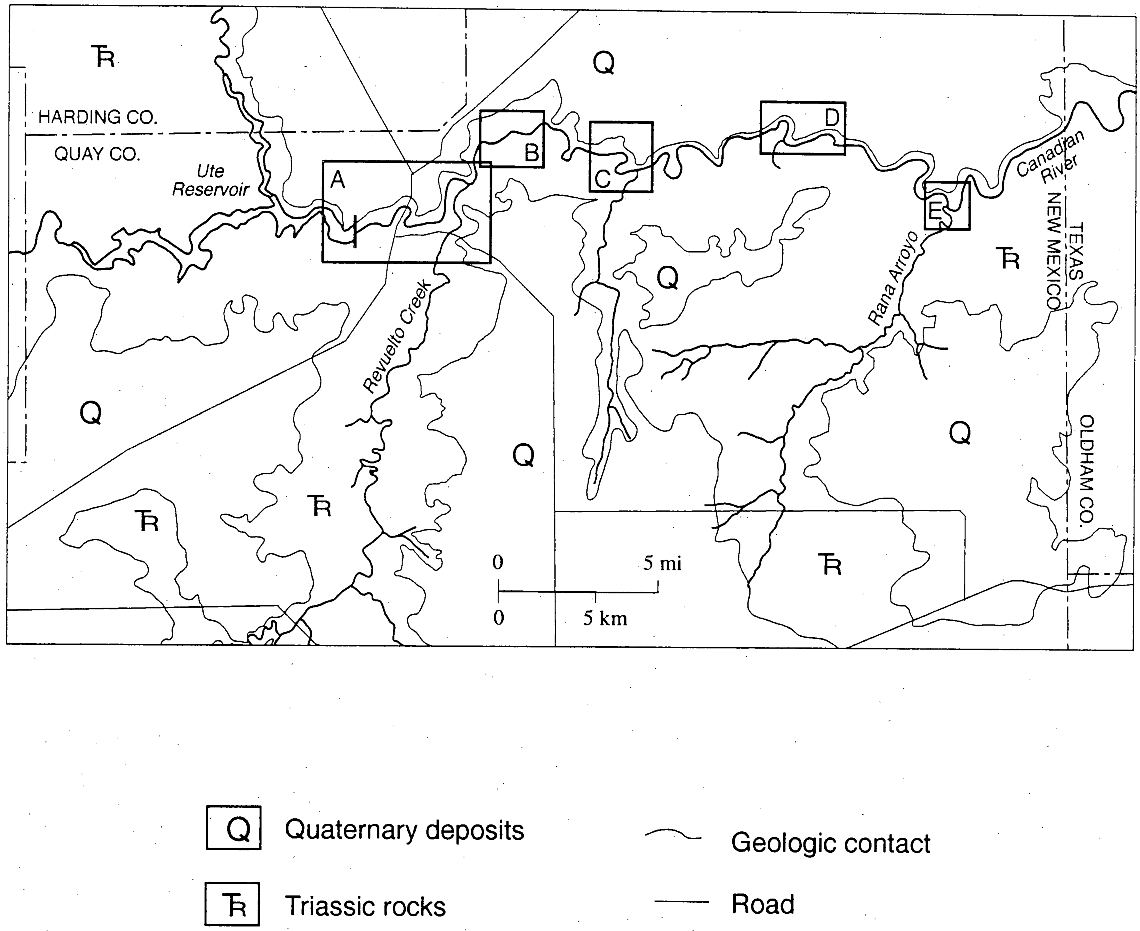

Figure 2. Generalized geologic map of eastern New Mexico segment of Canadian River showing areas selected for electromagnetic surveys: A – Ute Dam to Revuelto Creek, B – Claer Well area, C – Jones Well area, D – Dunes area, E – Rana Canyon area.

that entering Lake Meredith) was occurring along the river channel 3 to 8 km downstream from Ute Dam (U.S. Bureau of Reclamation, 1979). In 1975 two holes were drilled in bedrock adjacent to the river channel; one hole encountered a sandstone "brine aquifer" (>20,000 mg/L NaCl) a depth of at 80 m that had sufficient hydraulic head to flow to the ground surface. Geophysical investigations (seismic refraction and electrical resistivity soundings) were conducted in 1976 to determine the gross physical characteristics of the postulated brine aquifer. Although the data were sparse, they indicated the existence of low-resistivity zones in the subsurface between Ute Reservoir and a point about 2.8 km east of Revuelto Creek (U.S. Bureau of Reclamation, 1976). In 1978 a pumping test of the brine aquifer was conducted to determine feasibility of pumping to reduce its hydraulic head (determined to be about 10 ft above river level) and thereby prevent natural discharge of saline water to the riverbed alluvium (U.S. Bureau of Reclamation, 1979, 1985). The study concluded that pumping was possible but that additional studies would be needed to determine optimum pumping well location(s) and an acceptable means of disposal. Studies completed in 1984 included further streamflow–water-quality surveys (including an analysis of the apparent distribution of fresh-water inflows and saline-water inflows), periodic sampling and analysis of water quality in the alluvium, water-level monitoring and chemical analysis of the brine aquifer, completion of an additional test hole in the brine aquifer, and a seismic survey to evaluate potential brine disposal zones (Hydro Geo Chem, 1984; U.S. Bureau of Reclamation, 1984). The additional test hole (drilled on the upland surface north of the river) encountered the brine aquifer at a depth of 100 m with a hydraulic head 3 to 6 m above river elevation; data from this well supported the conclusion that the brine aquifer is a sandstone interval near the base of the Triassic section (U.S. Bureau of Reclamation, 1984). The series of investigations described above are also summarized in a report of the U.S. Bureau of Reclamation (1985).

A new round of streamflow–water quality surveys between Ute Reservoir and Lake Meredith commenced in February 1992 to determine if any changes had occurred since the expansion of Ute Dam and the subsequent increase of reservoir volume and water-surface elevation in 1987. The first of these surveys (Gustavson and others, 1992), conducted jointly by the CRMWA, the Bureau of Economic Geology (BEG), and Lee Wilson & Associates, Inc., included a regional analysis of well logs and evaporite dissolution patterns as well as chemical analyses of waters collected along the survey route. Five additional surveys were conducted by the CRMWA between February 1992 and February 1993 to obtain a full season of streamflow and surface-water quality changes of the Canadian River.

Geologic and Environmental Setting

The Canadian River in eastern New Mexico and the western Texas Panhandle occupies a broad valley underlain principally by Triassic Dockum Group rocks (Group status of the Dockum follows standard BEG nomenclature—see McGowen and others, 1979; Eifler and others, 1983; and Dutton and Simpkins, 1986), which are locally veneered with Quaternary sediments (figs. 3 and 4). The valley is about 120 km wide in eastern New Mexico and narrows to less than 50 km between escarpments of the High Plains surface in Texas (fig. 1). Permian rocks underlie the Triassic as shallow as 60 m beneath the surface near Logan, New Mexico (Gustavson and others, 1992, pl. 2), and are locally exposed in structural domes in Texas (Bravo Dome and Amarillo Uplift) (figs. 1 and 2). The Permian section includes a number of evaporite-bearing strata and discrete evaporite beds, which thin because of dissolution or pinch out within siliciclastic strata adjacent to Precambrian basement uplifts (fig. 3) (Gustavson and others, 1980, 1992). Dissolution has caused subsidence and collapse of overlying rocks and localization of the Canadian River valley (Gustavson and Finley, 1985). The edges of the evaporites have retreated southward from their original depositional limits and now underlie the center of the valley (Gustavson and others, 1992, p. 2–6, pls. 1 and 2).

In most of the study area in eastern New Mexico, the Canadian River flows through a narrow canyon (15 to 30 m deep and about 150 m wide) in the resistant Trujillo Formation of the Dockum Group. Past dissolution and collapse have produced monoclinal flexures,

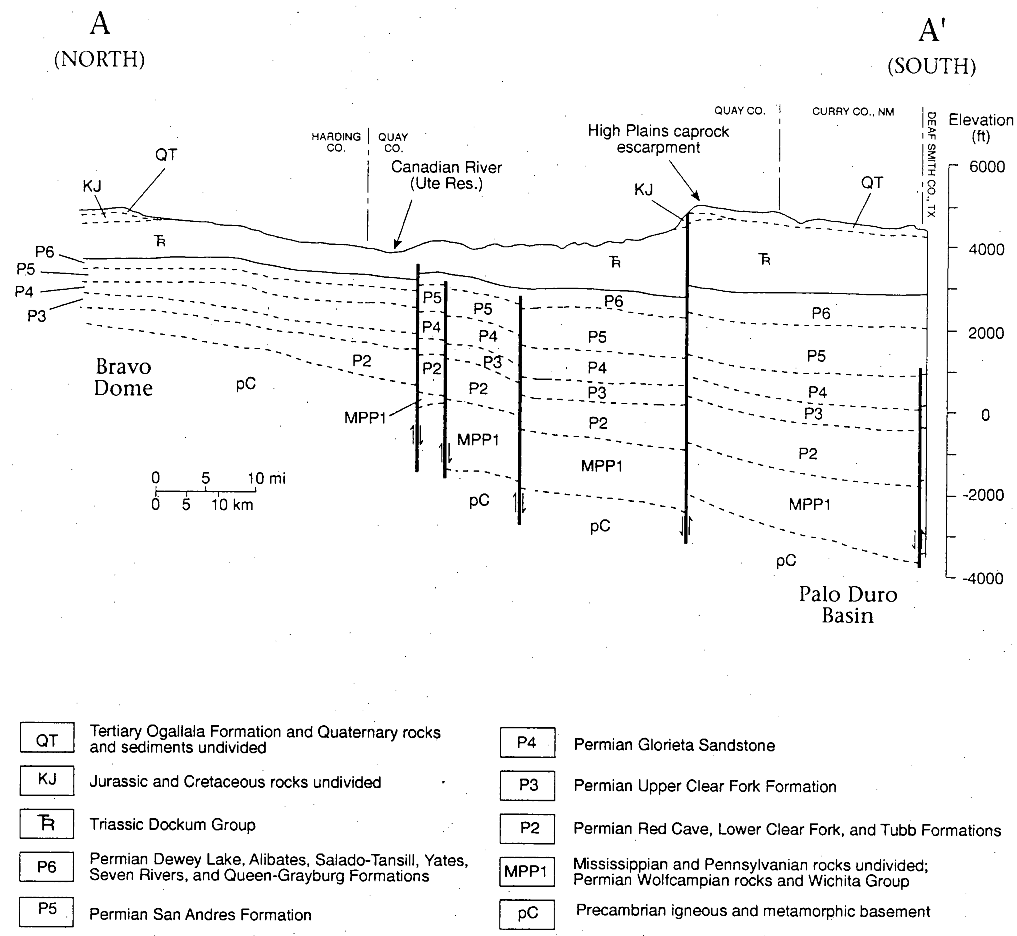

Figure 3. Simplified north-south geologic cross section through Canadian River valley in eastern New Mexico; line of section shown in figure 1. Thinning of Permian units P2 through P6 is due mainly to dissolution of halite from the updip margin of the Palo Duro Basin (adapted from Murphy, 1987, figs. 27 and 31).

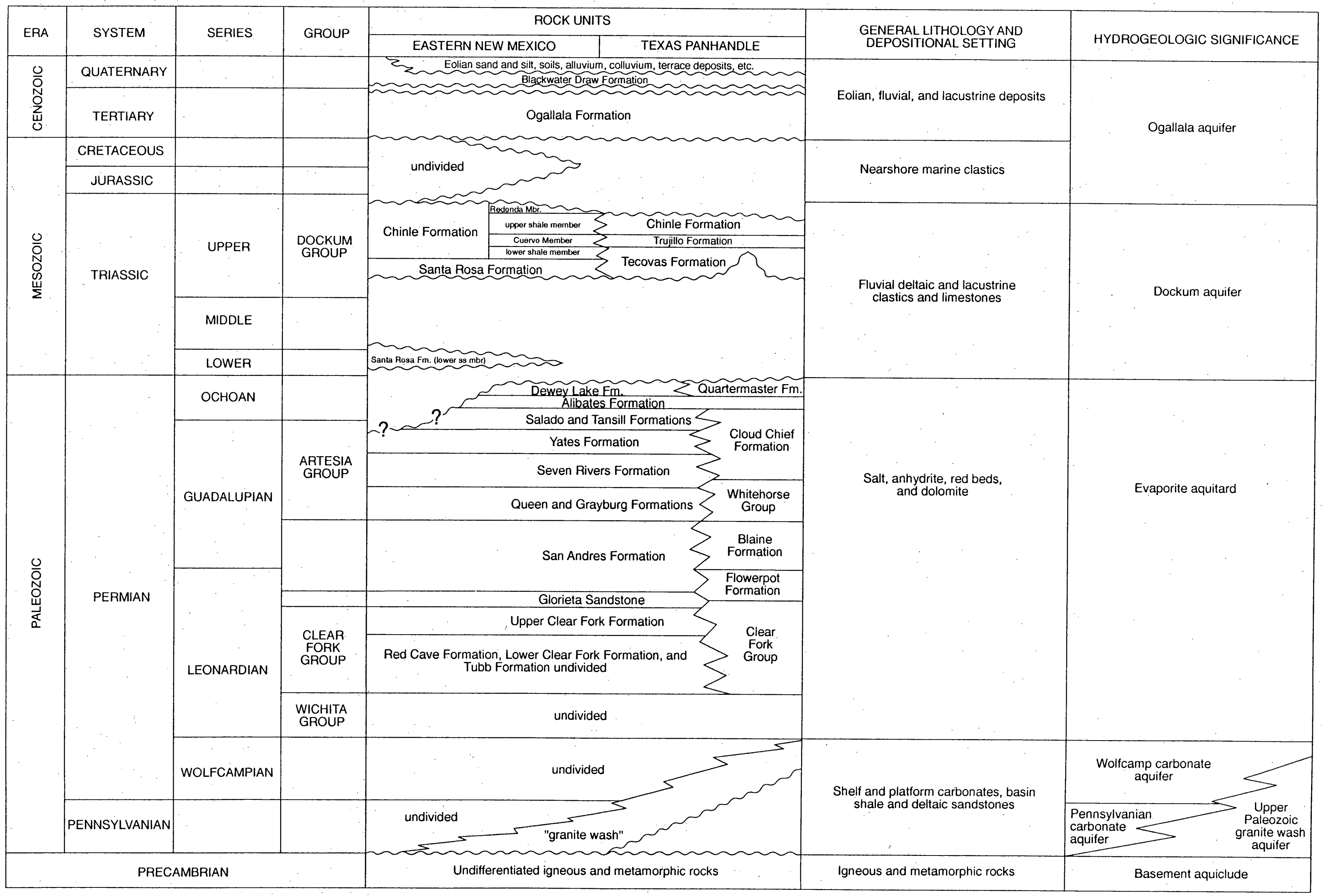

Figure 4. Stratigraphic nomenclature of rocks beneath the Canadian River valley in eastern New Mexico and Texas Panhandle (compiled from Gustavson and others, 1980, fig. 3; Presley, 1981, table 1; Bassett and Bentley, 1983, table 1; Lucas and Kues, 1985, fig. 1; Lucas and others, 1985, fig. 6; and Murphy, 1987, fig. 3).

observable in the canyon walls, that have amplitudes as great as 15 m in the otherwise gently dipping Triassic strata. These flexures also appear regionally as a series of anticlines and synclines (Hydro Geo Chem, 1984). The bedrock floor of the canyon extends below the present river surface and cuts into the lowest unit of the Dockum Group, the Tecovas Formation, and possibly also into the uppermost part of the Permian section in structural highs between collapse depressions (U.S. Bureau of Reclamation, 1979, appendix D). In most of the study area only the Trujillo Formation is exposed because Quaternary riverbed alluvium has backfilled the canyon to a depth of 15 m or more. Well-developed fractures exposed in the Trujillo Formation define a regional pattern that may reflect regional tectonic stresses, local stresses related to dissolution and collapse, or both.

The discharge of saline ground water in the study area indicates that dissolution of evaporites in the Canadian River ground-water system is continuing. Direct evidence of saline water discharge areas include evaporative mineral crusts on fine-grained alluvial sediments, dense thickets of salt cedars (*Tamarix gallica* L.), and patches of salt-tolerant sedges (*Scirpus americana* Pers.) and grasses (*Distichlis spicata* L.).

METHODS

Lateral Conductivity Surveys

Lateral conductivity surveys were completed along the Canadian River and tributaries to locate sites of potential saline ground-water entry into river alluvium. In these surveys, a Geonics EM34-3* ground conductivity meter was used to measure apparent conductivity along seven river and tributary stretches (table 1): (1) along the Canadian River between Ute Reservoir and downstream from Revuelto Creek, (2) Revuelto Creek, (3) in the Claer well area,

*The use of firm and brand names in this report is for identification purposes only and does not constitute endorsement by the Bureau of Economic Geology.

(4) in the Jones well area, (5) in the Dunes area, (6) near Rana Canyon, and (7) along Rana Arroyo (fig. 2).

The EM34-3 supports a 10-, 20-, or 40-m transmitter and receiver coil separations and two principal coil orientations (horizontal dipole [or vertical coplanar] and vertical dipole [or horizontal coplanar]). A 20-m coil separation was used, which has an effective penetration depth of 12 m for the horizontal dipole orientation and 24 m for the vertical dipole orientation. Station spacings were also 20 m for all stretches except near Ute Reservoir, where 10-m station spacings were used for the first 76 sites.

Conductivity measurements at 20-m spacings were taken as follows: (1) the transmitter coil was placed on the ground in the vertical dipole (horizontal coplanar) orientation at a chosen site; (2) the receiver coil was placed on the ground at an approximate distance of 20 m from the transmitter coil; (3) the receiver coil position was adjusted until the separation meter on the receiver indicated the proper separation; (4) apparent conductivity (in mS/m) was read from the meter, transcribed by hand, and digitally logged on a data logger attached to the receiver; (5) both coils were realigned in the horizontal dipole (vertical coplanar) orientation at the same station locations and coil separation; (6) apparent conductivity for the horizontal dipole orientation was read from the meter, transcribed by hand, and digitally logged; and (7) the transmitter coil was moved to the location of the receiver coil, which was moved forward about 20 m; and the entire process repeated. We attempted to follow a smoothly curving path that was as near as possible to the central part of the canyon. In some areas, particularly between Ute Reservoir and the railway bridge, vegetation, terrain, or water impounded by beaver dams forced an alternate course nearer the canyon wall.

More than 2,200 conductivity measurements were taken at 1,073 sites in the study area (table 1 and appendix I). More than half of the measurements (583 unique sites) were taken along an 11-km reach of the Canadian River between Ute Reservoir and a point 1.5 km beyond the confluence of the river with Revuelto Creek (fig. 5), where previous studies estimated that as much as one-third of the salt load enters the river. Revuelto Creek was surveyed from its

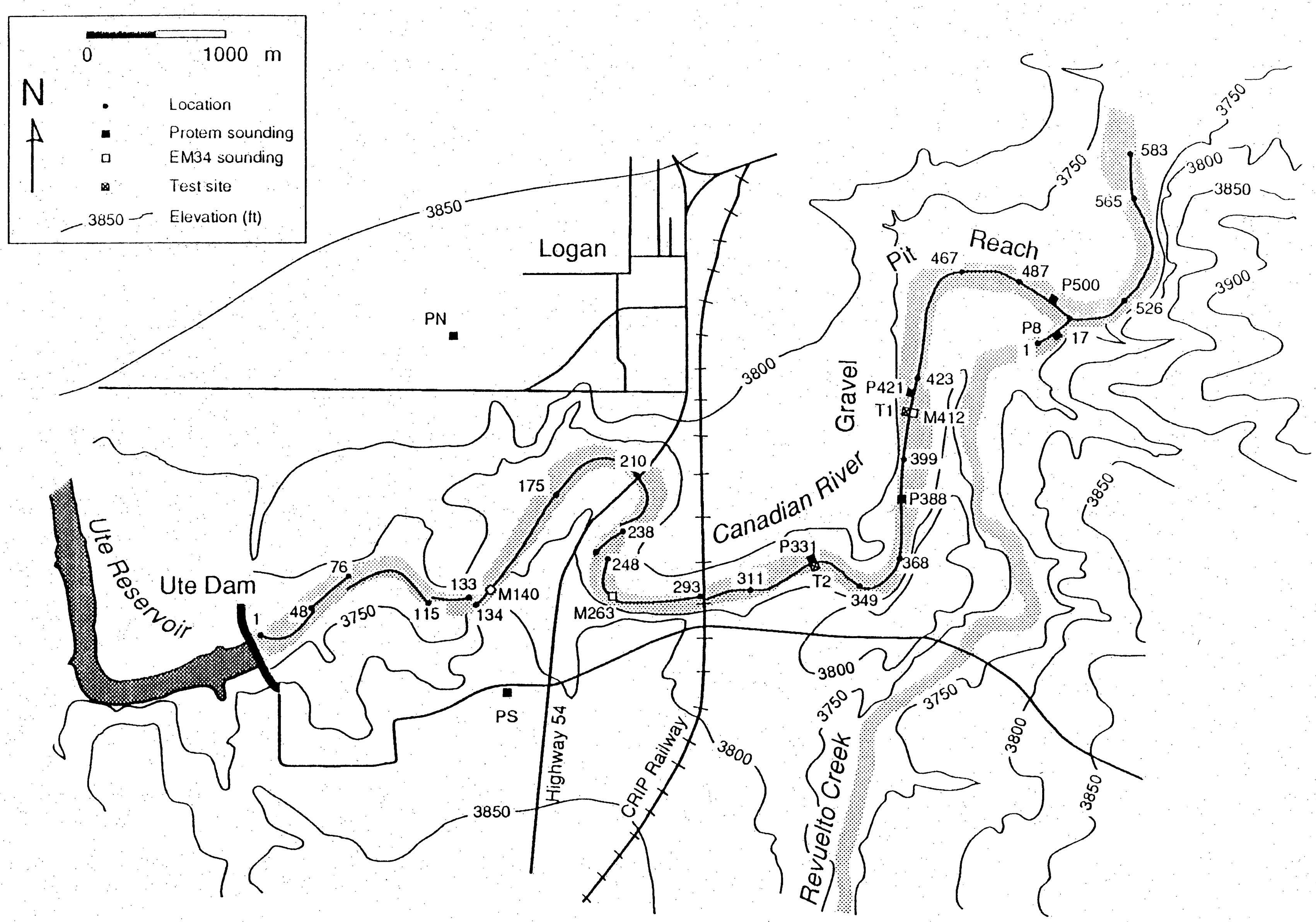

Figure 5. Topographic map of the Ute Reservoir and Revuelto Creek area (area A, fig. 2) showing station locations, test sites, and sounding sites.

confluence with the Canadian River to a distance 340 m upstream (fig. 5). Short segments were surveyed between Revuelto Creek and the Dunes in areas of prominent tributary valleys (1,500 m in the Claer well area, fig. 6) or evident surface collapse (1,850 m in the Jones well area, fig. 7). The second longest survey, 4.8 km, was completed in the Dunes area (fig. 8), where previous analysis of river conductivity data indicated an increase in salt load (Gustavson and others, 1992). A short conductivity survey (1,000 m) was also completed at Rana Canyon and along Rana Arroyo from its confluence with the Canadian River to a distance 340 m upstream (fig. 9).

Tests of the lateral conductivity methods consisted of (1) radial surveys at 45° intervals of a 40 × 40 m grid at site T1 (fig. 5) to determine how conductivity varies with direction relative to the valley axis, (2) three parallel transects along the river at site T2 (fig. 5) to determine the importance of position within the valley, and (3) several reoccupations of sites between Ute Reservoir and Revuelto Creek to determine the repeatability of measurements and the variation of conductivity with time.

Vertical Conductivity Surveys

Multiple Coil-Spacing Soundings

Because the effective penetration depth of the field generated by the EM34-3 increases with coil spacing for a given coil orientation (table 2), conductivities measured at different coil spacings and coil orientations can be used to infer conductivity changes with depth beneath a

Table 2. Effective penetration depth (EPD) for various coil spacings and coil orientations for the Geonics EM34-3.

Coil Spacing (m)	Transmitter Frequency (Hz)	Horizontal Dipole EPD (m)	Vertical Dipole EPD (m)
10	6400	5.9	12.6
20	1600	11.8	25.3
40	400	23.5	50.6

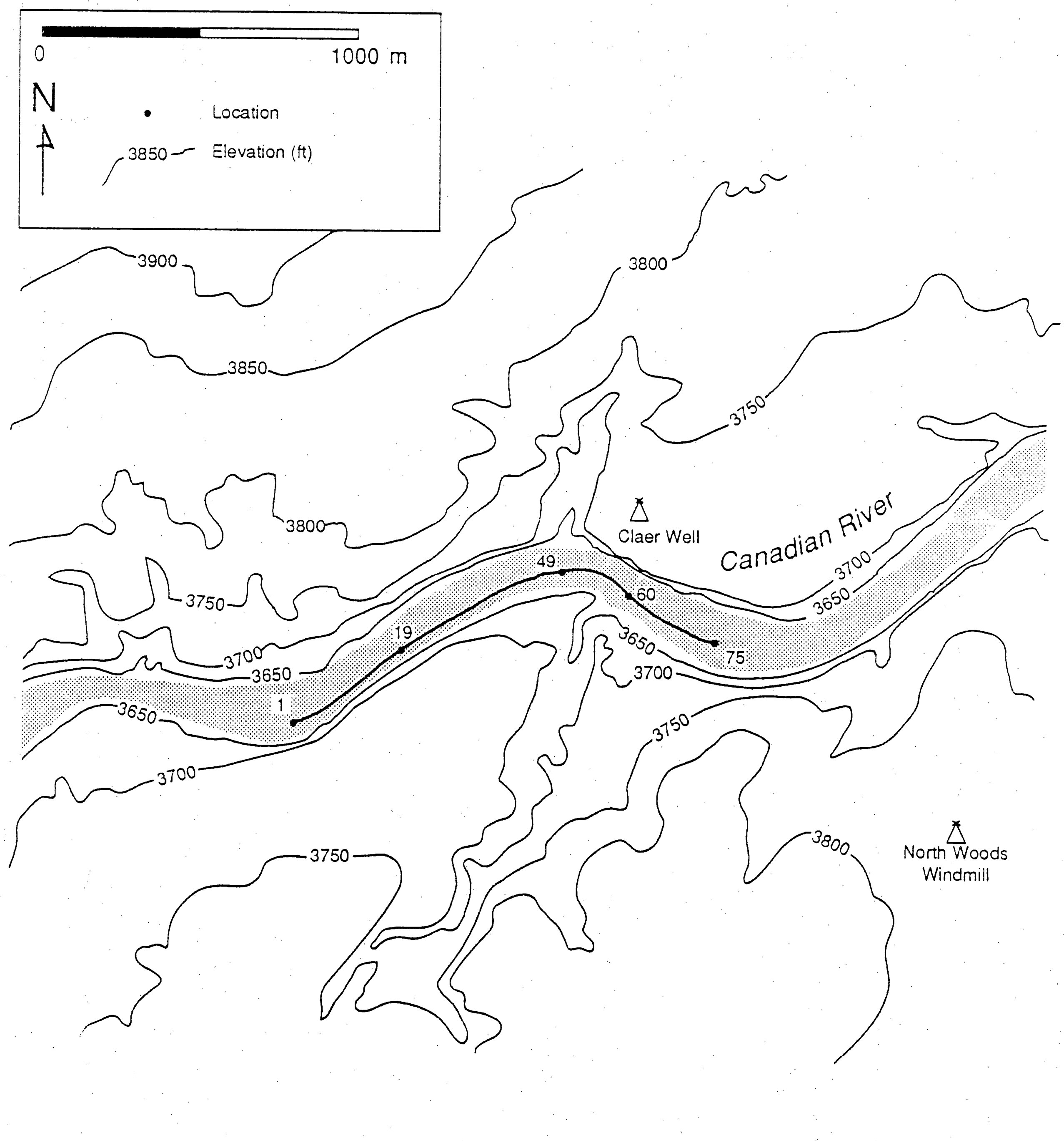

Figure 6. Topographic map of the Claer Well area (area B, fig. 2) of the Canadian River showing station locations.

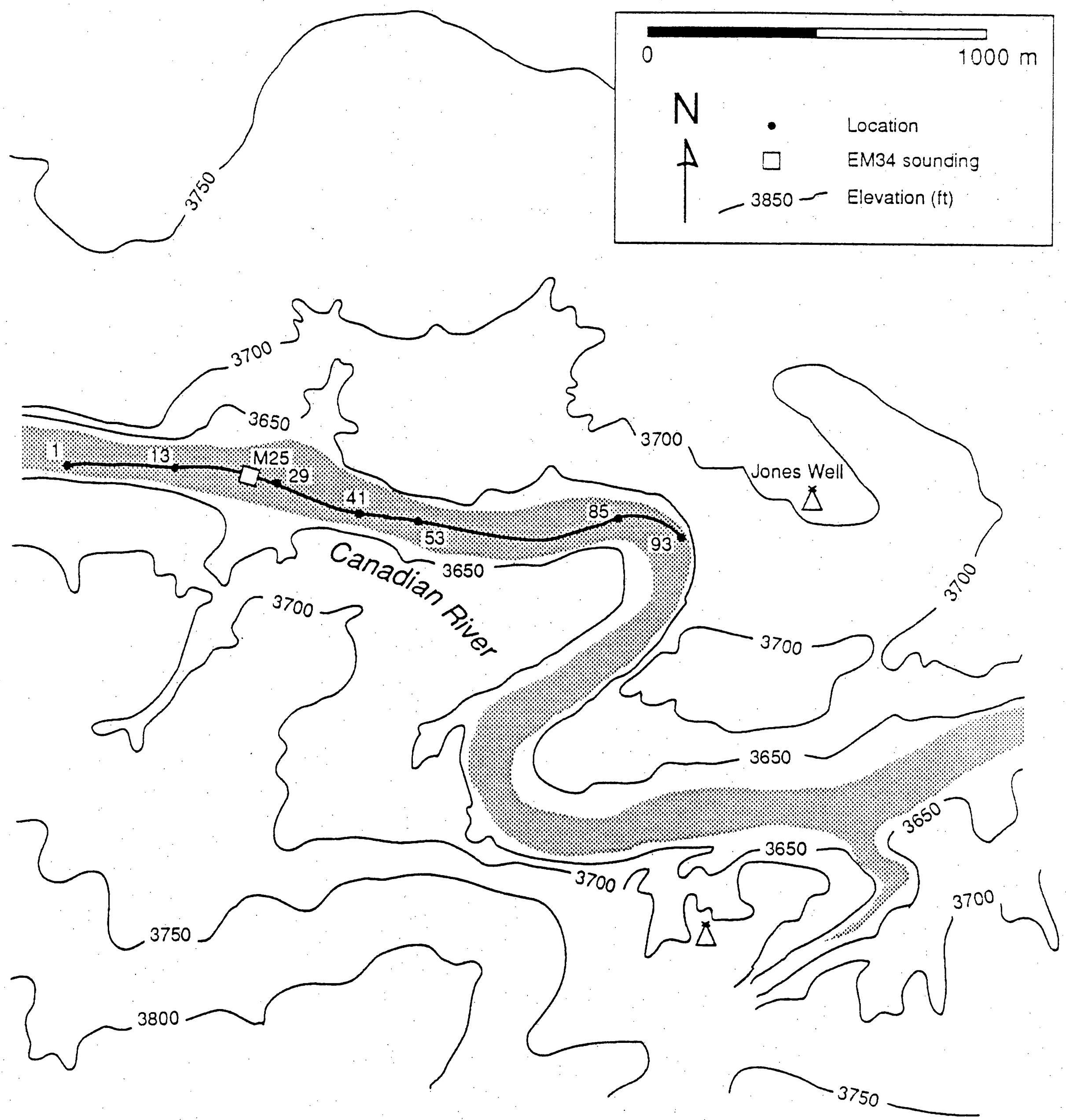

Figure 7. Topographic map of the Jones Well area (area C, fig. 2) of the Canadian River showing station locations and sounding sites.

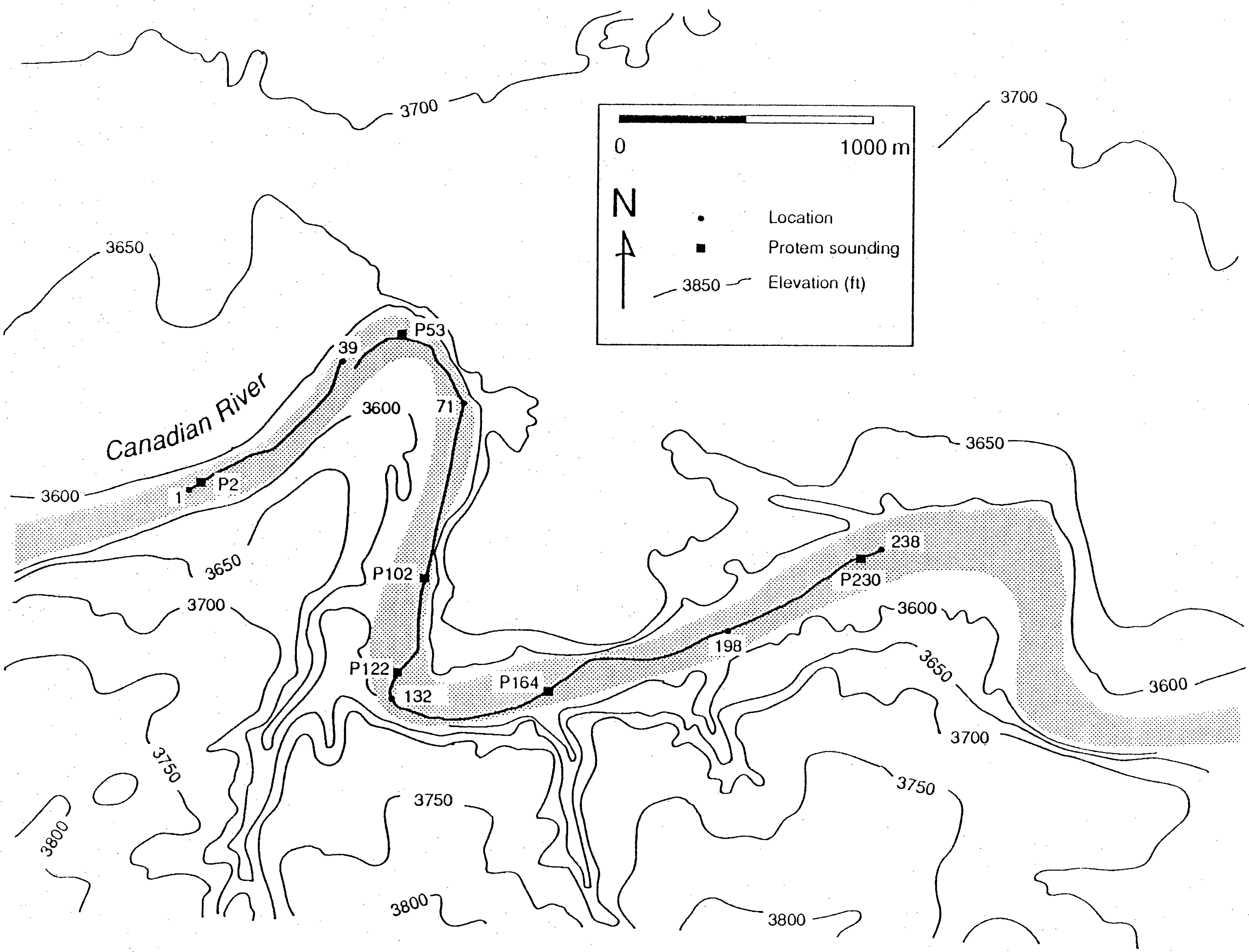

Figure 8. Topographic map of the Dunes area of the Canadian River (area D, fig. 2) showing station locations and sounding sites.

