

GROUND WATER HYDROCHEMISTRY IN THE
SOUTHEASTERN HUECO BOLSON, TRANS-PECOS TEXAS

R. Stephen Fisher and William F. Mullican, III

Prepared for

Texas Low-Level Radioactive Waste Disposal Authority
under Interagency Contract Number IAC (88-89)-0932

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78713

August 1989

ABSTRACT

The hydrochemical history of ground water in the arid southeastern Hueco Bolson was investigated by collection of soil-moisture samples from unsaturated siliciclastic bolson-fill sediments and ground-water samples from the Diablo Plateau aquifer, the Hueco Bolson silt and sand aquifer, and the Rio Grande alluvial aquifer. Major, minor, and trace solutes, stable isotopic compositions, and activities of tritium and carbon-14 were measured in ground-water samples; major solute concentrations were determined in soil-moisture samples. Soil samples were collected to determine the type and amount of material that could be readily dissolved by recharge water. Core samples of Cretaceous carbonate and bolson-fill material were analyzed to determine the mineralogy of sediment and aquifer matrix.

The Hueco Bolson and Diablo Plateau aquifers contain mainly Na-SO_4 ground water that derived solutes by carbonate and gypsum dissolution, coupled with exchange of aqueous calcium and magnesium for sodium on clay minerals and other ion exchange sites. Rio Grande ground water is dominated by sodium and chloride derived from dissolution of salts precipitated in irrigated fields during times of high evaporation. All ground waters appear to acquire major compositional characteristics early in the flow history, principally through reactions in the unsaturated zone.

Ages estimated from tritium and carbon-14 activities show that Rio Grande ground waters are youngest, reflecting the short flow paths from land surface following irrigation, infiltration, and deep penetration and from the river to sampled wells. Ground water from the Diablo Plateau and Hueco Bolson aquifers ranges in age from a few hundred to nearly 29,000 yr. Carbon-14 ages and tritium activities do not vary systematically along a flow path; however, the oldest waters occur in wells near the center of the bolson pediment. The irregular distribution of carbon-14

and tritium indicates that the Bolson and Diablo Plateau aquifers are internally complex, and flow velocities are not readily predictable solely on the basis of the potentiometric gradient and estimates of regional porosity and permeability data.

INTRODUCTION

Purpose and Scope

Geologic and hydrologic investigations of two areas in Trans-Pecos Texas were initiated in 1985 at the request of the Texas Low-Level Radioactive Waste Disposal Authority (TLLRWDA), which had selected these areas as candidates to host a low-level radioactive waste repository. Results of the preliminary investigation (Kreitler and others, 1986, 1987) led to more detailed studies of the southeastern Hueco Bolson near Fort Hancock, Texas. As part of this work, water samples from all accessible wells and springs were evaluated to determine hydrologic and hydrochemical factors that could impact the suitability of the area to host a radioactive waste repository. This investigation also presents an opportunity to investigate the hydrology and ground-water geochemistry of arid land where the unsaturated zone is exceptionally thick. This report summarizes the results of an extensive ground-water sampling program conducted in 1988 and 1989, combined with data derived from earlier studies and related work conducted during the same period.

Location

The Hueco Bolson (fig. 1) is a major basin in the southeastern Basin and Range physiographic province. It is located in Trans-Pecos Texas and southeastern

New Mexico, extending along and northeast of the Rio Grande from the Quitman Mountains near Sierra Blanca to the Franklin Mountains near El Paso and north into New Mexico. In Texas it is bounded to the northeast by the Diablo Plateau and to the southwest by the Chihuahua tectonic belt, a part of the Laramide fold belt. Major topographic and geographic features of the area are the (1) Rio Grande to the southwest, (2) Arroyo Alamo, Camp Rice Arroyo, Arroyo Campo Grande, Arroyo Madden, and Arroyo Diablo that dissect the bolson surface, (3) Campo Grande Mountain, which rises more than 200 ft above the bolson surface, and (4) Diablo Plateau, which lies above the bolson surface and is separated from it by an escarpment of more than 400 ft.

The bolson developed during regional east-northeast extension and normal faulting approximately 24 million years ago (Henry and Price, 1985). This tectonic activity resulted in topographically high ranges separated by low basins. The Hueco Bolson was filled mainly with fine sand, silt, and clay brought from New Mexico and Colorado by the ancestral Rio Grande in late Pliocene and early Pleistocene time; the Sierra Madre Occidental and local topographic highs were sources of coarser basin-filling detritus (Strain, 1973). The Hueco Bolson lies within the northern Chihuahuan Desert and has a subtropical arid climate (Thornthwaite, 1931, as modified by Larkin and Bomar, 1983) characterized by high mean annual temperatures, marked temperature fluctuations over broad diurnal and annual ranges, low mean annual precipitation, and wide extremes in seasonal and annual precipitation (Orton, 1964).

Major Aquifer Units

Regional structure and stratigraphy are summarized here only as they affect the major aquifers. The oldest strata from which ground water is pumped are Cretaceous

carbonate and clastic rocks of the Finlay, Cox, and Bluff Mesa Formations that underlie bolson sediments and form the Diablo Plateau. Water-bearing units in these strata are grouped together and designated the Diablo Plateau aquifer (Mullican and Senger, 1989). Whether there is one integrated aquifer system in the Cretaceous carbonate rocks or several unconnected or poorly connected carbonate aquifers is not resolved. In this report we group all samples from the Diablo Plateau aquifer because geochemical and hydrologic criteria are inadequate for distinguishing different aquifers or different hydrochemical histories of the ground-water samples.

Cenozoic bolson-fill sediments constitute a second major aquifer unit. Most wells that produce water from the Hueco Bolson silt and sand aquifer (Texas Department of Water Resources, 1984) do so from sand lenses that occur between clays and silty clays. Physical discontinuities are common within the bolson fill both because of the lenticular nature of the sand, silt, and clay deposits, and because the basin fill may be displaced by Basin and Range faults. Hydrologic discontinuities also are expected; however, information is insufficient to allow mapping of separate aquifer units. The bolson fill is therefore considered a single aquifer unit for the purposes of this hydrochemical investigation.

The third major aquifer is in the Quaternary alluvium of the Rio Grande. This Rio Grande alluvial aquifer is probably physically more homogeneous than the other two, but extensive pumping from wells and local recharge during times of high irrigation may result in minor hydrochemical heterogeneities in the ground-water system.

Potentiometric Surface

The regional potentiometric surface map has been constructed on the basis of water-level measurements (fig. 2). The general trend shows high water levels on the

Diablo Plateau that decrease toward the southwest. Ground-water flow as a result of the potentiometric surface configuration should be from the Diablo Plateau toward the Rio Grande. Depths to water in the study area are as great as 590 ft; the water table is nearer land surface on the Plateau and in the Rio Grande alluvium (fig. 3).

INFORMATION SOURCES

Water Samples

Relatively few sources of ground-water samples exist because the study area is semiarid, the water table is deep, and specific yields are low. During 1988 and 1989, ground-water samples were collected from 16 wells and 1 spring. Two of these wells were drilled and completed specifically for this project, and several other abandoned wells were recompleted for hydrologic testing and sample collection. Eleven wells and 1 spring were sampled repeatedly during the 12-month period of investigation, producing a total of 39 water samples. This data base is augmented by 14 samples collected during a previous investigation (Kreitler and others, 1986, 1987) and 3 analyses reported by the Texas Water Development Board and the Texas Department of Water Resources.

Two soil-moisture samplers were installed in each of three wells to collect water from the unsaturated zone. Samplers were placed at depths ranging from 23.5 to 110 ft in strata that were considered most likely to yield water on the basis of stratigraphic information derived from a nearby stratigraphic test borehole that was cored and geophysically logged. The soil-moisture samplers consist of a porous ceramic cup attached to 1.5-inch-diameter, high-temperature PVDC pipe. Two internal check valves are arranged such that the cup could be placed under vacuum to collect water, which could then be driven to the surface under pressure for collection

(Wood, 1973). Prior to installation the ceramic cups were thoroughly acid-cleaned and rinsed with distilled water to remove soluble ions that could contaminate water samples. The ceramic cups were seated in 200-mesh silica flour to ensure good contact between cup and sediment, and a vacuum of 20 inches of mercury was placed on the samplers after installation was complete.

Soil Samples

Soil types in the southeastern Hueco Bolson have been regionally mapped (Texas Agricultural Experiment Station, 1973) and can be correlated with the more detailed descriptions of soils to the northwest in El Paso County (Jaco, 1971). Soil on the Diablo Plateau is described as calcareous, gypsiferous loamy outwash and sediment, whereas soil on the bolson is described as sandy, loamy, alkaline, calcareous wind-laid deposits. Soil developed on the Rio Grande alluvium is described as calcareous loamy to clayey material that supports salt-tolerant grasses, salt cedar, and cottonwood trees. Other studies have found that solutes derived from soils significantly affect the composition of stream (Miller and Drever, 1977) and spring (Smith and Drever, 1976) waters; therefore, soil samples from the Diablo Plateau, the bolson pediment, and the Rio Grande alluvium were collected for chemical and mineralogic characterization as part of this hydrochemical investigation.

METHODS

Ground-Water Samples

Ground-water samples collected from the three principal aquifers (table 1) during the 1988-89 field season were analyzed at the collection site for unstable

constituents and were treated and preserved for laboratory analysis of major, minor and trace inorganic components, selected organic constituents, and stable (^{18}O , D, ^{13}C , and ^{34}S) and cosmogenic (^3H and ^{14}C) isotopic compositions. Complete sampling procedures are described in a Specific Work Instruction prepared for this study (Fisher, 1989); these methods are briefly summarized as follows.

All sample containers and equipment used for field testing of unstable species were thoroughly cleaned and rinsed prior to each sampling trip. At the well site, pH, Eh, and water temperature were measured in a flow cell connected to the well such that the sample was not exposed to the atmosphere. Measurements were monitored until values had stabilized, at which time final values were recorded and the well was considered suitable for sampling. Alkalinity was determined by titration at the well site, and the resulting titration curves were examined to ascertain that carbonate species were the major sources of alkalinity. A 300 mL BOD bottle was rinsed, the sample was added, and all air bubbles were dislodged. The sample was then preserved for determination of dissolved oxygen concentration; this measurement was performed later the same day by titration with sodium thiosulfate.

Aliquots for measurement of major, minor, and trace cations and anions, stable isotopic compositions of oxygen, hydrogen, carbon, and sulfur, tritium activity, dissolved sulfide, total organic carbon, and cyanide were passed through a $0.45\ \mu$ filter and preserved. Three 50 L carboys were filled with sample and 500 ml saturated ammoniacal strontium chloride was added to raise the pH above 11. Later the same day the strontium carbonate precipitate from each carboy was transferred to a 1 quart jar without exposure to the atmosphere. This precipitate was removed, rinsed, and dried in a CO_2 -free atmosphere for subsequent carbon-14 analysis. Chemical analyses were performed at the Bureau of Economic Geology Mineral Studies Laboratory. Tritium activities were determined by the University of Miami

Tritium Laboratory. Stable isotopic compositions and carbon-14 activities were measured at the University of Arizona Laboratory of Isotope Geochemistry. Total organic carbon, dissolved sulfide, and cyanide were analyzed at Core Laboratories, Corpus Christi, Texas.

Samples collected during 1988 and 1989 provide the primary data base for this report. Samples collected during earlier investigations (Kreitler and others, 1986, 1987) or reported by the Texas Water Development Board or the Texas Department of Water Resources lack field measurement of unstable constituents and thus are less complete analyses. However, data from these samples are included in the following discussions because they provide important information from wells that could not be sampled during the recent field investigations.

Soil-Moisture Samples

Water drawn to the samplers under vacuum was forced to sample containers at the surface under moderate air pressure. Because of the pressure changes during collection and sampling and because of the small volumes of water that could be removed from the unsaturated section, only the major and some minor constituents could be analyzed. Despite these limitations, the major species present in soil water are useful in interpreting the origin of deeper ground waters.

Soil Samples

Soils in the study area have a crust that is a fraction of an inch to a few inches thick and is significantly better consolidated than underlying material. Paired

samples of this crust were collected on the Diablo Plateau, on the bolson, and on the Rio Grande alluvium. Each pair from the plateau and the bolson consists of one sample from a topographically high site where rainfall or surface runoff would drain quickly and one from a low site that could function as a drainage path or infiltration area. On the Rio Grande alluvium, one sample was collected from a crop field that had a long history of irrigation, and one sample was taken from an area that had never been cultivated where surface runoff ponded during heavy rainfall or runoff events and subsequently evaporated.

Each of the six samples was homogenized and a 75-gram subsample was placed in a flask with 100 ml distilled water. The soil-water mixture was shaken for 15 minutes, after which the leachate was removed by centrifugation and passed through a 0.45 μ filter. This process was repeated to give extraction times of 15, 240, and 360 minutes. Each leachate solution was analyzed to determine the amount of readily soluble ions that could be removed from surface soil samples.

Core Samples

Five samples of Fort Hancock Formation bolson fill were collected from core at depths of 147 to 537 ft to aid interpretation of the chemical evolution of ground water compositions. Mineralogic composition of the whole-rock sample and of the clay-size fraction was determined by standard X-ray diffraction (XRD) analysis. A representative split of each sample was leached in distilled water, and the leachate was analyzed by standard methods to determine water soluble constituents. Exchangeable cations were displaced into solution from a second split of each sample (Thomas, 1982), and the composition of the exchangeable ion population was

measured to evaluate the amount and composition of exchangeable cations and total cation exchange capacity.

RESULTS

Ground-Water Samples

The chemical composition of ground-water samples is listed in tables 2 and 3; isotopic compositions are shown in table 4. Ten additional trace metals were determined for all samples collected in 1988 and 1989 but are not listed in table 3 because they were found to be at or below detection limits for all samples. These metals and their detection limits in mg/L are Cr (0.03), Cu (0.03), Ni (0.06), As (0.12), Cd (0.03), Pb (0.25), Sn (0.06), Co (0.03), Se (0.28), and Ag (0.0002). The mean charge balance (meq cations/meq anions) for samples collected in 1988 and 1989 is 0.96 ($1\sigma=0.15$) for 38 analyses. Data from previous studies and reported by the Texas Water Development Board or Texas Department of Water Resources are included here because these samples extend the sparse data coverage to areas that could not be resampled. Stable isotope compositions (table 4) are given in parts per thousand ($^{\circ}/_{\infty}$) with respect to the standards SMOW (oxygen and hydrogen), PDB (carbon), and CDT (sulfur). Uncertainties ($^{\circ}/_{\infty}$ 2σ) in stable isotopic data are <2.0 (δD), <0.4 ($\delta^{34}S$), and <0.2 ($\delta^{18}O$ and $\delta^{13}C$). Tritium activity is reported in tritium units (TU: one TU= $^3H/^1H$ ratio of 10^{-18}), with accuracy and precision certified to be 0.1 TU or 3.5%, whichever is larger. Carbon-14 activities are reported as percent modern carbon (pmc, table 4) with analytical uncertainty as listed for each sample.

Many wells and one spring were sampled repeatedly for this investigation. These data permit evaluation of possible changes in water composition over time.

Nine wells were sampled both in 1986 and in 1988-89. Of these, four present valid comparisons of water chemistry over a 2-yr period. Other samples include spring waters that seep into a standing pool (No. 106), water collected from a holding tank because the windmill-driven pump had not been operating for several weeks prior to the 1988 sampling (No. 107), water from a well that had recently been completed and may have not yet been developed sufficiently to remove all drilling fluid (No. 92), and water from an irrigation well that shows large seasonal variations in composition (No. 110). Table 5 summarizes the major ionic compositions of wells sampled in 1986 and again in 1988 or 1989. In most cases, 1986 compositions are slightly lower than 1988-89 compositions. However, the differences are not consistent for all ions and are within the uncertainty expected for separate sampling and analytical runs. This suggests that compositional changes over a 2-yr period are not significant.

