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April 9, 1993

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Mr. John Ashworth
Texas Water Development Board
P.O. Box 13087, Capitol Station
Austin, TX 78711

Dear Mr. Ashworth:

Enclosed is a draft copy of the Bureau's final contract report, "Electromagnetic Delineation of Saline-Water Plumes in Alluvium and Bedrock along the Canadian River, Eastern New Mexico. The report is being reviewed and edited at the Bureau, and a final version will be available shortly. Please feel free to review the report and give us your comments.

If you have any questions, please call me at (512)471-1534.

Sincerely,

T C Gustavson
LH

Thomas C. Gustavson
Senior Research Scientist

TCG:lch
Enclosure

cc: A. Mitchell, TBEG
J. Raney, TBEG
J. Williams, CRMWA

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

by

Thomas C. Gustavson, Jeffrey Paine, and Arten J. Avakian

Final Contract Report

Prepared for

Texas Water Development Board

by

BUREAU OF ECONOMIC GEOLOGY

W. L. Fisher, ,Director

THE UNIVERSITY OF TEXAS AT AUSTIN

April, 1993

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TABLE OF CONTENTS

DRAFT
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Figures

Tables

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EXECUTIVE SUMMARY

Ground conductivity surveys, consisting of more than 2,200 conductivity measurements along seven segments of the Canadian River and its tributaries, located four 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 surely 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 extends 1,600 m between Ute Dam and the Highway 54 bridge and 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 groundwater 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 farthest downstream segment was near Rana Canyon. Apparent conductivities were relatively low along this segment and no peaks were encountered. Short segments surveyed along Revuelto Creek and Rana Arroyo showed that conductivities increased downstream, but no distinct conductivity peaks were identified.

Vertical conductivity surveys were completed at three sites between Ute Reservoir and Revuelto Creek and at one site in the Jones Well area to examine vertical conductivity variations. At each site, a thin (0.8 to 1.8 m), low conductivity (5 to 22 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 mS/m to 150 mS/m at a depth of 12 m. The boundary between these layers is probably the bedrock-alluvium contact, where alluvium saturated with saline groundwater overlies partly saturated bedrock or unsaturated bedrock with fractures filled with saline groundwater. 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 groundwater that has been diluted with fresh water.

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 with secondary joints, which are not open and terminate against primary joints. Primary joints, therefore, may well be preferred pathways for ground 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 (Murphy, 1992). 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 bore hole 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 for environments like th e Canadian River. 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

Lake Meredith, which supplies water to all major cities on the Southern High Plains in Texas, has high salinity levels due primarily to discharge of subsurface brines into its source the Canadian River in eastern New Mexico (Gustavson and others, 1980). Subsurface dissolution of Permian salt (NaCl) and gypsum ($CaSO_4$) supplies as much as 53,000 metric tons (58,400 tons) of salt and similar amounts of gypsum per year to the Canadian River. Salinity of Lake Meredith, which is fed primarily by the Canadian River, has doubled from approximately 200 ppm to more than 430 ppm over the past 10 years (John Williams, Manager, Canadian River Municipal Water Authority (CRMWA), personal communication), and exceeds EPA limits for drinking water. To reduce salinity of Lake Meredith water to EPA standards for domestic consumption (>250 ppm Na^+) requires these communities to pump large volumes of low-salinity water from the Ogallala aquifer.

Location of the distribution of 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 nonpoint 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 perferred flowpaths is also important if natural salt polution 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 effectively a measure of ground-water conductivity and indirectly, of salinity. Field studies were focused in five segments of the river between Ute Dam and the Texas - New Mexico state line (figs. 1 and 2), which was identified in previous studies to be the greatest contributor of saline water. The segments include: (1) a 11.4-km (6.8-mi) reach from Ute Dam to approximately 1.5 km (1 mi) downstream from Revuelto Creek, (2) a 1.5- km (0.9-mi) reach in the vicinity of Claer well, (3) a 4.7-km (2.8-mi) reach in the vicinity of Jones well, (4) a 1.9-km (1.1-mi) reach in the area of the originally-proposed "Dunes" dam and reservoir, and (5) a 1.3-km (0.8-mi) reach in the vicinity of Rana Canyon.

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 portion 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 combined with reservoir evaporation that 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). Analyses of waters in riverbed alluvium in 1974 suggested that subsurface inflow of saline water was occurring along the river channel 2 to 5 mi 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) at 261 ft, which 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 - the data were sparse, but demonstrated the existence of some sort of low-resistivity zone extending in the subsurface from Ute Dam to a point about 1.5 mi east (U.S. Bureau of Reclamation, 1976; 1979). In 1978 a pump 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 encountered the brine aquifer at a depth of 100 m (350 ft) with a hydraulic head of nearly 30 m (90 ft) above the land surface adjacent to the river, and supported the conclusion that the brine aquifer is a sandstone interval near the base of the Triassic section or top of the Permian section (U.S. Bureau of Reclamation, 1984). The series of investigations described above are also summarized in U.S. Bureau of Reclamation (1985). Dutton and Simpkins (1986) described the hydrogeochemistry and water resources of the Lower Dockum Group in eastern New Mexico and the Texas Panhandle.

A new round of steamflow-water quality surveys between Ute Reservoir and Lake Meredith commenced in February 1992 to determine if any changes had occurred since the raising of Ute Dam and increase of reservoir volume and water surface elevation in 198?. The first of these (Gustavson and others, 1992) was conducted jointly by the CRMWA, the Bureau of

Economic Geology, and Lee Wilson & Associates, Inc. (consultant) and included a regional analysis of well logs and evaporite dissolution patterns, and 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 stream flow and surface water quality changes for 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, which are locally veneered with Quaternary sediments (figs. 3 and 4). The valley is about 120- km (70-mi) wide in eastern New Mexico, and narrows to less than 50 km (30 mi) between escarpments of the High Plains surface in Texas (fig. 1). Permian rocks underlie the Triassic as shallow as 60m (200 ft) beneath the surface in the Logan, New Mexico area, 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 salt beds which thin or pinch out mostly as a result of dissolution within siliciclastic strata adjacent to Precambrian basement uplifts (fig 3) (Gustavson and others, 1980; 1992). Through time, removal of evaporites by 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 central portion of the valley (Gustavson and others, 1992, p. 2-6, plates 1 and 2).

The Canadian River across most of the study area in eastern New Mexico flows through a narrow gorge (15-30 m [50-100 ft] deep and about 150 m [500 ft] wide) in the resistant Trujillo Formation of the Dockum Group. Past dissolution and collapse has produced abrupt monoclinal flexures observable in the walls of the gorge with amplitudes as great as 15 m (50 ft) in the otherwise gently-dipping Triassic strata, and which appear regionally as a series of anticlines and synclines (depressions) (Hydro Geo Chem, 1984).

The bedrock floor of the gorge extends some 15 m (50 ft) or more 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). The gorge was backfilled by Quaternary riverbed alluvium to a depth of 15 m (50 ft) or more so that in most of the study area only the Trujillo Formation is exposed. Fractures are well developed and exposed in the Trujillo Formation, and 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 its tributaries to locate potential entry sites of saline groundwater into Canadian River alluvium. In these surveys, a Geonics EM34-3 ground conductivity meter was used to measure apparent conductivity along seven river stretches and tributaries (table 1): along the Canadian River between Ute Reservoir and downstream from Revuelto Creek, in the Claer Well area, in the Jones Well area, in the Dunes area, and near Rana Canyon, and along Revuelto Creek and Rana Arroyo (fig. 2).

The EM34-3 supports 10, 20, and 40 m transmitter and receiver coil separations and two principal coil orientations (horizontal dipole or vertical coplanar and vertical dipole or horizontal coplanar). We used a 20 m coil separation, which has an effective penetration depth of 12 m for the horizontal dipole orientation and 25 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 (vertical dipole or 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 a horizontal dipole or vertical coplanar orientation at the same station location and coil separation; (6) apparent conductivity for the horizontal dipole orientation was read from the meter, transcribed by hand, and digitally logged; (7) the transmitter coil was moved to the location of the receiver coil, which was moved forward about 20 m and the entire process was repeated. We attempted to follow a consistent path that was as near as possible to the central part of the alluvial valley. 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 valley wall.

More than 2,000 conductivity measurements were taken at 1,073 sites in the study area (table 1 and appendix I). The most measurements (583 unique sites) were taken along an 11 km reach of the Canadian River between Ute Reservoir and beyond the confluence with Revuelto Creek (fig. 5) where previous studies indicated that most of the salt load entered the river. Revuelto Creek was surveyed from its 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 secondary 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 a radial survey at 45° intervals of a 40 x 40 m grid at site T1 (fig. 5) to determine how conductivity varies with direction relative to the valley axis, three parallel transects along the river at site T2 (fig. 5) to determine the importance of position within the valley, and several reoccupations of sites between Ute Reservoir and Revuelto Creek to determine the repeatability of measurements and the variation of conductivity with time.

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

At each site, apparent conductivites for the 10 m coil spacing were collected first; these 10 m spacings 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. Once all sites were occupied 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 as was used for the 10 and 20 m coil spacings.

Preparation for processing of the EM34-3 sounding data consisted of 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 the observed data and the synthetic data from the chosen model. The model was then adjusted to better fit the observed data. Once 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. Once 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.

Transient soundings were conducted at 13 sites in November 1992. Seven sites were located in the Ute Reservoir to Revuelto Creek area (fig. 5), with two of these conducted on upland north (PN) and south (PS) of the Canadian River valley. Four of the remaining five (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 transient soundings were collected with a 40 x 40 m transmitter antenna and the receiver coil outside the transmitter loop.

Geologic Studies

Dockum Group strata are well exposed in the gorge of the Canadian River between Ute Dam and Rana Canyon. Dockum strata are dominated by channel-filling pebble conglomerates and coarse poorly sorted pebbly sandstones. Channel sandstones are typically lens-shaped in cross section and interbedded with thinner sandstone and mudstone beds. The subsurface distribution of these beds is unknown.

Geologic structures, especially joints, are commonly perferred pathways for fluid movement. Joints in Triassic fluvial channel sandstones exposed in the Canadian River Valley were examined to determine their spatial distribution and to determine their possible influence on flow of saline waters through underlying bedrock and into Canadian River alluvium. Joint data were collected at 15 field sites (figs.), 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-foot-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 more than 1 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 end of Revuelto Creek and Rana Arroyo.

Ute Reservoir to beyond Revuelto Creek

Nearly 1300 conductivity measurements were made along an 11 km stretch of the Canadian River between Ute Reservoir and a point about 1 km downstream from its confluence with Revuelto Creek (figs. 2 and 5). The 380 horizontal dipole conductivites ranged from a low of 78 mS/m at station 446 to 288 mS/m at station 335 (fig. 10 and appendix 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.

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). 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 high 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 increases 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 B7, 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, or 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 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 drainage crosses the main Canadian

River valley. A lateral conductivity survey was completed along the Canadian River across its intersection with the side drainage (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 into an unsurveyed area.

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 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 appendix 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. 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 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, located 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 appendix 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). Conductivities were generally lower along the arroyo than along the Canadian River near Rana Canyon (fig. 16 and appendix I), but Rana Arroyo conductivities increased downstream. Conductivities increased from 29 to 103 mS/m (horizontal dipole) and from 35 to 77 mS/m (vertical dipole) between the upstream end of the survey in Rana Arroyo and its confluence with the Canadian River. No significant conductivity peaks were detected along the arroyo.

Vertical Conductivity Surveys

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 (appendix II and fig. 16). Conductivities for 10 m 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. 16) 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 139.5 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 (fig. 17) that 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 139.5 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 groundwater.

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 appendix 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 128 to 168 mS/m at 10 m to 195 to 216 mS/m at 20 m to 241 to 262 mS/m at 40 m (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 (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 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.

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

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 (appendix II). This site is located at conductivity peak B7, which was 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 185 to 217 mS/m at 10 m to 236 to 252 mS/m at 20 m to 284 to 292 mS/m at 40 m. Horizontal dipole values also show a peak near station 412, but the peak is not as well defined as in the vertical dipole measurements. Increasing conductivity with coil separation suggests that ground conductivities increase with depth.

Horizontal dipole conductivities at station 412 were used to construct a model vertical conductivity profile (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. Conductivities in these layers increase downward, from 870 mS/m in the 5.6 m thick layer 2 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, but 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 valley. 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 appendix 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; there is no large difference in conductivities measured at the different coil separations.

Vertical and horizontal conductivities recorded for station 25 were used to construct a model vertical conductivity profile beneath the station. Relationships between conductivity measurements and penetration depths support a model with at least four layers (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 basal conductive (106 mS/m) 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.

STRATIGRAPHY AND STRUCTURE

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

Joint Analysis

Joints are fractures in rocks, which occur without displacement, that result from post-depositional stresses such as folding, removal of overburden, or subsidence. The joint surface is usually planar and commonly occurs 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 spaced less than a meter apart. Measurements were made at 9 sites between the Ute Dam and the confluens of the Canadian River and Revuelto Creek and at 6 sites along the Dunes segment of the Canadian River (figs. 25, 26, and 27).

Joint systems adjacent to the Canadian River can usually be divided into two groups; through-going or primary joints and 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 inner gorge of the Canadian River contain near vertical primary joint faces that are in excess of 35 m long 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 Valley and collectively 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, 26, and 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 also may have been influenced by later subsidence resulting from dissolution of Permian bedded salt that underlies 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 Valley near Logan, New Mexico (fig. 25), and the east southeast trend of the valley near the Dunes area (fig. 26). Secondary or crossing joints formed at high angles to primary joints and typically comprise one or more subsets of joints of varying orientations at each field site.

Joint Dilation

Comparison of primary and secondary joints in plan view indicates that primary joints are likely to be slightly dilated or open. Separation along joints is usually less than a millimeter. Locally primary joints are 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 on-the-other-hand show little evidence of separation or mineralization. Open joints are important high permeability pathways for groundwater flow.

Calcium carbonate vein fillings in joints has two potential sources; 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 CaCo3 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 evaportated. In either case CaCO3 is left behind as a vein-filling precipitate. Vein fillings could also have formed in much the same fashion as groundwater calcretes as CaCO3 is precipitated in the unsaturated zone at or slightly above the water table. In both cases the presence of vein filling calcite indicates that the joint was open prior to mineralization and capable of transmitting fluids.

The effectiveness of joints as pathways for groundwater 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 5-7 m above the river. Typically, the efflorescence is several decimeters higher along vertical joints. Accelerated weathering and erosion is also common along joints producing small scale cavernous weathering.

Joint Distribution

East-west or primary joints are more numerous than secondary joints. For example in thick fluvial sandstones east of site 400, 25 joints crossed a 100 ft-long north-south line, but only 9 joints crossed a 100 ft-long e-w line (fig. 28). At most other sites primary joints also outnumber secondary joints. Joints also are 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 common joints. To record variations in the horizontal distribution of joints a 100-foot-long tape was laid out approximately normal to the trend of primary joints and the spacing of joints that crossed the tape were recorded. Typically, several groups of 6-10 relatively closely spaced joints were recognized, which were separated by areas of rock with either a few widely separated or no joints (figs. 28, 29, and 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 and thereby prevent natural discharge of saline water to Canadian River alluvium. To successfully carry out a pumping program the location of areas of significant saline water discharge into Canadian River alluvium must be accurately known. 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 can not 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 (appendix I), located four broad high conductivity zones and 18 individual conductivity peaks that may represent sites of saline groundwater 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 along the downstream parts 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 an undetermined distance 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 groundwater 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 drainage crosses the main Canadian River valley. 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 located in the Dunes area (figs. 2 and 8). Extremely low conductivities were recorded along the river near station 53, which is 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 Canadian River tributaries Revuelto Creek and Rana Arroyo. Ground conductivities increased downstream along Revuelto Creek (fig. 11), but no distinct conductivity peaks were identified. Conductivities were relatively low along Rana Arroyo near its confluence with the Canadian River (fig. 16). Conductivities also increased downstream along Rana Arroyo. No conductivity peaks were identified in the short segment surveyed.

Vertical conductivity surveys 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 surveys in the Ute Reservoir to Revuelto Creek segment were located 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 lower salinities of water that saturates the alluvium beneath the site.

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 groundwater overlies partly saturated bedrock or unsaturated bedrock with fractures filled with saline groundwater. 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 groundwater diluted with fresh water.

Joints and Ground-Water Flow

Ground-water movement through Dockum Group strata is likely the result of the combined processes of non-preferential 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, while joints in thick rigid channel sandstones are relatively more widely spaced. Primary or through-going joints are roughly oriented east-west, and commonly show some evidence of dilation including mineralization, filling with clastic debris, millimeter-wide separation of joint faces.