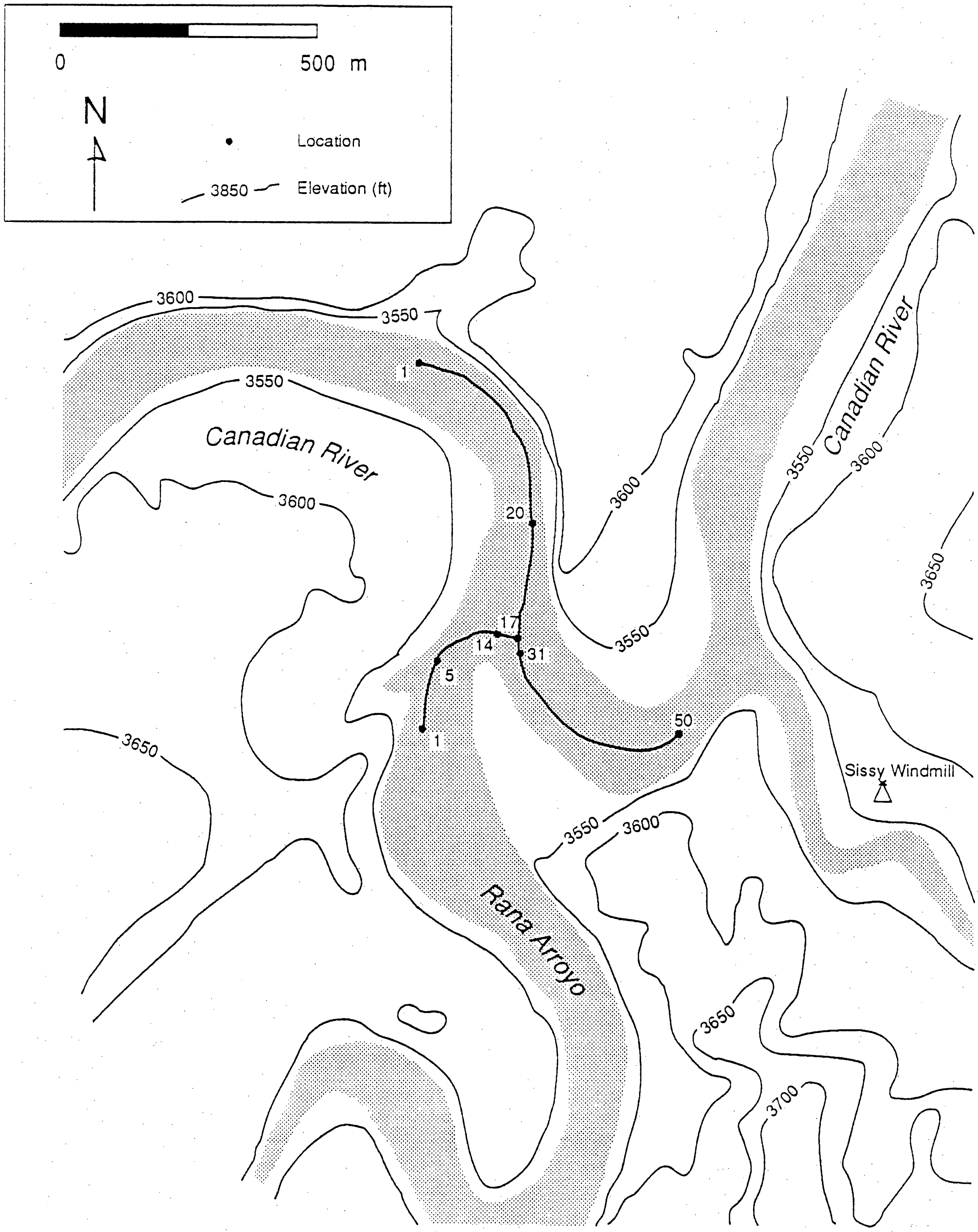

Figure 9. Topographic map of the Rana Canyon area of the Canadian River (area E, fig. 2) showing station locations.

site. Conductivities were measured at 10-, 20-, and 40-m coil spacings and horizontal and vertical dipole orientations at three sites between Ute Reservoir and Revuelto Creek (sites M140, M263, and M412, fig. 5 and app. II) and at one site in the Jones well area (M25, fig. 7).

At each site, apparent conductivities were collected first at 10-m coil spacing; these 10-m stations were used to determine the 10-m intervals between stations for the longer coil separations. Horizontal and vertical dipole conductivities at 10-m coil spacings were measured over a distance of at least 80 m at each site to determine lateral variability. After all sites were measured using the 10-m coil spacing, the 20-m spacing was selected, the instrument was recalibrated, and horizontal and vertical dipole data were collected across the same stretch at the same 10-m station spacing. Finally, the 40-m spacing was selected, the instrument was recalibrated, and apparent conductivities for both dipole orientations were measured at 10-m station spacings across the same line used for the 10- and 20-m coil spacings.

Processing of the EM34-3 sounding data first required transferring the data from the digital data logger to a computer and selecting a representative point along each profile for analysis. EMIX34 v. 2.0, a computer program published by Interpex, was used to process and interpret the data. Horizontal and vertical dipole conductivities for each coil spacing at the chosen common midpoint were entered in the program, a starting conductivity model was chosen, and the computer displayed both the observed and synthetic data from the chosen model. The model was then adjusted to better fit the observed data. After reasonable agreement was obtained manually, the program adjusted layer thicknesses and conductivities to obtain the best fit. The program then performed equivalence analysis to determine the range of model thicknesses and conductivities that produced an equivalent fit to the observed data.

Time-Domain Soundings

Time-domain soundings using a Geonics Protem 47/S instrument were intended to give a more detailed conductivity profile at several sites to a depth of about 100 m. Instead of using different coil spacings to change penetration depth, the time-domain devices measure the decay of a transient electromagnetic field produced by the termination of an alternating primary electromagnetic field. The secondary field strength is measured by the receiving coil at 20 times (or "gates") following transmitter current termination. Field strength at early times gives information about the shallow conductivity; strength at later times is related to conductivity at depth. After the transient decay curve is known for a given site, computer programs such as Interpex's TEMIX can be used to construct a model conductivity profile for the site that provides the best fit for the observed data.

Time-domain soundings were conducted at 13 sites in November 1992. Seven sites were located in the Ute Reservoir to Revuelto Creek area (fig. 5), including two on the uplands north (PN) and south (PS) of the Canadian River canyon. Four sites (P331, P388, P421, and P500) were located on the Canadian River between the railway bridge and Revuelto Creek, and one (P8) was located on Revuelto Creek near its confluence with the Canadian River. Six soundings (P2, P53, P102, P122, P164, and P230) were collected along the Canadian River in the Dunes area (fig. 8). All time-domain soundings were collected with a 40 × 40 m transmitter antenna and the receiver coil outside the transmitter loop.

Joint Analysis

Geologic structures, especially joints, are commonly preferred pathways for fluid movement. Joints in Triassic fluvial-channel sandstones exposed in the Canadian River valley were examined to determine their spatial distribution and possible influence on flow of saline waters through underlying bedrock and into Canadian River alluvium. Joint data were collected at 13 field sites, and were analyzed using a two-dimensional orientation program (Rosy©). These data were plotted as half-rose diagrams, and vector means were calculated. The distribution of joints was also measured by recording the distance between joints that cross 100- to 300-ft-long transects.

RESULTS

Lateral Conductivity Surveys

Lateral conductivity surveys were completed along five segments of the Canadian River and two tributaries (table 1). In downstream order, the Canadian River sections included a long segment beginning at Ute Dam and ending about 1.5 km downstream from Revuelto Creek, two short segments near the Claer Well and the Jones Well, a long segment in the Dunes area, and a short segment upstream and downstream from Rana Canyon (fig. 2). Short segments were also completed at the downstream ends of Revuelto Creek and Rana Arroyo.

Ute Reservoir to beyond Revuelto Creek

Nearly 1,300 conductivity measurements were made along an 11-km stretch of the Canadian River between Ute Reservoir and a point about 1.5 km downstream from its confluence with Revuelto Creek (figs. 2 and 5). The 380 horizontal dipole conductivities ranged from a low of 78 mS/m at station 446 to 288 mS/m at station 335 (fig. 10 and app. I). The 890 vertical dipole conductivities, which ranged from 128 mS/m at station 97 to –244 mS/m at station 413, were nearly a mirror image of the horizontal dipole conductivities. The highest negative apparent conductivity values for the vertical dipole orientation were coincident with the highest positive conductivity values for the horizontal dipole orientation. The negative apparent conductivity values, which have no intuitively obvious meaning, indicate areas where near-surface conductivities are so high that the assumed linear relationship between instrument response and ground conductivity no longer holds for the vertical dipole coil orientation (Frischknecht and others, 1991). Vertical dipole values (fig. 10) increase with increasing horizontal dipole values to about 100 mS/m, at which point the measurements diverge. Horizontal dipole conductivities continue to increase, whereas vertical dipole values decrease and, with increasing horizontal dipole conductivity, actually become negative.

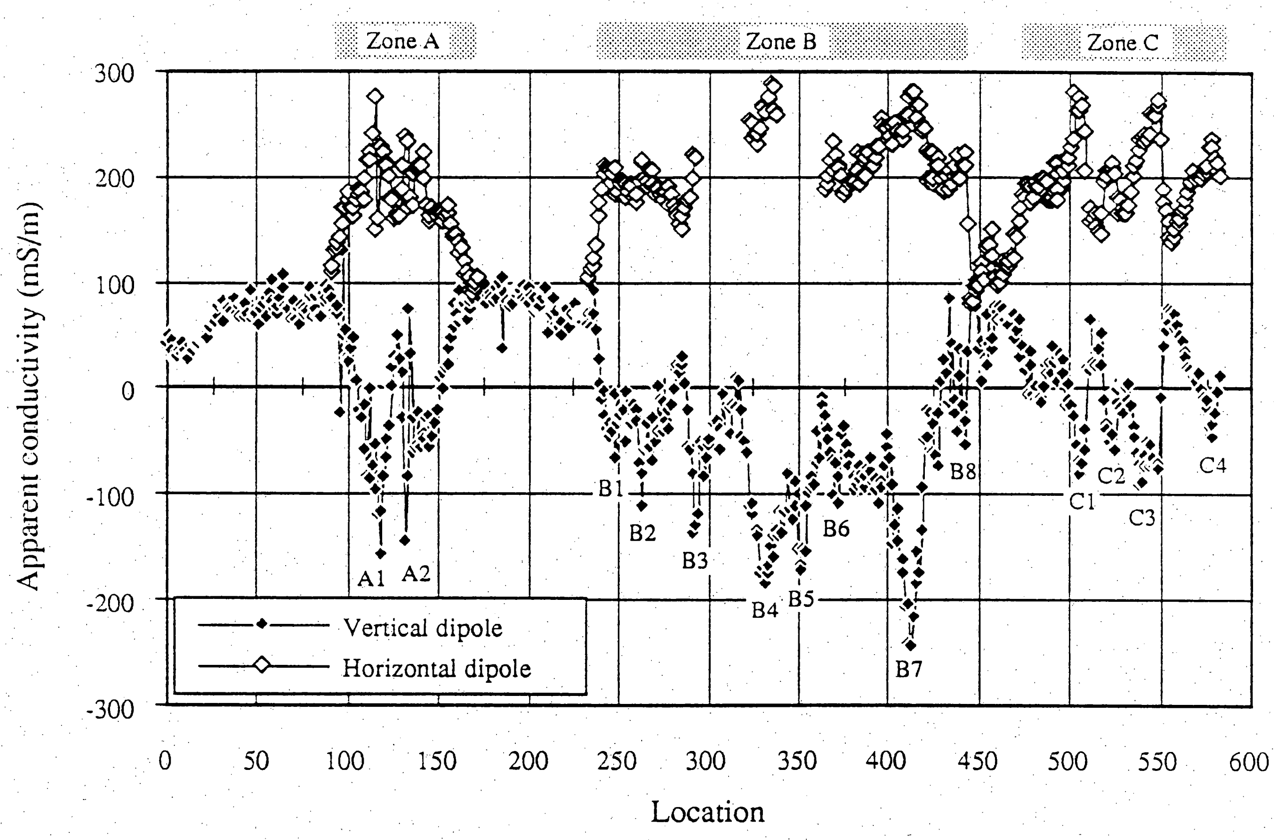

Figure 10. Apparent conductivity (in milliSiemens/m) along the Canadian River from Ute Reservoir to beyond Revuelto Creek. Locations 1 through 76 are 10 m apart; all others are 20 m apart..

The lateral conductivity survey indicates three broad zones of high conductivity along this segment of the Canadian River. The first, zone A (fig. 10), extends 1,600 m between Ute Dam and the highway bridge (stations 90 and 170, fig. 5). In this zone, horizontal dipole conductivities increase from about 100 mS/m on the flanks of the zone to a maximum of 275 mS/m; vertical dipole values are mostly negative in this zone and reach values as low as –156 mS/m. Within zone A are two distinct peaks: peak A1 is between stations 111 and 122 and peak A2 is between stations 131 and 142 (fig. 10).

Zone B is a broad zone of generally high conductivity (fig. 10). It extends about 4,200 m between the Highway 54 bridge and the "gravel pit" reach (stations 233 to 444, fig. 5). Conductivities in this zone, which range from 102 to 288 mS/m (horizontal dipole) and from 74 to –244 mS/m (vertical dipole), are the highest measured during the project. There are eight distinct peaks in zone B (fig. 10). The highest conductivities measured at these peaks increase downstream from B1 through B4. Peak B1, located between stations 242 and 248, has horizontal dipole conductivities as high as 209 mS/m and vertical dipole conductivities to –67 mS/m. Conductivities are slightly higher at B2 (stations 262 to 270), reaching 215 mS/m (horizontal dipole) and –112 mS/m (vertical dipole). Maximum conductivities increase to 219 mS/m (horizontal dipole) and –136 mS/m (vertical dipole) at peak B3 (stations 291 to 294). The highest horizontal dipole conductivity measured, 288 mS/m, was recorded at peak B4 (stations 323 to 340). Here the vertical dipole conductivity reached –183 mS/m. Two peaks of lesser lateral extent are located downstream from peak B4. These peaks, B5 (stations 349 to 355) and B6 (stations 368 to 373), break the trend of downstream increases in peak conductivities. The highest conductivity at B5, measured in vertical dipole mode only, is –173 mS/m. Conductivities in peak B6 reach 233 mS/m (horizontal dipole) and –110 mS/m (vertical dipole). Peak B7 (stations 403 to 419) has the highest observed vertical dipole conductivity (–244 mS/m) and nearly the highest horizontal dipole conductivity (279 mS/m). The most downstream peak in zone B, peak B8, is characterized by variable vertical dipole conductivities as high as –53 mS/m and horizontal dipole conductivities reaching 221 mS/m.

High-conductivity zone C, which begins upstream from Revuelto Creek (station 476, fig. 5) and may extend beyond the last point measured downstream from Revuelto Creek (station 583), covers at least 2,140 m along the river. Conductivities in this zone (fig. 10) range from 136 to 275 mS/m (horizontal dipole) and 75 to –9 mS/m (vertical dipole). Horizontal dipole values are slightly lower than those in zone B; vertical dipole values are also not as negative as those found in zone B. Four conductivity peaks, characterized by horizontal dipole conductivities above 200 mS/m and negative vertical dipole conductivities, were located in zone C. Peak C1 (stations 502 to 509), located near the confluence of the Canadian River and Revuelto Creek, had conductivities as high as 279 mS/m (horizontal dipole) and –82 mS/m (vertical dipole). Lower maximum conductivities of 212 mS/m (horizontal dipole) and –59 mS/m (vertical dipole) were observed at peak C2 (stations 520 to 525). Conductivities were as high as 271 mS/m (horizontal dipole) and –91 mS/m (vertical dipole) at peak C3 (stations 536 to 550), the broadest of the peaks in zone C. The last peak located, C4 (stations 572 to 583), had conductivities reaching 234 mS/m (horizontal dipole) and –45 mS/m (vertical dipole).

Revuelto Creek

A lateral conductivity survey was completed for the lower 340 m of Revuelto Creek (fig. 5 and appendix I). This survey, which consisted of 29 vertical dipole conductivity measurements and 13 horizontal dipole measurements, showed that ground conductivity generally increases toward the Canadian River (fig. 11). Nevertheless, conductivities measured along Revuelto Creek were not as high as those encountered along the Canadian River in high-conductivity zones A, B, and C. Conductivity measured in the horizontal dipole mode ranged from 105 mS/m at station 1 to 178 mS/m at station 11. Vertical dipole conductivity values ranged from a high of 85 mS/m at station 1 to a low of 18 mS/m at station 17 near the confluence with the Canadian River. The apparent disagreement in trend between the horizontal and vertical dipole measurements is caused by the nonlinear response of the instrument in the vertical dipole coil orientation; for this conductivity range, decreasing vertical dipole conductivity

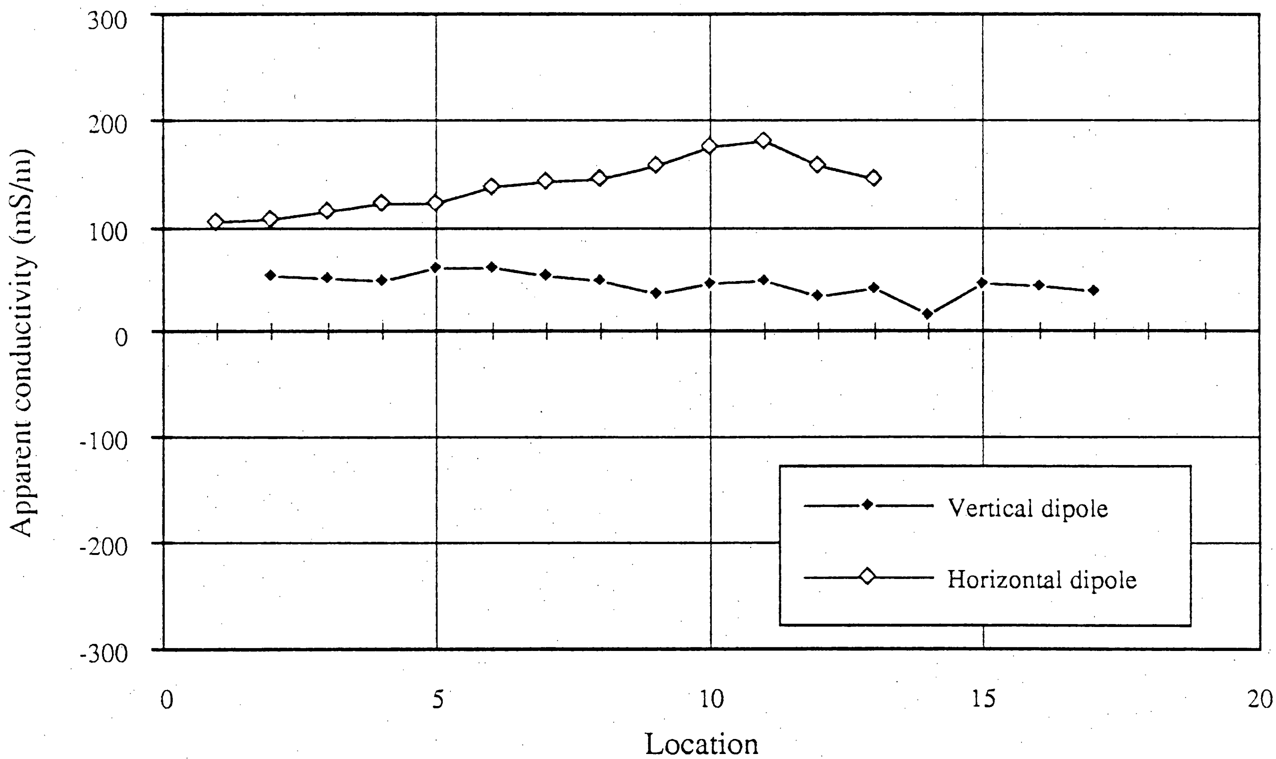

Figure 11. Apparent conductivity (in milliSiemens/m) along Revuelto Creek (fig. 5). Locations are 20 m apart.

values indicate increasing ground conductivity, as shown by the horizontal dipole measurements.

Claer Well area, Canadian River

The Claer Well area of the Canadian River, located downstream from Revuelto Creek (fig. 3), is an area where a prominent northeast-southwest drainages join the main Canadian River canyon. A lateral conductivity survey was completed along the Canadian River across its intersection with the side drainages (fig. 6). The survey consisted of horizontal and vertical dipole conductivity measurements at 75 sites covering 1,500 m.

Horizontal and vertical dipole conductivity measurements were a mirror image of each other (fig. 12), suggesting that nonlinear instrument response in the vertical dipole coil orientation caused declining apparent conductivity measurements with increasing ground conductivity. Horizontal dipole conductivities show a general increase in a downstream direction, from 96 mS/m at station 1 to 207 mS/m at station 75. Conversely, vertical dipole conductivities decrease from 78 mS/m at the upstream end of the segment to –14 mS/m near the downstream end. Three local conductivity highs are evident in the horizontal dipole mode, each with successively higher peak conductivities downstream. The upstream peak (stations 2 to 12) has horizontal dipole conductivities as high as 144 mS/m, the middle peak (stations 36 to 47) has a higher maximum conductivity of 189 mS/m, and the downstream peak (stations 66 to 75) has the highest conductivity (207 mS/m) observed for the segment. This peak probably continues farther downstream beyond the survey endpoint.

Jones Well area, Canadian River

The Jones Well area of the Canadian River, located between Revuelto Creek and the Dune (figs. 2 and 7), is an area where a large surface collapse feature has been mapped (Hydro Geo

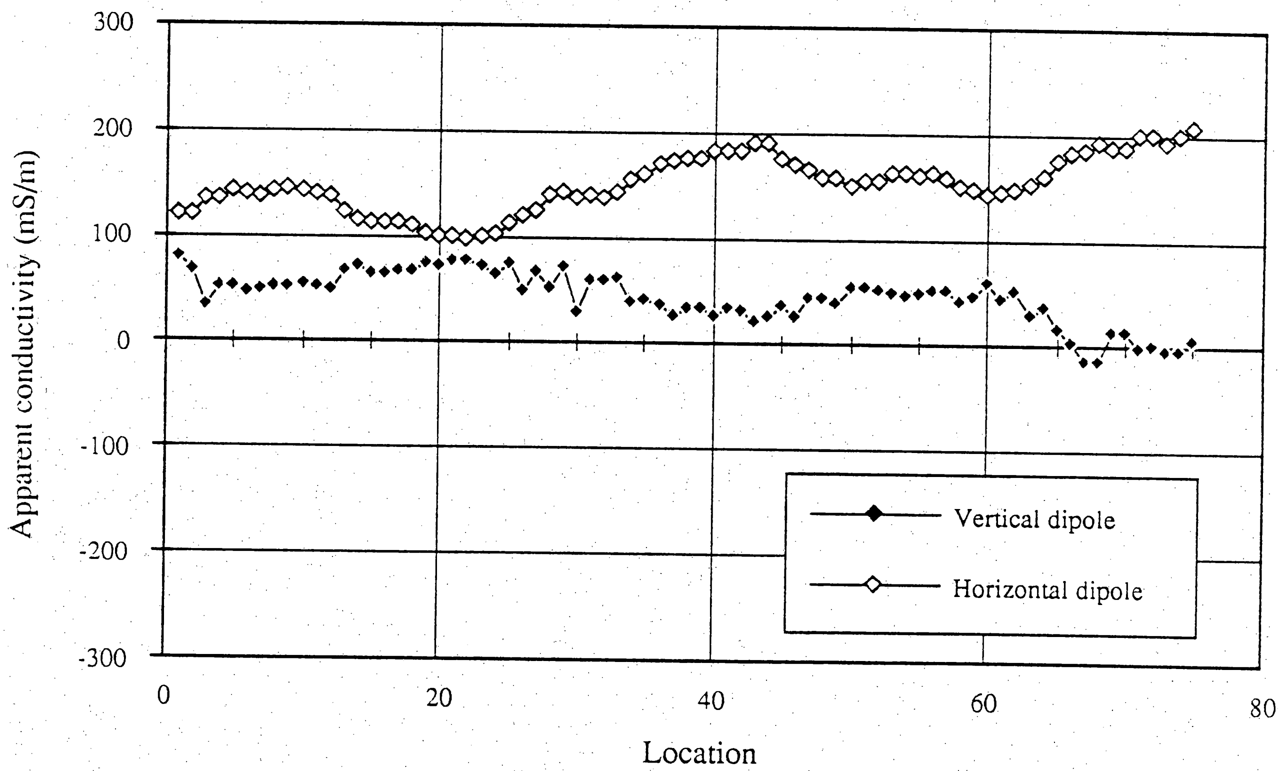

Figure 12. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Claer Well area (fig. 6). Locations are 20 m apart.

Chem, 1984). A lateral conductivity survey across this feature included 93 horizontal and vertical dipole conductivity measurements along 1,860 m of the river (fig. 13 and app. I).

Horizontal and vertical dipole conductivities were generally lower along this stretch than farther upstream. Observed conductivities ranged from 34 to 105 mS/m (horizontal dipole) and 19 to 80 mS/m (vertical dipole). Changes in conductivity indicated by vertical dipole measurements were similar to those indicated by horizontal dipole measurements, which suggests that conductivities in this area are low enough to keep instrument response linear in the vertical dipole mode.

No prominent conductivity peaks were encountered in this section. Conductivity values were as low as 34 mS/m (horizontal dipole) and 19 mS/m (vertical dipole) across a conductivity trough located between stations 11 and 40 (fig. 13). The center of this trough (station 29) is near the center of the mapped collapse depression.

Dunes area, Canadian River

The lateral conductivity survey in the Dunes area consisted of horizontal and vertical dipole measurements at 238 sites along 4,760 m of the Canadian River (figs. 2 and 8). Conductivities measured along this stretch varied greatly, ranging from 20 to 245 mS/m (horizontal dipole) and from 96 to –73 mS/m (vertical dipole). In areas of lower horizontal dipole conductivity (100 mS/m or less), horizontal and vertical dipole measurements were similar. In areas where horizontal dipole conductivities were greater than 100 mS/m, horizontal and vertical dipole conductivities changed in opposite directions. As in other areas of high ground conductivity, these differences can be attributed to nonlinear instrument response in the vertical dipole coil orientation.

Prominent features in the conductivity survey of the Dunes area include a low conductivity zone between stations 15 and 95 (fig. 14) and a broad zone of high conductivity (zone D) between stations 104 and 238. In the low-conductivity area, measured conductivities

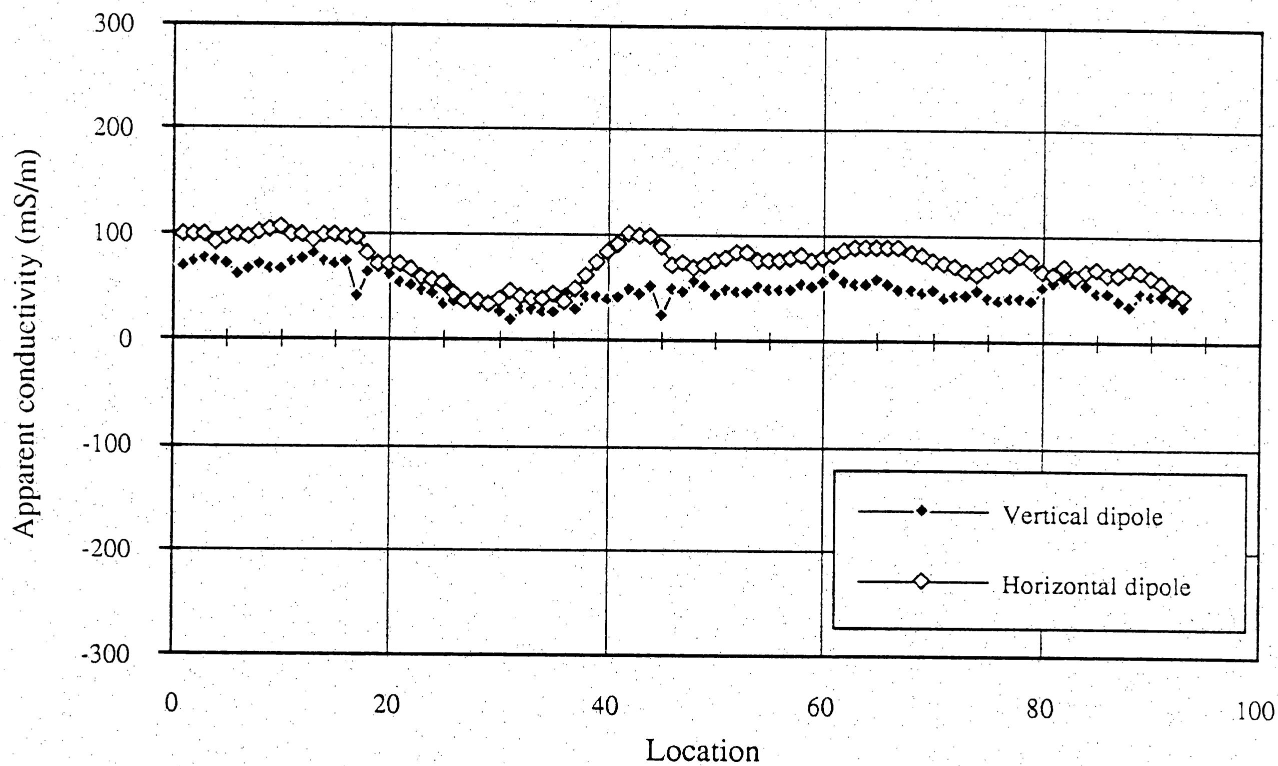

Figure 13. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Jones Well area (fig. 7). Locations are 20 m apart.

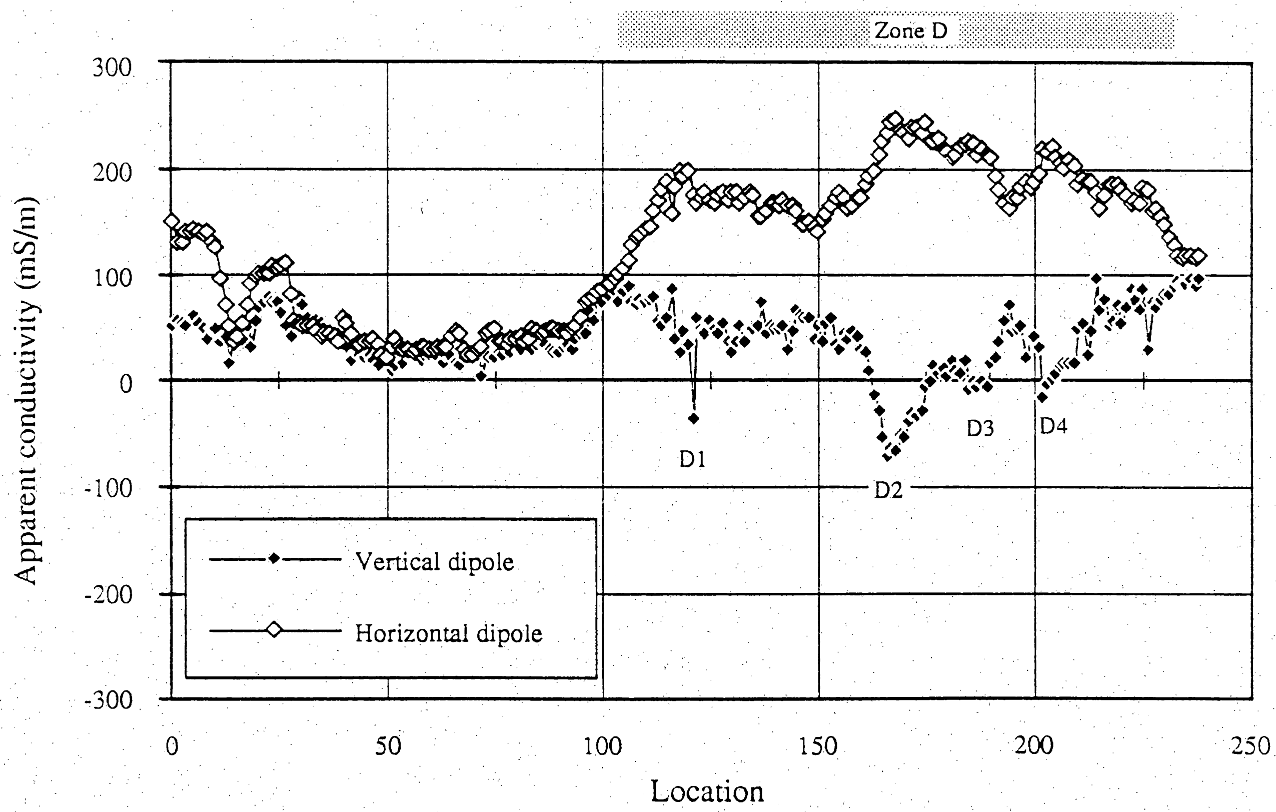

Figure 14. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Dunes area (fig. 8). Locations are 20 m apart.

were as low as 20 mS/m (horizontal dipole) and 3 mS/m (vertical dipole). This area includes a fresh-water spring near station 50 that was flowing during the survey.

Four conductivity peaks were located within the broad zone of high conductivity (fig. 14). Maximum conductivities in peak D1, between stations 113 and 124, reached 197 mS/m (horizontal dipole) and –38 mS/m (vertical dipole). The highest conductivities in the Dunes area, to 245 mS/m (horizontal dipole) and –73 mS/m (vertical dipole), were recorded for peak D2 (stations 163 to 176). Peak D3, located just downstream from peak D2 (stations 182 to 190), was characterized by lower maximum conductivities of 226 mS/m (horizontal dipole) and –11 mS/m (vertical dipole). Similar maximum conductivities of 220 mS/m (horizontal dipole) and –18 mS/m (vertical dipole) were recorded for peak D4 (stations 202 and 209).

Rana Canyon area, Canadian River

The lateral conductivity survey of the Canadian River valley near Rana Canyon consisted of horizontal and vertical dipole conductivity measurements at 50 sites beginning about 600 m upstream from Rana Canyon and ending about 400 m downstream from the canyon (figs. 2 and 9). Conductivities were relatively low in this area (fig. 15 and app. I), ranging from 32 to 121 mS/m (horizontal dipole) and from 24 to 77 mS/m (vertical dipole). Although the variations were small, conductivities decreased downstream. No significant conductivity peaks were detected.