Four wells and one spring were sampled quarterly from summer 1988, to spring 1989 (table 6). Comparison of major ionic compositions for these samples shows minor, nonsystematic variation attributable to random errors in sampling and analysis in three of the four samples (No. 97, 108, and 93). Well No. 110, an irrigation well that pumps from Rio Grande alluvium, shows marked compositional changes. These variations are attributed to the effects of irrigation, dissolution of salts on irrigated fields, and soil water evaporation, as discussed in a later section. With this exception, the major ionic compositions of ground waters sampled quarterly for a 1-yr period remain essentially constant, within the resolution of analytical uncertainty. Long-term quarterly monitoring of selected wells and springs may show systematic seasonal variations in ground-water compositions that could provide important information about the regional hydrologic system. Such trends cannot be identified in the available data.

Salinity varies widely within each major aquifer. Mean, minimum, and maximum concentrations of total dissolved solids (TDS) are 1,590, 800, and 2,900 (mg/L) for Diablo Plateau aquifer ground waters; 1,730, 1040, and 3,830 for Bolson aquifer ground waters; and 2,890, 940, and 5,703 for Rio Grande alluvium ground waters, respectively. Total dissolved solids values do not vary systematically either among the principal aquifers or with geographic position (fig. 4). The distribution of hydrochemical facies as determined by predominant cations and anions shows a more regular pattern regardless of salinity. All samples from Rio Grande alluvium have sodium and chloride as the predominant cation and anion, respectively. Most ground water from wells or springs on the bolson pediment or the edge of the Diablo Plateau, whether from bolson or Diablo Plateau aquifers, has sodium and sulfate as the predominant cation and anion, respectively. Samples from the Diablo Plateau aquifer collected from wells away from the edge of the plateau have sodium and bicarbonate as the major cation and anion, respectively. One well from the Diablo Plateau aquifer near the toe of the escarpment produces calcium-sulfate water.

Ionic speciation and mineral saturation states of the ground waters collected in 1988 and 1989 were computed by the geochemical modeling program SOLMNEQ (Kharaka and Barnes, 1973, with revised thermodynamic data provided by Kharaka in 1986). Samples that lacked field pH measurement, that were collected from holding tanks because windmill-driven pumps were not functioning, or that were taken from springs of very low discharge were not included in the SOLMNEQ runs because the water composition was unlikely to represent geochemical conditions in the aquifer. Dissolved Al was set at 10^{-6} molal (0.027 mg/L) because this is the approximate value expected for aluminum concentrations determined by bayerite or gibbsite (polymorphs of $\text{Al}(\text{OH})_3$), the phases most likely to control Al concentrations in shallow siliciclastic sediments at neutral to slightly alkaline conditions (Hem, 1985).

This was necessary so that the saturation of aluminosilicate minerals could be estimated despite the lack of Al analyses. Calculated values for the ionic strength of the water samples range from 0.0155 to 0.1074 molal, corresponding to an activity of water of 0.9997 to 0.9974. These values indicate that the ground waters are sufficiently dilute that SOLMNEQ can accurately compute thermodynamic activities of aqueous species.

Results of the SOLMNEQ program show that all waters are highly oversaturated with common aluminosilicate and silicate minerals because of the high observed dissolved Si concentrations. Total aqueous Si in the ground-water samples ranges up to 17.6 mg/L. In contrast, results of SOLMNEQ simulations show that Hueco Bolson ground water should contain only about 6 mg/L Si at observed temperatures if concentrations were controlled by saturation with quartz, the dominant silicate mineral in alluvium, bolson, and carbonate strata.

Equilibrium between ground water and common carbonate or sulfate minerals was evaluated by computing the appropriate saturation index (SI), equal to the logarithm of the ion activity product minus the logarithm of the dissolution reaction equilibrium constant at sample temperature. A value of zero indicates equilibrium, negative values indicate undersaturation, and positive values indicate oversaturation. Because dissolution and precipitation reaction rates may be slow and because such reactions may have high activation energies, a state of undersaturation or oversaturation does not indicate that a particular mineral is being dissolved or precipitated, respectively. These indices are significant, however, because they show which reactions are not thermodynamically possible. Water oversaturated with a particular phase cannot dissolve that phase, nor can water undersaturated with some phase precipitate that phase. Ground water from the Bolson and Diablo Plateau

aquifers is essentially saturated with calcite and possibly also with dolomite, whereas water from the Rio Grande alluvium is slightly oversaturated with both these minerals. Despite high sulfate concentrations in many of the water samples, none are saturated with gypsum (table 7).

Stable isotopic compositions of oxygen and hydrogen generally cluster between values of -6 to -8 ‰ and -45 to -65 ‰ SMOW, respectively (fig. 5). All samples from the bolson aquifer fall within this range. The most depleted isotopic compositions are found in wells on the Diablo Plateau and in the Rio Grande alluvium, reaching values as low as $\delta^{18}\text{O}$ of about -11 ‰ and δD of -85 ‰, respectively (fig. 6). Values for samples from wells on the bolson pediment are less depleted regardless of host aquifer.

Hueco Bolson ground waters are not in oxygen or hydrogen isotopic equilibrium with common sedimentary minerals. Carbonate minerals typically control oxygen isotopic compositions in ground waters and formation waters. The isotopic composition of local carbonates has not been measured for this study; however, it can be reasonably estimated. The main local source of carbonate is the Cretaceous strata that compose the Diablo Plateau aquifer. Sedimentary carbonates typically have oxygen isotopic compositions that range between 0 and -5 ‰ PDB (31 to 26 ‰ SMOW; Veizer, 1983). O'Neil and others (1969, as revised by Friedman and O'Neil, 1977) show that the equilibrium oxygen isotopic composition of calcite and water is related by the fractionation equation

$$10^3 \ln \alpha = 2.78 \times 10^6 T^{-2} - 2.89, \quad (1)$$

where α is the isotope fractionation factor, T is degrees Kelvin, and $10^3 \ln \alpha$ closely approximates the difference between the isotopic composition of the mineral and water. At 25°C, this equation predicts that water in isotopic equilibrium with calcite of $\delta^{18}\text{O} = 31$ or 26 ‰ SMOW should be 2.6 or -2.4 ‰, respectively. These calculated equilibrium values are much higher than the values observed in Hueco

Bolson ground waters, indicating that the waters have not reacted with calcite sufficiently extensively to attain isotopic equilibrium.

Controls on the hydrogen isotopic composition of ground waters are less well known. Clay minerals are the only significant hydrogen reservoir in the Hueco Bolson, and isotopic relations between water and clay minerals at surface temperatures are relatively well established (Lawrence and Taylor, 1971). Water equilibrated with kaolinite or smectite at surface temperatures in the Hueco Bolson would be expected to have hydrogen and oxygen isotopic compositions of about -50 to -80 ‰ and 15 to 20 ‰ SMOW, respectively, depending on the isotopic composition of local meteoric water. These hydrogen isotopic values are within the range observed in the ground waters, but the absence of such enriched oxygen isotopic compositions confirms that equilibration between water and clay minerals has not occurred.

Soil-Moisture Samples

Sodium and bicarbonate are the major cation and anion, respectively, in all samples (table 8). The few available dissolved silica values are higher than most concentrations observed in either ground-water samples (table 2) or in leachate from soil samples (discussed in the following section). The high silica content of soil-moisture samples may be due in part to dissolution of some silica flour that was used to ensure contact between the ceramic cup of the soil-moisture sampler and the encasing sediment.

Soil Samples

The composition of leachate from the irrigated Rio Grande alluvium sample differs significantly from all other leachate compositions (table 9). Calcium and

bicarbonate are the most abundant leachable ions in all samples except the irrigated Rio Grande alluvium; extremely high amounts of sodium, chloride, and nitrate are readily removed from the irrigated sample. Magnesium, calcium, and sulfate also are much more abundant in leachate from the irrigated Rio Grande sample than in other samples. Dissolved silica is high in all samples and is readily removed from the sediment even after only 15-minute exposure to water.

Core Samples

X-ray diffraction (XRD) patterns indicate that quartz is the predominant silt-sized or larger component of the bolson sediments; calcite is present in minor amounts in some samples, as is potassium feldspar. Although XRD analysis has not identified gypsum as a major or minor phase in the analyzed bolson sediments (Fuentes and others, 1987, 1988; this study), gypsum is common in trace amounts in surface sediments. Gypsum is also observed as discrete beds or as disseminated crystals in both the Fort Hancock and Camp Rice Formations (T. C. Gustavson, personal communication, 1989). The clay-size fraction contains illite, an expandable clay tentatively identified as chlorite/smectite, and kaolinite. The XRD pattern of clay-size material is very complex, indicating that other clay minerals may be present in amounts that cannot be identified in the presence of illite, kaolinite, and expandable clay. Similar results have been reported in previous work (Daniel and Nelson, 1987; Fuentes and others, 1987).

ORIGIN OF SOLUTES

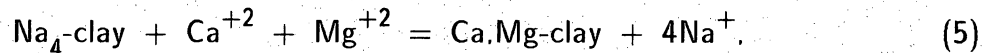
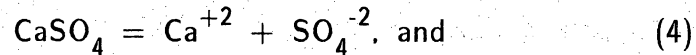
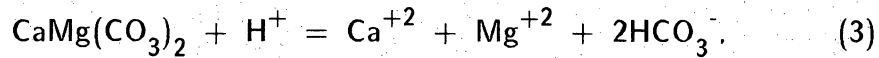
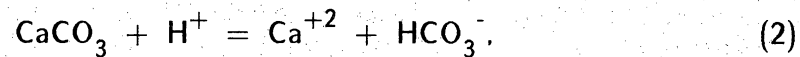
General Trends of Major Solutes

Two major compositional characteristics are common to nearly all ground waters in the Hueco Bolson area. First, most ground waters contain high silica

concentrations that range to 17.6 mg/L Si (table 2), with a mean value of 11.4. In comparison, values for saturation with quartz, cristobolite-A, and amorphous silica computed by SOLMNEQ (Kharaka and Barnes, 1973) are about 3, 8, and 51 mg/L Si, respectively. The high Si concentrations observed in ground-water samples and the ease with which Si is leached from soils (table 9) suggest that silica is derived mainly from amorphous phytoliths that can constitute as much as several percent by weight of grasses and the hardened spines that typify arid-climate vegetation (Iler, 1979).

A second common characteristic is that all water samples except those from the Rio Grande alluvium show an excess of sodium relative to chloride (fig. 7). Sodium and chloride are generally considered to be the most mobile cation and anion, respectively, in ground water; once released from minerals, they are most likely to remain in solution. A sodium/chloride molal ratio approximately equal to unity is usually attributed to halite dissolution, whereas a ratio greater than unity is typically interpreted as reflecting sodium addition from silicate weathering reactions (e.g., Mackenzie and Garrels, 1966; Meybeck, 1987). This explanation does not appear valid for Hueco Bolson ground water because (1) waters that derive solutes by silicate weathering reactions have bicarbonate as the most abundant anion, whereas bicarbonate is of secondary importance in all but one sample analyzed in this study, (2) water involved in typical silicate weathering reactions should have silica concentrations controlled by saturation with kaolinite or other clay minerals, if not by quartz (Mackenzie and Garrels, 1966), whereas all of the ground-water samples analyzed in this study are highly oversaturated with respect to all common clay minerals, and (3) very few unstable silicate minerals that would be subject to weathering reactions have been identified in surface sediments or bolson fill.

A third shared characteristic of water samples from the Bolson and Diablo Plateau aquifers and from the unsaturated zone is a strong correlation between dissolved sodium and sulfate (fig. 8). The excess of molal sodium over chloride, even though silicate weathering reactions seem unimportant in controlling water compositions, and the proportionality between sodium and sulfate suggest that dissolution of gypsum and exchange of aqueous divalent cations for sodium on clay minerals is the most likely explanation for the abundance of sodium and sulfate in most Hueco Bolson ground waters. Plausible reactions include



where $\text{Na}_4\text{-clay}$ and Ca,Mg-clay represent a clay mineral that has four ion exchange sites filled by either four Na^+ ions or by Ca^{+2} and Mg^{+2} . The equilibrium constant for reaction (5) has the form

$$K = \frac{(\alpha\text{Na}^+)^4(\alpha\text{Ca-Mg-clay})}{(\alpha\text{Ca}^{+2})(\alpha\text{Mg}^{+2})(\alpha\text{Na}_4\text{-clay})} \quad (6)$$

where α denotes the thermodynamic activity of each species. As calcium concentrations increase because of calcite, dolomite, and gypsum dissolution, ion exchange reactions proceed between aqueous species and exchangeable ions on clay mineral surfaces. According to equation (6), as divalent cations are added to solution by mineral dissolution, the number of exchange sites occupied by sodium must decrease and the number of exchange sites occupied by divalent cations must increase. No anions are added to solution as a result of cation exchange; therefore the total positive charge of the solution remains constant. With increasing ion exchange driven by increasing gypsum or carbonate dissolution, therefore, the sum $(2m\text{Na}^+ + m\text{Ca}^{+2} + m\text{Mg}^{+2})$ must increase proportionately. This relation accounts very

well for the relations between calcium, magnesium, sodium, sulfate, and carbonate alkalinity in water from the Diablo Plateau and Bolson aquifers; it also accounts for the major ionic compositions in water from the unsaturated zone (fig. 9).

Characteristics Unique to Rio Grande Alluvium Ground Waters

Major compositional differences between ground-water samples from the Rio Grande alluvium and water from the unsaturated zone, Bolson and Diablo Plateau aquifers must be understood in terms of the history of the Rio Grande and Upper Rio Grande Valley. A predominance of sodium and chloride over other cations and anions, respectively, is the most obvious difference between ground water from the Rio Grande alluvial aquifer and other ground waters in the Hueco Bolson (fig. 4). Rio Grande ground waters also have the highest mean concentrations of magnesium, calcium, and potassium. Furthermore, there is a deficiency of molal sodium relative to chloride in many Rio Grande samples (fig. 7), indicating that halite is not the sole contributor of chloride to Rio Grande ground water.

Intensive irrigation in the Upper Rio Grande Basin (north of Fort Quitman, Texas) began in the early 1880's; prior to that time the Pueblo Indians irrigated crops even before Spanish explorers came to the region. Post-1880 irrigation, combined with a series of droughts in the 1940's and 1950's, resulted in serious degradation of river quality and deposition of large quantities of salts in irrigated fields (e.g., Young, 1981). Irrigation water becomes concentrated on fields and in the shallow subsurface by evaporation. The resulting saline water eventually returns to the shallow alluvial aquifer or to the river, where it is subsequently used to irrigate fields downstream. As consequences of heavy irrigation, the Rio Grande has high

sodium, chloride, and TDS concentrations (No. 105, table 2), and large amount of salts are precipitated on irrigated fields. For example, Young (1981) estimated that approximately 10 tons of salt per acre were applied in the Lower El Paso Valley and Hudspeth Valley in 1955. These salts are readily soluble and can contribute significant amounts of sodium, calcium, magnesium, chloride, and sulfate (irrigated Rio Grande alluvium sample, table 9) when excess irrigation percolates below the root zone and recharges the aquifer.