The mapped potentiometric surface for ground water in the lower Dockum Group in eastern New Mexico 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 through Dockum strata 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 Canadian River gorge 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 bore holes 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 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 if the well bore is inclined slightly to the east or west for the bore hole to intersect only secondary or tightly closed joints.

Horizontal drilling, which is a rapidly evolving technology used in drilling oil and gas exploration wells that is beginning to have important applications for environmental purposes (Morgan, 1992), that 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 bore hole 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 for many environmental applications including (Murphy, 1992, p.100):

- Increased production interval contact with subsurface contaminant plumes
- Increased percentages of contaminant recovery
- Increased well production (specific capacity) rates
- Faster extraction of some contaminants
- Enhanced well geometry (multiple horizontal sections extending from a single vertical shaft)

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

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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							
3	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

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95	95	77.3
96	96	-23.1
97	97	128.2
98	98	47.7
99	99	53.1
100	100	29.5
101	101	24.8
102	102	35.4
103	103	45.9
104	104	6.4
105	105	7.3
106	106	-29.4
107	107	-20.6
108	108	-29.0
109	109	-15.2
110	110	-58.5
111	111	-85.0
112	112	0.0
113	113	-85.7
114	114	-73.5
115	115	-97.5
116	116	-53.4
117	117	-117.9
118	118	-155.6
119	119	-117.7
120	120	-83.9
121	121	-66.6
122	122	-49.0
123	123	-35.5
124	124	1.6
125	125	17.9
126	126	29.5
127	127	52.2
128	128	50.0
129	129	25.9
130	130	14.7
131	131	-28.0
132	132	-144.2
133	133	-84.4
134	134	73.9
135	135	30.5
136	136	-28.6
137	137	-60.8
138	138	-56.4
139	139	-22.8
140	140	-52.9
141	141	-56.4
142	142	-44.9
143	143	-48.1
144	144	-28.7
145	145	-56.5
146	146	-27.4
147	147	-47.2
148	148	-33.0

5	66.3	136.2
6	-6.3	140.4
7	132.6	153.3
8	34.2	168.9
9	72.3	169.8
10	20.1	176.4
11	16.8	183.0
12	11.4	170.4
13	42.9	162.9
14	-8.4	168.9
15	10.5	176.4
16	-22.8	181.2
17	-1.2	186.6
18	-12.0	184.2
19	-0.3	176.4
20	-48.6	195.6
21	-72.3	215.4
22	-74.4	222.3
23	-51.6	214.8
24	-48.3	240.6
25	-97.8	274.2
26	51.6	147.9
27	14.4	158.7
28	-91.8	226.8
29	-72.6	226.2
30	-65.4	222.6
31	-54.6	213.0
32	-45.6	209.7
33	-30.0	199.8
34	-8.4	179.4
35	17.4	177.0
36	5.7	159.0
37	25.8	162.0
38	8.7	165.3
39	38.1	162.0
40	-2.4	185.7
41	-50.1	209.7
42	-89.1	237.3
43	-76.8	232.5
34	26.4	168.0
35	21.9	178.2
36	11.7	172.5
37	-25.8	200.7
38	0.9	207.6
39	-5.4	207.9
40	-10.8	209.1
41	-15.9	208.2
42	-17.1	221.7
43	-0.3	197.7
44	8.4	171.6
45	38.1	156.6
46	49.5	161.1
47	5.4	169.8
48	11.4	163.2

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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

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

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Not for Distribution

203	203	83.4				
204	204	71.1				
205	205	73.5				
206	206	74.3				
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

DRAFT
Not for Distribution

257	257	-35.6
258	258	-34.4
259	259	-15.7
260	260	-20.9
261	261	-32.1
262	262	-70.2
263	263	-111.9
264	264	-80.9
265	265	-58.3
266	266	-33.4
267	267	-55.7
268	268	-56.6
269	269	-69.2
270	270	-29.7
271	271	-52.3
272	272	0.4
273	273	-40.7
274	274	-11.4
275	275	-42.3
276	276	-13.3
277	277	-32.2
278	278	-39.6
279	279	-22.1
280	280	-15.4
281	281	-0.2
282	282	16.3
283	283	22.3
284	284	13.6
285	285	21.8
286	286	28.7
287	287	3.6
288	288	-21.2
289	289	-56.7
290	290	-58.8
291	291	-81.5
292	292	-135.9
293	293	-128.7
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

258	-28.5	192.3
259	-22.5	189.9
260	-12.3	179.7
261	-16.8	173.7
262	-25.5	181.2
263	-62.1	194.4
264	-108.3	212.4
265	-69.9	214.5
266	-52.8	195.9
267	-10.5	188.4
268	-45.3	194.7
269	-45.9	204.0
270	-57.0	204.3
271	-30.0	192.6
272	-45.3	182.4
273	5.7	189.9
274	-33.0	187.2
275	-5.1	182.7
276	-26.4	183.0
277	11.4	177.3
278	-26.1	185.1
279	-22.5	189.9
280	-11.1	172.5
281	-10.2	180.9
282	16.5	171.6
283	9.9	166.2
284	24.0	160.8
285	13.2	154.2
286	46.8	148.5
287	31.5	160.8
288	-8.7	169.5
289	-7.2	176.7
290	-7.8	177.6
291	-11.7	179.7
292	-35.4	196.8
293	-91.8	219.0
294	-91.2	217.5

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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					

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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
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

DRAFT
Not for Distribution

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	

DRAFT
Not for Distribution

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

DRAFT
Not for Distribution

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	58.7	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						

DRAFT
Not for Distribution

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		

DRAFT
Not for Distribution

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

DRAFT
Not for Distribution

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		

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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 milliSiemens/m.

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

Coil spacing 10 m

Location	Coil 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

Location	Coil 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

Location	Coil 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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

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

Coil spacing 10 m

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

Location	Coil Midpoint	Field Site	Vertical Dipole (mS/m)	Horizontal Dipole (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

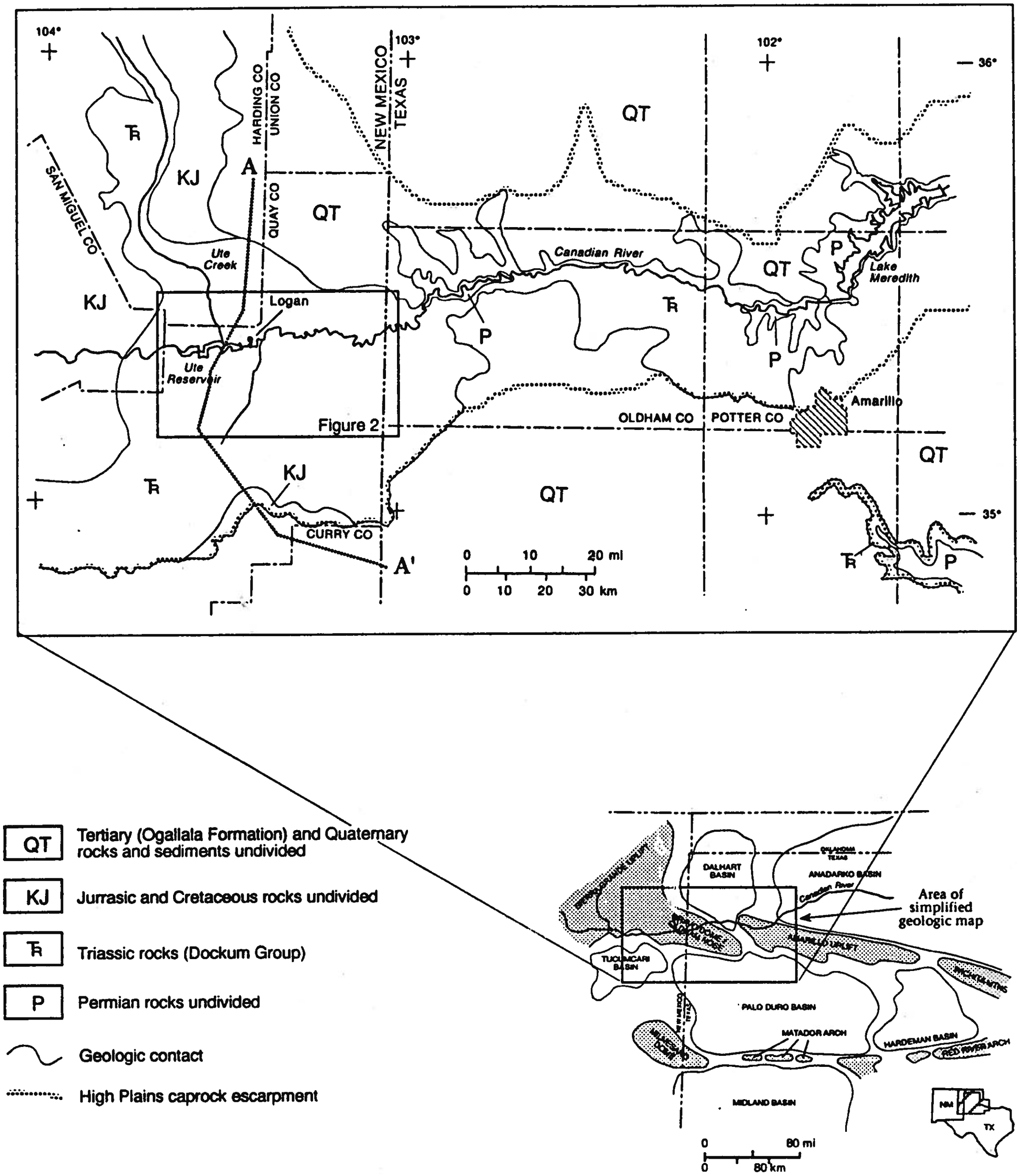

Figure 1. Regional structural elements and simplified geologic map of the Canadian River Valley in eastern New Mexico and Texas Panhandle; cross section along line A-A' is shown in figure 3 (compiled from Nicholson, 1960, fig. 1; Berkstresser and Mourant, 1963, plate 2; Eifler, 1969; Eifler and others, 1983; Suleiman and Kelley, 1985, figs. 6 and 7; Gustavson and others, 1992, fig. 1).

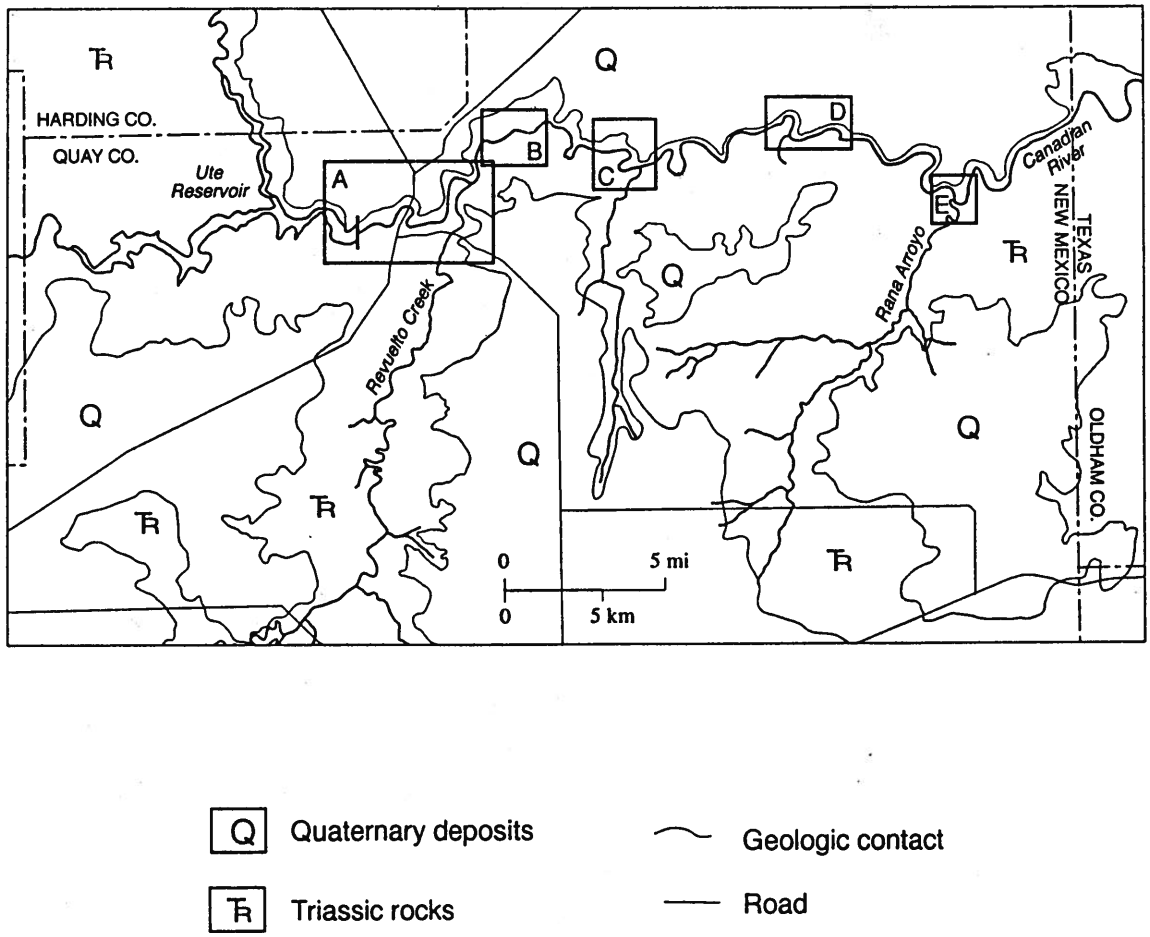

Figure 2. Generalized geologic map of eastern New Mexico portion of Canadian River showing outlines of areas selected for electromagnetic surveys: A - Ute Dam to Revuelto Creek, B - Claer well area, C- Jones well area, D - "Dunes" area, E - Rana Canyon area.

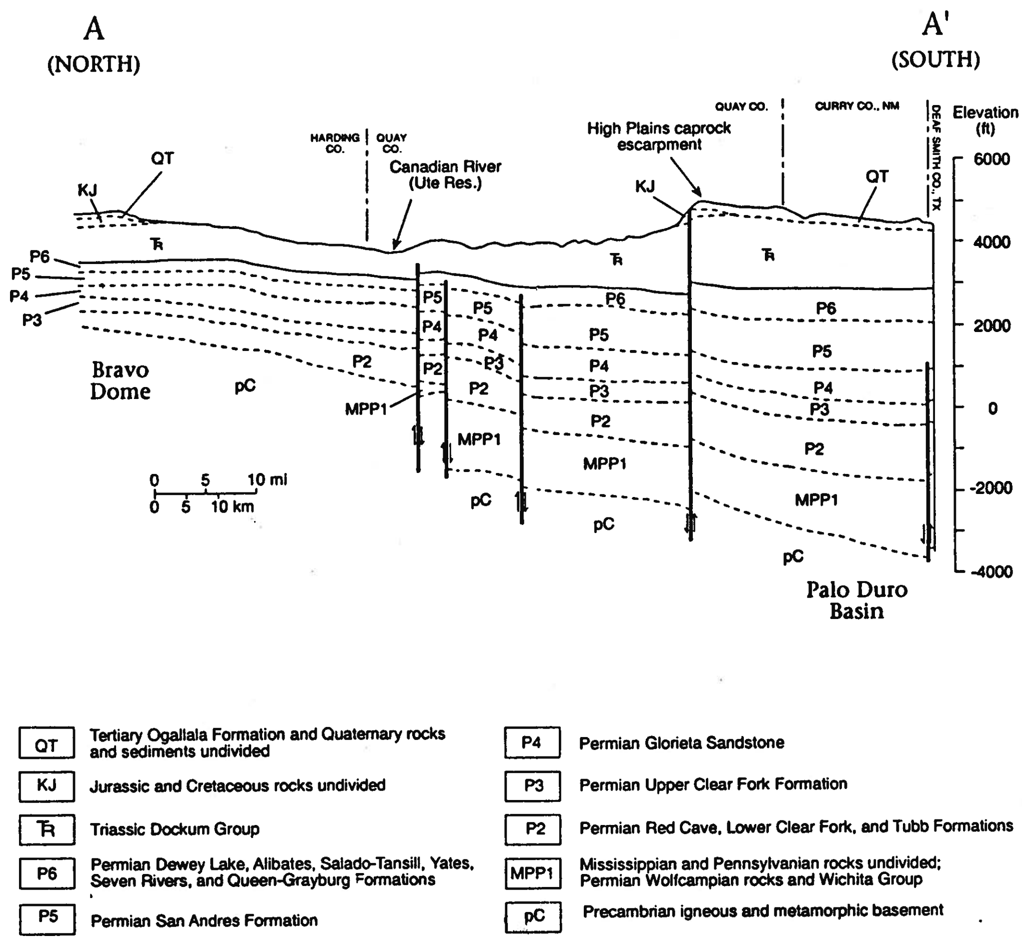

Figure 3. Simplified north-south geologic cross section through Canadian River Valley in eastern New Mexico; line of section shown in figure 1. Thinning of Permian units P2 through P6 is due mainly to dissolution of halite from the updip margin of the Palo Duro Basin (adapted from Murphy, 1987, figs.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

