Report of Investigations No. 225

Geophysical and Geochemical Delineation of Sites of Saline-Water Inflow to the Canadian River, New Mexico and Texas

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Abstract

Lake Meredith, which supplies water for domestic use to all major Texas cities on the Southern High Plains, exceeds State of Texas limits for chloride and sulfate content. Locating sources of these solutes along the Canadian River, which supplies Lake Meredith, marks the first step toward a remediation effort to reduce river salinity and improve the water quality of Lake Meredith. Our approach was to use surface-water conductivity and flow measurements, geological observations, and previous studies to identify areas where highly saline water enters the Canadian River, then complete detailed ground-conductivity studies in the probable inflow areas to locate discharge points.

Our measurements of conductivity and salinity of Canadian River waters indicated that the most important saline ground-water discharge areas are concentrated in two river segments between Ute Reservoir and Rana Canyon, New Mexico: one between the reservoir and a point 14 to 16 km downstream, and the other 32 to 64 km downstream from the reservoir. Chemical analyses of surface water and subsurface log data suggest that saline water in the Canadian River valley evolved by the mixing of fresh water derived from meteoric precipitation and highly saline water derived from dissolution of halite from the Permian San Andres Formation and the Artesia Group. Modern dissolution occurs along a front that lies about 335 m beneath the Canadian River in the Ute Reservoir area and that extends about 16 km south of the river at depths of 305 m.

Analysis of near-vertical joints in bedrock along the river valley indicates that the primary joints are oriented east-west and may be dilated and open to ground-water flow, whereas the secondary joints are oriented north-south, commonly terminate against the primary joints, and are not dilated. These observations are consistent with a hypothesis that saline water from depth preferentially flows into Canadian River alluvium through open bedrock joints, either directly beneath the Canadian River valley or indirectly beneath tributary valleys, and subsequently flows into the river.

Electromagnetic surveys, consisting of more than 2,200 ground-conductivity measurements along seven segments of the Canadian River and its tributaries, reveal that apparent conductivities in alluvium within the Canadian River valley range from a few to nearly 300 milliSiemens per meter. Three broad high-conductivity zones, ranging from 1.6 to 4.2 km long, were detected between Ute Reservoir and Revuelto Creek; a fourth high-conductivity zone, 2.7 km long, was located 35 km downstream in the Dunes area. Each zone spans a number of individual conductivity peaks that range from 60 to 320 m across and may represent discrete brine discharge sites in Canadian River alluvium. Many of these peaks are located where tributary drainages enter the main Canadian River valley. Conductivity profiles computed from vertical electromagnetic soundings show increasing conductivity with depth at most sites.

Keywords: Canadian River, eastern New Mexico, electromagnetic methods, induction methods, salt dissolution, soil conductivity, Texas Panhandle, water chemistry, water quality, water salinity

Introduction

Problem

Lake Meredith (fig. 1), which supplies water to all major cities on the Southern High Plains in Texas, has a high salinity that originates primarily from natural discharge of subsurface brine into the eastern New Mexico segment of its main contributor, the Canadian River (U.S. Bureau of Reclamation, 1979; Gustavson and others, 1980). These brines, which form by subsurface dissolution of Permian salt (NaCl), anhydrite ($CaSO_4$), and gypsum ($CaSO_4 \cdot 2H_2O$), deliver an estimated 24,400 metric tons of sodium, chloride, and sulfate per year to the Canadian River (U.S. Bureau of Reclamation, 1979). Salinity of Lake Meredith has risen since water was first impounded behind Sanford Dam in 1964 (Dougherty, 1980), doubling between 1983 and 1993 (fig. 2). Analyses in 1991 showed chloride concentrations as great as 430 mg/L and sulfate greater than 300 mg/L (John Williams, Canadian River Valley Authority, personal communication, 1992), which exceed aesthetic chloride and sulfate standards of 300 mg/L set by the Texas Natural Resource Conservation Commission (TNRCC). To reduce the salinity of Lake Meredith water to TNRCC standards for domestic consumption, communities on the Southern High Plains must dilute it with large volumes of low-salinity water pumped from the Ogallala aquifer. Salinization of surface water has caused the Canadian River Municipal Water Authority (CRMWA) to consider pumping the saline waters to locally lower the hydraulic head and prevent discharge to the Canadian River.

Objectives

Locating saline ground-water plumes in alluvium or bedrock is the critical first step in any remediation process designed to reduce Lake Meredith salinity. This report describes geologic investigations, surface-water conductivity and ground-conductivity surveys, and hydrochemical analyses that delineated likely ground-water discharge sites where the Canadian River (and eventually Lake Meredith) are naturally polluted by highly saline waters. The distribution of joints in Dockum Group strata was also examined because the joints may be preferred pathways for ground-water flow. Recognition of the distribution of discharge areas and preferred flow paths will enable optimum design of a salinity-control program. This report is based on work completed for CRMWA (Gustavson and others, 1992) and the Texas Water Development Board (Gustavson and others, 1993).

Previous Studies

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

Preliminary geochemical studies completed in 1960 showed that the quality of water in the segment of the Canadian River that would supply the planned Lake Meredith reservoir was marginal for human consumption and that during critical periods of low flow and reservoir evaporation, the salinity of water held in Lake Meredith would increase beyond aesthetic limits (U.S. Bureau of Reclamation, 1985). A streamflow and 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 the salt pollution was due to poor-quality water that flowed from bedrock beneath the riverbed directly into the alluvium and then into the river (U.S. Bureau of Reclamation, 1979). Streamflow measurements and analyses of waters in the alluvial aquifer in 1974 suggested that the greatest amount of subsurface inflow of saline water

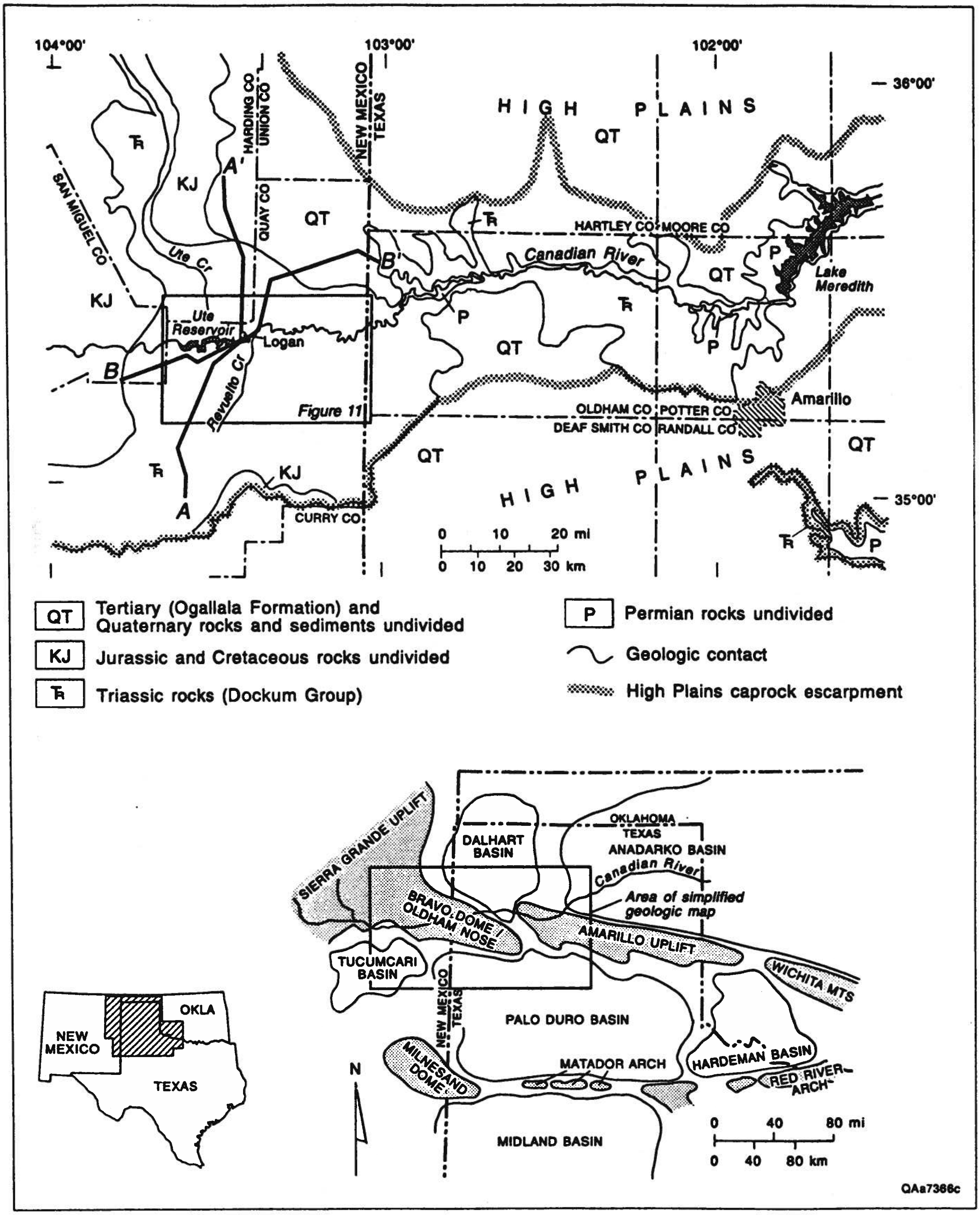


Figure 1. Regional structural elements and simplified geologic map of the Canadian River valley in eastern New Mexico and Texas Panhandle; lines of cross sections A–A′ (fig. 4) and B–B′ (fig. 5) are shown (compiled from Nicholson, 1960; Berkstresser and Mourant, 1966; Eifler, 1969; Eifler and others, 1983; Suleiman and Keller, 1985; Gustavson and others, 1992).

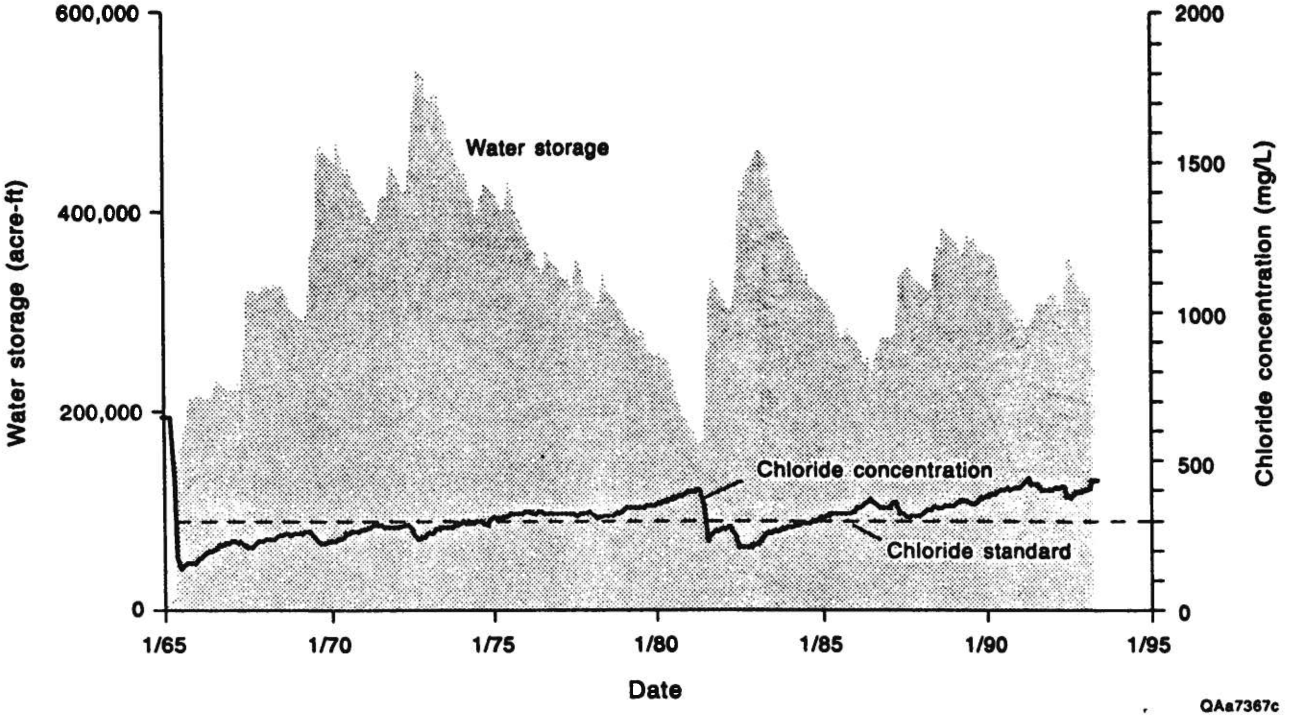


Figure 2. Lake Meredith historical water storage and chloride concentration. Chloride concentration currently exceeds the drinking-water standard set by the Texas Natural Resource Conservation Commission. Unpublished data from the Canadian River Municipal Water Authority.

(as much as one-third of that entering Lake Meredith) was occurring along the river channel 3 to 8 km downstream from Ute Dam (U.S. Bureau of Reclamation, 1979).

In 1975 two holes were drilled in bedrock adjacent to the river channel; one hole encountered a sandstone "brine aquifer" (greater than 20,000 mg/L NaCl) at an 80-m depth that had sufficient hydraulic head to flow at the ground surface (U.S. Bureau of Reclamation, 1976). Geophysical investigations (seismic refraction and electrical resistivity soundings) were conducted in 1976 to determine the physical characteristics and water quality of the postulated brine aquifer. Although the data were sparse, they indicated the existence of low-resistivity zones in the subsurface between Ute Reservoir and a point about 2.8 km east of Revuelto Creek (U.S. Bureau of Reclamation, 1976). In 1978 a pumping test of the brine aquifer was conducted to determine feasibility of pumping to reduce its hydraulic head (determined to be about 3 m above average 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 locations and an acceptable means of disposal. Studies completed in 1984 included further streamflow and 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 locate potential brine-disposal zones (Hydro Geo Chem, 1984; U.S. Bureau of Reclamation, 1984). The additional test hole (drilled on the upland surface north of the river) encountered the brine aquifer at a depth of 100 m with a hydraulic head 3 to 6 m above river elevation; data from this well supported the conclusion that the brine aquifer is a Triassic sandstone near the base of the Triassic section (U.S. Bureau of Reclamation, 1984).

Geologic and Environmental Setting

The Canadian River in eastern New Mexico and in the western Texas Panhandle flows west to east in a broad valley underlain principally by Triassic Dockum Group rocks, which are locally veneered with Quaternary sediments (fig. 1). The valley is about 120 km wide in eastern New Mexico and narrows to less than 50 km between escarpments of the High Plains surface in Texas. Permian units are exposed locally in the Canadian River valley in structural domes in Oldham and Potter Counties, Texas (Bravo Dome and Amarillo Uplift, fig. 1), and dip gently to the south in the subsurface. Permian rocks underlie the Triassic as shallow as 60 m beneath the surface in the area of this investigation near Logan, New Mexico. The base of the Permian section, where it unconformably onlaps Precambrian uplifts, consists of dominantly siliciclastic units (coarse-grained arkoses known as granite wash, the Red Cave Formation, and Tubb Formation) and an intervening evaporite-bearing unit, the lower Clear Fork Group (figs. 3 through 5). The overlying Permian section includes numerous evaporite-bearing strata and discrete evaporite beds, which thin because of dissolution or pinch out within siliciclastic strata adjacent to Precambrian basement uplifts (figs. 3 through 5). Cyclic evaporites containing thick halite units interbedded with carbonate, anhydrite and gypsum, and fine-grained siliciclastic mudstones and sandstones include the upper Clear Fork Group, Glorieta Formation, and San Andres Formation (figs. 3 through 5). Updip siliciclastic-halite units of the Artesia Group (Queen-Grayburg and Seven Rivers Formations) contain thin, regionally traceable anhydrite beds (figs. 4 and 5).

The top of the Permian section is characterized by depositional pinch-out of evaporites into siliciclastic rocks in the Salado and Alibates Formations. Permian evaporites have been studied extensively in the Palo Duro Basin of the Texas Panhandle, and their log facies have been identified in stratigraphic cross sections (Handford and others, 1981; Presley, 1981; McGookey and others, 1988). Dissolution has caused subsidence and collapse of overlying rocks and is perhaps responsible for the present location of part of the Canadian River valley (Gustavson and Finley, 1985; Gustavson, 1986). The edges of the evaporites have retreated southward from their original depositional limits. The uppermost Permian unit is the siliciclastic Dewey Lake Formation. The Permian strata are truncated toward the north by the erosional unconformity beneath the Triassic Dockum Group (Murphy, 1987). Jurassic and Cretaceous units in the northwestern parts of the study area (Eifler and others, 1983) are truncated by an erosional unconformity beneath the Tertiary Ogallala Formation and Quaternary Blackwater Draw Formation (fig. 1).

In most of the study area in eastern New Mexico, the Canadian River flows through a narrow canyon (15 to 30 m deep and about 150 m wide) in the resistant Trujillo Formation of the Triassic Dockum Group (fig. 6). Canyon wall outcrops consist primarily of channel-filling pebble conglomerate and pebbly coarse sandstones, laterally extensive tabular beds of laminated fluvial sandstone, and overbank mudstones. Channel-filling sandstones and conglomerates are common but are not distributed in an obvious pattern. No information is available about the distribution of channel sandstones in the subsurface. Past dissolution and collapse in underlying strata have produced broad open folds and monoclinal flexures, observable in the canyon walls, that have

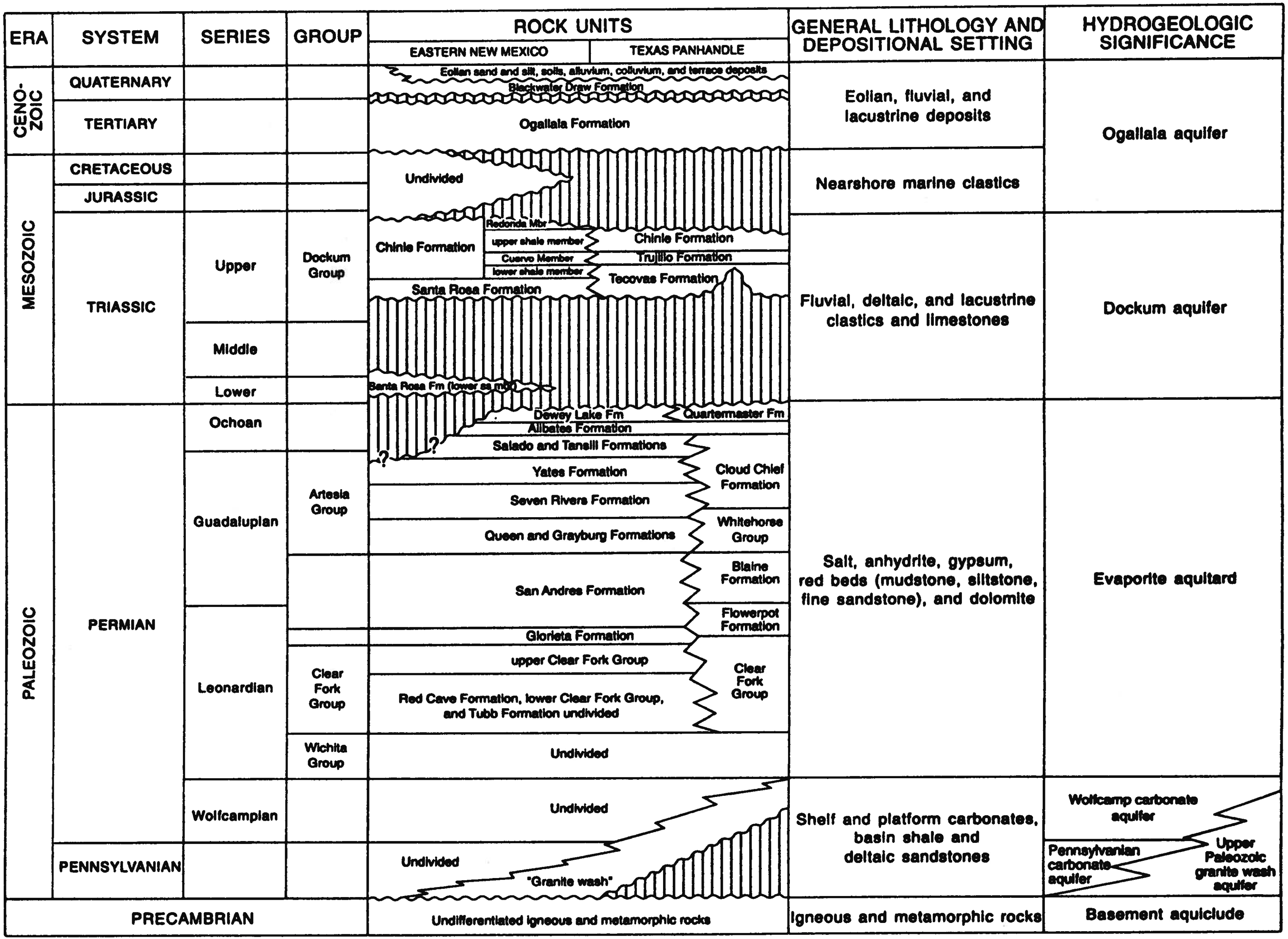


Figure 3. Stratigraphic nomenclature of rocks beneath the Canadian River valley in eastern New Mexico and Texas Panhandle (compiled from Gustavson and others, 1980; Presley, 1981; Bassett and Bentley, 1983; Lucas and Kues, 1985; Lucas and others, 1985; Murphy, 1987).

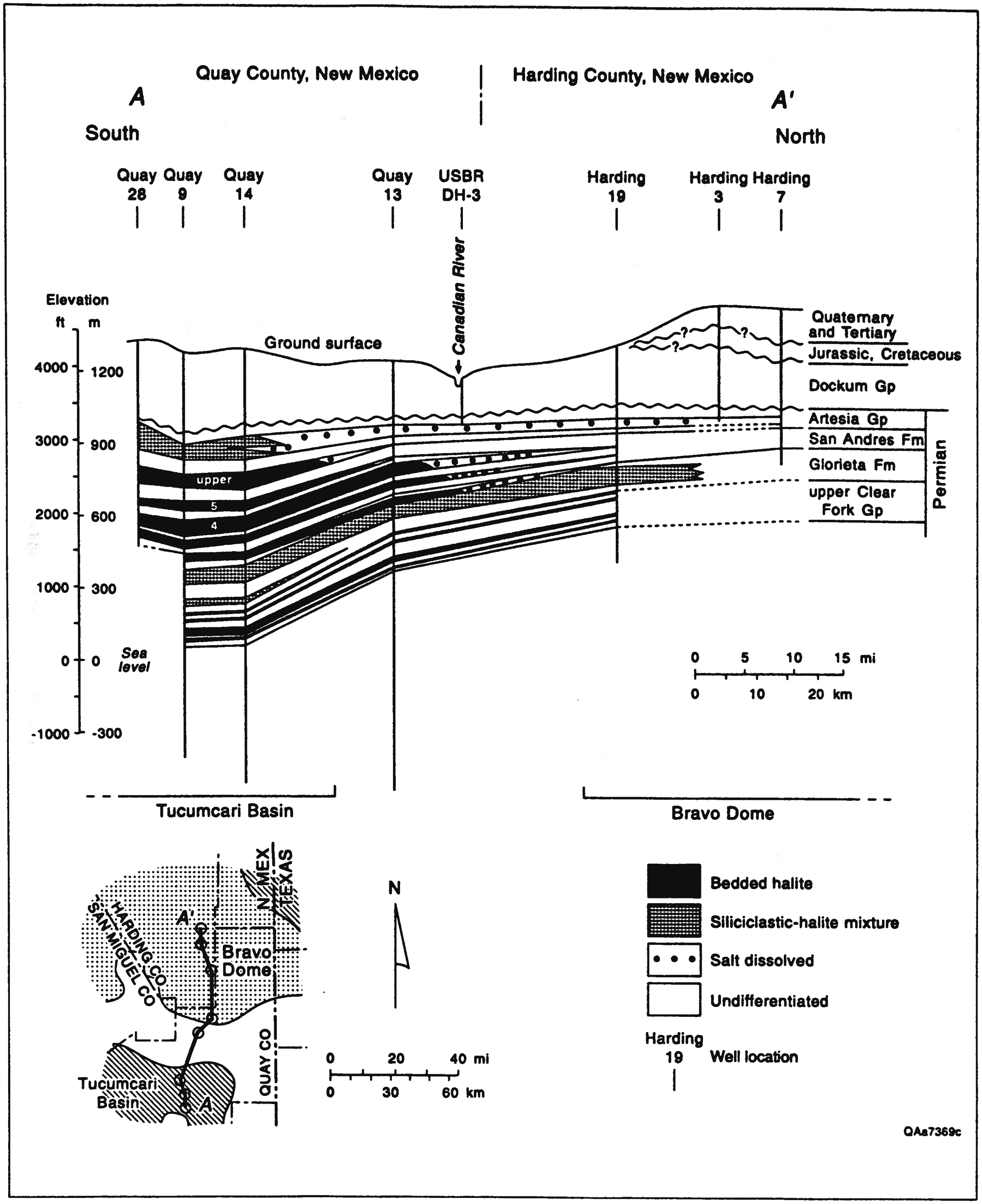


Figure 4. North-south structural cross section A–A′ through the Ute Dam area. Well locations shown on inset map. Well names listed in appendix.

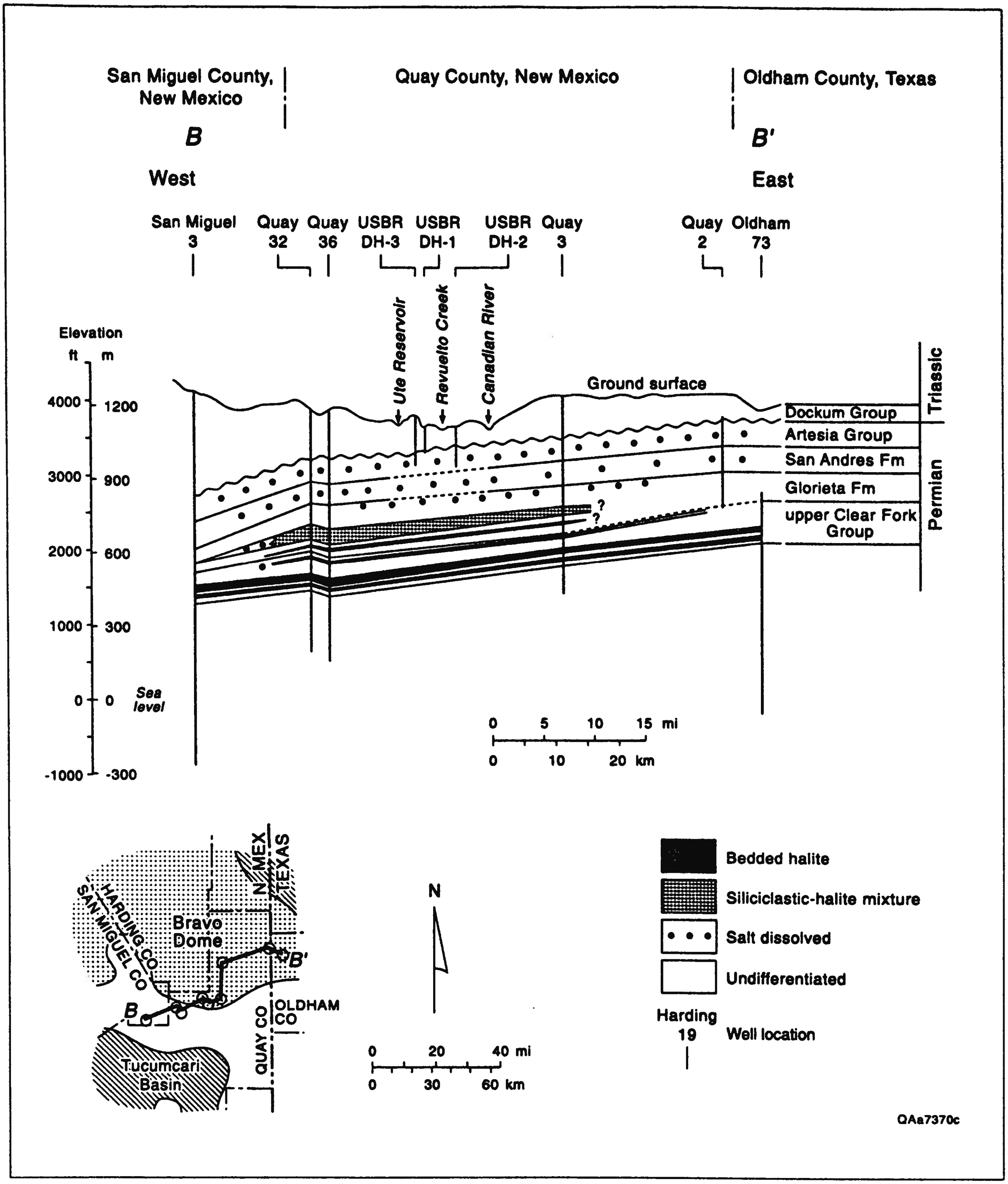


Figure 5. East-west structural cross section B–B′ through the Ute Dam area. Well locations shown on inset map. Well names listed in appendix.

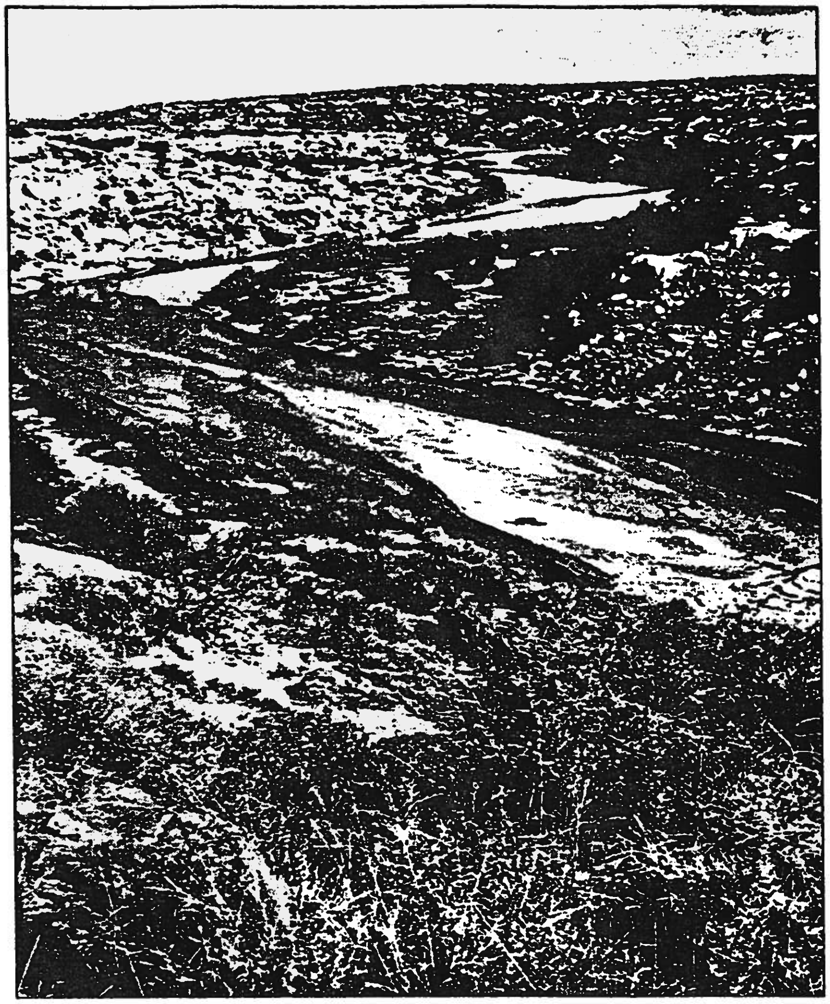


Figure 6. Canadian River canyon at the confluence of the Canadian River (background) and Revuelto Creek (foreground). Photograph by David M. Stephens.

amplitudes as great as 15 m in the Triassic strata that generally dip gently to the southeast (Johns, 1989). These flexures also appear regionally as a series of anticlines and synclines (Hydro Geo Chem, 1984). The bedrock floor of the canyon extends below the present alluvial surface and cuts into the lowest unit of the Dockum Group, the Tecovas Formation, and possibly into the uppermost part of the Permian section in structural highs (U.S. Bureau of Reclamation, 1979). Well-developed joints exposed in the Trujillo Formation define a regional pattern that may reflect either regional tectonic stresses or local stresses related to dissolution and collapse.