One soil sample from an irrigated field does not adequately represent the amount and composition of Rio Grande irrigation salts, nor does the leaching experiment we performed necessarily simulate the derivation of solutes from shallow sediments by recharge to the Rio Grande alluvial aquifer. Nevertheless, leachate from the soil sample shares many compositional characteristics with Rio Grande ground water. Leachate from the irrigated Rio Grande sediment sample has sodium and chloride as the dominant cation and anion, respectively, whereas all other soil leachates have calcium and bicarbonate as the dominant ions (table 9). Irrigated and nonirrigated Rio Grande soils also have higher leachable concentrations of potassium, magnesium, and sulfate than any other surface sediments.

Minor and Trace Solutes

Saturation states of minerals that commonly limit concentrations of minor and trace species were computed using the SOLMNEQ code (Kharaka and Barnes, 1973). None of the ground waters are saturated with celestite, the mineral that typically controls strontium concentrations in natural waters (Hem, 1985). Fluorite is at or near saturation in 13 ground waters, principally those from the Diablo Plateau aquifer; all ground waters sampled are saturated with barite. Fluorite and barite solubility probably control fluoride and barium concentrations in most ground-water

samples, although the presence of fluorite and barite has not been confirmed in the few sediment samples examined. Concentrations of other minor and trace elements (table 3) are apparently not limited by mineral-water equilibrium.

AGE OF GROUND WATER

Background

Under favorable conditions the age of ground water can be determined from the activities of the cosmogenic isotopes tritium (^3H) and carbon-14 (^{14}C) (summarized by Gat, 1980, and Mook, 1980). Both tritium and carbon-14 are produced by the interaction of cosmic-ray neutrons with atmospheric nitrogen; however, ages based on the radioactive decay of carbon-14 and tritium in ground water do not necessarily record the same time interval. Tritium is rapidly incorporated into water molecules and removed from the atmosphere as precipitation. Tritium ages therefore reflect length of time since a water sample was last in open communication with the atmosphere. Cosmogenic carbon-14 enters the carbon cycle as carbon dioxide, which is subsequently incorporated in organic matter, carbonate minerals, and aqueous carbonate species. Carbon-14 ages therefore reflect the time since ground water was last free to exchange carbon isotopes between water and atmospheric or soil gas carbon dioxide.

The short half-life of tritium (12.26 yr) should make this an ideal isotope for tracer studies and age determinations of water that was removed from contact with the atmosphere less than about 75 yr ago. However, two major problems exist. The first is that the tritium content of atmospheric water vapor and precipitation varies regionally and seasonally, so it is difficult to determine the initial activity of tritium in recharge. The second is that massive amounts of tritium were produced during

atmospheric testing of nuclear bombs in the 1950's to mid-1960's. Atmospheric tritium levels exceeding 2,200 TU were reported in the northern hemisphere in 1964. Although approximately 2 tritium half-lives have passed since atmospheric testing of nuclear devices ended, levels as high as several hundred TU could still remain in some ground waters. Post-nuclear testing activities of atmospheric tritium are probably on the order of about 25 TU, but local variations are not well documented. Small amounts of tritium can be produced by natural subsurface processes, so values in the range 0.05 to 0.5 TU are possible in water that is very old.

The half-life of carbon-14 is 5,730 yr, making it suitable for resolving ages of about 35,000 yr or less. In ground-water investigations, however, other sources and sinks of carbon must be evaluated before ages can be estimated from carbon-14 activity (Pearson and White, 1967; Pearson and Hanshaw, 1970; Wigley, 1975; Wigley and others, 1978). First, the initial carbon-14 activity must be determined. Usually this is taken to be the carbon-14 activity of soil gas at the location and time of recharge. Second, a correction must be made to account for the fact that natural waters commonly derive older carbon that contains no carbon-14 from dissolution of carbonate minerals. Third, if carbonate minerals are precipitated from ground water, some carbon-14 will be removed from solution to the solid phase.

For the simple case where recharge acquires carbon-14 from CO₂ in soil gas and also dissolves carbonate minerals that contain no carbon-14, the standard equation for calculating age from percent modern carbon is

$$\text{years} = \frac{5,730}{\ln 2} \ln \frac{^{14}\text{C (pmc)}}{100(\delta^{13}\text{C}_{\text{water}}/\delta^{13}\text{C}_{\text{recharge}})} \quad (7)$$

(Pearson and White, 1967). Values of ¹⁴C pmc and δ¹³_{water} for Hueco Bolson ground waters are given in table 4. A value of -17 ‰ PDB for δ¹³_{recharge} was

chosen to represent soil gas in arid west Texas (Rightmire, 1967). Computed carbon-14 ages are given in table 4.

Such ages are sensitive to the value used for $\delta^{13}\text{C}_{\text{recharge}}$, which in turn depends chiefly on the type of vegetation present in the recharge area, the percent of land surface covered by vegetation, and the mean annual temperature at the time of recharge. The value of -17 ‰ was chosen for age calculations because Rightmire (1967) found that the $\delta^{13}\text{C}$ value of soil carbon dioxide in west Texas ranged from -15 to -19 ‰ with a mean value of -17 ‰. Values for $\delta^{13}\text{C}_{\text{recharge}}$ in other arid terrains range from about -16 to -19 ‰ (Rightmire and Hanshaw, 1973; Parada and others, 1983). In other areas and climates, $\delta^{13}\text{C}_{\text{recharge}}$ may be as low as -25 ‰ (Pearson and White, 1967). To evaluate the effect of the assumed $\delta^{13}\text{C}_{\text{recharge}}$ value on calculated Hueco Bolson ground-water carbon-14 ages, we repeated the calculation for samples that have low and high pmc values using measured pmc and $\delta^{13}\text{C}_{\text{water}}$ values and setting $\delta^{13}\text{C}_{\text{recharge}}$ equal to -16 and -19 rather than -17 ‰. Ground water sample No. 97 (pmc=5.97, $\delta^{13}\text{C}_{\text{water}} = -4.36$ ‰) gives ages of 12,550, 12,050, and 11,130 yr for $\delta^{13}\text{C}_{\text{recharge}} = -16, -17, \text{ and } -19$ ‰ respectively. Ground water sample No. 92 (pmc=87.64, $\delta^{13}\text{C}_{\text{water}} = -9.41$ ‰) gives ages of 3,297, 3,799, and 4,717 yr for $\delta^{13}\text{C}_{\text{recharge}} = -16, -17, \text{ and } -19$ ‰ respectively. Therefore the uncertainty in the value of $\delta^{13}\text{C}_{\text{water}}$ affects the age estimates of table 4 by less than approximately 1,000 yr.

Equation (7) is based on the assumption that the isotopic composition of recharge water can be adequately represented by a single value and that soil gas and mineral carbonate are the sole sources of dissolved carbon in ground water. The validity of these assumptions can be evaluated by testing the mass balance relation between the concentration and isotopic composition of dissolved carbonate (Pearson and White, 1967). If ground-water samples meet the criteria for application of

equation (7), a plot of the logarithm of total dissolved carbonate versus the logarithm of $(\delta^{13}\text{C}_{\text{water}}/\delta^{13}\text{C}_{\text{recharge}})$ should define a straight line. With the exception of samples from the irrigation well (No. 110), Hueco Bolson ground water samples (fig. 10) generally fall along a linear trend. The width of the linear data band suggests that the true value of $\delta^{13}\text{C}_{\text{recharge}}$ varies from -17 to nearly -25 ‰ for some samples. Nevertheless, the linear trend of the plotted data strongly suggests that dissolved carbonate is a two-component mixture of mineral and soil carbon of variable isotopic composition; therefore it is valid to apply equation (7) to these samples.

Incongruent dissolution is a third factor that can affect carbon-14 ages of ground water (Wigley and others, 1978). As previously discussed, recharge in the Hueco Bolson rapidly dissolves calcite and/or dolomite to saturation. Subsequent dissolution of gypsum raises the concentration and thermodynamic activity of calcium in ground water, some of which is removed by ion exchange and some of which may be removed by precipitation of carbonate minerals. If carbonate precipitation occurs, some carbon-14 also will be removed, thus reducing the carbon-14 activity of ground water and yielding an apparent age that is greater than the age of the water. These effects are thought to be insignificant but cannot be quantitatively evaluated for Hueco Bolson ground water.

Age of Hueco Bolson ground water

Data from Hueco Bolson ground waters generally show the expected inverse relation between tritium activity and carbon-14 age (fig. 11). However, some Rio Grande ground waters have nearly 22 TU and carbon-14 ages of about 4,500 yr (367 tritium half-lives), and one sample from the Bolson aquifer contains about 3 TU and

has a calculated carbon-14 age of nearly 29,000 yr (over 2,300 tritium half-lives). Clearly the two types of data are not recording the same time interval in all samples.

Comparison of tritium and carbon-14 isotopic activities in ground water samples suggests that young, old, and mixed water is present in the Hueco Bolson. Young water is characterized by high tritium activity and low carbon-14 ages, old water is characterized by low tritium activity and high carbon-14 age values, and mixed water has derived tritium and carbon-14 from different sources, as demonstrated by high tritium content and high carbon-14 age in the same water sample.

Ground water that contains more than about 1 TU is considered young. As previously discussed, TU values less than one can be maintained by natural geologic processes; therefore, tritium activities less than unity are not valid age indicators. A reasonable estimate of ambient tritium activity is provided by analyses of sample 105 (Rio Grande) and well 110 (Rio Grande irrigation well). Tritium activities for these samples range to 27 TU (table 4), with a mean value of 20.5. If the highest measured tritium activity (27 TU for Rio Grande irrigation well 110; table 4) is assumed to represent modern ambient recharge, 5 half-lives or approximately 60 yr are sufficient to reduce ground water tritium activity to less than 1TU. Carbon-14 ages of a few thousand years are possible for these samples because of the uncertainty in $\delta^{13}\text{C}_{\text{recharge}}$. Therefore, samples that contain more than about one TU and that have carbon-14 ages less than a few thousand years (fig. 11) represent relatively recent recharge. Such water is found in the Diablo Plateau aquifer at wells on the Diablo Plateau and near the toe of the escarpment (fig. 12).

Ground water that contains less than 1 TU and has a carbon-14 age in excess of several thousand years is considered old. In most samples the carbonate concentration and carbon isotopic compositions suggest that application of equation

(7) is justified (fig. 10), therefore the carbon-14 age probably gives a representative age for such ground waters within the uncertainty that results from not knowing the precise value of $\delta^{13}\text{C}_{\text{recharge}}$ for each sample. This type of ground water occurs in the Diablo Plateau aquifer in wells on the plateau and on the bolson pediment, in the Bolson silt and sand aquifer, and issues from a spring at the base of the plateau escarpment (fig. 12).

High tritium activities and carbon-14 ages of several thousand years in Rio Grande ground water is readily explained as reflecting a mixture of (1) ground-water that has been isolated from the atmosphere for several hundred to several thousand years, and (2) water that was rapidly recharged during times of high irrigation or high seasonal rainfall. Type (1) water would have no detectable tritium and could contain significant amounts of carbonate derived from both soil gas and dissolution of carbonate minerals. Type (2) water would have high tritium activity and could contain very little dissolved carbonate if it passed quickly through the unsaturated zone, and if most readily soluble carbonate phases had been removed from the unsaturated zone earlier in the recharge episode. The result of mixing types (1) and (2) would be a ground water in which the carbonate isotopic system reflected the age of type (1) water but the tritium activity reflected the time since type (2) water was in isotopic communication with the atmosphere. An age of 500 to 600 yr seems reasonable for sample 93 (fig. 12) on the basis of both tritium and carbon-14 compositions. Sample 126 from the Bolson aquifer has the oldest calculated carbon-14 age but also contains approximately 3 TU (fig. 12 and table 4). This well was sampled shortly after completion, and appears to show effects similar to the Rio Grande irrigation wells. The carbon isotopic system indicates that the water is very old; however, tritium data suggest a young water. It is likely that the true age of the ground water is accurately represented by the carbon isotopic data, whereas high

tritium activity reflects the presence of some water that was used in drilling and completing the well. Subsequent samples from this well contained less than 0.3 TU; however, results of carbon-14 analyses for samples collected in 1989 have not yet been reported.

The regional distribution of tritium and carbon-14 values (fig. 12) shows general features that are consistent with the distribution of hydrochemical (fig. 4) and hydrologic characteristics. Ground water from the Rio Grande alluvial aquifer generally contains a high percent of modern carbon-14 and high tritium activities. These data are consistent with water compositions that would result from mixing old ground water (recharged prior to extensive irrigation and containing relatively high carbonate concentrations, old carbon-14, and negligible tritium) and recent recharge (representing either irrigation water or high seasonal rainfall, containing modern carbon-14 but low total dissolved carbonate, and having high tritium activity).

Ground water from wells on the Diablo Plateau contains about 6 to 43 percent modern carbon and 0.07 to 21.9 TU (table 4). Conditions for valid application of equation (7) appear to be met; however, contradictions between tritium activities and carbon-14 ages exist for water from wells 96 and 112 (fig. 12). Waters from these two wells apparently represent mixed carbon and tritium sources. Such mixing is likely in carbonate terrain where recharge along fractures can allow young water to quickly reach the water table and mix with older water of the regional flow system. Other wells yield water that contains negligible tritium and has carbon-14 ages of several thousand years. Carbon-14 ages probably reflect the true age of these ground waters.

One spring (No. 106) and one well (No. 114) produce water from the Diablo Plateau aquifer at the toe of the escarpment (fig. 12). Water from the spring must

be collected from a standing pool because of the very low discharge rate; therefore, exchange of both hydrogen and carbon with the atmosphere is likely. On the basis of the lowest tritium activity measured, spring water must be at least more than 60 yr old. Well 114 is located near the toe of the fault-bounded escarpment and contains tritium and carbon-14 activities that do not yield consistent age estimates. Contamination of ground water by recent recharge along the fault plane is likely because of the position and shallow depth of the well (approximately 100 ft). The calculated carbon-14 age probably reflects the maximum possible age of this water. As previously discussed, this is the only water that does not have sodium as the most abundant cation, probably because ion exchange has been less significant in the hydrochemical evolution of this sample.

Wells on the bolson pediment sample both Diablo Plateau and Bolson aquifers. Calculated carbon-14 ages of a few thousand to nearly 28,000 yr probably represent the true age of ground water for all but one sample. The single case of conflicting isotopic activities (No. 113, fig 12) occurs in a well near the escarpment base and probably reflects mixing of old water that has traveled within the Diablo Plateau aquifer and more recent recharge that moved vertically down from the surface with little interaction between water and bolson sediments or aquifer matrix.

SUMMARY

The major solute chemistry of Hueco Bolson ground water is generally not controlled by solution-mineral equilibrium but rather by reactions such as mineral dissolution and ion exchange whose progress rates are not limited by precipitation kinetics. Calcium and bicarbonate levels reflect dissolution of calcite and perhaps dolomite until saturation is reached. Gypsum is also dissolved, but gypsum is

apparently not present in sufficient quantities for saturation to be achieved.

Dissolution of carbonate minerals and gypsum raises the divalent cation concentration in ground-water and soil-water samples, which drives exchange of aqueous divalent cations for sodium on ion exchange sites. This coupled process results in water compositions dominated by sodium and sulfate in most samples from the Bolson and Diablo Plateau aquifers. Diablo Plateau ground waters that have bicarbonate as the most abundant anion occur only from wells on the Plateau. These waters have dissolved less gypsum relative to calcite than waters that have sulfate as the most abundant anion. The single ground-water sample from the Diablo Plateau aquifer that has calcium as the most abundant cation (No. 114) occurs at the base of the plateau escarpment. This water differs from other Diablo Plateau ground waters in that it has encountered little clay or other phases with ion exchange capacity.