Rana Arroyo

Vertical and horizontal dipole conductivities were measured at 17 sites along the lower 340 m of Rana Arroyo (fig. 9). Rana Arroyo conductivities increased downstream but were generally lower along the arroyo than along the Canadian River near Rana Canyon (fig. 16 and app. I). Conductivities increased from 29 to 103 mS/m (horizontal dipole) and from 35 to

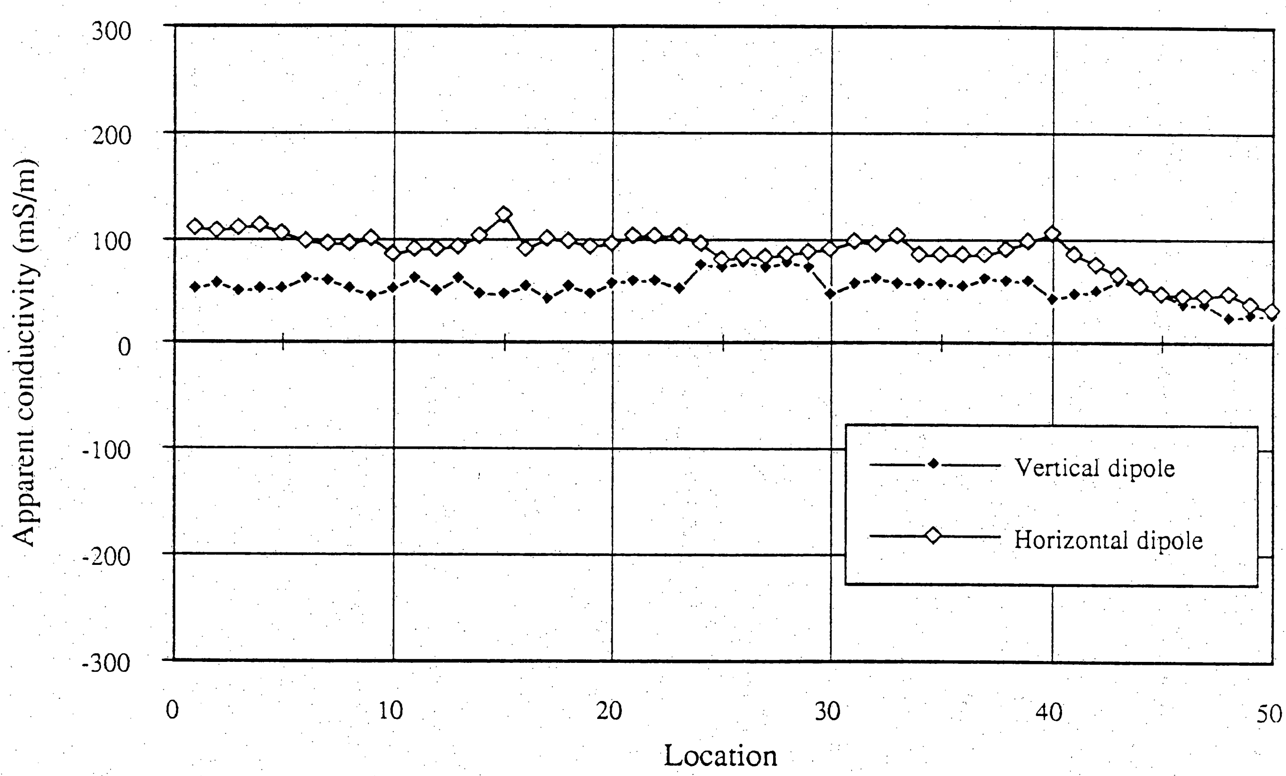

Figure 15. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Rana Canyon area (fig. 9). Locations are 20 m apart.

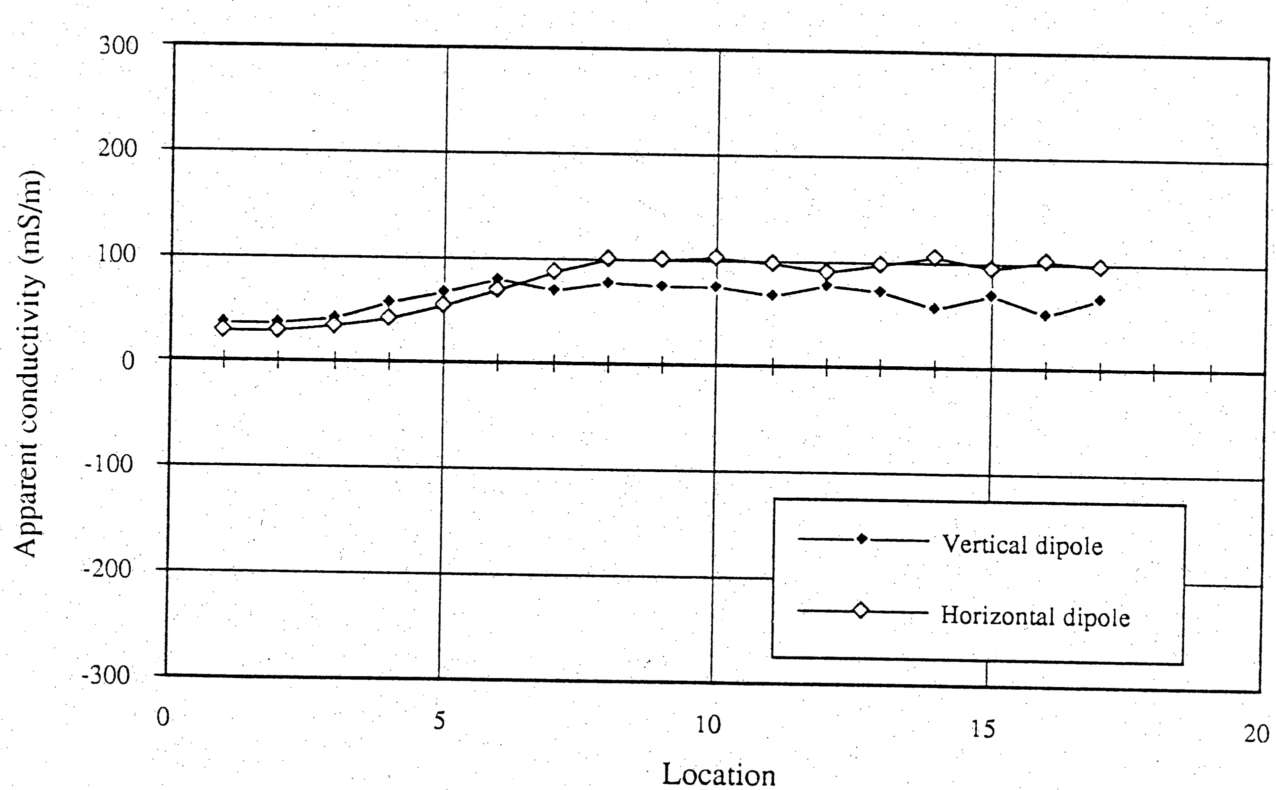

Figure 16. Apparent conductivity (in milliSiemens/m) along Rana Arroyo (fig. 9). Locations are 20 m apart.

77 mS/m (vertical dipole) from the upstream end of the survey to its confluence with the Canadian River. No significant conductivity peaks were detected along the arroyo.

Multiple-Coil Spacing Soundings

Changes in ground conductivity with depth can be determined by either repeated surveys over the same point using different transmitter and receiver coil separations (greater penetration depth with longer coil separations and lower instrument frequency) or by analyzing the decay of a transient electromagnetic field. Three sites along the Canadian River between Ute Reservoir and Revuelto Creek (fig. 5) and one site in the Jones well area (fig. 7) were surveyed using multiple coil separations.

Site M140, Ute Reservoir to Revuelto Creek

Site M140 is located between Ute Dam and the Highway 54 bridge (fig. 5) and is within peak A2. Vertical and horizontal conductivities were measured at this site between stations 136 and 144 (fig. 17 and app. II). Conductivities for 10- and 40-m coil separations were collected at 10-m station spacings; conductivities at the 20-m coil spacing were collected at 20-m station intervals.

Conductivities measured in the vertical dipole orientation ranged from –48 mS/m to 41 mS/m along the section (fig. 17) and had the greatest variation at a coil separation of 10 m. Negative values again indicate that near-surface conductivities were high enough to cause a nonlinear instrument response for this coil orientation. Horizontal dipole conductivities were more consistent across the site. Measured conductivities increased from 151 to 187 mS/m for the 10 m coil separation to generally more than 200 mS/m for the longer separations.

Horizontal conductivity data collected near station M140 were used to construct a vertical conductivity model because nearby conductivity values were known and rapid lateral conductivity changes were not observed nearby. A three-layer model (table 3 and fig. 18) that

Table 3. Best-fit conductivity models for EM34-3 soundings along the Canadian River between Ute Reservoir and Revuelto Creek and in the Jones well area. Sounding locations on figures 5 and 7.

Canadian River, Ute Reservoir to Revuelto Creek

Sounding	Location	Layer	Conductivity (mS/m)	Thickness (m)	Depth to top (m)
M140	Station 140 (fig. 5)	1	5.0	1.6	0.0
(figs. 17, 18)		2	577.0	10.7	1.6
		3	149.9		12.3
M263	Station 263 (fig. 5)	1	5.0	1.8	0.0
(figs. 19, 20)		2	703.2	9.2	1.8
		3	854.8		11.0
M412	Station 412 (fig. 5)	1	5.0	1.1	0.0
(figs. 21, 22)		2	869.5	5.6	1.1
		3	1869.7		6.7

Canadian River, Jones Well Area

Sounding	Location	Layer	Conductivity (mS/m)	Thickness (m)	Depth to top (m)
M25	Station 25 (fig. 7)	1	21.9	0.8	0.0
(figs. 23, 24)		2	67.4	8.0	0.8
		3	19.1	10.0	8.8
		4	106.0		18.8

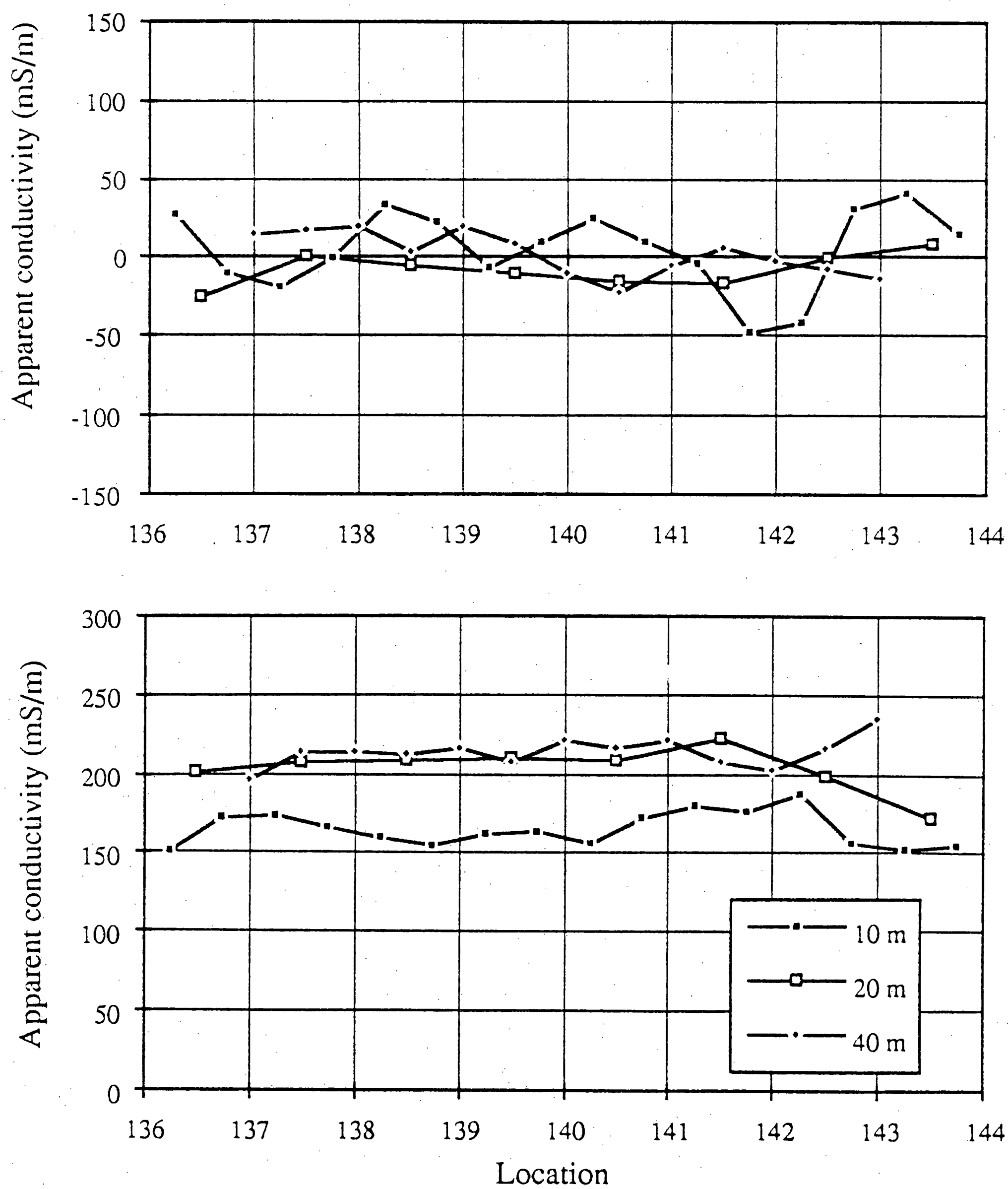

Figure 17. Apparent conductivity at 10-, 20-, and 40-m coil separations between locations 136 and 144 (site M140), Ute Reservoir to Revuelto Creek. Vertical dipole coil orientation is shown on upper panel, and horizontal dipole orientation is shown on lower panel. Numbered locations are 20 m apart.

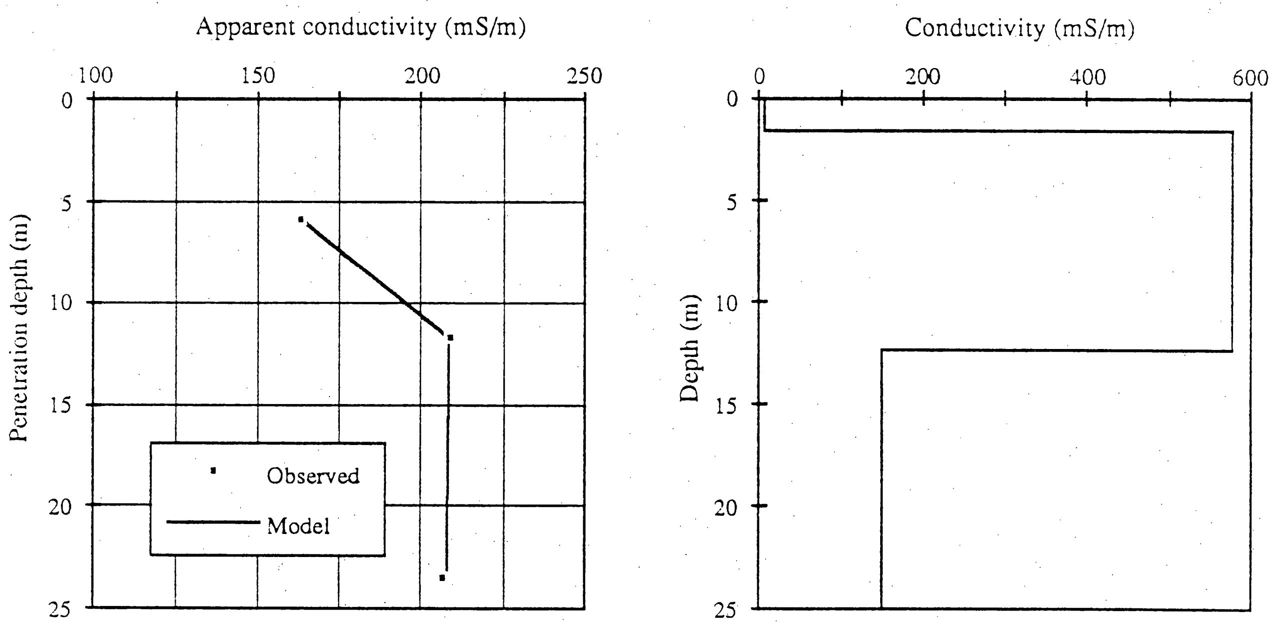

Figure 18. Left: Apparent conductivity versus penetration depth for multiple coil spacings (horizontal dipole orientation) at Ute to Revuelto site M140 (fig. 5). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed data at left.

provided the best fit to the observed data consisted of a surface low-conductivity (5 mS/m) layer 1.6 m thick, a layer of higher conductivity (577 mS/m) layer 10.7 m thick, and a third layer of intermediate conductivity (150 mS/m) that begins 12.3 m below the surface and extends at least to the maximum penetration depth of 25 m.

One possible interpretation of the best-fit vertical conductivity profile at station M140 is that the thin, low-conductivity layer at the surface represents either relatively dry, nonconductive alluvium or alluvium saturated with relatively fresh water. The underlying high-conductivity layer represents alluvium saturated with saline water; this layer is underlain at a depth of about 12 m by a moderate-conductivity layer that represents bedrock that is partly saturated by highly saline ground water.

Site M263, Ute Reservoir to Revuelto Creek

Vertical conductivity site M263 is located at conductivity peak B2 between the Highway 54 bridge and the railway bridge (fig. 5). At this site, horizontal and vertical dipole conductivity measurements were made between stations 261 and 265 using 10-, 20-, and 40-m coil separations and 10-m station intervals (fig. 19 and app. II). Vertical dipole conductivities at all three coil spacings were mostly negative, ranging from 12 mS/m to –108 mS/m. Higher negative apparent conductivities for the 20- and 40-m coil spacings than for the 10-m spacing suggests that, for this nonlinear range of instrument response, conductivity increases downward. Conductivities measured in the horizontal dipole orientation increased with coil spacing, from a maximum of 168 mS/m at 10-m spacing to a maximum of 262 mS/m at 40-m spacing (fig. 19). Because effective penetration depth increases with coil separation, horizontal dipole data also indicate that conductivity increases with depth.

Horizontal dipole conductivities were used to produce a vertical conductivity profile for station 263 (table 3 and fig. 20). The three-layer model that fits the observed conductivities best consists of a thin (1.8 m), low-conductivity (5 mS/m) surface layer that overlies a high-

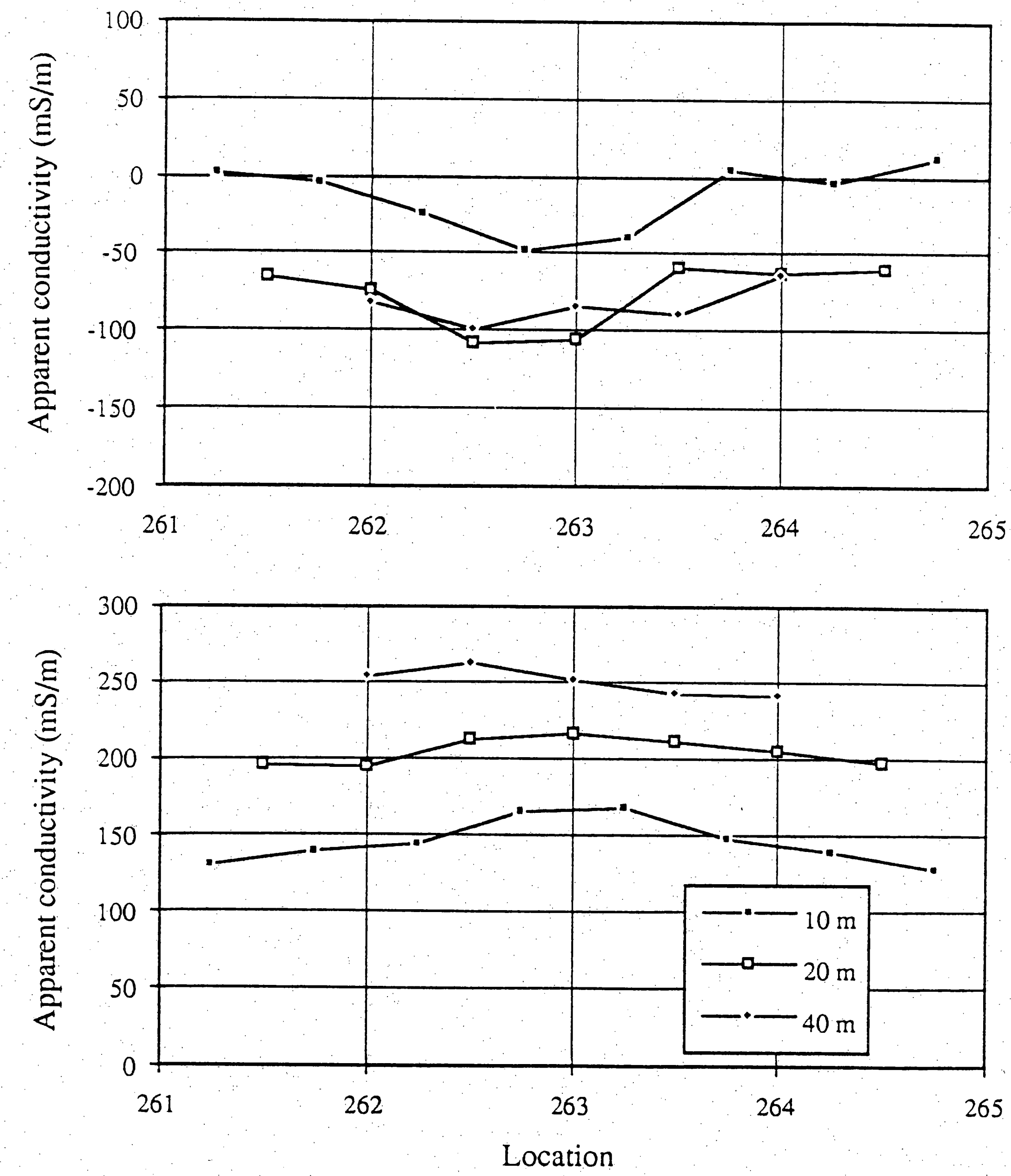

Figure 19. Apparent conductivity at 10-, 20-, and 40-m coil separations between locations 261 and 265 (site M263), Ute Reservoir to Revuelto Creek. Vertical dipole coil orientation is shown on upper panel, and horizontal dipole orientation is shown on lower panel. Numbered locations are 20 m apart.

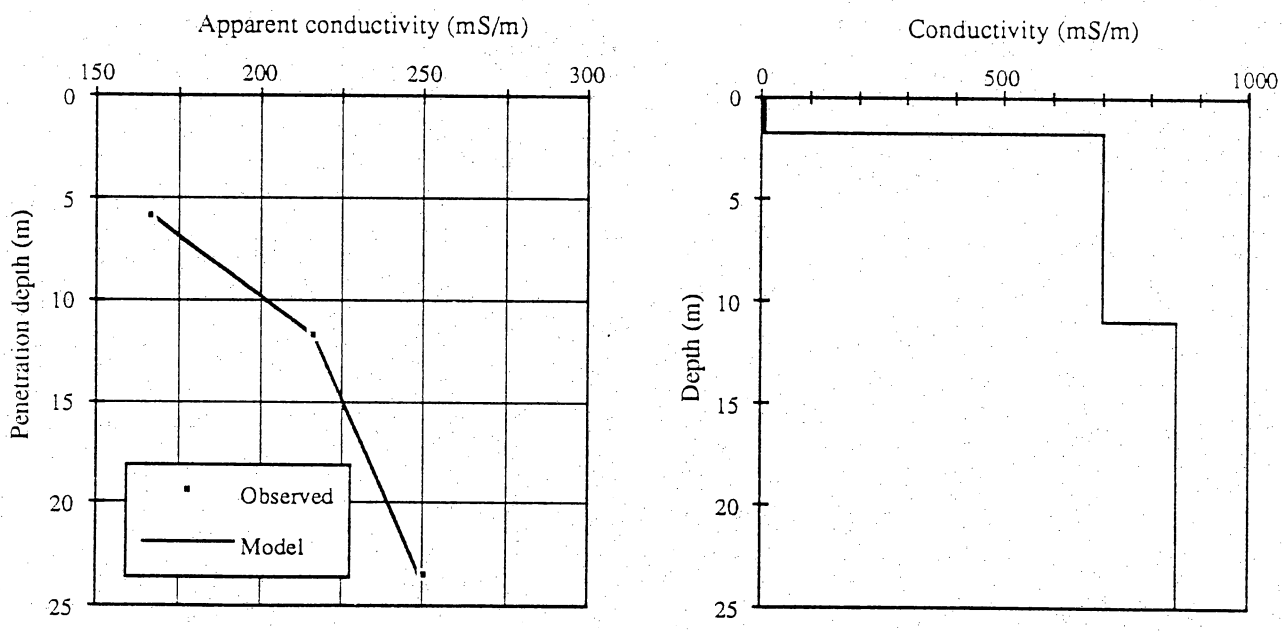

Figure 20. Left: Apparent conductivity versus penetration depth for multiple coil spacings (horizontal dipole orientation) at Ute to Revuelto site M263 (fig. 5). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed data at left.

conductivity (703 mS/m) layer that is 9.2 m thick. The deepest layer detected, a high conductivity (855 mS/m) layer that begins 11 m below the surface, extends to at least the maximum penetration depth of about 25 m.

This profile may have a thin surface layer of alluvium that is either dry or saturated with relatively fresh water, underlain by alluvium that is saturated with highly conductive, saline water. Continued increases in conductivity with depth suggest that
(1) bedrock is deeper than the maximum penetration depth at this site (about 25 m), (2) the salinity of ground water in the bedrock is much higher than that in the overlying alluvium, or (3) bedrock at this site is as saturated with saline ground water as the overlying alluvium. The most likely situation is that bedrock is deeper than the depth of signal penetration.

Site M412, Ute Reservoir to Revuelto Creek

The vertical conductivity survey at site M412, located between the railway bridge and Revuelto Creek (fig. 5), consisted of horizontal and vertical dipole conductivity measurements at 10-, 20-, and 40-m coil separations between stations 410 and 414 (app. II). This site is located at conductivity peak B7, where the highest conductivities were measured during the lateral conductivity survey.

Vertical dipole apparent conductivities were all negative across the site (fig. 21). Values ranged from –107 to –213 mS/m but were most negative for the 20-m coil spacing. These conductivities, recorded in the nonlinear range of instrument response, show a conductivity peak at station 412 that coincides with the peak detected during the lateral conductivity survey. Horizontal dipole apparent conductivities increase with coil separation from a maximum of 217 mS/m at 10-m spacing to a maximum of 292 mS/m at 40-m spacing. Horizontal dipole values also show a peak near station 412, but the peak is not as well defined as in the vertical dipole measurements. The trend of increasing conductivity with greater coil separation suggests that ground conductivities increase with depth.

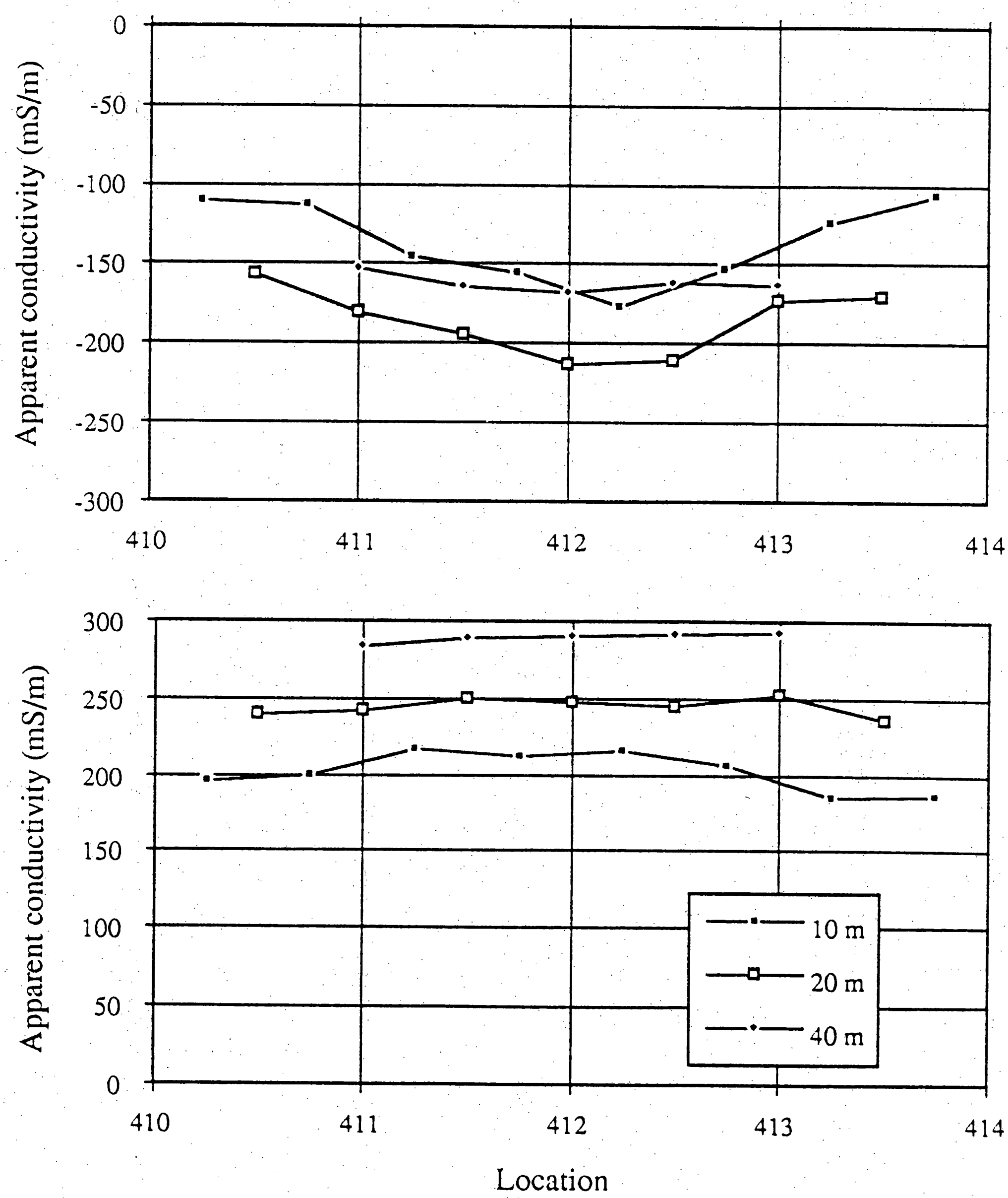

Figure 21. Apparent conductivity at 10-, 20-, and 40-m coil separations between locations 410 and 414 (site M412), Ute Reservoir to Revuelto Creek. Vertical dipole data are shown on upper panel, and horizontal dipole data are shown on lower panel. Numbered locations are 20 m apart.

Horizontal dipole conductivities at station 412 were used to construct a model vertical conductivity profile (table 3 and fig. 22). The three-layer model that best fits the data consists of a thin, low-conductivity surface layer (1.1 m at 5 mS/m) overlying two highly conductive layers. Conductivity of the lower layers increases downward from 870 mS/m in layer 2 (5.6 m thick) to 1870 mS/m in the basal layer. The basal layer begins at a depth of 7.7 m and continues at least to the maximum effective penetration depth of about 25 m.

Interpretations of the conductivity model are similar to those at site M263, with a thin surface layer of dry alluvium or alluvium saturated with relatively fresh water. Underlying layers probably represent alluvium saturated with highly conductive saline water. Bedrock is probably deeper than 25 m at this site, although the interpretation that there may be shallower bedrock saturated by water with salinities as high or higher than that in alluvium cannot be rejected.

Site M25, Jones Well Area

Vertical conductivity survey M25 was located between stations 23 and 27 along the Canadian River in the Jones well area (fig. 7). This survey, which consisted of vertical and horizontal dipole conductivity measurements at 10-, 20-, and 40-m coil separations, was completed near the center of a surface collapse feature that is bisected by the Canadian River. A lateral conductivity survey of the Jones well area showed the collapse feature to be an area of low ground conductivity.

Vertical and horizontal dipole conductivities across the site are low and decrease downstream (fig. 23 and app. II). Ground conductivities are low enough that measured vertical dipole conductivities, which are all less than 50 mS/m, are similar to horizontal dipole conductivities. Vertical dipole values are slightly higher for the 40-m coil spacing than for the 10- or 20-m coil spacings, suggesting that conductivity is higher at depth than at the surface. Horizontal dipole values are in the narrow range of 36 to 56 mS/m for all three coil separations.

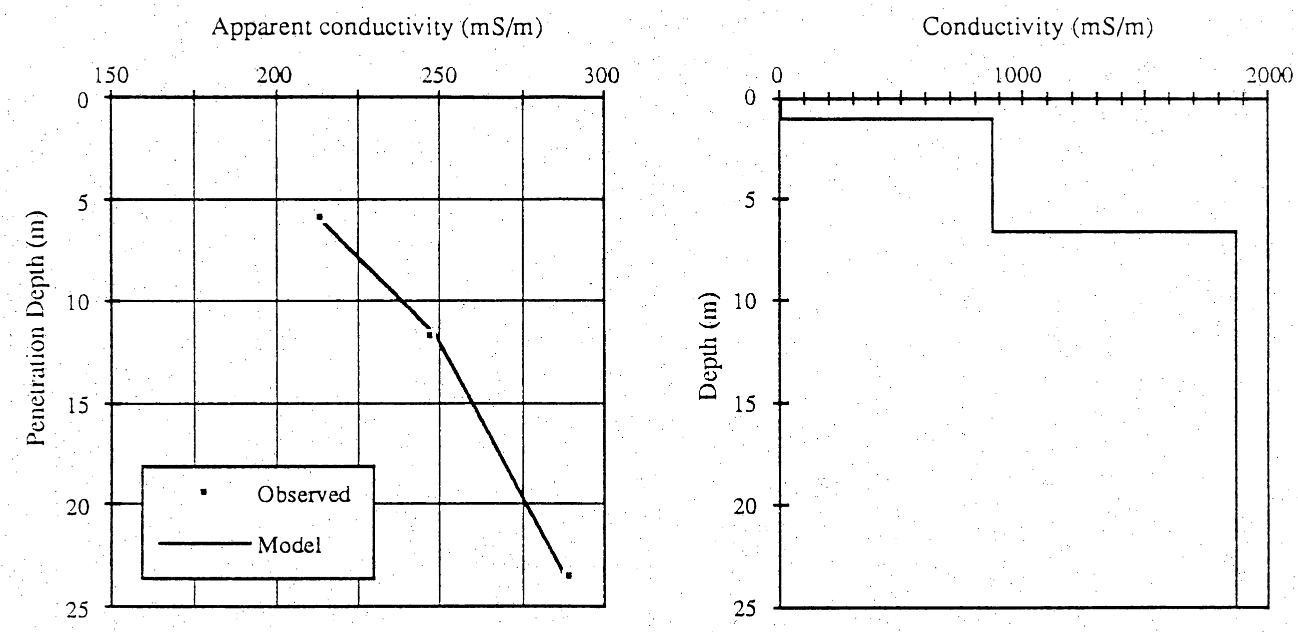

Figure 22. Left: Apparent conductivity versus penetration depth for multiple coil spacings (horizontal dipole orientation) at Ute to Revuelto site M412 (fig. 5). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed data at left.

