Final Report

Site Investigation of the Montague Salt-Water Seep, Montague County, Texas (RRC Cleanup No. 09-50211)

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EXECUTIVE SUMMARY

The Bureau of Economic Geology, The University of Texas at Austin, investigated the Montague site (RRC Site Code 09-50211, District 9, Wichita Falls) for the Railroad Commission of Texas (RRC) between August 1996 and December 1997. The complaint is based on saltwater contamination of shallow ground water and on the formation of an area barren of vegetation on agricultural acreage. The barren ground lies on a Pleistocene alluvial terrace of the Red River just north of the Nocona North–Spanish Fort part of the Montague County Regular Field in an upland area underlain by Permian bedrock. This data report presents and interprets the hydrogeology of a subsurface saltwater plume at the site on the basis of geophysical data, cores and borehole logs, hydrological tests and water-level measurements, and analyses of the chemical composition of soil and ground water. This report also provides a preliminary interpretation of the saltwater sources, an assessment of possible impact on surface water and water-supply wells, and a prognosis for the barren ground without remediation.

On the basis of our data it is reasonable to conclude the following points:

- The barren ground originates where a subsurface saltwater plume lies within 6 or 7 ft of the ground surface.
- This minimum depth to water is controlled by the coincidence of a topographic low along a drainage tributary of Village Creek and a water-table high related to locally focused recharge from upland surface-water runoff.
- It is probable that the lateral extent of the barren area has reached a nearly stable limit and is not likely to expand over the entire area underlain by the saline plume. It is possible, however, that surface soil salinization may affect adjacent fields and increase the size of the barren area; the risk of this occurring cannot be determined on the basis of observations made during one field season.
- The predominant source of saltwater in the subsurface plume was the use of unlined saltwater disposal pits in the upland area between the early days of the field in the 1920's

and the "no-pit order" implemented by the RRC in 1969. Other sources are identified but are minor relative to the total volume of salt observed.

- The primary source of saltwater contamination was ended by the no-pit order, but an inferred secondary source remains with salt in storage in the unsaturated zone beneath pits and above the water table.
- The volume of saltwater estimated to have entered the subsurface from disposal pits is 14 million barrels (MMbbl), which is reasonable given the history of oil production from the field. Dilution of the brine in the subsurface plume has increased the volume of salt-contaminated water to approximately 100 MMbbl. These estimates do not take into account the salt remaining in the unsaturated zone beneath the upland source area.
- At least two deep drinking-water supply wells located on the terrace (one of which appears to be abandoned) are potentially and imminently at risk of contamination because they lie within the footprint of the subsurface saltwater plume. Saltwater contamination of the deeper-water supply is possible if the surface casing does not seal off the upper 50 ft of the wells.
- There are other, non-oilfield-related reasons for some of the water-quality changes, such as increased contribution of naturally occurring, poor-quality water from lower-permeability zones within the aquifer, inflow of poor-quality surface-water runoff owing to problems in well completion, or both.
- The subsurface saltwater plume is continuous with and genetically related to a separate salinity complaint on the Holocene terrace of the Red River floodplain (Williams complaint).
- The Red River adjacent to the study area has an elevated background salinity with an average chloride content of 735 mg/L (long-term average of chloride load and flow volume).
- Total incremental loading from discharge of the northwest lobe of the saltwater plume would add another 0.02 to 0.2 percent to the annual average chloride load in the Red River, or less than 1 mg/L of chloride under average flow conditions.

INTRODUCTION

The Railroad Commission of Texas (RRC) has statutory responsibility under S.B. 1103 (72nd Legislature, 1991) for oversight of cleanup of abandoned oilfield sites throughout Texas, including the Montague site (RRC Site Code 09-50211, Cleanup No. 09-50211), located in northern Montague County about 15 mi north of Nocona (fig. 1). Saltwater contamination in the shallow subsurface has caused an area barren of vegetation to form in cultivated land near the Red River on a Pleistocene fluvial terrace that lies below the Nocona North–Spanish Fort part of the Montague County Regular Field (fig. 2). The main barren area (MBA), which was first reported in 1986, has been the source of several complaints to the RRC, including the Roger Russell complaint (RRC no. 9-90-2507). Since 1986 this barren area has expanded somewhat northward and eastward from its original position. This investigation of the Montague site studies the extent, distribution, source, and movement of the subsurface saltwater plume to account for the barren ground and predict the potential for other impact.