Supporting evidence for this interpretation is that this sample has a low potassium content; potassium may be exchanged from clays but much less readily than sodium. The water from this well is also relatively young, suggesting that a number of pore volumes of water sufficient to saturate all ion exchange sites may have passed since the flow path was established.

The major solute characteristics of Hueco Bolson ground waters are apparently established early in the flow history, largely by processes that occur at the sediment surface. Evidence to support this conclusion includes the observation that the composition of soil leachate and soil-moisture samples fall on the same compositional evolution trends as Diablo Plateau and Bolson ground water. Soil leachate contains the same major species as Bolson and Diablo Plateau ground water, but in proportions that reflect simple dissolution without ion exchange. Soil-moisture samples from bolson sediments well above the water table show the same major solutes as soil leachate and ground waters from the Bolson and Diablo Plateau aquifers and

also show evidence that ion exchange of sodium on clay for calcium and magnesium in solution has occurred. The fact that ground-water samples from carbonate strata sampled at wells on the Diablo Plateau where soil thickness ranges from zero to only a few tens of feet is compositionally similar to soil moisture and ground waters from bolson siliciclastic strata is further evidence that geochemical processes in the vadose zone establish the major features of ground-water chemistry.

Ground water in the Rio Grande alluvial aquifer also apparently derives most major solutes from dissolution of salts at the sediment surface. Alluvium from an irrigated field readily yields high concentrations of sodium and chloride, the most abundant solutes in Rio Grande ground water. Potassium, magnesium, calcium, silica, sulfate, and nitrate also are readily available in irrigated surface sediments.

Ground-water ages estimated from tritium and carbon-14 activities range from modern for most Rio Grande ground waters to nearly 28,000 yr. Water less than 1,000 yrs old is found along the Rio Grande, in wells on the Diablo Plateau, and in wells and springs near the toe of the plateau escarpment. The three oldest waters (approximately 14,500 to 28,000 carbon-14 yrs) are produced from wells on the bolson pediment from both the Bolson and Diablo Plateau aquifers. Age distributions for Diablo Plateau or Bolson aquifer waters do not vary systematically along the potentiometric gradient, suggesting that both Bolson and Diablo Plateau aquifers have very heterogeneous hydrologic properties.

ACKNOWLEDGMENTS

Funding for this research was provided by the Texas Low-Level Radioactive Waste Disposal Authority under contract no. IAC (88-89)-0932. The conclusions

presented in this report are not necessarily endorsed or approved by the Authority.

This investigation could not have been completed without the kind help of many residents of Hudspeth County. In particular we express our appreciation to Mr. and Mrs. Scott Wilkey, Mr. and Mrs. Dennis Walker, Mr. E. Franklin, and Mr. J. Gavin. We also sincerely thank Doug Ratcliff for purchasing and outfitting the Bureau of Economic Geology field vehicle for hydrologic and hydrochemical studies. Bernd Richter provided unpublished chemical analyses of soil-moisture samples. Alan Dutton and Tucker Hentz reviewed and improved early versions of this report. Figures were drafted under the direction of Richard L. Dillon. Report preparation was by Stephen Fisher and Melissa Snell and report assembly was by Jamie S. Haynes.

REFERENCES

- Craig, H., 1961. Isotopic variations in meteoric waters. *Science*, v. 133, p. 1702-1703.
- Daniel, D. E., and Nelson, P. P., 1987. Engineering properties of soils at a site in Hudspeth County, Texas: A report for the Texas Low-Level Radioactive Waste Disposal Authority, Austin, Texas. 42 p.
- Fisher, R. S., 1988. Collection, determination of unstable properties, and field treatment of water samples for isotopic and ionic analyses: The University of Texas at Austin, Bureau of Economic Geology Specific Work Instruction 3.1, 13 p.
- Friedman, I., and O'Neil, J. R., 1977. Compilation of stable isotope fractionation factors of geochemical interest: U.S. Geological Survey Professional Paper 440-KK, 12 p.
- Fuentes, H. R., Picornell, M., McClure, J. C., Lopez, G. M., and Polzer, W. L., 1987. Exploratory characterization of unsaturated zone samples from the primary study area in Hudspeth County, Texas: A report for the Texas Low-Level Radioactive Waste Disposal Authority, Austin, Texas. 136 p.
- Fuentes, H. R., Picornell, M., Gutierrez, M., Hill, K. W., and Wilkinson, M., 1988. Physicochemical characterization of older bolson samples from the primary study area in Hudspeth County, Texas: A report for the Texas Low-Level Radioactive Waste Disposal Authority, Austin, Texas. 101 p.
- Gat, J. R., 1980. The isotopes of hydrogen and oxygen in precipitation: in Fritz, P., and Fontes, J. Ch., *Handbook of Environmental Isotope Geochemistry*, volume 1: The Terrestrial Environment, A, p. 21-47.
- Hem, J. D., 1985. Study and interpretation of the chemical characteristics of natural water: U. S. Geological Survey Water-Supply Paper 2254, third edition, 263 p.
- Henry, C. D., and Price, J. G., 1985. Summary of the tectonic development of Trans-Pecos Texas: The University of Texas at Austin, Bureau of Economic Geology, Miscellaneous Map No. 36, 8 p.
- Iler, R. K., 1979. The chemistry of silica. solubility, polymerization, colloidal and surface properties, and biochemistry: New York, John Wiley and Sons, 866 p.
- Jaco, H. B., 1971. Soil survey of El Paso County, Texas: U.S. Department of Agriculture, Soil Conservation Service, 59 p.
- Kharaka, Y. K., and Barnes, I., 1973. SOLMNEQ: Solution-mineral equilibrium computations: National Technical Information Service, Publication PB 215 899, 81 p.
- Kreitler, C. W., Raney, J. A., Nativ, R., Collins, E. W., Mullican, W. F. III, Gustavson, T. C., and Henry, C. D., 1986. Final report for the Low-Level Radioactive Waste Disposal Authority: Preliminary geologic and hydrologic studies

of selected areas in Culberson and Hudspeth Counties, Texas: The University of Texas at Austin, Bureau of Economic Geology, 184 p.

- Kreitler, C. W., Raney, J. A., Nativ, R., Collins, E. W., Mullican, W. F. III, Gustavson, T. C., and Henry, C. D., 1987, Siting a low-level radioactive waste disposal facility in Texas, volume four-geologic and hydrologic investigations of State of Texas and University of Texas lands: The University of Texas at Austin, Bureau of Economic Geology, report prepared for the Texas Low-Level Radioactive Waste Disposal Authority under contract no. IAC (86-87)-1790, 330 p.
- Larkin, T. J., and Bomar, G. W., 1983, Climatic atlas of Texas: Texas Department of Water Resources Publication LP-192, 151 p.
- Lawrence, J. R., and Taylor, H. P., 1971, Deuterium and oxygen-18 correlation: clay minerals and hydroxides in Quaternary soils compared to meteoric waters: *Geochimica et Cosmochimica Acta*, v. 35, p. 993-1003.
- Mackenzie, F. T., and Garrels, R. M., 1966, Chemical mass balance between rivers and oceans: *American Journal of Science*, v. 264, p. 507-525.
- Meybeck, M., 1987, Global chemical weathering of surficial rocks estimated from river dissolved loads: *American Journal of Science*, v. 287, p. 401-428.
- Miller, W. R., and Drever, J. I., 1977, Water chemistry of a stream following a storm, Absoraka Mountains, Wyoming: *Geological Society of America Bulletin*, v. 88, p. 286-290.
- Mook, W. G., 1980, Carbon-14 in hydrogeological studies, in Fritz, P., and Fontes, J. Ch., *Handbook of Environmental Isotope Geochemistry*, volume 1: The Terrestrial Environment, A, p. 49-74.
- Mullican, W. F. III, and Senger, R. K., 1989, Hydrologic investigations of the saturated zone in south-central Hudspeth County, Texas. The University of Texas at Austin, Bureau of Economic Geology contract report to the Texas Low-Level Radioactive Waste Disposal Authority.
- O'Neil, J. R., Clayton, R. N., and Mayeda, T. K., 1969, Oxygen isotope fractionation in divalent metal carbonates: *Journal of Chemical Physics*, v. 51, p. 5547-5558.
- Orton, R. B., 1964, *Climates of the states - Texas*: Washington, D.C., U.S. Department of Commerce, Environmental Data Center, *Climatology of the United States* No. 60-41, 46 p.
- Parada, C. B., Long, A., and Davis, S. N., 1983, Stable isotopic composition of soil carbon dioxide in the Tucson Basin, Arizona, U. S. A: *Isotope Geoscience*, v. 1, p. 219-236.
- Pearson, F. J., Jr., and White, D. E., 1967, Carbon-14 ages and flow rates of water in Carrizo Sands, Atascosa County, Texas: *Water Resources Research*, v. 3, p. 251-261.

- Pearson, F. J., Jr., and Hanshaw, B. B., 1970, Sources of dissolved carbonate species in groundwater and their effects on carbon-14 dating, in *Isotope Hydrology*: IAEA, Vienna, p. 271-286.
- Rightmire, C. T., 1967, A radiocarbon study of the age and origin of calcrete deposits: The University of Texas at Austin, Master's thesis.
- Rightmire, C. T., and Hanshaw, B. B., 1973, Relationships between the carbon isotope composition of soil CO₂ and dissolved carbonate species in groundwater: *Water Resources Research*, v. 9, p. 958-967.
- Smith, C. L., and Drever, J. I., 1976, Controls on the chemistry of springs at Teels Marsh, Mineral County, Nevada: *Geochimica et Cosmochimica Acta*, v. 40, p. 1081-1093.
- Strain, W. S., 1973, Late Cenozoic bolson integration in the Chihuahua Tectonic Belt, in Seewald, K., and Sundeen, D., (eds.), *Geologic Framework of the Chihuahua Tectonic Belt: West Texas Geological Society Publication 71-59*, p. 167-173.
- Texas Agricultural Experiment Station, 1973, General soil map of Texas: Texas A&M University, Department of Agricultural Communications.
- Texas Department of Water Resources, 1984, Water for Texas-a comprehensive plan for the future: Austin, Texas Department of Water Resources, GP-4-1, v. 1, 72 p.
- Thomas, G. W., 1982, Exchangeable cations, in Page, A. L. (ed.), *Methods of Soil Analysis, Part 2: Chemical and microbiological properties*, second edition: Madison, Wisconsin, American Society of Agronomy, Inc., and Soil Science Society of America, Inc., p. 159-166.
- Thorntwaite, C. W., 1931, The climates of North America according to a new classification: *Geographical Review*, v. 21, p. 633-655.
- Veizer, J., 1983, Trace elements and isotopes in sedimentary carbonates, in Reeder, R. J. (ed), *Carbonates: mineralogy and chemistry*, Mineralogical Society of America *Reviews in Mineralogy* v. 11, p. 265-300.
- Wigley, T. M. L., 1975, Carbon-14 dating of groundwater from closed and open systems: *Water Resources Research*, v. 11, p. 324-328.
- Wigley, T. M. L., Plummer, L. N., and Pearson, F. J., Jr., 1978, Mass transfer and carbon isotope evolution in natural water systems: *Geochimica et Cosmochimica Acta*, v. 42, p. 1117-1139.
- Wood, W. W., 1973, A technique using porous cups for water sampling at and depth in the unsaturated zone: *Water Resources Research*, v. 9, p. 486-488.
- Young, P. W., 1981, Evaluation of surface and ground irrigation water: The Lower El Paso Valley emphasizing Hudspeth County, Texas: Report to the West Texas Council of Governments, 219 p.

FIGURE CAPTIONS

Figure 1. Location map showing major geographic features of the southeastern Hueco Bolson, well locations and identification numbers, and ground-surface elevations.

Figure 2. Map of the potentiometric surface as determined from water-level measurements (after Mullican and Senger, 1989). The closed potentiometric high on the Diablo Plateau is interpreted on the basis of water-level measurements to the north, northeast, and east that are not shown on this map.

Figure 3. Hydrologic cross section showing vertical relations between Diablo Plateau and Bolson aquifers and depth to water (after Mullican and Senger, 1989).

Figure 4. Map showing distribution of total dissolved solids concentrations and distribution of predominant cation and anion in ground-water samples.

Figure 5. Plot of $\delta^{18}\text{O}$ versus δD , Hueco Bolson ground waters. Solid line is the global meteoric water line (Craig, 1961).

Figure 6. Map showing distribution of $\delta^{18}\text{O}$ and δD in Hueco Bolson ground waters.

Figure 7. Plot of Na^+ versus Cl^- in Hueco Bolson ground waters, soil-moisture samples, and soil leachates.

Figure 8. Plot of $\text{Na}^+ - \text{Cl}^-$ versus SO_4^{+2} in Hueco Bolson ground waters, soil-moisture samples, and soil leachates.

Figure 9. Plot of $2\text{Na}^+ + \text{Ca}^{+2} + \text{Mg}^{+2}$ versus SO_4^{+2} in ground waters, soil-moisture samples, and soil leachates.

Figure 10. Plot of log alkalinity versus $\log (\delta^{13}\text{C}_{\text{water}} / -17)$.

Figure 11. Plot of tritium activity versus carbon-14 age in ground-water samples.

Figure 12. Map showing distribution of tritium activities and carbon-14 ages in ground-water samples.

Table 1. List of ground-water samples by aquifer.

Aquifer	BEG well identification
Diablo Plateau	22, 91, 95, 96, 97, 106, 112, 113, 114, 115, 116
Bolson	98, 99, 107, 108, 111, 126
Rio Grande	92, 93, 109, 110

Table 2. Field and laboratory measurements of major ions (mg/L), pH, Eh, and temperature in ground-water samples.