In most of the study area, only the Trujillo Formation is exposed because Canadian River alluvium has backfilled the canyon to a depth of 15 m or more and covers older strata. Borings (DH-1 and DH-2, U.S. Bureau of Reclamation, 1979) reveal that alluvium is 9 m thick near the Highway 54 bridge across the Canadian River and 10 m thick about 600 m downstream from the confluence with Revuelto Creek (fig. 7a). Near the bridge, the alluvium defines an upward-fining, bedload-dominated sequence that consists of poorly sorted gravel from the bedrock contact at 9.1 m to a depth of 4.3 m, coarse and poorly sorted sand from 4.3 m to 1.0 m depth, and a surface layer of poorly sorted medium sand with some fine gravel and fine to very fine sand (U.S. Bureau of Reclamation, 1979). A similar sequence probably exists at the boring site downstream from Revuelto Creek, but the log of the boring describes the alluvial section only as

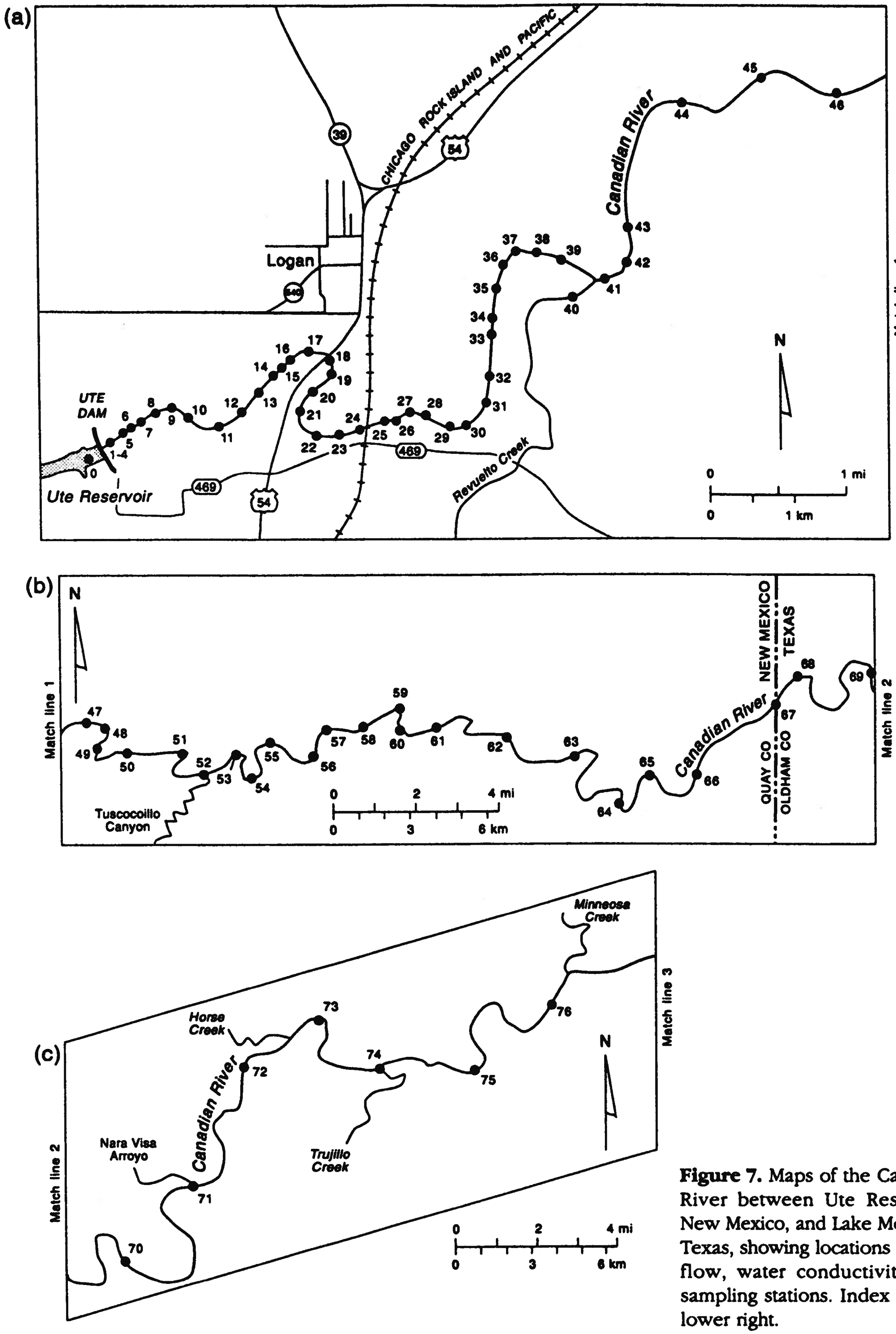
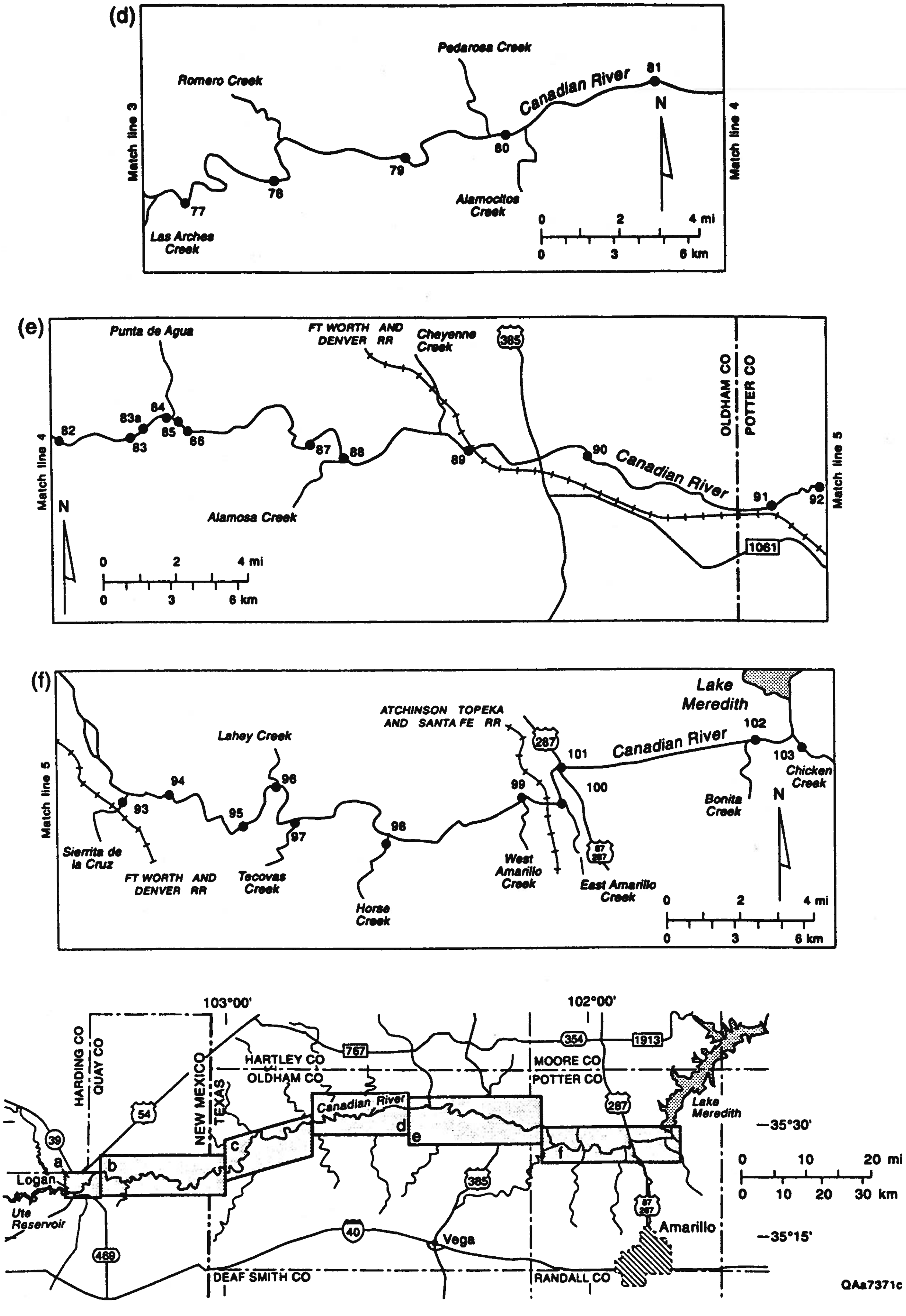


Figure 7. Maps of the Canadian River between Ute Reservoir, New Mexico, and Lake Meredith, Texas, showing locations of river flow, water conductivity, and sampling stations. Index map at lower right.

(d)
Match line 3
Romero Creek
Pedarosa Creek
Canadian River
81
N
Match line 4
80
79
78
77
Las Arches Creek
Alamocitos Creek
0 2 4 mi
0 3 6 km
(e)
Punta de Agua
FT WORTH AND DENVER RR
Cheyenne Creek
385
OLDHAM CO
POTTER CO
Match line 4
82
83a
84
85
86
83
87
88
89
90
Canadian River
91
92
Match line 5
N
Alamosa Creek
1061
0 2 4 mi
0 3 6 km
(f)
Lake Meredith
ATCHINSON TOPEKA AND SANTA FE RR
287
101
Canadian River
102
103
Chicken Creek
Lahey Creek
96
94
99
100
Bonita Creek
N
Match line 5
93
95
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98
Sierrita de la Cruz
FT WORTH AND DENVER RR
Tecovas Creek
Horse Creek
West Amarillo Creek
87 287
East Amarillo Creek
0 2 4 mi
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103°00'
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HARDING CO
QUAY CO
NEW MEXICO
TEXAS
HARTLEY CO
OLDHAM CO
767
354
1913
MOORE CO
POTTER CO
54
39
Canadian River
287
Lake Meredith
-35°30'
a
b
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e
f
Logan
Ute Reservoir
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Vega
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DEAF SMITH CO
RANDALL CO
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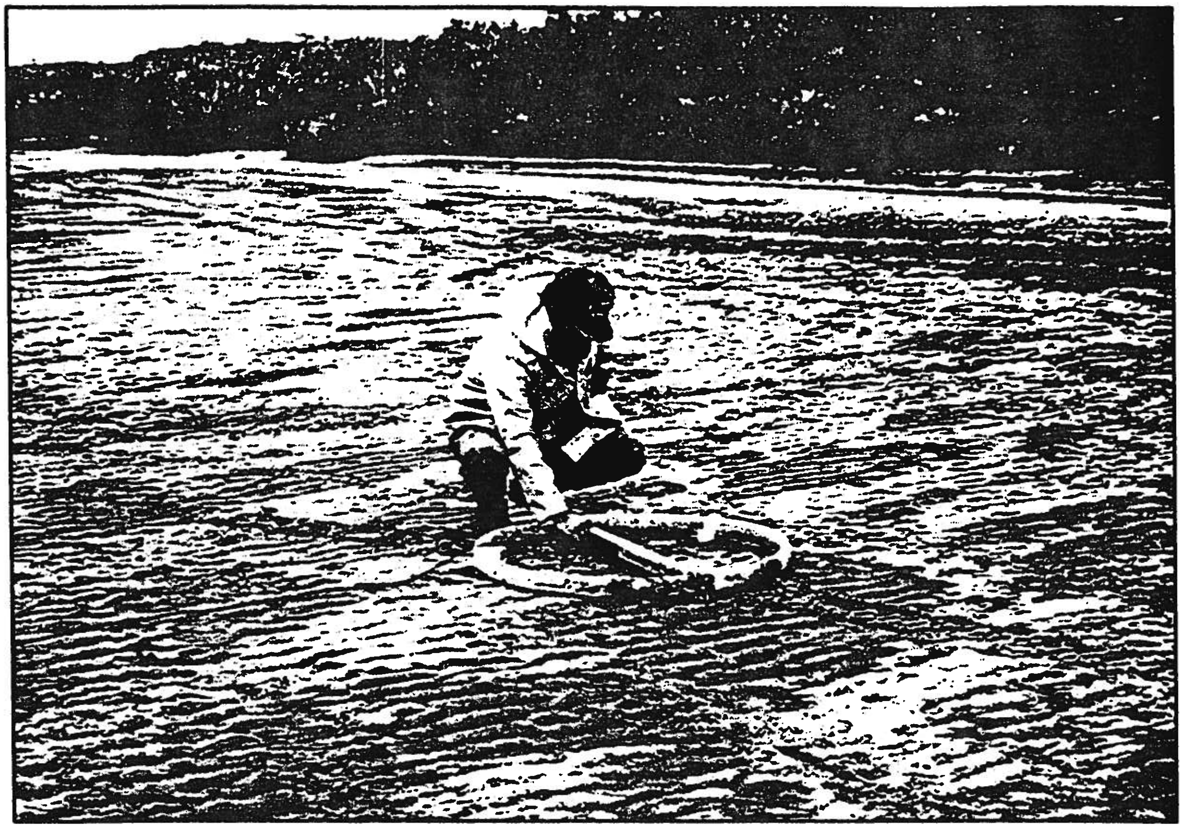


Figure 8. White efflorescence, such as that shown here on the riverbed in the Dunes area, New Mexico, is common along the Canadian River. Also pictured is receiver coil of Geonics PROTEM 47/S electromagnetic induction system.

fine to medium sand with some gravel (U.S. Bureau of Reclamation, 1979). Gravels are more common at the surface of the riverbed near tributary canyons and probably constitute a greater percentage of the alluvial section near these canyons. The alluvial aquifer is thus unconfined.

Discharge of saline ground water in the study area indicates that dissolution of evaporites in the Canadian River ground-water system continues. Evidence of saline-water discharge areas includes evaporative mineral crusts on fine-grained alluvial sediments (efflorescence, fig. 8), dense thickets of salt cedars (*Tamarix gallica*), patches of salt-tolerant sedges (*Scirpus americana*) and grasses (*Distichlis spicata*), and absence of less salt-tolerant species.

Methods

Our methodology included use of surface-water conductivity and flow measurements, geological observations, and previous studies to identify areas where highly saline water probably enters the river, then complete detailed ground-conductivity studies in these probable inflow areas to locate discharge points. Once located and characterized, these discharge points can be further studied to determine the effectiveness of pumping programs designed to reduce or eliminate the flow of saline ground water into the Canadian River and Lake Meredith.

Specific parts of the investigation were (1) geologic studies of geophysical logs and outcrops in eastern New Mexico and the Texas Panhandle to locate likely areas of subsurface evaporite dissolution and to examine potential brine migration paths to the surface, (2) joint analyses to document potential preferred paths for ground-water flow, (3) geochemical analyses of river water to determine salt content, water quality, and types of salinity sources and mixing trends, (4) water-conductivity measurements along the entire length of river between Ute Reservoir and Lake Meredith to identify areas of potential saline-water inflow, and (5) ground-conductivity measurements using the electromagnetic induction method in apparent inflow areas to try to pinpoint sites of saline-water discharge.

Several scientific instruments and computer programs from various manufacturers were used in this study. The use of firm and brand names in this report is for identification purposes and is not an endorsement by the Bureau of Economic Geology.

Subsurface Stratigraphy and Evaporite Dissolution

Subsurface data used in this study to identify areas of past and possibly continuing evaporite dissolution and to investigate possible paths of ground-water circulation were extracted from commercial wireline and sample logs and lithologic logs of three holes drilled east of Ute Dam (U.S. Bureau of Reclamation, 1979, 1984). Criteria for recognition of halite on wireline logs include increasing borehole diameter (as shown on caliper logs), low gamma-ray response, and low density, low porosity, or high sonic velocity. Siliciclastic/halite mixtures that result from interbedding or chaotic admixture of mud and halite are recognized by responses intermediate between those of halite and siliciclastic mudstones and siltstones. Criteria that indicate past halite dissolution in the Ute Reservoir area are thinning of halite-bearing units in sections where thicknesses of other lithologic units do not change, decreased regional structural dip or dip reversal of strata above areas of thin or missing halite, and variable sonic velocity and cycle-skipping (a process by which some of the first arrivals of a sonic wave pulse are lost, resulting in anomalously long apparent travel-times through some intervals, and typically caused by attenuation of sonic waves in fractured zones [Schlumberger, 1989]).

Joint Analysis

Joints are fractures in rocks that occur without displacement and result from postdepositional stresses such as folding, faulting, removal of overburden, or subsidence. A joint, which can be a preferred path for ground-water flow, is typically planar and commonly lies subparallel to other joints to form a joint set. Joints in Triassic fluvial-channel sandstones exposed in the Canadian River valley were examined for orientation, spatial distribution, joint continuity, and evidence of mineralization. Joint data, collected at 13 field sites, were analyzed using the two-dimensional orientation plotting program Rosy© and then were plotted as half-rose diagrams. Variations in the horizontal distribution of joints were measured by recording the distance between joints that crossed transects of 30 to 90 m in length. A measuring tape was laid out normal to the trend of primary joints, and the spacing of joints that crossed the tape was recorded.

Surface-Water Quality Survey

The Canadian River surface-water quality survey, completed in February 1992, covered a distance of about 240 km. The survey began at the toe of Ute Dam and ended at Chicken Creek, about 6 km upstream from Lake Meredith (figs. 1 and 7). Personnel from the Bureau of Economic Geology measured conductivity, water temperature, chloride concentration, and alkalinity and collected samples of waters from the Canadian River, from flowing tributaries, and from isolated pools in the riverbed and in several nonflowing tributaries (fig. 7). Personnel from CRMWA and Lee Wilson and Associates (LWA) measured conductivity, water temperature, chloride and sulfate concentrations, and pH, and also measured flows in the river and in flowing tributaries. CRMWA staff returned to collect additional flow and chemistry data at closely spaced intervals along one segment of the river where data from the earlier survey indicated a substantial increase in flow.

Gates at Ute Dam were held closed during the survey so that no water was directly released from Ute Reservoir. Discharge into the Canadian River during the survey period was contributed entirely by leakage through the dam and its workings, by baseflow and surface runoff, by inflow from tributaries, and by minor flows from several small springs.

The survey area was limited to the river, the riverbed and its banks, and tributary mouths. Spacing between survey sites varied: (1) average spacing between stops in the first 11 km below Ute Reservoir was about 0.24 km (sites 0 through 43, spacing up to 0.6 km); (2) average spacing along the next 29 km of the river was about 1.6 km (sites 43 through 61, spacing 0.6 to 2.4 km); and (3) average spacing along the remaining length was about 4.8 km (sites 61 through 103, spacing 0.3 to 9.2 km) (fig. 7).

Conductivity and water temperature were measured using a Yellow Springs Instrument model 33 S-C-T conductivity meter. Conductivity was measured at ambient temperature and then corrected and expressed as equivalent conductivity in milliSiemens per meter (mS/m) at 25°C.

Chloride concentration was measured in the field using Quantab chloride titrator strips (for chloride less than 6,000 ppm). The indicator strips gave slightly higher readings than did laboratory measurements (fig. 9). Chloride concentration can also be judged indirectly from conductivity measurements, although it is a less reliable technique. The line of best fit on a plot of laboratory-determined chloride values versus field conductivity data yields a conductivity value of 181 mS/m (corrected to 25°C) at a chloride concentration of zero (fig. 10). This anomaly is caused by the fact that at low concentrations of total dissolved solids (TDS), ions other than sodium and chloride are major contributors to conductivity. As TDS increases, the conductance caused by sodium and chloride ions increases more rapidly than that caused by other ions, so that high values of conductivity can be considered to closely reflect chloride concentrations.

During the surface-water conductivity and flow survey, 28 water samples were collected from pools alongside the Canadian River, from tributaries, from seeps, and from the main channel of the river. The sampling was deliberately biased toward collection of waters with high conductivity, as determined by field measurements. The 28 samples were analyzed for major chemical constituents (calcium, magnesium, sodium, potassium, bicarbonate [field determination], sulfate, and chloride) and for bromide.

Electromagnetic Surveys

Electromagnetic induction methods (Parasnis, 1973; Frischknecht and others, 1991; West and Macnae, 1991) were used to measure apparent ground conductivity, which is a proxy for ground-water conductivity and is an indirect measure of ground-water salinity at moderate to high levels. Electromagnetic induction methods use a changing primary magnetic field created around a transmitter coil to induce a current to flow in the ground, which in turn creates a secondary magnetic field that is sensed by the receiver coil. In general, the strength of the secondary field is proportional to the conductivity of the ground. An assumption inherent in the method is that the near-surface

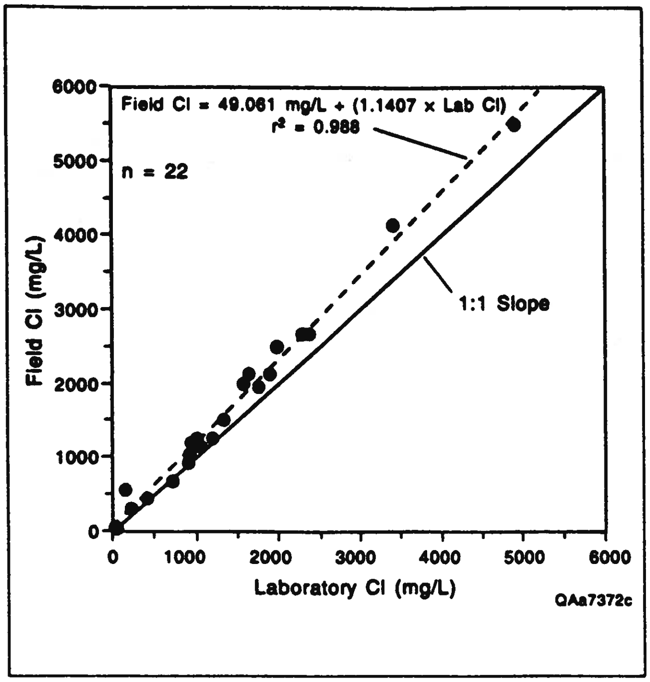


Figure 9. Comparison between field-measured chloride concentrations and laboratory-measured chloride concentrations in samples collected during surface-water survey. Solid line represents perfect agreement between measuring techniques; dashed line is best-fit relationship.

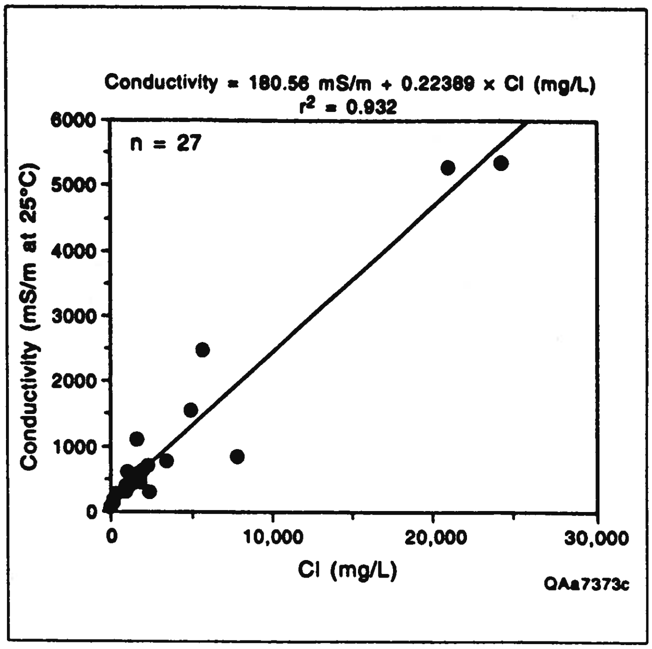


Figure 10. Relationship between surface-water conductivity measurements at sample sites and chloride concentrations determined in the laboratory for water samples collected during the river survey of February 1992.

environment consists of horizontal layers of infinite lateral extent; this is not strictly true along the Canadian River, but the near-surface layers probably do have sufficient lateral extent to render this assumption valid at the scale of investigation.

Electromagnetic field studies were focused in probable or potential saline-water inflow areas identified in the surface-water quality survey. Five segments of the river and two segments of tributaries between Ute Dam and the Texas–New Mexico state line (figs. 1 and 11) were surveyed, including (a) an 11.4-km reach from Ute Dam to a point approximately 1.5 km downstream from Revuelto Creek and a 0.3-km reach at the end of Revuelto Creek, (b) a 1.5-km reach in the vicinity of Claer well, (c) a 1.9-km reach in the vicinity of Jones well, (d) a 4.8-km reach in the area of the originally proposed "Dunes" dam and reservoir, and (e) a 1.3-km reach in the vicinity of Rana Canyon and a 0.3-km reach at the end of Rana Arroyo.

Lateral Ground-Conductivity Surveys

Lateral ground-conductivity surveys were completed along the Canadian River and tributaries to locate sites of potential saline groundwater entry into river alluvium. In these surveys, a Geonics EM34-3 ground-conductivity meter was used to measure apparent conductivity (McNeill, 1980a) along the seven river and tributary stretches. The EM34-3 supports 10-, 20-, or 40-m transmitter and receiver coil separations (fig. 12) and two principal coil orientations: horizontal dipole (or vertical coplanar) and vertical dipole (or horizontal coplanar). A 20-m coil separation was used, which has an effective penetration depth of 12 m for the horizontal dipole orientation and 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

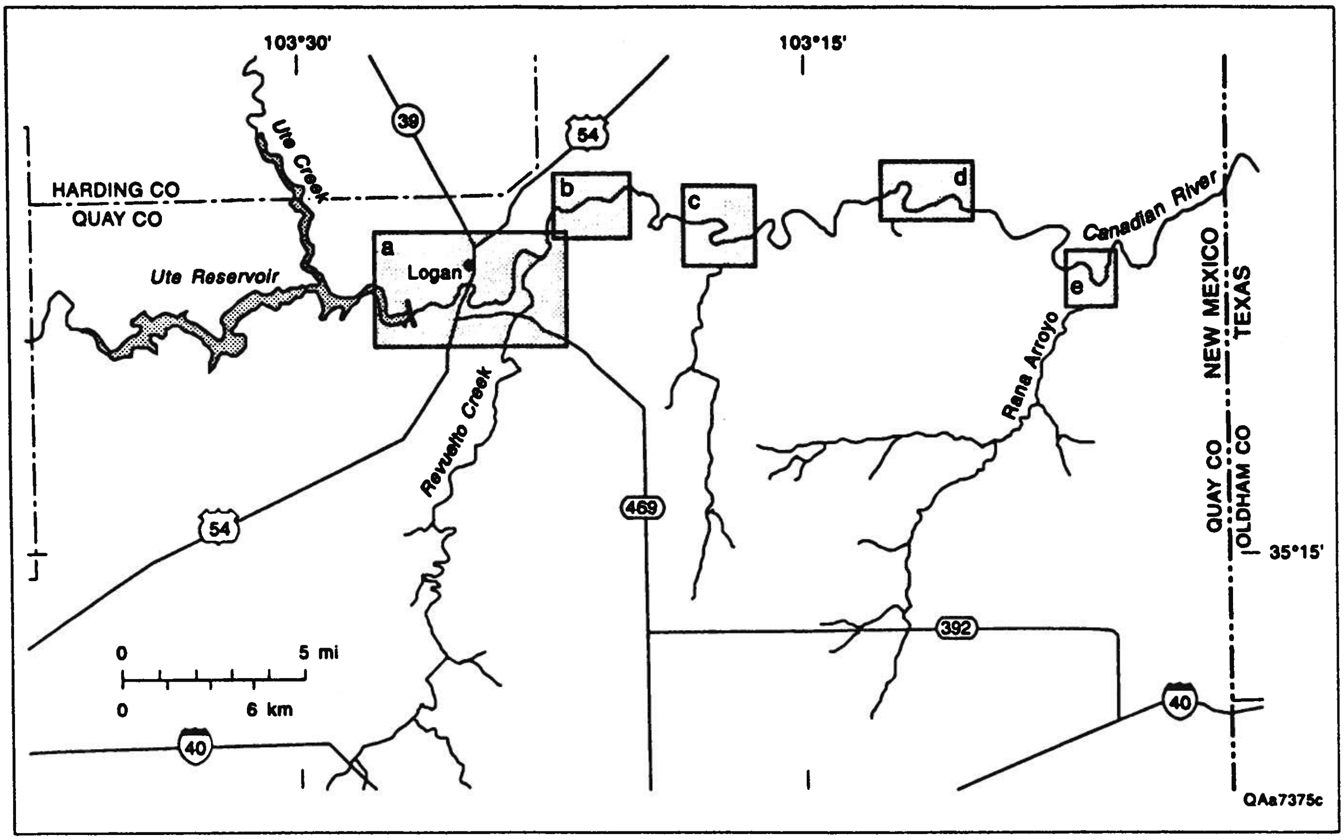


Figure 11. Generalized geologic map of the Canadian River valley and adjacent areas in eastern New Mexico showing areas selected for electromagnetic surveys: Ute Dam to Revuelto Creek (a), Claer Well area (b), Jones well area (c), Dunes area (d), and Rana Canyon area (e). Location shown in figure 1.

were used for the first 76 sites. Although conductivity values represent "bulk" conductivities, or an average conductivity of the soil volume beneath the transmitter and receiver coils, these values are listed in tables and on maps by receiver coil location.

Conductivity measurements were taken as follows: (1) the transmitter coil was placed on the ground in the vertical dipole (horizontal coplanar) orientation at a chosen site, (2) the receiver coil was placed on the ground at an approximate distance of 20 m from the transmitter coil, (3) the receiver coil position was adjusted until the separation meter on the receiver indicated the proper separation, (4) apparent conductivity was read from the meter in milliSiemens per meter, transcribed by hand, and logged on a digital data logger attached to the receiver, (5) both coils were realigned in the horizontal dipole (vertical coplanar) orientation at the same station locations and coil separation, (6) apparent conductivity for the horizontal dipole orientation was read from the meter, transcribed by hand, and digitally logged, and (7) the transmitter coil was moved to the location of the receiver coil, and the receiver coil was moved forward about 20 m. The entire process was then repeated. We attempted to follow a smoothly curving path near the center of the canyon.

More than 2,200 conductivity measurements were taken at 1,073 sites in the study area. More than half of the measurements (583 unique sites) were taken along an 11-km reach of the Canadian River between Ute Reservoir and a point 1.5 km beyond the confluence of the river with Revuelto Creek (fig. 13), which includes the 5-km-long segment where previous studies

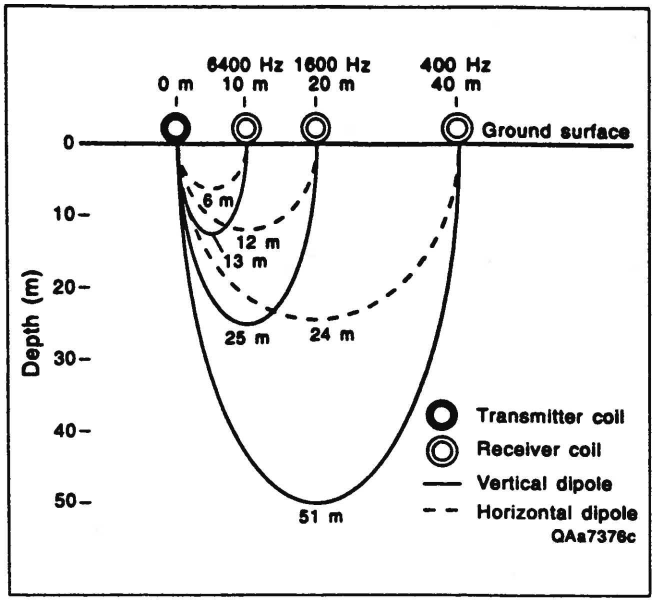


Figure 12. Effective penetration depth of various coil separations and coil orientations of the Geonics EM34-3.

estimated that as much as one-third of the salt load enters the river (U.S. Bureau of Reclamation, 1985). Revuelto Creek was surveyed from its confluence with the Canadian River to a distance 340 m upstream (fig. 13). Short segments were surveyed in the Claer well area in the vicinity of several prominent tributary canyons (fig. 14) and in the Jones well area (fig. 15) near a surface-collapse feature identified by Hydro Geo Chem (1984). The second longest survey, 4.8 km, was completed in the Dunes area (fig. 16), where analysis of river flow and conductivity data indicated an increase in salt load. A short conductivity survey (1,000 m) was also completed in the Rana Canyon area and along Rana Arroyo from its confluence with the Canadian River to a distance 340 m upstream (fig. 17).

Tests of the lateral conductivity methods consisted of (1) radial surveys of a 40- by 40-m

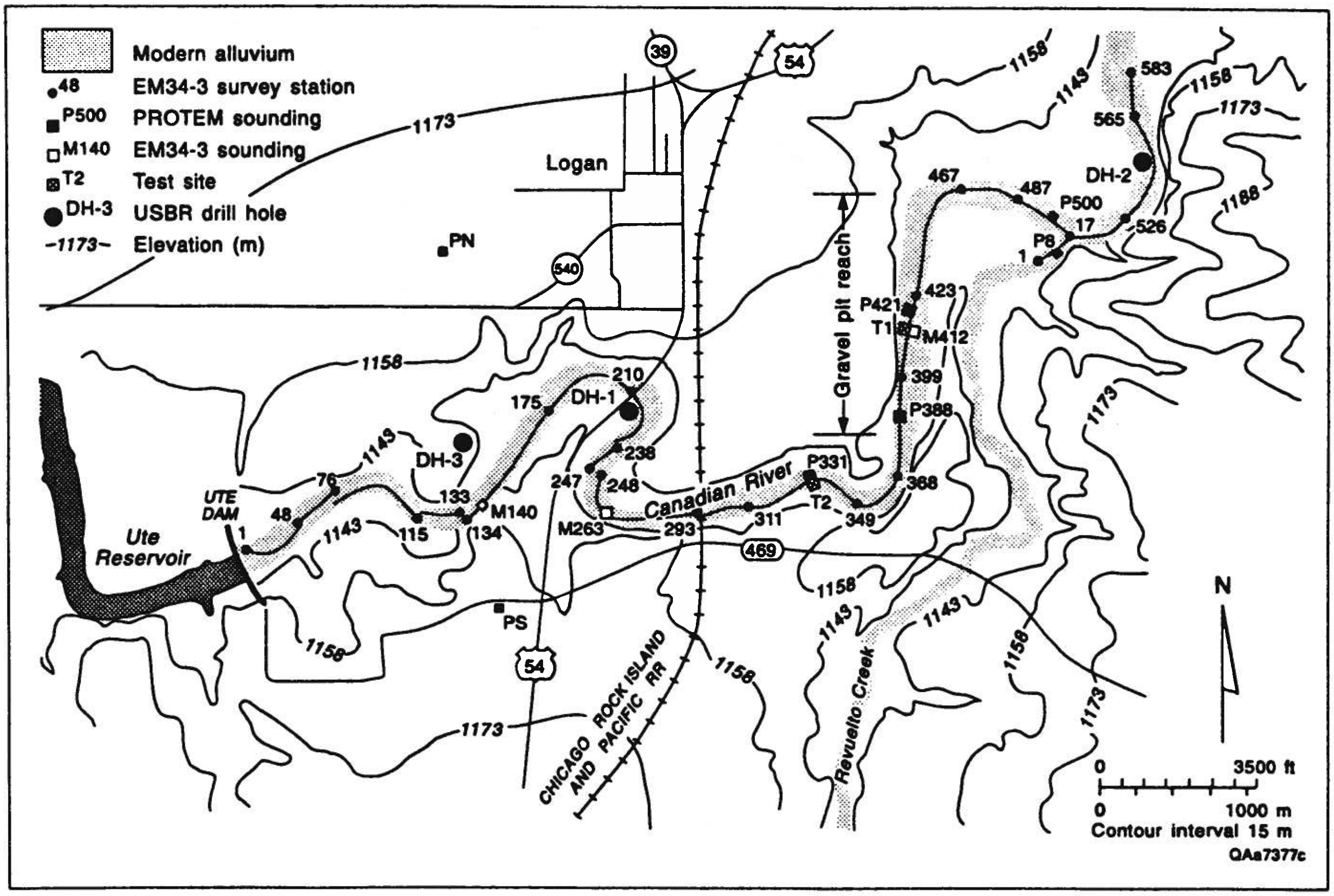


Figure 13. Topographic map of the Ute Reservoir to Revuelto Creek area (area a, fig. 11) of the Canadian River canyon showing key station locations, test sites, and sounding sites. Locations of U.S. Bureau of Reclamation (1979, 1984) drill holes DH-1, DH-2, and DH-3 are also shown.

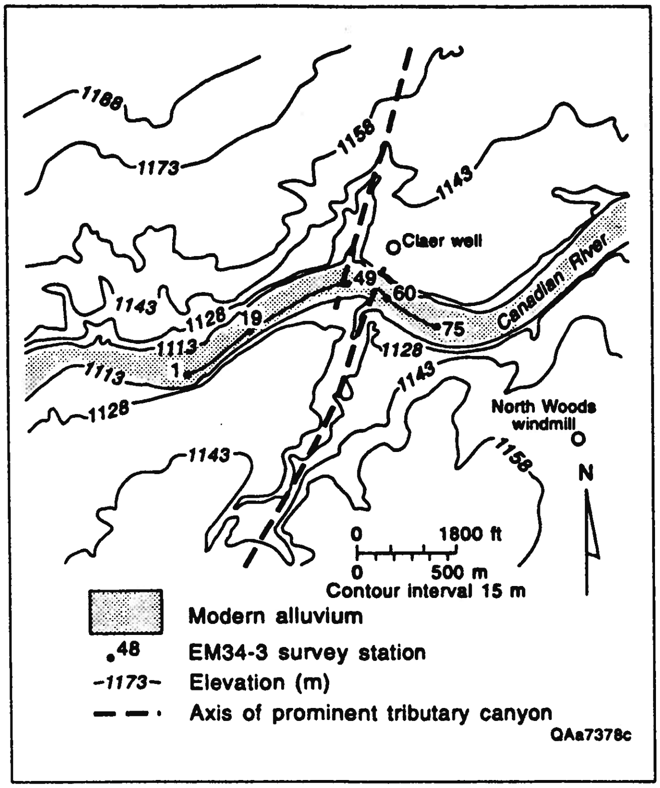


Figure 14. Topographic map of the Claer well area (area b, fig. 11) of the Canadian River canyon showing key station locations and axes of prominent tributary canyons.

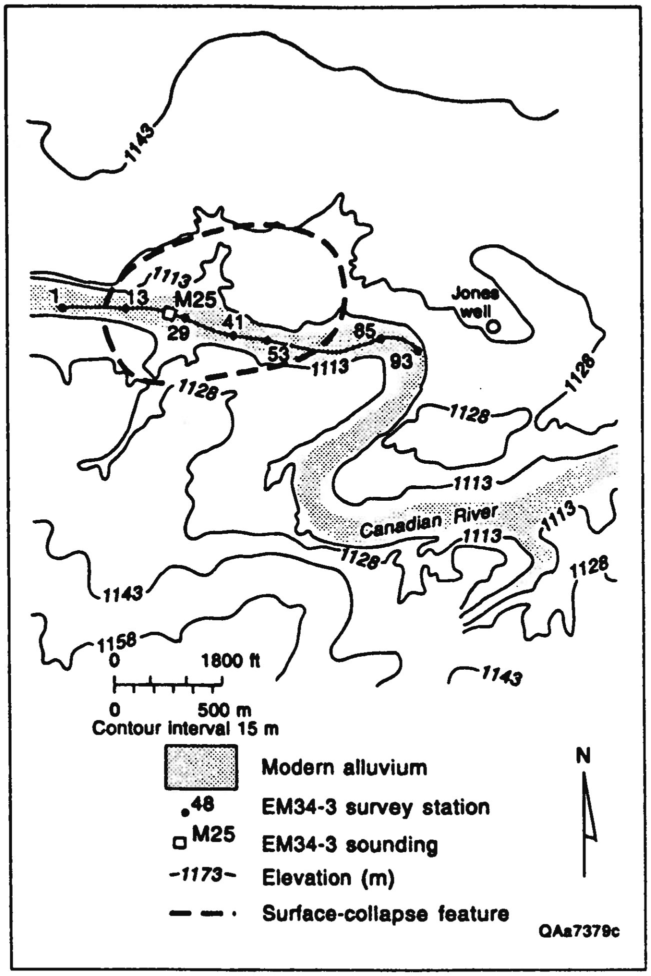


Figure 15. Topographic map of the Jones well area (area c, fig. 11) of the Canadian River canyon showing key station locations, sounding sites, and approximate outline of surface-collapse feature identified by Hydro Geo Chem (1984).

grid conducted parallel to, perpendicular to, and at 45° to the river and canyon wall at site T1 (fig. 13) to determine how conductivity varies with direction relative to the valley axis, (2) three transects parallel to the river at site T2 (fig. 13) to determine the importance of position within the valley, and (3) several reoccupations of sites between Ute Reservoir and Revuelto Creek to determine repeatability of measurements and variation in conductivity through time.