Possible sources of saltwater that were considered at this site include natural sources, injection wells and abandoned oil wells that might be leaking saltwater, and inactive, unlined evaporation pits that were extensively used for the disposal of coproduced saltwater since the 1920's until the no-pit order was implemented by the RRC in 1969. Most of the oilfield is located on Permian sandstone that forms a bluff overlooking the high Pleistocene fluvial terrace of the Red River. Three principal ephemeral streams drain the north part of the upland, and may at one time have provided potential surface paths for saltwater to move from overflowing pits, along the drainages, and down onto the Pleistocene terrace. Sandy surface deposits and permeable Permian sandstones and conglomerates underlying the upland area also provide potential paths for saltwater to infiltrate the ground, reach the shallow water table, and migrate to the terrace by subsurface flow.

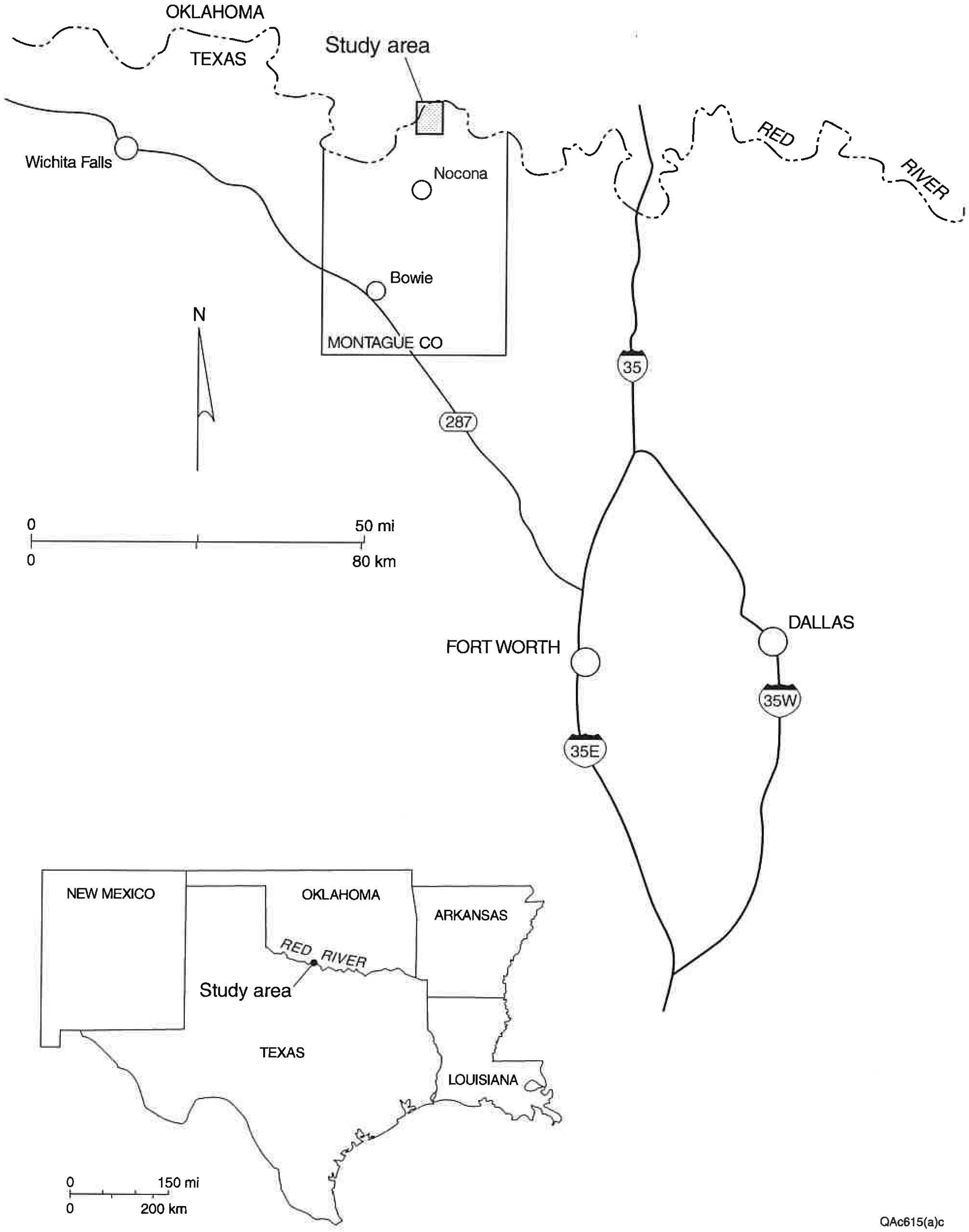


Figure 1. Location of the study area.