BEG ID	TWC ID	Date	T (°C)	Field pH	Lab pH	Eh (mv)	Dissolved Oxygen	Na	Mg	Ca	K	Si	Field Alkalinity	Lab Alkalinity	Cl	SO ₄	NO ₃	TDS
22	48-35-4	10/5/88	NA	NA	7.49	NA	NA	805	13.6	73.7	6.8	6.4	NA	72	456	1210	23.9	2653
22	48-35-4	3/16/89	25.0	8.25	7.54	30	3.00	784	16.0	100.0	5.7	7.2	54	64	461	1360	10.9	2806
22	48-35-4	4/24/89	20.0	7.85	7.69	240	4.70	820	16.0	103.0	5.2	7.5	56	56	473	1410	7.6	2901
91	48-43-1	4/28/89	32.0	7.60	8.14	290	3.60	234	12.4	32.9	3.0	7.7	290	311	71	270	4.4	949
95	48-36-3	6/30/88	20.0	7.60	8.15	NA	NA	166	26.9	62.6	3.0	7.9	344	336	88	230	32.7	927
96	48-36-2	6/30/88	27.0	7.40	8.18	NA	NA	221	28.0	64.0	2.6	9.7	336	325	118	300	23.9	1075
97	48-28-7	6/30/88	27.0	7.00	8.09	NA	NA	355	45.1	104.0	4.4	11.1	512	498	173	500	10.8	1698
97	48-28-7	10/6/88	20.0	7.20	8.12	400	5.00	361	49.0	106.0	5.1	11.6	512	379	181	580	7.2	1680
97	48-28-7	1/26/89	14.0	6.70	7.89	NA	3.60	371	52.1	113.0	5.3	11.9	495	497	183	600	0.4	1842
97	48-28-7	5/2/89	21.0	7.06	8.09	300	4.00	363	48.2	106.0	5.0	11.1	488	496	177	602	<0.8	1816
106	48-35-401	1/22/86	9.0	NA	8.61	NA	NA	475	22.9	26.8	4.6	NA	NA	501	148	520	11.3	1718
106	48-35-401	6/29/88	26.0	8.50	8.59	NA	NA	411	19.8	34.7	3.8	7.4	466	454	117	530	17.3	1584
106	48-35-401	10/5/88	23.0	8.30	8.63	NA	NA	562	25.6	28.2	11.4	8.7	701	579	158	680	10.3	2061
106	48-35-401	1/26/89	11.5	8.15	8.28	NA	6.60	535	28.3	37.2	5.3	10.1	561	510	147	720	4.6	2004
106	48-35-401	5/3/89	12.0	8.70	8.11	NA	3.24	490	24.9	32.0	7.5	8.5	NA	542	147	629	10.8	1888
112	48-27-801	2/13/86	14.0	NA	8.14	NA	NA	177	19.3	61.6	5.4	NA	NA	282	116	168	26.3	862
113	48-35-801	2/11/86	20.0	NA	8.01	NA	NA	237	43.1	77.1	3.4	NA	NA	336	88	438	11.8	1241
114	48-35-901	2/12/86	11.0	NA	7.61	NA	NA	55	24.6	131.0	1.5	NA	NA	284	10	275	11.3	801
114	48-35-901	7/6/88	25.0	7.20	8.06	NA	NA	56	28.0	145.0	2.1	7.9	306	297	12	340	14.0	897
114	48-35-901	10/6/88	21.0	7.20	8.48	90	2.32	68	27.8	112.0	1.8	8.2	323	304	7	280	11.8	818
115	48-36-801	2/14/86	19.0	NA	7.92	NA	NA	454	22.1	37.3	7.4	NA	NA	411	137	570	<0.5	1649
116	48-34-901	2/13/86	14.0	NA	7.90	NA	NA	362	15.3	48.4	3.5	NA	NA	278	128	525	<0.5	1369
116	48-34-901	1/18/89	23.0	7.50	8.02	NA	0.60	365	17.1	53.8	3.4	8.5	274	303	131	530	0.3	1421
116	48-34-901	5/3/89	23.0	NA	8.00	NA	1.04	360	16.0	50.3	3.4	7.9	NA	292	127	556	<0.8	1419
98	48-42-5	5/11/89	32.0	7.93	7.84	260	5.30	288	7.2	20.8	3.8	11.8	336	252	125	335	7.4	1046
99	48-34-8	12/5/88	20.5	8.95	7.33	-150	0.00	1094	24.7	151.0	6.9	0.6	27	29	818	1690	7.8	3825
107	48-42-101	1/22/86	24.5	NA	7.50	NA	NA	1250	35.3	169.0	7.7	NA	NA	161	520	2270	1.3	4422
107	48-42-101	6/29/88	26.0	8.70	8.44	NA	NA	1200	23.1	88.7	8.2	8.5	231	212	533	1870	0.6	3951

Table 2 (continued).

BEG ID	TWC ID	Date	T (°C)	Field pH	Lab pH	Eh (mv)	Dissolved Oxygen	Na	Mg	Ca	K	Si	Field Alkalinity	Lab Alkalinity	Cl	SO ₄	NO ₃	TDS
108	48-42-404	1/21/86	22.5	NA	7.97	NA	NA	410	11.9	34.7	4.5	NA	NA	263	259	395	5.1	1388
108	48-42-404	7/1/88	26.0	7.50	8.11	NA	NA	412	11.5	36.2	4.0	15.8	273	263	269	400	6.4	1416
108	48-42-404	10/4/88	24.0	7.90	8.48	350	1.75	415	12.1	36.3	4.6	16.6	277	265	261	450	5.5	1465
108	48-42-404	1/17/89	18.0	7.96	7.88	120	3.30	417	13.1	38.9	4.6	16.5	244	263	274	460	5.4	1493
108	48-42-404	5/1/89	24.0	7.82	8.04	280	2.42	419	11.9	36.0	4.4	16.9	256	264	260	469	3.3	1486
111	48-33-901	1/22/86	21.0	NA	8.09	NA	NA	327	10.5	26.8	4.2	NA	NA	242	168	360	11.4	1154
111	48-33-901	7/6/88	26.0	7.70	8.14	NA	NA	310	11.6	28.7	4.2	14.5	256	248	155	360	12.8	1137
111	48-33-901	10/5/99	18.0	8.50	8.34	NA	NA	373	13.5	25.1	4.9	17.4	294	279	189	460	7.5	1364
111	48-33-901	5/2/89	27.0	7.60	8.00	300	2.54	321	11.5	27.6	4.3	14.8	233	248	155	340	10.9	1126
126	48-35-701	4/23/86	17.0	NA	7.69	NA	NA	549	6.9	70.7	4.4	NA	NA	60	416	710	18.3	1850
126	48-35-701	1/19/89	21.0	8.24	7.65	NA	1.70	523	8.2	62.5	4.1	10.2	62	70	386	730	16.7	1805
126	48-35-701	4/27/89	20.0	8.23	7.90	260	1.98	567	7.9	67.2	4.0	10.0	51	64	398	804	6.6	1934
92	48-50-2	5/6/86	24.0	NA	7.79	NA	NA	445	114.0	403.0	15.7	NA	NA	119	1180	371	28.0	2683
92	48-50-2	6/28/88	25.0	6.80	7.84	NA	NA	422	87.2	280.0	11.7	17.4	164	145	881	530	26.8	2386
93	48-42-4	7/5/88	24.0	7.55	7.97	NA	NA	710	35.7	132.0	6.5	12.6	197	193	1120	320	0.7	2534
93	48-42-4	10/4/88	25.0	7.70	8.15	340	0.60	748	37.2	129.0	7.0	13.3	206	177	1150	380	<0.2	2646
93	48-42-4	1/17/89	13.0	7.69	7.82	NA	3.08	747	41.2	143.0	7.3	13.5	178	202	1153	380	4.1	2692
93	48-42-4	4/27/89	21.0	7.67	8.03	290	3.96	757	38.6	136.0	7.3	12.8	201	194	1150	397	<0.8	2697
105	Rio Grande	1/21/86	11.0	NA	7.80	NA	NA	186	18.5	86.9	7.8	NA	NA	214	185	234	6.6	942
109	48-41-618	1/21/86	NA	NA	8.07	NA	NA	486	23.9	23.8	14.6	NA	NA	96	555	315	<0.5	1517
110	48-41-624	1/21/86	19.0	NA	7.69	NA	NA	881	91.7	387.0	12.8	NA	NA	495	1450	770	<0.5	3604
110	48-41-624	7/5/88	28.0	7.20	7.85	NA	NA	842	78.5	342.0	11.4	17.5	495	473	1320	720	14.0	3814
110	48-41-624	10/5/88	21.0	7.20	7.81	-30	NA	899	91.8	383.0	12.4	17.6	516	366	1670	820	<0.2	4271
110	48-41-624	1/18/89	19.5	6.93	7.89	NA	0.70	1220	137.0	502.0	14.8	17.4	508	501	2290	1020	2.0	5719
110	48-41-624	5/1/89	20.0	7.42	7.83	-80	0.78	379	27.1	116.0	7.3	16.3	329	347	397	414	<0.8	1707

NA = No Analysis

Table 3. Minor and trace ions (mg/L) in ground-water samples.

BEG ID	Date	Sr	Ba	Fe	Mn	Zn	Li	B	Br	I	F	NH ₄	Cs	Hg	U (ug/L)	Cyanide	Sulfide	TOC
22	10/5/88	3.58	0.02	<0.02	0.02	0.05	0.15	1.08	2.20	0.1	3.60	0.2	NA	NA	NA	NA	NA	NA
22	3/16/89	3.59	0.03	0.05	0.05	0.11	0.15	1.68	2.50	0.2	1.70	<0.2	P	P	P	NA	NA	NA
22	4/24/89	4.28	<0.01	<0.02	0.04	<0.03	0.12	1.24	2.70	0.3	3.10	<0.2	P	P	P	<0.01	<0.05	9.6
91	4/28/89	1.54	0.02	0.27	0.03	0.44	0.05	0.49	0.50	0.1	4.70	<0.2	P	P	P	<0.01	<0.05	<0.1
95	6/30/88	1.79	0.02	<0.02	<0.02	0.05	0.11	0.55	0.70	0.1	4.00	<0.2	0.9	<2	13.3	NA	NA	NA
96	6/30/88	1.81	0.02	<0.02	<0.02	0.32	0.12	0.65	0.90	0.1	4.50	<0.2	0.5	<2	16.4	NA	NA	NA
97	6/30/88	3.34	0.02	<0.02	<0.02	0.07	0.16	0.84	1.40	0.2	2.80	<0.2	1.1	<2	29.4	NA	NA	NA
97	10/6/88	3.62	0.02	<0.02	<0.02	0.06	0.11	0.88	1.40	0.1	2.51	<0.2	1.2	<2	29.8	NA	NA	NA
97	1/26/89	3.40	0.02	0.03	<0.02	0.05	0.11	0.93	1.60	0.3	3.85	0.6	1.2	<2	29.8	NA	NA	NA
97	5/2/89	3.42	0.02	<0.02	<0.02	0.04	0.10	0.82	1.60	0.8	2.70	<0.2	P	P	P	<0.01	<0.05	13.1
106	1/22/86	1.63	0.02	0.02	NA	NA	0.13	NA	1.34	NA	5.57	NA	NA	NA	NA	NA	NA	NA
106	6/29/88	1.60	0.02	<0.02	<0.02	0.03	0.17	1.28	0.70	0.3	4.30	0.4	0.4	<2	26.6	NA	NA	NA
106	10/5/88	1.97	0.03	0.08	<0.02	<0.03	0.16	1.99	1.00	0.5	5.03	0.4	0.4	8	29.8	NA	NA	NA
106	1/26/89	1.89	0.02	0.03	<0.02	<0.03	0.15	1.62	1.00	0.1	8.59	<0.4	0.4	<2	31.6	NA	NA	NA
106	5/3/89	1.78	0.03	0.15	<0.02	<0.03	0.13	1.42	0.90	0.9	4.70	<0.2	P	P	P	<0.01	<0.05	29.2
112	2/13/86	1.72	0.02	0.10	NA	NA	0.06	NA	1.14	NA	2.79	NA	NA	NA	NA	NA	NA	NA
113	2/11/86	3.90	0.03	0.71	NA	NA	0.05	NA	0.77	NA	1.60	NA	NA	NA	NA	NA	NA	NA
114	2/12/86	7.50	0.03	<0.02	NA	NA	0.03	NA	0.44	NA	0.90	NA	NA	NA	NA	NA	NA	NA
114	7/6/88	7.49	0.04	0.04	<0.02	0.28	0.12	<0.23	0.20	<0.1	0.80	0.2	<0.2	<2	3.8	NA	NA	NA
114	10/6/88	8.59	0.04	0.02	<0.02	0.32	0.06	0.31	<0.10	0.4	0.80	<0.2	<0.2	9	5	NA	NA	NA
115	2/14/86	3.32	0.03	2.15	NA	NA	0.12	NA	1.15	NA	3.10	<0.5	NA	NA	NA	NA	NA	NA
116	2/13/86	2.87	0.12	0.20	NA	NA	0.07	NA	1.10	NA	4.30	NA	NA	NA	NA	NA	NA	NA
116	1/18/89	2.79	0.01	0.63	<0.02	0.30	0.07	0.84	0.80	0.2	5.03	<0.4	<0.2	<2	14.2	NA	NA	NA
116	5/3/89	2.90	0.01	0.70	<0.02	0.35	0.07	0.75	0.80	0.2	2.20	<0.2	P	P	P	<0.01	<0.05	0.1
98	5/11/89	0.45	0.03	0.05	0.04	0.12	0.11	1.14	0.70	1.6	1.10	<0.2	P	P	P	<0.01	<0.05	20.9
99	12/5/88	4.65	0.06	0.02	0.14	0.07	0.23	1.52	3.30	0.2	2.51	<0.4	<0.4	<4	<0.4	NA	NA	NA

Table 3 (continued).

BEG ID	Date	Sr	Ba	Fe	Mn	Zn	Li	B	Br	I	F	NH ₄	Cs	Hg	U (ug/L)	Cyanide	Sulfide	TOC
107	1/22/86	3.20	0.02	0.04	NA	NA	0.26	NA	2.66	NA	1.05	NA	NA	NA	NA	NA	NA	NA
107	6/29/88	2.07	0.02	0.03	<0.02	0.07	0.35	1.66	2.60	0.3	2.80	0.4	<0.2	<2	15.2	NA	NA	NA
108	1/21/86	1.01	0.04	0.05	NA	NA	0.10	NA	1.25	NA	2.37	NA	NA	NA	NA	NA	NA	NA
108	7/1/88	1.37	0.02	0.02	<0.02	<0.03	0.17	0.59	0.90	0.1	2.20	0.4	<0.2	<2	20	NA	NA	NA
108	10/4/88	1.10	0.02	<0.02	<0.02	<0.03	0.12	0.63	1.00	0.2	1.90	0.3	<0.2	<2	24.6	NA	NA	NA
108	1/17/89	1.05	0.03	<0.02	<0.02	<0.03	0.11	0.66	1.70	<0.1	2.77	<0.4	<0.2	<2	22.6	NA	NA	NA
108	5/1/89	1.07	0.02	0.02	<0.02	<0.03	0.11	0.63	1.00	2.4	2.30	0.5	P	P	P	<0.01	<0.05	1.3
111	1/22/86	0.81	0.02	0.49	NA	NA	0.10	NA	1.01	NA	2.03	NA	NA	NA	NA	NA	NA	NA
111	7/6/88	0.78	0.02	0.03	0.03	0.11	0.15	0.54	0.60	0.1	3.20	0.2	<0.2	<2	15.8	NA	NA	NA
111	10/5/99	0.88	0.02	<0.02	<0.02	0.04	0.11	0.71	0.60	0.1	0.68	<0.2	<0.2	6	20.6	NA	NA	NA
111	5/2/89	0.80	0.01	0.02	0.02	0.05	0.09	0.54	0.80	0.1	2.60	<0.2	P	P	P	<0.01	<0.05	19.5
126	4/23/86	8.30	0.19	0.13	NA	NA	0.10	NA	2.10	NA	4.30	NA	NA	NA	NA	NA	NA	NA
126	1/19/89	5.40	0.03	0.03	<0.02	<0.03	0.10	1.02	1.70	0.1	4.37	<0.4	<0.2	<2	2.9	NA	NA	NA
126	4/27/89	7.35	0.03	<0.02	<0.02	0.06	0.09	1.01	2.20	<0.1	2.00	<0.2	P	P	P	<0.01	<0.05	1.4
92	5/6/86	9.70	0.42	5.07	NA	NA	0.22	NA	1.90	NA	1.40	NA	NA	NA	NA	NA	NA	NA
92	6/28/88	8.54	0.05	<0.02	<0.02	0.99	0.23	0.27	1.50	<0.1	1.40	0.2	<0.2	<2	10.0	NA	NA	NA
93	7/5/88	2.22	0.07	<0.02	0.04	0.03	0.28	0.35	0.90	<0.1	1.20	0.2	<0.2	<2	<0.2	NA	NA	NA
93	10/4/88	2.30	0.07	<0.02	0.02	0.03	0.20	0.43	0.90	<0.1	0.86	0.2	<0.2	<2	<0.2	NA	NA	NA
93	1/17/89	2.24	0.07	<0.02	0.03	<0.03	0.19	0.44	1.00	0.1	1.78	0.4	<0.2	<2	<0.2	NA	NA	NA
93	4/27/89	2.42	0.06	<0.02	0.03	<0.03	0.19	0.37	1.00	0.8	1.10	<0.2	P	P	P	<0.01	<0.05	41.4
105	1/21/86	1.36	0.06	0.69	NA	NA	0.11	NA	0.22	NA	0.66	NA	NA	NA	NA	NA	NA	NA
109	1/21/86	1.43	0.01	0.02	NA	NA	0.21	NA	0.59	NA	0.39	NA	NA	NA	NA	NA	NA	NA
110	1/21/86	6.69	0.06	1.35	NA	NA	0.26	NA	2.27	NA	0.61	NA	NA	NA	NA	NA	NA	NA
110	7/5/88	5.56	0.05	1.78	1.62	0.03	0.36	0.48	1.20	0.2	0.80	0.2	<0.2	<2	2.8	NA	NA	NA
110	10/5/88	6.99	0.05	2.31	1.82	0.03	0.28	0.57	1.40	0.2	0.45	0.2	<0.4	<4	3.4	NA	NA	NA
110	1/18/89	10.60	0.06	2.74	0.99	<0.03	0.33	0.69	2.00	0.2	0.80	<0.4	<0.2	<2	2.2	NA	NA	NA
110	5/1/89	1.93	0.02	0.51	0.52	<0.03	0.15	0.30	0.50	0.4	0.80	<0.2	P	P	P	<0.01	<0.05	19.2

NA = No analysis

P = Analysis Pending

Table 4. Isotope composition of ground-water samples.