Vertical Ground-Conductivity Surveys

Two vertical survey techniques were used to determine conductivity variations with depth at potential areas of saline-water inflow located by the lateral conductivity surveys. Frequency-domain soundings were completed at four sites using the Geonics EM34-3; simple vertical conductivity profiles were constructed at each site by analyzing apparent conductivity data collected using multiple coil separations and both vertical and horizontal dipole orientations for each coil separation. Time-domain, or transient, soundings were completed at 13 sites using the Geonics PROTEM 47/S. Both methods reveal information about the variation of "bulk" ground conductivity with depth.

Multiple-Coil-Separation Soundings

The effective penetration depth of the field generated by the EM34-3 increases with coil separation for a given coil orientation (fig. 12).

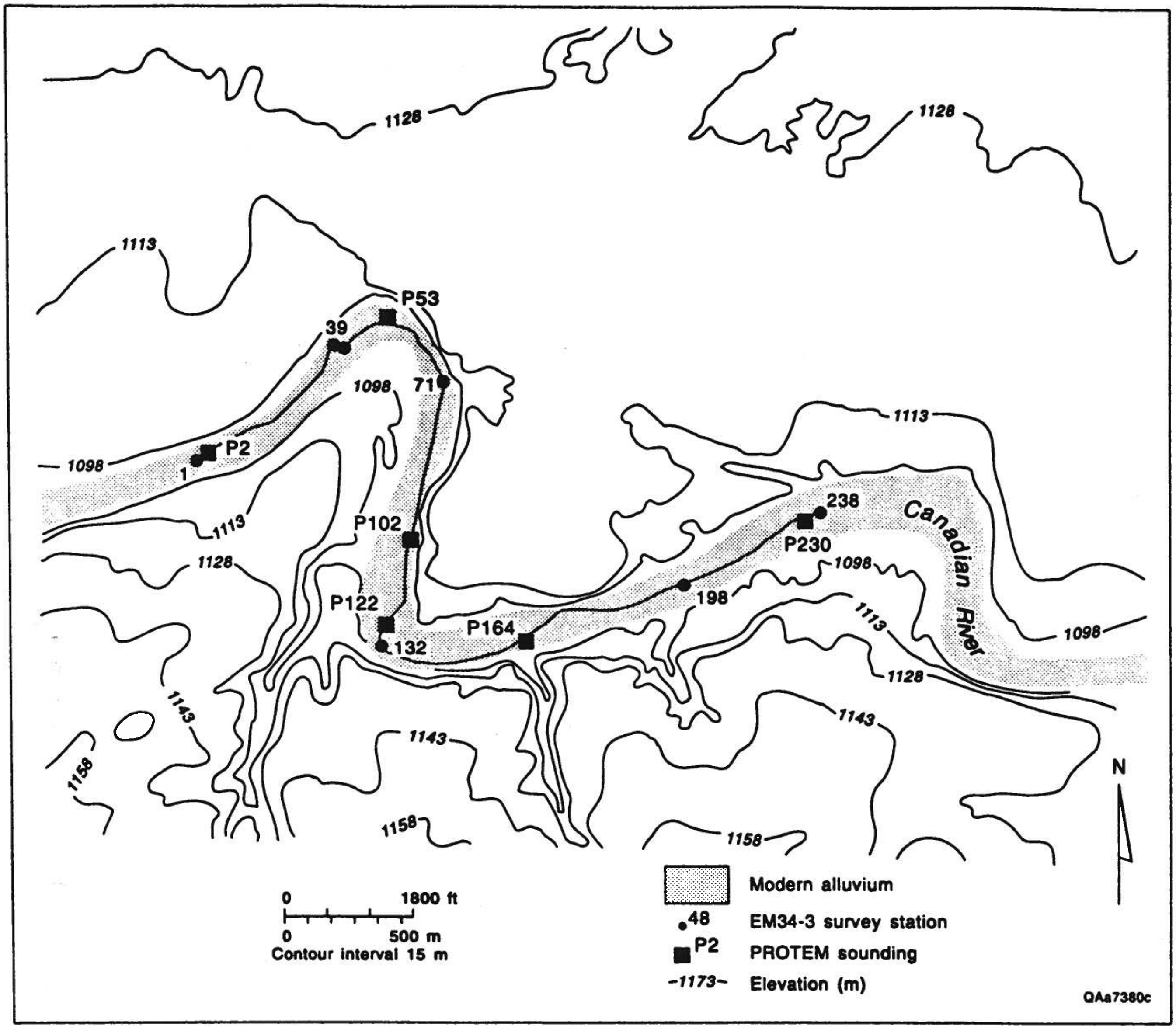


Figure 16. Topographic map of the Dunes area (area d, fig. 11) of the Canadian River canyon showing key station locations and sounding sites.

Consequently, conductivities measured at different coil separations and orientations can be used to infer conductivity changes with depth beneath a site (McNeill, 1980a, b) if lateral conductivity variations are small. Conductivities were measured using the Geonics EM34-3 with 10-, 20-, and 40-m coil separations and horizontal and vertical dipole orientations at three sites between Ute Reservoir and Revuelto Creek (sites M140, M263, and M412, fig. 13) and at one site in the Jones well area (M25, fig. 15).

At each sounding site, apparent conductivities (in milliSiemens per meter [mS/m]) were collected first at 10-m coil separations across the site. Horizontal and vertical dipole conductivities at 10-m coil separations were measured over a distance of at least 80 m at each sounding site to determine lateral variability. After all measurements were made at a site using the 10-m coil separation, the 20-m separation was selected, the instrument was recalibrated, and horizontal and vertical dipole data were collected across the

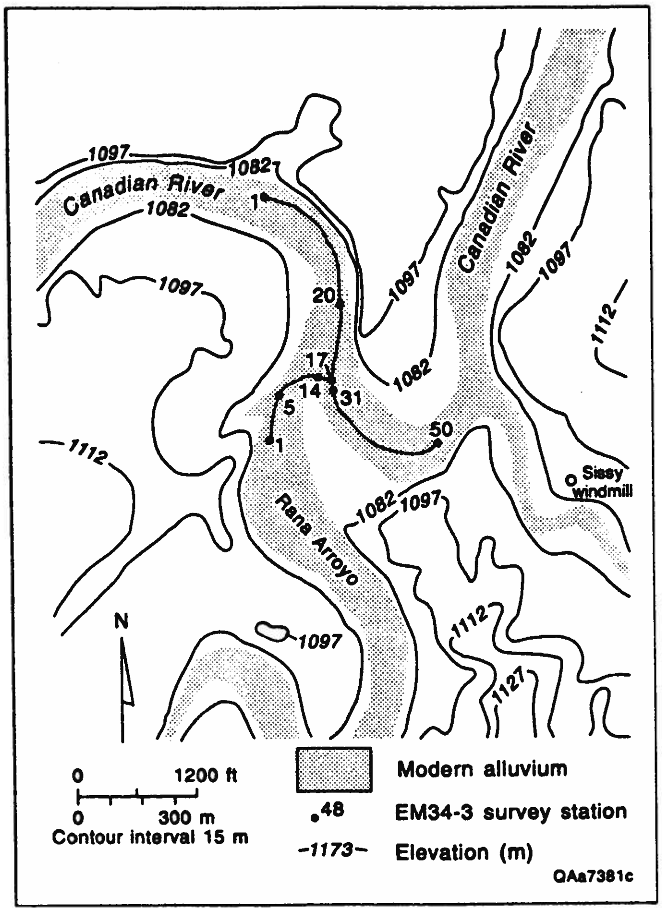


Figure 17. Topographic map of the Rana Canyon area (area e, fig. 11) of the Canadian River canyon showing key station locations.

same stretch at the same 10-m intervals. Finally, the 40-m separation was selected, the instrument was recalibrated, and apparent conductivities for both dipole orientations were measured at 10-m intervals across the same line used for shorter coil separations.

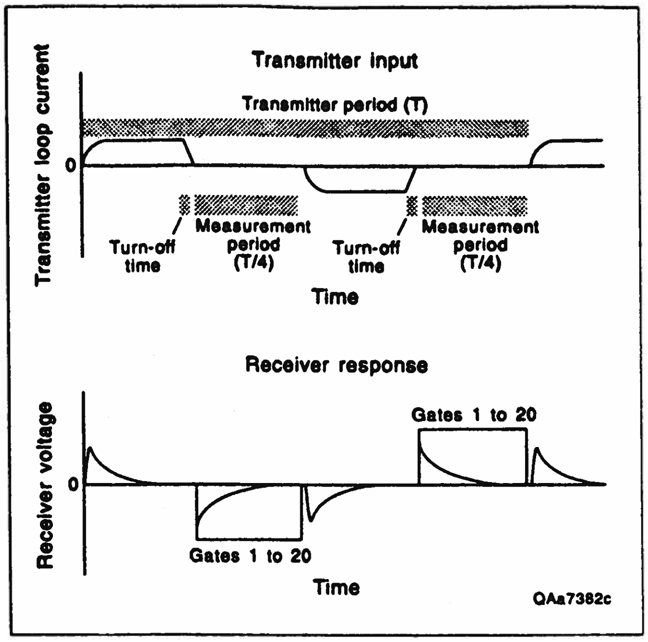


Figure 18. PROTEM 47/S transmitter input and receiver response. Adapted from Geonics Limited (1992).

Processing of the EM34-3 sounding data first required transferring the data from the digital data logger to a computer and selecting a representative point along each profile for analysis. EMIX34 v. 2.0, a computer program developed by Interpex, was used to process and interpret the data. Horizontal and vertical dipole conductivities for each coil separation at a chosen point were entered in the program, a starting conductivity model (consisting of layer thicknesses and conductivities) was entered that qualitatively fit the observed data, and then the computer displayed both the observed conductivities and conductivities calculated from the chosen model. The model was then adjusted by the user to better fit the observed data. After reasonable agreement was obtained manually, the program was directed to adjust 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 a nearly equivalent fit to the observed data.

Time-Domain Soundings

Time-domain, or transient, electromagnetic soundings (Kaufman and Keller, 1983; Spies and Frischknecht, 1991) using a Geonics PROTEM 47/S instrument (fig. 8) were used to give a more detailed conductivity profile at several sites to a maximum depth of about 100 m. Instead of using different coil separations to vary penetration depth, the time-domain device measures the decay of a transient secondary electromagnetic field produced by the termination of an alternating primary electromagnetic field (fig. 18).

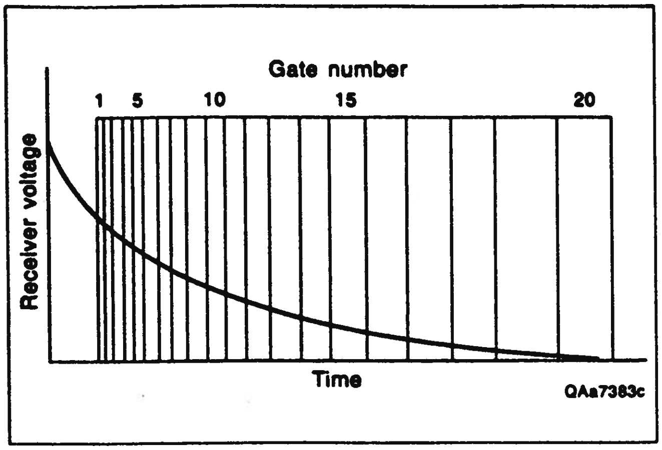


Figure 19. Decay of transient secondary electromagnetic field and time distribution of measurement gates for the PROTEM 47/S. Adapted from Geonics Limited (1992).

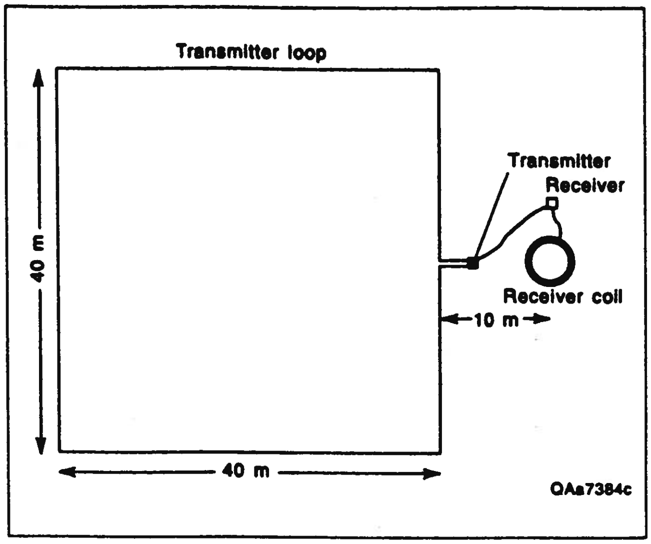


Figure 20. Instrument configuration of PROTEM 47/S sounding.

The secondary field strength is measured by the receiving coil at 20 moments in time (or "gates") following transmitter current termination (figs. 18 and 19). Secondary field strength at early times gives information about conductivity in the shallow subsurface; field strength at later times is related to conductivity at depth. The computer program TEMIX, by Interpex, was used to construct model conductivity profiles that best fit the observed transient decay at each sounding site.

Time-domain electromagnetic soundings were conducted at 13 sites in November 1992. Seven sites were located in the Ute Reservoir to Revuelto Creek area (fig. 13), including one each on the upland north (PN) and south (PS) of the Canadian River canyon. Four sites (P331, P388, P421, and P500) were located along the Canadian River between the railway bridge and Revuelto Creek, and one (P8) was located along Revuelto Creek near its confluence with the Canadian River. Six soundings (P2, P53, P102, P122, P164, and P230) were conducted along the Canadian River in the Dunes area (fig. 16). All time-domain soundings were collected with a 40- by 40-m transmitter antenna with the receiver coil outside the transmitter loop (fig. 20).

Whereas results of multiple-coil-separation soundings are given in the conductivity unit mS/m, results of time-domain soundings are customarily given in the resistivity unit ohm-m. These units are the inverse of each other and are converted by the following equation:

Conductivity (mS/m) = 1000/resistivity (ohm-m).

Results and Interpretations

Evaporite Dissolution Patterns in Permian Salt-Bearing Strata

Extensive dissolution of Permian bedded halite and gypsum has occurred in the Canadian River valley in central Quay County, New Mexico. Approximately 213 m of halite has been dissolved from the Seven Rivers and San Andres Formations and from the top of the Glorieta Formation to depths of 335 m beneath the Canadian River (fig. 4). At higher elevations 16 km south of the Canadian River, only 108 m of halite has been dissolved from the Seven Rivers and Upper San Andres Formations. Gypsum probably has been dissolved from beds in the Seven Rivers Formation (Artesia Group) in the shallow subsurface of the Canadian River valley. Release of calcium and sulfate ions probably also occurred in the dissolution zone during hydration of anhydrite to gypsum.

Areas of past and possibly continuing halite dissolution can be identified on regional structural cross sections through parts of eastern New Mexico and the Texas Panhandle (Gustavson and others, 1980; Hydro Geo Chem, 1984; Gustavson and Finley, 1985; McGookey and others, 1988). More detailed cross sections through the area of Ute Reservoir and Revuelto Creek (figs. 4 and 5) were constructed during the present study to investigate the depths and possible pathways of ground-water circulation. The cross sections identify areas where large amounts of halite are still present and may be subject to modern salt dissolution. These areas of preserved halite are potential contributors to the solute load of the Canadian River.

Halite (NaCl) Dissolution

The following variations in halite distribution were determined from logs and constrain areas where halite dissolution has occurred (figs. 4 and 5). There is no evidence of halite in the Red Cave Formation, lower Clear Fork Group, or Tubb Formation beneath the study area; these strata are characterized by siliciclastic-dominated facies that were probably deposited in an environment proximal to the ancestral Rocky Mountains, away from areas of evaporite precipitation. Halite units are present in the upper Clear Fork Group and are laterally continuous through the study area. Halite units are also present in the Glorieta Formation, but the uppermost halite beds are missing from beneath the Canadian River valley, presumably because of dissolution.

Thick-bedded halite units appear in the San Andres Formation in the Tucumcari Basin but progressively disappear northward and are completely dissolved from beneath the Canadian River valley (figs. 4 and 5). The thickness of the interval between the top of the San Andres Formation and the base of lower San Andres unit 5 decreases from 174 m at the Quay 14 well, 30 km south of the Canadian River, to 66 m at the Quay 13 well, 10 km south of the Canadian River (fig. 4). The thickness of the lower part of the San Andres Formation, from the top of San Andres unit 4 to the base of halite in the upper Glorieta Formation, decreases from 165 m at Quay 13 to 61 m beneath the Canadian River (fig. 4). The thickness decrease of almost 213 m is interpreted to be entirely the result of halite dissolution. The opposite interpretation (that thinning reflects the original depositional pattern) is contradicted by the observation that individual San Andres carbonate and anhydrite units can be correlated farther north with only very gradual depositional thinning and pinch-out. The interpretation that dissolution of halite has resulted in subsidence of the overlying strata is suggested by an abrupt decrease in the regional dip of the units above the missing halite and by cycle skipping on sonic logs (suggesting fracturing). Thick carbonate beds in the lower San Andres Formation and sandstones at the top of the Glorieta Formation have high porosity in areas where halite has been dissolved and may serve as zones of enhanced flow promoting transmission of fresh waters into zones of preserved halite. Highly porous beds developed from dissolution of halite cements have been observed in the shallow subsurface of San Andres in the eastern Texas Panhandle (Hovorka and Granger, 1988).

Halite exists within the Artesia Group in the southern part of the study area in mixed siliciclastic-halite beds and as separate halite interbeds. Halite has been dissolved from the mixed siliciclastic-halite beds in the Queen-Grayburg and Seven Rivers Formations beneath the Canadian River valley, leaving strata dominated by siliciclastic material. The siliciclastic component thins by 25 percent, from 73 m at the Quay 13 well to 55 m over the Bravo Dome at the Harding 7 well (fig. 4). This thinning suggests that the depositional environment changed significantly toward the Bravo Dome, where subsidence rates were slower than in basin areas. Farther south, at the Quay 14 well, the thickness and gamma-ray response of the Artesia Group are preserved, but the sonic log response indicates that the unit may be highly fractured. The sonic log response suggests that partial or incipient halite dissolution has occurred in this area. Minor amounts (less than 5 m) of upper San Andres halite beneath Queen-Grayburg sandstones (Artesia Group) are missing in central Quay County 50 km south of the Canadian River, ahead of the main dissolution front. This intrastratal halite dissolution demonstrates that the presence of highly permeable units within the evaporite section can promote hydrologic circulation and locally increase halite dissolution.

Anhydrite ($CaSO_4$) and Gypsum ($CaSO_4 \cdot 2H_2O$) Dissolution

Partial dissolution of anhydrite and the eventual complete dissolution of gypsum both contribute to the solute load of the Canadian River. Calcium sulfate dissolution can occur when anhydrite comes in contact with low-salinity water and is hydrated to gypsum. In the subsurface, this hydration generally proceeds without a major volume increase. However, because the molar volume of gypsum (about 75 cm^3) is much greater than that of anhydrite (about 46 cm^3), a volume-for-volume replacement of anhydrite by gypsum requires removal of some calcium sulfate.

Units characterized by low gamma-ray response and interpreted as gypsum (or anhydrite) beds can be traced within the Seven Rivers Formation throughout the study area. However, no gypsum beds were noted on the lithologic logs of cores from holes drilled into the upper part of the Artesia Group just downstream from Ute Dam (DH-1 and DH-2). Note that regional correlation during this study indicates that only the upper part of the Artesia Group was penetrated by these holes, contrary to the original interpretations indicated on the logs (U.S. Bureau of Reclamation, 1979), which were later corrected by data from an additional drill hole (DH-3, U.S. Bureau of Reclamation, 1984). The absence of gypsum beds in these cores may indicate that gypsum has already been dissolved from near-surface environments in the Canadian River valley. Extensive gypsum dissolution has been documented in very shallow subsurface environments in the San Andres Formation in the eastern Texas Panhandle (Hovorka and Granger, 1988).

Joint Analysis

Orientations of more than 500 joints were recorded from exposures of Dockum fluvial channel sandstones that crop out within a few hundred meters of the Canadian River and Revuelto Creek in eastern New Mexico. Measurements were made at nine sites between Ute Dam and the confluence of the Canadian River and Revuelto Creek, at one site in the Jones well area, and at six sites along the Dunes segment of the Canadian River (figs. 21 through 23).

In the areas studied, the joints are typically near vertical and are spaced less than a meter apart (fig. 24). Most of the joints can be assigned to either of two groups: systems of through-going (or primary) joints or systems of crossing (or secondary) joints that terminate against through-going joints. Primary joints may extend for several tens of meters before dying out and may be part of a group of closely spaced, en echelon

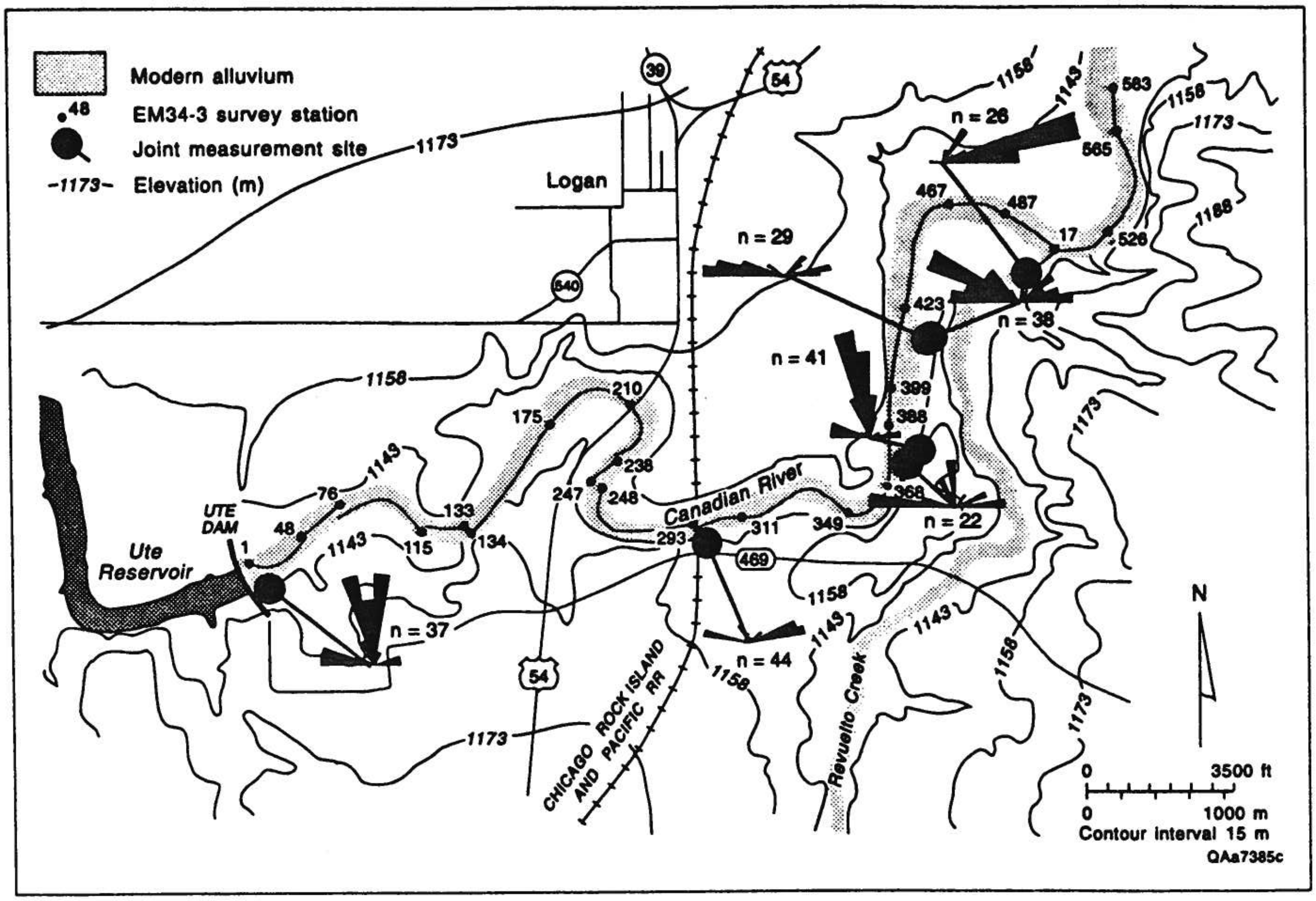


Figure 21. Simplified topographic map of the Canadian River valley between Ute Reservoir and Revuelto Creek (area a, fig. 11) showing locations of joint measurements plotted as half roses.

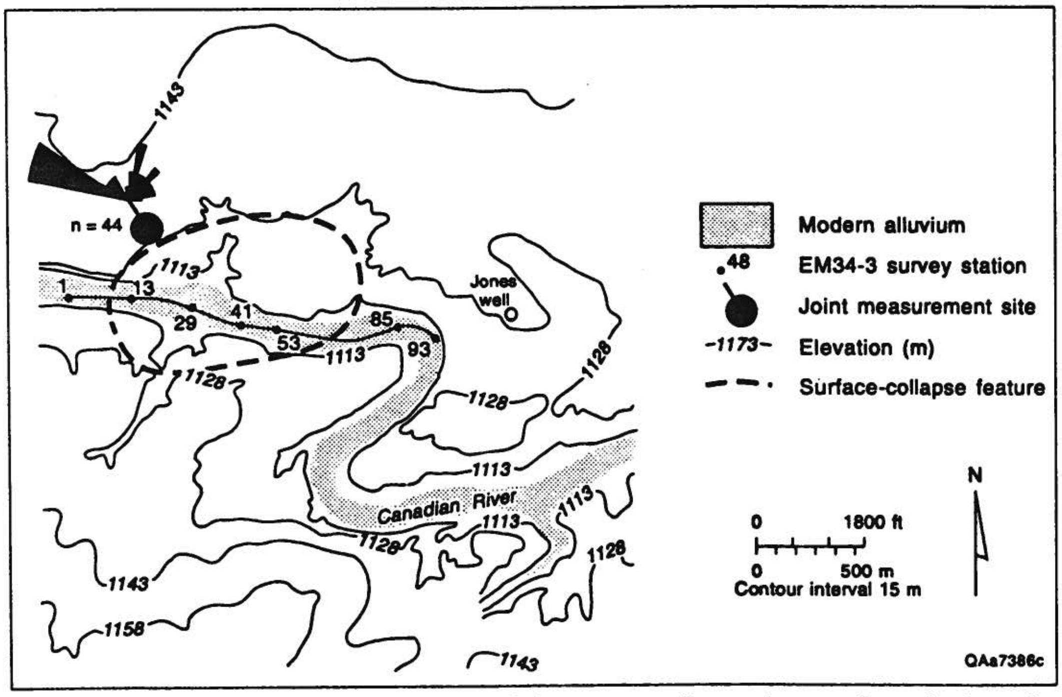


Figure 22. Simplified topographic map of the Jones well area (area c, fig. 11) along the Canadian River showing location of joint measurements plotted as a half rose.

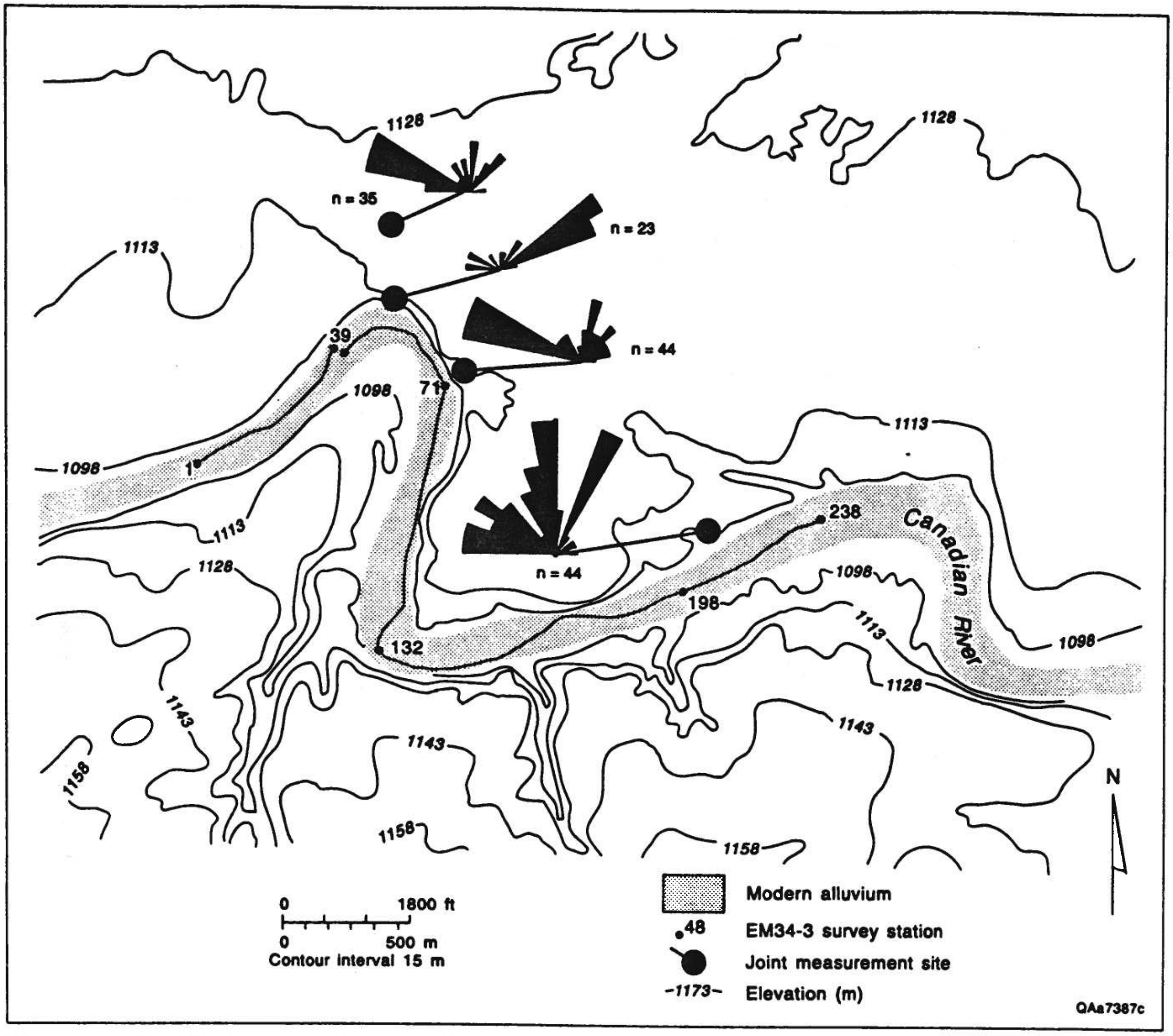


Figure 23. Simplified topographic map of the Dunes area (area d, fig. 11) along the Canadian River showing locations of joint measurements plotted as half roses.

joints. Primary joint faces exposed in the canyon walls are more than 35 m long and 12 m high. Secondary joint faces are typically less than 1 m long, but they may extend for several meters in height.

Orientation

Several dominant joint orientations were recognized in the Canadian River canyon (figs. 21 through 23). Primary joints are roughly parallel to the northern margin of the Palo Duro and Tucumcari Basins and the southern margin of the Bravo Dome in eastern New Mexico (fig. 1). Jointing that was related to the development of these tectonic features may also have been influenced by later subsidence resulting from dissolution of Permian salt beds underlying 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

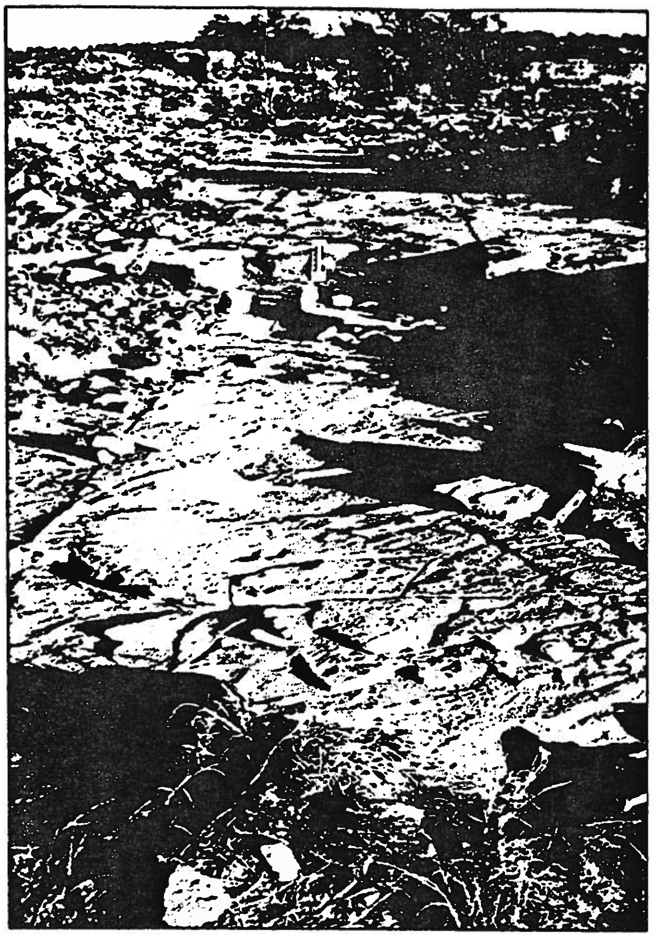


Figure 24. Primary through-going joints (roughly top-to-bottom) and secondary joints (left-to-right) terminating against primary joints in Dockum Group sandstone. Photograph taken by David M. Stephens along the Canadian River canyon between Ute Reservoir and Revuelto Creek.

sets. The general east-west orientation of primary joints roughly parallels the overall east-northeast trend of the Canadian River canyon near Logan, New Mexico (fig. 21) and the east-southeast trend of the valley near the Dunes area (fig. 23). Secondary joints developed at high angles to primary joints and typically define subsets with varying orientations at each field site.

Dilation

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

Calcium carbonate fillings in joints may have precipitated from ground water or surface water. Calcium carbonate is likely to accumulate within the upper 1 or 2 m of joints in arid and semiarid climates for the same reasons that $CaCO_3$ accumulates in calcic soils in dry environments (Gile and others, 1981): (1) loss of CO_2, causing a decrease of $CaCO_3$ solubility, and (2) high evaporation and transpiration rates, which prevent water from most precipitation events from penetrating more than a few decimeters into surface sediments before it is taken up by plants or drawn back to the surface by capillary forces and evaporated. Under these conditions, $CaCO_3$ is left behind as a joint-filling precipitate. Joint fillings could also have formed in much the same fashion as ground-water calcretes, in which $CaCO_3$ is precipitated in the unsaturated zone at or slightly above the water table (Estaban, 1976). In both cases the presence of a joint filling indicates that the joint was open prior to mineralization and could transmit fluids.

The effectiveness of joints as pathways for ground-water flow is also indirectly illustrated by widespread efflorescence (fig. 8) of gypsum and halite on alluvium exposed near river 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 high as 5 to 7 m above the river. The efflorescence is typically highest along vertical joints. Accelerated weathering and erosion are also common along joints, producing small-scale caverns and indentations in the canyon walls.