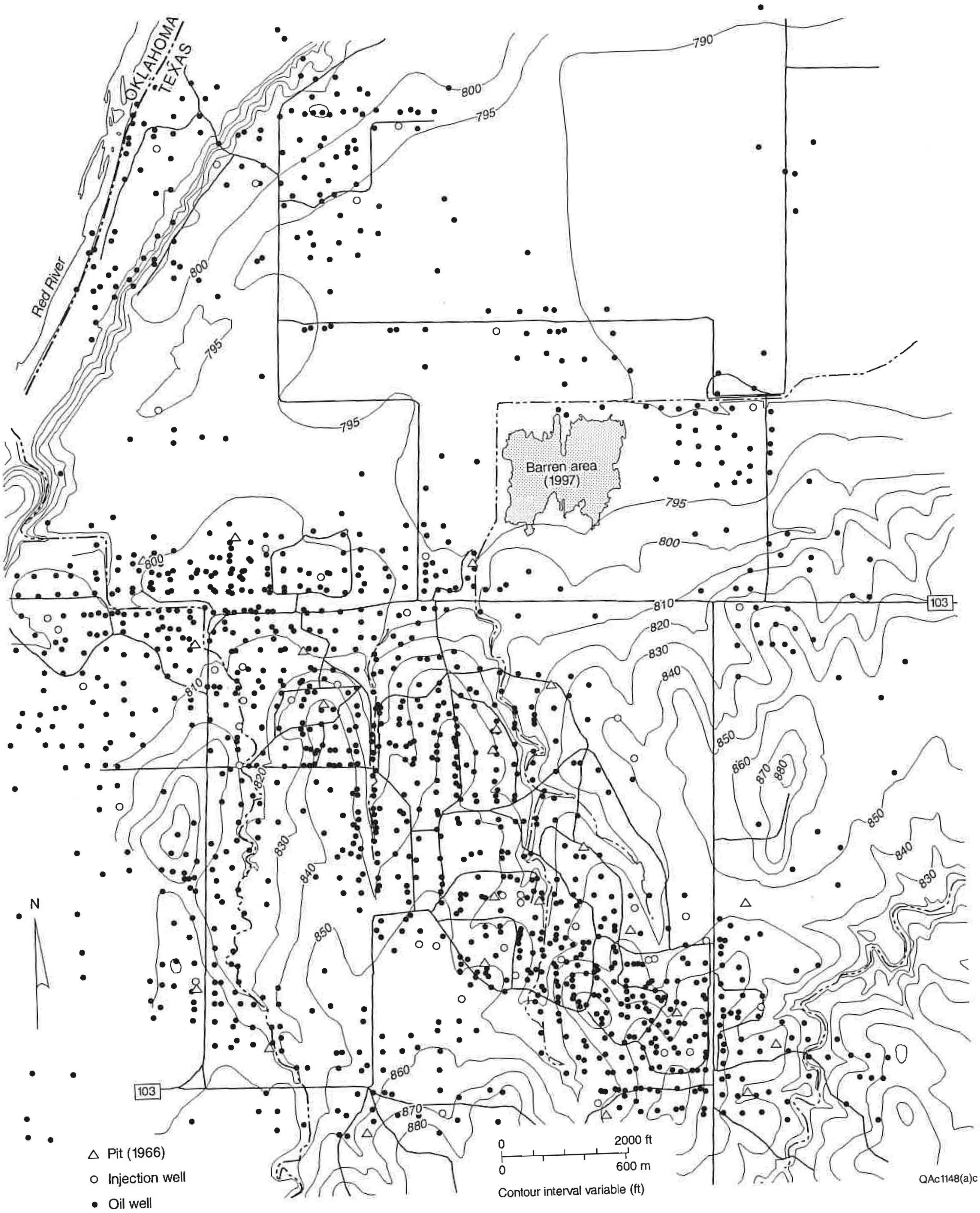


Figure 2. Site map showing roads, oil wells, and pits located on a 1966 air photograph (appendix 6), and the location of the barren area in fall 1997.

Geologic and Hydrologic Setting

Permian bedrock beneath the site is mapped as the Permian Nocona Formation (Hentz and Brown, 1987), which is composed of several numbered channel-fill sandstones and conglomerate and interbedded red-brown mudstone units (Hentz, 1988). Outcropping Permian units forming the uplands regionally dip gently to the north, becoming younger toward the Red River. High Pleistocene fluvial terrace deposits associated with the Red River overlie Permian bedrock and form the agricultural lands, including the large barren area, in the north part of the study area. The Holocene Red River floodplain is incised into the Pleistocene terrace, creating a bluff about 50 ft high.