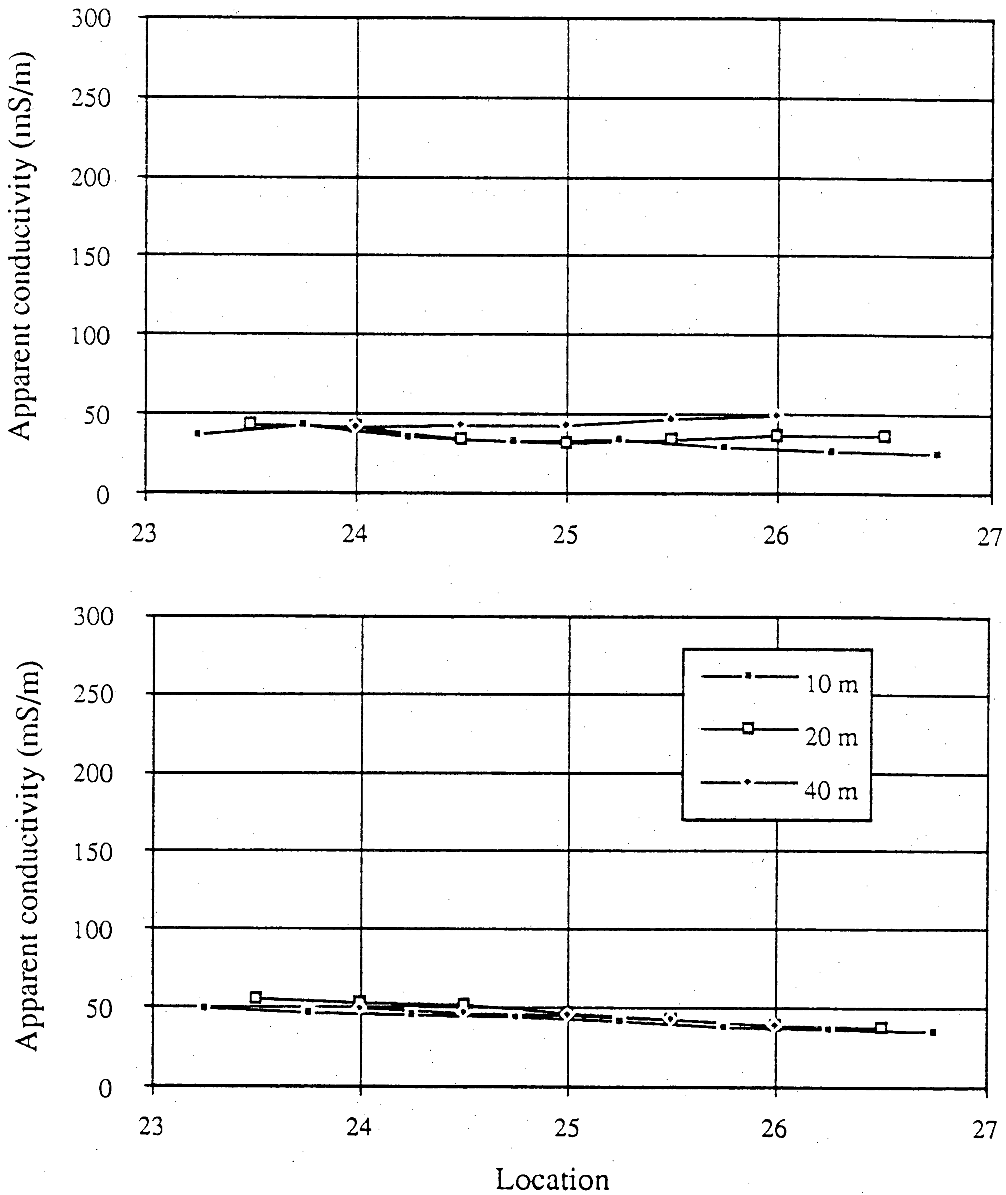

Figure 23. Apparent conductivity at 10-, 20-, and 40-m coil separations between locations 23 and 27 (site M25), Jones Well area. Vertical dipole data are shown on upper panel, and horizontal dipole data are shown on lower panel. Numbered locations are 20 m apart.

Vertical and horizontal conductivities recorded at station 25 were used to construct a model vertical conductivity profile beneath the station. Relationships between conductivity measurements and penetration depths support results of a model with at least four layers (table 3 and fig. 24). The four-layer model that fits the observed conductivities best includes a thin (0.8 m), low-conductivity (22 mS/m) layer at the surface, a second layer 7.9 m thick with somewhat higher conductivity (67 mS/m), a third layer 10.0 m thick with low conductivity (19 mS/m), and a modestly conductive (106 mS/m) basal layer from 18.8 m depth to the maximum penetration depth of at least 50 m. Compared to other model conductivity profiles, the profile at M25 has a small total conductivity range and is relatively nonconductive.

As at other sites, the low-conductivity surface layer probably represents alluvium that is either relatively dry or saturated with relatively fresh water. Beneath the surface layer is alluvium that is saturated with higher salinity water, although salinities are much lower than those encountered at the other vertical conductivity profile sites. The decrease in conductivity between layer 2 and layer 3 at 8.7-m depth is difficult to interpret but may represent (1) the top of bedrock or (2) the base of a salinity gradient supported by surface evaporation. If the conductivity reversal is caused by a salinity gradient, the increase in conductivity between layer 3 and the basal layer at 18.8-m depth may represent the bedrock contact. Conductivities inferred for the basal layer are similar to inferred bedrock conductivities (150 mS/m) at site M140 between Ute Reservoir and Revuelto Creek.

Time-Domain Soundings

Thirteen soundings to a maximum penetration depth of about 100 m were obtained using the time-domain electromagnetic sounding technique. Two soundings were located on the upland near Ute Reservoir (fig. 5), four were located along the Canadian River between Ute Reservoir and Revuelto Creek (fig. 5), one was located along Revuelto Creek near its confluence with the Canadian River (fig. 5), and six were located along the Canadian River in the Dunes area (fig. 8).

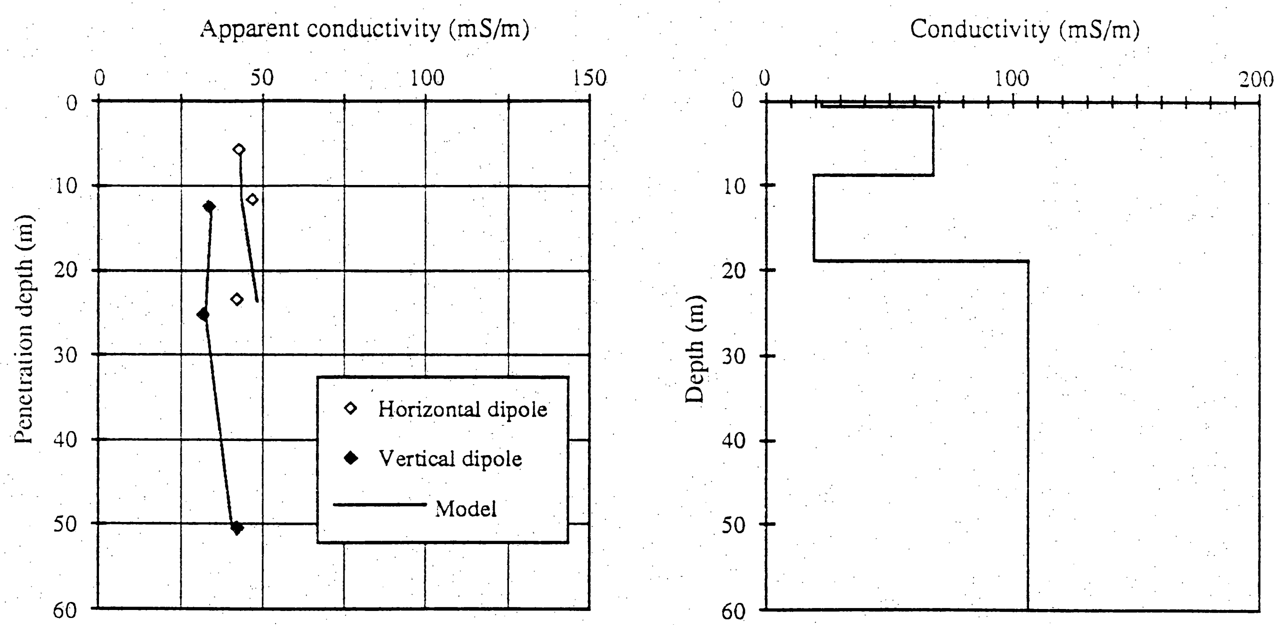

Figure 24. Left: Apparent conductivity versus penetration depth for multiple coil spacings (both dipole orientations) at Jones Well site M25 (fig. 7). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed data at left.

Whereas results of multiple coil-spacing soundings are given in conductivity units (mS/m), results of the time-domain method are customarily given in resistivity units (ohm-m). These units are the inverse of each other, such that the following equation holds:

Conductivity (in mS/m/meter) = 1/Resistivity (in ohm-m).

To convert from the resistivity units used in this section (ohm-m) to the conductivity units used elsewhere in this report (mS/m), take the inverse of the resistivity value and multiply it by 1,000.

Upland near Ute Reservoir

The two Protem soundings obtained on the upland surface were located 1.5 km west of Logan on the north side of the Canadian River valley (site PN, fig. 5) and 3 km south of Logan on the south side of the valley (site PS, fig. 5). These soundings show a pattern of decreasing apparent resistivities with time (pls. 1 and 2), indicating that, in general, resistivity decreases with depth. Best-fit resistivity profiles at both of these sites indicate the existence of a thin, highly resistive layer at the surface which is underlain by a thin, conductive layer below (pls. 1 and 2 and table 4). Below the thin conductive layer is a relatively thick resistive layer, which is in turn underlain by a conductive layer to the maximum depth penetrated by the instrument. Resistivity profiles that fits give nearly as good a as the best-fit models (shown as dashed lines on the resistivity profiles, pls. 1 and 2) show the same general profile but differ slightly in thickness and resistivity values for individual layers.

The thin, highly resistive surface layers have about the same thickness and resistivity at both sites (table 4). At the northern site, the underlying conductive layer is thicker and less conductive and the thick resistive layer beneath it is thicker and more resistive. Consequently,

Table 4. Best-fit resistivity models for Protem 47/S soundings along the Canadian River between Ute Reservoir and Revuelto Creek and in the Dunes area. Sounding locations on figures 5 and 8. Complete sounding data in appendix D.

Upland Areas

Sounding	Location	Fitting Error (%)	Layer	Resistivity (ohm-m)	Thickness (m)	Depth to top (m)
PN (plate 1)	1.5 km west of Logan, N.M.	13.6	1	4220.4	3.1	0.0
	(fig. 5)		2	2591.7	4.6	3.1
			3	9.4	11.4	7.7
			4	2454.7	65.2	19.1
			5	6.6		84.2
PS (plate 2)	3 km south of Logan, N.M.	12.0	1	6030.8	5.9	0.0
	(fig. 5)		2	3.0	3.4	5.9
			3	124.2	34.5	9.3
			4	4.3		43.8

Canadian River, Ute Reservoir to Revuelto Creek

Sounding	Location	Fitting Error (%)	Layer	Resistivity (ohm-m)	Thickness (m)	Depth to top (m)
P331 (plate 3)	Near station 331 (fig. 5)	20.1	1	89.4	1.1	0.0
			2	0.9	6.7	1.1
			3	0.4	7.0	7.8
			4	15.0	14.0	14.8
			5	1.0		28.8
P388 (plate 4)	Near station 388 (fig. 5)	14.8	1	87.3	1.5	0.0
			2	1.1	4.8	1.5
			3	0.4	8.5	6.3
			4	10.0	13.8	14.8
			5	0.8		28.6
P421 (plate 5)	Near station 421 (fig. 5)	14.2	1	337.1	0.6	0.0
			2	0.9	2.6	0.6
			3	48.9	2.9	3.2
			4	0.7	8.0	6.2
			5	8.6		14.2
P500 (plate 6)	Near station 500 (fig. 5)	14.2	1	512.4	0.9	0.0
			2	1.4	3.8	0.9
			3	48.8	2.9	4.7
			4	1.0	7.1	7.6
			5	4.1		14.6

Revuelto Creek

to Sounding	Location	Fitting Error (%)	Layer	Resistivity (ohm-m)	Thickness (m)	Depth top (m)
P8 (plate 7)	Near station 8 (fig. 5)	6.4	1	809.1	1.4	0.0
			2	3.6	5.3	1.4
			3	1.5	14.5	6.7
			4	98.7	18.8	21.2
			5	0.7		40.0

Table 4 (cont.)

Canadian River, Dunes Area

Sounding	Location	Fitting Error (%)	Layer	Resistivity (ohm-m)	Thickness (m)	Depth to top (m)
P2 (plate 8)	Near station 2 (fig. 8)	15.0	1	16.1	2.1	0.0
			2	1.5	2.7	2.1
			3	216.2	16.6	4.8
			4	1.0	1.9	21.4
			5	4012.9	51.8	23.3
			6	4.2		75.0
P53 (plate 9)	Near station 53 (fig. 8)	13.5	1	100.0	4.0	0.0
			2	3.1	1.3	4.0
			3	1918.6	29.6	5.4
			4	17.7		34.9
P102 (plate 10)	Near station 102 (fig. 8)	15.4	1	499.8	1.0	0.0
			2	49.8	2.9	1.0
			3	3.9	25.0	3.9
			4	8.6		28.8
P122 (plate 11)	Near station 122 (fig. 8)	21.9	1	45.0	1.2	0.0
			2	1.9	10.9	1.2
			3	0.8	6.6	12.2
			4	0.9		18.8
P164 (plate 12)	Near station 164 (fig. 8)	12.2	1	1.4	5.6	0.0
			2	1.2	3.6	5.6
			3	0.5	2.9	9.2
			4	2.9		12.1
P230 (plate 13)	Near station 230 (fig. 8)	49.6	1	1096.9	3.3	0.0
			2	2.0	14.3	3.3
			3	248.8	6.2	17.5
			4	0.2		23.7

the basal conductive layer is deeper at the northern site (84 m than at the southern site (44 m).

Without the benefit of nearby boreholes, it is difficult to interpret the physical meaning of these resistivity profiles. Nevertheless, a likely interpretation is that the highly resistive surface layers represent unsaturated surface deposits and that the basal conductive layer represents the top of the postulated "brine aquifer." The thick resistive layer above that may represent a fractured aquitard or a zone of rock saturated with fresher water. Lower resistivities in the resistive unit at site PS suggest greater infiltration of saline water south of the river valley. The thin conductive unit near the surface at both sites could represent pooled saline water above the fractured aquitard or a conductive shale unit below the soil zone.

Ute Reservoir to Revuelto Creek

Four sounding sites were located in the Canadian River valley between Ute Reservoir and Revuelto Creek. Three of these sites (P331, P388, and P421, fig. 5) are within high-conductivity zone B (fig. 10) and the fourth (P500) is in high-conductivity zone C. Sounding P331 was taken near conductivity peak B4, sounding P388 was taken between peaks B6 and B7, sounding P421 was taken near peak B7, and sounding P500 was taken near peak C1.

In general, the resistivity profiles at these sites (pls. 3, 4, 5, and 6) are more conductive than those at sites on the upland, along Revuelto Creek, and in the Dunes area. They each contain a thin resistive surface layer that overlies a conductive layer that is 3 to 14 m thick (table 4). The conductive layer overlies a somewhat resistive layer, which is above a basal conductive layer that extends to the maximum penetration depth of the instrument. Compared to upland sites, the surface resistive layer is thinner and much less resistive at the floor of the valley; in addition, the basal conductive layer is shallower and more conductive at the valley floor.

Resistivity profiles for soundings P331 at conductivity peak B4 and P388 between peaks B6 and B7 are similar. They show a resistive layer to a depth of about 1 m, highly conductive layers to depths of 15 m, a more resistive layer to about 29 m, and a highly conductive basal layer. Soundings P421 and P500 are also similar, but have higher surface layer resistivities, more resistive intermediate layers at depths of 3 to 8 m, and shallower depths to the basal conductive layer (14 m) than at sites P331 and P388.

Aside from the obvious interpretation that the alluvium along the Ute Reservoir to Revuelto Creek segment of the Canadian River is extremely conductive, tentative interpretations of the profiles are that (1) the near-surface resistive layer represents unsaturated alluvium, (2) the underlying conductive layer is brine-saturated alluvium, and (3) the slight increase in resistivity at about 15 m depth at each of the four sites probably represents the contact between saturated alluvium and saturated bedrock.

Revuelto Creek

One time-domain sounding (P8, fig. 5) was located along Revuelto Creek near its confluence with the Canadian River. At this site, a thin resistive surface layer overlies about 20 m of conductive material (table 4 and pl. 7). Resistivity increases between depths of 21 and 40 m; a highly conductive layer extends from 40 m to the maximum depth investigated by the instrument.

As at other sites within the valley, the thin resistive layer at the surface probably represents the unsaturated zone. This is underlain by conductive, brine-saturated alluvium to a depth of about 21 m, which probably represents the contact between alluvium and bedrock.

Dunes Area

Time-domain soundings are located at sites P2, P53, P102, P122, P164, and P230 (pls. 8 through 13) in the Dunes area of the Canadian River valley (fig. 8). P2 is in a moderately conductive area at the upstream end of the river stretch (fig. 14), P53 is located in a low conductivity area near a fresh-water spring, P102 is near the upstream edge of high-conductivity zone D, P122 and P164 are located within zone D at individual peaks D1 and D2, and P230 is at the downstream end of zone D.

Resistivity profiles calculated for each of these sites from apparent resistivity data show considerable variability across the area (table 4). Profiles P122 (pl. 11) and P164 (pl. 12), located at conductivity peaks D1 and D2, have the lowest resistivity layers. The profile at P164 is the least resistive; modeled resistivities range from 0.5 to 2.9 ohm-m at this site. This site also had the highest conductivities measured for the Dunes area in the lateral conductivity survey (fig. 14). The profile at site P122 has only slightly higher resistivities.

The most resistive profiles are found at sites P2 (pl. 8) and P53 (pl. 9) at the upstream end of the Dunes area. These profiles have relatively thin conductive layers between thick resistive layers. A thick resistive layer extends from 23 to 75 m depth at site P2 and from 5 to 35 m at site P53. At each of these sites, the thick resistive layers are underlain by conductive layers to the maximum depth penetrated.

Soundings P102 (pl. 10) and P230 (pl. 13), located at the edges of high-conductivity zone D, both have thin resistive surface layers underlain by more conductive layers. Thick conductive layers extend below 4 m depth at P102 and below 3 m at P230; a 6-m-thick resistive layer contained in the model for P230 must be considered suspect because of the poor fit between the model profile and the observed data (pl. 13).

In the Dunes area, profiles with the lowest resistivities were found at points where the lateral conductivity surveys showed conductivity peaks. These profiles are consistent with an interpretation of alluvium and underlying bedrock saturated with saline ground water to the deepest level penetrated by the instrument. A slight increase in resistivity in sounding P164 at 12 m depth may represent the bedrock-alluvium contact and a concomitant decrease in porosity. More resistive soundings at the upstream end of the Dunes area indicate the presence of less saline alluvial ground water that may be related to nearby fresh water inflow. The top of the basal low-resistivity zone is deepest in this part of the Dunes area.

Joint Analysis

Triassic Dockum Group strata are well exposed along the canyon of the Canadian River in eastern New Mexico. Outcrops consist primarily of channel-filling pebble conglomerate and pebbly coarse sandstones, laterally extensive tabular beds of laminated fluvial sandstone, and overbank mudstones. Channel-filling sandstones and conglomerates are common, but are not distributed in any obvious pattern. No information is available about the distribution of channel sandstones in the subsurface. All of these rocks are jointed.

Joints are fractures in rocks that occur without displacement and result from postdepositional stresses such as folding, removal of overburden, or subsidence. The joint surface is typically planar and commonly lies parallel to other joints to form a joint set. The orientations of more than 500 joints were recorded from exposures of fluvial sandstones of the Triassic Dockum Group that crop out within a few hundred meters of the Canadian River and Revuelto Creek in eastern New Mexico. Joints, which are likely pathways for ground-water flow, were examined for orientation, spatial distribution, joint continuity, and evidence of mineralization. In the study area joints are typically near vertical and are spaced less than a meter apart. Measurements were made at nine sites between Ute Dam and the confluence of the Canadian River and Revuelto Creek, at one site in the Jones well area, and at six sites along the Dunes segment of the Canadian River (figs. 25 through 27).

Most joint systems adjacent to the Canadian River can be divided into two groups: through-going (or primary) joints and crossing (or secondary) joints that terminate against through-going joints. Primary joints may extend for several tens of meters before dying out and may be part of a closely spaced group of en echelon joints. Exposures of Dockum Group channel sandstones in the canyon walls of the Canadian River contain nearly vertical primary

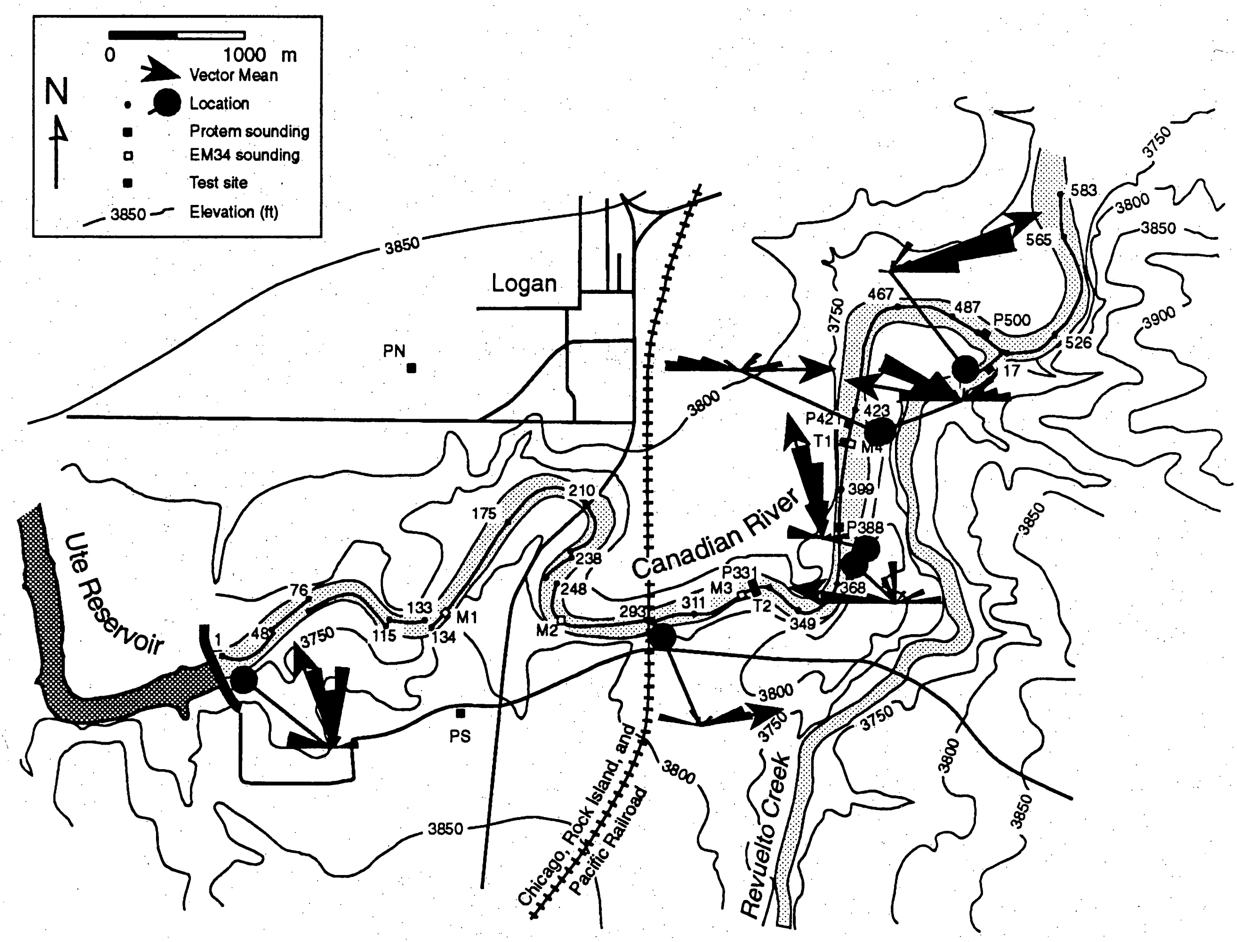

Figure 25. Simplified topographic map of the Canadian River Valley between Ute Reservoir and Revuelto Creek (area A) showing locations of joint measurements plotted as half roses and vector means. See fig. 2 for location.

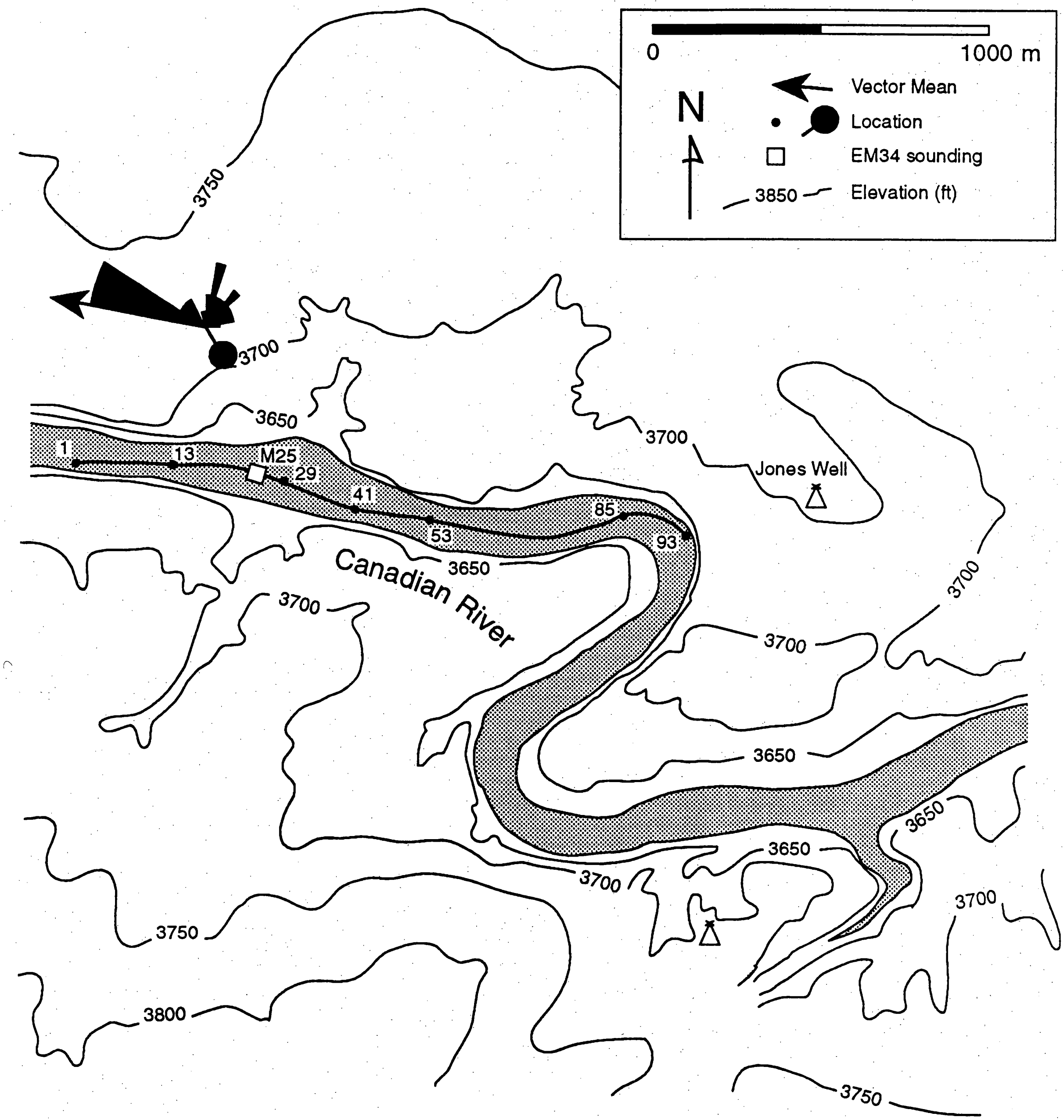

Figure 26. Simplified topographic map of the Jones Well area (area C) along the Canadian River showing joint data plotted as a half rose diagram and its vector mean. See fig. 2 for location.

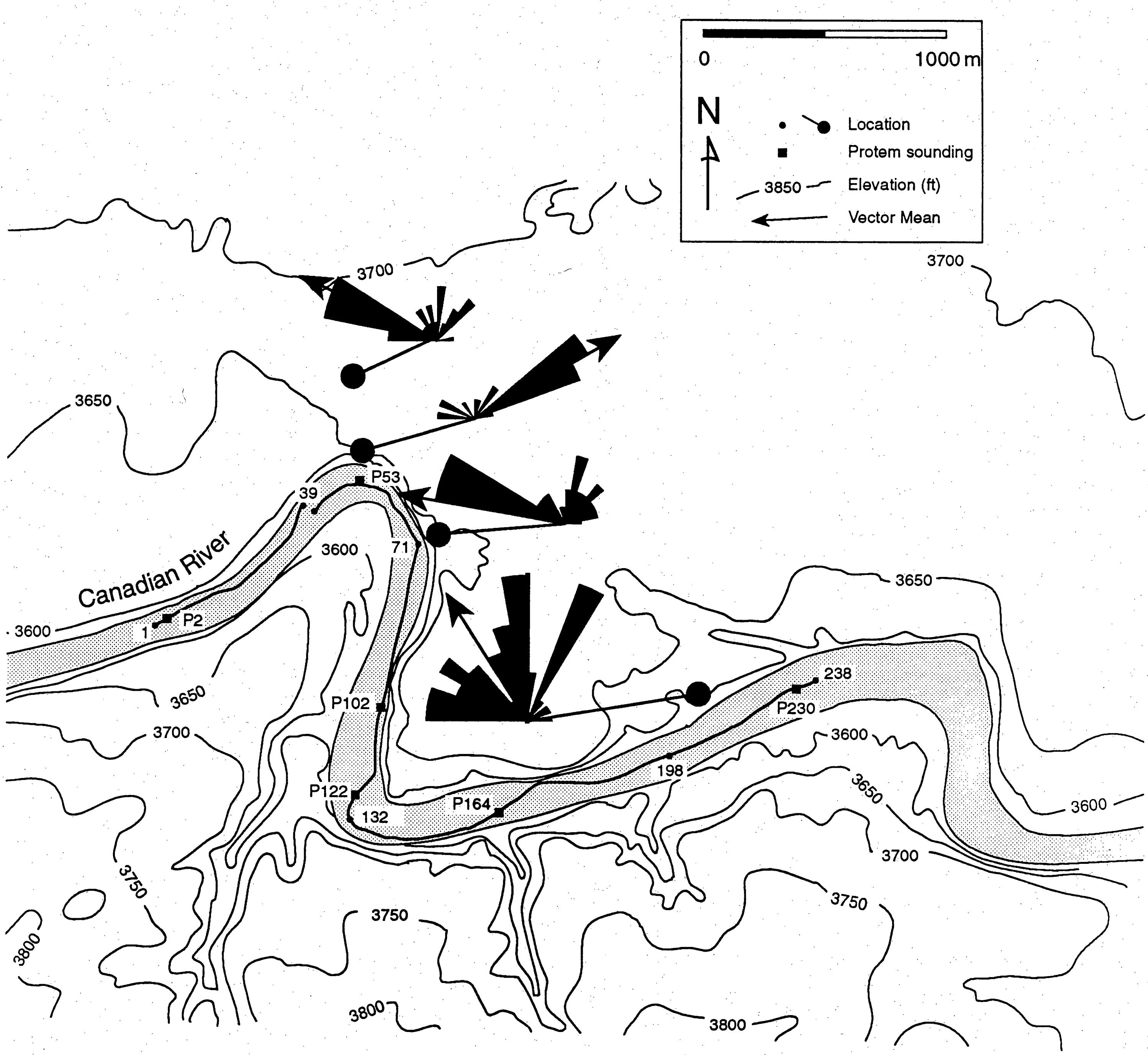

Figure 27. Simplified topographic map of the dunes area along the Canadian River showing joint data plotted as half roses and vector means. See fig. 2 for location.

joint faces that are more than 35 m long and 12 m high. Secondary joints, which terminate at through-going joints, are typically only several decimeters to a meter long, although they may extend several meters vertically.

Joint Orientations

Several sets of joints were recognized in the Canadian River canyon; the vector mean for all measured joints is 278°. Primary joints vary in orientation from approximately N50°E to S50°E throughout the study area (figs. 25 through 27). Primary joints are roughly parallel to the northern margin of the Palo Duro Basin and the southern margin of the Bravo Dome in eastern New Mexico. Jointing that was related to the development of these tectonic features may also have been influenced by later subsidence resulting from dissolution of Permian salt beds that underlie the southern half of the Canadian River valley. Tensional stresses resulting from subsidence following salt dissolution may have been responsible for dilation of east-west primary joint sets. The general east-west orientation of primary joints roughly parallels the overall east-northeast trend of the Canadian River canyon near Logan, New Mexico (fig. 25), and the east-southeast trend of the valley near the Dunes area (fig. 27). Secondary joints formed at high angles to primary joints and typically define subsets with varying orientations at each field site.

Joint Dilation

Comparison of primary and secondary joints in plan view on the canyon rims suggests that primary joints are slightly dilated (open). Separation between joint faces is usually less than 1 mm. Locally, primary joints may be open, partly filled by calcite veins, coated with films of manganese and/or iron oxides or hydroxides, or less commonly filled with clastic sediment. Secondary joints, however, show little evidence of dilation or mineralization. Open joints are important high-permeability pathways for ground-water flow.

Calcium carbonate fillings in joints may have precipitated from ground water or surface water. Calcium carbonate is likely to accumulate within the upper 1 or 2 m of joints in arid and semiarid climates for the same reasons that $CaCO_3$ accumulates in calcic soils in dry environments. High evaporation and transpiration rates do not allow water from most recharge events to penetrate more than a few decimeters into surface sediments before it is taken up by plants or drawn back to the surface and evaporated. Under these conditions, $CaCO_3$ is left behind as a joint-filling precipitate. Joint fillings could also have formed in much the same fashion as ground-water calcretes when $CaCO_3$ is precipitated in the unsaturated zone at or slightly above the water table. In both cases the presence of a joint filling indicates that the joint was open prior to mineralization and was capable of transmitting fluids.

The effectiveness of joints as pathways for ground water is also indirectly illustrated by widespread efflorescence of halite and gypsum on rocks exposed near water level along the Canadian River and its tributaries. Where bedrock exposures are in contact with alluvium or river water, patchy efflorescence may be present as much as 5 to 7 m above the river. The efflorescence is typically several decimeters higher along vertical joints. Accelerated weathering and erosion is also common along joints, producing small-scale cavernous weathering.