Distribution

Typically, several groups of 6 to 10 relatively closely spaced joints were recognized, which were separated by areas of rock with either no joints or a few widely spaced joints (figs. 25 through 27). Primary joints (east-west through-

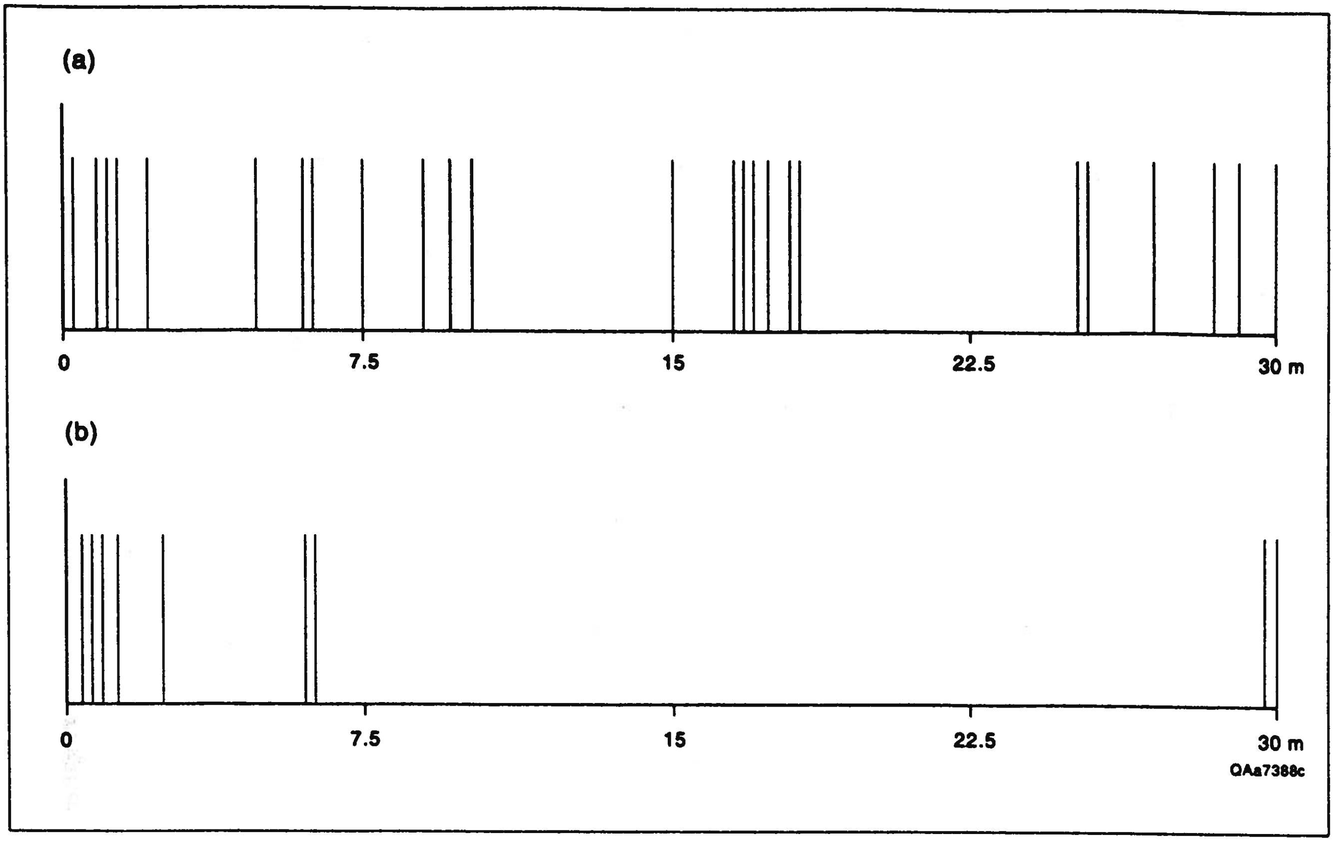


Figure 25. Joint distributions along (a) north-south and (b) east-west lines southeast of station 423 on the Canadian River (fig. 21). Note that east-west joints, which cross the north-south line, are more common than north-south joints and that joints in general appear to be grouped.

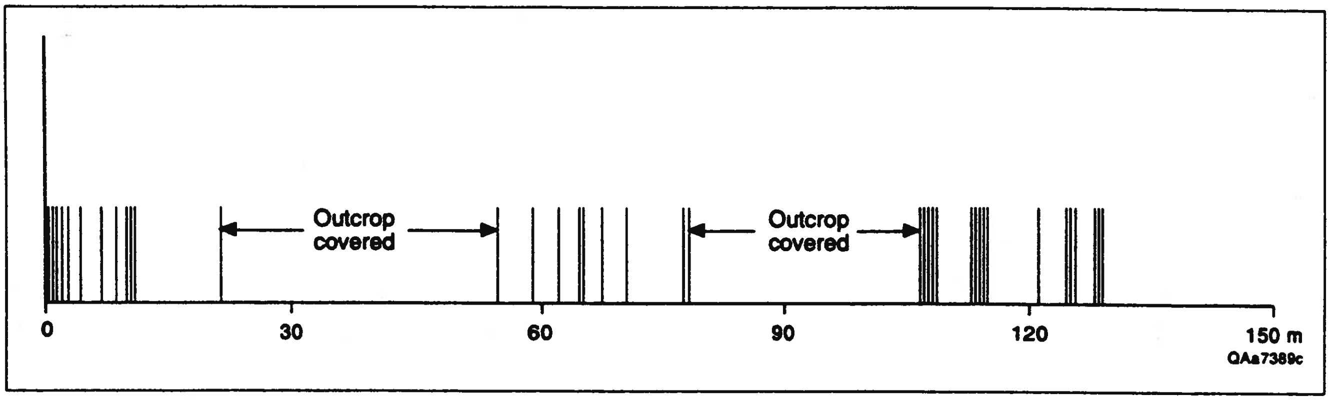


Figure 26. Joint distribution southeast of station 423 on the Canadian River (fig. 21) along a 150-m north-south exposure. Note that the joints are apparently grouped.

going joints) are more numerous than secondary joints. For example, in thick fluvial sandstones southeast of station 423 in the Ute Reservoir to Revuelto Creek area, 25 joints crossed a 30-m-long north-south line, but only 9 joints crossed a 30-m-long east-west line (fig. 25). At most other sites, primary joints also outnumber secondary joints. Joints are not evenly distributed vertically or horizontally. The vertical distribution of joints is strongly affected by variations in bed thickness

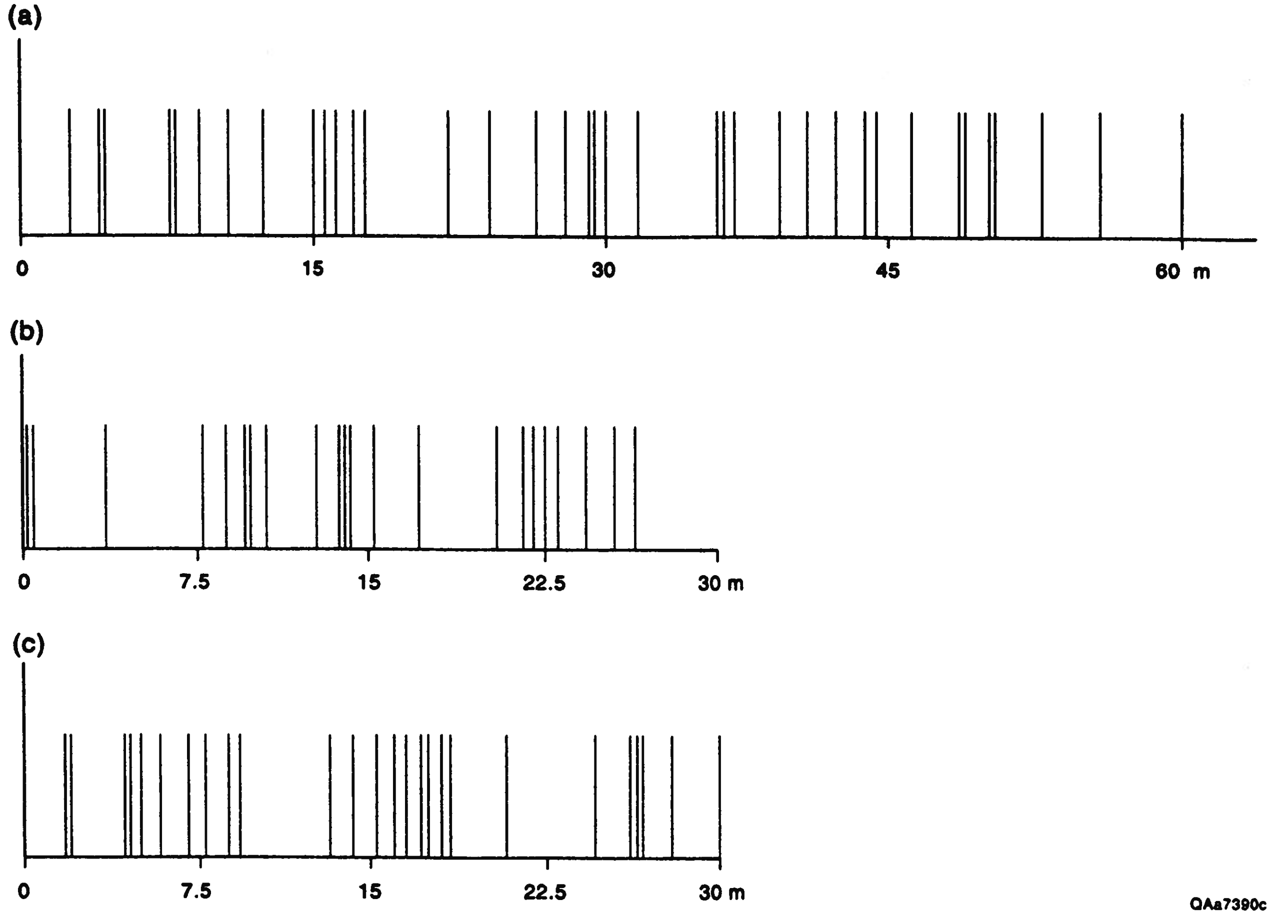


Figure 27. Joint distributions (a) at the foot of Ute Dam, (b) southeast of station 388 along the Canadian River between Ute Reservoir and Revuelto Creek, and (c) at the intersection of Revuelto Creek and the Canadian River (fig. 21). Note that in each area joints are apparently grouped.

and grain size. Thick sandstone bodies are relatively competent and hence contain fewer or more widely spaced joints than weaker thin sandstone beds. Mudstone beds, which are the least competent lithologic units, contain abundant closely spaced joints.

Surface-Water Conductivity and Flow Survey

The highest conductivities recorded during the water conductivity and flow survey were found along the first 11 km of the Canadian River below Ute Reservoir (fig. 28). Conductivity of river water increased steadily along the first 10 km below Ute Reservoir, from less than 100 to greater than 1,000 mS/m (fig. 29). River flow also increased along this segment of the river, from about 0.06 m^3/s just downstream from the dam (site 8—all apparent surface flows and most canyon wall seeps have joined the river above this point) to more than 0.13 m^3/s upstream from the confluence with Revuelto Creek. There were no flowing tributaries along this segment of the river at the time of the survey and no recent rain,

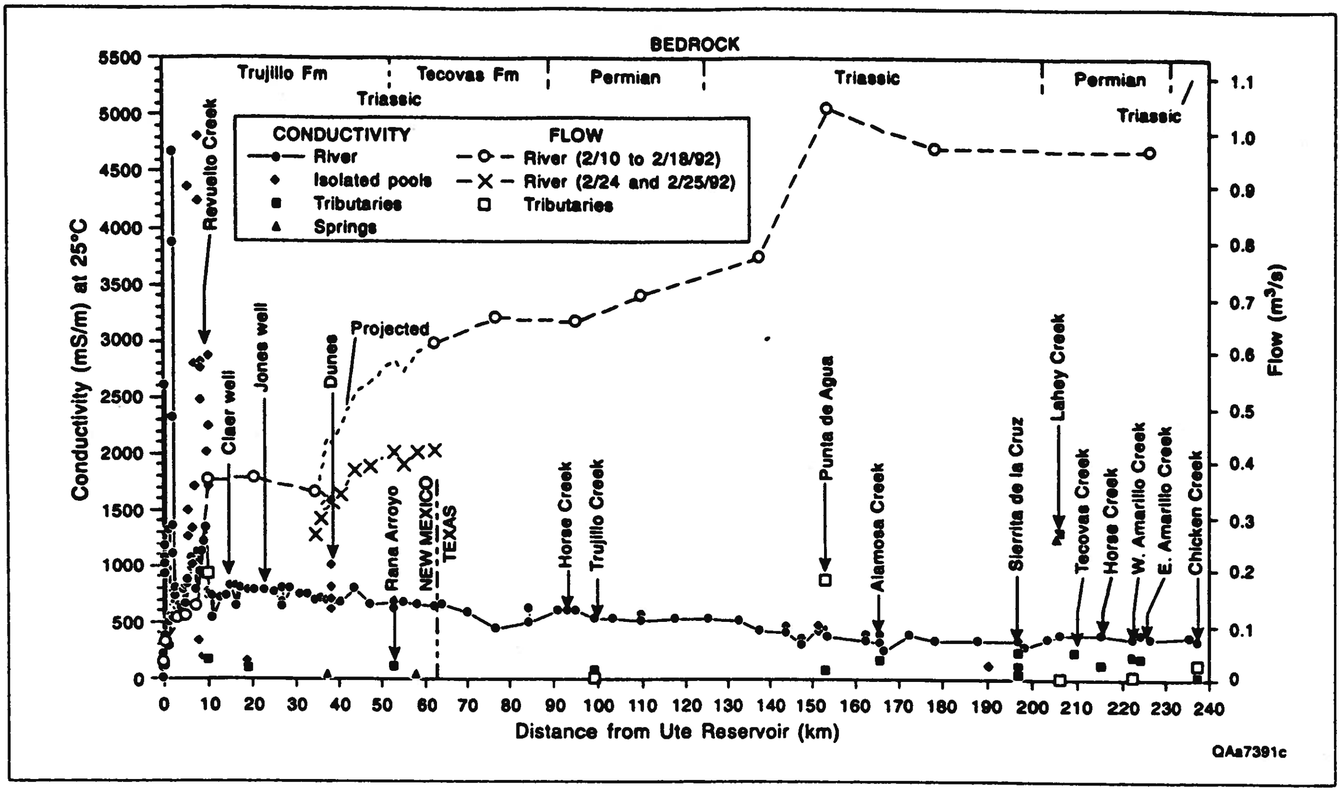


Figure 28. Conductivity (scale on left) and flow (scale on right) along the Canadian River between Ute Reservoir, New Mexico, and Lake Meredith, Texas. The exposed bedrock in the canyon walls is indicated along the top.

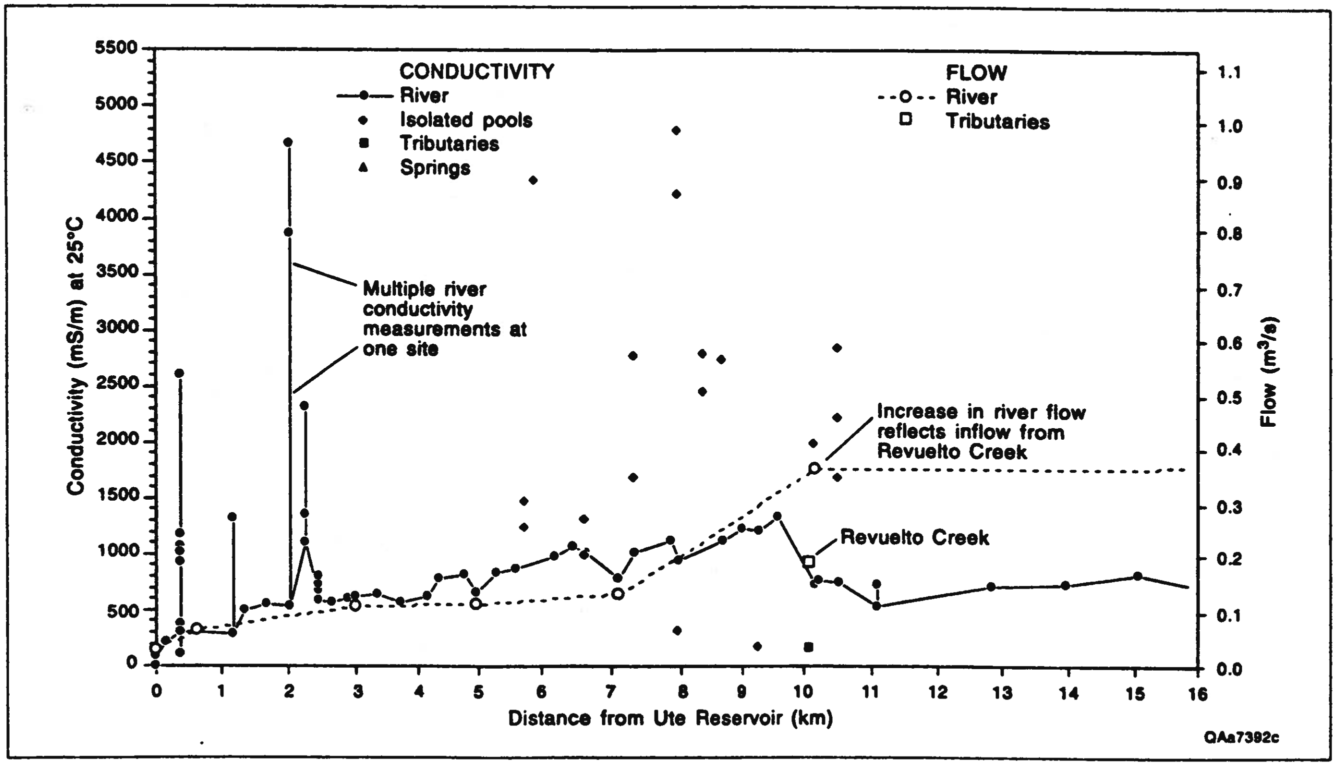


Figure 29. Conductivity (scale on left) and flow (scale on right) along first 16 km of the Canadian River below Ute Reservoir, New Mexico. The exposed bedrock in canyon walls along this stretch of the river canyon consists almost entirely of fluvial channel sandstones of the Triassic Trujillo Formation (Dockum Group).

indicating that the added volume must have entered directly by discharge of ground water from the alluvium.

The trend of increasing conductivity and flow in the first 10 km downstream from Ute Reservoir indicates that water in the alluvium has high conductivity. Measured conductivities along the first 2.4 km were highest in slow-moving pool stretches, where turbulence is at a minimum, suggesting that these high values (fig. 29) represent waters that had entered the river nearby but had not yet thoroughly mixed with the river water. These high values probably reflect the conductivity of the water contained in and discharged from the alluvium. The inference that water in the alluvium has high conductivity is further suggested by the presence of high-conductivity waters in pools isolated from the river between 5.6 and 10.5 km downstream (sites 26 through 42, figs. 7a and 29); water in the isolated pools is thought to be representative of ground water from the alluvial aquifer, although its chemistry may be altered by evaporation. The measured conductivity within many of the pools (including pool sections of the river and isolated pools in the riverbed) varied greatly with placement of the conductivity probe; measured conductivity was generally lowest when the probe was suspended within the upper part of the water column and highest when the probe was positioned on or within the sediment on the bottom. The downward increase in conductivity is probably due to density stratification, where denser, more saline water occupies the deepest parts of the pools.

Conductivity of the Canadian River decreased substantially (from 1,000 to 500 mS/m) just downstream from its confluence with Revuelto Creek (10 km downstream from Ute Dam; site 40), because of the diluting effect of the added flow from the creek, which carried water of low conductivity (less than 200 mS/m). Below this point, river conductivity increased again and continued to increase to a point 15 km downstream from Ute Dam (site 46, figs. 7a and 29). Conductivity of the Canadian River remained fairly constant between 16 and 32 km downstream from Ute Reservoir (sites 46 through 56, figs. 7a, 7b, and 28). Measured flow decreased slightly, probably because of infiltration of river water into the alluvial aquifer. These observations suggest limited inflow to the river in this stretch and no increase in salinity.

River flow nearly doubled from about 0.34 to more than 0.59 m^3/s between about 32 and 64 km downstream from Ute Reservoir (sites 57 through 67, figs. 7b and 28). Although river flow increased, conductivity remained fairly constant, implying that the net salinity of incoming waters must have been about the same as that of the river waters. About 12 percent of the increase in river flow in this segment was due to inflow from two tributaries that were flowing at the time of the survey (unnamed tributary near kilometer 39, site 60, fig. 7b; and Rana Arroyo near kilometer 53, site 64, fig. 7b). The major part of the flow increase, however, must have been contributed by discharge from the alluvial aquifer. Additional discharge measurements and water samples at closely spaced intervals along this segment of the river (from sites 57 through 67, fig. 7b) indicated that most of the increase in flow occurred along the first half of the river segment (fig. 28); those data also showed that overall flow had decreased by about 30 percent since the original survey. The decrease in flow resulted not only from decreased inflows from tributaries but also from decreased discharge from the alluvium along that river segment (fig. 28). This suggests that the contributions from the alluvium were not strictly baseflow but must have also included some subsurface runoff from storms.

The segment along which river flow increased dramatically (between sites 57 and 67, fig. 7b) begins approximately at an isolated location of high-conductivity waters (up to 1,550 mS/m) in pools in the riverbed and in pools along an unnamed flowing tributary on the south side of the river near kilometer 39 (site 60, figs. 7b and 28). Between about 64 and 77 km downstream from Ute Dam, conductivity declined, whereas river flow increased. This indicates dilution of through-flowing river water by fresher water from springs or tributaries, or discharge from the alluvial aquifer, with little or no increase in salt load.

River conductivity increased modestly, whereas river flow remained the same or decreased slightly because of infiltration or evaporation

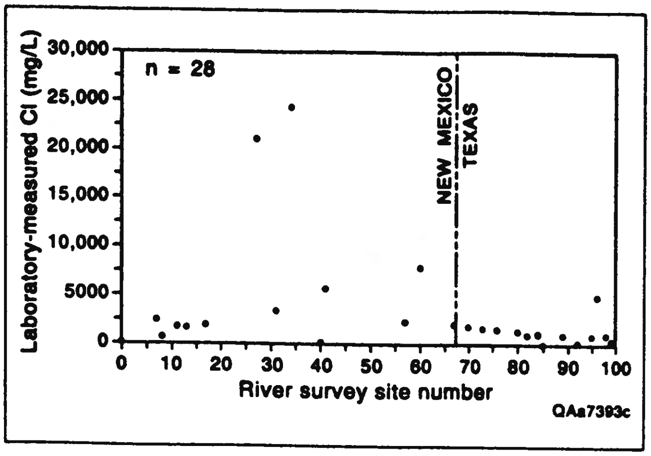


Figure 30. Chloride concentrations in river-survey samples collected between Ute Reservoir, New Mexico, and Lake Meredith, Texas, February 1992 (see fig. 7 for sample locations and table 1 for chloride data).

along the broad, widely meandering part of the Canadian River near Nara Visa Arroyo and Horse Creek in Texas (77 to 92 km, sites 68 through 72, fig. 7b and 7c). River conductivity declined slightly between 92 and 137 km (sites 72 through 80, fig. 7c and 7d), whereas river flow increased slightly. Again, this suggests a dilution of through-flowing river water, with little or no increase in salt load.

Beyond 137 km to the end of the survey, river conductivity varied slightly, although conductivity remained approximately the same (about 300 mS/m). Notable features along this stretch included (1) one isolated saline pool in the riverbed just upstream from Punta de Agua, (2) substantial inflow from Punta de Agua, followed by a slight loss of flow between there and the next flow station, (3) modest conductivities (235 mS/m) in pools in Alamosa Creek and in Sierrita de la Cruz, (4) very high conductivities (1,300 mS/m) in Lahey Creek and in a seep immediately upstream from the creek, and (5) modest conductivities (as much as 230 mS/m) in pools in Tecovas Creek, Horse Creek, West Amarillo Creek, and East Amarillo Creek. Although conductivities at and near Lahey Creek were high, flow was quite low and insignificant to river conductivity. Nevertheless, these high conductivities suggest that this is another potential salinity source area.

Surface-Water Chemistry

Water quality of analyzed samples (table 1) ranges from fresh (chloride less than 250 mg/L) to highly saline (chloride greater than 10,000 mg/L); most of the higher salinity waters were collected from areas in New Mexico (fig. 30). Similar ratios among major cations and anions in the different samples suggest that the waters are related; this pattern is reflected in bivariate plots by more or less linear trends of the data points (figs. 31 and 32). These trends suggest mixing between two water types, mixing products falling between the end members. One end member of this mixing trend is fresh water derived from meteoric precipitation. The chemistry of this fresh water changes as it infiltrates the ground, where it interacts with soil and aquifer material before being discharged to the Canadian River. The other end member is highly saline water derived primarily from dissolution of halite (NaCl), as indicated by molar sodium-to-chloride ratios (Na/Cl) of approximately 1 in virtually all the analyzed samples, and by bromide-to-chloride weight ratios (Br/Cl) of smaller than 0.001 in all but the freshest water samples (fig. 33). Ratios of Na/Cl and Br/Cl have been used successfully to identify halite-dissolution brines in other parts of Texas and in Kansas (Whittemore and Pollock, 1979; Richter and Kreitler, 1986).

Published chemical analyses of ground waters sampled from wells in the drainage area of Revuelto Creek (Hydro Geo Chem, 1984) show that evaporite-bearing Permian strata, in which halite dissolution occurs, have a water chemistry different from that of overlying Triassic aquifer units (fig. 34a and 34b). Revuelto Creek, the only tributary along the 16-km stretch downstream from Ute Reservoir where inflows are significant, appears to be influenced by discharge from both Permian and Triassic units (fig. 34c). At times, Revuelto Creek carries water of low salinity with Na/Cl ratios that follow a trend typical of well waters from Triassic strata (fig. 34b and 34c). At other times, the creek carries water of much higher salinities with Na/Cl ratios that

Table 1. Results of chemical analyses of water samples collected during the February 1992 conductivity survey of the Canadian River between Ute Reservoir, New Mexico, and Lake Meredith, Texas.*

River survey site no.	Sample type[a]	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SO_4 (mg/L)	Cl (mg/L)	Br (mg/L)	Quantab Cl[b] (ppm)	HCO_3[c] (mg/L)	Br / Cl (wt. ratio)	TDS (mg/L)	Conductivity (mS/m)
0	R	43.4	34.8	131	6.47	281	49.4	<0.25	45	216	<0.00506	762	—
7	R	123	58.4	1,840	7.66	555	2,370	0.42	2,678	457	0.00018	5,411	923
8	R	67.1	41.7	625	5.13	349	717	0.44	670	353	0.00061	2,158	298
11	R	99.9	54.3	1,310	6.89	439	1,750	0.32	1,958	387	0.00018	4,047	552
13	R	96.9	52.4	1,250	7.16	436	1,630	0.43	2,138	375	0.00026	3,848	1,109
17	R	103	56.2	1,420	7.70	451	1,890	0.38	2,138	389	0.00020	4,317	623
27	P	609	169	14,140	37.6	2,010	21,010	0.48	>6,000	775	0.00002	38,751	5,303
31	R	153	72.3	2,434	10.4	615	3,415	0.25	4,150	485	0.00007	7,185	781
34	P	782	200	16,950	43.3	2,520	24,350	0.46	>6,000	997	0.00002	45,843	5,365
40	T	76.8	66.5	407	3.44	757	153	0.49	570	355	0.00320	1,819	200
41	P	303	111	3,920	15.3	1,120	5,650	0.38	>6,000	803	0.00007	11,923	2,487
57	R	126	75.9	1,708	6.01	692	2,286	<0.25	2,680	388	0.00011	5,282	700
60	P	279	113	5,050	16.1	790	7,870	<0.25		642	<0.00003	14,760	1,120
67	R	116	72.2	1,472	6.85	558	1,980	<0.25	2,500	360	<0.00013	4,565	648
70	R	105	69.5	1,346	7.18	490	1,817	0.57		346	0.00031	4,181	438
73	R	106	67.6	1,242	6.36	519	1,656	0.46		332	0.00028	3,929	602
76	R	121	69.5	1,110	7.17	538	1,560	0.27	2,000	377	0.00017	3,783	510
80	R	112	64.0	985	6.66	504	1,329	0.46	1,500	277	0.00035	3,278	434
82	R	36.7	59.0	757	6.34	482	919	0.34	1,040	251	0.00037	2,511	346
84	P	208	112	1,370	11.5	1,090	1,060	0.70	1,145	1,419	0.00066	5,271	610
84	R	110	63.3	918	6.83	563	1,200	0.23	1,250	316	0.00019	3,177	449
85	T	53.7	48.6	78.4	6.50	66.4	32.8	<0.25	<45	469	<0.00762	755	81
89	R	93.5	57.7	740	5.40	399	945	0.34	1,200	335	0.00036	2,576	392
92	P	47.0	21.2	247	1.81	78.3	217	<0.25	<300	415	<0.00115	1,027	137
95	R	91.6	56.2	684	5.26	450	904	0.31	935	313	0.00034	2,504	362
96	S	719	172	3,390	6.47	2,160	4,910	<0.25	5,500	191	<0.00005	11,548	1,554
98	R	118	63.1	764	6.49	652	1,000	0.27	1,250	280	0.00027	2,884	362
99	R	273	80.8	345	4.15	844	409	<0.25	436	291	<0.00061	2,247	362

*Conductivity measurements at sample locations (not of samples) are also included; conductivity values were converted from instrument units of micromho/cm to mS/m by dividing by 10.

[a] Samples obtained from river (R), isolated pools in riverbed (P), tributaries (T), and springs or seeps (S).

[b] Chloride value measured in field using Quantab chloride titrator strips no. 1175 (45–600 ppm) and no. 1176 (300–6,000 ppm). Values not measured for sites 60c, 70, and 73.

[c] Alkalinity measured in field by acid titration.

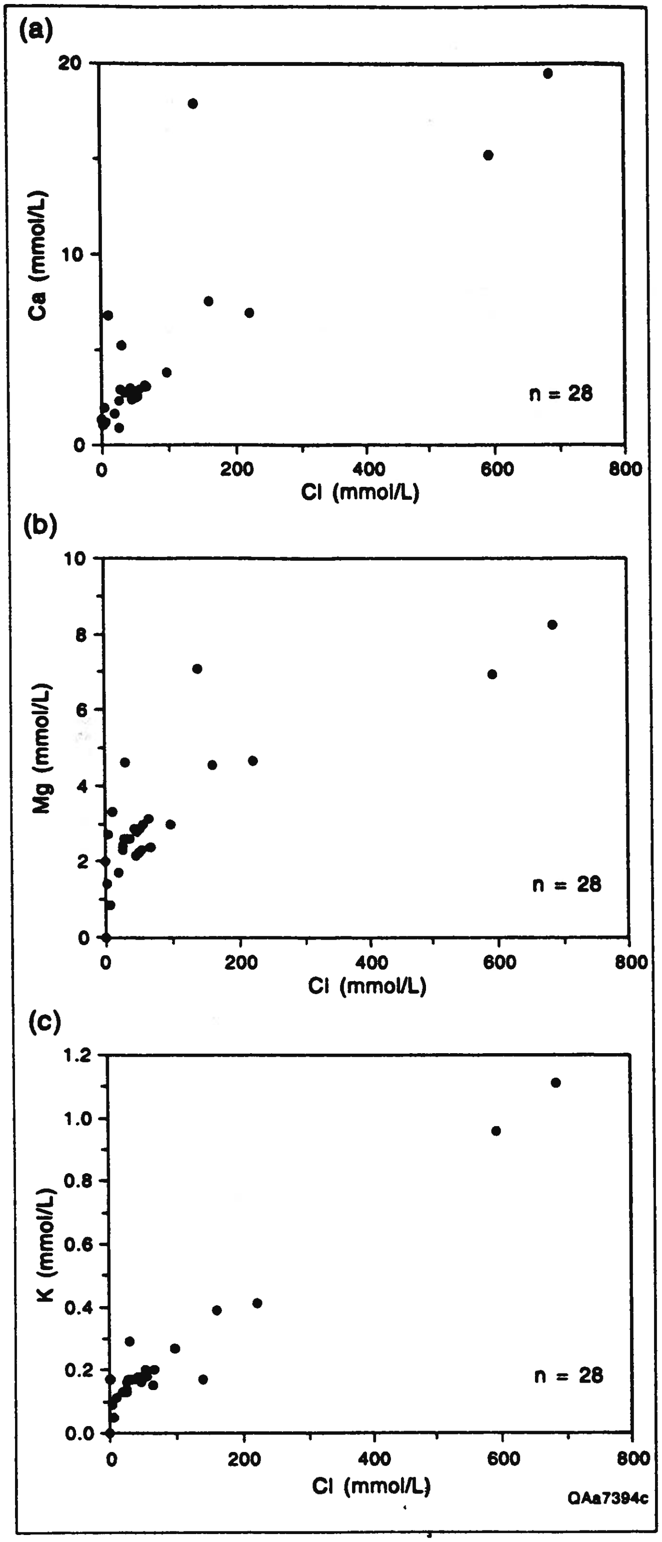


Figure 31. Plots of (a) calcium versus chloride, (b) magnesium versus chloride, and (c) potassium versus chloride for surface-water samples (table 1). The linear trends suggest mixing between meteoric waters and salt-dissolution waters.

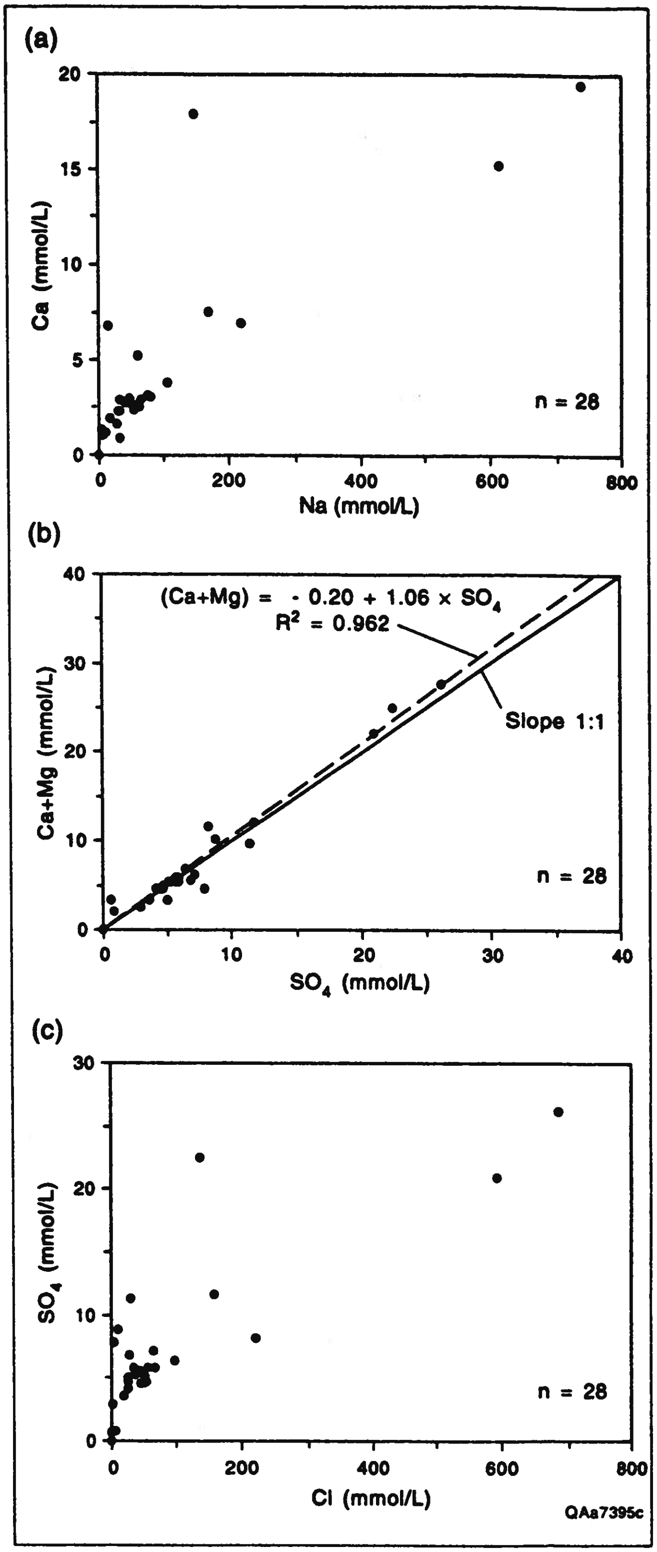


Figure 32. Plots of (a) calcium versus sodium, (b) calcium plus magnesium versus sulfate, and (c) sulfate versus chloride for surface-water samples (table 1). The linear trends suggest mixing between meteoric waters and salt-dissolution waters.