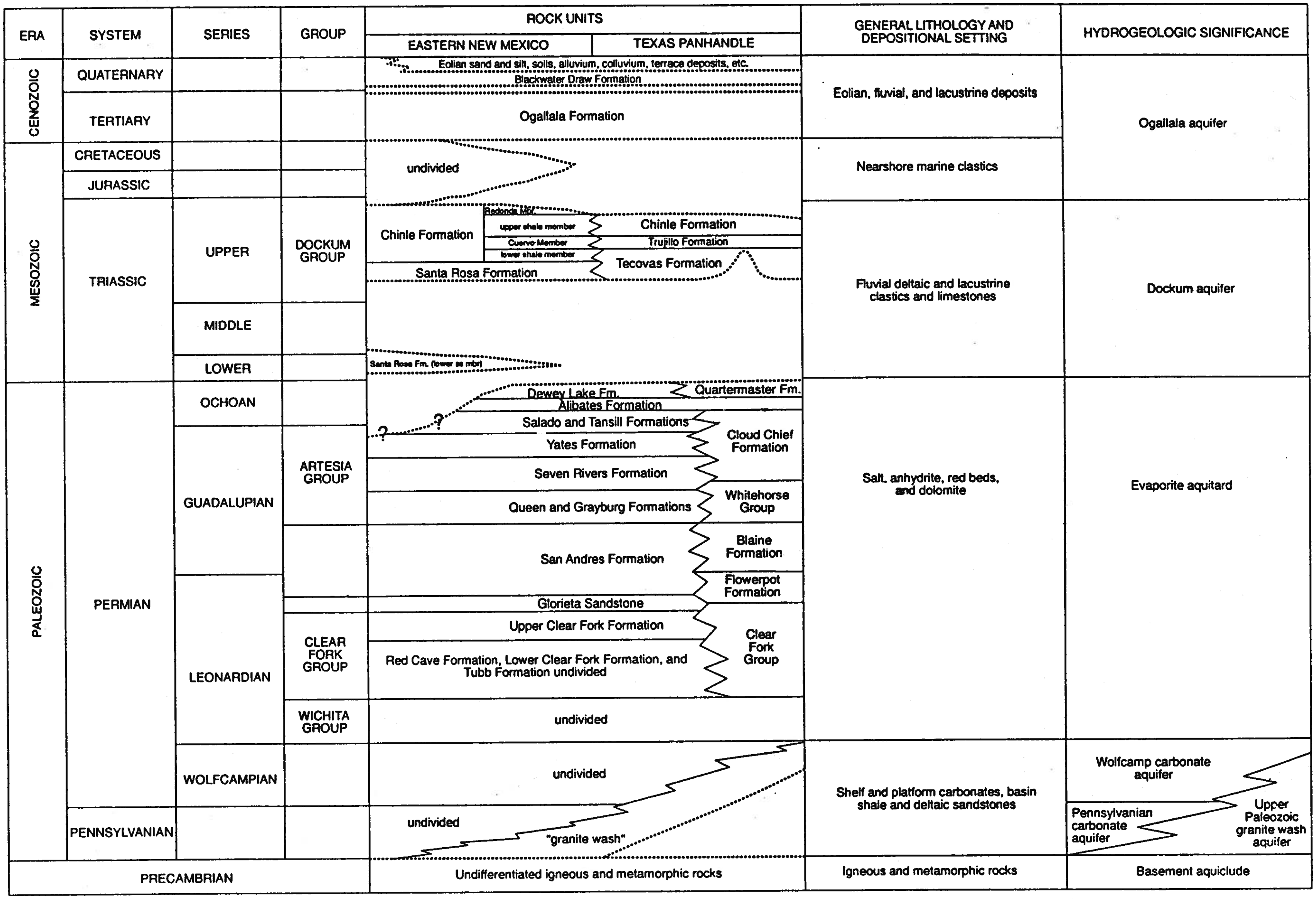

Figure 4. Stratigraphic nomenclature of strata beneath the Canadian River Valley in eastern New Mexico and Texas Panhandle (compiled from Gustavson and others, 1980, fig. 3; Presley, 1981, table 1; Bassett and Bentley, 1983, table 1; Lucas and Kues, 1985, fig. 1; Lucas and others, 1985, fig. 6; Murphy,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

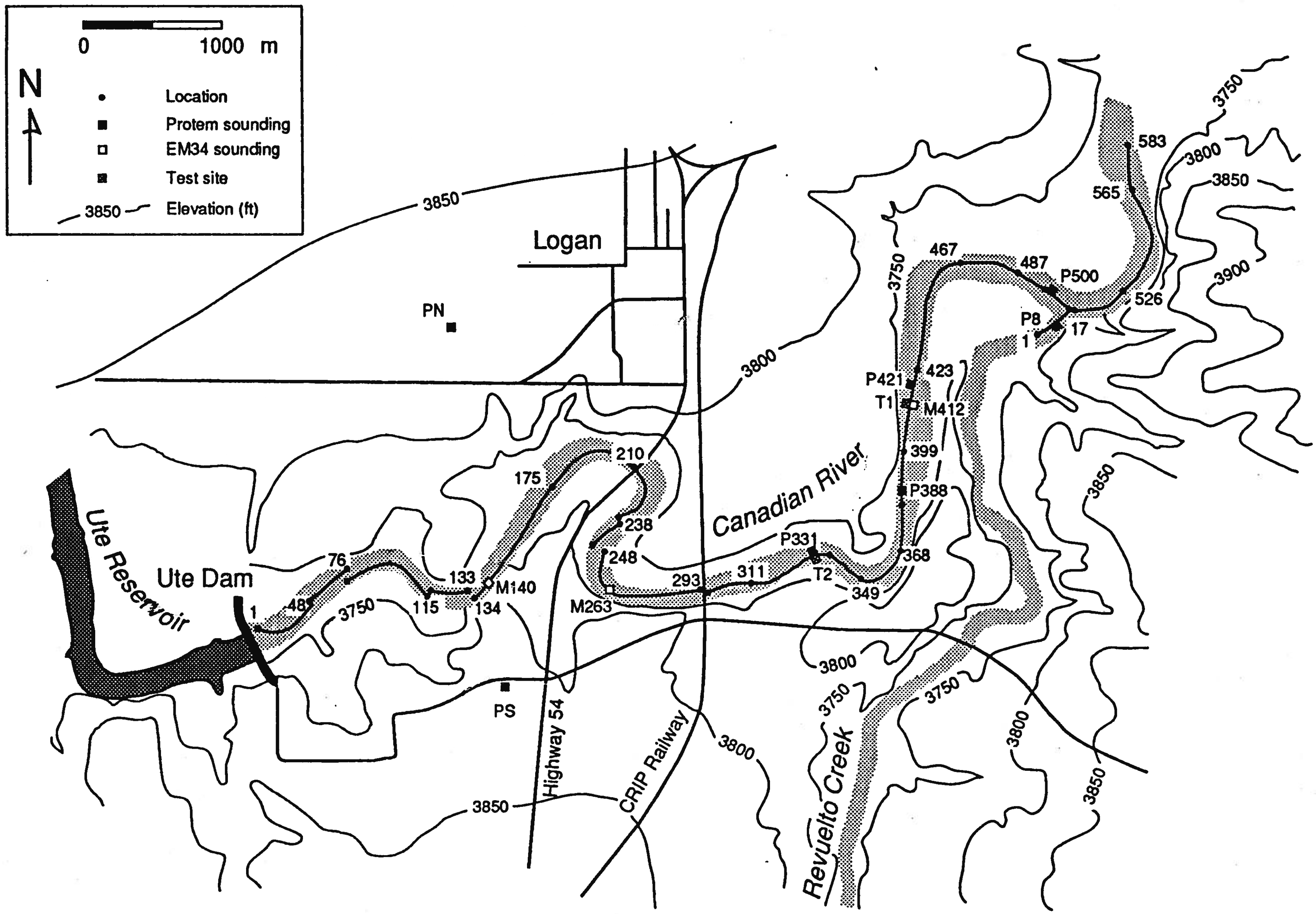

Figure 5. Topographic map of the Ute Reservoir and Revuelto Creek area showing station locations, test sites, and sounding sites. Map location shown on fig. 2.

CR002

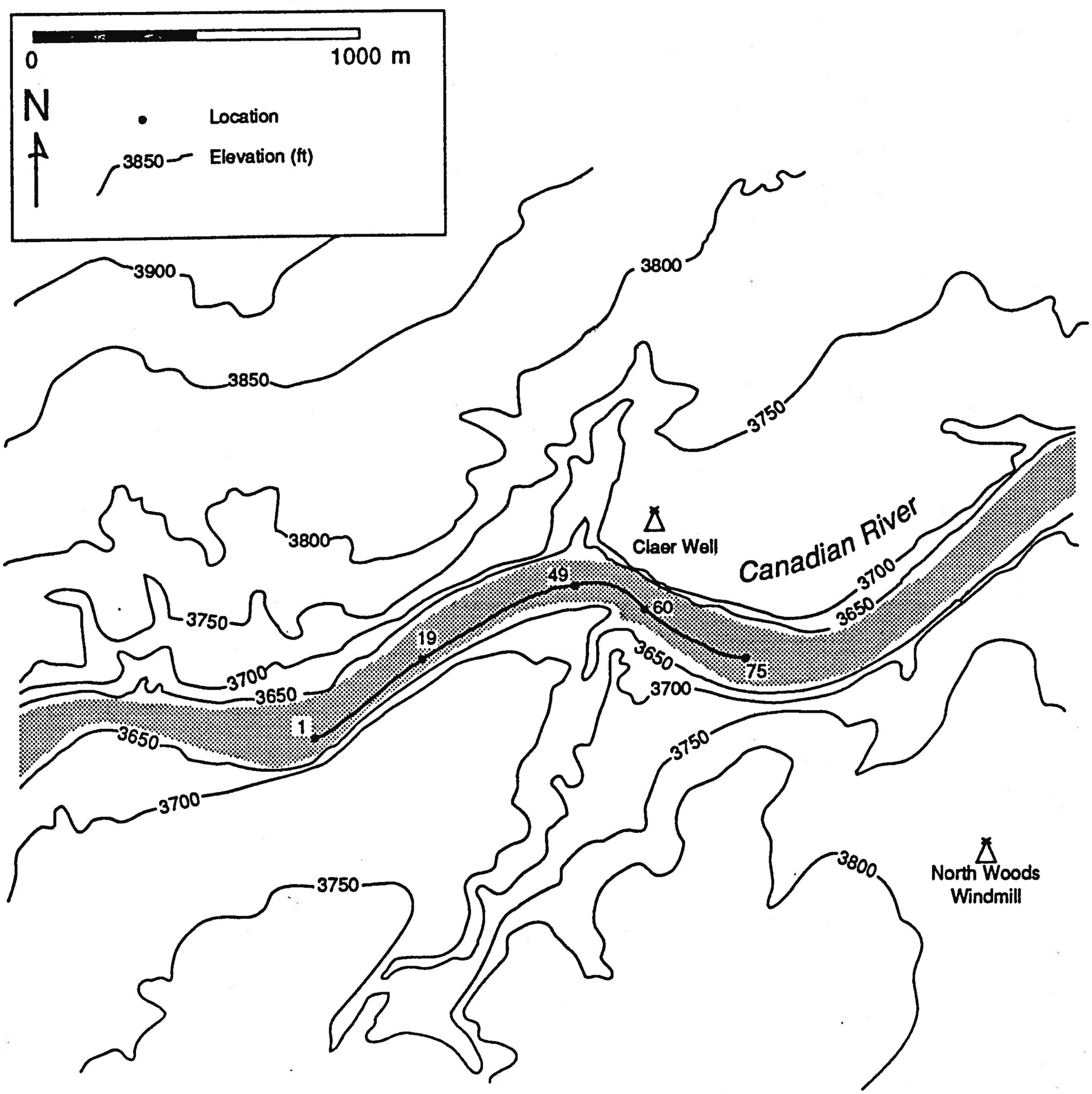

Figure 6. Topographic map of the Claer Well area of the Canadian River showing station locations. Map location shown on fig. 2.

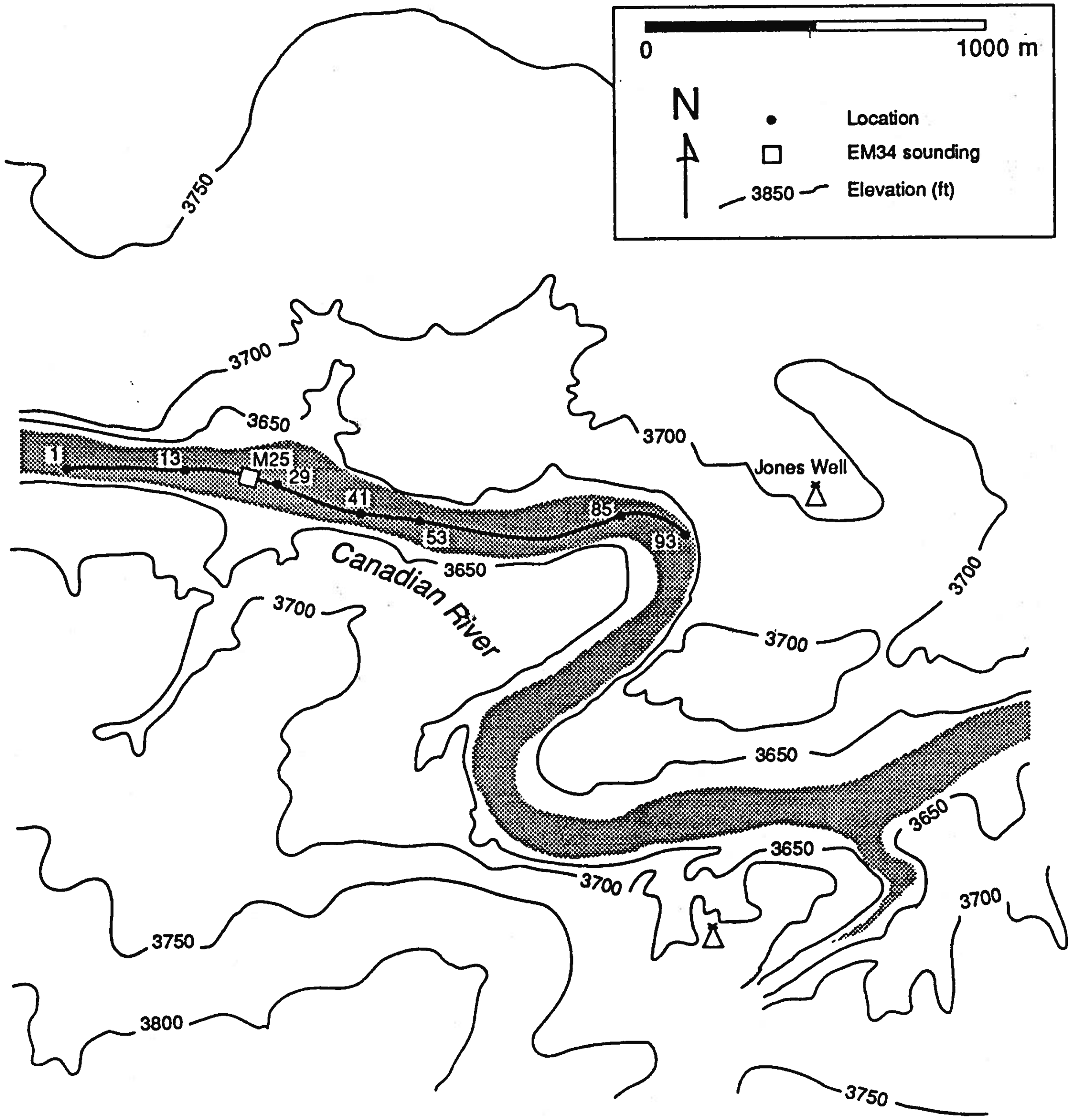

Figure 7. Topographic map of the Jones Well area of the Canadian River showing station locations and sounding sites. Map location shown on fig. 2.