Joint Distribution

Primary joints (east-west or through-going joints) are more numerous than secondary joints. For example, in thick fluvial sandstones southeast of site 423 in the Ute Reservoir to Revuelto Creek area, 25 joints crossed a 100-ft-long north-south line, but only 9 joints crossed a 100-ft-long east-west line (fig. 28). At most other sites, primary joints also outnumber secondary joints. Joints are also not evenly distributed vertically or horizontally. The vertical distribution of joints is strongly affected by variations in bed thickness in Dockum Group sediments. Thick sandstone bodies are relatively strong and hence contain fewer or more widely spaced joints than weaker thin sandstone beds. Mudstone beds, which are the weakest lithologic units, contain abundant joints. To record variations in the horizontal distribution of joints, a 100-ft-long tape was laid out approximately normal to the trend of primary joints, and the spacing of joints that crossed the tape was recorded. Typically, several groups of 6 to 10 relatively closely spaced joints were recognized, which were separated by areas of rock with either no joints or a few widely separated joints (figs. 28 through 30).

DISCUSSION AND SUMMARY

The U.S. Bureau of Reclamation (1979, 1985) concluded that it would be possible to reduce the hydraulic head of saline ground water in Dockum Group strata by pumping, thereby preventing natural discharge of saline water to Canadian River alluvium. To successfully carry out a pumping program, areas of significant saline water discharge into Canadian River alluvium must be accurately located. Furthermore, the character and distribution of permeable rocks in the subsurface should be known in order to place wells so that they can efficiently draw down the potentiometric surface. Although the distribution of permeable strata in the subsurface is not known and cannot be inferred from surface exposures, the patterns of permeable pathways such as joints can be inferred from surface data.

Ground Conductivity Surveys

Lateral ground conductivity surveys, consisting of more than 2,200 conductivity measurements along seven segments of the Canadian River and its tributaries (app. I), located four broad high-conductivity zones and 18 individual conductivity peaks that may represent sites of saline ground water inflow into the Canadian River system. Each measurement represents an average conductivity between the surface and a depth of about 12 m (horizontal dipole mode) or 24 m (vertical dipole mode). Surveys were completed in New Mexico along the Canadian River from Ute Reservoir to Revuelto Creek, in the Claer well area, in the Jones well area, in the Dunes area, and near Rana Canyon. Short surveys of tributaries were completed

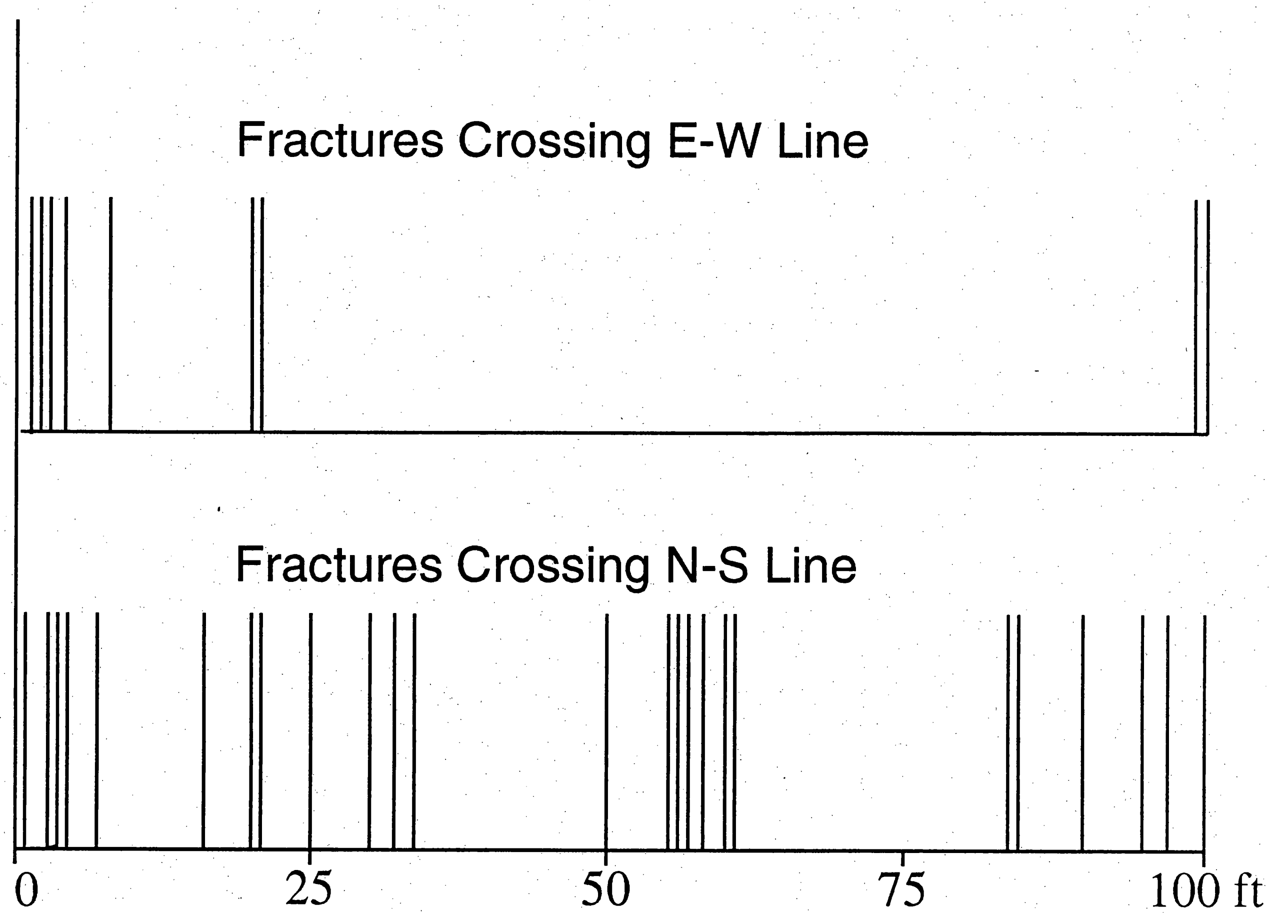

Figure 28. Plot of the number and spacing of joints crossing 33-m- (100-ft) long tapes oriented east-west and north-south, southeast of location 423 on the Canadian River (fig. 25). Note that east-west joints, which cross the north-south line, are more common than north-south joints, and that joints that cross both lines appear to be grouped.

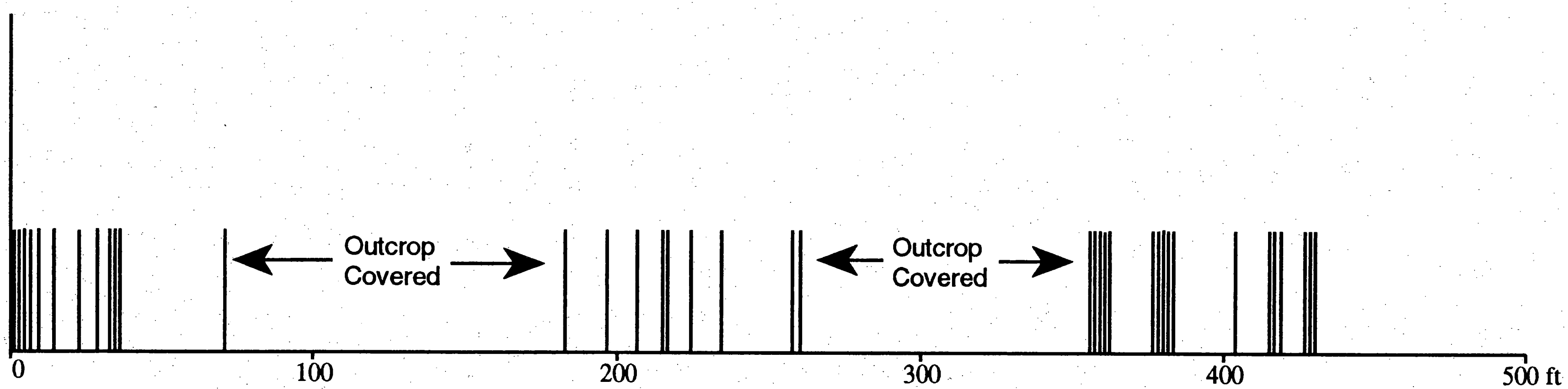

Figure 29. Plot of joint spacing southeast of location 423 on the Canadian River (fig. 25) along a 500–ft north-south exposure. Note that the joints are apparently grouped.

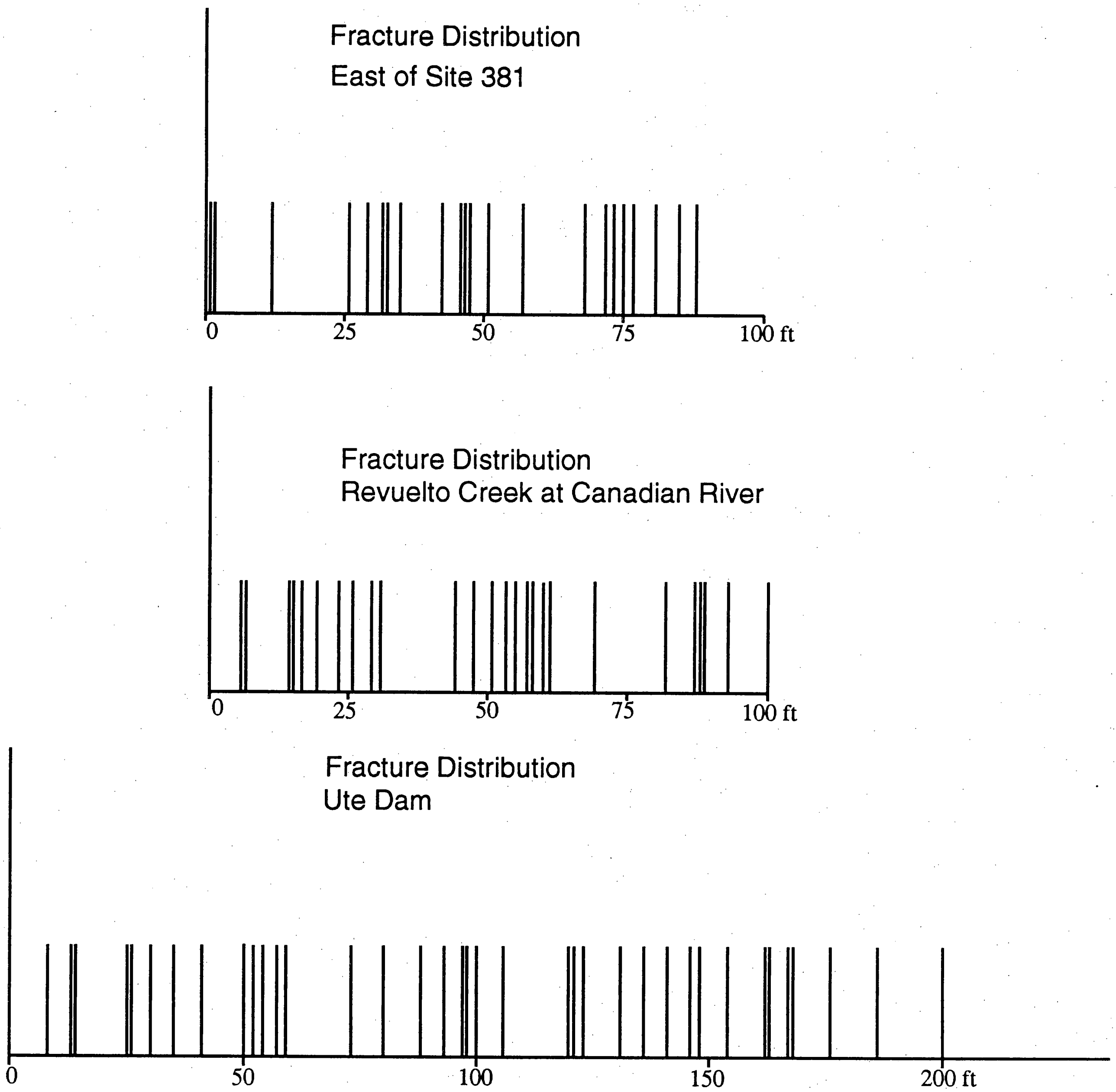

Figure 30. Plots of the spacing of joints intersecting a 33-m- (100-ft-) long tape at a location southeast of P388 on the Canadian River and at the foot of Ute Dam (fig. 25), and a plot of joints intersecting a 66-m- (200-ft-) tape at the intersection of Revuelto Creek and the Canadian River. Note that in each area joints are apparently grouped.

along the downstream ends of Revuelto Creek and Rana Arroyo. Other high-conductivity zones are almost certainly present in unsurveyed areas, particularly farther upstream along Revuelto Creek, in the unsurveyed areas between Revuelto Creek and the Dunes area, and downstream from the Dunes area.

Three broad high-conductivity zones were located along the Canadian River between Ute Reservoir and Revuelto Creek. Zone A, which extends for about 1,600 m between Ute Dam and the Highway 54 bridge (stations 90 to 170, fig. 5), contains two distinct conductivity peaks that are each about 200 m long (fig. 10). Zone B begins between the highway and railway bridges and ends about 4,200 m downstream in the gravel pit reach (stations 233 to 444, fig. 5). The highest conductivities, and thus the highest ground-water salinities measured during this project, were found in zone B. Within this broad zone of high conductivity were eight distinct conductivity peaks (fig. 10). High-conductivity zone C, which begins a few hundred meters upstream from Revuelto Creek and continues beyond the confluence to the farthest downstream point surveyed (stations 476 to 583, fig. 5), is more than 2,000 m long and contains four separate conductivity peaks (fig. 10). It is likely that zone C extends some distance downstream from station 583, the last point surveyed along this segment.

The next surveyed segment of the Canadian River was in the Claer well area (figs. 2 and 6), where a prominent secondary drainages join the main Canadian River canyon. Apparent ground conductivities were high along this segment (fig. 12), but generally not as high as those in the Ute Reservoir to Revuelto Creek segment. No distinct conductivity peaks were identified in this section. Farther downstream in the Jones well area (figs. 2 and 7), a lateral survey was completed across a collapse feature that is bisected by the Canadian River valley. Relatively low conductivities were measured along this segment (fig. 13), particularly across the collapse feature. There were no conductivity peaks in the Jones well area.

The second longest lateral survey segment was in the Dunes area (figs. 2 and 8). Extremely low conductivities were recorded along the river near station 53, where a fresh-water spring was discharging into the river during the survey. Farther downstream, the fourth broad zone of high conductivity (zone D) was encountered (fig. 14). This zone, which extends 2,700 m along the river, begins near station 104 and continues at least as far as station 238, the last point measured. Four distinct conductivity peaks, each between 140 and 260 m long, were identified in zone D.

The farthest downstream segment of the lateral conductivity survey was near Rana Canyon (figs. 2 and 9). Apparent conductivities measured along this segment were relatively low (fig. 15) and no peaks were encountered. Short segments were also surveyed along the tributaries Revuelto Creek and Rana Arroyo. Ground conductivities increased downstream along Revuelto Creek (fig. 11), but no distinct conductivity peaks were identified. Conductivities also increased downstream along Rana Arroyo (fig. 16), but were lower than those measured along Revuelto Creek. No conductivity peaks were identified in the short Rana segment surveyed.

Two types of electromagnetic soundings (multiple coil-spacing soundings and time-domain soundings) were completed to examine conductivity variations with depth. Multiple coil spacing soundings were completed at three sites between Ute Reservoir and Revuelto Creek (fig. 5) and at one site in the Jones well area (fig. 7) to examine variations in conductivity with depth. The three vertical surveys in the Ute Reservoir to Revuelto Creek segment were conducted/completed at peaks A2, B2, and B7; effective penetration depth at these sites was about 25 m. Effective penetration depth for the Jones well survey was 50 m.

At each of the four sites, a thin (0.8 to 1.8 m thick), low-conductivity (5 to 22 mS/m) layer was encountered at the surface. This layer probably represents either relatively dry alluvium or alluvium partly saturated with relatively fresh water. At the three sites (M140, M263, and M412, fig. 5) between Ute Reservoir and Revuelto Creek, the thin, low-conductivity layer overlies highly conductive layers that are 10.7 to more than 20 m thick. Conductivities in these layers, which probably represent alluvium saturated with highly conductive saline water, range from 577 to 1,870 mS/m. At site M25 in the Jones well area (fig. 7), the layer that underlies the thin surface layer is more conductive than the surface layer, but much less conductive than correlative layers at the other sites. Lower conductivities at Jones well imply that the alluvium beneath the site is saturated with water of lower salinity than at other sites.

Bedrock was probably encountered at two of the four sites. At site M140 between Ute Dam and the Highway 54 bridge, layer conductivity decreases from 577 mS/m to 150 mS/m at a calculated depth of 12.3 m. The boundary between these two layers is probably near the bedrock-alluvium contact, where alluvium saturated with saline ground water overlies partly saturated bedrock or unsaturated bedrock with fractures filled with saline ground water. A similar situation exists at Jones well site M25, where conductivity increases from 19 to 106 mS/m at a calculated depth of 18.8 m. At this site, the low-conductivity layer above the bedrock contact may represent alluvium saturated with saline ground water that has been diluted with fresh water.

Time-domain electromagnetic soundings, with a maximum penetration depth of about 100 m, were completed at two sites on the upland near Ute Reservoir, four sites within the Canadian River valley between Ute Reservoir and Revuelto Creek, one site along Revuelto Creek, and six sites along the Canadian River in the Dunes area. Vertical conductivity profiles computed from the time-domain data indicate that (1) a high conductivity layer that may represent the top of the postulated "brine aquifer" was found at a depth of 44 m on the upland south of the river and at a depth of 84 m north of the river; (2) subsurface conductivities are higher along the Canadian River between Ute Reservoir and Revuelto Creek than they are at Revuelto Creek, farther downstream in the Dunes area, and on the upland; and (3) subsurface conductivities in the Dunes area vary from relatively resistive profiles near a fresh water spring to relatively conductive profiles within high conductivity zone D.

Joints and Ground-Water Flow Paths

Ground-water movement through Dockum Group strata is likely the result of the combined processes of nonpreferential (or matrix) flow and preferential (or fracture) flow.

Joints in the Dockum Group strata were closely examined because field observations suggested that they may provide important pathways for ground-water movement. Jointing is well developed in the Dockum Group, which is primarily a fluvial sandstone with secondary overbank mudstones. Typically, thin-bedded sandstones and mudstones have closely spaced joints, whereas joints in thick rigid channel sandstones are relatively more widely spaced. Primary, or through-going, joints are oriented roughly east-west and commonly show some evidence of dilation, including millimeter-wide separation of joint faces, mineral fillings (calcite veins), and clastic debris fillings.

The mapped potentiometric surface for ground water in the lower Dockum Group in eastern New Mexico (which is apparently laden with dissolved salts in the Logan area [the "brine aquifer" described by U.S. Bureau of Reclamation (1976, 1979)]) lies from 3 to 30 m (10 to 100 ft) above Canadian River alluvium (Dutton and Simpkins, 1986) (fig. 31). Because the potentiometric surface lies above Canadian River alluvium, Dockum Group ground waters have the potential to flow upward to discharge into Canadian River alluvium and thence flow into the Canadian River. The high potentiometric surface also explains the presence of efflorescence of halite and gypsum on the bedrock wall of the Canadian River canyon as much as 10 m (30 ft) above the river. The presence of numerous well-developed joints in Dockum strata, especially with evidence of dilation of primary joints, indicates that preferential ground-water flow through joints is likely an important part of the process of ground-water discharge to Canadian River alluvium.

Drilling Applications in Jointed Dockum Group Strata

The potential for preferred ground-water flow along near-vertical joints in Dockum Group strata suggests that the placement of boreholes may be critical to the success of a mitigation program designed to reduce saline water discharge to the Canadian River. If joints are preferred pathways in the subsurface, then the productivity of a pumping well may be controlled by the

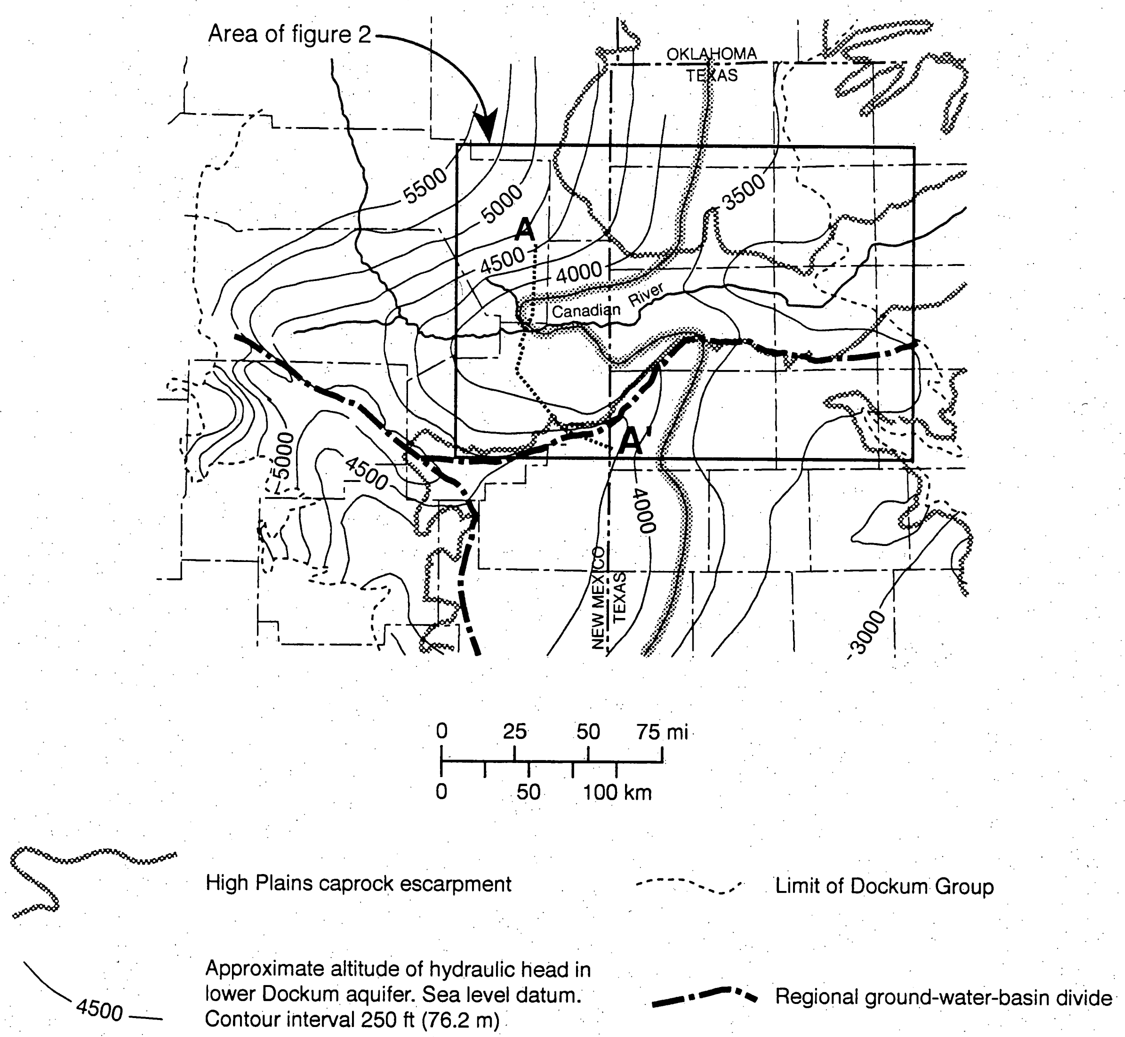

Figure 31. Potentiometric surface map of lower Dockum Group ground water. Regional ground-water-basin divides (inferred from topography and shape of potentiometric surface) separate regional groundwater basins. The 3750-ft contour, which crosses Canadian River in vicinity of Ute Reservor, is highlighted in gray; cross section along line A–A' is shown in figure 3 (modified from Dutton and Simpkins, 1986, fig. 5).

number of joints the well bore intersects. Results from this study show that joints are grouped and not evenly distributed. Furthermore, primary joints show evidence of dilation at the surface and are much more continuous than secondary joints. Thus, it is possible for the screened interval of a conventional vertical well to end up in a block of Dockum strata without intersecting any joints. It is also possible that if the well bore is inclined slightly to the east or west, the borehole will intersect only secondary or tightly closed joints.

Horizontal drilling, a rapidly evolving technology used in drilling oil and gas exploration wells, is beginning to have important applications for environmental purposes (Morgan, 1992) and therefore may be a useful alternative to conventional drilling. Horizontal wells are drilled with conventional drilling rigs and consist of an initial vertical section to reach planned depth, a short curved section where the borehole is deflected to horizontal, and a horizontal section of varying length. The curved and horizontal sections are drilled with a downhole rotary motor, which is powered by drilling fluid pumped through flexible drill pipe.

Several significant advantages over conventional vertical wells can be expected for many environmental applications, including (Morgan, 1992, p. 100):

- increased production interval contact with subsurface contaminant plumes,
- increased percentages of contaminant recovery,
- increased well production rates (specific capacity),
- faster extraction of some contaminants, and
- enhanced well geometry (multiple horizontal sections extending from a single vertical shaft).

The disadvantages of using horizontal drilling are that drilling is technically more difficult and more expensive.

Properly oriented horizontal drilling in Dockum strata in the Canadian River area would intersect numerous vertical primary joints, which are potential preferred flow paths. In addition, the horizontal screened section of production wells could be placed at relatively shallow depths in the bedrock beneath the canyon of the Canadian River. Ability to place screened intervals beneath the river and to intersect numerous preferred pathways could significantly increase the effectiveness of a pumping program designed to draw down the local water table.

CONCLUSIONS

Lateral conductivity surveys using the frequency-domain electromagnetic induction method proved effective in locating three highly conductive zones along the Canadian River between Ute Reservoir and Revuelto Creek and a fourth highly conductive zone in the Dunes area. These zones were between 1.6 and 4.2 km long and are interpreted to represent areas underlain by alluvium saturated with highly saline water.

The high-conductivity zones encompassed individual conductivity peaks that may represent sites of saline inflow into Canadian River alluvium. Two peaks were located along the Canadian River between Ute Dam and the Highway 54 bridge, 12 peaks were found between the Highway 54 bridge and a point downstream from Revuelto Creek, and 4 peaks were found in the Dunes area. Low-conductivity zones near a collapse feature in the Jones Well area and near a fresh water spring in the Dunes area suggest little saline intrusion in these areas.

Vertical soundings (both multiple coil spacing and time domain) confirmed that the Ute Reservoir to Revuelto Creek segment (particularly the "gravel pit" reach) is the most highly conductive segment surveyed and thus probably the most important source area for highly saline waters discharging into the Canadian River alluvium. Time-domain soundings were most practical and successful outside of the valley and perhaps can be used to map the top of the postulated brine aquifer. Effective penetration depths of these soundings is limited in some parts of the valley by extremely high near-surface conductivities. It is also difficult to find open areas in the valley large enough to accommodate the large transmitter antenna used for deep time-domain soundings.

Common near-vertical, slightly dilated east–west joints are likely preferred pathways for saline groundwater flow. Near-vertical, slightly dilated, east–west joints are common in exposures of Dockum Group sediments in the study area. Because these joints are dilated, they are likely preferred pathways for saline ground-water flow to the Canadian River.

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Appendices

APPENDIX I

Apparent conductivities from Ute Reservoir to beyond Revuelto Creek (fig. 5), along Revuelto Creek (fig. 5), in the Claer well area (fig. 6), in the Jones well area (fig. 7), in the Dunes area (fig. 8), in the Rana Canyon area (fig. 9), and along Rana Arroyo (fig. 9). Locations are those indicated on figures. Conductivities were measured with a Geonics EM34-3 ground conductivity meter using a 20-m transmitter and receiver coil separation and, in most cases, both vertical (VD) and horizontal (HD) dipole modes. Conductivities in milliSiemens/m.

Canadian River, Ute Reservoir to beyond Revuelto Creek

	October 19–23, 1992			November 16–20, 1992			February 1–5, 1993		
Location	Field Site	VD	HD	Field Site	VD	HD	Field Site	VD	HD
1	1	40.9							
2	2	48.1							
3a	3	43.8							
4	4	34.0							
5	5	26.3							
6	6	25.8							
7	7	27.7							
8	8	34.9							
9	9	40.8							
10	10	31.0							
11	11	33.7							
12	12	28.7							
13	13	27.3							
14	14	38.7							
15	15	34.4							
16	16	39.6							
17	17	42.3							
18	18	41.7							
19	19	43.2							
20	20	46.5							
21	21	46.9							
22	22	46.0							
23	23	47.4							
24	24	56.6							
25	25	63.4							
26	26	62.5							
27	27	60.7							
28	28	67.2							
29	29	75.9							
30	30	81.5							
31	31	80.8							
32	32	60.6							

33	33	73.3
34	34	71.2
35	35	74.8
36	36	72.0
37	37	85.3
38	38	84.9
39	39	68.9
40	40	77.1
41	41	67.1
42	42	79.1
43	43	79.6
44	44	66.2
45	45	68.7
46	46	89.6
47	47	91.8
48	48	63.9
49	49	65.2
50	50	69.1
51	51	59.1
52	52	74.8
53	53	73.6
54	54	79.2
55	55	83.7
56	56	65.6
57	57	88.4
58	58	81.8
59	59	101.3
60	60	75.0
61	61	69.4
62	62	77.1
63	63	83.6
64	64	93.2
65	65	107.6
66	66	77.1
67	67	74.7
68	68	73.8
69	69	63.9
70	70	84.2
71	71	81.4
72	72	63.3
73	73	59.7
74	74	74.2
75	75	75.5
76	76	75.1
77	77	70.1
78	78	71.3
79	79	87.4
80	80	94.6
81	81	66.0
82	82	72.9
83	83	86.0
84	84	66.2
85	85	88.0
86	86	66.8
87	87	88.2
88	88	96.2
89	89	83.5
90	90	91.7

91	91	83.6		1	77.1	110.1
92	92	84.0		2	90.3	115.2
93	93	71.2		3	69.0	128.4
94	94	69.1		4	53.4	132.3
95	95	77.3		5	66.3	136.2
96	96	–23.1		6	–6.3	140.4
97	97	128.2		7	132.6	153.3
98	98	47.7		8	34.2	168.9
99	99	53.1		9	72.3	169.8
100	100	29.5		10	20.1	176.4
101	101	24.8		11	16.8	183.0
102	102	35.4		12	11.4	170.4
103	103	45.9		13	42.9	162.9
104	104	6.4		14	–8.4	168.9
105	105	7.3		15	10.5	176.4
106	106	–29.4		16	–22.8	181.2
107	107	–20.6		17	–1.2	186.6
108	108	–29.0		18	–12.0	184.2
109	109	–15.2		19	–0.3	176.4
110	110	–58.5		20	–48.6	195.6
111	111	–85.0		21	–72.3	215.4
112	112	0.0		22	–74.4	222.3
113	113	–85.7		23	–51.6	214.8
114	114	–73.5		24	–48.3	240.6
115	115	–97.5		25	–97.8	274.2
116	116	–53.4		26	51.6	147.9
117	117	–117.9		27	14.4	158.7
118	118	–155.6		28	–91.8	226.8
119	119	–117.7		29	–72.6	226.2
120	120	–83.9		30	–65.4	222.6
121	121	–66.6		31	–54.6	213.0
122	122	–49.0		32	–45.6	209.7
123	123	–35.5		33	–30.0	199.8
124	124	1.6		34	–8.4	179.4
125	125	17.9		35	17.4	177.0
126	126	29.5		36	5.7	159.0
127	127	52.2		37	25.8	162.0
128	128	50.0		38	8.7	165.3
129	129	25.9		39	38.1	162.0
130	130	14.7		40	–2.4	185.7
131	131	–28.0		41	–50.1	209.7
132	132	–144.2		42	–89.1	237.3
133	133	–84.4		43	–76.8	232.5
134	134	73.9		34	26.4	168.0
135	135	30.5		35	21.9	178.2
136	136	–28.6		36	11.7	172.5
137	137	–60.8		37	–25.8	200.7
138	138	–56.4		38	0.9	207.6
139	139	–22.8		39	–5.4	207.9
140	140	–52.9		40	–10.8	209.1
141	141	–56.4		41	–15.9	208.2
142	142	–44.9		42	–17.1	221.7
143	143	–48.1		43	–0.3	197.7
144	144	–28.7		44	8.4	171.6
145	145	–56.5		45	38.1	156.6
146	146	–27.4		46	49.5	161.1
147	147	–47.2		47	5.4	169.8
148	148	–33.0		48	11.4	163.2

149	149	-17.7
150	150	-22.2
151	151	7.5
152	152	-1.1
153	153	14.7
154	154	18.2
155	155	20.8
156	156	35.6
157	157	46.2
158	158	78.9
159	159	56.4
160	160	68.7
161	161	61.2
162	162	91.9
163	163	79.5
164	164	78.3
165	165	63.0
166	166	62.8
167	167	74.5
168	168	81.6
169	169	82.9
170	170	92.9
171	171	90.7
172	172	96.7
173	173	85.9
174	174	84.6
175	175	93.1
176	176	95.6
177	177	79.3
178	178	86.6
179	179	87.9
180	180	85.1
181	181	81.1
182	182	94.4
183	183	84.9
184	184	99.5
185	185	35.8
186	186	104.0
187	187	89.3
188	188	82.0
189	189	82.4
190	190	75.8
191	191	82.0
192	192	78.7
193	193	91.6
194	194	87.3
195	195	90.3
196	196	91.3
197	197	83.5
198	198	95.7
199	199	80.4
200	200	92.8
201	201	77.8
202	202	86.6
203	203	83.4
204	204	71.1
205	205	73.5
206	206	74.3

49	16.8	163.8
50	24.0	162.6
51	32.1	164.4
52	33.0	165.0
53	28.5	156.9
54	22.8	161.7
55	29.7	164.4
56	28.2	170.7
57	46.8	153.0
58	66.0	141.0
59	65.7	144.9
60	51.9	144.6
61	80.1	127.2
62	51.6	136.8
63	75.6	131.1
64	59.1	120.0
65	70.5	105.9
66	90.6	108.0
67	85.2	103.8
68	85.5	91.5
69	92.4	87.9
70	74.4	93.6
71	84.0	99.0
72	85.5	103.5