Production in the Nocona North–Spanish Fort part of the Montague County Regular Field is from Pennsylvanian Canyon and Cisco (Markley Formation) sands at depths of 800 to 1,400 ft (fig. 3). Production is strongly influenced by a faulted basement uplift, part of the Muenster-Waurika Arch trend that brings Precambrian basement to elevations of less than 1,000 ft below sea level (Ball, 1951; McBee and Vaughan, 1956; Ardmore Geological Society, 1965; Denison, 1982; Ewing, 1990). Lower Paleozoic Simson and Arbuckle carbonates (Luzardo, 1971) are unconformably overlain by stratigraphically complex Pennsylvanian arkosic sandstones, conglomerates, and carbonates of the Canyon group (Erxleben, 1975; Bowker, 1982). Overlying the Canyon Group is less than 900 ft of Cisco and Wichita Group redbeds of the Markley, Archer City, and Nocona Formations (McBee and Vaughan, 1956; Morrison, 1980a, 1980b; Hentz, 1988).

Quaternary deposits related to regional geomorphic evolution of the area include (1) arkosic gravel remnants of formerly widespread predissection surfaces; (2) terrace alluvium composed of a lower coarse-grained (predominantly gravel) facies and upper fine-grained partly eolian facies; (3) valley-floor alluvium; and (4) eolian loess and dune sand belts on the south side of the Red River (Frye and Leonard, 1963; Madole and others, 1991).