BEG ID	DATE	Percent Modern Carbon	¹⁴ C Age (corrected)	δ ¹³ C	Tritium	δ ¹⁸ O	δD	δ ³⁴ S
22	10/5/88	NA	NA	NA	NA	NA	NA	NA
22	3/16/89	P	P	P	0.14	-7.9	P	P
22	4/24/89	P	P	P	0.00	-7.4	P	P
91	4/28/89	P	P	P	1.10	-8.3	P	P
95	6/30/88	21.90 ± 1.10	3665	-5.80	0.00	-8.0	-52.0	3.3
96	6/30/88	27.20 ± 0.40	1282	-5.40	5.61	-8.1	-56.0	3.4
97	6/30/88	5.97 ± 0.28	12050	-4.36	0.62	-9.8	-71.0	4.9
97	10/6/88	7.40 ± 0.40	11889	-5.30	0.53	NA	NA	NA
97	1/26/89	6.60 ± 0.30	11296	-4.40	0.59	-10.5	P	5.1
97	5/2/89	P	P	P	0.51	-10.3	P	P
106	1/22/86	NA	NA	NA	<0.80	-7.5	-58.0	-1.8
106	6/29/88	NA	NA	NA	NA	-8.3	-58.0	-1.4
106	10/5/88	NA	NA	NA	NA	NA	NA	P
106	1/26/89	NA	NA	NA	2.64	-6.8	P	-3.5
106	5/3/89	NA	NA	P	2.85	-7.0	P	P
112	2/13/86	43.00	746	-8.00	11.80	-7.1	-50.0	5.8
113	2/11/86	36.90 ± 0.37	3343	-9.40	3.74	-7.7	-58.0	5.2
114	2/12/86	60.00 ± 0.42	699	-11.30	20.67	-7.5	-54.0	10.9
114	7/6/88	61.08 ± 0.80	551	-11.10	14.00	-7.6	-49.0	11.4
114	10/6/88	61.80 ± 1.8	228	-10.80	11.60	NA	NA	NA
115	2/14/86	9.60 ± 0.36	13037	-7.90	0.50	-10.7	-83.0	-0.5
116	2/13/86	8.90 ± 0.36	13465	-7.80	1.52	-8.0	-62.0	7.0
116	1/18/89	6.60 ± 0.30	14522	-6.50	0.00	-9.0	P	7.5
116	5/3/89	P	P	P	0.40	-9.4	P	P
98	5/11/89	P	P	P	0.60	-7.4	P	P
99	12/5/88	P	P	P	P	-7.5	P	8.4
107	1/22/86	16.60	14747	-16.80	<0.80	-8.0	-59.0	1.0
107	6/29/88	NA	NA	NA	NA	-0.5	-28.5	3.9
108	1/21/86	61.00 ± 0.42	638	-9.60	<0.80	-6.9	-48.0	3.8
108	7/1/88	43.50 ± 1.80	1983	-9.40	0.35	-6.5	-54.0	5.3
108	10/4/88	52.30 ± 1.3	282	-9.20	<0.08	NA	NA	NA
108	1/17/89	56.30 ± 1.00	327	-9.20	NA	-7.0	P	5.7
108	5/1/89	P	P	P	0.18	-7.0	P	P
111	1/22/86	21.80	8288	-10.10	<0.80	-7.3	-51.0	7.2
111	7/6/88	20.90 ± 0.80	6914	-8.20	0.10	-6.3	-50.0	8.2
111	10/5/99	NA	NA	NA	NA	NA	NA	NA
111	5/2/89	P	P	P	0.00	-7.3	P	P
126	4/23/86	3.30	28718	-18.10	3.30	-8.3	-61.0	4.1
126	1/19/89	P	P	P	0.28	-8.0	P	4.8
126	4/27/89	P	P	P	0.25	-8.4	P	P

Table 4 (continued).

BEG ID	DATE	Percent Modern Carbon	¹⁴ C Age (corrected)	δ ¹³ C	Tritium	δ ¹⁸ O	δD	δ ³⁴ S
92	5/6/86	NA	NA	NA	NA	NA	NA	NA
92	6/28/88	87.64 ± 1.04	3799	-9.41	10.90	-7.9	-55.0	5.5
93	7/5/88	51.85 ± 1.08	638	-8.16	0.00	-10.6	-80.0	5.5
93	10/4/88	52.90 ± 0.70	564	-8.40	0.00	NA	NA	NA
93	1/17/89	50.10 ± 0.60	518	-8.00	0.06	-11.1	P	NA
93	4/27/89	P	P	P	0.11	-11.0	P	P
105	1/21/86	NA	NA	NA	24.40	-9.1	-69.0	1.1
109	1/21/86	NA	NA	NA	27.20	-7.4	-71.0	16.9
110	1/21/86	116.00 ± 0.72	4106	-12.00	21.80	-8.8	-74.0	4.7
110	7/5/88	109.00 ± 1.00	3661	-11.90	18.70	-8.3	-70.0	6.0
110	10/5/88	112.70 ± 0.70	4512	-11.10	18.70	NA	NA	NA
110	1/18/89	107.60 ± 0.50	4356	-10.80	NA	-9.2	P	6.2
110	5/1/89	P	P	P	19.10	-9.2	P	P

NA = No Analysis
P = Analysis Pending

Table 5. Comparison of major ion compositions (mg/L) in wells sampled in both 1986 and 1988 or 1989.

Well No.	Na	Ca	HCO ₃	SO ₄	Cl
114	55	131	284	275	10
1986					
1988	56	145	297	340	12
116	362	48.4	278	525	128
1986					
1989	365	53.8	303	530	131
108	410	34.7	263	395	259
1986					
1988	412	36.2	263	320	269
111	327	26.8	242	360	168
1986					
1988	310	28.7	248	360	155

Table 6. Major ionic compositions (mg/L) of samples collected quarterly from summer 1988 to spring 1989.

Well	season	Na	Ca	HCO ₃	SO ₄	Cl
97	summer	355	104	498	500	173
	fall	361	106	379	580	181
	winter	371	113	497	600	183
	spring	363	106	496	602	177
108	summer	412	36.2	263	400	269
	fall	415	36.3	265	450	261
	winter	417	38.9	263	460	274
	spring	419	36.0	264	469	260
93	summer	710	1327	193	320	1120
	fall	748	1292	177	380	1150
	winter	747	143	202	380	1153
	spring	757	136	194	397	1150
110	summer	842	342	473	720	1320
	fall	899	383	366	820	1670
	winter	1220	502	501	1020	2290
	spring	379	116	347	414	397

Table 7. Values for mean saturation index and standard deviation (1σ) for ground-water samples from each principal aquifer

Mineral	Aquifer					
	Bolson		Diablo Plateau		Rio Grande	
Calcite	-0.022	(0.329)	0.034	(0.200)	0.360	(0.311)
Dolomite	-0.397	(0.583)	-0.216	(0.473)	0.356	(0.579)
Gypsum	-1.432	(0.342)	-1.174	(0.260)	-0.941	(0.296)

Table 8. Results of chemical analyses of soil-moisture samples.

Sample	Depth	Date	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	Si
17a-1	54	10/24/88	35.6	6.5	117	7.7	237	102	44	--
17a-2	54	10/24/88	35.6	6.4	123	7.7	223	110	43	--
17a-3	54	12/06/88	34.4	6.7	129	7.9	260	107	43	36
17a-4	54	1/28/89	34.2	8.0	157	12.0	220	150	46	29
16a-1	78	10/24/88	23.5	5.3	190	4.7	359	132	48	--
16a-2	78	12/06/88	25.2	5.9	210	5.2	370	154	53	40
16b-3	110	10/24/88	21.1	6.9	102	5.2	230	49	48	--

Depths are in feet; analytical data are in mg/L.

--: not analyzed

Table 9. Results of leaching surface sediments in distilled water for 15, 240, and 360 minutes. Concentrations are in milligrams solute per gram sediment.

Aquifer	Time	Na	K	Mg	Ca	Fe	Si	SO ₄	Cl	HCO ₃	NO ₃
Diablo Plateau high area	15	0.8	14.3	4.5	42.8	2.5	22.2	10.8	1.4	130	9.4
	240	0.8	21.7	6.9	76.7	0.3	17.8	9.9	1.8	245	8.1
	360	0.6	24.3	7.9	85.3	0.5	19.8	11.7	1.7	281	9.2
Diablo Plateau low area	15	0.1	5.2	2.9	57.2	0.5	10.9	6.1	5.7	120	7.0
	240	nd	7.4	3.9	59.9	0.2	13.3	9.9	1.7	162	7.5
	360	nd	8.2	4.5	65.9	0.1	14.2	9.7	1.4	175	9.4
Bolson arroyo	15	0.3	21.6	7.0	61.2	9.1	57.7	5.8	2.7	170	5.8
	240	0.3	24.0	3.4	48.4	0.5	15.6	6.9	2.5	173	7.0
	360	0.1	26.5	3.5	46.4	0.2	15.3	6.9	2.2	169	5.6
Bolson interarroyo	15	1.0	19.6	10.0	33.9	16.5	92.4	4.3	1.4	965	1.8
	240	1.4	17.8	3.5	48.2	1.3	20.2	6.8	1.3	166	0.1
	360	1.6	19.5	3.6	53.8	0.5	16.6	9.2	2.6	178	1.0
Rio Grande irrigated	15	728	29.6	43.5	262.6	0.1	10.9	900	949	92	188
	240	744	29.1	43.3	257.3	0.5	14.3	876	949	112	170
	360	750	30.8	43.0	257.0	0.1	13.0	913	937	119	181
Rio Grande not irrigated	15	7.5	48.9	30.1	37.4	42.4	220	7.9	5.8	122	6.8
	240	10.8	44.2	8.7	68.8	0.2	15.7	10.9	5.8	295	7.1
	360	9.7	46.5	9.6	72.9	1.0	20.8	10.4	4.5	289	6.0

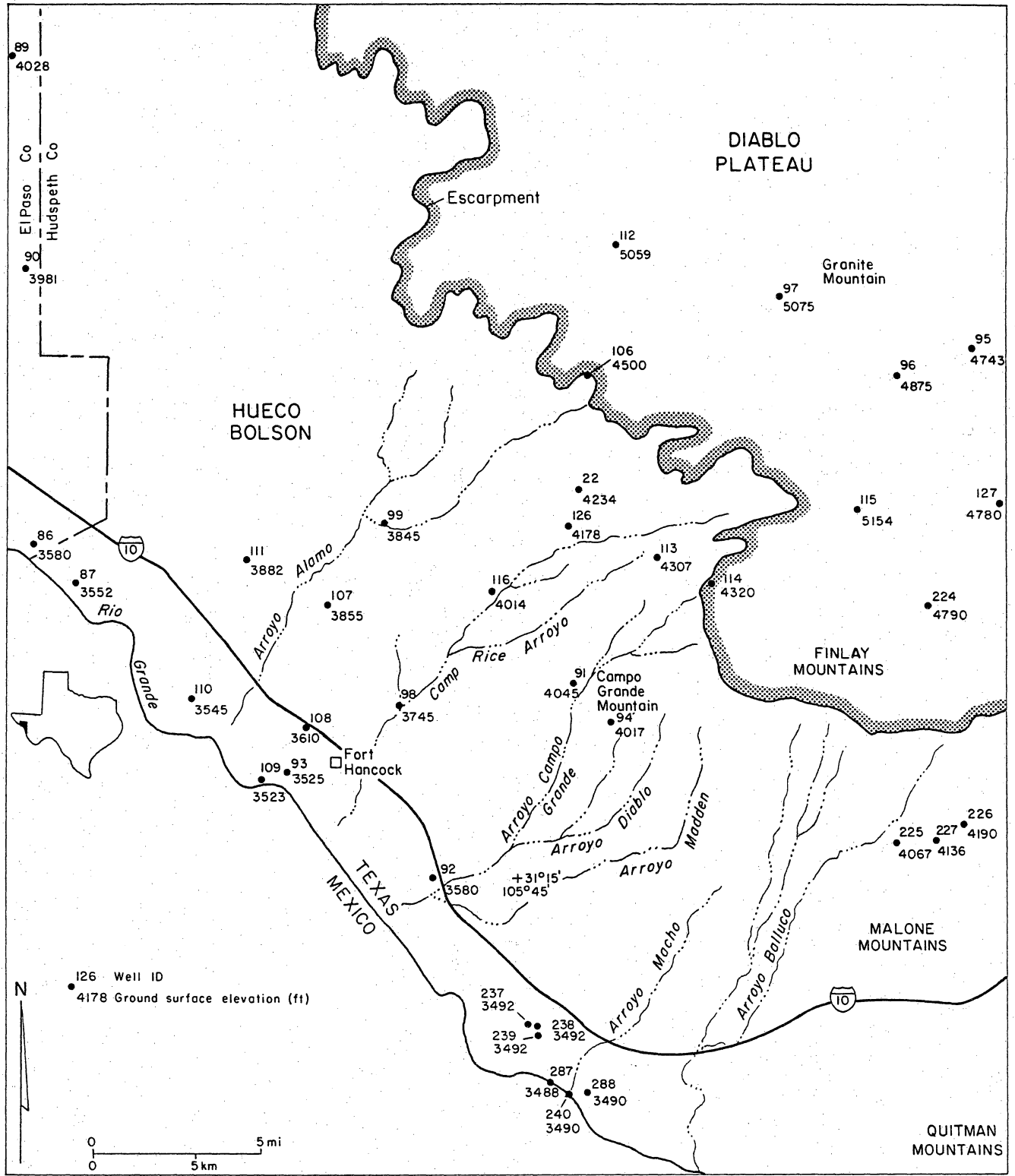


Figure 1.