207	207	76.9				
208	208	84.7				
209	209	90.6				
210	210	93.1				
211	211	51.0				
212	212	69.3				
213	213	83.8				
214	214	84.1				
215	215	71.8				
216	216	59.0				
217	217	55.7				
218	218	61.7				
219	219	49.7				
220	220	74.7				
221	221	73.9				
222	222	75.2				
223	223	57.2				
224	224	66.6				
225	225	69.5				
226	226	78.2				
227	227	68.3				
228	228	69.0				
229	229	68.7				
230	230	61.4				
231	231	69.5				
232	232	68.7				
233	233	69.5		233	74.4	101.7
234	234	59.6		234	63.0	104.4
235	235	56.6		235	54.9	110.7
236	236	69.3		236	51.9	113.7
237	237	91.7		237	39.3	122.1
238	238	54.3		238	56.7	135.0
239	239	25.5		239	11.7	162.6
240	240	3.1		240	–0.9	174.0
241	241	–10.9		241	–1.5	186.6
242	242	–4.9		242	–26.1	201.3
243	243	–25.6		243	–27.9	208.5
244	244	–38.2		244	–28.2	206.7
245	245	–33.5		245	–24.0	205.2
246	246	–45.4		246	–19.2	204.9
247	247	–42.3		247	–30.0	202.2
248	248	–67.0		248	–26.1	206.1
249	249	–6.6		250	–23.7	181.2
250	250	–34.8		251	–22.2	185.4
251	251	–29.9		252	–39.3	191.1
252	252	–25.1		253	–44.1	191.1
253	253	–20.7		254	–30.6	193.5
254	254	–52.0		255	–38.7	190.8
255	255	–4.2		256	–15.0	179.4
256	256	–36.9		257	–17.7	185.4
257	257	–35.6		258	–28.5	192.3
258	258	–34.4		259	–22.5	189.9
259	259	–15.7		260	–12.3	179.7
260	260	–20.9		261	–16.8	173.7
261	261	–32.1		262	–25.5	181.2
262	262	–70.2		263	–62.1	194.4
263	263	–111.9		264	–108.3	212.4
264	264	–80.9		265	–69.9	214.5

265	265	−58.3	266	−52.8	195.9
266	266	−33.4	267	−10.5	188.4
267	267	−55.7	268	−45.3	194.7
268	268	−56.6	269	−45.9	204.0
269	269	−69.2	270	−57.0	204.3
270	270	−29.7	271	−30.0	192.6
271	271	−52.3	272	−45.3	182.4
272	272	0.4	273	5.7	189.9
273	273	−40.7	274	−33.0	187.2
274	274	−11.4	275	−5.1	182.7
275	275	−42.3	276	−26.4	183.0
276	276	−13.3	277	11.4	177.3
277	277	−32.2	278	−26.1	185.1
278	278	−39.6	279	−22.5	189.9
279	279	−22.1	280	−11.1	172.5
280	280	−15.4	281	−10.2	180.9
281	281	−0.2	282	16.5	171.6
282	282	16.3	283	9.9	166.2
283	283	22.3	284	24.0	160.8
284	284	13.6	285	13.2	154.2
285	285	21.8	286	46.8	148.5
286	286	28.7	287	31.5	160.8
287	287	3.6	288	−8.7	169.5
288	288	−21.2	289	−7.2	176.7
289	289	−56.7	290	−7.8	177.6
290	290	−58.8	291	−11.7	179.7
291	291	−81.5	292	−35.4	196.8
292	292	−135.9	293	−91.8	219.0
293	293	−128.7	294	−91.2	217.5
294	527	−120.1			
295	526	−54.2			
296	525	−51.5			
297	524	−57.5			
298	523	−83.4			
299	522	−66.4			
300	521	−54.8			
301	520	−49.0			
302	519	−33.8			
303	518	−37.0			
304	517	−34.9			
305	516	−30.6			
306	515	−38.3			
307	514	−59.5			
308	513	−5.6			
309	512	−46.6			
310	511	−44.2			
311	510	−43.3			
312	509	−43.0			
313	508	−18.4			
314	507	−16.3			
315	506	7.7			
316	505	−18.2			
317	504	6.9			
318	503	−22.1			
319	502	−46.2			
320	501	−50.5			
321	500	−63.4			
322	499	−61.2			

323	498	-111.0	105	-94.8	251.4			
324	497	-120.1	104	-132.5	249.4			
325	496	-107.8	103	-107.8	234.7			
326	495	-134.1	102	-147.4	238.8			
327	494	-134.3	101	-102.5	229.3			
328	493	-139.3	100	-121.5	239.0			
329	492	-173.1	99	-153.5	245.1			
330	491	-169.0	98	-191.2	265.7			
331	490	-169.5	97	-171.9	263.5			
332	489	-183.1	96	-158.0	260.4			
333	488	-173.1	95	-153.3	271.4			
334	487	-165.7	94	-161.7	275.7			
335	486	-149.1	93	-113.9	288.2			
336	485	-138.9	92	-113.8	285.4			
337	484	-159.8	91	-120.3	261.3			
338	483	-133.1	90	-118.2	257.2			
339	482	-139.9						
340	481	-116.7						
341	480	-137.0						
342	479	-118.1						
343	478	-116.5						
344	477	-81.7						
345	476	-113.8						
346	475	-115.1						
347	474	-124.3						
348	473	-89.7						
349	472	-110.5						
350	471	-151.9						
351	470	-166.2						
352	469	-172.5						
353	468	-152.7						
354	467	-153.3						
355	466	-111.5						
356	465	-99.5						
357	464	-94.1						
358	463	-84.3						
359	462	-90.3						
360	461	-72.6						
361	460	-41.9						
362	459	-66.5						
363	458	-9.5						
364	457	-17.3						
365	456	-27.2				456	-21.9	187.2
366	455	-38.2				455	-18.9	191.4
367	454	-48.7				454	-35.7	199.8
368	453	-61.5				453	-58.5	215.4
369	452	-69.6				452	-63.9	204.6
370	451	-101.3				451	-69.0	232.5
371	450	-71.5				450	-57.3	219.9
372	449	-84.4				449	-67.5	210.0
373	448	-109.8				448	-70.2	205.8
374	447	-45.1				447	-37.8	199.5
375	446	-36.9				446	-32.7	184.5
376	445	-36.3				445	-22.5	181.5
377	444	-53.1				444	-37.2	186.3
378	443	-64.8				443	-52.2	193.8
379	442	-72.8				442	-53.1	192.9
380	441	-83.0				441	-73.2	193.5

381	440	–95.7				440	–87.0	196.5
382	439	–84.4				439	–78.3	195.3
383	438	–92.1	81	–96.5	222.6	438	–102.0	203.1
384	437	–74.9	80	–55.6	209.1	437	–72.6	192.3
385	436	–87.3	79	–80.1	208.0	436	–56.4	190.5
386	435	–81.4	78	–73.8	218.1	435	–63.6	198.3
387	434	–93.4	77	–103.8	216.0	434	–94.8	199.8
388	433	–82.7	76	–86.1	200.5			
389	432	–76.6	75	–82.5	221.1			
390	431	–80.1	74	–76.6	207.9			
391	430	–67.2	73	–76.0	207.5			
392	429	–89.4	72	–84.3	209.8			
393	428	–87.0	71	–89.9	216.9			
394	427	–97.1	70	–88.8	228.1			
395	426	–109.7	69	–101.7	227.3			
396	425	–90.1	68	–82.6	254.5			
397	424	–94.4	67	–97.7	246.4			
398	423	–74.3	66	–73.0	245.4			
399	422	–56.5	65	–55.1	245.2			
400	421	–44.7	64	–31.2	244.5			
401	420	–65.9	63	–59.8	237.7			
402	419	–92.3	62	–90.7	229.3			
403	418	–146.2	61	–124.1	246.2			
404	417	–129.5	60	–123.3	248.4			
405	416	–114.8	59	–107.0	239.9			
406	415	–144.7	58	–156.6	243.0			
407	414	–162.4	57	–159.5	236.8			
408	413	–160.8	56	–168.8	234.5			
409	412	–174.7	55	–166.9	243.1			
410	411	–206.7	54	–192.5	256.8			
411	410	–205.0	53	–210.0	256.1			
412	409	–242.5	52	–226.5	273.7			
413	408	–243.8	51	–231.6	279.0			
414	407	–216.0	50	–217.2	278.4			
415	406	–185.0	49	–172.9	254.6			
416	405	–155.3	48	–161.9	255.4			
417	404	–174.8	47	–154.2	266.7			
418	403	–134.5	46	–131.7	246.6			
419	402	–93.6	45	–113.2	242.8			
420	401	–48.6	44	–61.2	243.3			
421	400	–47.1	43	–33.8	221.5	400	–18.9	197.7
422	399	–21.7	42	–23.0	223.8	399	–9.0	194.1
423	398	–24.9	41	–19.8	221.2	398	–10.2	196.8
424	397	–34.2	40	–14.2	222.4	397	–4.2	191.7
425	396	–60.2				396	–35.1	196.8
426	395	–63.6				395	–39.3	210.3
427	394	–72.9				394	–33.9	217.8
428	393	–23.2				393	–12.0	208.5
429	392	5.9				392	8.4	197.7
430	391	27.1				391	18.3	183.3
431	390	25.2				390	23.7	186.9
432	389	14.3				389	32.1	199.5
433	388	82.9				388	73.5	186.6
434	387	–13.4				387	11.1	203.1
435	386	41.7				386	44.1	191.7
436	385	–22.6				385	9.6	200.4
437	384	–10.2				384	18.0	210.0
438	383	–40.4				383	–19.2	219.9

Appendix I (cont.)

439	382	35.6				382	31.8	198.6
440	381	10.8				381	31.5	195.6
441	380	−15.5				380	0.3	210.3
442	379	−52.8				379	−24.3	221.4
443	378	−31.0				378	5.1	210.0
444	377	33.6				377	22.5	153.9
445	376	95.3				376	81.3	84.6
446	375	101.0				375	95.7	77.7
447	374	101.1				374	95.4	82.5
448	373	77.3				373	60.3	91.2
449	372	76.7				372	78.0	96.3
450	371	35.7				371	85.2	95.7
451	370	6.4				370	39.3	117.0
452	369	43.0				369	56.4	108.9
453	368	20.8				368	63.9	100.5
454	367	20.4				367	42.3	134.1
455	366	68.8				366	50.1	131.4
456	365	41.6				365	29.7	134.4
457	364	35.6				364	44.1	149.4
458	363	46.3				363	57.3	123.3
459	362	77.0				362	80.4	103.5
460	361	70.9				361	68.1	97.8
461	360	64.2				360	62.7	96.6
462	359	76.1				359	84.6	98.1
463	358	64.5				358	70.5	105.9
464	357	73.8				357	61.5	118.8
465	356	63.7				356	39.3	114.0
466	355	68.4				355	62.1	114.3
467	354	58.0				354	54.0	118.5
468	353	68.4				353	79.5	123.3
469	352	68.8				352	59.1	121.8
470	351	47.5				351	39.6	143.4
471	350	54.8				350	34.2	142.8
472	349	63.1				349	32.7	156.0
473	348	28.4				348	11.7	170.1
474	347	39.3				347	24.9	181.2
475	346	19.1				346	8.4	178.5
476	345	17.4				345	1.8	192.9
477	344	−6.6				344	−0.6	192.6
478	343	34.7				343	35.7	188.4
479	342	20.1				342	14.7	173.4
480	341	−7.3				341	6.3	180.0
481	340	2.5				340	11.4	189.9
482	339	−11.9				339	6.3	195.3
483	338	−14.8				338	−8.7	189.9
484	337	−8.2				337	−0.6	196.2
485	336	−13.4				336	−2.4	195.9
486	335	0.2				335	10.8	196.8
487	334	21.5				334	27.3	194.1
488	333	13.5				333	20.4	177.9
489	332	24.7				332	29.7	177.9
490	331	14.0				331	23.1	177.3
491	330	38.7				330	28.8	180.0
492	329	23.1	37	42.5	211.6	329	43.8	183.6
493	328	5.2	36	28.4	212.5	328	23.7	186.3
494	327	28.4	35	16.0	202.7	327	32.1	177.6
495	326	31.4	34	35.1	185.9			
496	325	25.5	33	29.5	193.2			

497	324	12.8	32	20.8	205.2
498	323	−15.7	31	−7.3	217.5
499	322	3.3	30	6.8	209.8
500	321	−11.5	29	−6.6	217.8
501	320	−15.3	28	−8.2	226.5
502	319	−27.2	27	−21.5	234.2
503	318	−54.6	26	−47.3	278.6
504	317	−53.2	25	−40.1	262.9
505	316	−68.6	24	−55.8	261.0
506	315	−81.6	23	−73.1	275.2
507	314	−72.0	22	−65.9	268.2
508	313	−58.4	21	−67.8	242.9
509	312	−39.7	20	−41.6	203.3
510	309	18.0			
511			528	63.1	169.4
512			529	16.7	156.7
513			530	24.9	159.2
514			531	17.6	164.3
515			532	20.7	151.9
516			533	35.2	145.7
517			534	50.2	143.2
518			535	22.4	164.1
519			536	−10.3	194.4
520			537	−32.9	203.3
521			538	−38.1	198.2
522			539	−51.4	206.4
523			540	−42.9	206.9
524			541	−58.6	211.8
525			542	−58.6	201.9
526			543	−14.6	179.0
527			544	−0.8	163.9
528			545	−19.0	176.0
529			546	−23.2	169.3
530			547	2.3	164.6
531			548	0.4	164.3
532			549	−10.8	172.9
533			550	3.6	170.5
534			551	−15.5	183.2
535			552	−36.5	198.7
536			553	−45.7	209.8
537			554	−61.3	214.4
538			555	−71.1	224.0
539			556	−91.2	234.3
540			557	−89.0	236.0
541			558	−64.3	230.8
542			559	−73.7	239.4
543			560	−50.5	233.8
544			561	−54.1	239.6
545			562	−74.3	258.3
546			563	−67.4	257.4
547			564	−73.5	257.4
548			565	−72.1	266.7
549			566	−77.3	271.4
550			567	−8.4	234.8
551			568	37.8	187.3
552			569	53.4	173.2
553			570	53.8	167.4
554			571	61.9	156.4

555			572	74.5	142.2			
556			573	70.3	135.7			
557			574	69.4	141.4			
558			575	55.5	150.4			
559			576	58.2	156.2			
560			577	48.4	155.1			
561			578	49.2	158.3			
562			579	43.9	166.2			
563			580	33.7	170.0			
564			581	28.2	176.5			
565			582	19.9	183.8			
566			583	12.3	191.9			
567			584	17.5	194.5			
568			585	10.8	203.8			
569			586	14.4	197.2			
570			587	7.1	196.7			
571			588	12.6	199.3			
572			589	–1.5	202.3			
573			590	–0.9	195.7			
574			591	–9.3	201.1			
575			592	–18.3	203.8			
576			593	–10.1	208.6			
577			594	–35.4	225.7			
578			595	–45.2	233.7			
579			596	–35.0	226.0			
580			597	–24.6	216.4			
581			598	–4.8	205.3			
582			599	–4.5	210.6			
583			600	10.9	199.5			

Revuelto Creek

1			5	85.4	105.1			
2	294	76.0	4	77.4	107.5			
3	295	82.5	3	75.0	115.2			
4	296	74.2	2	75.0	120.4			
5	297	65.1	1	75.8	121.4			
6	298	66.9	6	72.2	137.1			
7	299	61.9	7	63.3	140.8			
8	300	62.8	8	60.5	145.2			
9	301	61.2	9	55.1	156.2			
10	302	40.7	10	27.1	173.7			
11	303	37.3	11	24.7	178.2			
12	304	50.9	12	49.1	156.6			
13	305	64.7	13	71.5	145.2			
14	306	70.4						
15	307	43.7						
16	308	18.9						
17	309	18.0						

Canadian River, Claer Well Area

1						75	78.0	118.5
2						74	66.3	120.0
3						73	34.8	134.4
4						72	51.6	134.7
5						71	52.2	141.6
6						70	47.4	140.1
7						69	49.2	136.8
8						68	52.2	142.5
9						67	51.0	143.7
10						66	53.1	141.3

11			65	51.0	138.6
12			64	49.8	137.1
13			63	66.6	122.1
14			62	71.4	113.7
15			61	64.8	111.0
16			60	64.8	111.6
17			59	66.0	110.4
18			58	66.0	108.9
19			57	74.4	100.5
20			56	71.4	99.0
21			55	76.2	97.8
22			54	76.2	95.7
23			53	72.3	99.9
24			52	63.0	102.0
25			51	74.1	110.4
26			50	48.0	118.8
27			49	65.7	123.3
28			48	51.6	138.6
29			47	72.0	141.0
30			46	27.6	137.4
31			45	58.2	139.5
32			44	59.4	136.5
33			43	61.2	141.9
34			42	38.7	153.3
35			41	42.3	158.1
36			40	35.7	168.0
37			39	26.4	172.2
38			38	33.3	173.4
39			37	33.3	174.3
40			36	26.7	181.8
41			35	32.7	180.9
42			34	32.1	181.5
43			33	22.5	188.1
44			32	27.0	189.0
45			31	35.1	174.9
46			30	25.2	169.8
47			29	45.0	164.7
48			28	44.7	157.2
49			27	39.3	156.0
50			26	54.0	149.4
51			25	54.0	153.6
52			24	51.6	154.2
53			23	48.9	160.5
54			22	47.1	161.4
55			21	49.2	159.0
56			20	51.0	160.8
57			19	50.4	156.0
58			18	42.6	150.0
59			17	46.2	145.5
60			16	57.9	141.9
61			15	44.1	143.1
62			14	51.9	147.0
63			13	30.0	151.8
64			12	36.0	160.2
65			11	17.1	173.7
66			10	3.0	181.5
67			9	–14.4	183.3
68			8	–14.4	191.4

69			7	13.5	185.7
70			6	13.8	187.5
71			5	−2.1	198.3
72			4	0.0	199.2
73			3	−4.8	192.9
74			2	−4.2	199.5
75			1	6.0	206.7
Canadian River, Jones Well Area					
1			93	68.1	99.0
2			92	72.0	97.8
3			91	74.7	97.6
4			90	73.2	90.6
5			89	70.2	95.4
6			88	59.1	97.2
7			87	64.8	96.6
8			86	69.6	100.2
9			85	64.5	103.5
10			84	66.3	105.0
11			83	71.9	98.7
12			82	76.4	97.8
13			81	79.8	92.7
14			80	72.4	97.2
15			79	69.2	98.9
16			78	72.0	94.8
17			77	41.2	96.3
18			76	61.7	81.4
19			75	68.0	69.7
20			74	59.1	69.7
21			73	53.7	69.5
22			72	49.9	65.5
23			71	46.2	57.7
24			70	43.1	56.0
25			69	32.7	51.7
26			68	35.8	41.4
27			67	37.0	35.0
28			66	30.6	36.1
29			65	29.4	33.6
30			64	25.2	38.7
31			63	18.6	44.4
32			62	27.0	40.2
33			61	27.6	38.1
34			60	25.8	37.2
35			59	24.3	42.0
36			58	41.4	35.7
37			57	27.9	47.1
38			56	40.2	60.3
39			55	41.1	73.2
40			54	38.1	82.2
41			53	40.8	89.7
42			52	46.8	99.6
43			51	42.3	97.5
44			50	50.7	96.9
45			49	21.3	88.8
46			48	46.5	71.4
47			47	44.7	72.6
48			46	54.9	68.4
49			45	51.3	71.4
50			44	43.8	75.9

51							43	46.5	78.9
52							42	45.6	82.2
53							41	45.3	82.5
54							40	50.1	75.6
55							39	48.3	75.3
56							38	48.6	76.5
57							37	46.5	78.0
58							36	53.4	79.2
59							35	51.3	76.2
60							34	55.8	78.9
61							33	62.1	79.5
62							32	54.9	84.3
63							31	53.7	87.9
64							30	53.4	87.9
65							29	58.5	87.9
66							28	51.6	88.8
67							27	48.3	87.0
68							26	48.0	83.4
69							25	46.2	79.5
70							24	48.0	74.4
71							23	39.0	71.7
72							22	42.3	69.3
73							21	42.9	64.8
74							20	46.8	63.0
75							19	39.6	66.6
76							18	36.6	72.6
77							17	39.6	73.2
78							16	40.5	79.5
79							15	36.3	75.9
80							14	50.4	64.8
81							13	55.5	62.1
82							12	59.4	70.2
83							11	55.8	60.6
84							10	52.2	66.3
85							9	46.2	67.2
86							8	45.6	63.6
87							7	38.4	62.1
88							6	31.5	67.2
89							5	45.3	65.1
90							4	43.5	60.0
91							3	41.4	54.9
92							2	36.9	48.0
93							1	31.5	42.3
Canadian River, Dunes Area									
1	1	50.3	150.0						
2	2	54.8	129.0						
3	3	51.9	131.0						
4	4	49.0	141.0						
5	5	60.7	141.0						
6	6	61.2	142.0						
7	7	53.7	139.0						
8	8	48.4	138.0						
9	9	36.8	141.0						
10	10	47.1	130.0						
11	11	48.5	125.0						
12	12	33.9	95.0						
13	13	40.4	70.0						
14	14	16.4	49.0						

15	15	45.4	35.0		
16	16	43.7	39.0		
17	17	38.3	52.0		
18	18	48.9	69.0		
19	19	31.3	91.0		
20	20	55.5	98.0		
21	21	67.1	100.0		
22	22	72.7	100.0		
23	23	78.5	101.0		
24	24	73.7	108.0		
25	25	72.0	106.0		
26	26	63.2	108.0		
27	27	50.2	111.0		
28	28	41.2	81.0		
29	29	79.1	55.0		
30	30	76.4	52.0		
31	31	71.0	50.0		
32	32	56.9	51.0		
33	33	53.3	49.2		
34	34	54.9	44.9		
35	35	52.8	41.0		
36	36	46.6	42.4		
37	37	42.0	42.3		
38	38	36.6	39.8		
39	39	41.9	36.0		
40	40	30.3	58.8		
41	41	30.9	51.4		
42	42	18.8	43.4		
43	43	40.9	33.7		
44	44	22.2	33.3		
45	45	21.0	34.1		
46	46	23.0	35.1		
47	47	17.7	36.7		
48	48	12.9	32.0		
49	49	23.8	22.3		
50	50	28.4	20.1		
51	51	7.9	30.4		
52	52	11.9	36.8		
53	53	24.3	29.5		
54	54	14.5	27.8		
55	55	22.4	27.4		
56	56	21.3	25.7		
57	57	20.8	28.2		
58	58	18.8	30.0		
59	59	23.3	30.2		
60	60	23.5	27.6		
61	61	23.2	26.7		
62	62	30.3	30.2		
63	63	14.6	31.4		
64	64	23.5	29.8		
65	65	19.0	40.1		
66	66	15.0	45.0		
67	67	12.8	42.2		
68	68	20.5	28.6		
69	69	24.4	21.9		
70	70	21.5	23.9		
71	71	22.6	28.6		
72	72	2.8	30.6		

73	73	22.0	42.4		
74	74	21.3	44.5		
75	75	19.5	46.8		
76	76	24.9	36.2		
77	77	23.5	34.5		
78	78	27.5	33.4		
79	79	25.1	37.8		
80	80	29.2	38.9		
81	81	27.0	40.7		
82	82	38.3	36.2		
83	83	31.7	37.4		
84	84	28.6	47.3		
85	85	33.8	44.3		
86	86	31.9	42.6		
87	87	32.1	45.7		
88	88	28.0	46.6		
89	89	25.2	48.1		
90	90	25.5	45.1		
91	91	30.5	44.3		
92	92	32.8	42.9		
93	93	28.6	48.3		
94	94	37.1	50.2		
95	95	42.9	57.5		
96	96	43.6	71.7		
97	97	66.3	75.8		
98	98	54.7	78.3		
99	99	81.3	82.7		
100	100	72.2	85.7		
101	101	81.6	90.5		
102	102	78.4	89.1		
103	103	83.3	95.2		
104	104	73.1	100.5		
105	105	81.4	105.4		
106	106	86.4	112.5		
107	107	71.5	128.5		
108	108	69.9	135.1		
109	109	75.2	137.7		
110	110	73.1	143.1		
111	111	74.5	146.1		
112	112	77.8	160.3		
113	113	55.5	171.2		
114	114	49.7	180.0		
115	115	58.6	187.5		
116	116	85.1	158.4		
117	117	37.7	182.4		
118	118	25.1	196.7		
119	119	44.8	193.0		
120	120	32.0	196.9		
121	121	-38.2	176.1		
122	122	56.7	168.6		
123	123	42.8	172.3		
124	124	43.1	178.7		
125	125	56.4	168.8		
126	126	47.5	167.5		
127	127	41.7	173.9		
128	128	52.2	176.6		
129	129	34.7	170.9		
130	130	25.9	178.7		

131	131	35.5	177.6		
132	132	50.7	168.7		
133	133	35.8	172.6		
134	134	46.7	177.2		
135	135	48.5	174.9		
136	136	50.3	155.5		
137	137	72.1	154.3		
138	138	43.0	159.9		
139	139	50.5	166.9		
140	140	48.8	168.5		
141	141	46.6	165.1		
142	142	50.9	169.8		
143	143	27.9	165.9		
144	144	44.1	164.8		
145	145	66.0	159.3		
146	146	59.6	147.4		
147	147	57.9	147.3		
148	148	57.1	148.9		
149	149	37.0	146.3		
150	150	50.5	140.3		
151	151	35.1	153.5		
152	152	52.0	158.6		
153	153	56.5	164.2		
154	154	32.3	172.2		
155	155	26.4	178.0		
156	156	42.8	172.0		
157	157	36.7	163.6		
158	158	44.5	164.7		
159	159	41.0	171.6		
160	160	27.6	171.3		
161	161	25.0	184.4		
162	162	8.8	193.7		
163	163	−13.6	197.6		
164	164	−28.7	212.4		
165	165	−53.6	224.3		
166	166	−72.6	233.1		
167	167	−64.1	242.6		
168	168	−67.6	245.2		
169	169	−52.0	234.4		
170	170	−54.6	233.2		
171	171	−40.0	228.0		
172	172	−32.2	236.9		
173	173	−33.9	236.8		
174	174	−29.3	233.3		
175	175	−7.8	242.2		
176	176	−3.3	224.7		
177	177	11.9	226.0		
178	178	5.0	226.9		
179	179	10.3	216.6		
180	180	2.4	214.3		
181	181	18.1	209.4		
182	182	8.6	213.5		
183	183	6.1	220.1		
184	184	17.8	223.5		
185	185	−10.7	225.6		
186	186	−1.6	222.2		
187	187	−7.1	213.0		
188	188	−2.7	217.9		

189	189	-8.3	213.5		
190	190	14.1	209.2		
191	191	20.9	193.5		
192	192	34.9	179.2		
193	193	54.9	166.8		
194	194	69.0	161.8		
195	195	44.4	173.7		
196	196	48.2	171.8		
197	197	49.9	181.9		
198	198	19.9	187.5		
199	199	40.4	183.5		
200	200	40.6	187.5		
201	201	31.0	196.1		
202	202	-17.6	217.2		
203	203	-6.0	214.7		
204	204	0.1	219.6		
205	205	6.1	209.2		
206	206	11.5	204.2		
207	207	16.1	200.8		
208	208	15.2	206.4		
209	209	14.3	201.3		
210	210	48.1	184.9		
211	211	51.7	189.1		
212	212	21.5	188.5		
213	213	45.8	186.5		
214	214	95.3	178.6		
215	215	66.0	162.3		
216	216	74.6	174.2		
217	217	50.5	186.2		
218	218	55.0	186.1		
219	219	71.3	185.3		
220	220	52.8	179.8		
221	221	68.1	174.2		
222	222	84.8	166.4		
223	223	74.7	168.9		
224	224	64.0	167.2		
225	225	84.8	182.8		
226	226	26.6	179.8		
227	227	72.1	159.4		
228	228	67.2	163.5		
229	229	75.8	156.0		
230	230	81.3	146.9		
231	231	80.8	134.9		
232	232	86.5	126.4		
233	233	93.8	116.8		
234	234	89.7	116.2		
235	235	89.0	118.4		
236	236	95.6	118.0		
237	237	87.9	116.1		
238	238	94.3	117.6		
Canadian River, Rana Canyon Area					
1	47	50.9	109.1		
2	46	57.0	107.2		
3	45	48.2	109.1		
4	44	52.4	111.5		
5	43	51.5	105.0		
6	42	62.2	96.2		
7	41	57.8	92.9		

8	40	51.5	93.6		
9	39	44.9	98.4		
10	38	52.4	84.1		
11	37	61.1	89.0		
12	36	49.6	88.0		
13	35	61.1	90.3		
14	34	45.7	100.9		
15	33	46.5	121.4		
16	32	53.4	89.2		
17	31	41.7	98.1		
18	30	54.0	97.3		
19	29	46.6	90.8		
20	28	57.2	93.5		
21	27	57.8	100.7		
22	26	58.9	102.3		
23	25	50.9	100.8		
24	24	75.2	93.2		
25	23	70.9	78.3		
26	22	77.2	80.9		
27	21	70.4	82.5		
28	20	75.5	84.9		
29	19	71.5	85.4		
30	18	46.0	88.5		
31	48	56.3	96.2		
32	49	61.4	94.4		
33	50	55.3	101.0		
34	51	56.7	85.0		
35	52	57.3	83.6		
36	53	53.9	84.7		
37	54	60.6	84.6		
38	55	58.6	87.9		
39	56	57.7	97.4		
40	57	41.8	103.4		
41	58	45.4	85.2		
42	59	50.0	72.9		
43	60	58.1	63.6		
44	61	52.7	53.2		
45	62	45.6	46.8		
46	63	37.1	43.7		
47	64	35.4	44.5		
48	65	23.5	46.3		
49	66	25.8	36.4		
50	67	26.6	32.1		
				Rana Arroyo	
1	1	35.2	29.0		
2	2	35.6	29.7		
3	3	41.9	34.5		
4	4	56.2	42.3		
5	5	66.9	53.0		
6	6	79.3	69.1		
7	7	67.7	87.2		
8	8	76.6	99.1		
9	9	73.7	98.8		
10	10	74.8	101.0		
11	11	66.8	97.4		
12	12	76.8	88.3		
13	13	70.4	95.4		
14	14	57.6	103.0		

15	15	69.7	94.0		
16	16	50.7	101.2		
17	17	67.3	95.8		

APPENDIX II

Apparent conductivities at selected sites (figs. 5 and 7) along the Canadian River using multiple coil spacings (10 m, 20 m, and 40 m). Conductivities in mS/m.

Ute Reservoir to Revuelto Creek, Location 138
February 2, 1993

Coil spacing 10 m

Coil Location	Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (mS/m)
136.5	136.25	36.5	27.0	150.9
137	136.75	37	–11.1	172.2
137.5	137.25	37.5	–19.5	173.4
138	137.75	38	–0.9	165.9
138.5	138.25	38.5	32.7	159.6
139	138.75	39	21.9	153.9
139.5	139.25	39.5	–6.3	162.3
140	139.75	40	9.0	163.5
140.5	140.25	40.5	24.0	156.0
141	140.75	41	9.6	171.9
141.5	141.25	41.5	–4.2	179.1
142	141.75	42	–48.0	175.8
142.5	142.25	42.5	–42.0	187.2
143	142.75	43	31.2	156.0
143.5	143.25	43.5	40.5	151.8
144	143.75	44	14.4	154.2

Coil spacing 20 m

Coil Location	Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (mS/m)
137	136.5	37	–25.8	200.7
138	137.5	38	0.9	207.6
139	138.5	39	–5.4	207.9
140	139.5	40	–10.8	209.1
141	140.5	41	–15.9	208.2
142	141.5	42	–17.1	221.7
143	142.5	43	–0.3	197.7
144	143.5	44	8.4	171.6

Coil spacing 40 m

Coil Location	Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (mS/m)
138	137	38	14.4	195.3
138.5	137.5	38.5	17.1	213.0
139	138	39	19.5	213.6
139.5	138.5	39.5	3.3	212.4
140	139	40	18.9	215.4
140.5	139.5	40.5	8.7	206.4
141	140	41	–11.1	220.2
141.5	140.5	41.5	–23.7	216.0
142	141	42	–6.0	221.1
142.5	141.5	42.5	5.4	206.7
143	142	43	–3.3	201.6
143.5	142.5	43.5	–8.4	216.0
144	143	44	–15.0	234.6

Ute Reservoir to Revuelto Creek, Location 263
February 2, 1993

Coil spacing 10 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
261.5	261.25	261.5	2.4	130.5
262	261.75	262	–4.5	139.2
262.5	262.25	262.5	–24.6	144.9
263	262.75	263	–48.6	165.9
263.5	263.25	263.5	–39.0	167.7
264	263.75	264	3.9	148.5
264.5	264.25	264.5	–4.8	139.2
265	264.75	265	12.3	128.1

Coil spacing 20 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
262	261.5	262	–65.4	195.6
262.5	262	262.5	–75.0	195.0
263	262.5	263	–108.0	212.4
263.5	263	263.5	–105.6	216.0
264	263.5	264	–59.1	210.9
264.5	264	264.5	–63.0	204.6
265	264.5	265	–60.9	197.4

Coil spacing 40 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
263	262	263	–82.2	253.8
263.5	262.5	263.5	–99.3	261.6
264	263	264	–84.3	250.5
264.5	263.5	264.5	–89.7	242.4
265	264	265	–64.5	240.6

Ute Reservoir to Revuelto Creek, Location 412
February 4, 1993

Coil spacing 10 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
410.5	410.25	410	–110.7	195.3
411	410.75	409.5	–113.4	199.2
411.5	411.25	409	–145.8	217.2
412	411.75	408.5	–156.0	211.5
412.5	412.25	408	–177.3	215.4
413	412.75	407.5	–153.0	206.1
413.5	413.25	407	–124.5	184.8
414	413.75	406.5	–106.5	185.7

Coil spacing 20 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
411	410.5	410	–156.6	239.4
411.5	411	409.5	–180.3	242.1
412	411.5	409	–195.0	249.6
412.5	412	408.5	–213.0	246.9
413	412.5	408	–210.6	244.8
413.5	413	407.5	–173.1	252.6
414	413.5	407	–171.0	236.4

Coil spacing 40 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
412	411	410	–153.3	283.5
412.5	411.5	409.5	–164.4	288.9
413	412	409	–168.6	289.2
413.5	412.5	408.5	–162.3	290.7
414	413	408	–162.9	292.2

Jones Well Area, Location 25

February 3, 1993

Coil spacing 10 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
23.5	23.25	70	37.1	49.3
24	23.75	69.5	42.8	47.2
24.5	24.25	69	35.7	45.2
25	24.75	68.5	33.4	44.1
25.5	25.25	68	34.0	41.9
26	25.75	67.5	29.4	37.6
26.5	26.25	67	26.2	36.7
27	26.75	66.5	24.9	35.6

Coil spacing 20 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
24	23.5	70	42.6	55.5
24.5	24	69.5	41.9	52.6
25	24.5	69	33.6	52.0
25.5	25	68.5	32.2	47.1
26	25.5	68	34.4	42.7
26.5	26	67.5	36.3	39.0
27	26.5	67	37.1	37.3

Coil spacing 40 m

Coil Location	Midpoint	Vertical Dipole Field Site	Horizontal Dipole (mS/m)	(mS/m)
25	24	70	42.2	48.8
25.5	24.5	69.5	43.3	47.2
26	25	69	42.4	44.9
26.5	25.5	68.5	46.9	43.1
27	26	68	49.7	39.4

APPENDIX III

Transient electromagnetic soundings outside the Canadian River Valley near Logan, New Mexico, along the Canadian River between Ute Reservoir and Revuelto Creek, along Revuelto Creek, and along the Canadian River in the Dunes area. Data were collected using a Geonics Protem 47/S instrument.