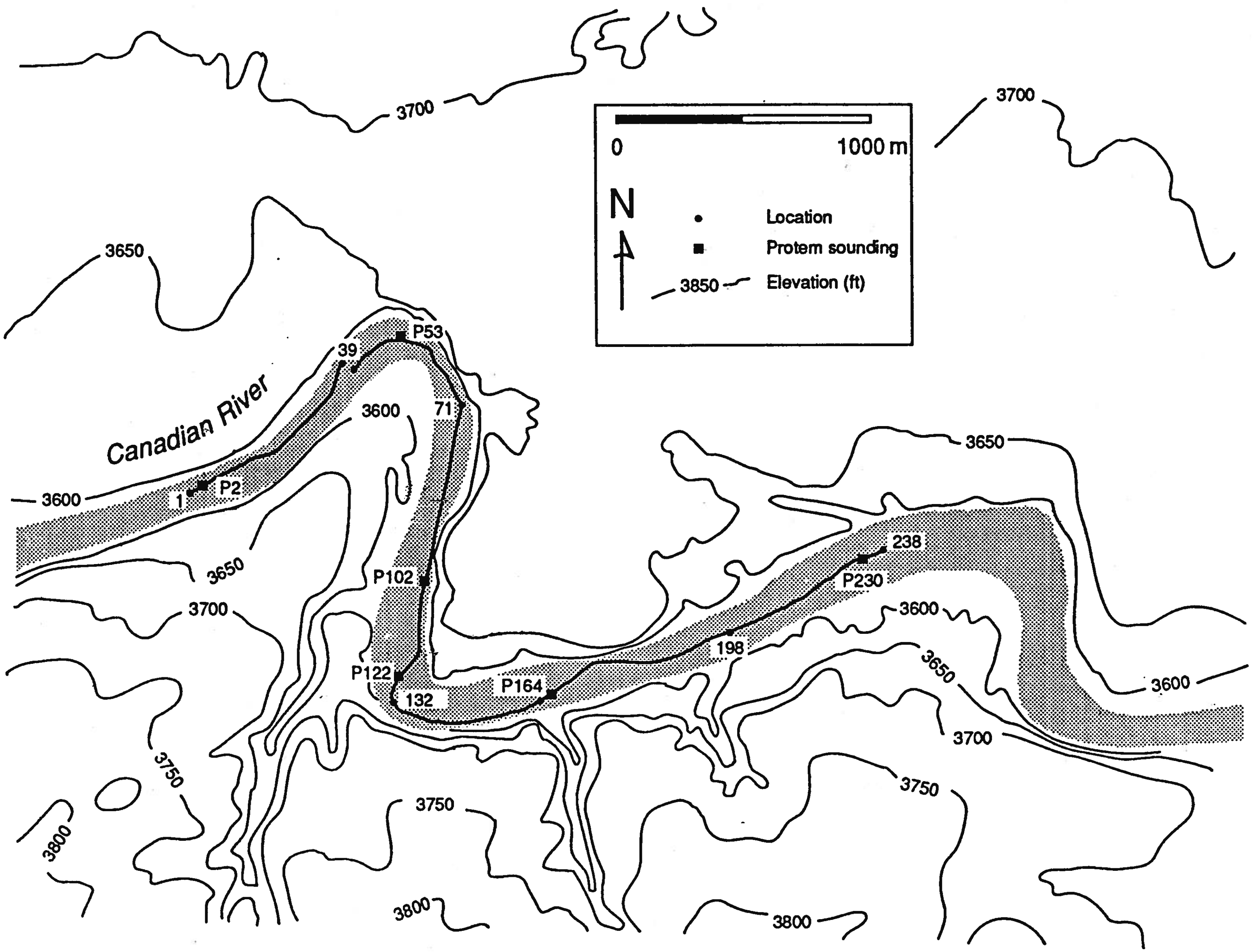

Figure 8. Topographic map of the Dunes area of the Canadian River showing station locations and sounding sites. Map location shown on fig. 2.

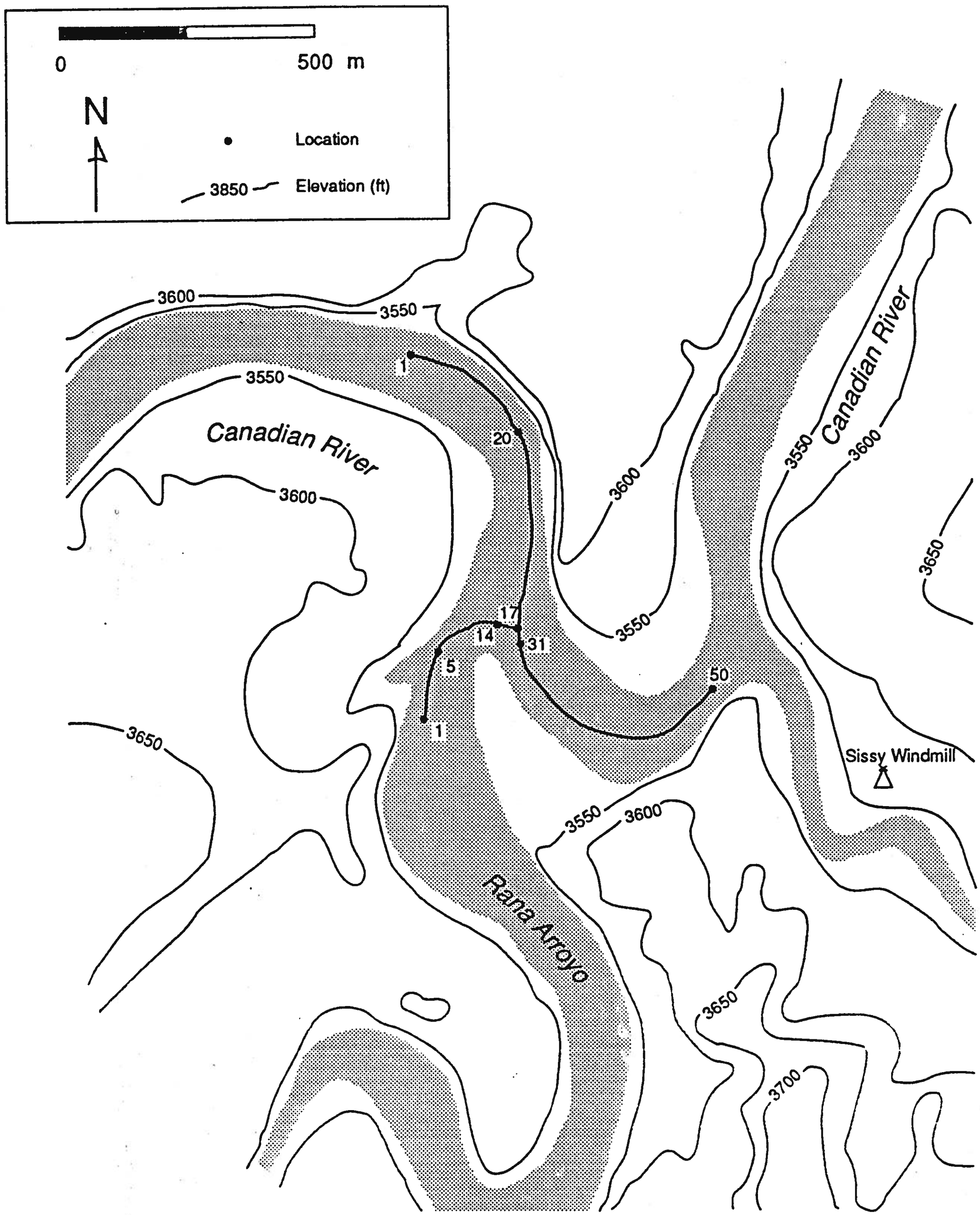

Figure 9. Topographic map of the Rana Canyon area of the Canadian River showing station locations. Map location shown on fig. 2.

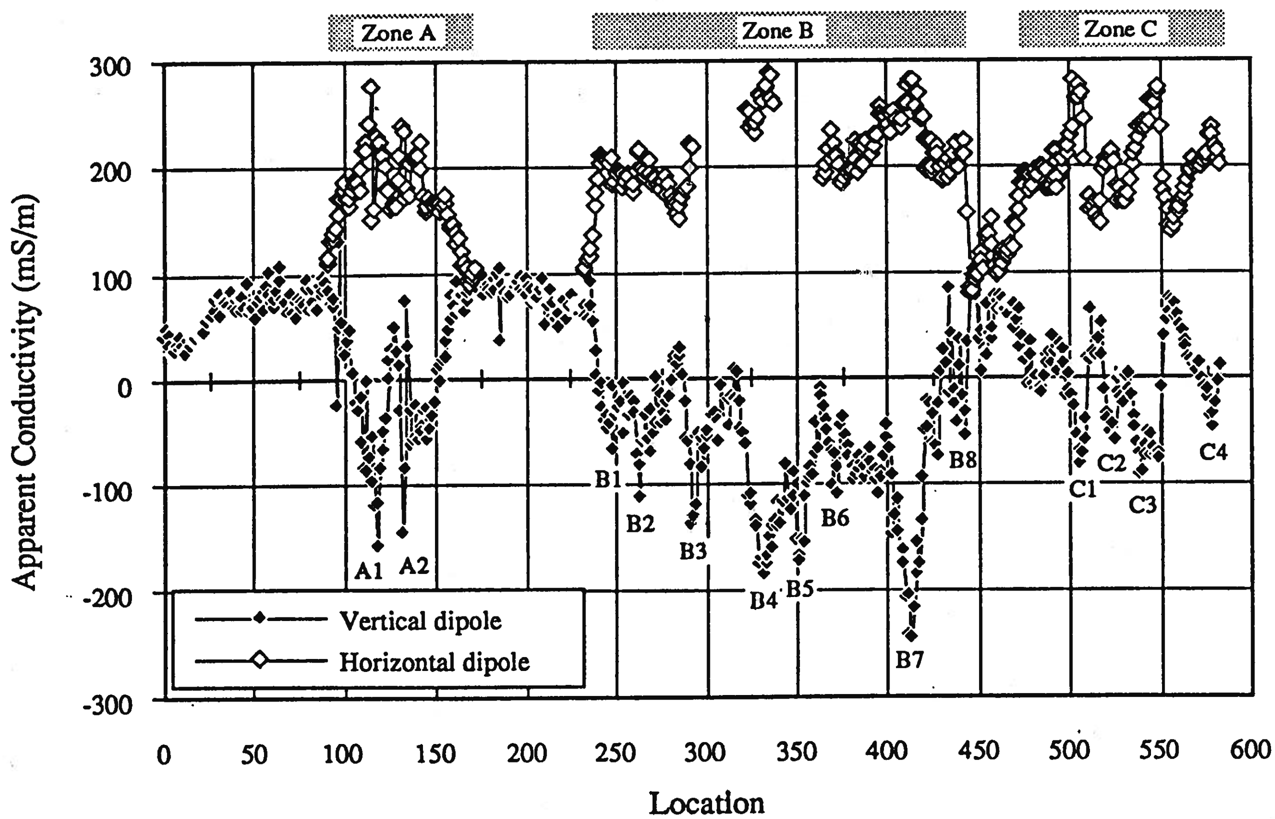

Figure 10. Apparent conductivity (in milliSiemens/m) along the Canadian River from Ute Reservoir to beyond Revuelto Creek. Locations 1 through 76 are 10 m apart; all others are 20 m apart.

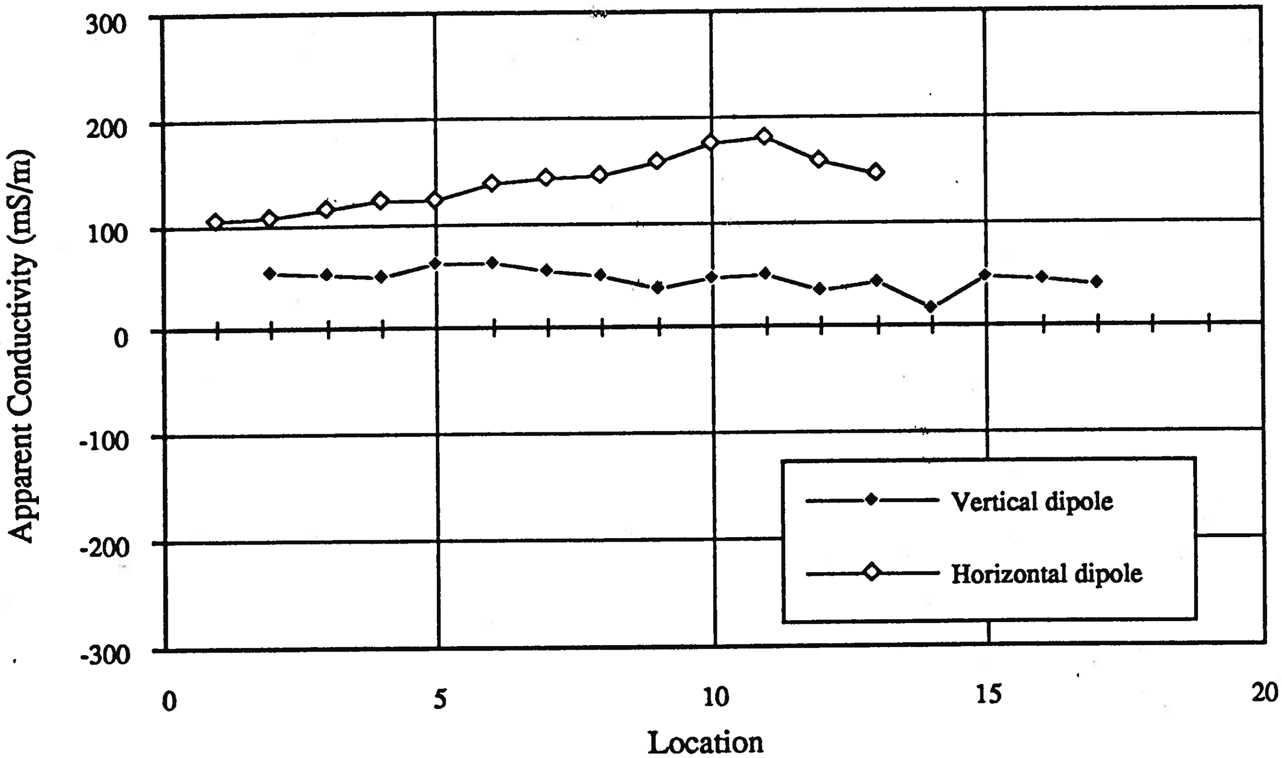

Figure 11. Apparent conductivity (in milliSiemens/m) along Revuelto Creek (fig. 5). Locations are 20 m apart.

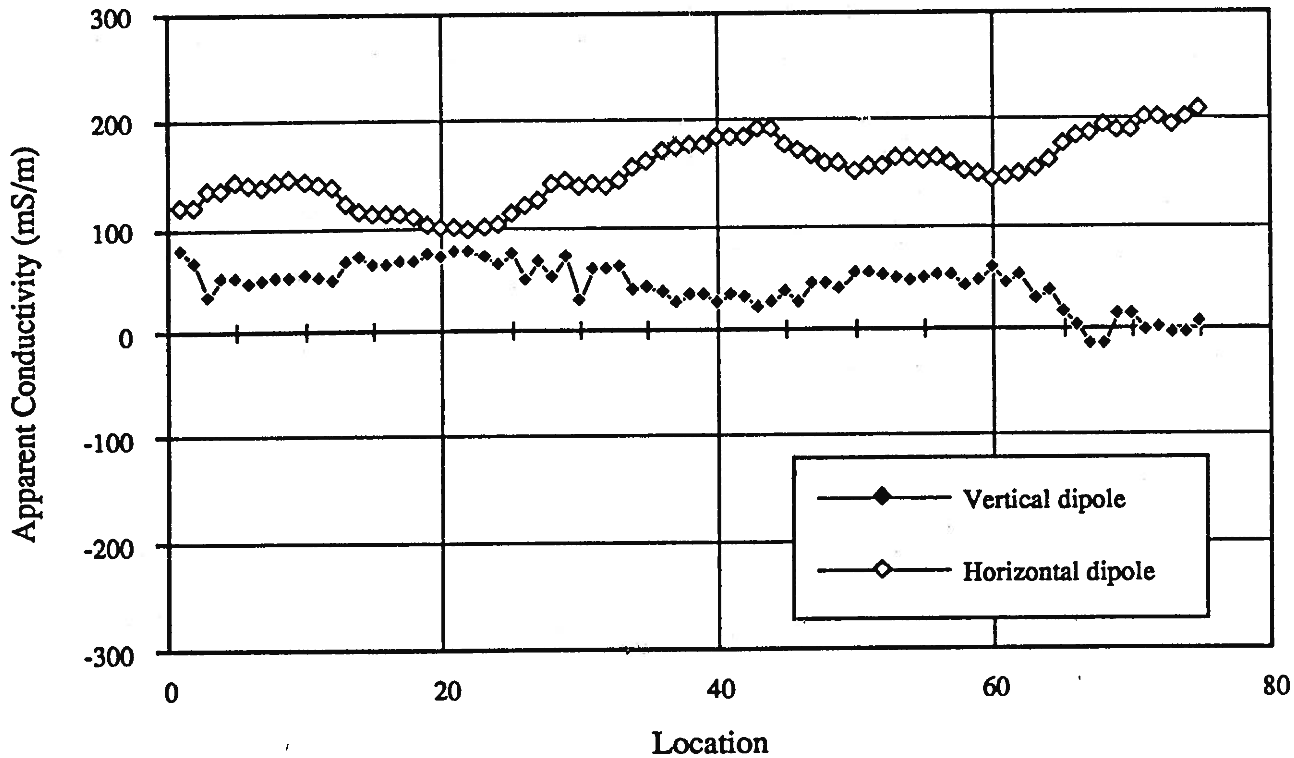

Figure 12. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Claer Well area (fig. 6). Locations are 20 m apart.