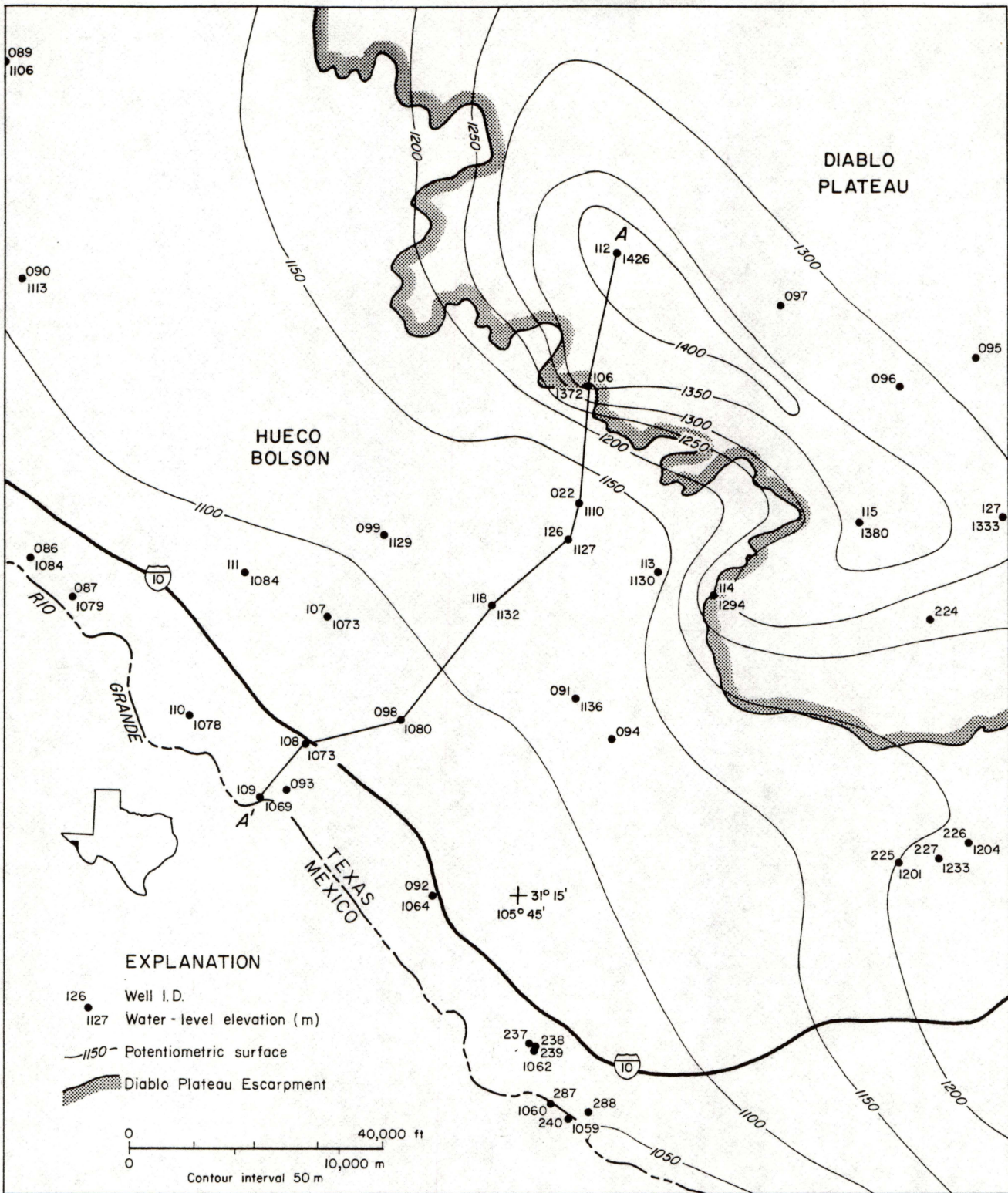
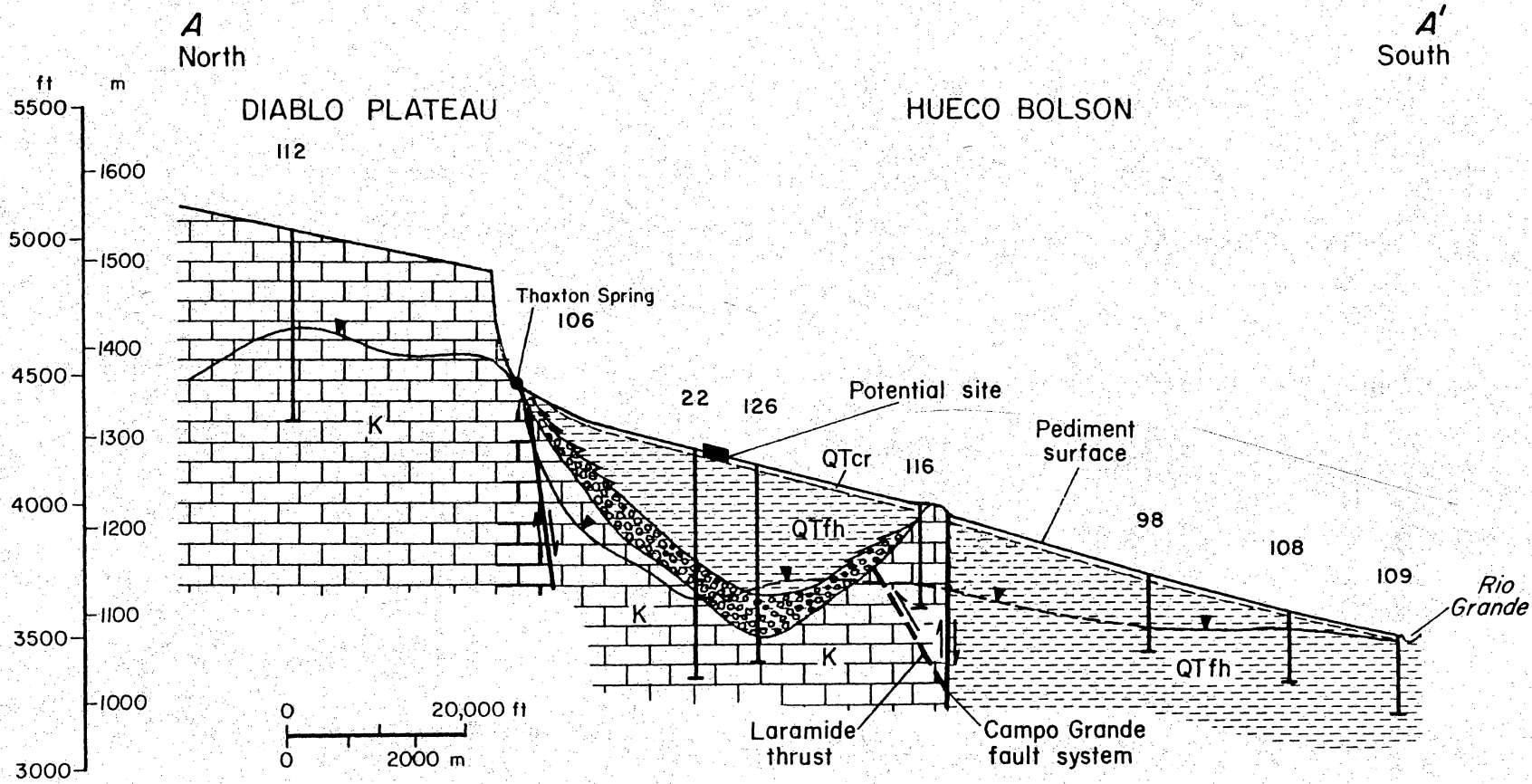


Figure 2.

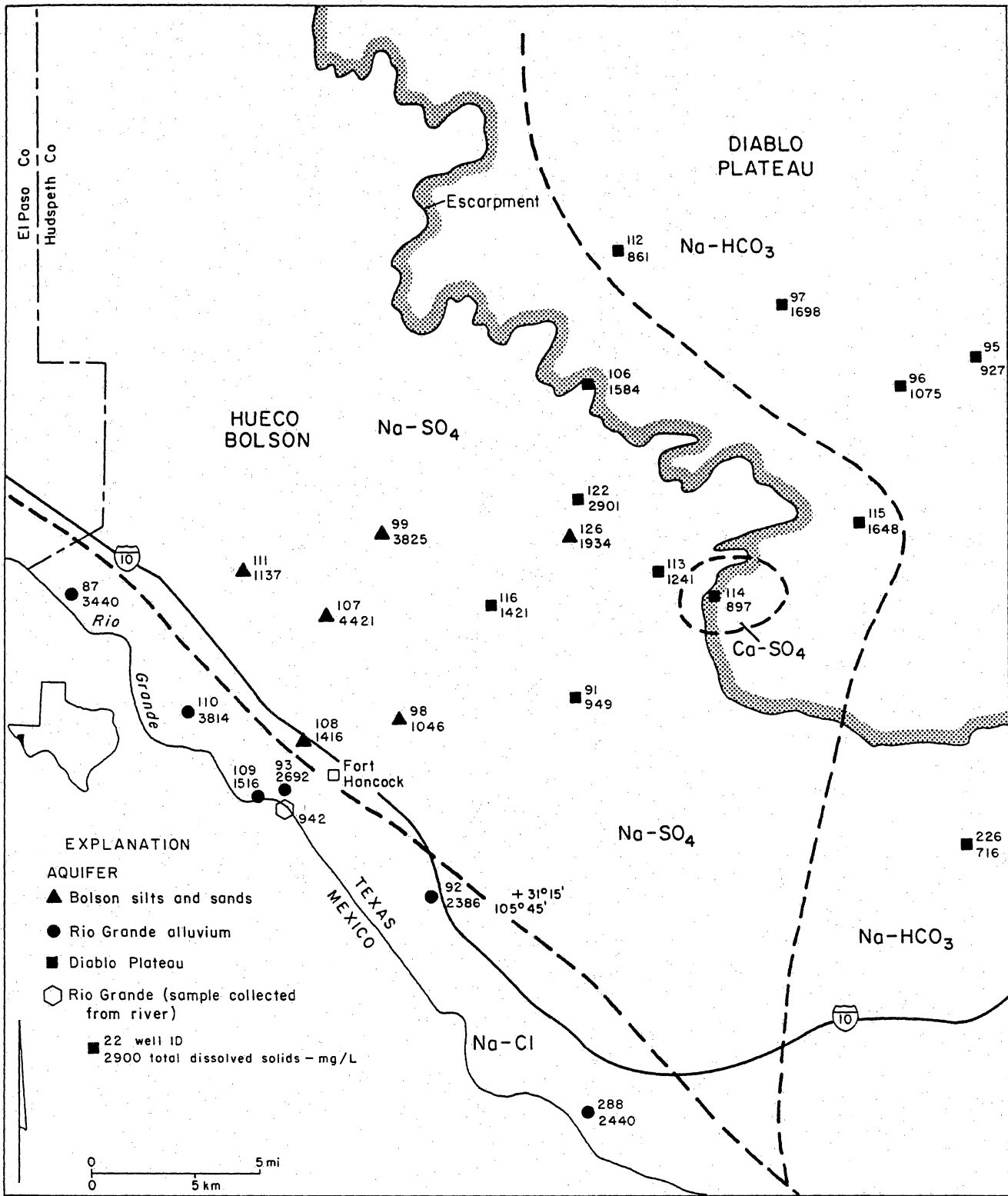


EXPLANATION

- | | | |
|---------------------|------------------------|----------------|
| QUATERNARY-TERTIARY | | 126 Well I. D. |
| QTcr | Camp Rice Formation | |
| QTfh | Fort Hancock Formation | |
| CRETACEOUS | | |
| K | Undifferentiated | |

QA 11458

Figure 3



QA 12298

Figure 4.

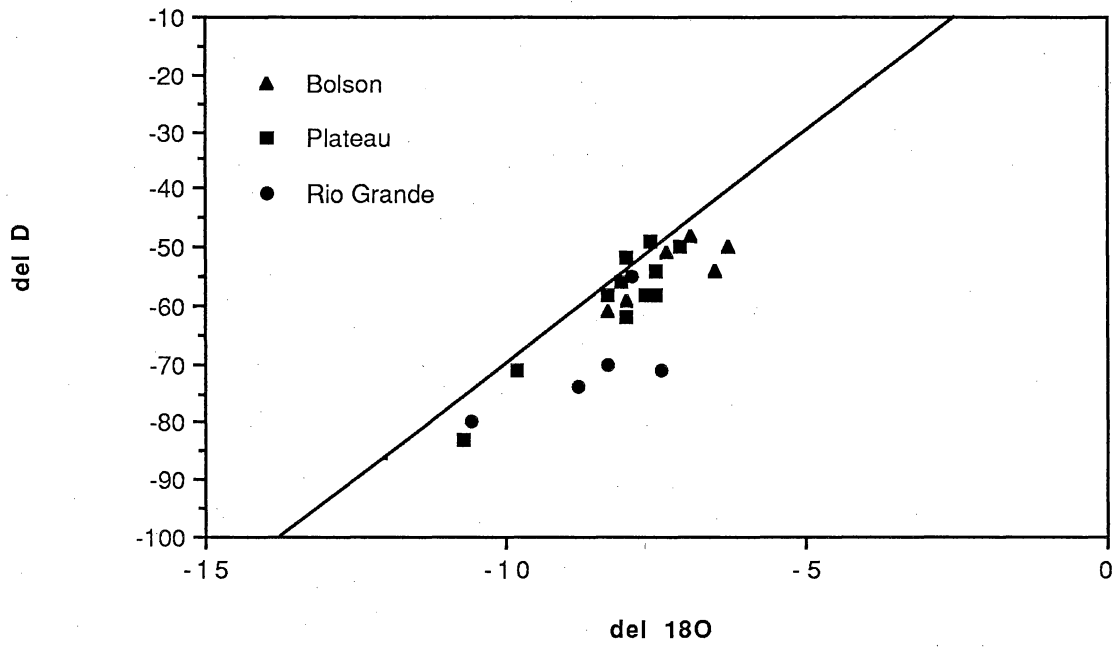


Figure 5.