Sounding: PN (plate 1)
Location: 1.5 km west of Logan, Quay County, New Mexico (fig. 5)
Date: November 19, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N79E; receiver coil 10 m to north

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	-183100	0.0483	-16339.9		
2	0.00895	-183800	0.0569	-10819.4		
3	0.0120	-160100	0.0693	-6647.5		
4	0.0157	-127100	0.0840	-3973.2		
5	0.0200	-97363.7	0.101	-2376.3		
6	0.0261	-64305.5	0.125	-1306.5		
7	0.0334	-40714.3	0.154	-706.7		
8	0.0421	-24733.4	0.189	-404.9		
9	0.0541	-13883.4	0.237	-221.5		
10	0.0682	-7595.0	0.294	-126.0		
11	0.0838	-4512.6	0.357	-84.81		
12	0.104	-2472.5	0.441	-51.95		
13	0.135	-1221.0	0.563	-32.85		
14	0.172	-602.4	0.710	-21.77		
15	0.214	-326.6	0.881	-14.51		
16	0.275	-168.0	1.12	-9.93		
17	0.436	-51.19	1.76	-3.43		
18	0.555	-30.18	2.24	-2.67		
19	0.701	-17.57	2.82	-2.29		

Sounding: PS (plate 2)
Location: 3 km south of Logan, Quay County, New Mexico (fig. 5)
Date: November 19, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N13W; receiver coil 10 m to east

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	19285.5	0.0483	-28431.6		
2	0.00895	-102700	0.0569	-18842.3		
3	0.0120	-150100	0.0693	-11537.7		
4	0.0157	-149900	0.0840	-6842.3		
5	0.0200	-132900	0.101	-4164.2		
6	0.0261	-97684.6	0.125	-2433.6		
7	0.0334		0.154			
8	0.0421	-41799.3	0.189	-962.7		
9	0.0541	-23621.7	0.237	-660.9		
10	0.0682	-12901.6	0.294	-397.3		
11	0.0838	-7602.6	0.357	-285.7		
12	0.104	-4226.1	0.441	-197.5		
13	0.135	-2215.8	0.563	-127.2		
14	0.172	-1245.8	0.710	-82.13		
15	0.214	-783.9	0.881	-53.86		
16	0.275	-482.5	1.12	-30.18		
17	0.436	-191.0	1.76	-19.86		
18	0.555	-120.3	2.24	-9.93		
19	0.701		2.82			

Sounding: P331 (plate 3)
Location: Station 331 between Ute Reservoir and Revuelto Creek (fig. 5)
Date: November 17, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N20W; receiver coil 10 m to east

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	1254000	0.0483	81910.1		
2	0.00895	977572.5	0.0569	55717.2		
3	0.0120	739972.1	0.0693	34567.2		
4	0.0157	550448.0	0.0840	19316.1		
5	0.0200	415449.2	0.101	9077.3		
6	0.0261	279502.9	0.125	764.0		
7	0.0334		0.154			
8	0.0421	121275.8	0.189	-5379.1		
9	0.0541	73046.6	0.237	-6785.0		
10	0.0682	41780.2	0.294	-6448.8		
11	0.0838	24084.0	0.357	-5681.7		
12	0.104	10578.0	0.441	-4560.0		
13	0.135	1112.5	0.563	-3199.9		
14	0.172	-3899.8	0.710	-2084.4		
15	0.214	-6024.0	0.881	-1308.1		
16	0.275	-6510.0	1.12	-721.2		
17	0.436	-4581.4	1.76	-238.3		
18	0.555	-3132.7	2.24	-79.46		
19	0.701		2.82			

Sounding: P388 (plate 4)
Location: Station 388 between Ute Reservoir and Revuelto Creek (fig. 5)
Date: November 17, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N90E; receiver coil 10 m to south

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	1067000	0.0483	60851.8		
2	0.00895	787345.5	0.0569	40832.7		
3	0.0120	569519.6	0.0693	24695.2		
4	0.0157	410620.2	0.0840	13050.6		
5	0.0200	307224.0	0.101	5042.9		
6	0.0261	207709.3	0.125	-764.0		
7	0.0334		0.154			
8	0.0421	90956.8	0.189	-6937.9		
9	0.0541	54586.3	0.237	-6785.0		
10	0.0682	29921.6	0.294	-6418.3		
11	0.0838	16467.5	0.357	-5489.1		
12	0.104	6030.1	0.441	-4321.6		
13	0.135	-1308.1	0.563	-2958.5		
14	0.172	-5137.7	0.710	-1891.8		
15	0.214	-6604.7	0.881	-1161.4		
16	0.275	-6668.9	1.12	-641.8		
17	0.436	-4419.4	1.76	-238.3		
18	0.555	-2891.3	2.24	-79.46		
19	0.701		2.82			

Sounding: P421 (plate 5)
Location: Station 421 between Ute Reservoir and Revuelto Creek (fig. 5)
Date: November 17, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N80E; receiver coil 10 m to north

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	-1888000	0.0483	-48381.9		
2	0.00895	-1494000	0.0569	-24420.2		
3	0.0120	-1089000	0.0693	-7090.7		
4	0.0157	-746100	0.0840	3239.7		
5	0.0200	-502900	0.101	8924.5		
6	0.0261	-294800	0.125	11675.2		
7	0.0334		0.154			
8	0.0421	-87167.0	0.189	11552.9		
9	0.0541	-37623.6	0.237	9046.7		
10	0.0682	-9872.0	0.294	6846.2		
11	0.0838	2472.5	0.357	5180.5		
12	0.104	9813.9	0.441	3624.8		
13	0.135	12738.8	0.563	2243.3		
14	0.172	12335.4	0.710	1320.3		
15	0.214	10626.9	0.881	767.1		
16	0.275	8117.6	1.12	400.3		
17	0.436	3857.1	1.76	79.46		
18	0.555	2408.4	2.24			
19	0.701		2.82			

Sounding:	P500 (plate 6)
Location:	Station 500 between Ute Reservoir and Revuelto Creek (fig. 5)
Date:	November 17, 1992
Transmitter loop size:	40 m by 40 m
Receiver coil area:	31.4 m^2
Geometry:	Transmitter baseline oriented N17E; receiver coil 10 m to east

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	-1098000	0.0483	-48381.9		
2	0.00895	-771700	0.0569	-24420.2		
3	0.0120	-504100	0.0693	-7090.7		
4	0.0157	-311900	0.0840	3239.7		
5	0.0200	-186000	0.101	8924.5		
6	0.0261	-95449.7	0.125	11675.2		
7	0.0334		0.154			
8	0.0421	-15893.0	0.189	11552.9		
9	0.0541	733.5	0.237	9046.7		
10	0.0682	7060.1	0.294	6846.2		
11	0.0838	9321.8	0.357	5180.5		
12	0.104	9884.2	0.441	3624.8		
13	0.135	8881.7	0.563	2243.3		
14	0.172	7151.8	0.710	1320.3		
15	0.214	5431.1	0.881	767.1		
16	0.275	3698.1	1.12	400.3		
17	0.436	1525.1	1.76	79.46		
18	0.555	883.2	2.24			
19	0.701		2.82			

Sounding: P8 (plate 7)
Location: Near station 8 along Revuelto Creek (fig. 5)
Date: November 16, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N17E; receiver coil 10 m to east

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: 30 Hz Current: 2.0 a	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	694203.3	0.0483	-18704.8	0.100	-21562.5
2	0.00895	414364.2	0.0569	-22540.5	0.121	-18735.4
3	0.0120	240962.4	0.0693	-24190.5	0.151	-15128.9
4	0.0157	139812.5	0.0840	-23381.0	0.188	-11461.3
5	0.0200	75843.2	0.101	-21562.5	0.231	-8236.8
6	0.0261	30685.7	0.125	-18276.9	0.291	-5394.4
7	0.0334	2674.3	0.154	-14487.0	0.365	-3361.9
8	0.0421	-12347.6	0.189	-11232.0	0.452	-2063.0
9	0.0541	-20355.2	0.237	-7854.8	0.570	-1191.9
10	0.0682	-23121.2	0.294	-5104.0	0.712	-672.3
11	0.0838	-22586.4	0.357	-3430.7	0.871	-417.1
12	0.104	-20294.1	0.441	-2134.8	1.08	-253.6
13	0.135	-16417.1	0.563	-1184.3	1.39	-152.8
14	0.172	-12277.3	0.710	-654.0	1.75	-96.27
15	0.214	-8800.7	0.881	-389.6	2.18	-65.71
16	0.275	-5622.1	1.12	-223.1	2.78	-41.26
17	0.349	-3342.1	1.41	-134.4	3.52	-21.39
18	0.436	-1960.6	1.76	-79.46	4.39	-15.28
19	0.555	-1042.2	2.24	-47.37	5.56	-9.16
20	0.701	-534.8	2.82	-33.61	7.04	-6.11

Sounding:	P2 (plate 8)
Location:	Near station 2 along the Canadian River in the Dunes area (fig. 8)
Date:	November 18, 1992
Transmitter loop size:	40 m by 40 m
Receiver coil area:	31.4 m^2
Geometry:	Transmitter baseline oriented N40W; receiver coil 10 m to east

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	1525000	0.0483	-45784.0		
2	0.00895	838997.8	0.0569	-39610.2		
3	0.0120	419636.4	0.0693	-31510.9		
4	0.0157	191143.9	0.0840	-22922.6		
5	0.0200	57795.5	0.101	-15862.4		
6	0.0261	-15281.7	0.125	-10116.5		
7	0.0334		0.154			
8	0.0421	-53058.1	0.189	-3850.9		
9	0.0541	-47251.1	0.237	-1497.6		
10	0.0682	-36645.6	0.294	-825.2		
11	0.0838	-26409.8	0.357	-485.9		
12	0.104	-16962.7	0.441	-268.9		
13	0.135	-9245.4	0.563	-140.5		
14	0.172	-4780.1	0.710	-76.40		
15	0.214	-2530.6	0.881	-45.84		
16	0.275	-1204.2	1.12	-79.46		
17	0.349		1.41			
18	0.436	-320.9	1.76	-79.46		
19	0.555	-158.9	2.24			
20	0.701		2.82			

Sounding: P53 (plate 9)
Location: Near station 53 along the Canadian River in the Dunes area (fig. 8)
Date: November 18, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N53W; receiver coil 10 m to east

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	520190.2	0.0483	8588.3		
2	0.00895	344542.0	0.0569	5638.9		
3	0.0120	211178.2	0.0693	3514.7		
4	0.0157	127403.8	0.0840	2215.8		
5	0.0200	77417.2	0.101	1467.0		
6	0.0261	42391.5	0.125	1161.4		
7	0.0334		0.154			
8	0.0421	13264.5	0.189	764.0		
9	0.0541	7014.3	0.237	366.7		
10	0.0682	3973.2	0.294	168.0		
11	0.0838	2506.2	0.357	114.6		
12	0.104	1535.8	0.441	76.40		
13	0.135	886.3	0.563	47.37		
14	0.172	530.2	0.710	30.56		
15	0.214	337.7	0.881	18.33		
16	0.275	200.1	1.12			
17	0.349		1.41			
18	0.436	79.46	1.76			
19	0.555	39.73	2.24			
20	0.701		2.82			

Sounding: P102 (plate 10)
Location: Near station 102 along the Canadian River in the Dunes area (fig. 8)
Date: November 18, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N30E; receiver coil 10 m to east

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	-581000	0.0483	30762.1		
2	0.00895	-207400	0.0569	27293.1		
3	0.0120	-47572.0	0.0693	23350.4		
4	0.0157	6418.3	0.0840	19086.8		
5	0.0200	30991.3	0.101	15281.7		
6	0.0261	37042.9	0.125	11308.4		
7	0.0334		0.154			
8	0.0421	36019.0	0.189	5394.4		
9	0.0541	31740.1	0.237	3774.5		
10	0.0682	26376.2	0.294	2185.2		
11	0.0838	21528.9	0.357	1422.7		
12	0.104	16504.2	0.441	860.3		
13	0.135	11436.8	0.563	463.0		
14	0.172	7518.6	0.710	247.5		
15	0.214	4903.9	0.881	136.0		
16	0.275	2894.3	1.12	79.46		
17	0.349		1.41			
18	0.436	924.5	1.76			
19	0.555	522.6	2.24			
20	0.701		2.82			

Sounding: P122 (plate 11)
Location: Near station 122 along the Canadian River in the Dunes area (fig. 8)
Date: November 18, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N65E; receiver coil 10 m to south

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	-1306000	0.0483	2934.0		
2	0.00895	-861400	0.0569	11522.4		
3	0.0120	-547100	0.0693	16657.0		
4	0.0157	-340500	0.0840	18246.3		
5	0.0200	-204100	0.101	18093.5		
6	0.0261	-103900	0.125	17146.1		
7	0.0334		0.154			
8	0.0421	-9841.4	0.189	13111.7		
9	0.0541	10330.4	0.237	9046.7		
10	0.0682	17971.3	0.294	6510.0		
11	0.0838	19915.1	0.357	4969.6		
12	0.104	19517.8	0.441	3649.2		
13	0.135	16864.9	0.563	2509.2		
14	0.172	13466.2	0.710	1726.8		
15	0.214	10486.3	0.881	1222.5		
16	0.275	7478.8	1.12	803.8		
17	0.349		1.41			
18	0.436	3536.1	1.76	320.9		
19	0.555	2490.9	2.24	241.4		
20	0.701		2.82			

Sounding: P164 (plate 12)
Location: Near station 164 along the Canadian River in the Dunes area (fig. 8)
Date: November 18, 1992
Transmitter loop size: 40 m by 40 m
Receiver coil area: 31.4 m^2
Geometry: Transmitter baseline oriented N40W; receiver coil 10 m to west

	Frequency: 285 Hz Current: 1.0 a		Frequency: 75 Hz Current: 1.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	-887900	0.0483	-31786.0		
2	0.00895	-694900	0.0569	-17421.1		
3	0.0120	-513200	0.0693	-6876.7		
4	0.0157	-363200	0.0840	-366.7		
5	0.0200	-254200	0.101	3239.7		
6	0.0261	-156600	0.125	5440.2		
7	0.0334		0.154			
8	0.0421	-52324.6	0.189	5409.7		
9	0.0541	-24359.0	0.237	4523.3		
10	0.0682	-8191.0	0.294	3606.4		
11	0.0838	-938.2	0.357	2772.1		
12	0.104	3557.5	0.441	1968.2		
13	0.135	5638.9	0.563	1222.5		
14	0.172	5843.7	0.710	718.2		
15	0.214	5232.4	0.881	421.7		
16	0.275	4181.0	1.12	241.4		
17	0.349		1.41			
18	0.436	2090.5	1.76			
19	0.555	1124.7	2.24			
20	0.701		2.82			

Sounding:	P230 (plate 13)
Location:	Near station 230 along the Canadian River in the Dunes area (fig. 8)
Date:	November 18, 1992
Transmitter loop size:	40 m by 40 m
Receiver coil area:	31.4 m^2
Geometry:	Transmitter baseline oriented N35W; receiver coil 10 m to west

	Frequency: 285 Hz Current: 2.0 a		Frequency: 75 Hz Current: 2.0 a		Frequency: Current:	
Channel	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)	Time (ms)	EMF (nV/m^2)
1	0.00685	665366.7	0.0483	-23839.5		
2	0.00895	398242.0	0.0569	-25520.4		
3	0.0120	237478.1	0.0693	-24909.2		
4	0.0157	140194.6	0.0840	-22158.5		
5	0.0200	70479.3	0.101	-18643.7		
6	0.0261	22127.9	0.125	-14028.6		
7	0.0334		0.154			
8	0.0421	-23503.3	0.189	-6173.8		
9	0.0541	-29524.3	0.237	-4523.3		
10	0.0682	-29524.3	0.294	-1956.0		
11	0.0838	-26171.4	0.357	-837.4		
12	0.104	-21388.3	0.441	-94.74		
13	0.135	-15278.6	0.563	382.0		
14	0.172	-10208.1	0.710	577.6		
15	0.214	-6552.8	0.881	641.8		
16	0.275	-3618.7	1.12	721.2		
17	0.349		1.41			
18	0.436	-883.2	1.76	562.3		
19	0.555	-482.9	2.24	400.3		
20	0.701		2.82			

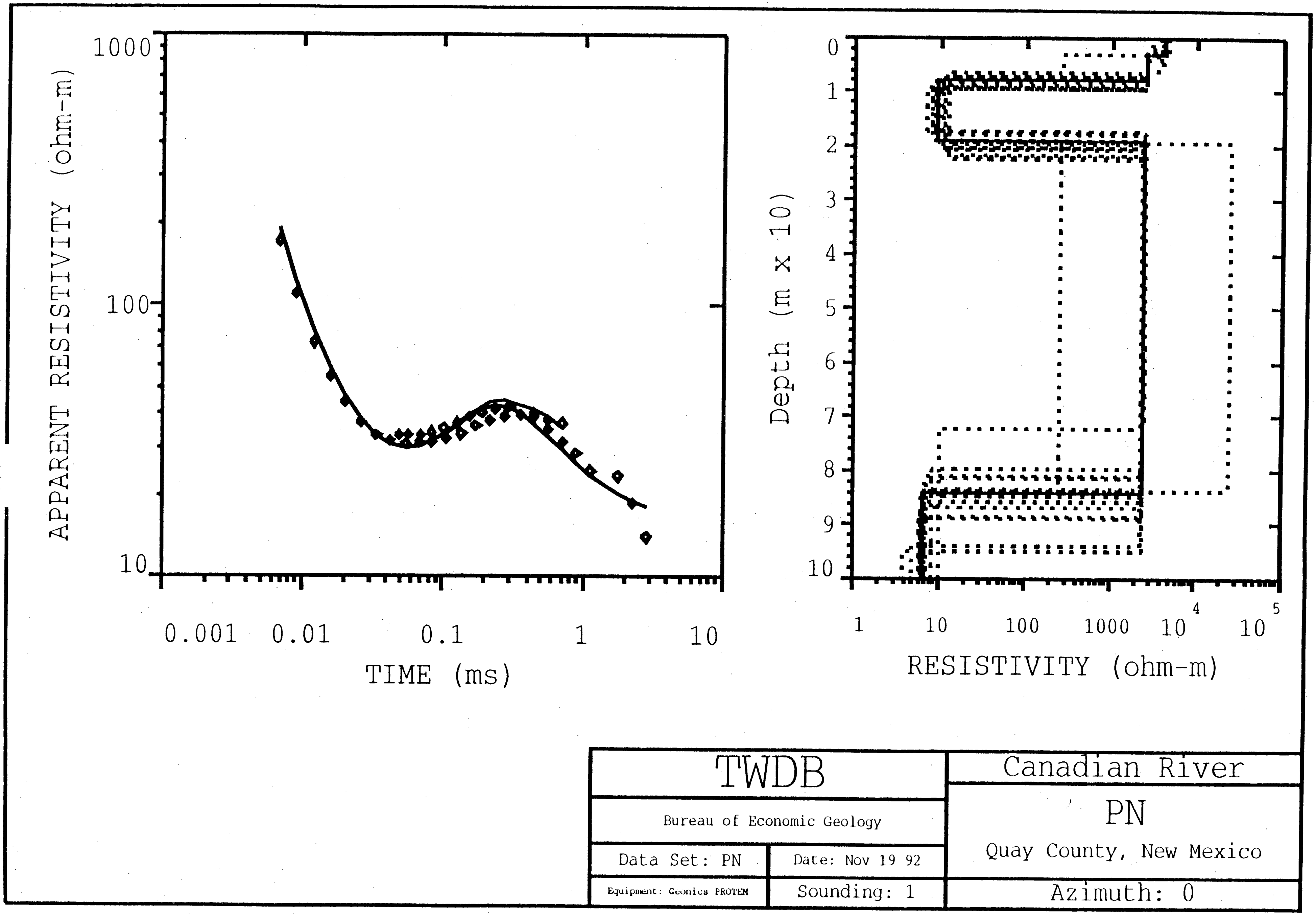


Plate 1. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site PN near Logan, New Mexico. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

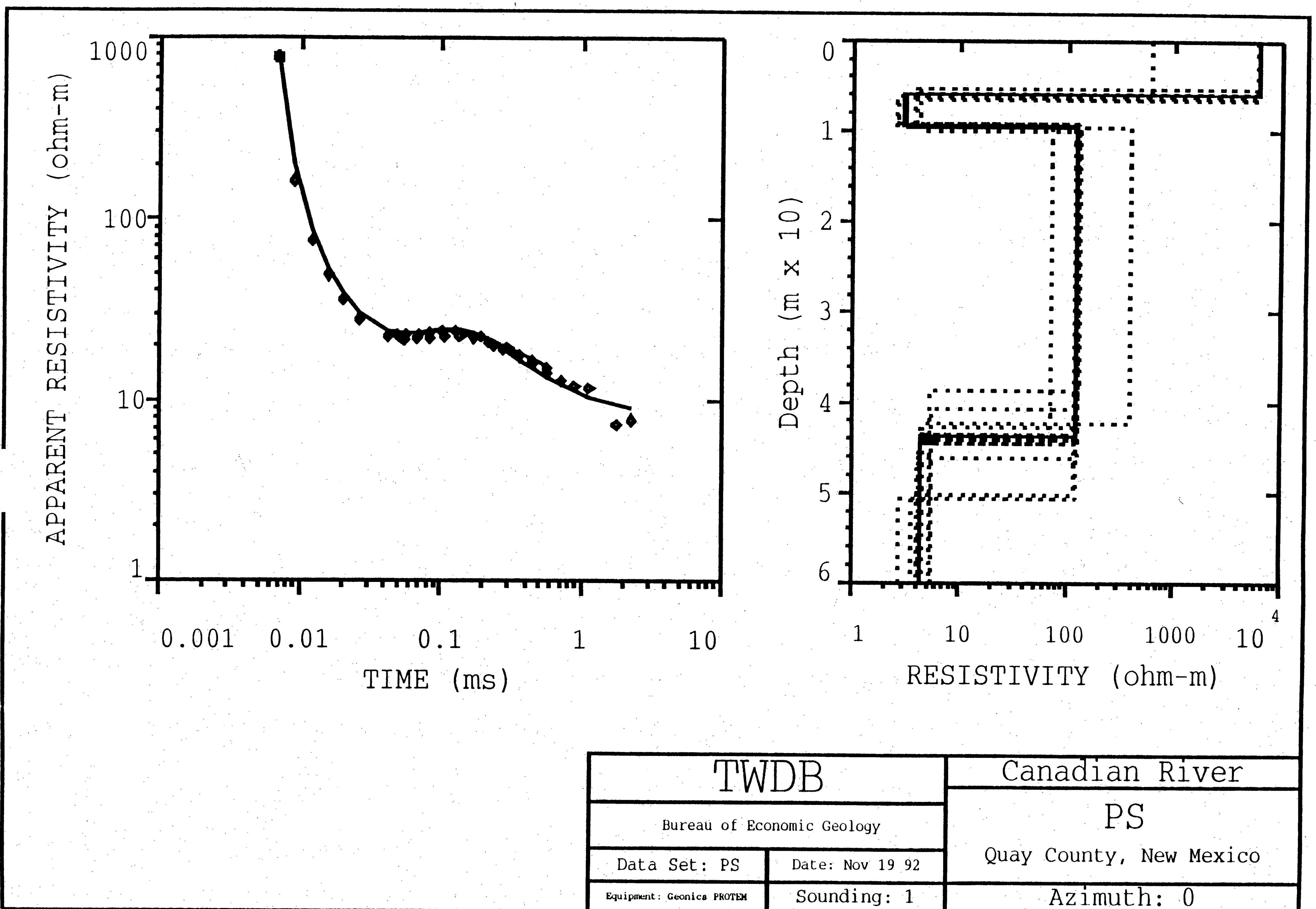
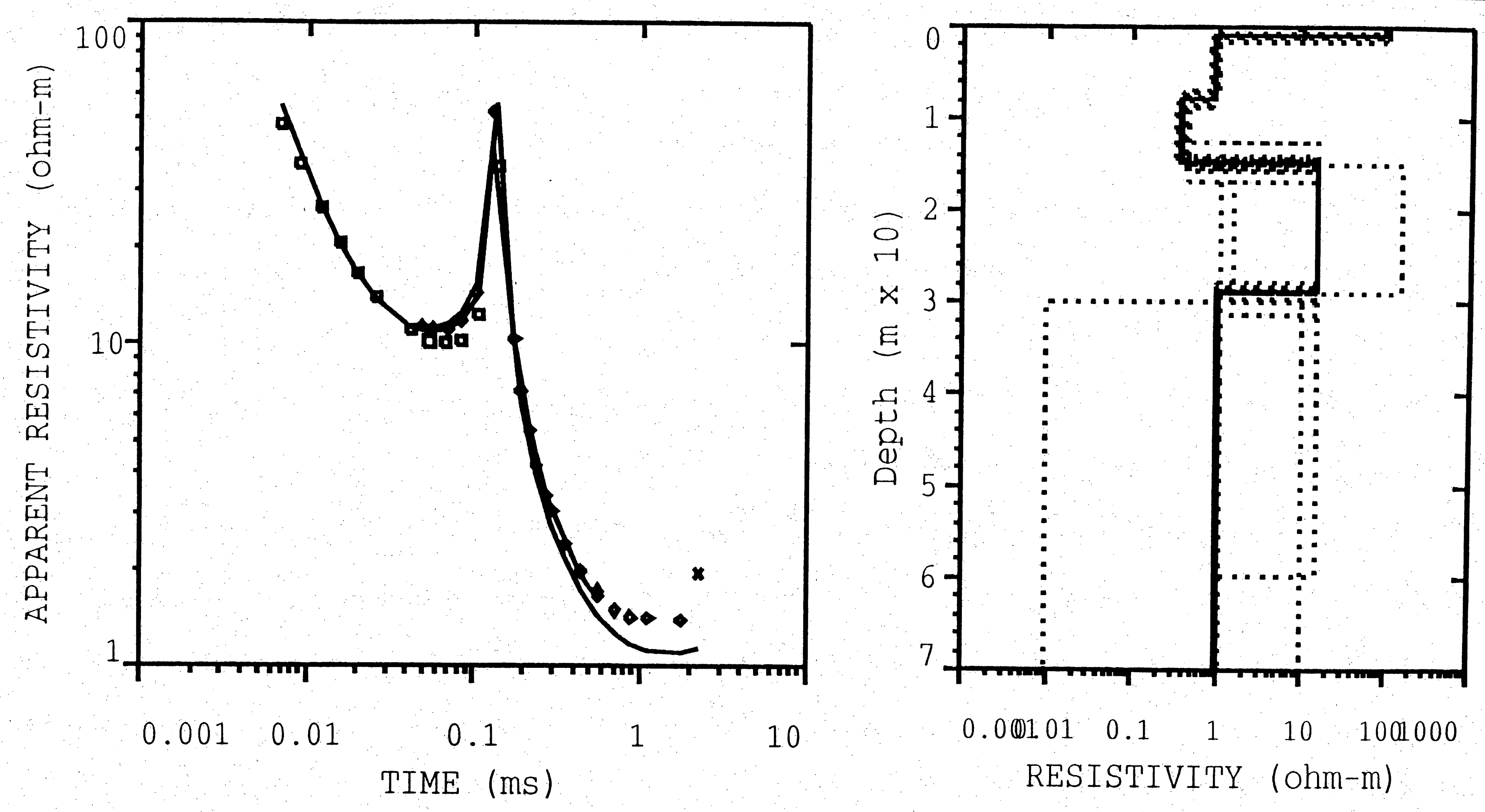


Plate 2. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site PS near Ute Reservoir State Park. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).



TWDB	Canadian River
Bureau of Economic Geology	P331, Ute-Revuelto
Data Set: P331 / Date: Nov 17 92	Quay County, New Mexico
Equipment: Geonics PROTEM / Sounding: 1	Azimuth: 0

Plate 3. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P331 between Ute Reservoir and Revuelto Creek. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

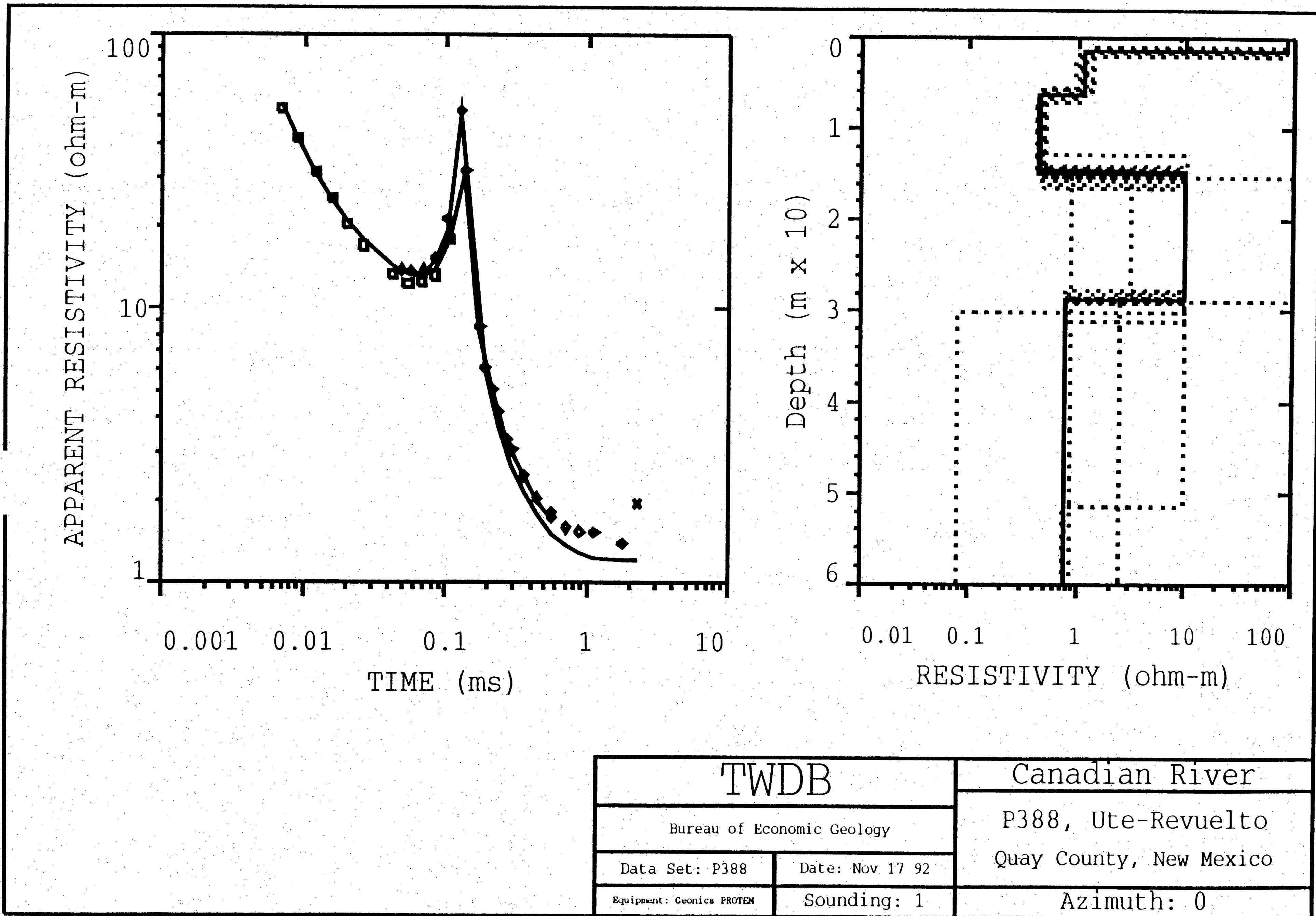


Plate 4. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P388 between Ute Reservoir and Revuelto Creek. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

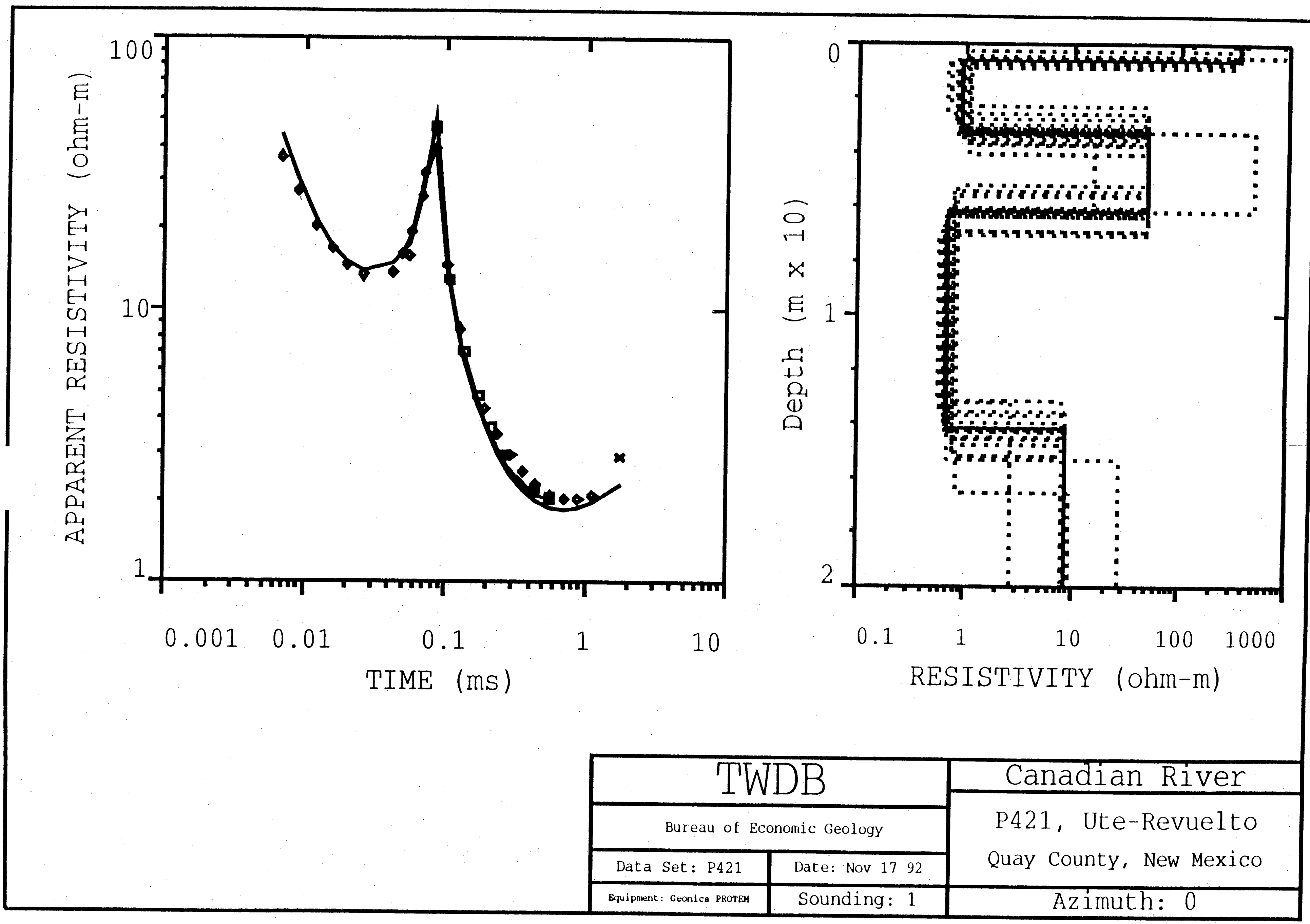


Plate 5. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P421 between Ute Reservoir and Revuelto Creek. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