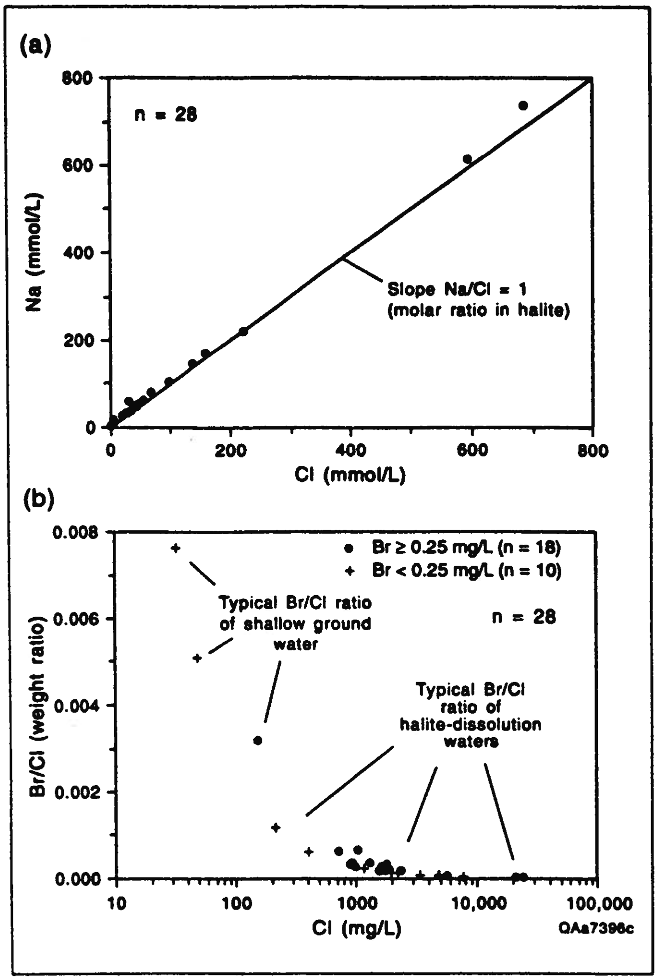


Figure 33. Plots of (a) sodium versus chloride and (b) bromide-to-chloride weight ratio versus chloride. Solutes in sampled waters are dominated by sodium chloride; the strong linear trend of sodium versus chloride (a) and bromide-to-chloride weight ratios (b) indicate that sodium and chloride are derived mainly from halite dissolution. In 10 samples, bromide concentration was at or below detection limits; actual bromide-to-chloride ratio for these samples is less than the plotted value.

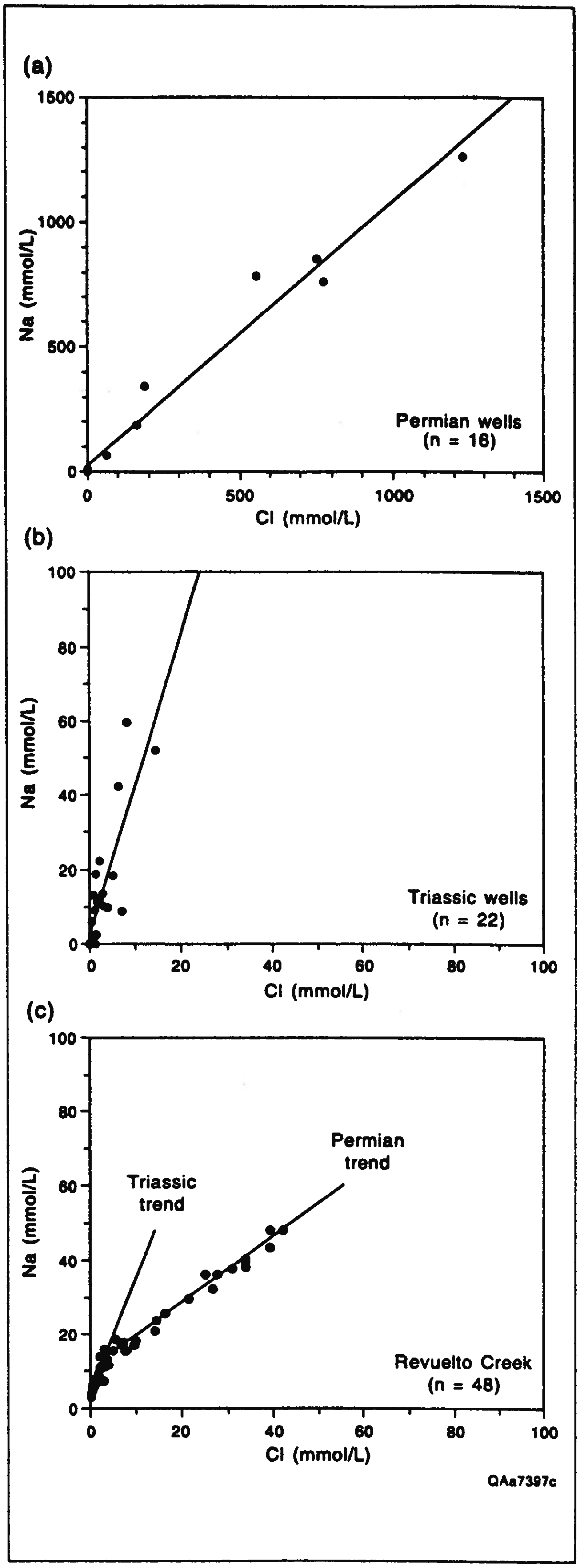


Figure 34. Comparison of water samples from (a) well producing from Permian strata, (b) wells producing from Triassic strata, and (c) Revuelto Creek, New Mexico. Water salinity in Revuelto Creek is low when flow is dominated by discharge of water from Triassic formations; salinity is high when flow is dominated by contributions from Permian units (data from Hydro Geo Chem, 1984).

approach 1, which is typical of halite-dissolution waters observed within Permian units in the area (fig. 34a and 34c), suggesting mixing between waters from Triassic and Permian water-bearing units.

A small fraction of solutes in the Canadian River is contributed by gypsum or anhydrite dissolution. Samples collected along the eastern part of the Canadian River show trends in bivariate plots of calcium versus chloride and of sulfate versus chloride that are distinctly different from those for samples collected farther west (figs. 35a and 35b). The absolute calcium and sulfate concentrations of surface waters in the two areas span the same range (fig. 35c), but calcium and sulfate make up a smaller proportion of the solutes in the western part of the Canadian River than in the eastern part (figs. 36 through 38). In the western part, sodium constitutes 80 to 95 percent of all cations and chloride makes up 75 to 90 percent of all anions (fig. 37), whereas farther east the respective ranges are 70 to 85 percent and 60 to 75 percent (fig. 38). Halite is thus a greater contributor to ion concentration than is anhydrite and gypsum dissolution in the western part of the river. Either the proportion of sulfate to halite dissolved was higher to the east, or halite-dissolution brine was diluted by fresher sulfate-dominated water in this area.

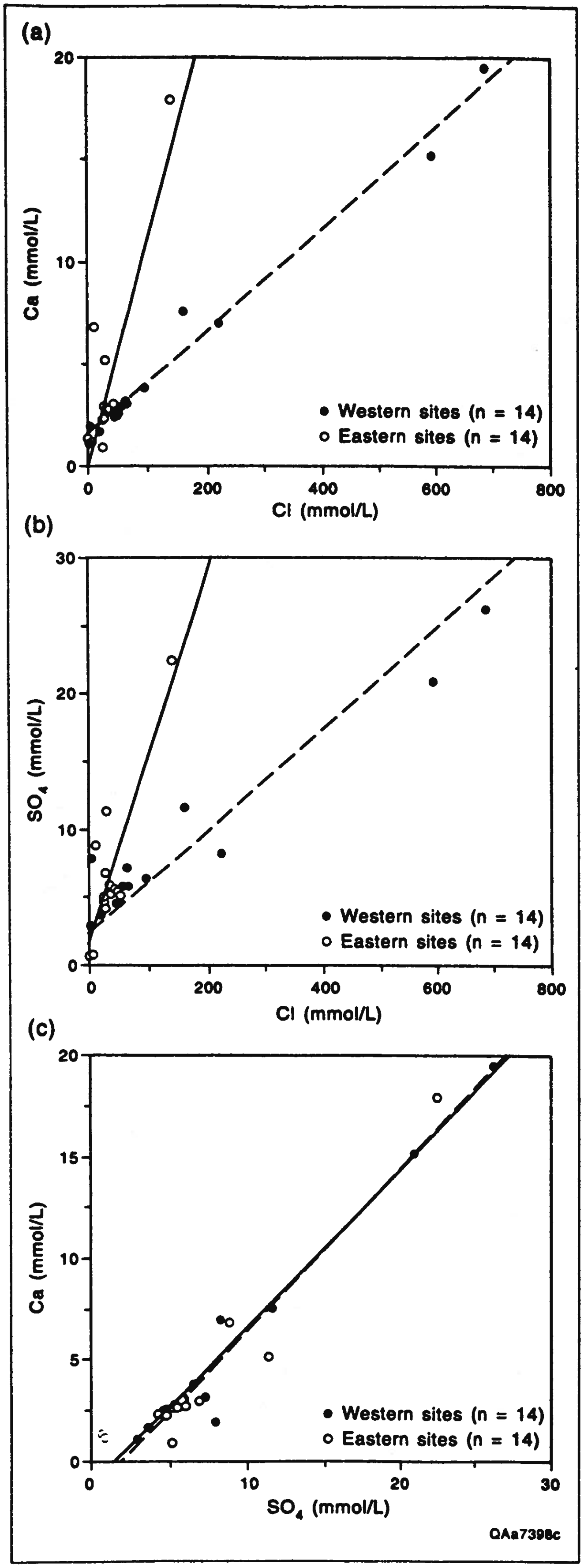


Figure 35. Plots of (a) calcium versus chloride, (b) sulfate versus chloride, and (c) calcium versus sulfate for surface-water samples (table 1). Samples from eastern sites typically exhibit greater calcium-to-chloride and sulfate-to-chloride ratios than samples from western sites.

Lateral Ground-Conductivity Surveys

Ute Reservoir to beyond Revuelto Creek

Nearly 1,300 conductivity measurements were made along an 11-km stretch of the Canadian River between Ute Reservoir and a point about

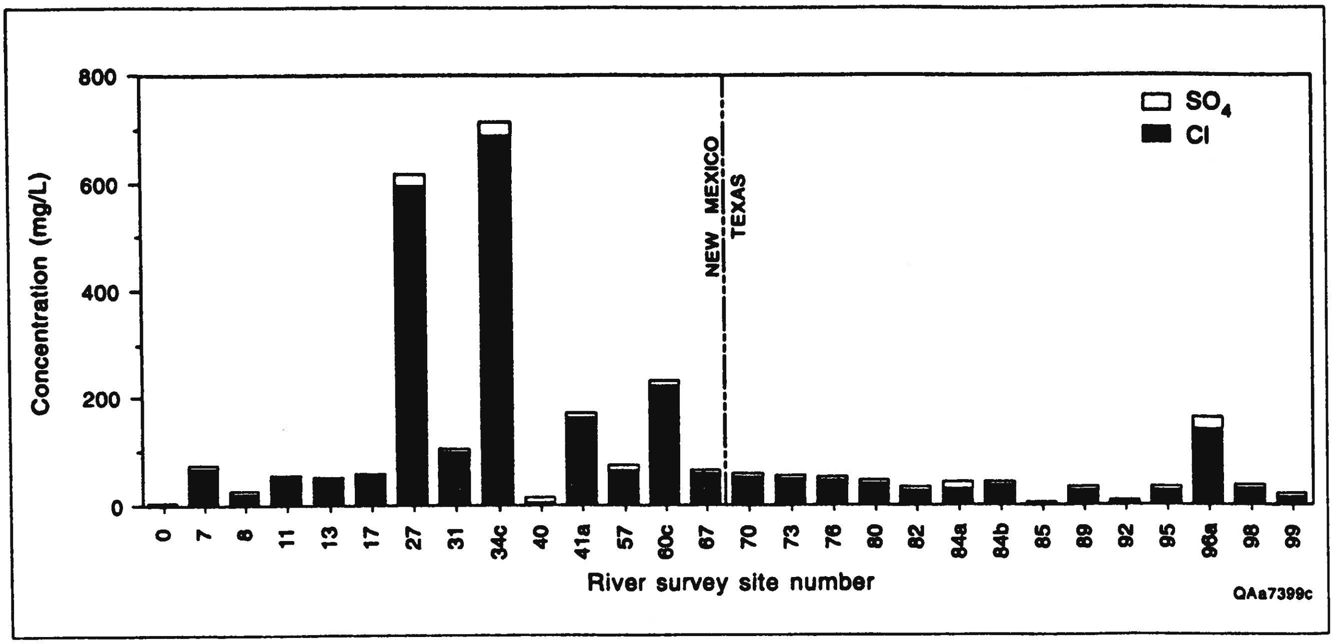


Figure 36. Relative concentrations of chloride and sulfate in the Canadian River and its tributaries, Texas and New Mexico. Site numbers 40 and 85 are in tributaries. Locations shown in fig. 7a through 7f; data from table 1.

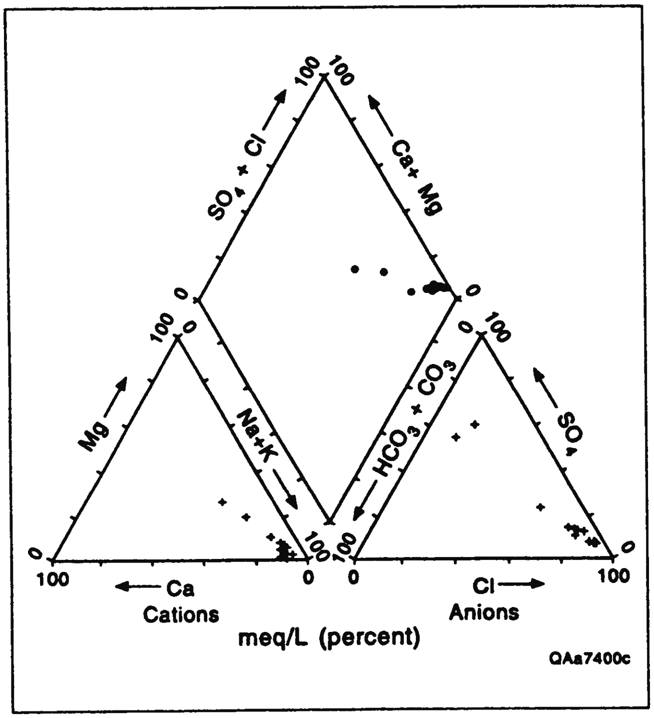


Figure 37. Piper diagram showing proportions of major cations and anions in surface-water samples collected along the western part of the Canadian River.

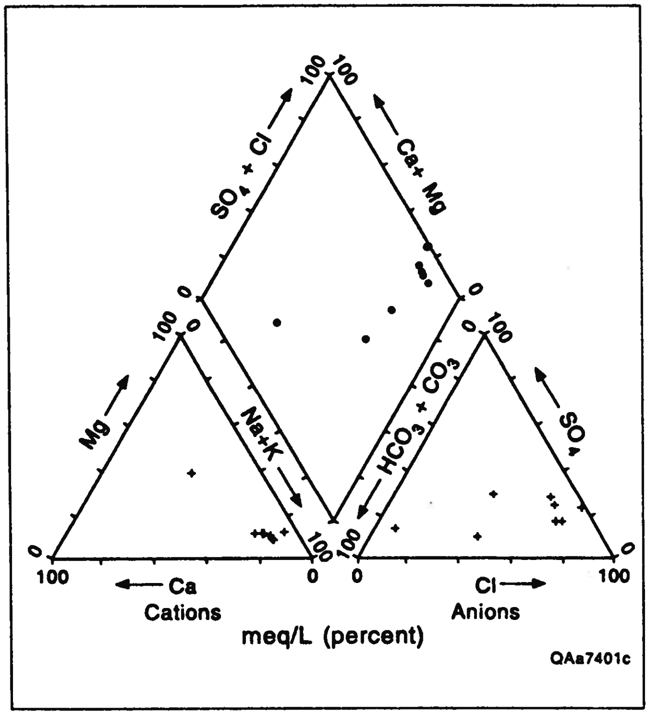


Figure 38. Piper diagram showing proportions of major cations and anions in surface-water samples collected along the eastern part of the Canadian River.

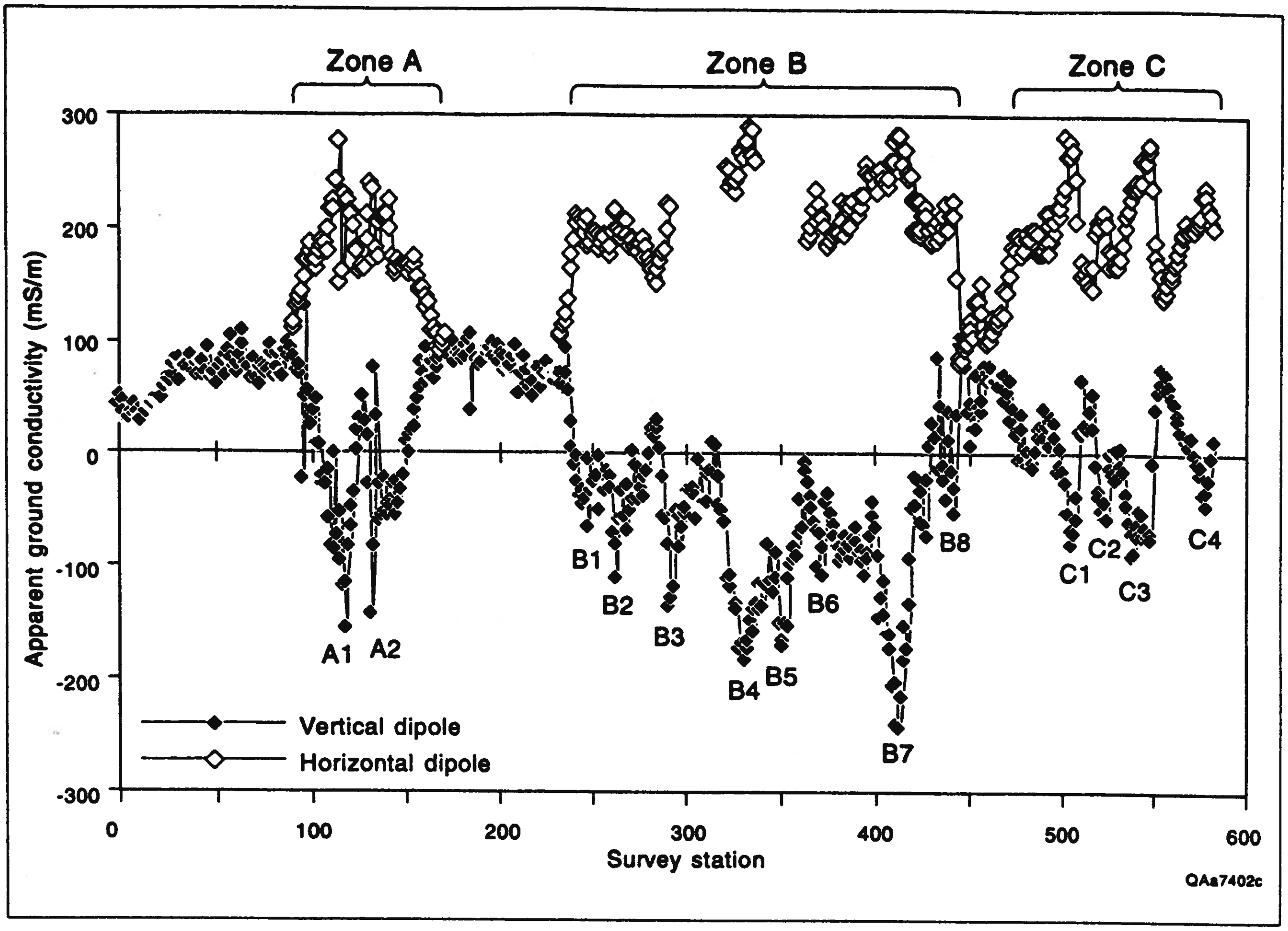


Figure 39. Apparent conductivity along the Canadian River from Ute Reservoir to a point 1.5 km downstream from Revuelto Creek (fig. 13). Stations 1 through 76 are 10 m apart; all others are 20 m apart. Conductivity values are plotted by receiver station number.

1.5 km downstream from its confluence with Revuelto Creek (figs. 11 and 13). The 380 horizontal dipole conductivities ranged from a low of 78 mS/m at station 446 to 288 mS/m at station 335 (fig. 39). 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 physical 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 (McNeill, 1980b; Frischknecht and others, 1991). Vertical dipole values (fig. 39) 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. This relationship suggests that the more negative the vertical dipole apparent conductivities, the higher the actual ground conductivity. These measurements can thus be used qualitatively to locate areas of extremely high ground conductivities. Vertical dipole measurements are also important because they are affected less by very near surface conductivity anomalies than are horizontal dipole values and because they are more successful in precisely locating major conductivity highs.

The lateral conductivity survey indicates three broad zones of high conductivity along this segment of the Canadian River. The first, zone A (stations 90 through 170, fig. 39), extends 1,600 m between Ute Dam and the Highway 54 bridge (fig. 13). In this zone, horizontal dipole conductivities increase from about 100 mS/m on the flanks of the zone to a maximum of 275 mS/m; vertical dipole values are mostly negative in this zone and reach values as low as −156 mS/m. Within zone A are two distinct peaks: peak A1 is between stations 111 and 122, and peak A2 is between stations 131 and 142 (fig. 39).

Zone B (stations 233 through 444) is a broad zone of generally high conductivity (fig. 39). It extends about 4,200 m between the Highway 54 bridge and the gravel pit reach (fig. 13). Conductivities in this zone, which range from 102 to 288 mS/m (horizontal dipole) and from 74 to −244 mS/m (vertical dipole), were the highest measured during the electromagnetic survey. There are eight distinct peaks in zone B (fig. 39). The highest ground conductivities measured at these peaks increase downstream from B1 through B4. Peak B1, located between stations 242 and 248, has horizontal dipole conductivities as high as 209 mS/m and vertical dipole conductivities to −67 mS/m. Conductivities are slightly higher at B2 (stations 262 through 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 through 294). The highest horizontal dipole conductivity measured, 288 mS/m, was recorded at peak B4 (stations 323 through 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 through 355) and B6 (stations 368 through 373), end the 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 through 419) has the highest observed vertical dipole conductivity (−244 mS/m) in zone B and nearly the highest horizontal dipole conductivity (279 mS/m). The peak farthest downstream in zone B, peak B8, is characterized by variable vertical dipole conductivities as high as −53 mS/m and horizontal dipole conductivities reaching 221 mS/m.

High-conductivity zone C begins at station 467 (fig. 13) upstream from Revuelto Creek and appears to continue beyond the last point measured downstream from Revuelto Creek (station 583, fig. 13). Zone C extends at least 2,140 m along the river. Conductivities in this zone (fig. 39) 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. Zone C includes four distinct conductivity peaks, characterized by horizontal dipole conductivities above 200 mS/m and negative vertical dipole conductivities. Peak C1 (stations 502 through 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 through 525). Conductivities were as high as 271 mS/m (horizontal dipole) and −91 mS/m (vertical dipole) at peak C3 (stations 536 through 550), which was the broadest of the peaks in zone C. The last peak surveyed, peak C4 (stations 572 through 583), had conductivities reaching 234 mS/m (horizontal dipole) and −45 mS/m (vertical dipole).

Reproducibility tests for conductivity measurements were completed along four river segments between Ute Reservoir and Revuelto Creek. Sites surveyed in October 1992 were reoccupied as near as possible to the original locations in November 1992 or February 1993 between stations 91 and 172 (zone A, peaks A1 and A2, fig. 39), stations 233 and 293 (zone B, peaks B1 through B3), stations 323 and 338

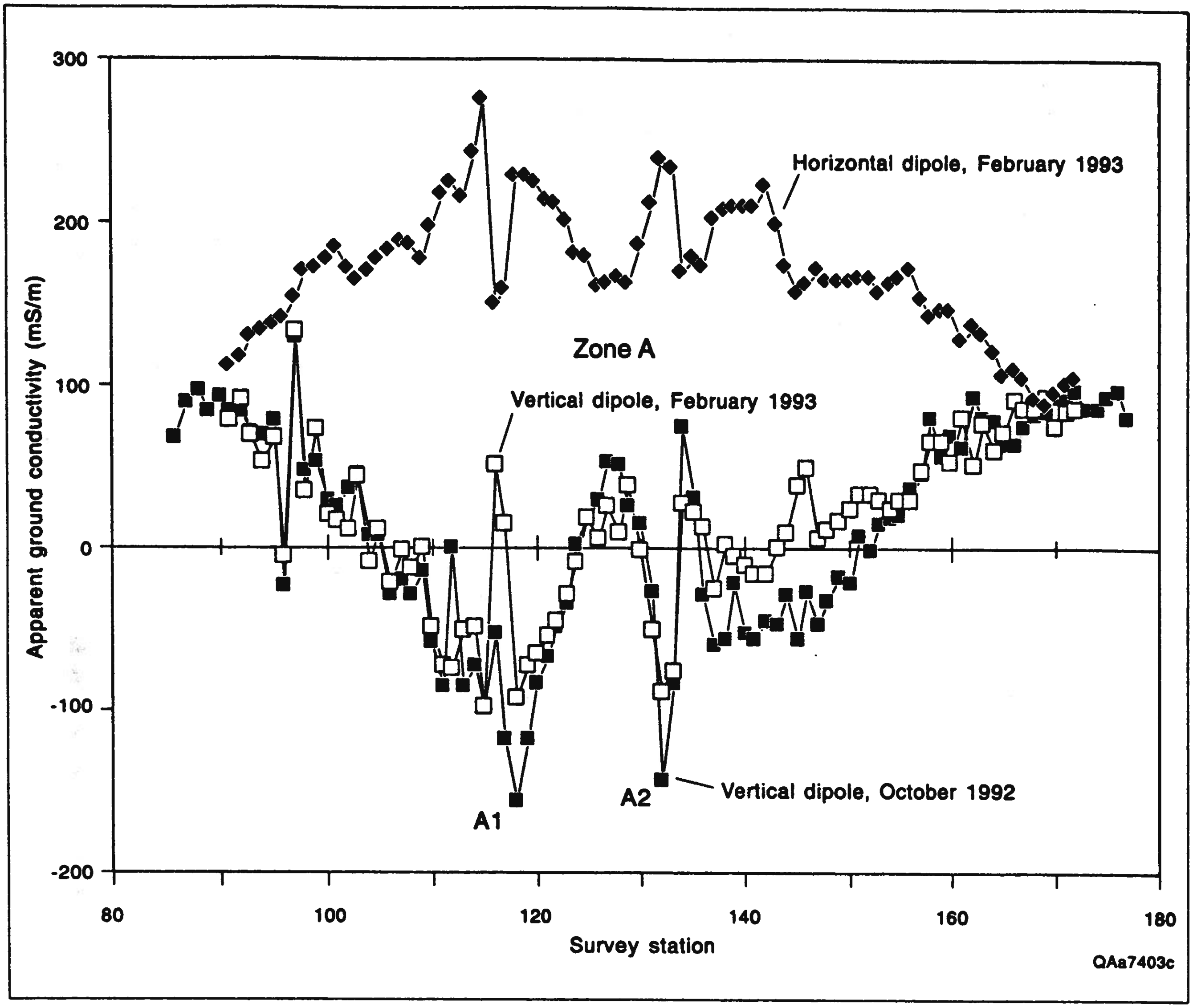


Figure 40. Comparison of apparent ground conductivities in zone A, Ute Reservoir to Revuelto Creek, determined in October 1992 (vertical dipole) and February 1993 (vertical and horizontal dipole). Stations are 20 m apart; conductivity values are plotted by receiver station number.

(zone B, peak B4), and stations 365 and 510 (zone B, peaks B6 through B8; zone C, peak C1).

Vertical dipole conductivities measured during the October survey and November or February surveys generally were in good agreement. For example, data collected at different times across high-conductivity zone A (fig. 40) show that vertical dipole conductivities follow the same trend throughout the segment. Values are virtually identical for the upstream part of the segment (stations 91 through 115), between peaks A1 and A2 (stations 120 through 130), and at the downstream end (stations 154 through 172). Vertical dipole values from the February 1993 survey are less negative than values from the October 1992 survey at peaks A1 and A2 and along a segment downstream from peak A2 (stations 136 through 153, fig. 40). These differences may be caused by slight deviations in survey paths or by a real decrease in ground conductivity. The nonrandom change illustrated by the close agreement of values in some areas

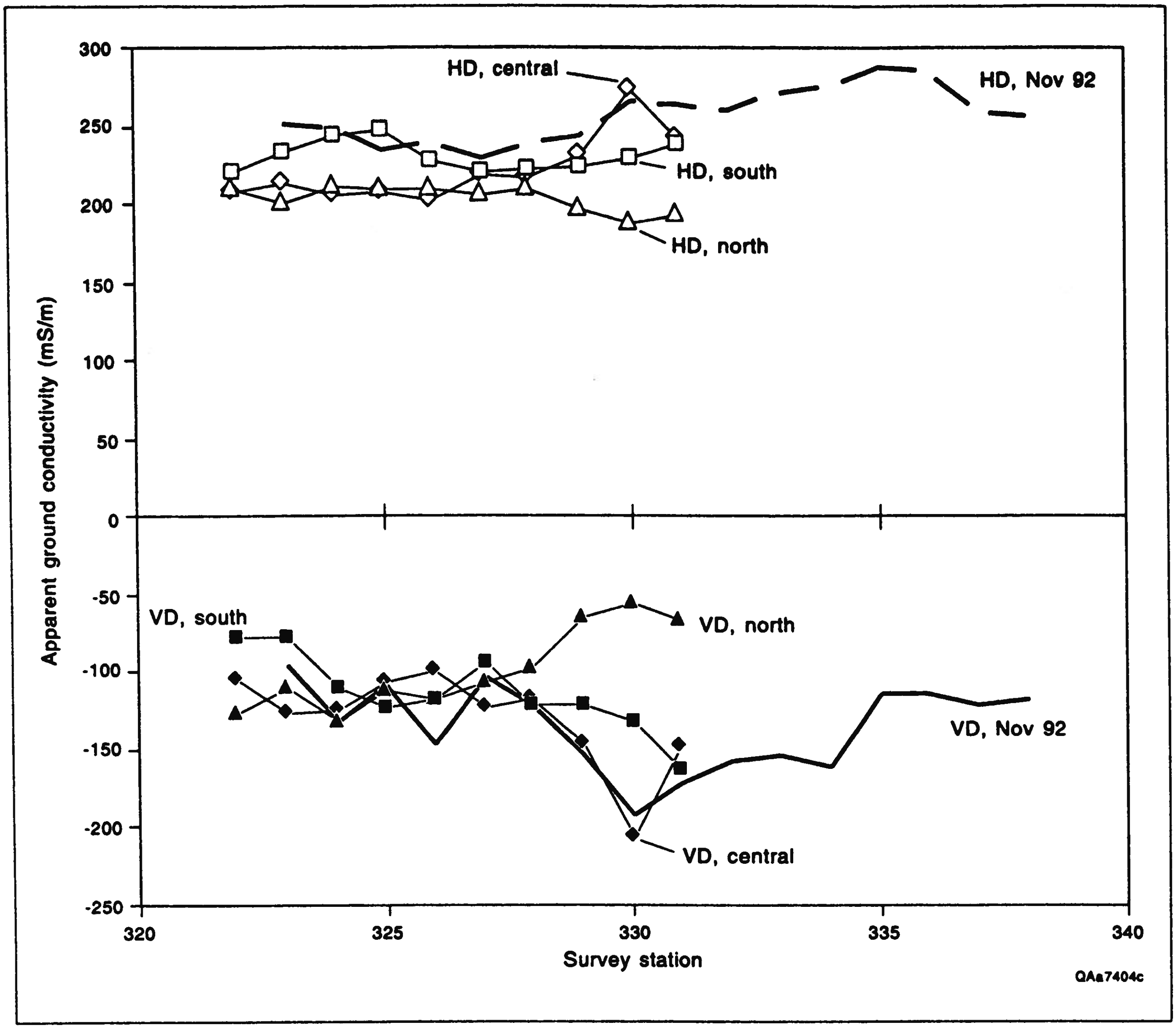


Figure 41. Apparent ground conductivities (HD = horizontal dipole; VD = vertical dipole) along three parallel EM34-3 transects at peak B4 in zone B (fig. 39) along the Canadian River between Ute Reservoir and Revuelto Creek. North, central, and south transects parallel the river and are 20 m apart; station spacing on each transect is 20 m. Conductivity values are plotted by receiver station number.

and the consistent direction of change in other areas suggests that the ground conductivities were actually lower in these areas in February 1993 than in October 1992 at peaks A1 and A2 and along the segment downstream from A2.

Three parallel transects were surveyed along a 160-m-long segment in zone B at peak B4 (stations 322 through 331, fig. 39) to examine how sensitive the measured conductivity is to the path chosen along the canyon floor and riverbed. The central transect most closely followed the path taken in the lateral conductivity survey; the northern transect was about 20 m closer to the north canyon wall, whereas the southern transect was about 20 m closer to the south canyon wall. Horizontal and vertical dipole conductivity measurements along all three transects indicate that the area is extremely conductive (fig. 41). The

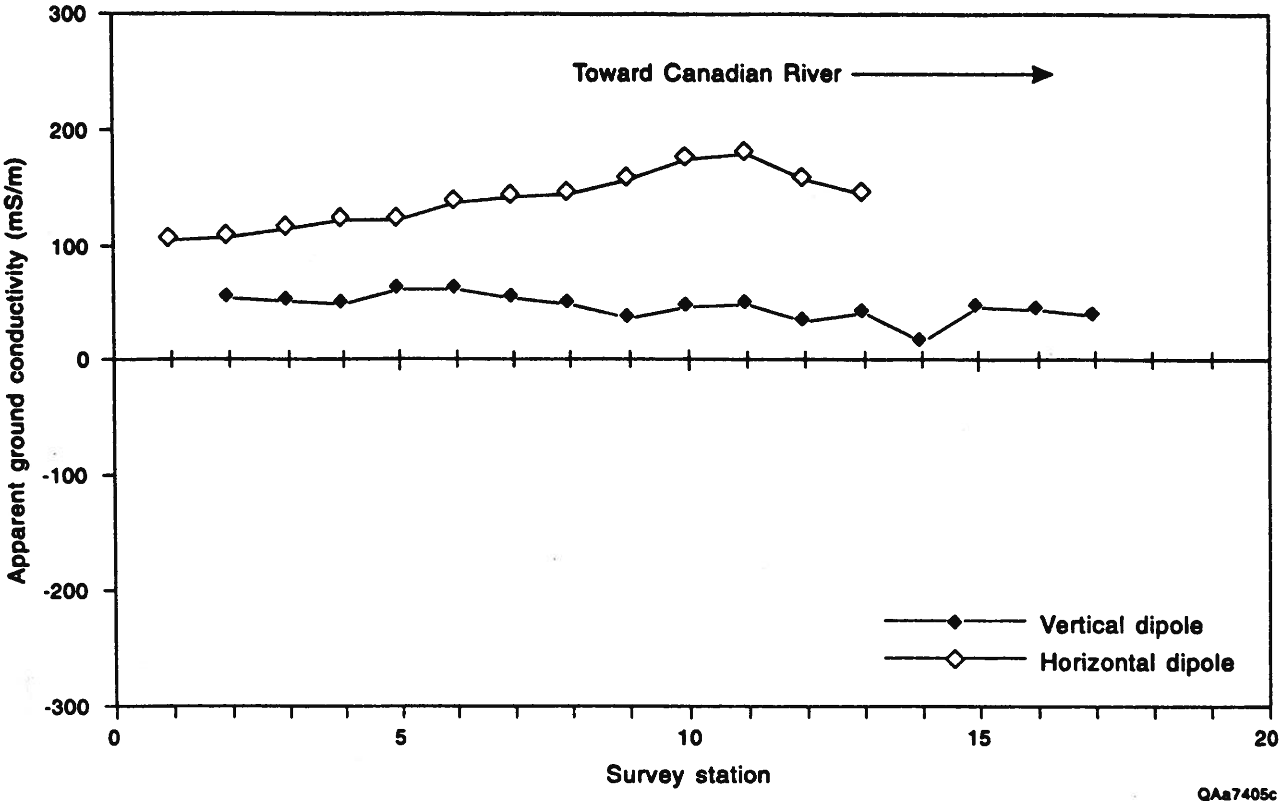


Figure 42. Apparent ground conductivity along Revuelto Creek (fig. 13). Stations are 20 m apart; conductivity values are plotted by receiver station number.

central transect shows the highest peak conductivities for both coil orientations and reproduces peak B4. The northern transect had the lowest apparent conductivities near peak B4 and did not clearly identify the peak. Conductivities along the southern transect were lower than those for the central path, but they do suggest a peak that is just downstream from peak B4 on the central transect. Conductivity differences between transects are probably related to changes in alluvial thickness across the valley.