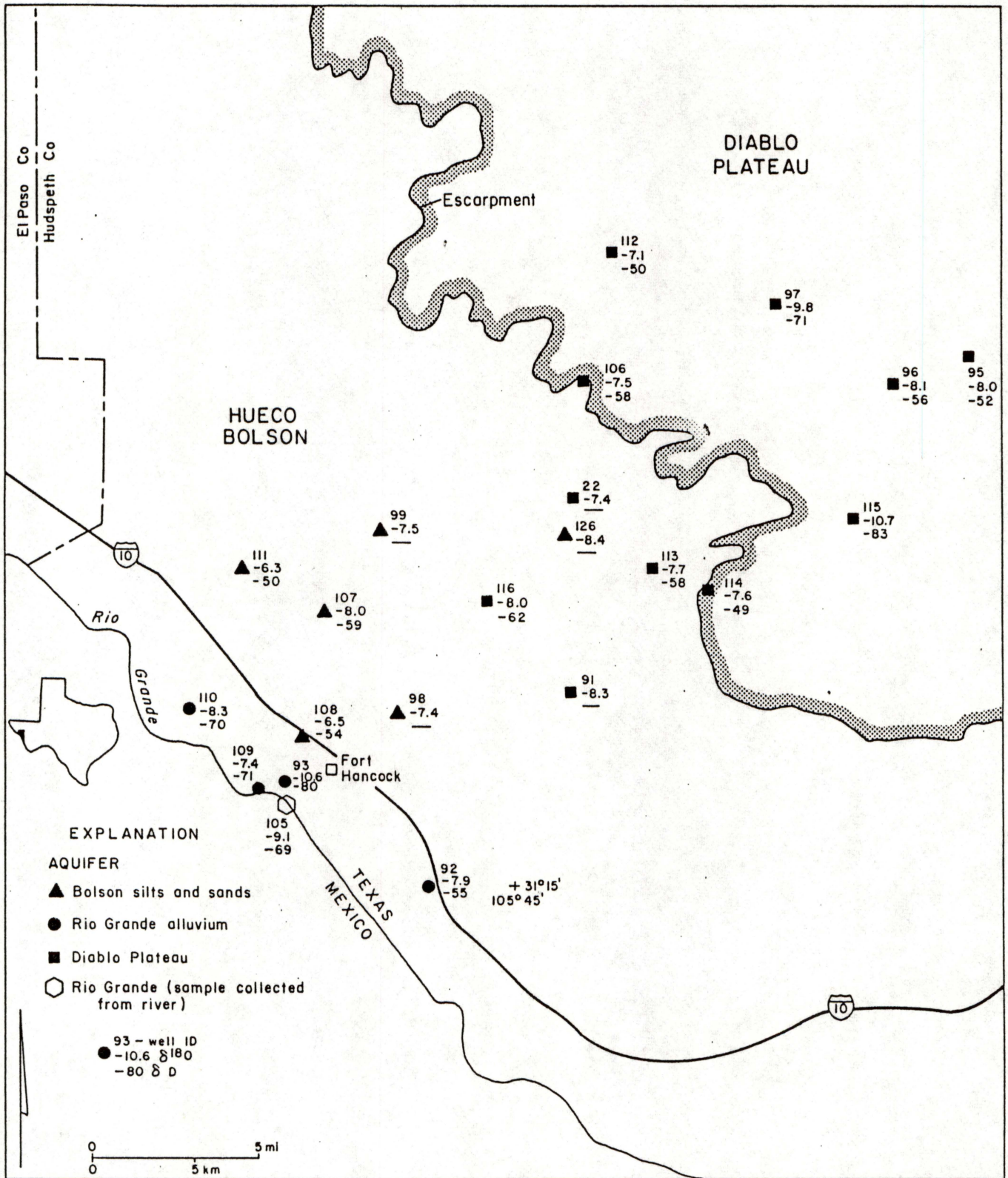


Figure 6.

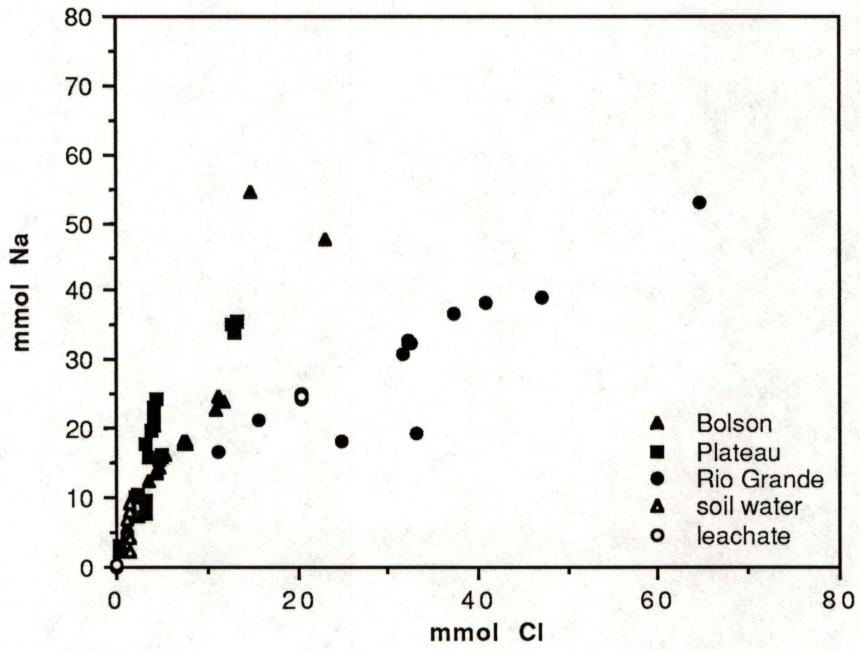


Figure 7

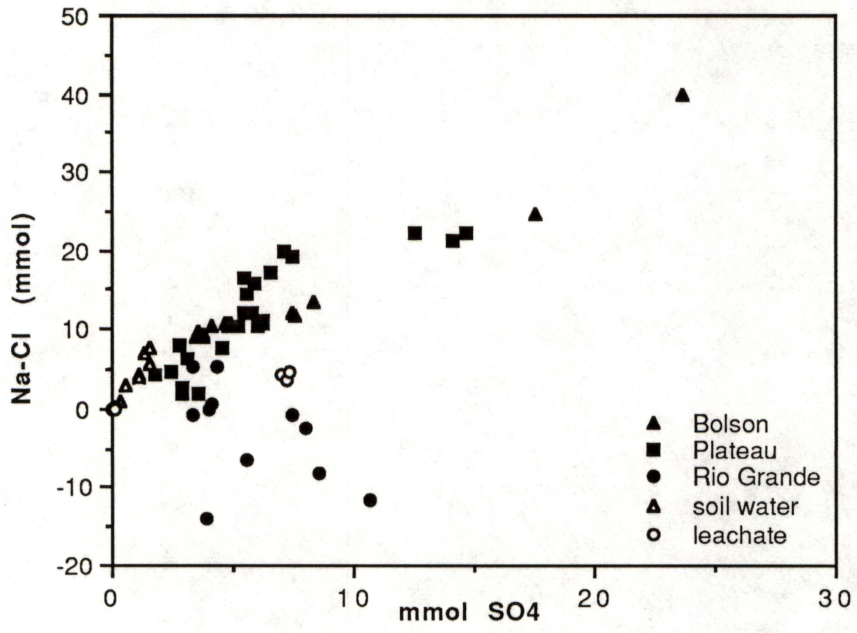


Figure 8.

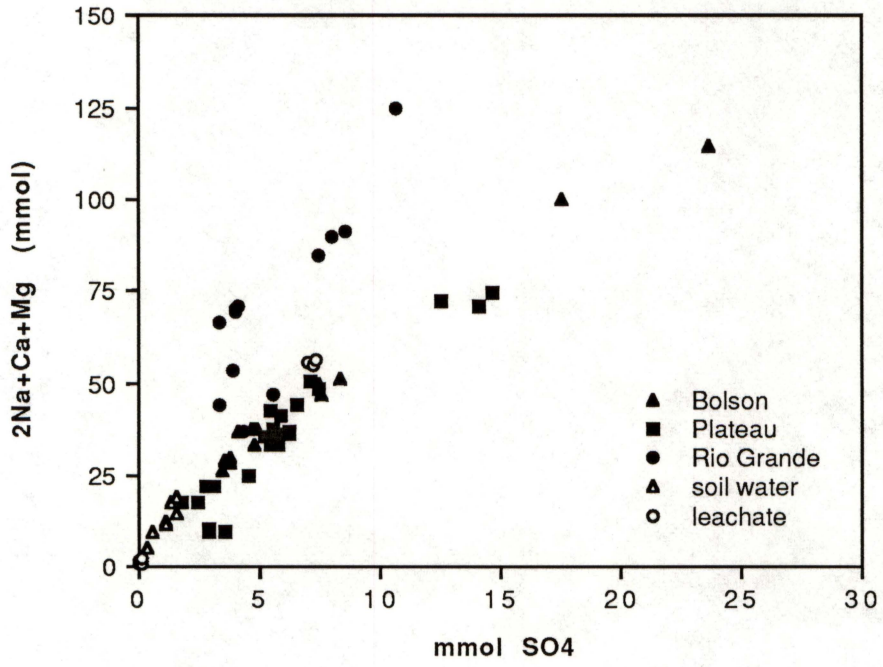


Figure 9.

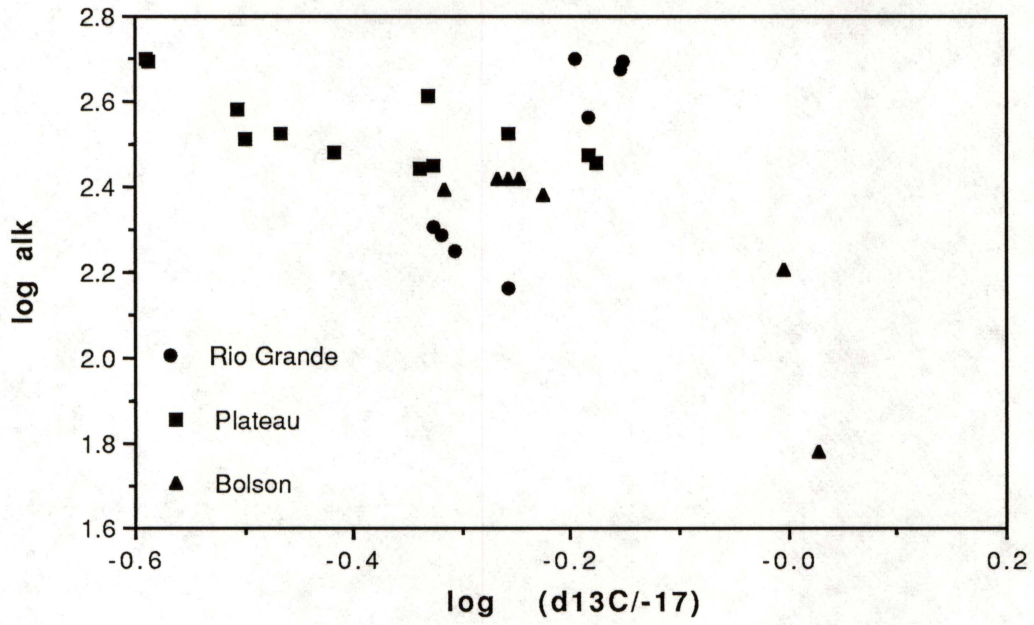


Figure 10.

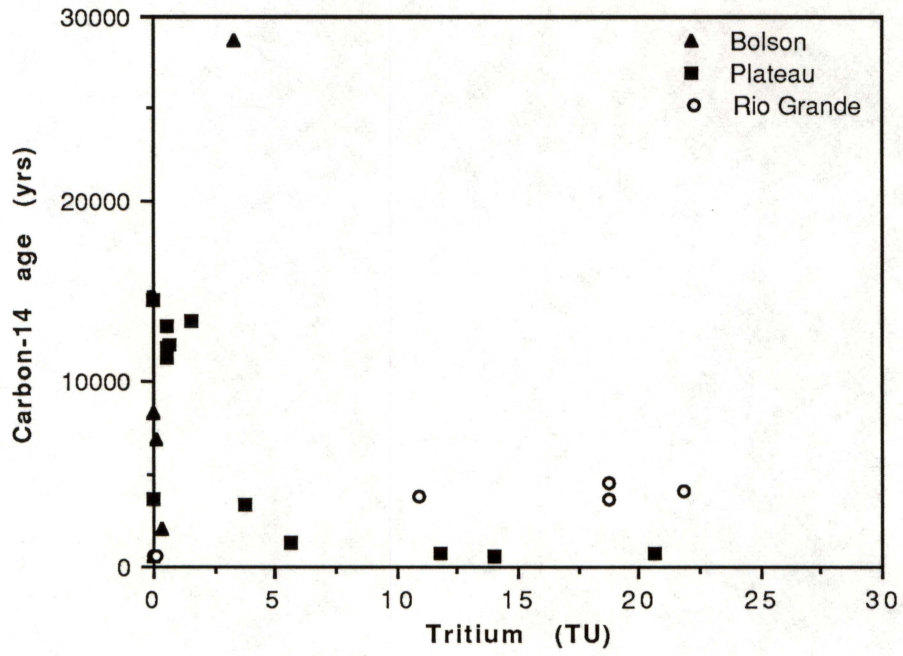
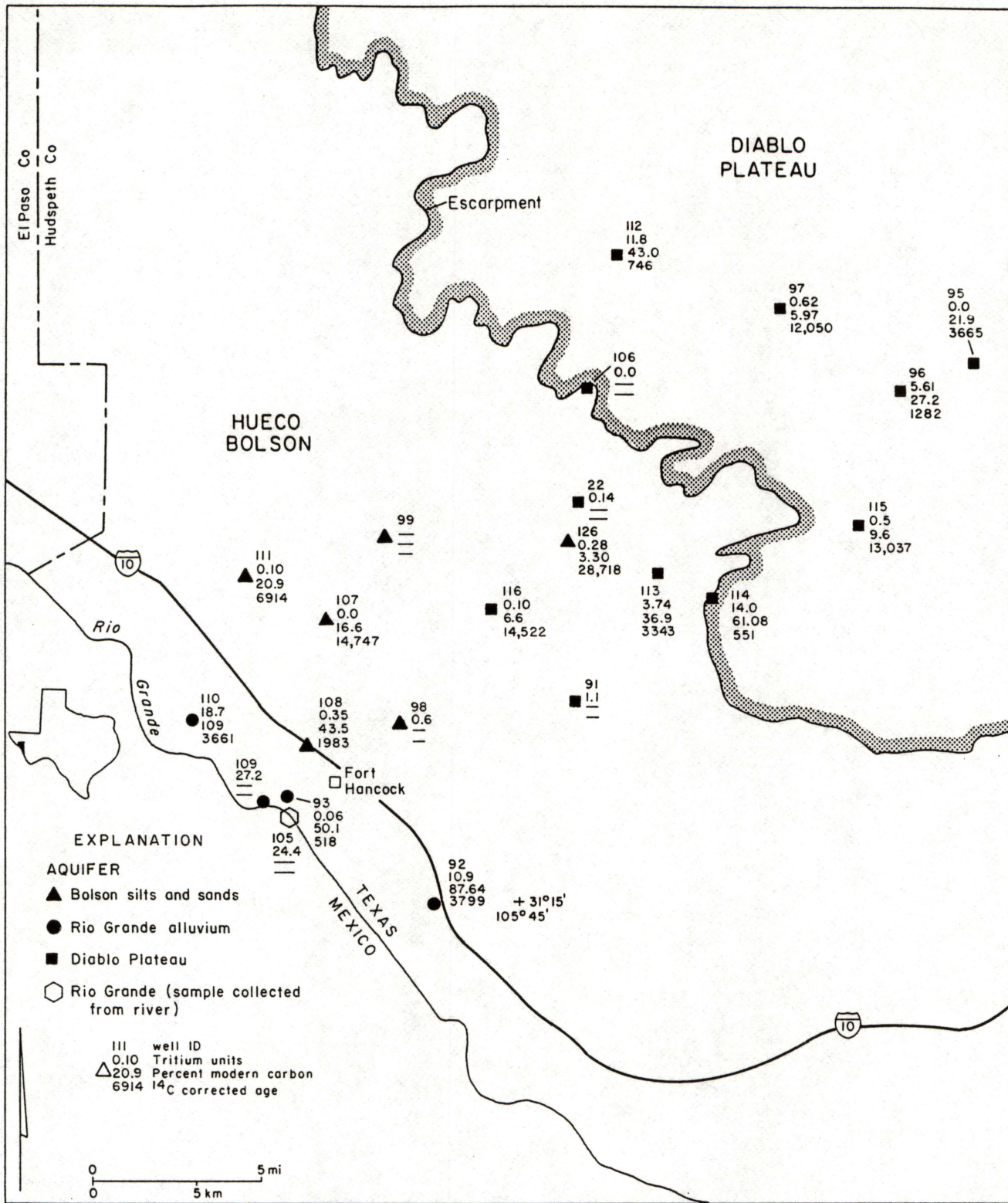


Figure 11.



QA 12201

Figure 12.