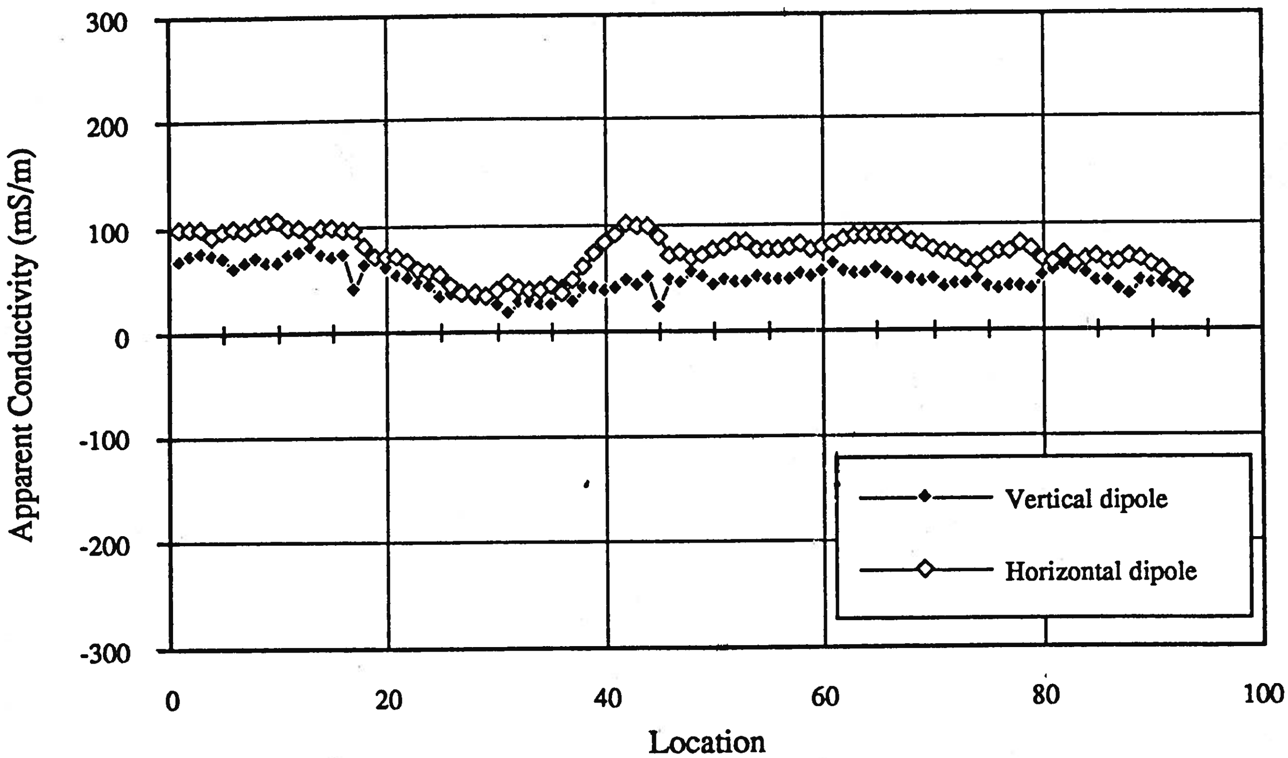

Figure 13. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Jones Well area (fig. 7). Locations are 20 m apart.

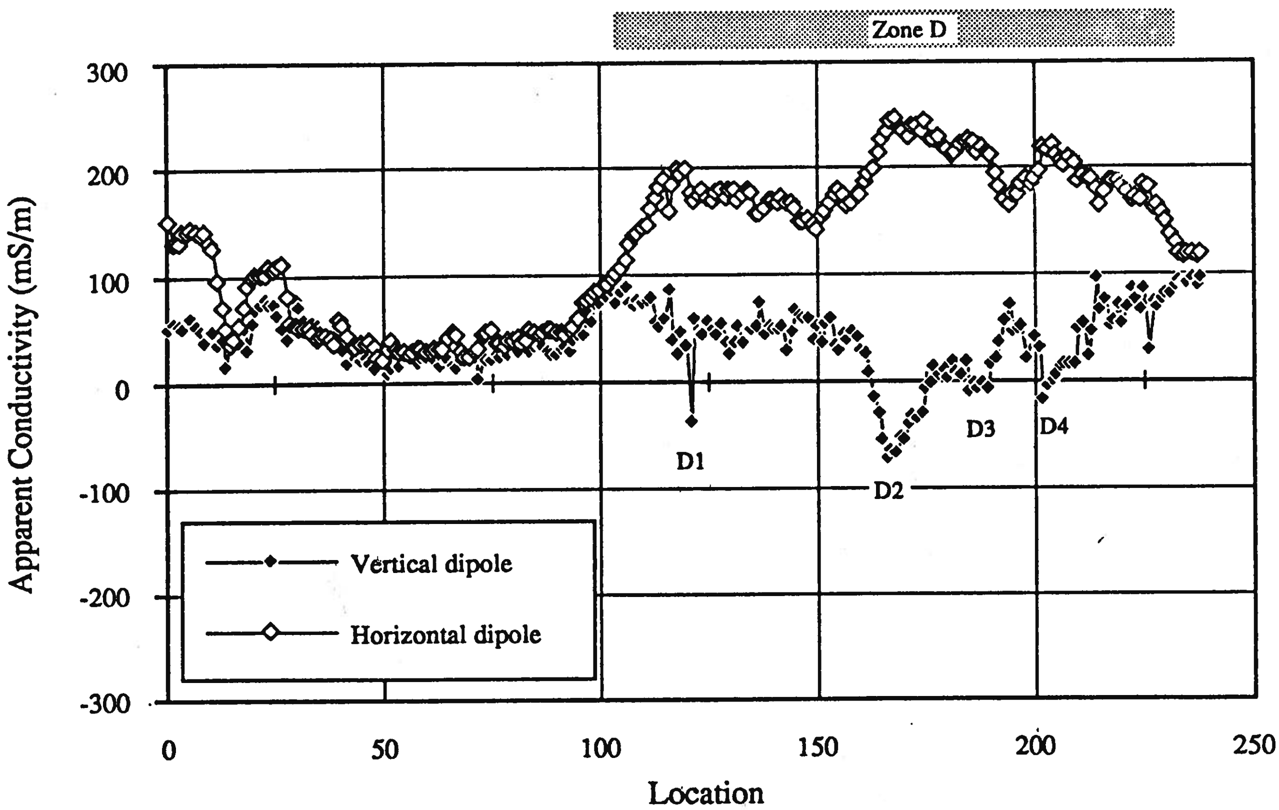

Figure 14. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Dunes area (fig. 8). Locations are 20 m apart.

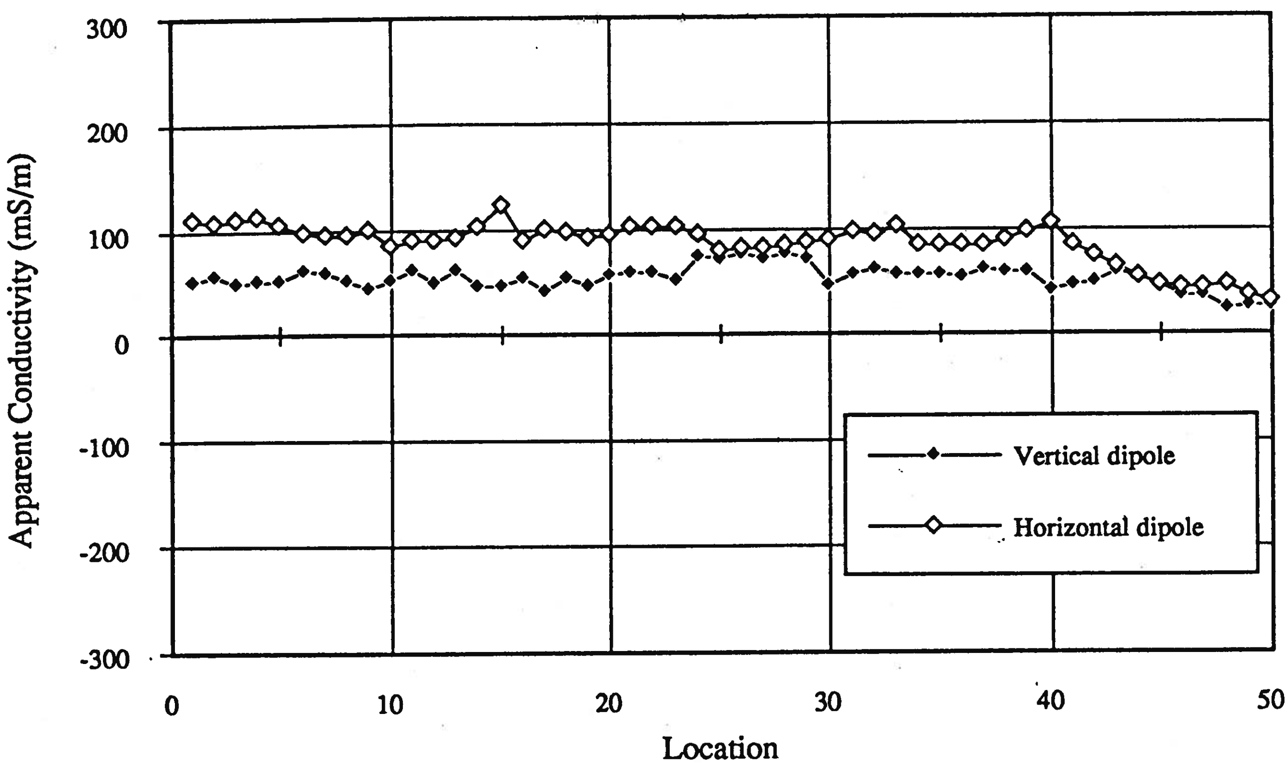

Figure 15. Apparent conductivity (in milliSiemens/m) along the Canadian River in the Rana Canyon area (fig. 9). Locations are 20 m apart.

CR012

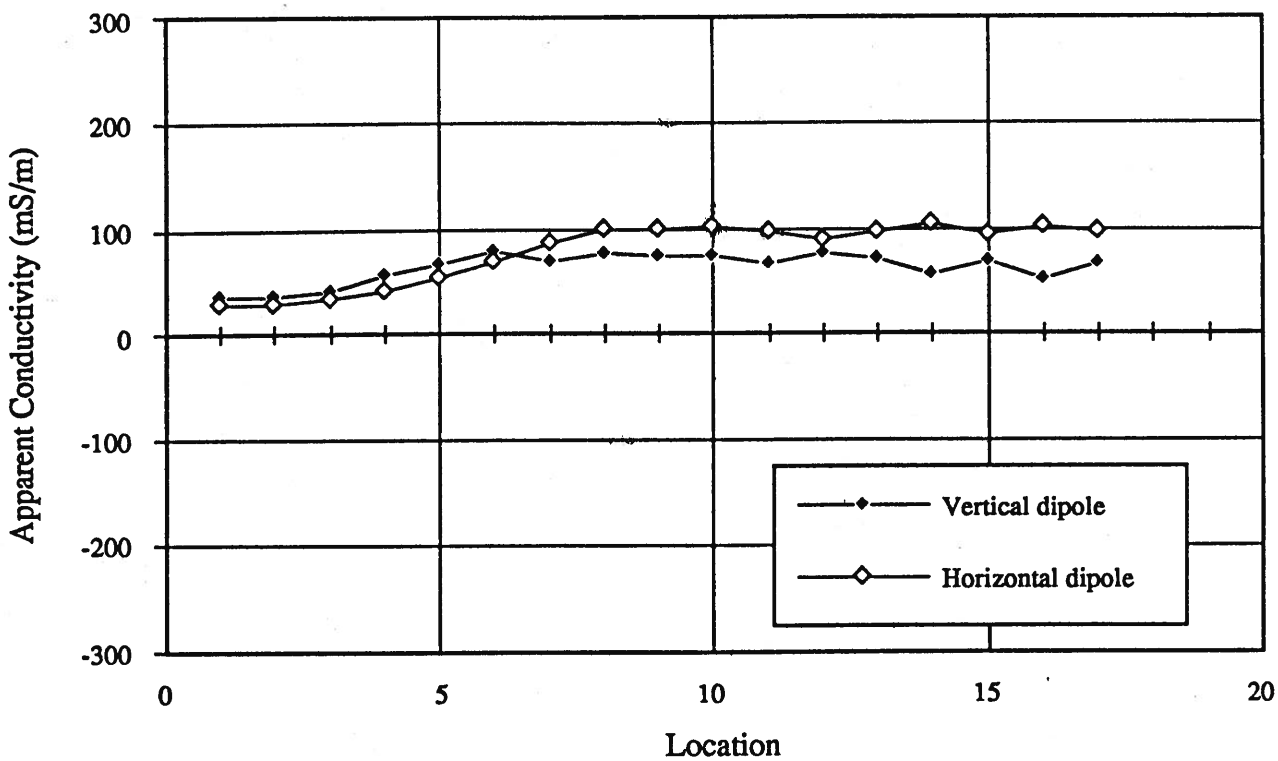

Figure 16. Apparent conductivity (in milliSiemens/m) along Rana Arroyo (fig. 9). Locations are 20 m apart.

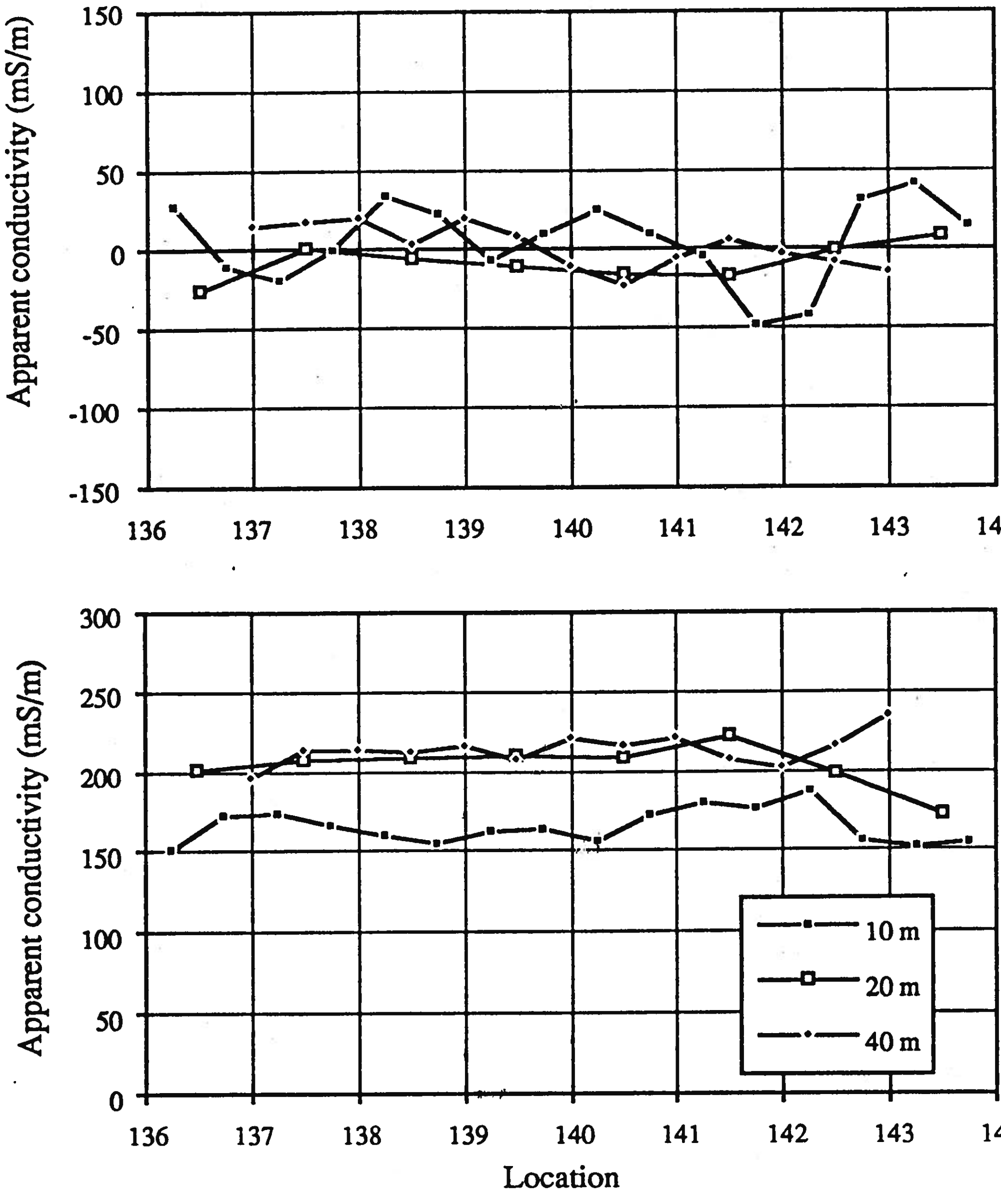

Figure 17. Apparent conductivity at 10, 20, and 40 m coil separations between locations 136 and 144, Ute Reservoir to Revuelto Creek. Vertical dipole coil orientation is shown on upper panel and horizontal dipole orientation is shown on lower panel. Numbered locations are 20 m apart.