Revuelto Creek

A lateral conductivity survey of the lower 340 m of Revuelto Creek (figs. 11 and 13), which consisted of 29 vertical and 13 horizontal dipole measurements, showed that ground conductivity generally increases toward the Canadian River (fig. 42). Conductivities measured along Revuelto Creek were not as high as those encountered along the Canadian River in high-conductivity zones A, B, and C. Conductivity measured in the horizontal dipole mode ranged from 105 mS/m at station 1 to 178 mS/m at station 11. Vertical dipole conductivity values ranged from a high of 85 mS/m at station 1 to a low of 18 mS/m at station 17 near the confluence with the Canadian River. The apparent disagreement in trend between the horizontal and vertical dipole measurements is caused by the nonlinear response of the instrument in the vertical dipole coil orientation; for this conductivity range, decreasing vertical dipole conductivity values indicate increasing ground conductivity, as shown by the horizontal dipole measurements.

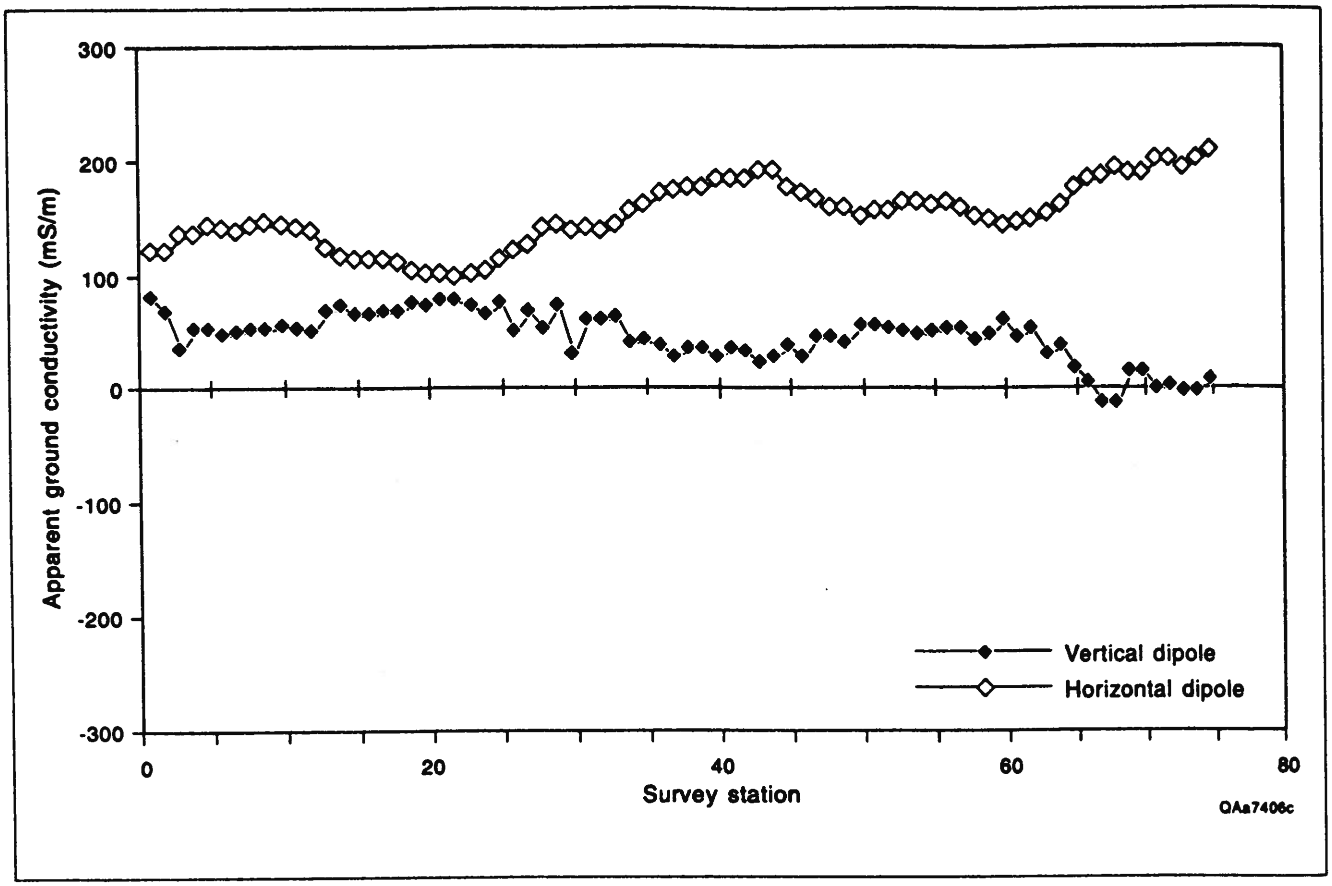


Figure 43. Apparent ground conductivity along the Canadian River in the Claer well area (fig. 14). Stations are 20 m apart; conductivity values are plotted by receiver station number.

Claer Well Area

The Claer well area of the Canadian River, downstream from Revuelto Creek (fig. 11), is an area where prominent north- to northeast-trending drainages join the main Canadian River canyon. A lateral conductivity survey was completed along the Canadian River across the intersection with the side drainages (fig. 14). The survey consisted of horizontal and vertical dipole conductivity measurements at 75 stations covering 1,500 m of the riverbed.

Horizontal and vertical dipole conductivity measurements produced mirror-image profiles (fig. 43), suggesting that nonlinear instrument response in the vertical dipole coil orientation caused declining apparent ground conductivity measurements with increasing actual 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 values in the downstream direction. The upstream peak (stations 2 through 12) has horizontal dipole conductivities as high as 144 mS/m, the middle peak (stations 36 through 47) has a higher maximum conductivity of 189 mS/m, and the downstream peak (stations 66 through 75) has the highest conductivity (207 mS/m) observed for the Claer well segment. This peak probably continues farther downstream beyond the survey endpoint.

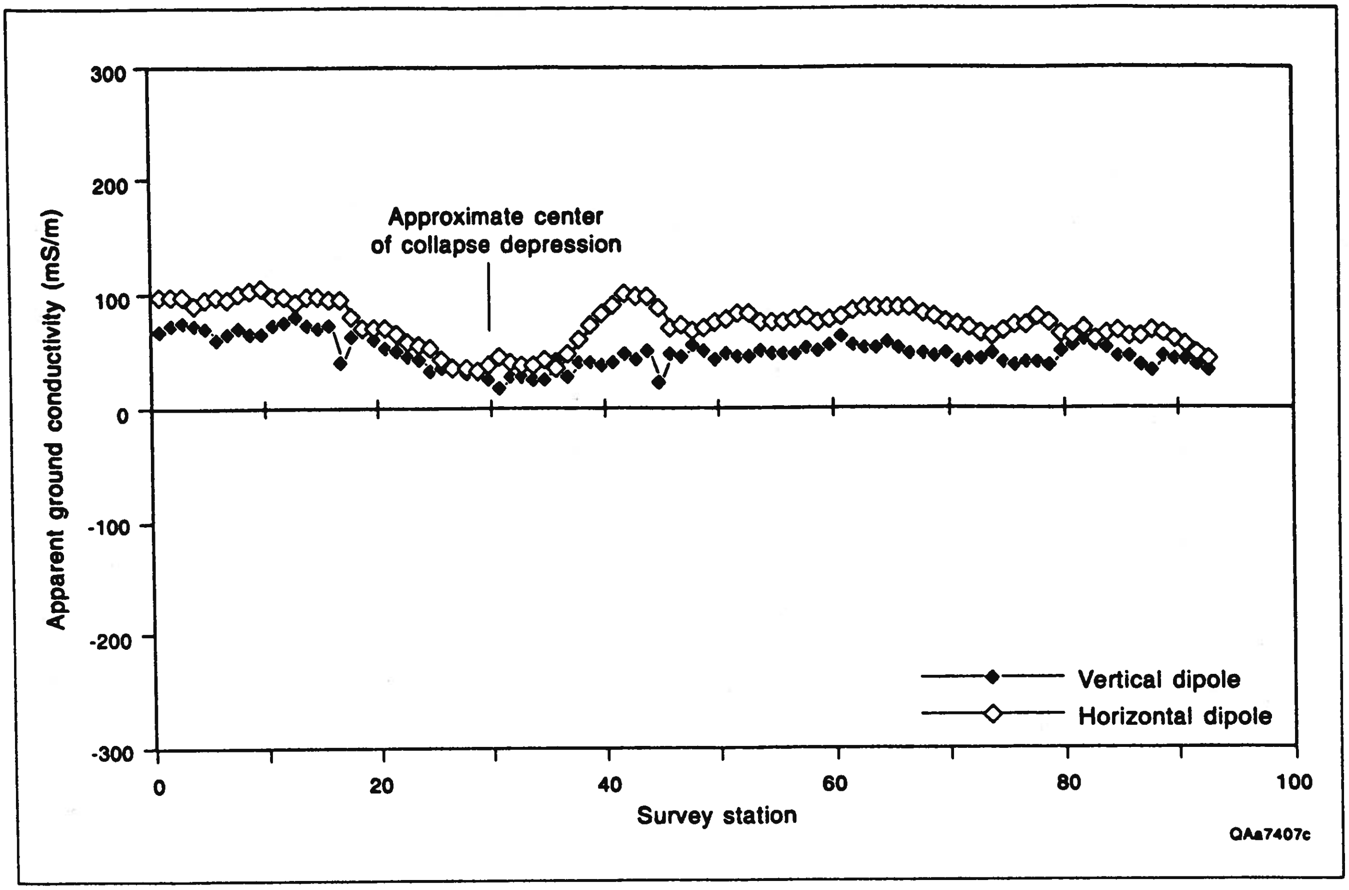


Figure 44. Apparent ground conductivity along the Canadian River in the Jones well area (fig. 15). Stations are 20 m apart; conductivity values are plotted by receiver station number.

Jones Well Area

In the Jones well area of the Canadian River, between Revuelto Creek and the Dunes area (figs. 11 and 15), 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. Horizontal and vertical dipole conductivities were generally lower along this stretch (fig. 44) than in the surveyed area 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 that the instrument response is linear in the vertical dipole mode.

No prominent conductivity peaks were observed 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 16 and 40 (fig. 44). The center of this trough (station 29) is near the center of the mapped collapse depression.

Dunes Area

The lateral conductivity survey in the Dunes area consisted of horizontal and vertical dipole measurements at 238 stations along 4,760 m of the Canadian River (figs. 11 and 16). Conductivities measured along this stretch varied greatly

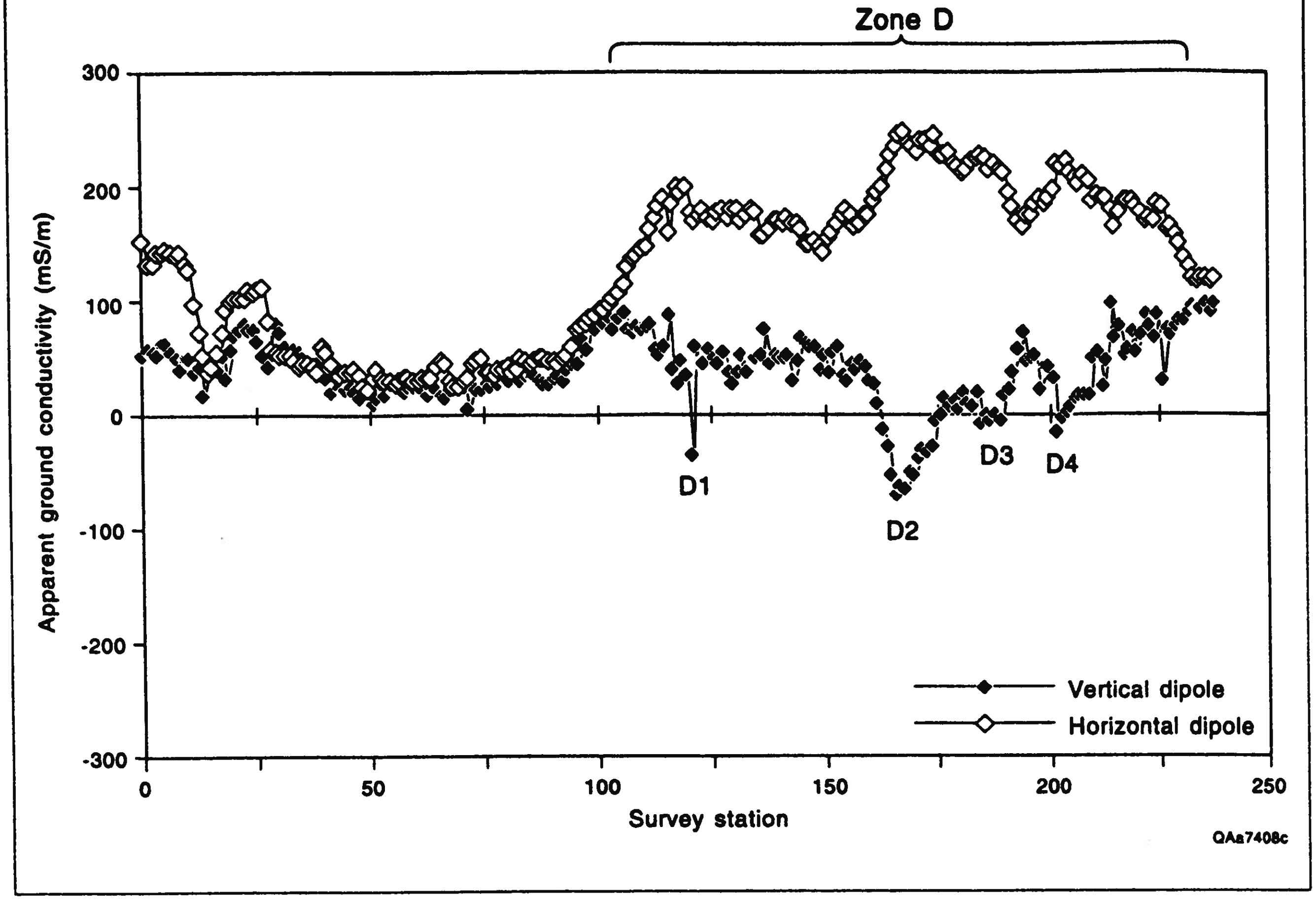


Figure 45. Apparent ground conductivity along the Canadian River in the Dunes area (fig. 16). Stations are 20 m apart; conductivity values are plotted by receiver station number.

(fig. 45), 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. 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. 45) 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 from Triassic strata during the survey.

Four conductivity peaks were located within the broad high-conductivity zone D (fig. 45). Maximum conductivities in peak D1, between stations 113 and 124, reached 197 mS/m (horizontal dipole) and –38 mS/m (vertical dipole). The highest conductivities in the Dunes area, to 245 mS/m (horizontal dipole) and –73 mS/m (vertical dipole), were measured for peak D2 (stations 163 through 176). Peak D3, located just downstream from peak D2 (stations 182 through 190), was characterized by lower maximum conductivities of 226 mS/m (horizontal dipole)

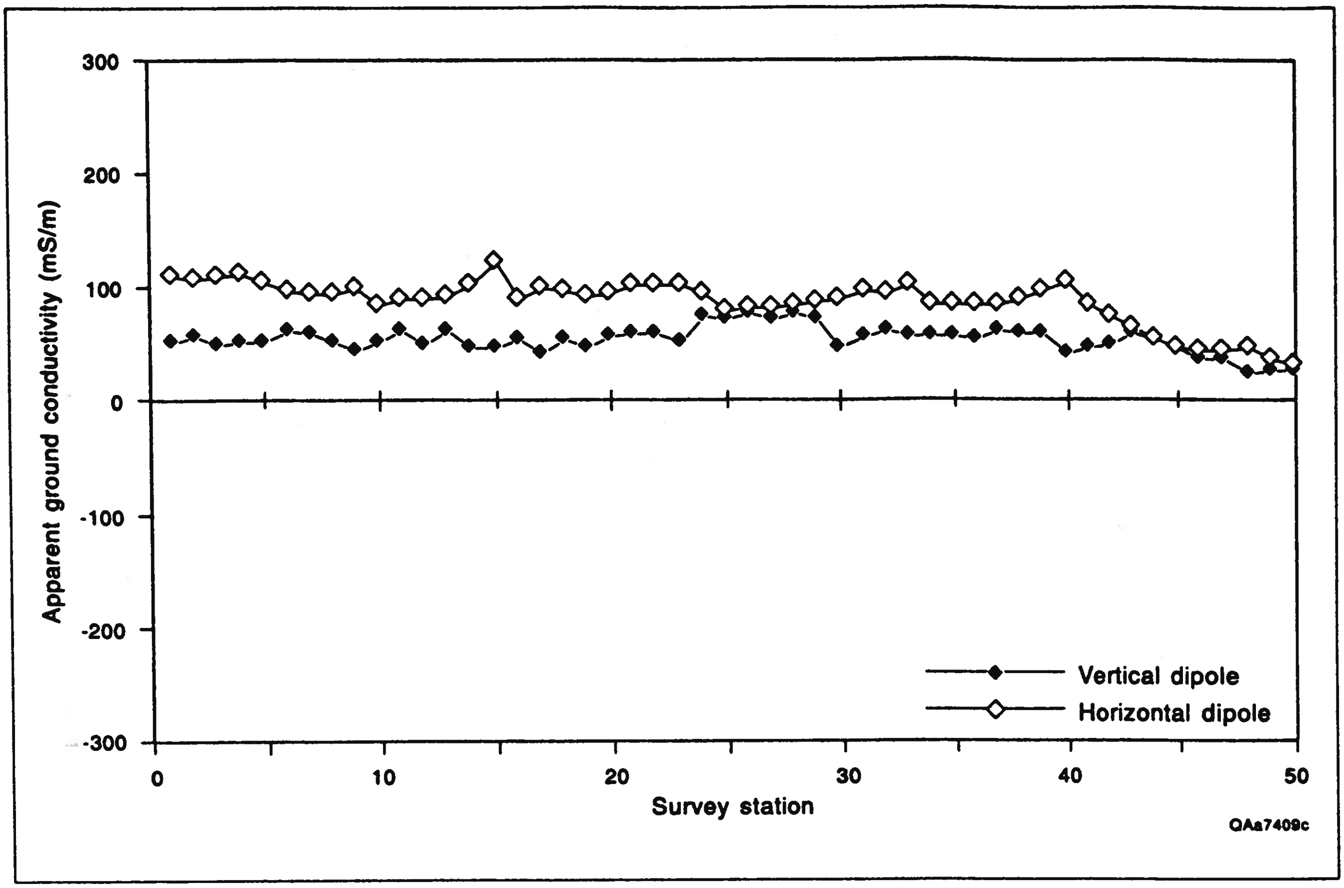


Figure 46. Apparent ground conductivity along the Canadian River in the Rana Canyon area (fig. 17). Survey stations are 20 m apart; conductivity values are plotted by receiver station number.

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 through 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 stations, beginning about 600 m upstream from Rana Canyon and ending about 400 m downstream from the canyon (figs. 11 and 17). Conductivities were relatively low in this area (fig. 46), 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 stations along the lower 340 m of Rana Arroyo (figs. 11 and 17). Rana Arroyo conductivities increased downstream but were lower along the arroyo than along the adjacent segment of the Canadian River (fig. 47). Conductivities increased from 29 to 103 mS/m (horizontal dipole) and from 35 to 77 mS/m (vertical dipole) from the upstream end of the survey to the confluence of Rana Arroyo with the Canadian River. No significant conductivity peaks were detected along the arroyo.

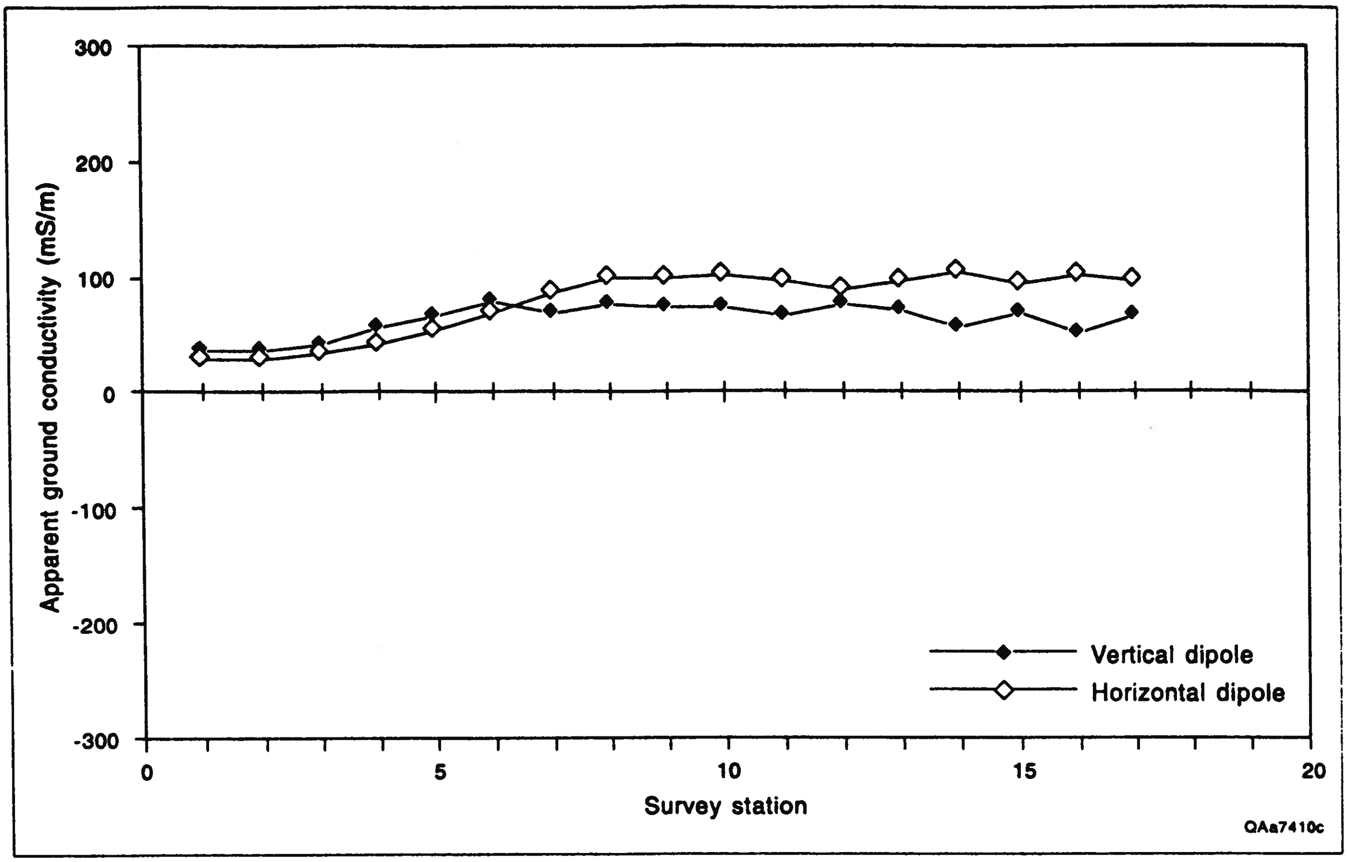


Figure 47. Apparent ground conductivity along Rana Arroyo (fig. 17). Survey stations are 20 m apart; conductivity values are plotted by receiver station number.

Vertical Ground-Conductivity Surveys

Multiple-Coil-Separation Soundings

Changes in ground conductivity with depth were determined either by repeatedly surveying over the same point using different transmitter and receiver coil separations or by analyzing the decay of a transient electromagnetic field. Three sites along the Canadian River between Ute Reservoir and Revuelto Creek (fig. 13) and one site in the Jones well area (fig. 15) were surveyed using multiple coil separations.

Ute Reservoir to Revuelto Creek, Site M140

Site M140, between Ute Dam and the Highway 54 bridge (fig. 13), lies within peak A2 (figs. 39 and 40). Vertical and horizontal dipole conductivities were measured at site M140 between stations 136 and 144 (fig. 48a). Conductivities for 10- and 40-m coil separations were collected at 10-m station spacings; conductivities at the 20-m coil spacing were collected at 20-m station spacings.

Conductivities measured in the vertical dipole orientation ranged from –48 mS/m to 41 mS/m along the transect (fig. 48a) 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 at site M140 were used to construct a vertical conductivity model. The three-layer model (fig. 49a and table 2) that provided the best fit to the observed

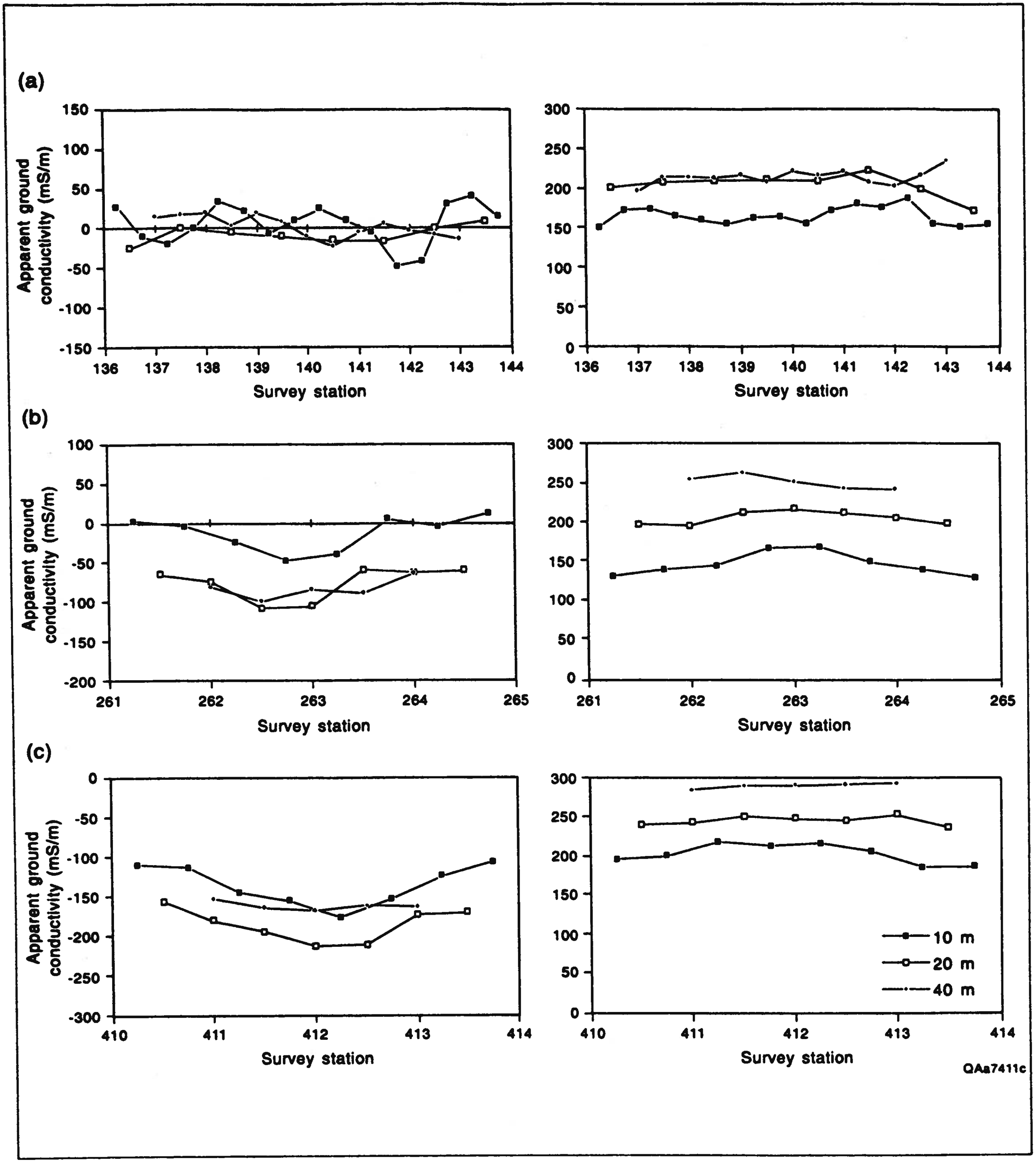


Figure 48. Multiple-coil-separation soundings at (a) site M140, (b) site M263, and (c) site M412 between Ute Reservoir and Revuelto Creek (fig. 13). Apparent ground conductivity at 10-, 20-, and 40-m coil separations for vertical dipole orientation is shown at left, and horizontal dipole orientation is shown at right. Numbered stations are 20 m apart; conductivity values are plotted at midpoints between transmitter and receiver coils.

Table 2. Best-fit conductivity models for EM34-3 multiple-coil-separation soundings along the Canadian River between Ute Reservoir and Revuelto Creek and in the Jones well area.

Canadian River, Ute Reservoir to Revuelto Creek

Sounding	Location	Layer	Conductivity (mS/m)	Thickness (m)	Depth to top (m)
M140 (figs. 48a, 49a)	Station 140 (fig. 13)	1	5.0	1.6	0.0
		2	577.0	10.7	1.6
		3	149.9	—	12.3
M263 (figs. 48b, 49b)	Station 263 (fig. 13)	1	5.0	1.8	0.0
		2	703.2	9.2	1.8
		3	854.8	—	11.0
M412 (figs. 48c, 49c)	Station 412 (fig. 13)	1	5.0	1.1	0.0
		2	869.5	5.6	1.1
		3	1,869.7	—	6.7

Canadian River, Jones Well Area

Sounding	Location	Layer	Conductivity (mS/m)	Thickness (m)	Depth to top (m)
M25 (figs. 50, 51)	Station 25 (fig. 15)	1	21.9	0.8	0.0
		2	67.4	8.0	0.8
		3	19.1	10.0	8.8
		4	106.0		18.8

Dash indicates value unknown.

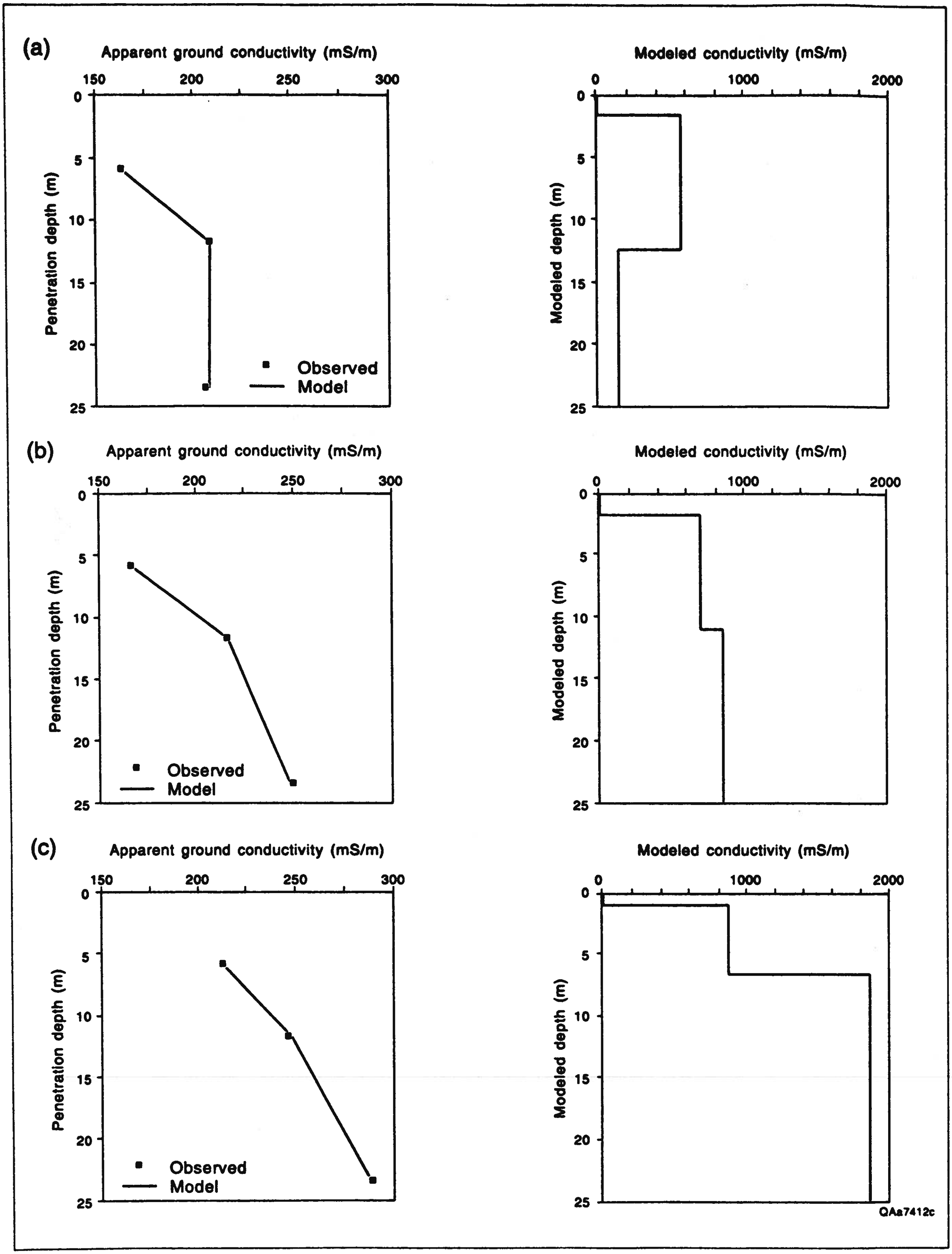
data consists of a low-conductivity (5 mS/m) surface layer 1.6 m thick, a higher conductivity (577 mS/m) second layer 10.7 m thick, and a third layer of intermediate conductivity (150 mS/m) that begins 12.3 m below the surface and extends at least to the maximum penetration depth of 25 m.

A probable interpretation of the best-fit vertical conductivity model at site M140 is that the thin, low-conductivity layer at the surface represents a combination of unsaturated, poorly conductive alluvium overlying alluvium saturated with relatively fresh water. The underlying high-conductivity layer probably represents alluvium saturated with saline water that has discharged from bedrock and that may have increased in salinity because of evaporation. The third layer has about one-third the modeled conductivity of the second layer and may represent (1) alluvium saturated by saline water that has an upward increase in salinity because of evaporative concentration or (2) lower porosity bedrock saturated with the same saline water as that in the overlying alluvium.

Ute Reservoir to Revuelto Creek, Site M263

Site M263 is located at conductivity peak B2 (fig. 39) between the Highway 54 bridge and the Chicago, Rock Island, and Pacific Railway bridge (fig. 13). 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

Figure 49. Apparent ground conductivity versus penetration depth (left) and best-fit computed conductivity model (right) for multiple-coil-separation soundings (horizontal dipole orientation) at (a) site M140, (b) site M263, and (c) site M412, Ute Reservoir to Revuelto Creek (fig. 13). Observed and computed data from the best-fit conductivity model are both shown. ▶


(a)
Apparent ground conductivity (mS/m)
150
200
250
300
0
5
10
15
20
25
Penetration depth (m)
Observed
Model
Modeled conductivity (mS/m)
0
1000
2000
Modeled depth (m)
(b)
Apparent ground conductivity (mS/m)
Observed
Model
Modeled conductivity (mS/m)
(c)
Apparent ground conductivity (mS/m)
Observed
Model
Modeled conductivity (mS/m)
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(fig. 48b). Vertical dipole conductivities at all three coil spacings were mostly negative, ranging from 12 mS/m to –108 mS/m. Apparent ground conductivities from the 20- and 40-m coil separations were more negative than those from the 10-m separation, which suggests that instrument response was nonlinear and that conductivity increases downward. Conductivities measured in the horizontal dipole orientation increased with coil separation, from a maximum of 168 mS/m at 10-m separation to a maximum of 262 mS/m at 40-m spacing (fig. 48b). These horizontal dipole data also indicate that conductivity increases with depth.

Horizontal dipole conductivities were used to produce a vertical conductivity profile for site M263 (fig. 49b; table 2). 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.

This profile suggests a thin surface layer of alluvium that is either unsaturated or saturated with relatively fresh water, underlain by alluvium that is saturated with highly conductive saline water (layer 2). Further increase of conductivity beyond about 10 m (layer 3) may reflect actual increasing conductivity with depth in the alluvium because of a progressive decrease of mixing with fresh water from the surface, or may reflect a transition to bedrock containing water of higher salinity. It is probable that the profile does not penetrate beyond the alluvium and that the increase in ground conductivity with depth is caused by the increase in salinity with depth in the alluvial aquifer.

Ute Reservoir to Revuelto Creek, Site M412

The vertical conductivity survey at site M412, between the Chicago, Rock Island, and Pacific Railway bridge and Revuelto Creek (fig. 13), consisted of horizontal and vertical dipole conductivity measurements at 10-, 20-, and 40-m coil separations between stations 410 and 414 (fig. 48c). This site, at conductivity peak B7 (fig. 39), has the highest conductivities measured during the lateral conductivity survey.