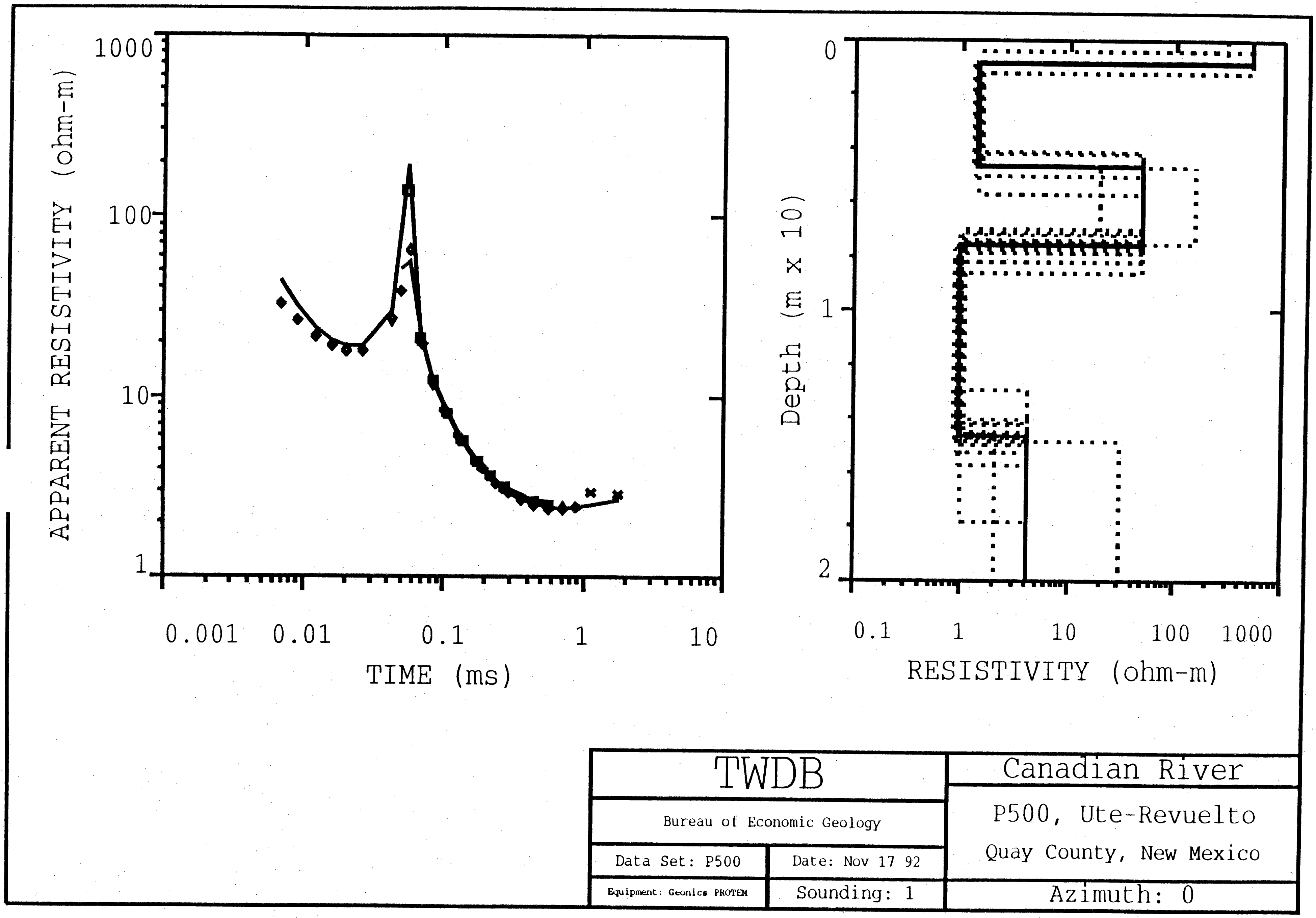


Plate 6. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P500 between Ute Reservoir and Revuelto Creek. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

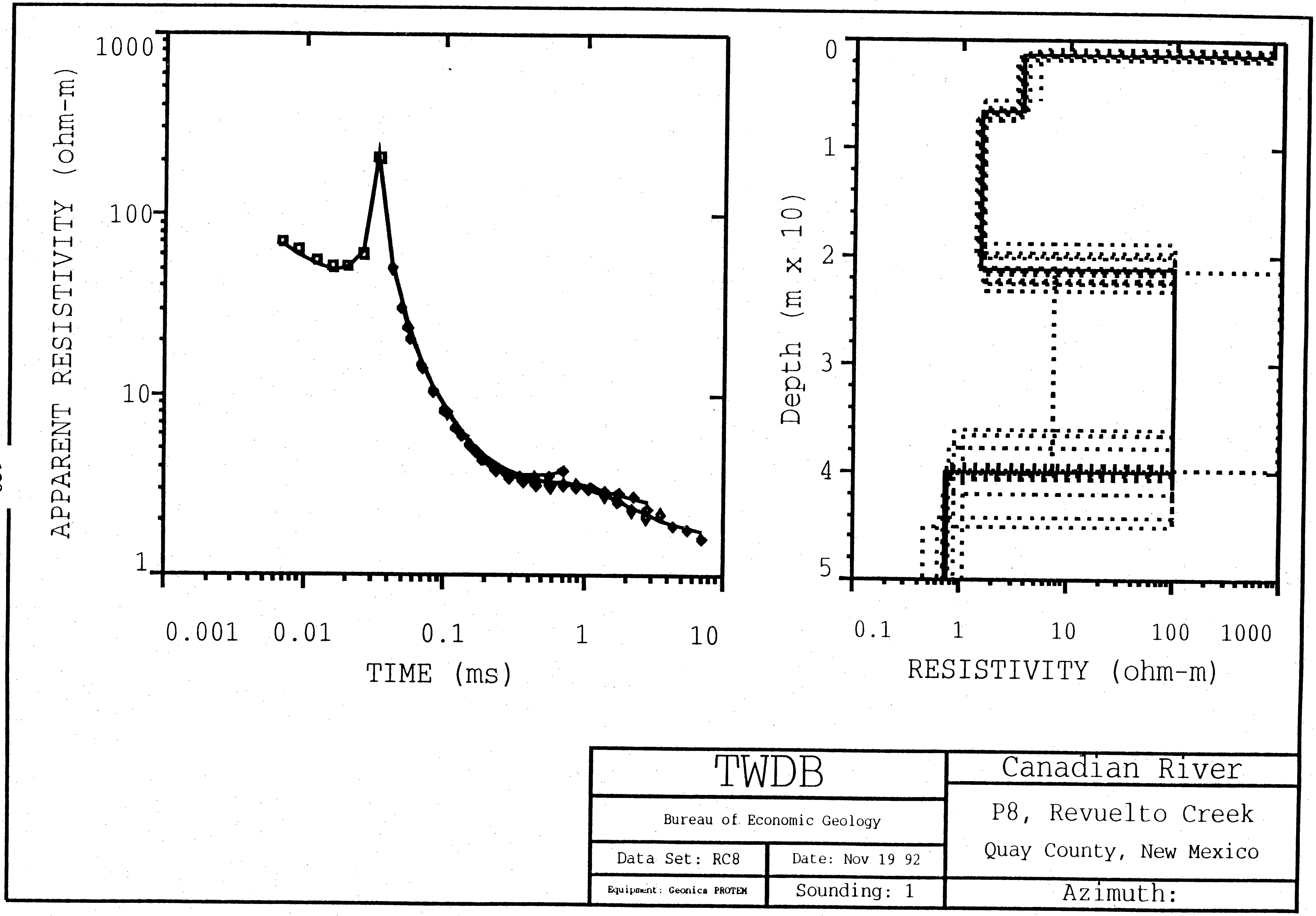


Plate 7. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P8 along Revuelto Creek. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

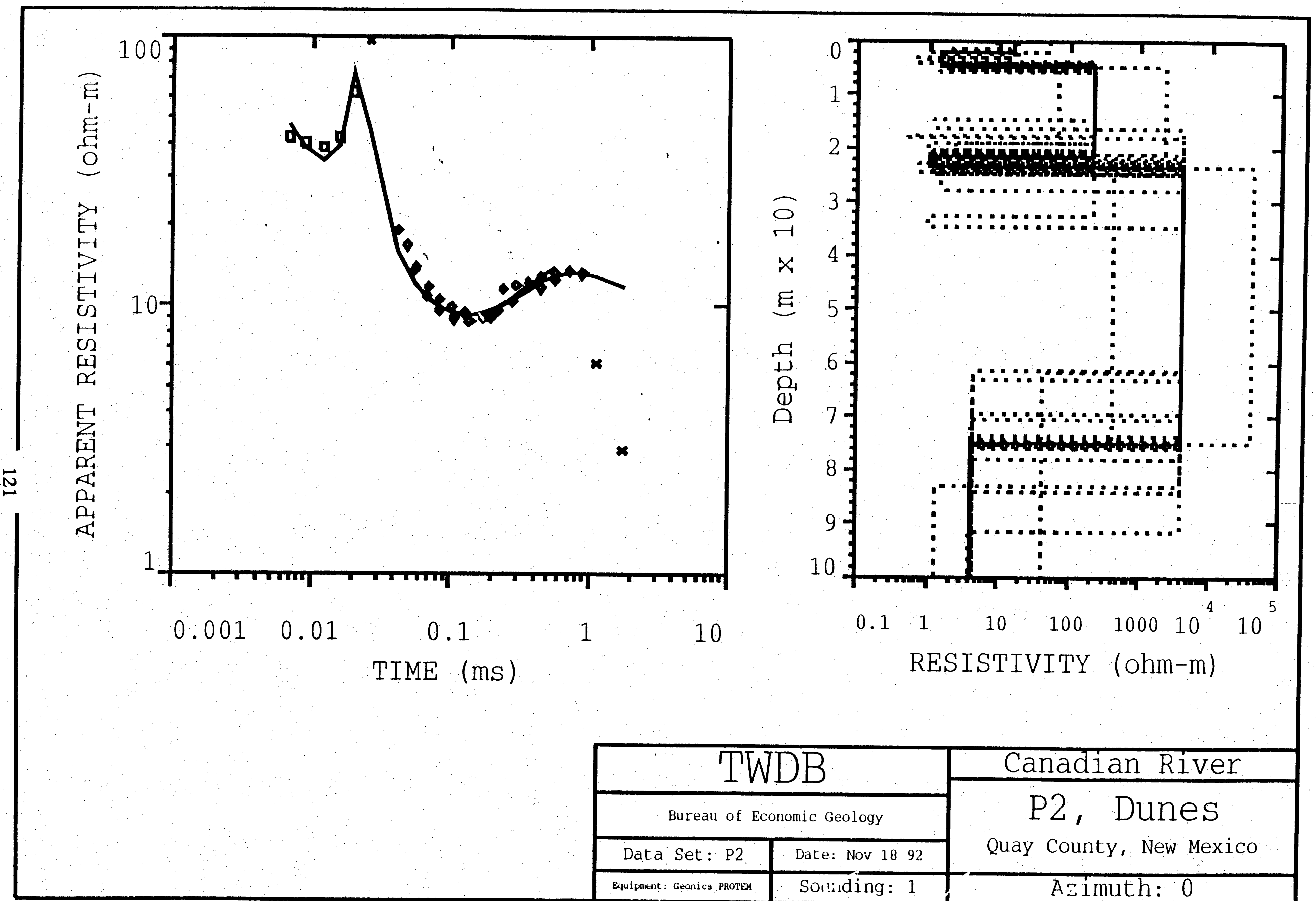
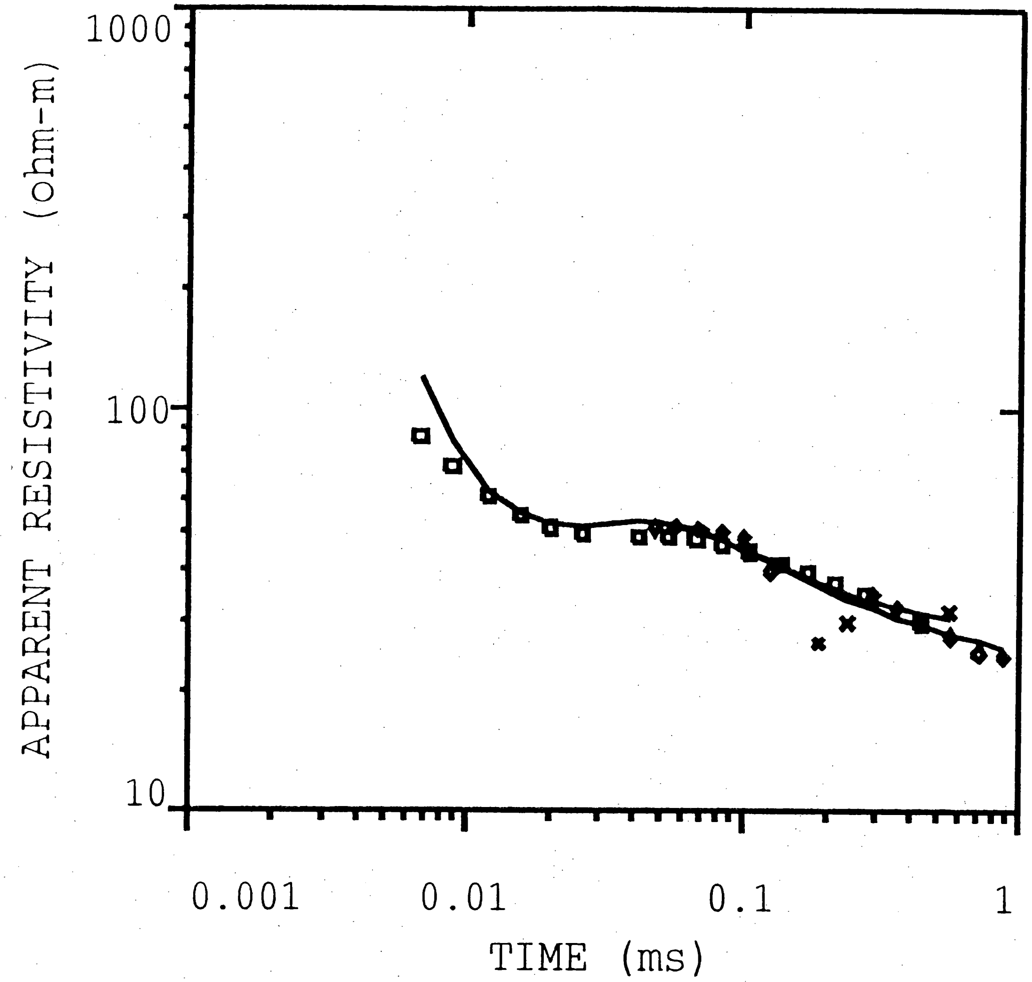
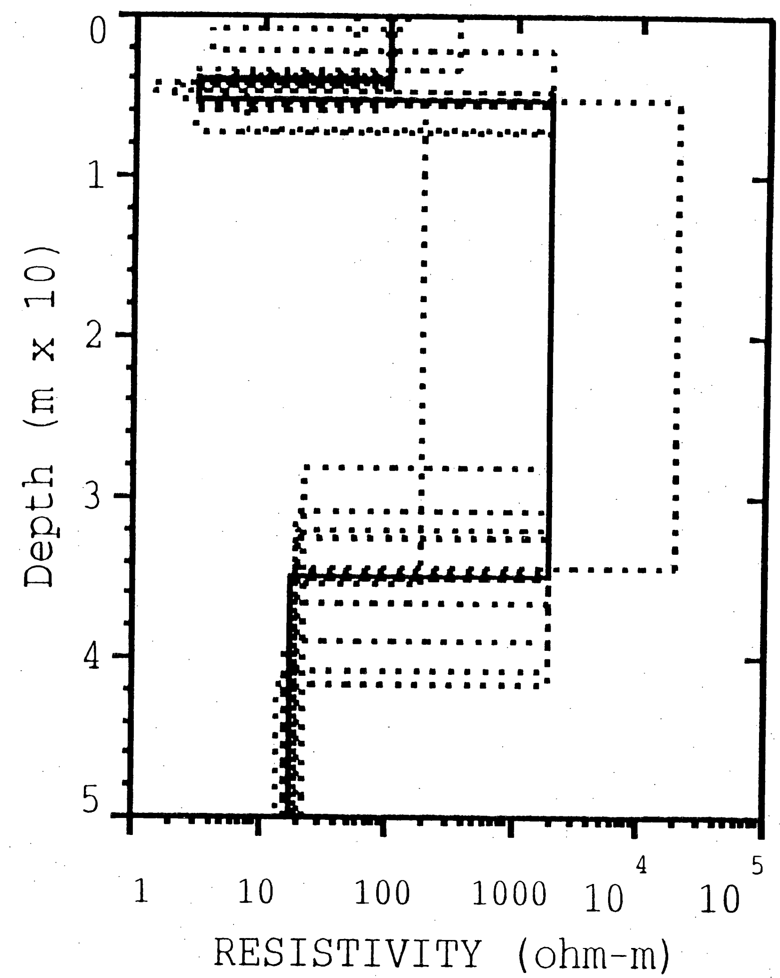


Plate 8. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P2 in the Dunes area. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).





TWDB		Canadian River
Bureau of Economic Geology		P53, Dunes Quay County, New Mexico
Data Set: P53	Date: Nov 18 92	
Equipment: Geonics PROTEM	Sounding: 1	Azimuth:

Plate 9. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P53 in the Dunes area.
Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

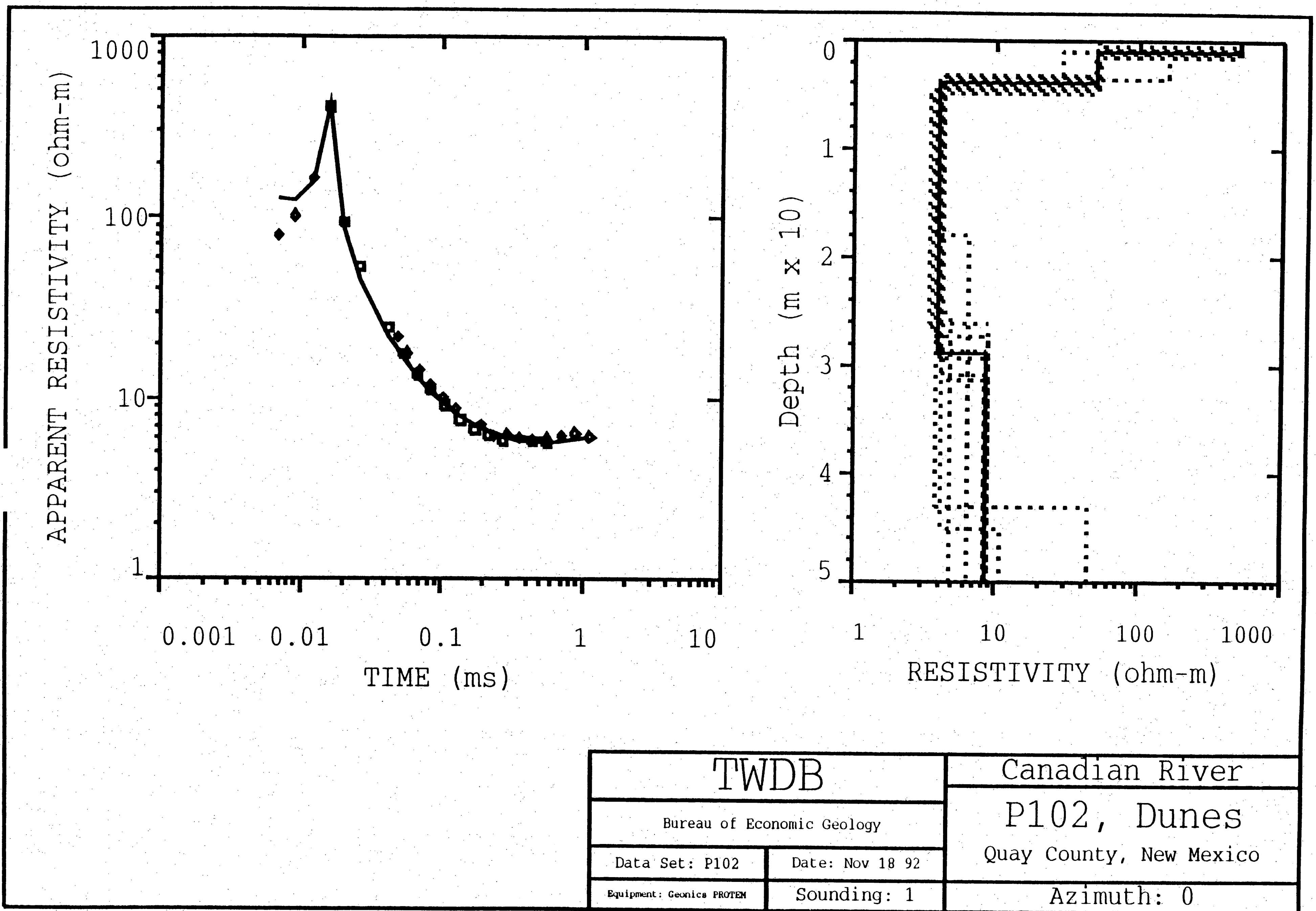
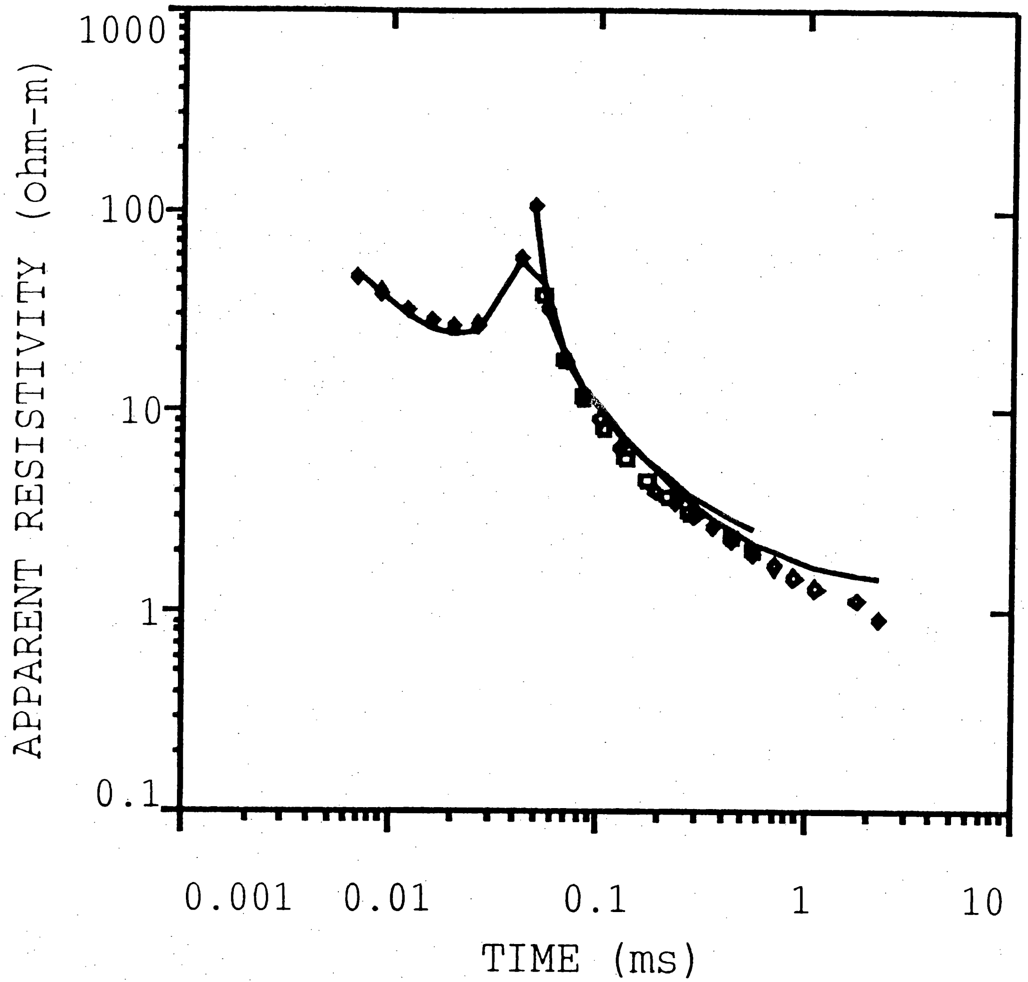
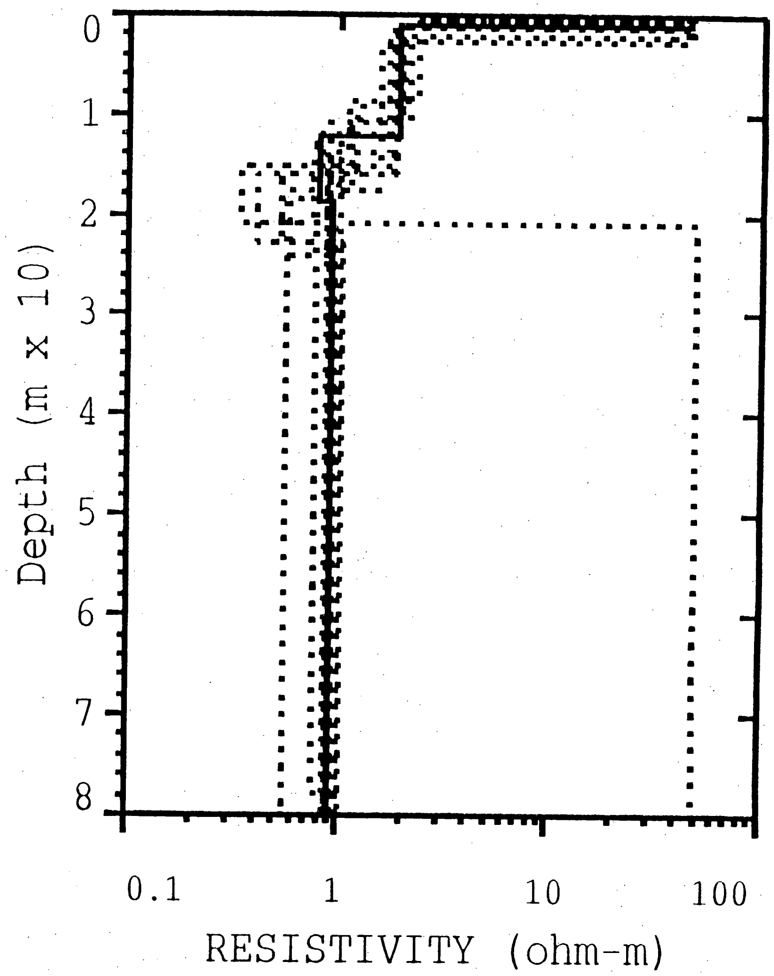


Plate 10. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P102 in the Dunes area. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).





TWDB	Canadian River
Bureau of Economic Geology	P122, Dunes
Data Set: P122 / Date: Nov 18 92	Quay County, New Mexico
Equipment: Geonics PROTEM / Sounding: 1	Azimuth: 0

Plate 11. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P122 in the Dunes area. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).

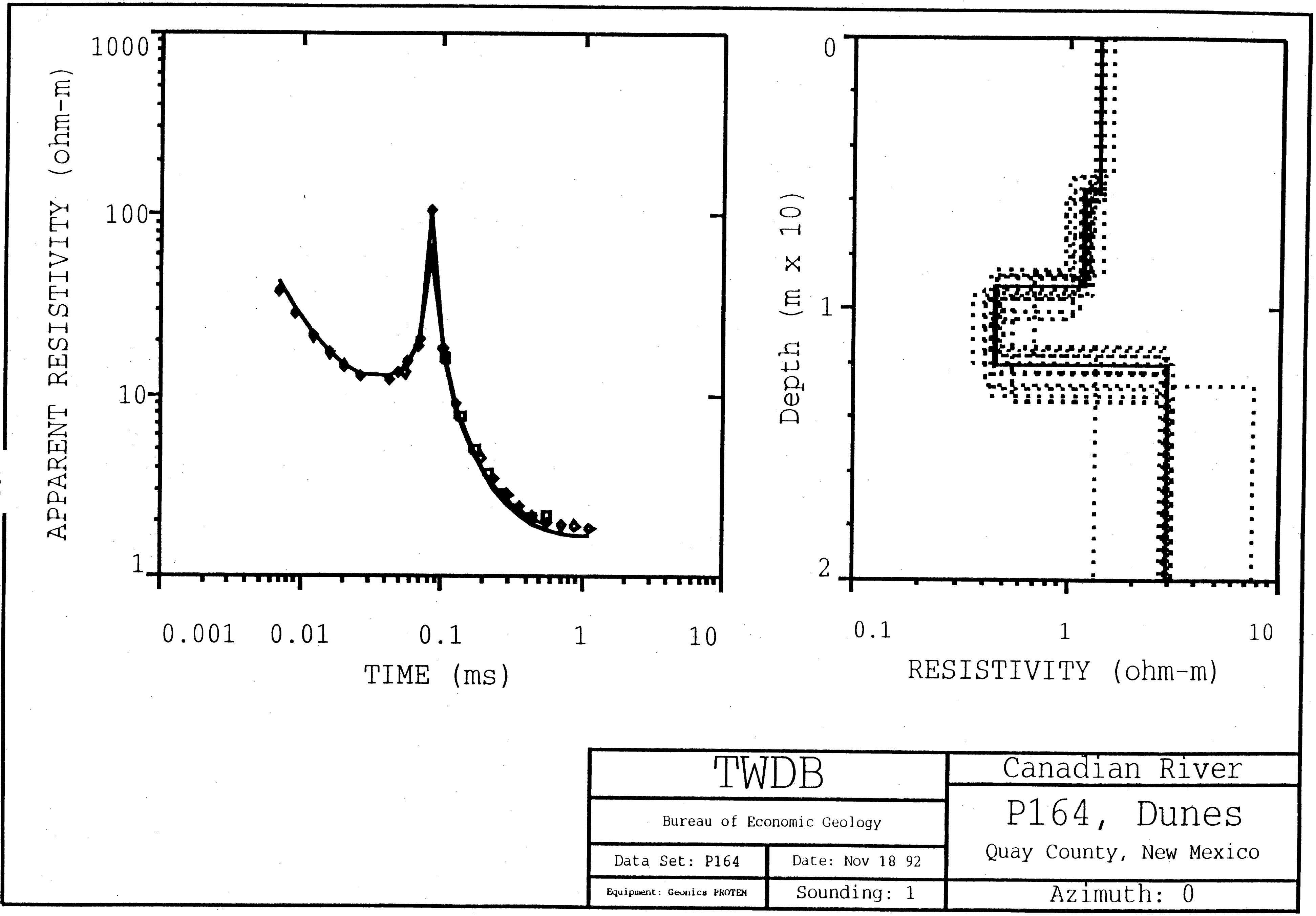
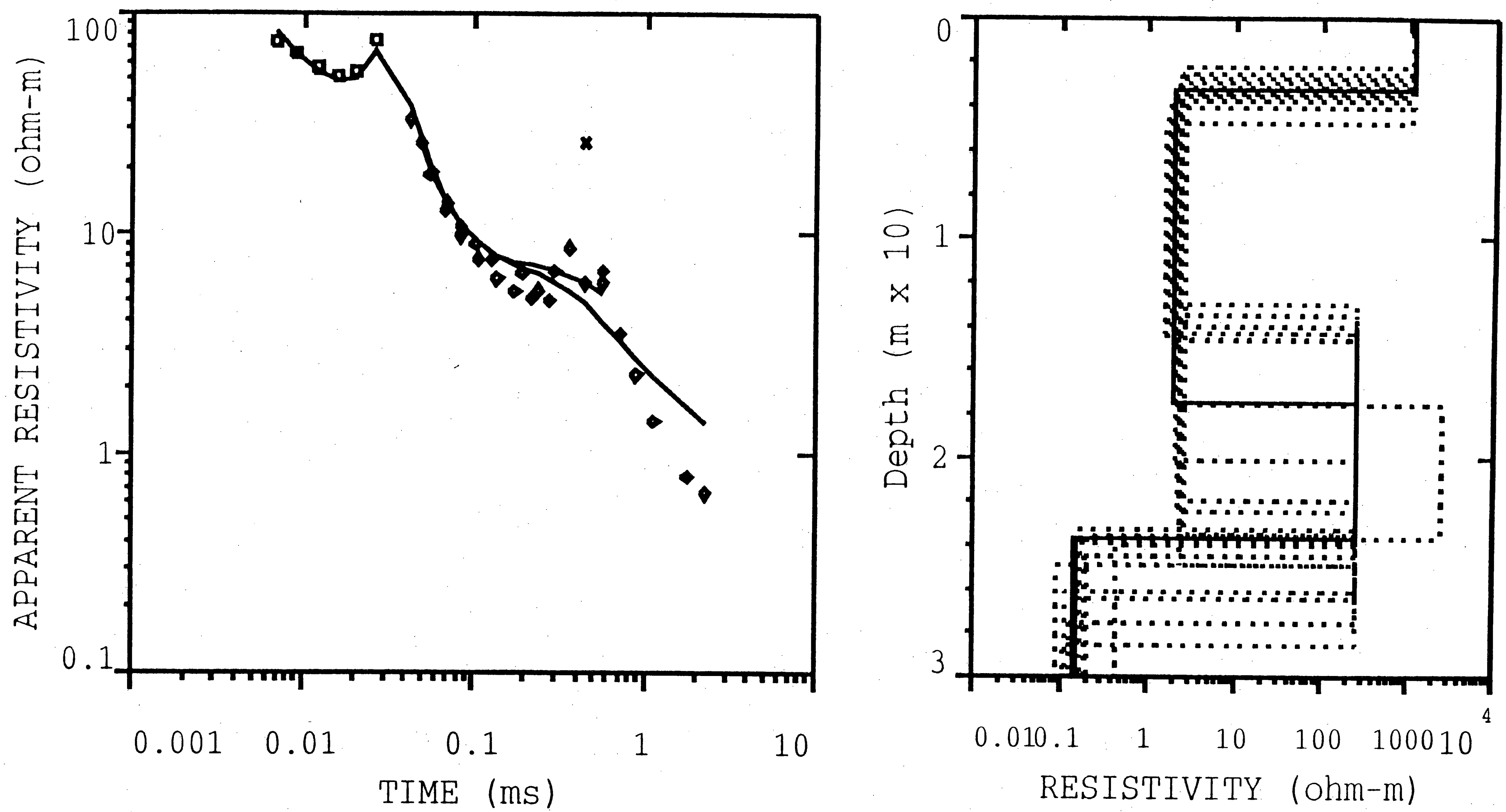


Plate 12. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P164 in the Dunes area. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).



TWDB		Canadian River
Bureau of Economic Geology		P230, Dunes Quay County, New Mexico
Data Set: P230	Date: Nov 18 92	
Equipment: Geonics PROTEM	Sounding: 1	Azimuth: 0

Plate 13. Left: observed (symbol) and calculated (line) apparent resistivity at Protem 47 site P230 in the Dunes area. Right: best-fit resistivity profile (solid line) and equivalent resistivity profiles (dashed line).