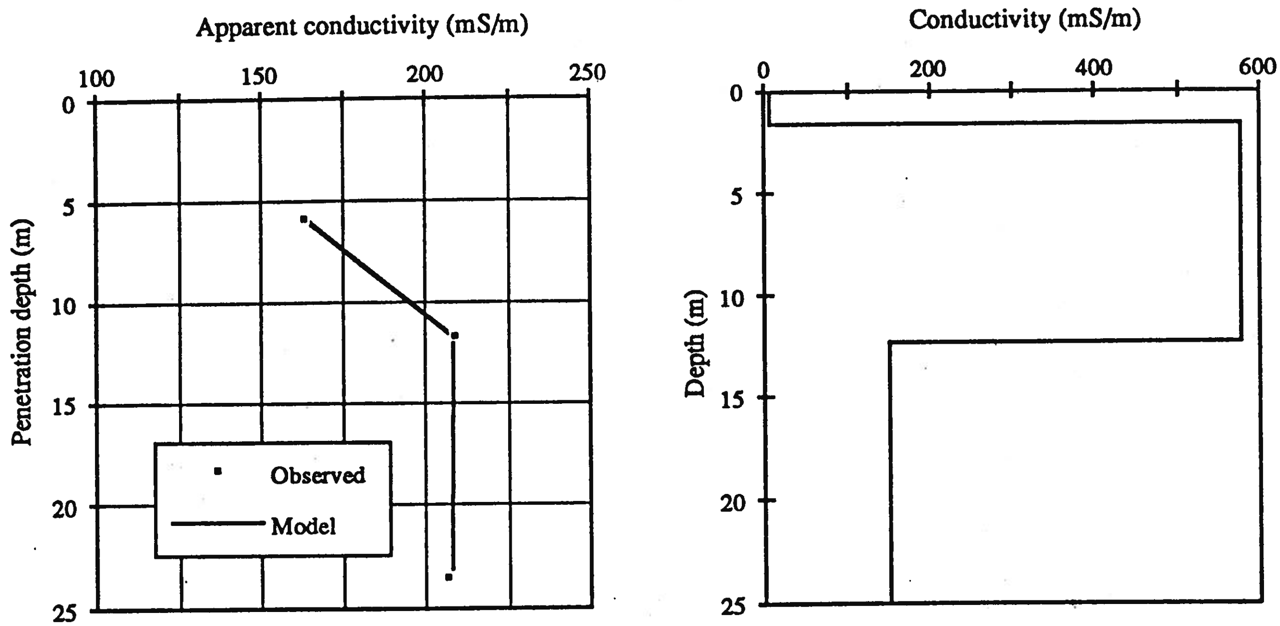

Figure 18. Left: Apparent conductivity versus penetration depth for multiple coil spacings (horizontal dipole orientation) at Ute to Revuelto site M140 (fig. 5). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed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

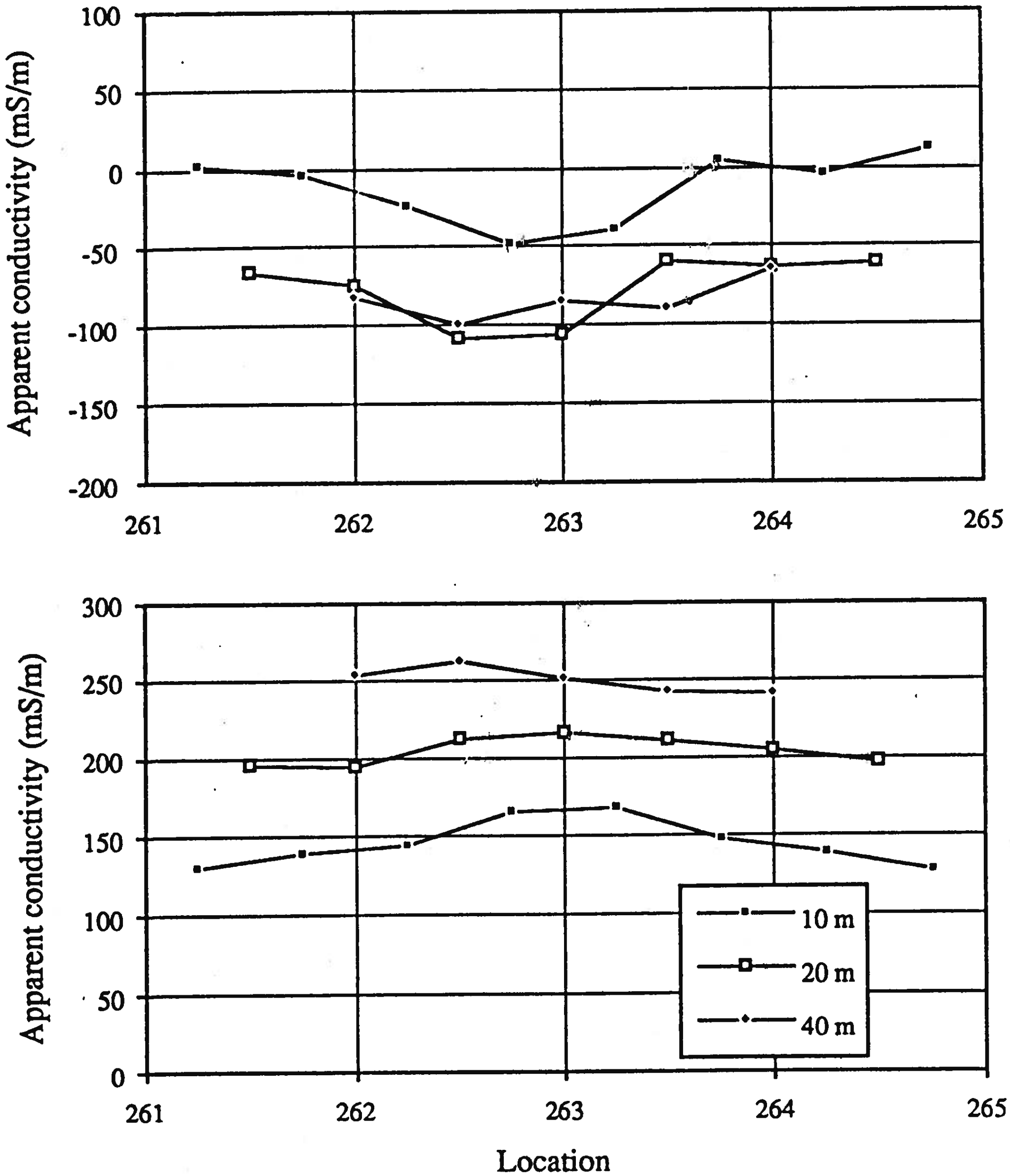

Figure 19. Apparent conductivity at 10, 20, and 40 m coil separations between locations 261 and 265, Ute Reservoir to Revuelto Creek. Vertical dipole coil orientation is shown on upper panel and horizontal dipole orientation is shown on lower panel. Numbered locations are 20 m apart.

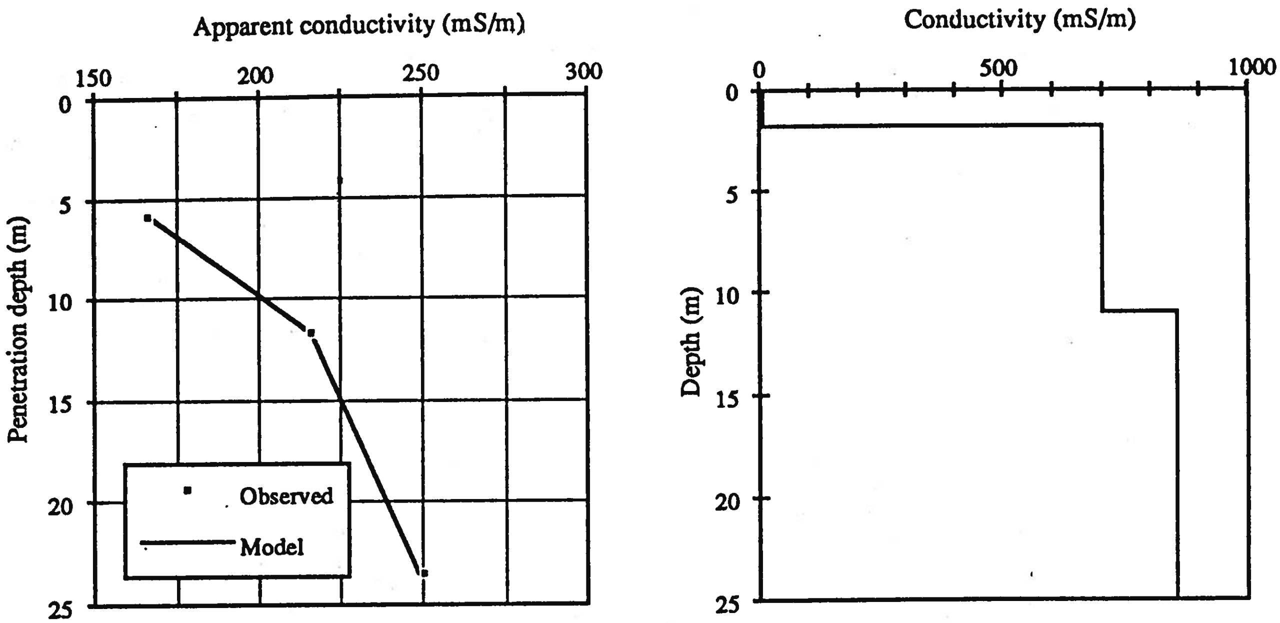

Figure 20. Left: Apparent conductivity versus penetration depth for multiple coil spacings (horizontal dipole orientation) at Ute to Revuelto site M263 (fig. 5). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed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

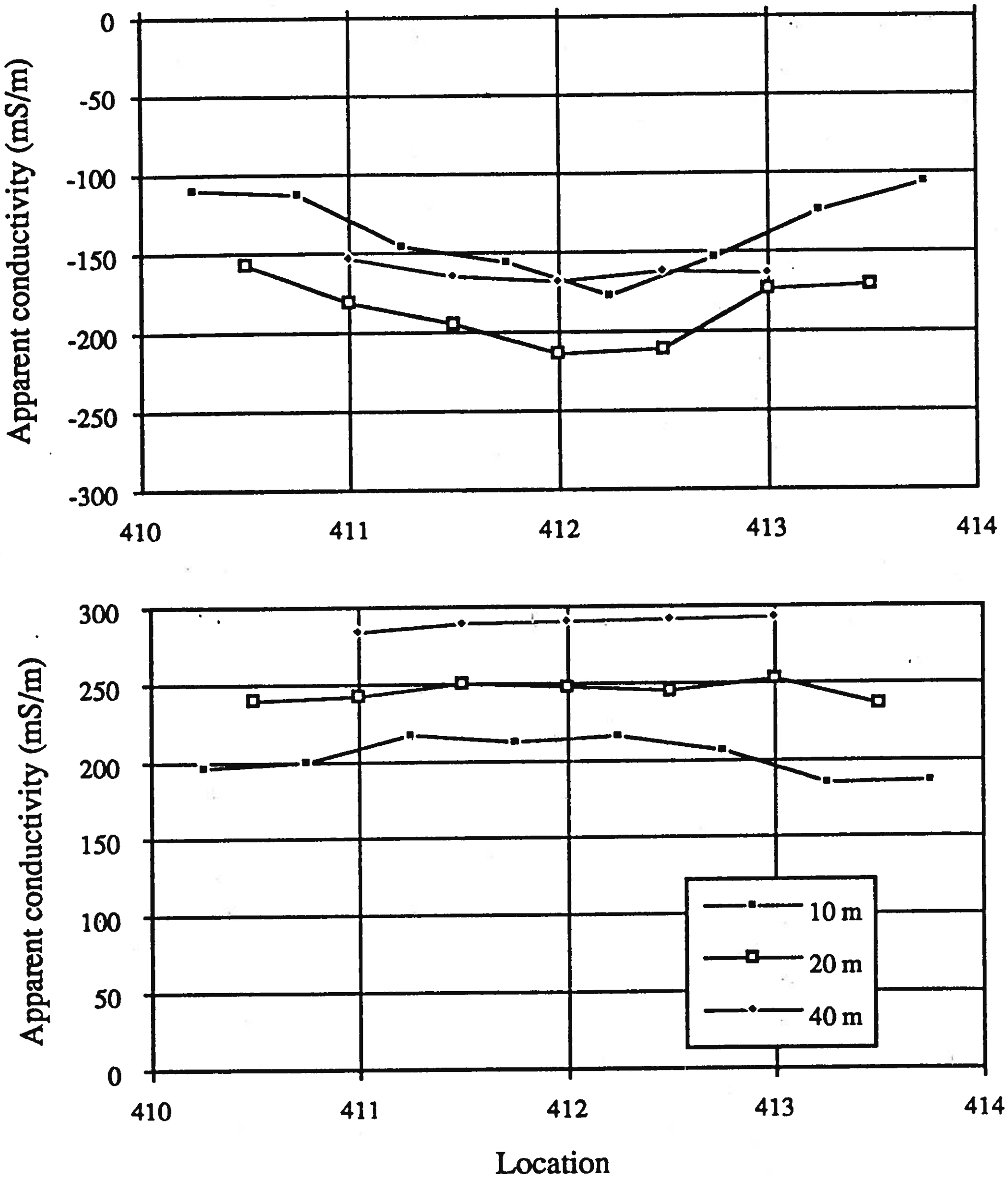

Figure 21. Apparent conductivity at 10, 20, and 40 m coil separations between locations 410 and 414, Ute Reservoir to Revuelto Creek. Vertical dipole data are shown on upper panel and horizontal dipole data are shown on lower panel. Numbered locations are 20 m apart.