Vertical dipole apparent conductivities were all negative at the site (fig. 48c). Values ranged from –107 to –213 mS/m but were most negative for the 20-m coil separation. These conductivities, recorded in the nonlinear range of instrument response, show a conductivity peak at station 412 that coincides with the peak detected during the lateral conductivity survey. Horizontal dipole apparent conductivities increase with coil separation from a maximum of 217 mS/m at 10-m separation to a maximum of 292 mS/m at 40-m separation. Horizontal dipole values also show a peak near station 412, but the peak is not as well defined as in the vertical dipole measurements. The trend of increasing conductivity with greater coil separation suggests that ground conductivities increase with depth.

Horizontal dipole conductivities at station 412 were used to construct a model vertical conductivity profile (fig. 49c and table 2). The three-layer model that best fits the data consists of a thin, low-conductivity surface layer (1.1 m at 5 mS/m) overlying two highly conductive layers. Conductivity of the lower layers increases downward from 870 mS/m in the middle layer (5.6 m thick) to 1,870 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 almost 25 m.

Interpretations of the conductivity model at site M412 are similar to those at site M263. A thin surface layer of unsaturated alluvium overlies alluvium saturated with relatively fresh water at the site. Underlying layers probably represent alluvium saturated with highly conductive saline water. The very high apparent ground conductivity detected here suggests that the site is located directly above or very near a point of saline-water discharge from bedrock to alluvium. The substantial upward decrease of modeled conductivity from layer 3 to layer 2 may imply mixing in layer 2 between deeper saline water and shallower fresh water. Earlier studies by the U.S. Bureau of Reclamation (1984) suggest that bedrock is shallower than 25 m but deeper than 10 m at this site. The constant value of modeled conductivity in this interval may indicate that

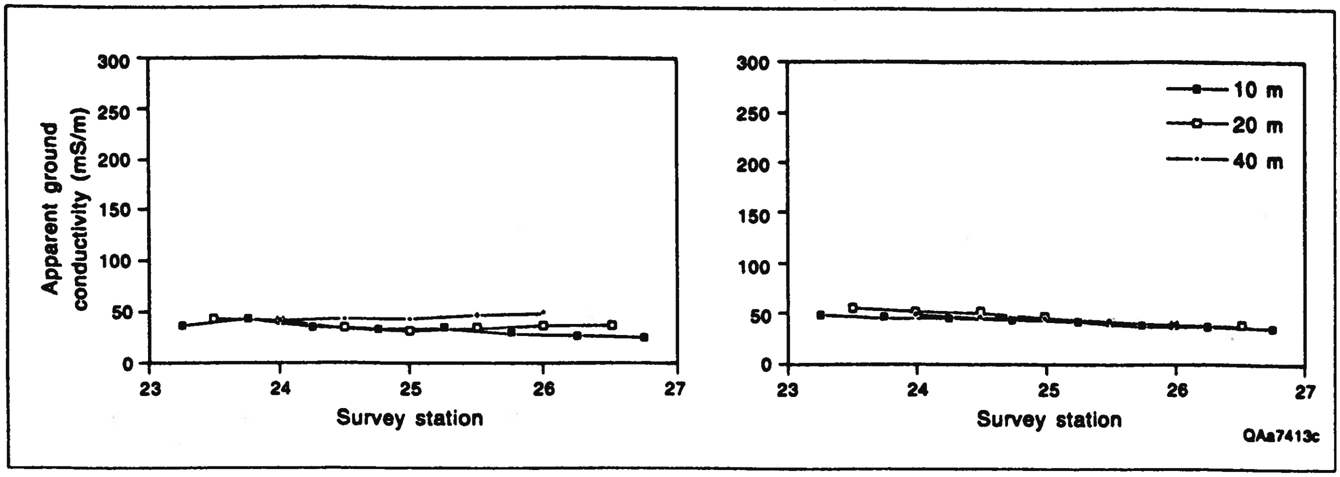


Figure 50. Multiple-coil-separation sounding near center of surface-collapse feature at Jones well site M25 (fig. 15). Apparent ground conductivity at 10-, 20-, and 40-m coil separations for vertical dipole orientation is shown at left, and horizontal dipole orientation is shown at right. Numbered stations are 20 m apart; conductivity values are plotted at midpoints between transmitter and receiver coils.

porosity and ground-water salinity are approximately the same in alluvium and bedrock.

Jones Well Area, Site M25

Vertical conductivity survey site M25 was located between stations 23 and 27 along the Canadian River in the Jones well area (fig. 15). 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 (Hydro Geo Chem, 1984) that is bisected by the Canadian River. A lateral conductivity survey of the Jones well area showed the collapse feature to be an area of low apparent ground conductivity.

Vertical and horizontal dipole conductivities across the site are low and decrease in a downstream direction (fig. 50). Apparent 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 separation than for the 10- and 20-m coil separations, 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.

At station 25, vertical and horizontal conductivities recorded were used to construct a model vertical conductivity profile. Because all six coil configurations produced usable data, conductivity models with as many as six layers can be considered. A four-layer model produced a reasonably good fit to the observed data (fig. 51; table 2); this model includes a thin, 0.8-m, low-conductivity (22 mS/m) layer at the surface, a second layer 7.9 m thick with higher conductivity (67 mS/m), a third layer 10.0 m thick with low conductivity (19 mS/m), and a conductive (106 mS/m) basal layer from a depth of 18.8 m to the maximum penetration depth of about 50 m. Compared with other modeled conductivity profiles, the profile at Jones well site 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 unsaturated or saturated with relatively fresh water. Beneath the surface layer is alluvium that is saturated with higher salinity water, although modeled conductivities (and associated salinities) are much lower than those observed at the other vertical conductivity profile sites. As at Ute to Revuelto Creek site M140, the decrease in modeled conductivity between layer 2 and layer 3 at 8.7-m depth is difficult to interpret but may represent (1) a layer of alluvium (layer 3) satu-

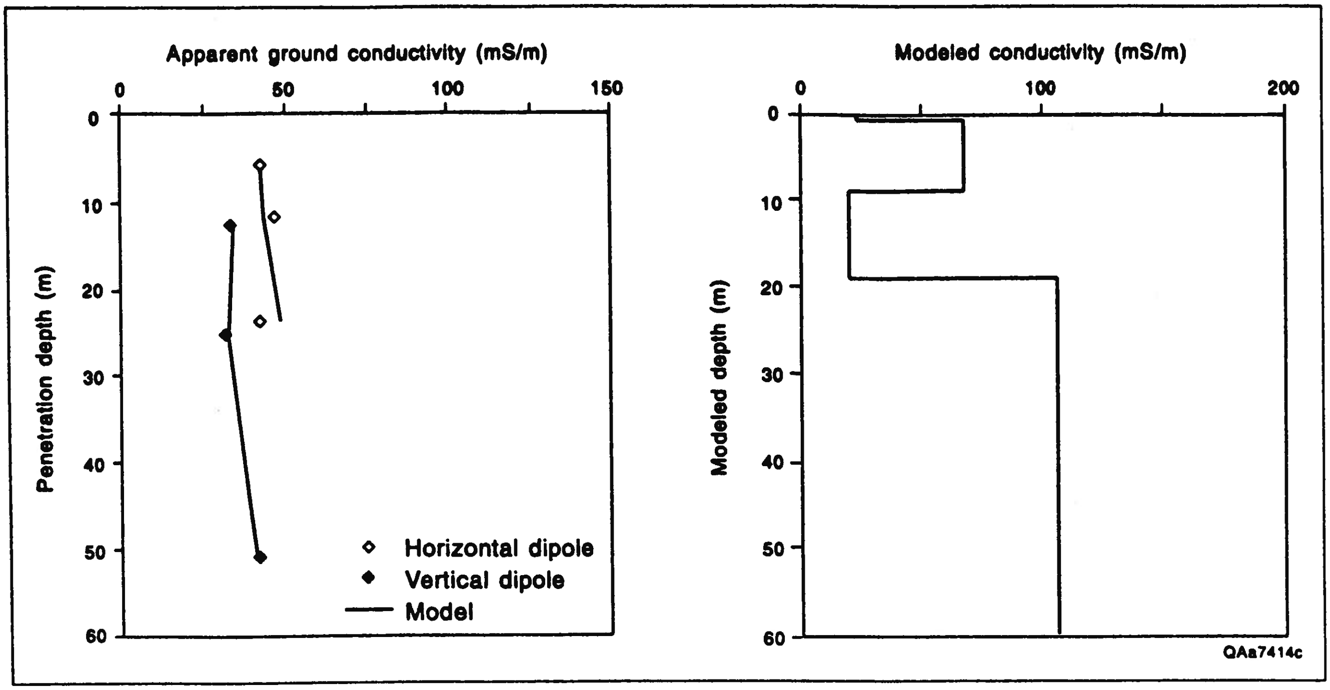


Figure 51. Apparent ground conductivity versus penetration depth (left) and best-fit computed conductivity model (right) for multiple-coil-separation sounding (horizontal dipole orientation) near center of surface-collapse feature at site M25, Jones well area (fig. 15). Observed and computed data from the best-fit conductivity model are both shown.

rated with fresher water because of greater permeability and more efficient flushing than overlying, higher conductivity alluvium (layer 2), (2) alluvium saturated with water of the same salinity as overlying alluvium, but with less porosity and thus lower bulk conductivity than overlying alluvium, or (3) alluvium saturated by fresh to slightly saline water that has become more saline (and more conductive) in overlying layer 2 because of evaporation. The increase in conductivity between layer 3 and the basal layer at 18.8-m depth may represent the contact with bedrock, which may contain water more saline than that in the alluvium.

Time-Domain Soundings

Thirteen soundings to a maximum penetration depth of about 100 m were obtained using the time-domain electromagnetic sounding technique. Of the 13 sounding locations, there were two on the upland near Ute Reservoir (fig. 13), four along the Canadian River between Ute Reservoir and Revuelto Creek (fig. 13), one along Revuelto Creek near its confluence with the Canadian River (fig. 13), and six along the Canadian River in the Dunes area (fig. 16).

Upland near Ute Reservoir, Sites PN and PS

The two time-domain soundings on the upland near Ute Reservoir were located 1.5 km west of Logan on the north side of the Canadian River canyon (site PN, fig. 13) and 3 km south of Logan on the south side of the canyon (site PS, fig. 13). These soundings show a pattern of decreasing apparent resistivity with time (fig. 52), indicating that, in general, resistivity decreases with depth. Best-fit resistivity profiles at both of these sites indicate the existence of a thin, highly resistive layer at the surface, which is underlain by a thin conductive layer (fig. 52; table 3). Below the thin conductive layer is a relatively thick resistive layer, which is in turn underlain by a conductive layer to the maximum depth penetrated by the instrument. Resistivity profiles that indicate fits that are nearly as good as those in

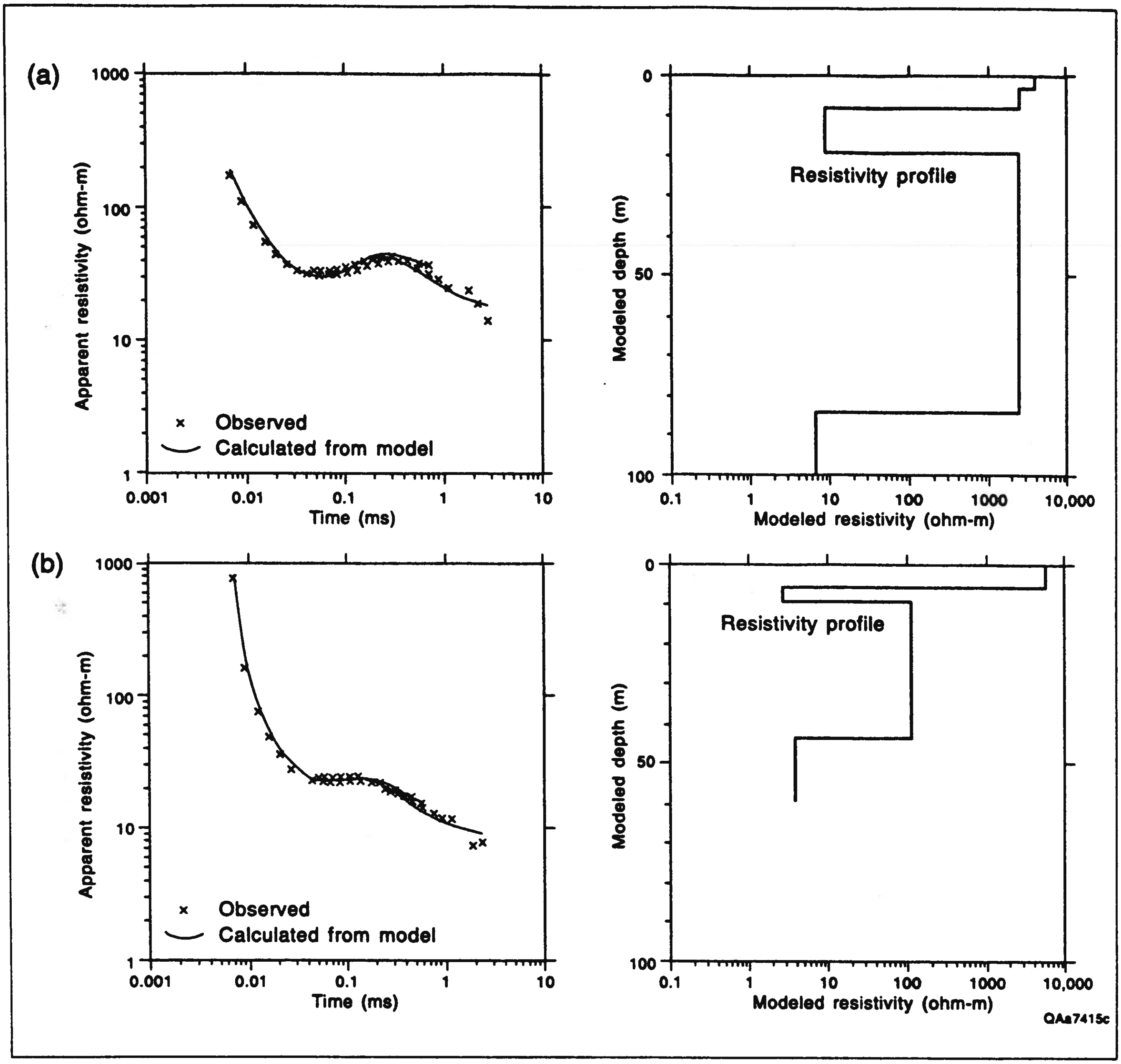


Figure 52. Time-domain soundings at (a) site PN and (b) site PS (fig. 13) on the upland near Logan, New Mexico. Observed and calculated apparent resistivity data shown at left; best-fit modeled resistivity profile shown at right.

the best-fit models show the same general profile but differ slightly in thickness and resistivity values for individual layers. The thin, highly resistive surface layers have about the same thickness and resistivity at both sites (table 3). At the north site, the underlying conductive layer is thicker and less conductive than at the south site, and the thick resistive layer beneath it is thicker and more resistive. Accordingly, the basal conductive layer is deeper at the north site (84 m) than at the south site (44 m).

The highly resistive surface layers probably represent unsaturated surface deposits and poorly sorted, low-porosity, near-surface bedrock. The more conductive layers, from as little as 5 m to as much as 20 m below the surface, probably represent zones of perched fresh water or possibly the water table. Underlying thick,

Table 3. Best-fit resistivity models for PROTEM 47/S time-domain soundings along the Canadian River between Ute Reservoir and Revuelto Creek and in the Dunes area.

Sounding	Location	Fitting error (%)	Layer	Resistivity (ohm-m)	Thickness (m)	Depth to top (m)
PN (fig. 52)	Upland	13.6	1	4,220.4	3.1	0.0
	1.5 km west of Logan, NM		2	2,591.7	4.6	3.1
	(fig. 13)		3	9.4	11.4	7.7
			4	2,454.7	65.2	19.1
			5	6.6	—	84.2
PS (fig. 52)	Upland	12.0	1	6,030.8	5.9	0.0
	3 km south of Logan, NM		2	3.0	3.4	5.9
	(fig. 13)		3	124.2	34.5	9.3
			4	4.3	—	43.8
P331 (fig. 53)	Ute Res. to Revuelto Creek	20.1	1	89.4	1.1	0.0
	Near station 331 (fig. 13)		2	0.9	6.7	1.1
			3	0.4	7.0	7.8
			4	15.0	14.0	14.8
			5	1.0	—	28.8
P388 (fig. 53)	Ute Res. to Revuelto Creek	14.8	1	87.3	1.5	0.0
	Near station 388 (fig. 13)		2	1.1	4.8	1.5
			3	0.4	8.5	6.3
			4	10.0	13.8	14.8
			5	0.8	—	28.6
P421 (fig. 53)	Ute Res. to Revuelto Creek	14.2	1	337.1	0.6	0.0
	Near station 421 (fig. 13)		2	0.9	2.6	0.6
			3	48.9	2.9	3.2
			4	0.7	8.0	6.2
			5	8.6	—	14.2
P500 (fig. 53)	Ute Res. to Revuelto Creek	14.2	1	512.4	0.9	0.0
	Near station 500 (fig. 13)		2	1.4	3.8	0.9
			3	48.8	2.9	4.7
			4	1.0	7.1	7.6
			5	4.1	—	14.6
P8 (fig. 54)	Revuelto Creek	6.4	1	809.1	1.4	0.0
	Near station 8 (fig. 13)		2	3.6	5.3	1.4
			3	1.5	14.5	6.7
			4	98.7	18.8	21.2
			5	0.7	—	40.0
P2 (fig. 55)	Dunes area	15.0	1	16.1	2.1	0.0
	Near station 2 (fig. 16)		2	1.5	2.7	2.1
			3	216.2	16.6	4.8
			4	1.0	1.9	21.4
			5	4,012.9	51.8	23.3
			6	4.2	—	75.0
P53 (fig. 55)	Dunes area	13.5	1	100.0	4.0	0.0
	Near station 53 (fig. 16)		2	3.1	1.3	4.0
			3	1,918.6	29.6	5.4
			4	17.7	—	34.9
P102 (fig. 55)	Dunes area	15.4	1	499.8	1.0	0.0
	Near station 102 (fig. 16)		2	49.8	2.9	1.0
			3	3.9	25.0	3.9
			4	8.6	—	28.8
P122 (fig. 55)	Dunes area	21.9	1	45.0	1.2	0.0
	Near station 122 (fig. 16)		2	1.9	10.9	1.2
			3	0.8	6.6	12.2
			4	0.9	—	18.8

Table 3 (cont.)

Sounding	Location	Fitting error (%)	Layer	Resistivity (ohm-m)	Thickness (m)	Depth to top (m)
P164 (fig. 55)	Dunes area	12.2	1	1.4	5.6	0.0
	Near station 164 (fig. 16)		2	1.2	3.6	5.6
			3	0.5	2.9	9.2
			4	2.9	—	12.1
P230 (fig. 55)	Dunes area	49.6	1	1,096.9	3.3	0.0
	Near station 230 (fig. 16)		2	2.0	14.3	3.3
			3	248.8	6.2	17.5
			4	0.2	—	23.7

Dash indicates value unknown.

resistive zones may represent lower porosity, poorly sorted bedrock units, such as mudstone, with lower water volumes and therefore higher bulk resistivities. The more conductive bottom layers probably represent more porous sandstones at or below the water table.

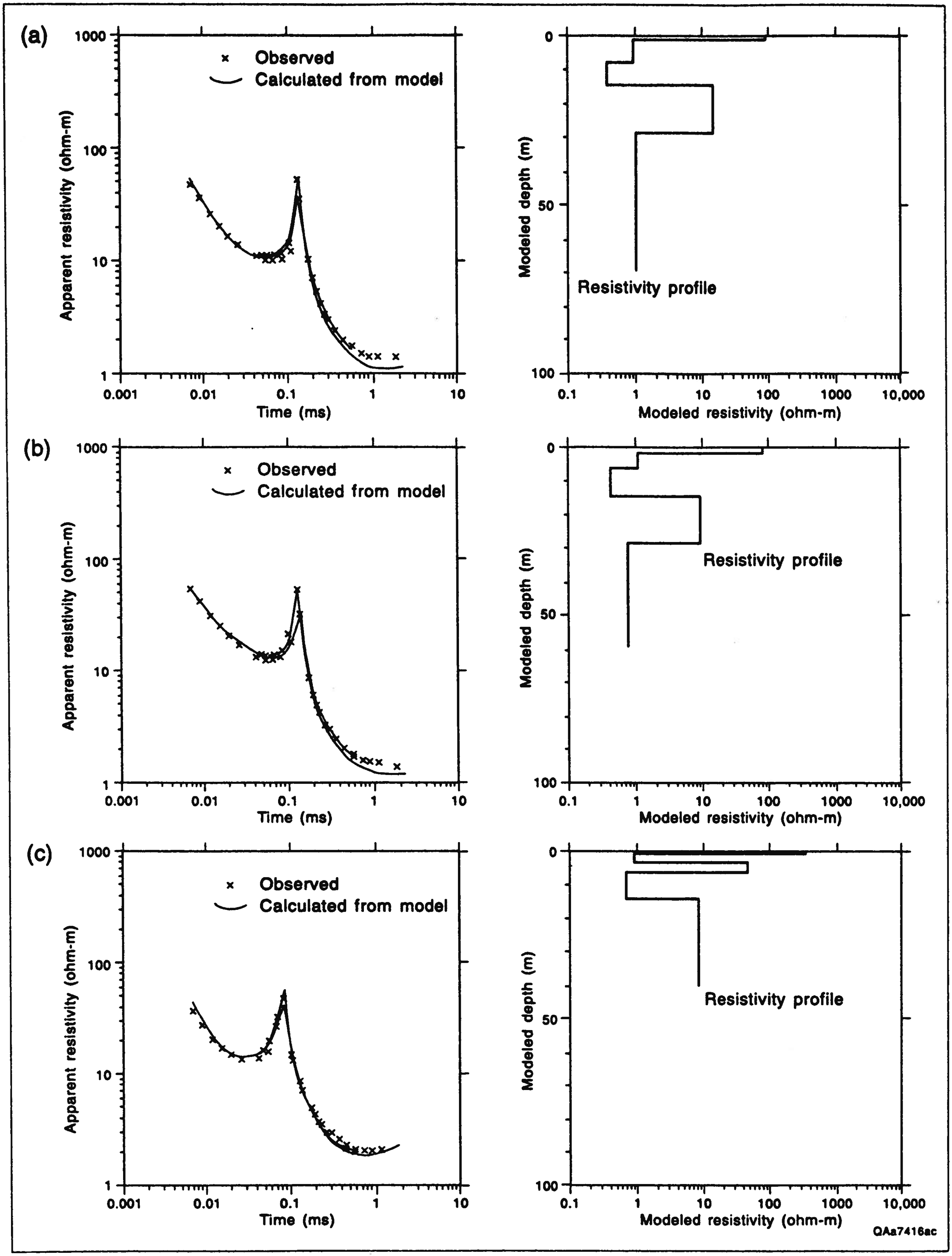
The lowest modeled resistivities at these sites are in the range of 4 to 7 ohm-m, which correspond to conductivities of 250 to 140 mS/m. These values are typical of fresh to slightly saline water and are relatively low compared with conductivities modeled for riverbed sites using frequency-domain data, suggesting that the time-domain soundings at PN and PS did not reach the postulated "brine aquifer" (U.S. Bureau of Reclamation, 1976). Comparison of modeled layer depths at sites PN and PS with depths inferred from earlier electrical resistivity surveys (U.S. Bureau of Reclamation, 1976) indicates that the top of the "brine aquifer" is more than 100 m deeper.

Ute Reservoir to Revuelto Creek, Sites P331, P388, P421, and P500

Of the four sounding sites in the Canadian River canyon between Ute Reservoir and Revuelto Creek, three (P331, P388, and P421, fig. 13) are within high-conductivity zone B and one (P500, fig. 13) is within high-conductivity zone C (fig. 39). Sounding P331 was taken near conductivity peak B4, sounding P388 was taken between peaks B6 and B7, sounding P421 was taken near peak B7, and sounding P500 was taken near peak C1.

The modeled resistivity profiles at these sites (fig. 53) indicate that the soundings penetrated much more conductive layers than at sites on the upland. Each profile contains a thin, resistive surface layer less than 2 m thick. In two profiles (P331 and P388), these thin layers overlie a conductive layer about 14 m thick (table 3), which in turn overlies a more resistive layer also about 14 m thick, and then a basal conductive layer that extends to the maximum penetration depth of the instrument. In the other two profiles (P421 and P500), the thin, resistive surface layer overlies a conductive layer less than 4 m thick, which in turn overlies a thin, resistive layer about 3 m thick, then another conductive layer about 8 m thick, and finally a more resistive layer that extends to the maximum penetration depth. The resistive surface layer at these four riverbed sites is thinner and much less resistive than at upland sites PN and PS. In addition, the basal conductive layer is shallower and more conductive at the valley floor.

Preliminary interpretations of the profiles are that the near-surface resistive layers represent unsaturated alluvium and that the underlying conductive layers to about 15-m depth are saturated by saline water that may have increased salinity because of evaporation. The increase in resistivity at about 15-m depth at each of the four sites may represent the contact between alluvium


(a)
1000
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× Observed
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Apparent resistivity (ohm-m)
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Time (ms)
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Modeled depth (m)
Resistivity profile
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Modeled resistivity (ohm-m)
(b)
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Apparent resistivity (ohm-m)
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Time (ms)
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Modeled depth (m)
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Modeled resistivity (ohm-m)
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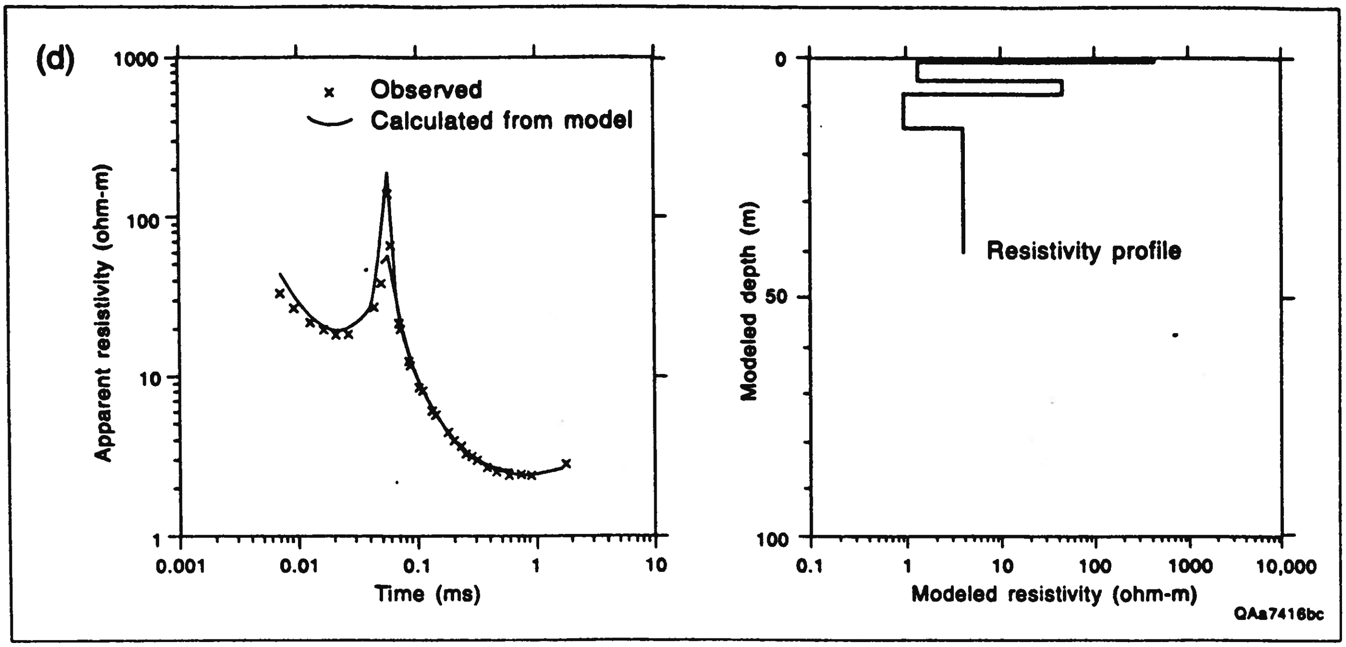

Figure 53. Time-domain soundings at (a) site P331, (b) site P388, (c) site P421, and (d) site P500 (fig. 13) along the Canadian River between Ute Reservoir and Revuelto Creek. Observed and calculated resistivity data shown at left; best-fit modeled resistivity profile shown at right.

(higher porosity) and bedrock (lower porosity) or alluvium containing saline water of an initial salinity (reflecting mix of saline ground water from bedrock and shallower, fresher ground water) that becomes more saline in overlying conductive layers because of evaporation. The substantial drop in resistivity at 15-m depth beneath sites P331 and P388 may represent the contact between alluvium with a mix of saline and fresh waters and bedrock dominated by saline water.

Revuelto Creek, Site P8

One time-domain sounding (P8, fig. 13) was located along Revuelto Creek near its confluence with the Canadian River. At this site, a thin resistive surface layer overlies about 20 m of conductive material (fig. 54, table 3). Resistivity increases between depths of 21 and 40 m; a highly conductive layer extends from 40 m to the maximum depth investigated by the instrument.

This profile (fig. 54) is qualitatively similar to those of the Ute Reservoir to Revuelto Creek sites (fig. 53) and is interpreted similarly. The basal conductive layers have the same resistivity as those at the Ute Reservoir and Revuelto Creek sites, and the resistivity variations in overlying layers are about the same. Overall resistivity is higher at site P8, suggesting slightly greater fresh-water influence.

Dunes Area, Sites P2, P53, P102, P122, P164, and P230

Time-domain soundings were located at sites P2, P53, P102, P122, P164, and P230 (fig. 55) in the Dunes area of the Canadian River canyon (fig. 16). P2 is in a moderately conductive area delineated by the lateral ground conductivity survey (fig. 45), and P53 is in a low-conductivity area near a fresh-water spring. The other sites are within high-conductivity zone D, delineated by the lateral conductivity survey (fig. 45); P102 is near the upstream edge of high-conductivity zone D, P122 and P164 are located within zone D at individual peaks D1 and D2, and P230 is at the downstream end of zone D.

Resistivity profiles of each of these sites, calculated from apparent resistivity data, show considerable variability (table 3). The sequence from

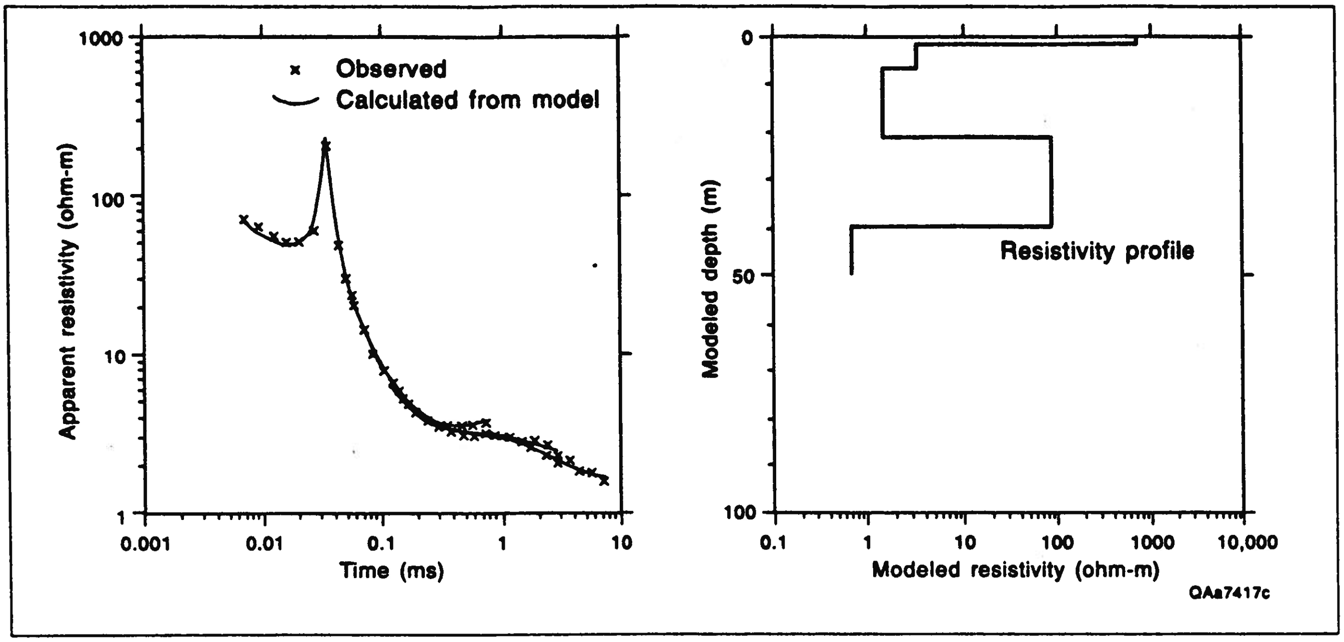

Figure 54. Time-domain sounding at site P8 (fig. 13) along Revuelto Creek. Observed and modeled resistivity data shown at left; best-fit modeled resistivity profile shown at right.

P2 through P230 (fig. 55) confirms that this segment of the river crosses an important zone of saline-water discharge. The profiles at sites P122 and P164 (fig. 55d and 55e) show the lowest modeled resistivities. Site P164 had the highest conductivities of all Dunes area sites, as measured by the lateral conductivity survey (fig. 45). The low resistivity in these profiles indicates saturation by saline fluids.

The most resistive profiles are found at sites P2 and P53 (fig. 55a and 55b) at the upstream end of the Dunes area. These profiles have relatively thin conductive layers between thick resistive layers. A thick resistive layer extends from 23- to 75-m depth at site P2 and from 5- to 35-m depth at site P53. At each of these sites, the thick resistive layers are underlain by conductive layers to the maximum depth penetrated.

Soundings P102 and P230 (fig. 55c and 55f), located at the edges of high-conductivity zone D, both have thin resistive surface layers, which suggest flushing by surface water, and are underlain by more conductive layers, reflecting input from saline-water discharge points. The 6-m-thick resistive layer between about 17- and 24-m depth in the model for P230 is suspect because of the poor fit between the model profile and the observed data (fig. 55f).

In the Dunes area, profiles with the lowest resistivities were found at points where the lateral conductivity surveys showed conductivity peaks. These profiles are consistent with an interpretation of alluvium and underlying bedrock saturated with saline ground water to the deepest level penetrated by the instrument. The slight increase in resistivity in sounding P164 at 12-m depth (fig. 55e) may represent the bedrock-alluvium contact and a lower porosity in the bedrock. The upper parts of these profiles probably reflect the salinity of through-flowing river water and fresh-water input from springs and seeps. The more conductive layers at depth probably reflect higher overall salinity of ground water in bedrock. The top of the basal low-resistivity zone is deepest in this part of the Dunes area.