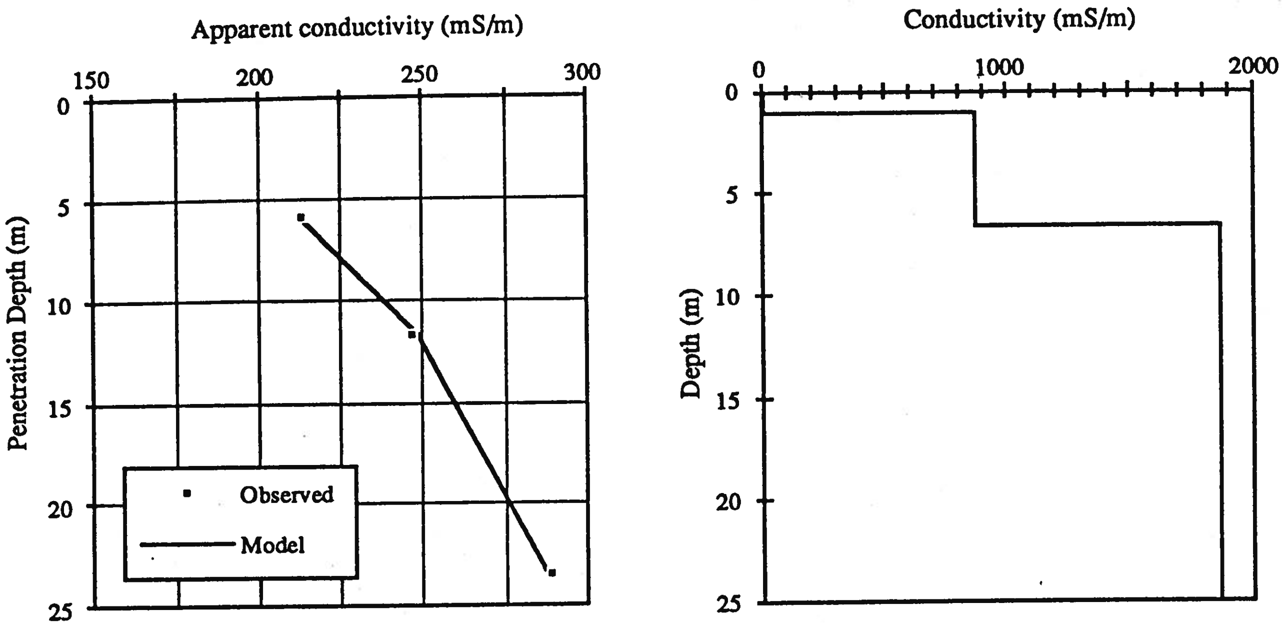

Figure 22. Left: Apparent conductivity versus penetration depth for multiple coil spacings (horizontal dipole orientation) at Ute to Revuelto site M412 (fig. 5). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed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

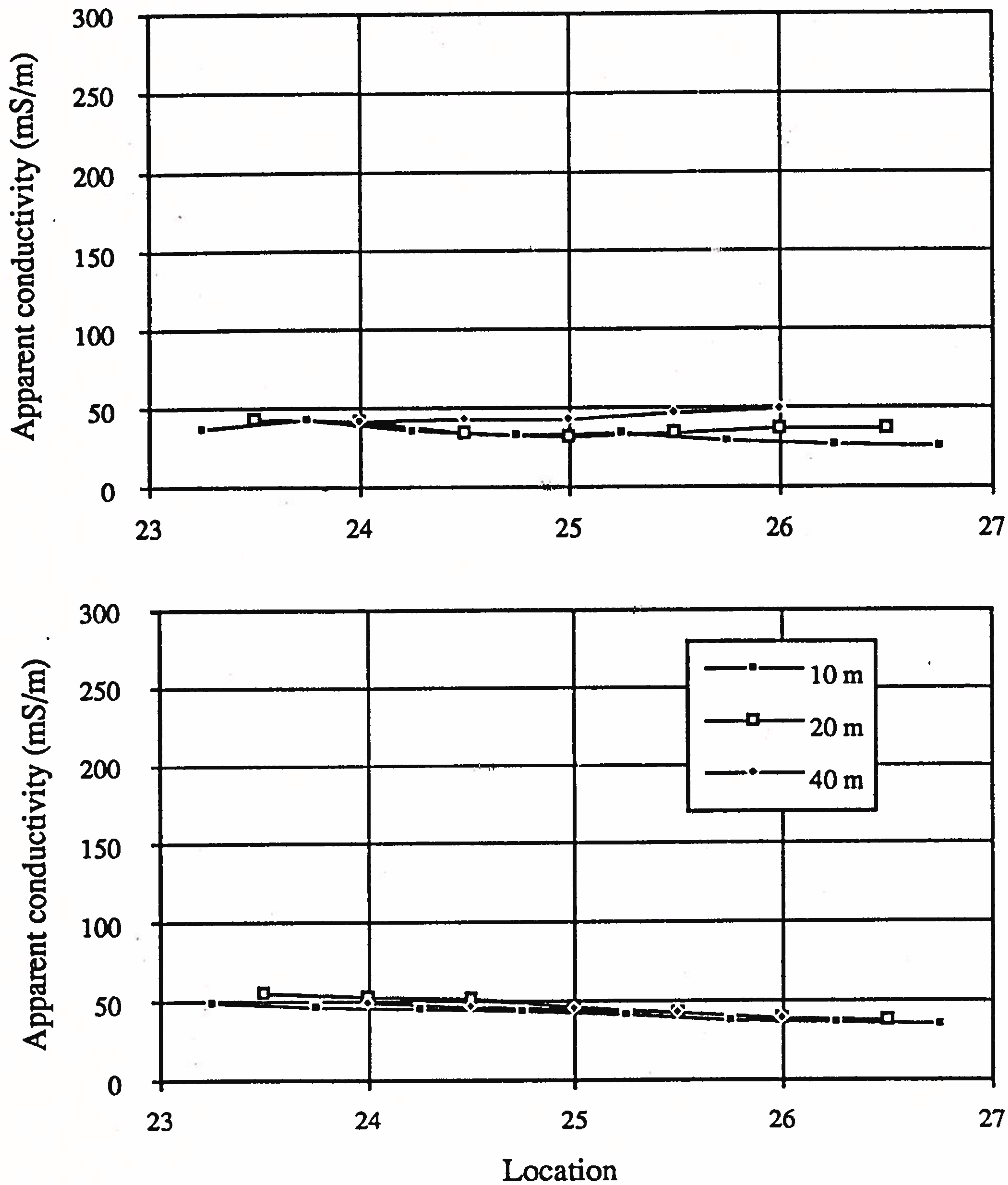

Figure 23. Apparent conductivity at 10, 20, and 40 m coil separations between locations 23 and 27, Jones Well area. Vertical dipole data are shown on upper panel and horizontal dipole data are shown on lower panel. Numbered locations are 20 m apart.

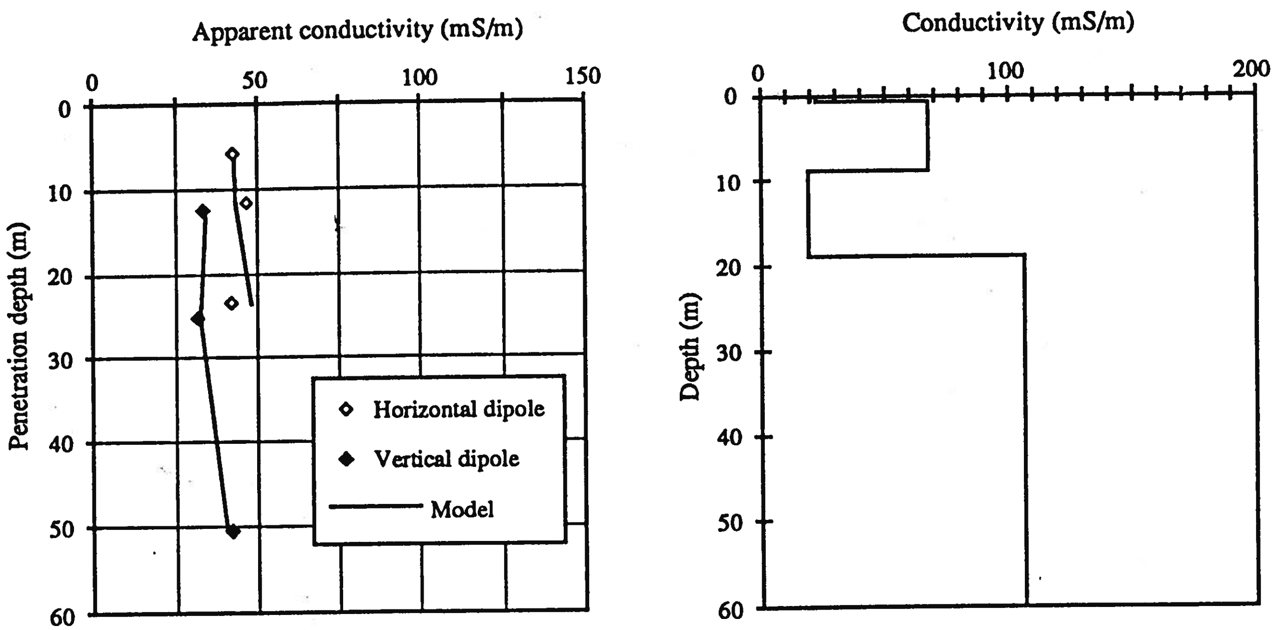

Figure 24. Left: Apparent conductivity versus penetration depth for multiple coil spacings (both dipole orientations) at Jones Well site M25 (fig. 7). Observed data and synthetic data from the best-fit conductivity model are both plotted. Right: best-fit conductivity model derived from observed data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

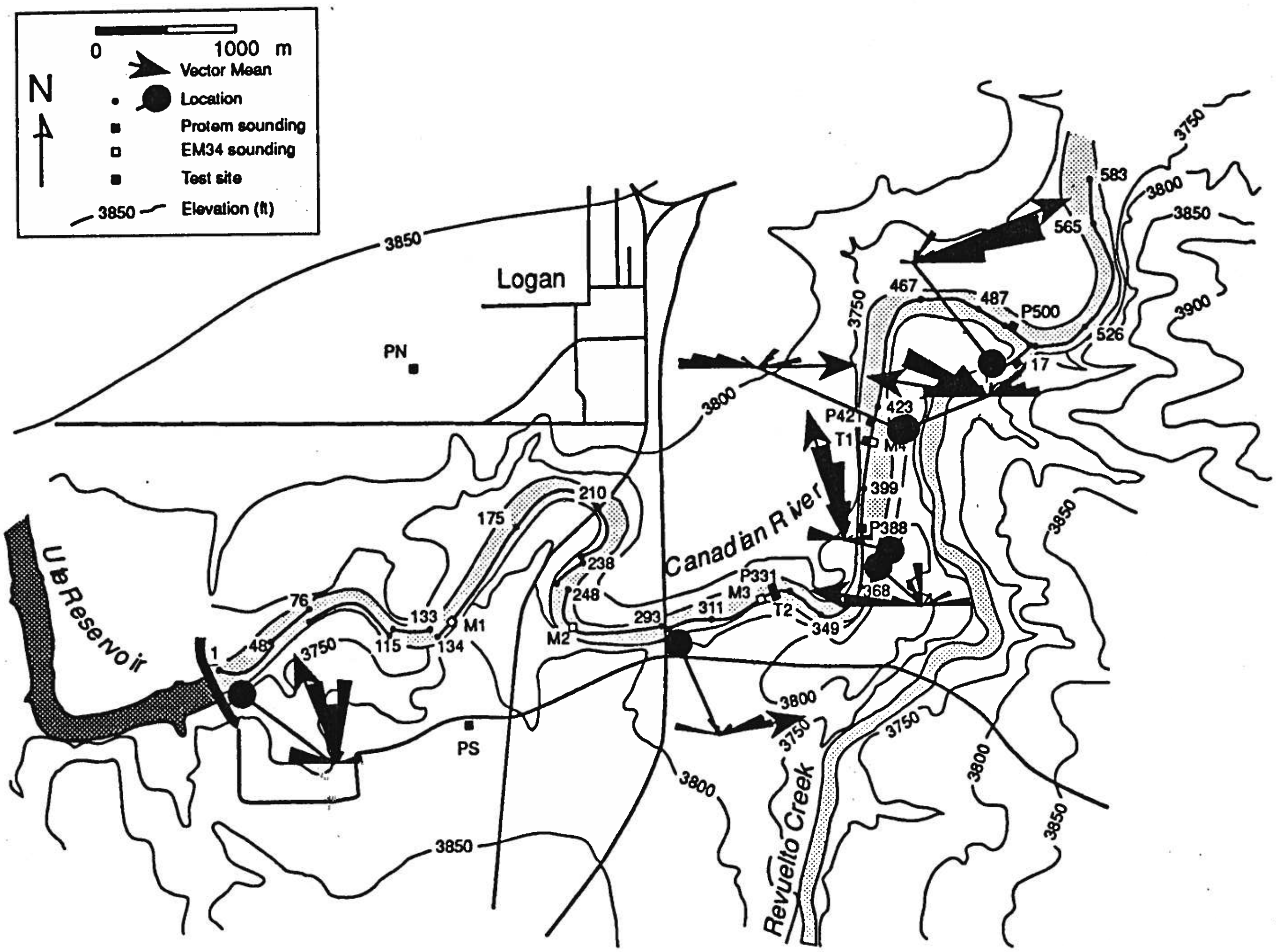

Figure 25. Simplified topographic map of the Canadian River Valley between Ute Reservoir and Revuelto Creek showing locations of joint measurements plotted as half roses and vector means. See fig. 2 for location.

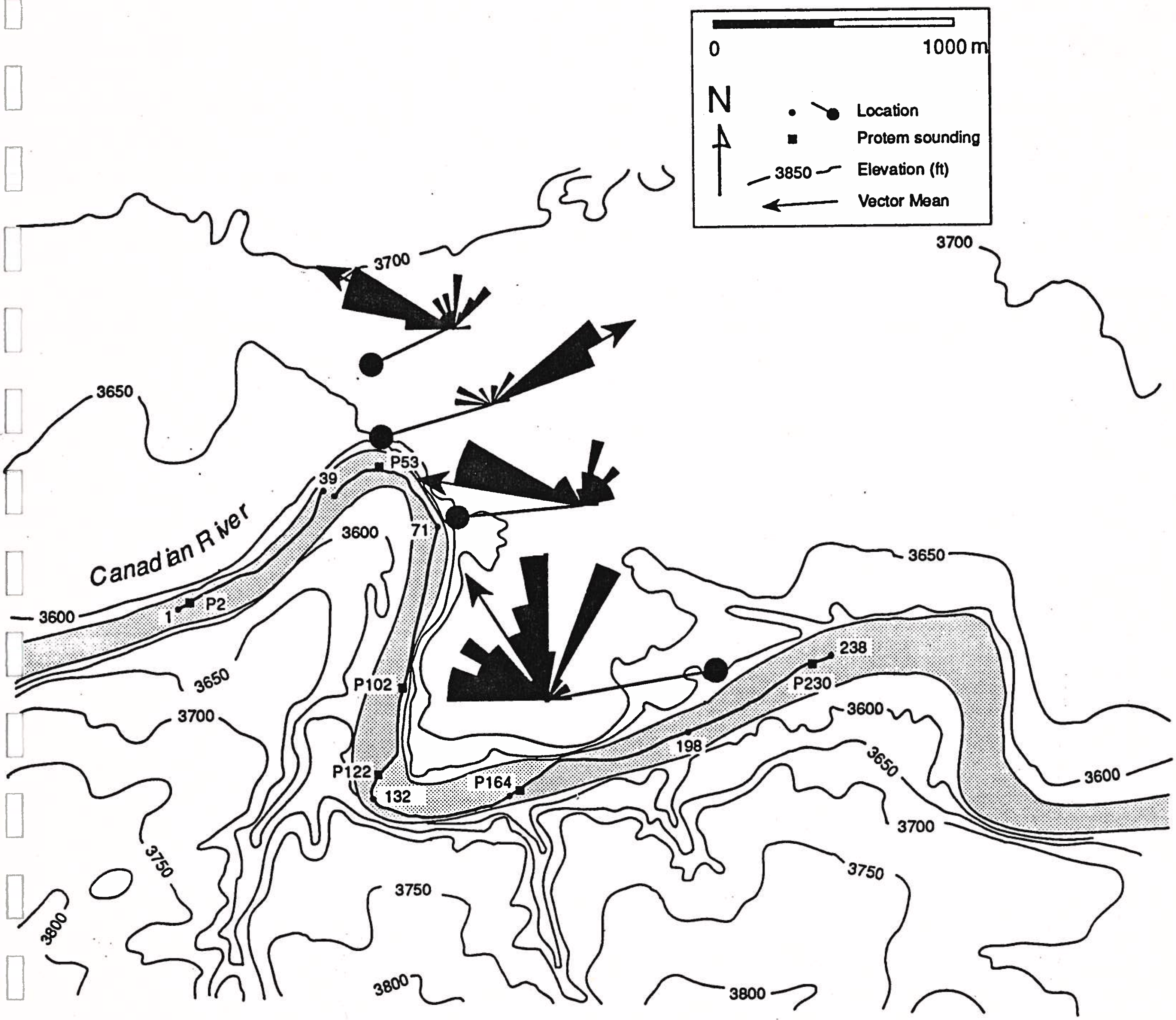

Figure 26. Simplified topographic map of the dunes area along the Canadian River showing joint data plotted as half roses and vector means. See fig. 2 for location.

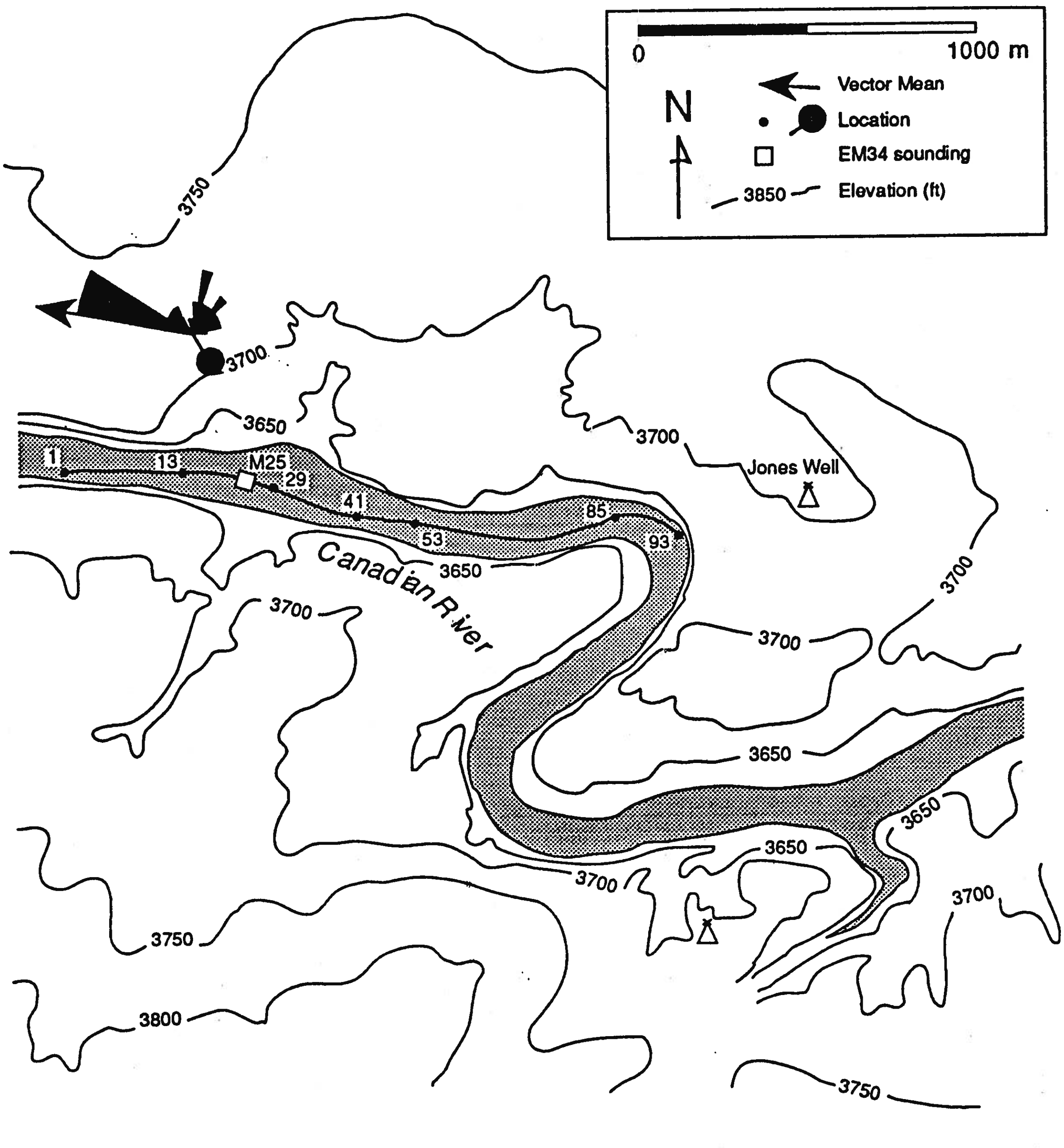

Figure 27. Simplified topographic map of the Jones well area along the Canadian River showing joint data plotted as a half rose diagram and its vector mean. See fig. 2 for location.

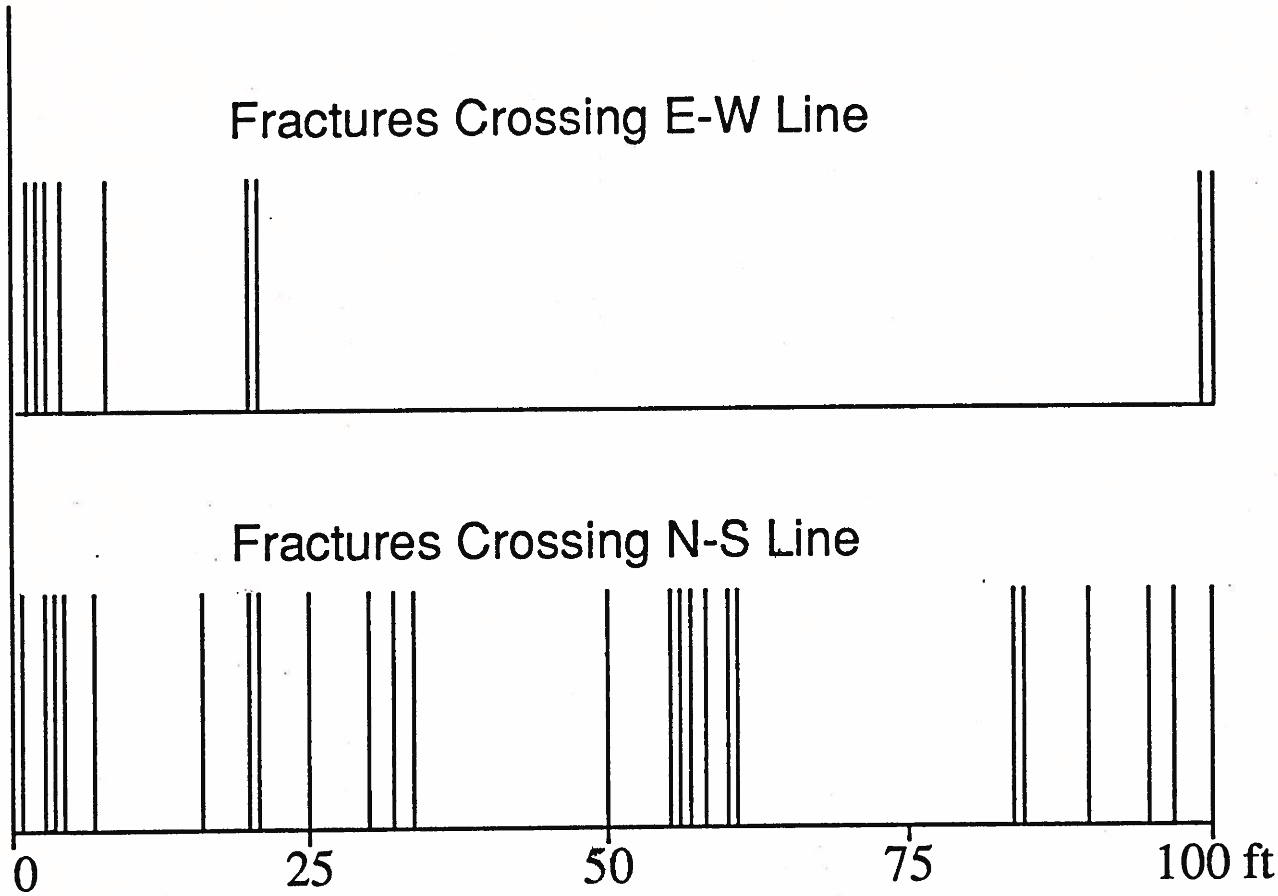

Figure 28. Plot of the number and spacing of joints crossing 33-m- (100-ft) long tapes oriented east-west and north-south southeast of location 423 on the Canadian River (fig. 25). Note that east-west joints, which cross the north-south line, are more common than north-south joints, and that joints that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

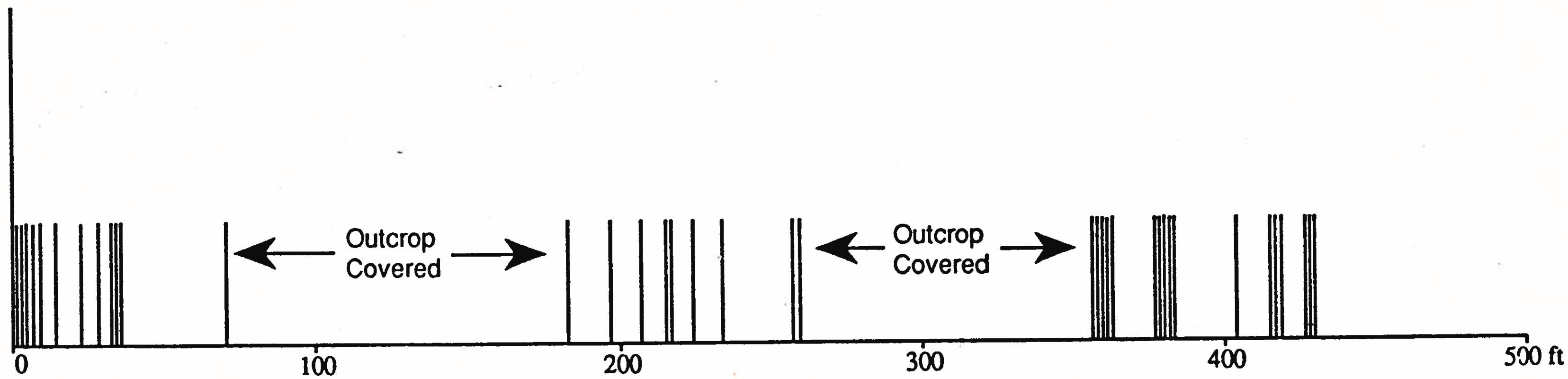

Figure 29. Plot of joint spacing southeast of location 423 on the Canadian River (fig. 25) along a 500 ft north-south exposure. Note that the joints are apparently grouped.

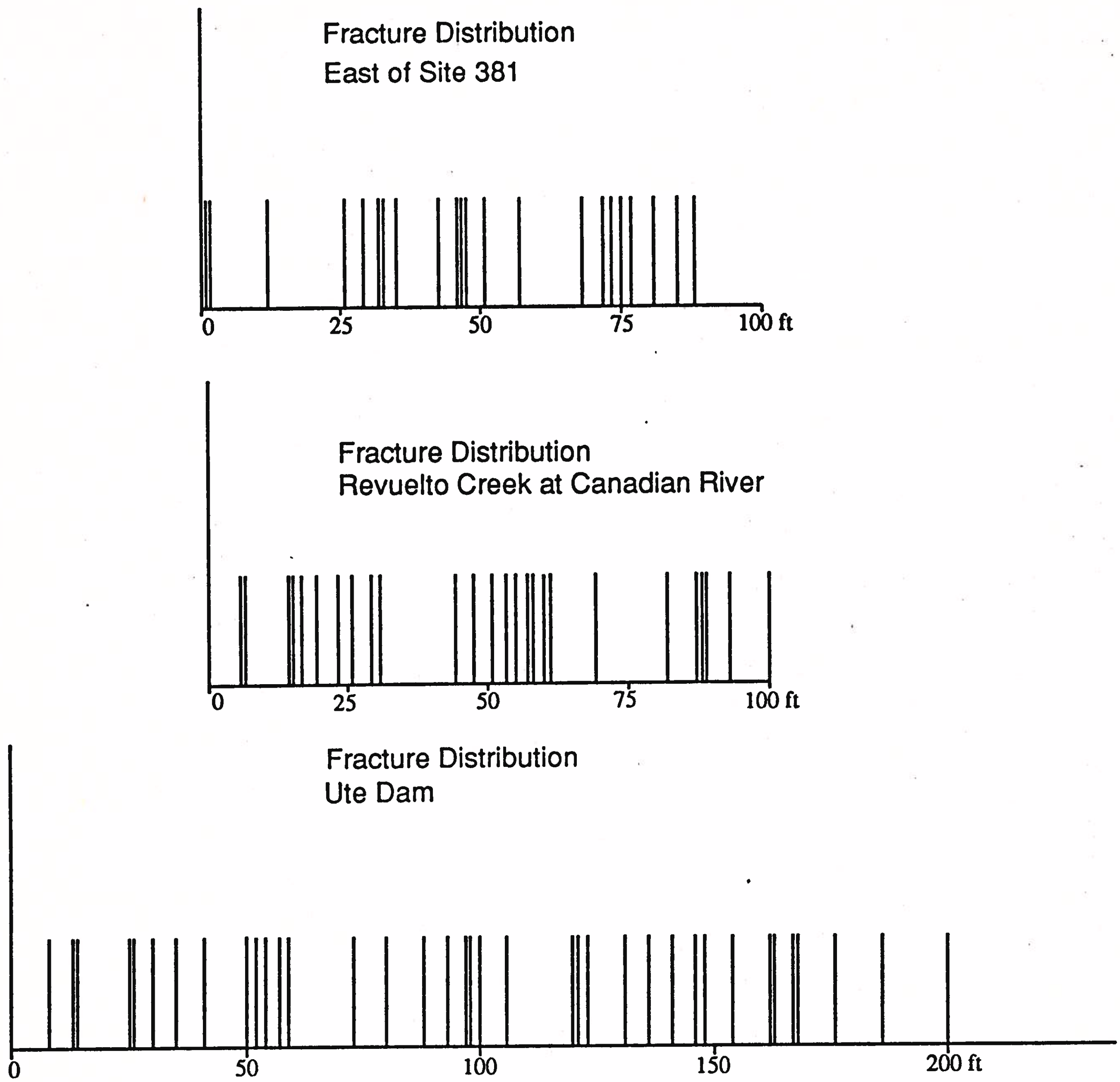

Figure 30. Plots of the spacing of joints intersecting a 33-m- (100-ft-) long tape at a location southeast of P388 on the Canadian River and at the foot of Ute Dam (fig. 25), and a plot of joints intersecting as 66-m- (200-ft-) tape at the intersection of Revuelto Creek and the Canadian River. Note that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

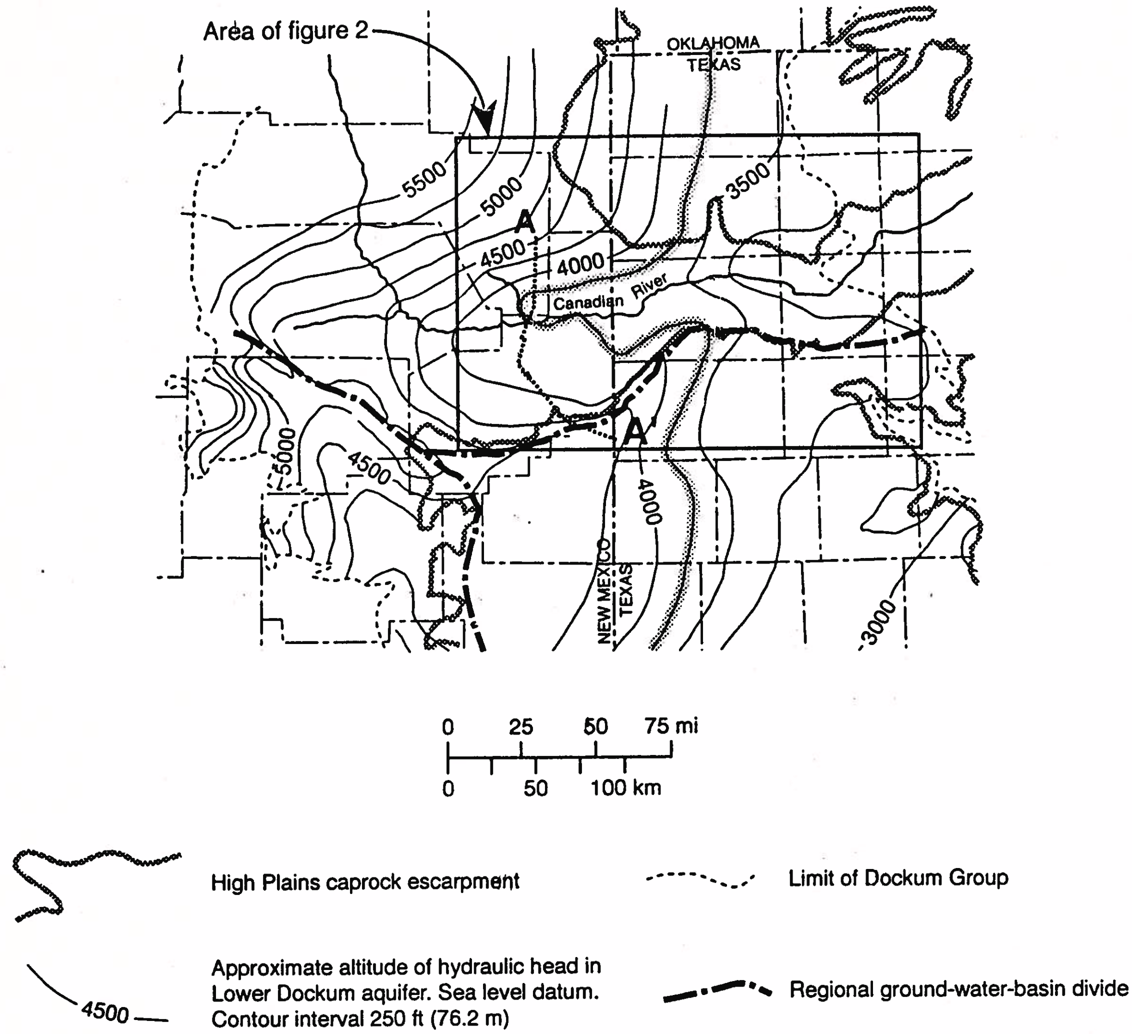

Figure 31. Potentiometric surface map of Lower Dockum Group ground water. Regonal ground-water-basin divides (inferred from from topography and shape of potentiometric surface) separate regional ground water basins. 3750-ft contour which crosses Canadian River in vicinity of Ute Reservor is highlighted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