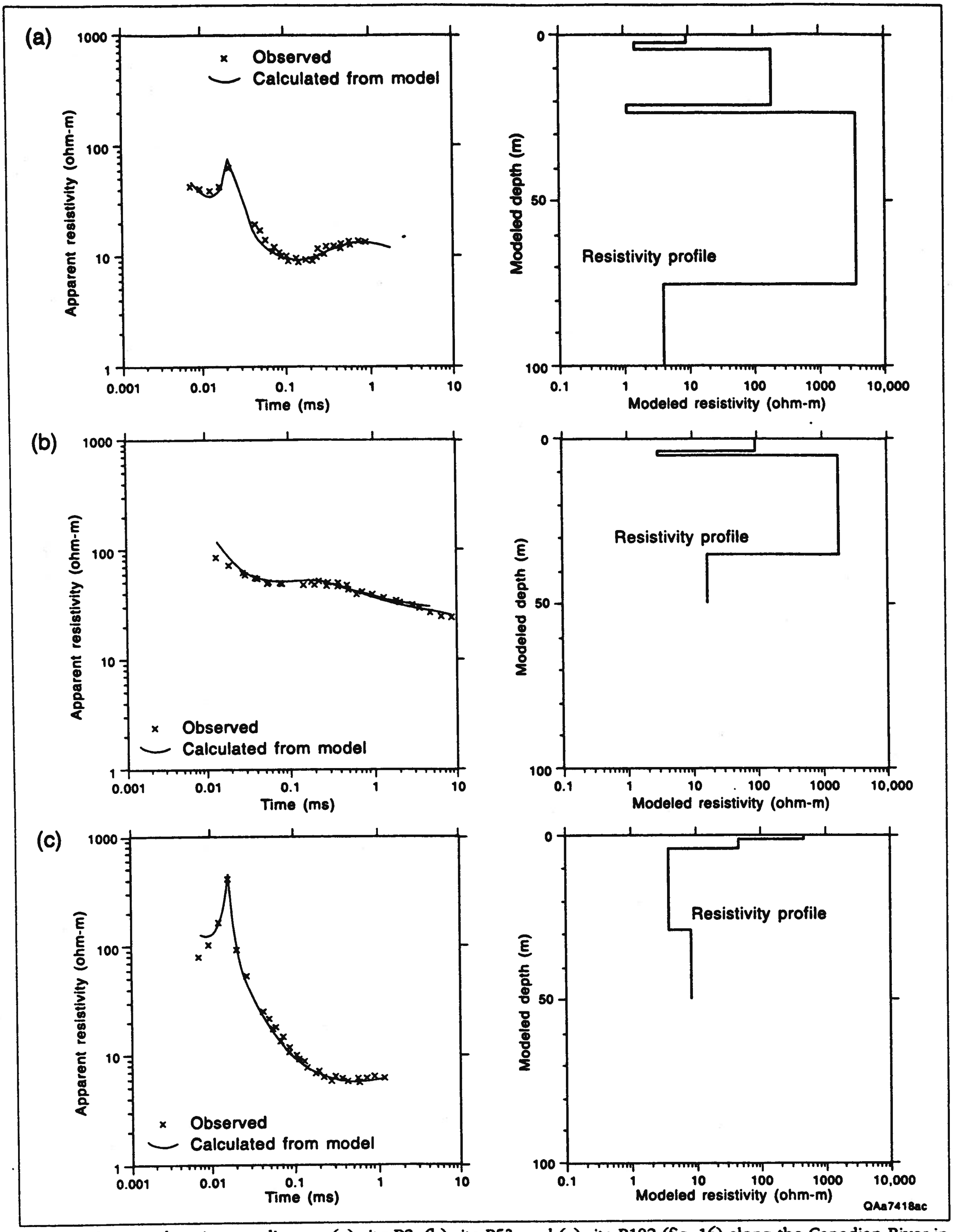

Figure 55. Time-domain soundings at (a) site P2, (b) site P53, and (c) site P102 (fig. 16) along the Canadian River in the Dunes area. Observed and calculated data shown at left; best-fit modeled resistivity profile shown at right.

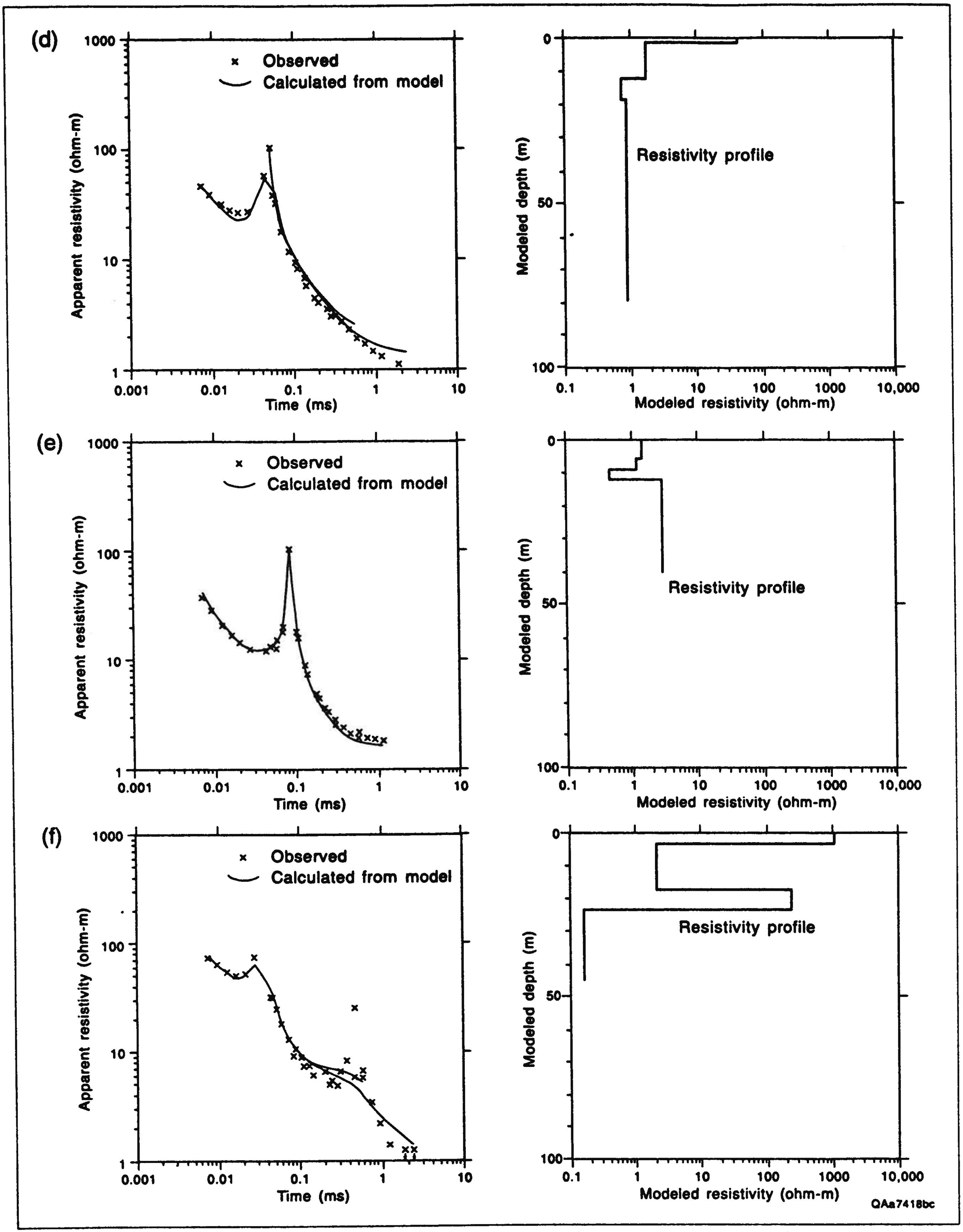

Figure 55 (cont.) Time-domain soundings at (d) site P122, (e) site P164, and (f) site P230 (fig. 16) along the Canadian River in the Dunes area. Observed and calculated data shown at left; best-fit modeled resistivity profile shown at right.

Discussion

Evaporite Dissolution and Water Flow, Conductivity, and Chemistry

Saline water forced from areas of high hydraulic head in Permian strata rises through fine-grained rocks in the upper part of the Permian section and the lower part of the Triassic section, probably along joints or fractures, then enters more permeable sandstone units. From there the saline water presumably discharges into riverbed sediments, either through the rock matrix or by preferential flow through joints, and then finally seeps into the Canadian River. The main contributor of solutes to the Canadian River has historically been the Permian San Andres Formation, as shown by the dissolution of nearly 215 m of halite from areas beneath the Canadian River valley (figs. 4 and 5). A large amount of NaCl was also contributed by dissolution of halite from mixed siliciclastic-halite beds and discrete halite beds in the Artesia Group beneath and as far south as 32 km from the Canadian River (fig. 4).

Results of the February 1992 water quality survey suggest two principal areas where saline waters currently enter the Canadian River: (1) along the first 14 to 16 km downstream from Ute Reservoir (figs. 28 and 29) and (2) between 32 and 64 km downstream from Ute Reservoir (fig. 28), which corresponds to the segment of the Canadian River where river flow begins to increase dramatically and is approximately the last point where high-conductivity waters (greater than 1,550 mS/m) are found, with the exception of the Lahey Creek area about 160 km farther downstream. This second principal area is also approximately where the river canyon cuts through the resistant sandstones of the Trujillo Formation (middle member of Upper Triassic Dockum Group) and exposes fine-grained sandstones and mudstones of the underlying Tecovas Formation (lower member of Dockum Group). This contact may actually have been crossed by the channel some distance upstream (0.8 km or more), because the bedrock floor of the canyon may be 15 m or more below the surface of the riverbed alluvium. Both of these river segments are in New Mexico.

Moderately high conductivities in the vicinity of Lahey Creek in Texas (about 1,300 mS/m, fig. 28) suggest that this area may be an important river salinity source. However, inflow from the creek and from seeps in the area at the time of the survey was insignificant relative to inflows in the other salinity source areas. Preliminary calculations by CRMWA, based on February 1992 chloride concentration and flow data, confirm the conclusion that most of the salt loading of the Canadian River occurs within the first 60 km (table 4), reaching a level of about 25,000 to 40,000 metric tons of chloride per year. Beyond 60 km, the chloride load trend remains approximately constant to about 155 km downstream from Ute Reservoir, and then declines to about 80 percent of the maximum value.

Laboratory chemical analyses (table 1) suggest that saline waters in the Canadian River valley evolved by mixing of fresh water derived from meteoric precipitation and highly saline water derived from dissolution of halite at depth. The most saline water sample obtained along the Texas portion of the Canadian River (from site 96a, table 1) contains relatively high concentrations of calcium, magnesium, and sulfate relative to other samples with similar sodium and chloride concentrations (figs. 31 and 32). This difference in water chemistry may reflect differences in flow paths through the dissolution zone in the New Mexico and Texas portions of the Canadian River. Flow paths in New Mexico may extend deep into the dissolution zone where halite is present, whereas flow paths in Texas may be more restricted to the upper part of the dissolution zone where anhydrite, gypsum, and dolomite remain but halite may have already been dissolved or perhaps was originally less abundant.

Table 4. Annualized salt loading in Canadian River, Ute Reservoir, New Mexico, to Lake Meredith, Texas.*

River survey site no.	Downstream distance (km)	Salt (chloride) (tonnes/yr)	Date measured	Notes
31†	7.10	10,045	2/11/92	Flowing pool section of river
40	10.07	423	2/11/92	Revuelto Creek
41	10.15	28,182	2/11/92	River, 60–90 m downstream from confluence with Revuelto Creek
50	20.47	27,842	2/12/92	River
57	34.50	25,897	2/13/92	River
67	62.67	40,461	2/13/92	River, ~0.2 km upstream from New Mexico–Texas state line
70	76.78	39,596	2/14/92	River
80	137.65	36,384	2/16/92	River, immediately downstream from Old Farm Crossing
85†	153.43	113	2/16/92	Punta de Agua
86	153.89	41,043	2/16/92	River, immediately downstream from Punta de Agua
90	178.52	30,506	2/17/92	River
101	226.16	32,665	2/18/92	River, under Highway 87-287 bridge
103	237.43	16	2/18/92	Chicken Creek

*Distance downstream measured from Ute Dam. Salt loading calculated from instantaneous chloride concentration and flow data by Canadian River Municipal Water Authority. Salt loading is a measure of the total quantity of salt in solution that is carried past a point.

†Sites where water samples were collected and analyzed.

Water samples collected during the February 1992 river survey appear representative of Canadian River water. The data reported here are similar to those for samples collected from the New Mexico portion of the river during previous surveys and from sampling stations in Texas near Tascosa and Amarillo (fig. 56). Data from these earlier surveys show similar divergence of trends in calcium versus chloride and sulfate versus chloride as data from the February 1992 survey between samples from the New Mexico portion of the river and samples from the Amarillo sample station. This supports the view that inflow of the halite brine is more dominant in the New Mexico part of the Canadian River than in the Texas part. Data from the February 1992 survey are also consistent with chemical data on samples of shallow ground water collected from piezometers in the Canadian River alluvium (fig. 57), indicating that the saline waters in isolated pools, tributaries, seeps, and in the main channel itself have the same origin as the shallow saline ground water in the river alluvium.

Joints and Ground-Water Flow Paths

Ground-water movement through Dockum Group strata probably results from the combined processes of nonpreferential (or matrix) flow and preferential (or fracture) flow. We examined joints in the Dockum Group strata closely because our field observations suggested that they might provide important pathways for ground-water movement. Jointing is well developed in the Dockum Group, which in eastern New Mexico is composed primarily of fluvial sandstones with secondary overbank mudstones. Typically, thin-bedded sandstones and mudstones have closely spaced joints, whereas joints in thick rigid channel sandstones are more widely spaced. Primary, or through-going, joints are oriented roughly east-west and commonly show evidence of dilation, including millimeterwide separation of joint faces, mineral fillings (calcite veins), and less commonly clastic debris fillings.

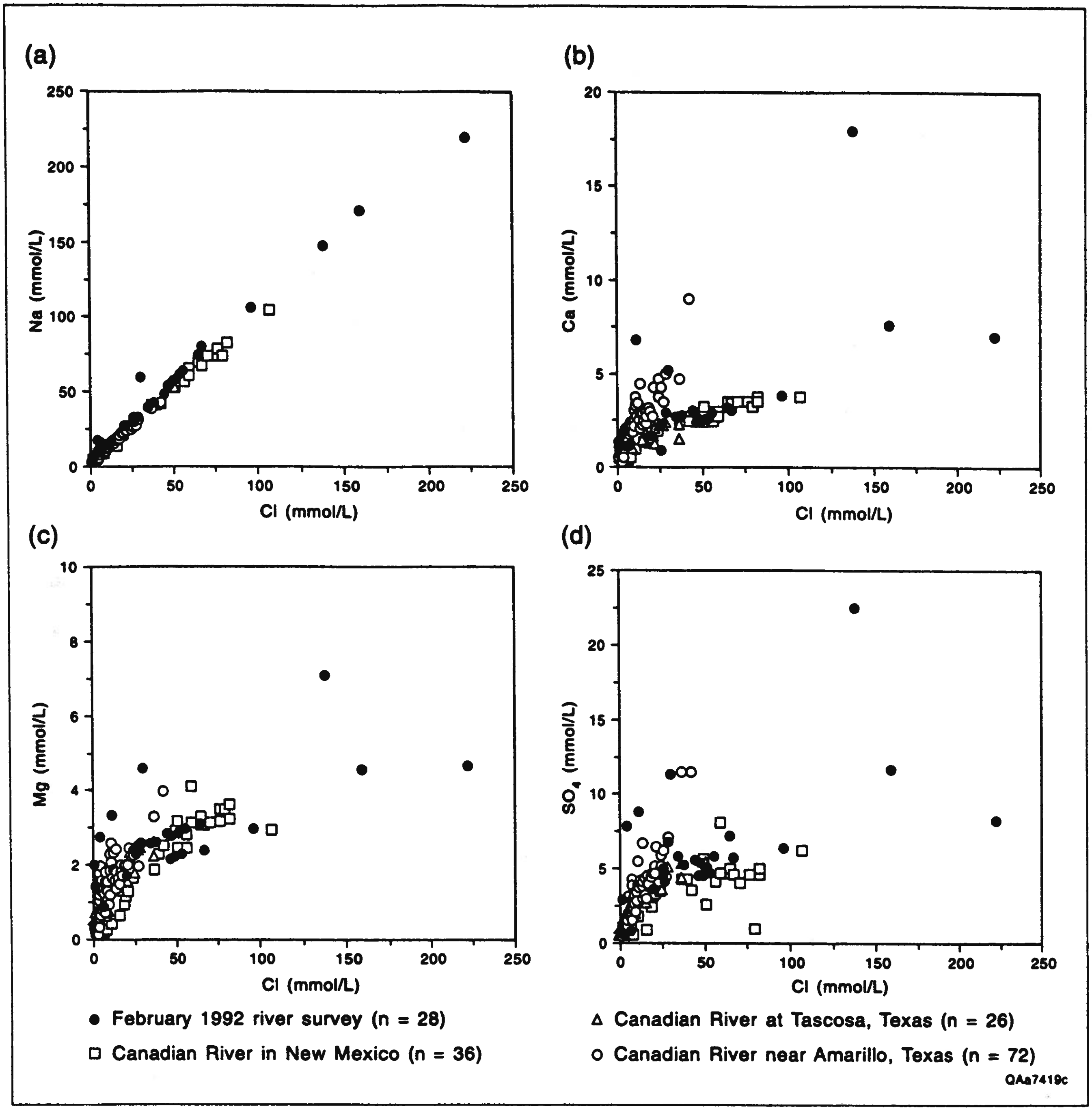

Figure 56. Comparisons of (a) sodium versus chloride, (b) calcium versus chloride, (c) magnesium versus chloride, and (d) sulfate versus chloride data from February 1992 river survey and previous investigations (Hydro Geo Chem, 1984).

The mapped potentiometric surface for ground water in the lower Dockum Group in eastern New Mexico (fig. 58), which in the Logan area receives water laden with dissolved salts from the "brine aquifer" described by the U.S. Bureau of Reclamation (1976, 1979), lies 3 to 30 m above Canadian River alluvium. Because the potentiometric surface lies above Canadian River alluvium, Dockum Group ground water has the potential to flow upward to discharge into Canadian River alluvium and thence flow into the Canadian River. The high potentiometric

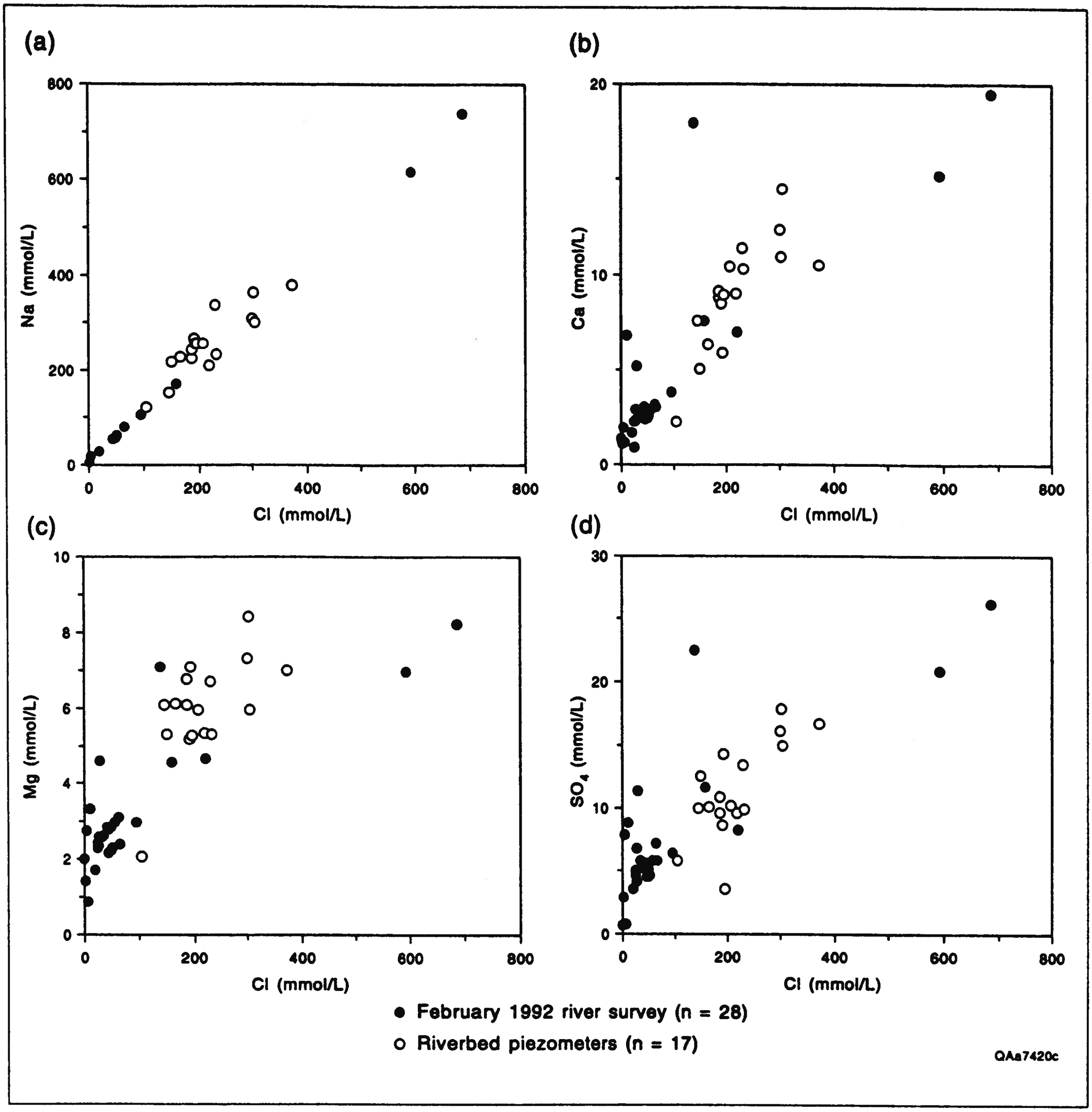

Figure 57. Comparisons of (a) sodium versus chloride, (b) calcium versus chloride, (c) magnesium versus chloride, and (d) sulfate versus chloride data from surface-water samples of February 1992 river survey and from samples collected from riverbed piezometers during previous investigations (Hydro Geo Chem, 1984).

surface also explains the presence of efflorescence of halite and gypsum on the bedrock wall of the Canadian River canyon as much as 10 m 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 probably an important part of the process of ground-water discharge to Canadian River alluvium.

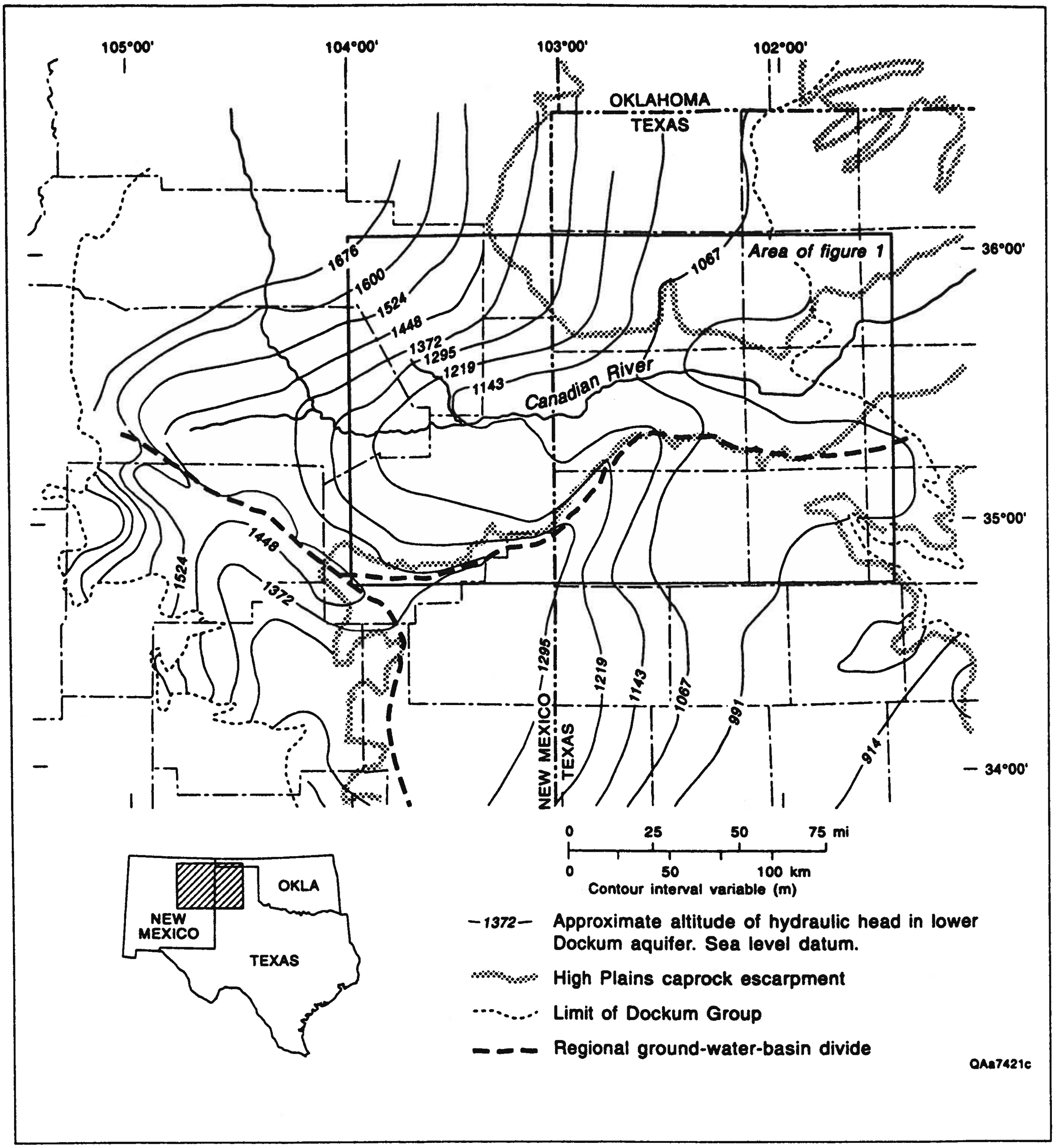

Figure 58. Potentiometric surface of lower Dockum Group ground water. Regional ground-water-basin divides (inferred from topography and shape of the potentiometric surface) separate regional ground-water basins. The 1,143-m contour crosses the Canadian River in the vicinity of Ute Reservoir. Modified from Dutton and Simpkins (1986).

Ground-Conductivity Surveys

We completed the lateral ground-conductivity surveys in suspected areas of saline-water inflow suggested by previous studies, by the water-quality survey, and by geologic and geomorphic analysis of surface exposures. The lateral surveys located 4 broad high-conductivity zones and 18 individual conductivity peaks that are likely sites of saline ground-water inflow into the Canadian River system. Vertical conductivity surveys, collected using frequency-domain and time-domain techniques, were used to examine conductivity variations with depth to ensure that lateral conductivity variations were not simply caused by near-surface anomalies.

Three of the four broad high-conductivity zones were located along the Canadian River between Ute Reservoir and Revuelto Creek, a segment that showed the highest water conductivities in the water-quality survey (fig. 28). Zone A, which extends for about 1,600 m between Ute Dam and the Highway 54 bridge (stations 90 through 170, figs. 13 and 39), contains two distinct conductivity peaks that are each about 200 m long. Zone B begins between the highway and railway bridges and ends about 4,200 m downstream in the gravel pit reach (stations 233 through 444, figs. 13 and 39). The highest conductivities, and thus the highest inferred ground-water salinities measured during this project, were found in zone B. Within this broad zone of high conductivity were eight distinct conductivity peaks that were each 60 to 340 m long. 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 467 through 583, figs. 13 and 39), is more than 2,000 m long and contains four separate conductivity peaks that were each 100 to 280 m long. Zone C most likely extends some distance downstream from station 583, the last point surveyed along this segment. Surveys along Revuelto Creek, a tributary that doubles the flow of the Canadian River (fig. 29), showed that ground conductivities increased downstream along Revuelto Creek (fig. 42), but no distinct conductivity peaks were identified.

Multiple-coil-separation soundings at peaks A2, B2, and B7 between Ute Reservoir and Revuelto Creek (fig. 13) reveal a thin (0.8 to 1.8 m thick), low-conductivity (5 to 22 mS/m) layer at the surface. This layer probably represents either unsaturated alluvium or alluvium saturated with relatively fresh water. This 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 and support the conclusion that the conductivity peaks detected in the lateral surveys are not simply surface anomalies. Bedrock was probably encountered at two of the sites, where a highly conductive alluvial layer saturated with saline water overlies a less conductive bedrock with pores and fractures filled with saline ground water. Time-domain electromagnetic soundings at four sites within the Canadian River valley between Ute Reservoir and Revuelto Creek and at one site along Revuelto Creek confirm that subsurface conductivities are higher along the Canadian River between Ute Reservoir and Revuelto Creek than they are at Revuelto Creek, in the Dunes area, and on the upland near Ute Reservoir (figs. 53 through 55). These observations support the conclusion that the high-conductivity zones in the Ute Reservoir to Revuelto Creek segment are the largest sites of saline water inflow into the Canadian River system.

High conductivities in isolated pools and increased river flow accompanied by no decrease in river conductivity between 35 and 65 km downstream from Ute Reservoir (fig. 28) suggested that major sources of saline-water inflow might also be found in the Dunes and Rana Canyon areas (fig. 11). In the Dunes area, the fourth broad zone of high conductivity (zone D) was encountered (fig. 45). 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. Extremely low conductivities were recorded along the river near station 53, where a fresh-water spring was discharging into the river during the survey. Vertical conductivity profiles computed from the time-domain data indicate that subsurface conductivities in the Dunes area range from relatively resistive profiles near the spring to conductive profiles within zone D. Near Rana Canyon, apparent conductivities were relatively low (fig. 46), and no peaks were encountered. Conductivities increased downstream along Rana Arroyo (fig. 47), a tributary that flows into the Canadian River at Rana Canyon, but no conductivity peaks were identified in the short Rana Arroyo segment surveyed.

In high-conductivity zone C in the Ute Reservoir to Revuelto Creek segment and zone D in the Dunes segment of the Canadian River valley, individual conductivity peaks showed some correlation with tributary valley locations. This relationship suggests that either highly saline water flows down the tributary valleys or that tributary valleys are located where zones of bedrock weakness, such as joints, exist. These weak zones may provide preferential flow paths between the brine aquifer and the surface. The Claer well area (figs. 11 and 14) is another area where prominent side drainages intersect the Canadian River valley but the water-quality survey indicated no increase in conductivity (fig. 28). Apparent ground conductivities measured upstream and downstream from the tributary valley intersection were high (fig. 43), but generally not as high as those in the Ute Reservoir to Revuelto Creek segment. No distinct conductivity peaks were identified, suggesting an absence of highly saline water sources in this segment of the valley.

The water-quality survey also revealed no increase in river conductivity in the Jones well area (fig. 28), but geomorphic evidence of surface collapse, probably related to subsurface evaporite dissolution, suggested that this would be another area where flow could potentially occur between the brine aquifer and the surface. Nevertheless, ground-conductivity surveys across the intersection of the collapse feature and the Canadian River valley (fig. 15) revealed relatively low conductivities along this segment (fig. 44), particularly across the collapse feature. There were no conductivity peaks in the Jones well area, again suggesting absence of sources of saline water in this vicinity. A multiple-coil-separation sounding on the valley floor near the center of the collapse feature revealed the presence of a thin, low-conductivity surface layer that probably represents either unsaturated alluvium or alluvium saturated with relatively fresh water. Underlying the thin surface layer is a more conductive layer, but this layer is much less conductive than similar layers at sites in the Ute Reservoir to Revuelto Creek segment. Lower conductivities at Jones well imply that the alluvium beneath the site is saturated with water of lower salinity than at other sites. At Jones well, conductivity again increases at a depth of about 19 m, marking the possible contact between conductive bedrock and a lower conductivity alluvial layer saturated with saline ground water that has been diluted with fresh water. The absence of large areas of saline-water inflow in the Claer well and Jones well areas helps validate the use of the river-conductivity survey as a screening tool for more intensive ground-conductivity surveys.

Drilling in Jointed Dockum Group Strata

The hydraulic head of saline ground water in Dockum Group strata could be reduced by pumping, thereby preventing natural discharge of saline water to Canadian River alluvium (U.S. Bureau of Reclamation, 1979, 1985). To successfully conduct a pumping program, areas of major saline water discharge into Canadian River alluvium must be accurately located. Furthermore, the character and distribution of permeable rocks in the subsurface should be known in order to drill wells where they can efficiently draw down the potentiometric surface. Although the distribution of permeable strata in the subsurface is unknown and cannot be inferred from surface exposures, the patterns of permeable pathways such as joints can be inferred from surface data.

The potential for preferred ground-water flow along near-vertical joints in Dockum Group strata suggests that the placement of boreholes may be critical to the success of a mitigation program designed to reduce saline-water discharge to the Canadian River. If joints are preferred pathways in the subsurface, then the productivity of a pumping well may be controlled by the number of joints the well bore intersects. Results from this study show that joints are grouped and not evenly distributed. Furthermore, primary joints show evidence of dilation at the surface and are much more continuous than secondary joints. Thus, it is possible for the screened interval of a conventional vertical well to end up in a block of Dockum strata without intersecting any joints. It is also possible that if the well bore is inclined slightly to the east or west, the borehole will intersect only secondary or tightly closed joints.

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

Several key advantages of horizontal over conventional vertical wells apply to many environmental applications (Morgan, 1992), including (1) increased contact with subsurface contaminant plumes in the production interval, (2) greater percentages of contaminant recovery, (3) higher well production rates (specific capacity), (4) faster extraction of some contaminants, and (5) more efficient well geometry (multiple horizontal sections extending from a single vertical shaft). The disadvantages of using horizontal drilling are that drilling is more difficult and more expensive. Properly oriented slanted wells offer some of the advantages of horizontal drilling, are less expensive, and are currently in wider use.

Horizontal or slant drilling oriented 90° to the primary joint orientation in Dockum strata would intersect numerous vertical primary joints, which are potential preferred flow paths. In addition, the screened section of production wells could be placed at relatively shallow depths in the bedrock beneath the canyon of the Canadian River. The ability to place screened intervals beneath the river and to intersect numerous preferred pathways could significantly increase the effectiveness of a pumping program designed to draw down the local water table.

Conclusions

The main contributor of solutes to the Canadian River throughout its history has been the dissolution of bedded halite from the Permian San Andres Formation and dissolution of halite from mixed siliciclastic-halite beds and discrete halite beds in the Artesia Group. Chemical analyses suggest that saline waters in the Canadian River valley evolved by mixing of fresh water derived from meteoric precipitation and highly saline water derived from dissolution of halite at depth.

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

Results of the 1992 water-quality survey suggest two principal areas where saline waters currently enter the Canadian River: (1) along the first 14 to 16 km downstream from Ute Reservoir and (2) between 32 and 64 km downstream from Ute Reservoir. Preliminary calculations by CRMWA, based on 1992 chloride concentration and flow data, confirm the conclusion that most of the salt loading of the Canadian River occurs within the first 64 km, reaching about 25,000 to 40,000 metric tons of chloride per year.

If halite dissolution continues along the same trends and by the same processes as in the past, then the focus of modern dissolution will be along a front at a depth of about 335 m beneath the Canadian River in the Ute Reservoir area and will extend in the subsurface about 16 km south of the Canadian River at depths of 305 m. A future program of drilling, sampling, and analysis of waters from various areas and depths would provide useful data to help test these hypotheses.

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

The high-conductivity zones encompassed individual conductivity peaks that probably represent sites of saline inflow into Canadian River alluvium. Two peaks were located along the Canadian River between Ute Dam and the Highway 54 bridge, 12 peaks were found between the Highway 54 bridge and a point downstream from Revuelto Creek, and 4 peaks were found in the Dunes area. Low-conductivity zones near a collapse feature in the Jones Well area and near a fresh-water spring in the Dunes area suggest little or no saline-water intrusion in these areas.

Vertical soundings (both frequency and time domain) confirmed that the Ute Reservoir to Revuelto Creek segment is the most highly conductive segment surveyed and thus probably the most important source area for highly saline waters discharging into the Canadian River alluvium. Time-domain soundings could be used to regionally map the top of the postulated brine aquifer. Effective penetration depths of these soundings are limited in some parts of the canyon by extremely high ground conductivities. It is also difficult to find open areas in the valley large enough to accommodate the large transmitter antenna used for deep time-domain soundings.

Acknowledgments

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Appendix. Wells Used in Structural Cross Sections A–A′ and B–B′ (Figs. 4 and 5).

BEG well name	Driller or operator and well name
Harding 3	Humble Oil and Refining Company "CL" State No. 1
Harding 7	Humble Oil and Refining Company "CM" State No. 1
Harding 19	Astro-Tex 1-X Olympic State
Oldham 73	British American Oil Producing Company Shelton No. 1
Quay 2	Humble Oil & Refining Company State "CP" No. 1
Quay 3	Powers Wire Products, Inc., State No. 2
Quay 9	J. C. Lee Drilling Company Dennis No. 1
Quay 13	O. L. Ledgerwood Kimes No. 1
Quay 14	Shell Oil Company North Pueblo No. 2
Quay 28	Shell Oil Company Pueblo Strat 19-69
Quay 32	Nucorp Energy Inc. State No. 1
Quay 36	National Oil Company Columbine State No. 1
San Miguel 3	Puretex Oil Company Chappell No. 3
USBR DH-1	U.S. Bureau of Reclamation (1979) Drill Hole 1
USBR DH-2	U.S. Bureau of Reclamation (1979) Drill Hole 2
USBR DH-3	U.S. Bureau of Reclamation (1984) Drill Hole 3