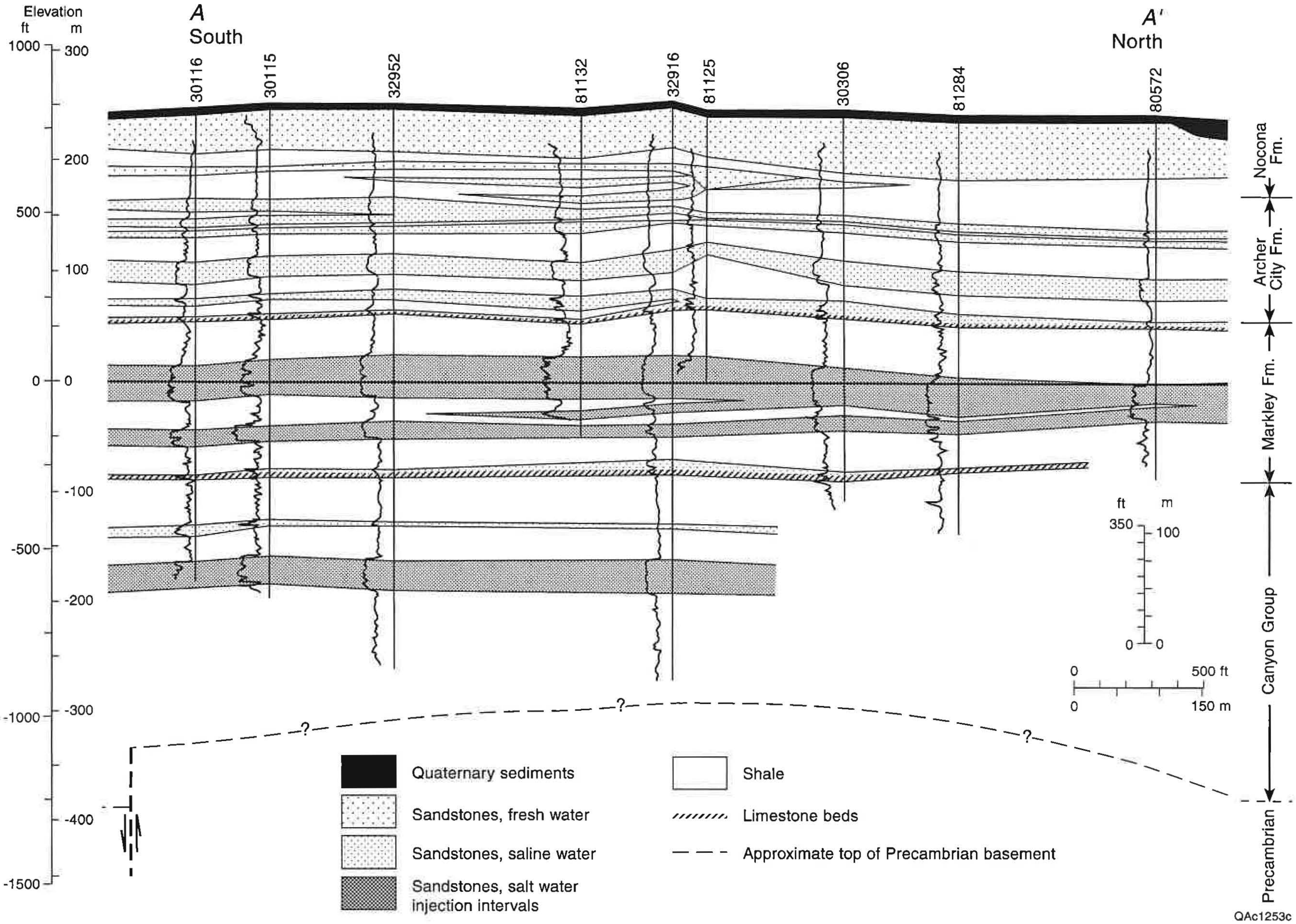


Figure 3. Regional structural cross section A–A′. Line of section shown in figure 7.

Soils developed on the Permian bedrock and on the dune areas fringing the Pleistocene terrace above the Red River are mapped as Bastrop loam; Pleistocene terrace soils are mapped as Teller loam (Clower, 1978). Soils along the drainage at the north edge of the barren area on the Pleistocene terrace are mapped as the Waurika-Renfrow complex.

The Nocona North–Spanish Fort part of the Montague County Regular Field was developed during the 1920's; workovers and infill drilling continue today. Waterflooding and saltwater injection for disposal have been permitted in this field as early as the late 1940's (RRC hearing files).

Naturally saline water occurs beneath the fresh-water zone in the North Nocona field area. A map of the elevation of the base of usable water (Bayha, 1967) shows a regional high that approximately corresponds to the basement uplift. Salinity and thermal anomalies over basement uplifts have been mapped in adjacent Carter County, Oklahoma (McConnell, 1985). Although shallow ground-water contamination complicates the interpretation in the site area, these regional relationships suggest that salinity of 1,000 to 10,000 mg/L at depths beneath the typical completion intervals of water wells is a naturally occurring feature associated with the uplifts. Ground-water contamination by oilfield brine and vegetative kill areas are recognized as significant problems in a several-mile area around the site under investigation as well as in other areas of Montague County where the thickness of fresh water is greater (Bayha, 1967).

Site History

This area is ranked high in priority for site assessment in part because ground-water contamination apparently is active, ongoing, and oilfield related. RRC has conducted several site visits since 1990 and continues to monitor the area. RRC-sponsored investigations have included soil and surface-water sampling in the barren area and nearby potential source areas in the adjacent oilfield, an electrical resistivity survey by the Texas Natural Resource Conservation Commission (TNRCC) to try to locate potential saltwater sources (Price, 1993) and inspections of all injection wells in the area. At least one abandoned well has been plugged at the site using State funds. RRC District 9 staff report that additional work has been done in and near the barren area by private consultants on behalf of local property owners; that work has included the installation of monitoring wells and acquisition of geophysical data.

METHODS

Investigative Approach

Geophysical methods, particularly electromagnetic induction (EM), are effective in locating salinized areas, mapping salinization extent, and tracing potential salinity sources. Very saline water has a high electrical conductivity (several hundred to several thousand milliSiemens per meter [mS/m]) that strongly contrasts with the low conductivities (a few tens to a few hundred mS/m) of natural earth materials (McNeill, 1980a). We measured apparent ground conductivity using EM induction methods (Parasnis, 1973; Frischknecht and others, 1991; West and Macnae, 1991) that employed airborne, ground-based, and borehole instruments. These instruments 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.

We employed several EM methods at the Montague site to address different aspects of salinization. Reconnaissance ground-based EM measurements were used to:

- establish the boundaries of the area impacted by saline water,
- suggest whether one or more salinity sources are present, and
- determine the range of electrical conductivity at the site.

Airborne conductivity measurements provided more continuous spatial coverage, necessary for establishing the relative intensity and lateral extent of salinization and locating potential salinity sources. The results were used to target borehole locations in likely background and salinized areas. Borehole measurements and time-domain EM soundings determined the vertical extent of salinization and helped establish the relationship between ground conductivity and chloride content. We then used the airborne EM data and the borehole-derived empirical relationship between chloride content and electrical conductivity in water to estimate the total mass of chloride present in the Montague saltwater plume.

Reconnaissance Ground-Based EM

In October and November 1996, reconnaissance ground conductivity measurements were taken at 1,088 sites along 11 line segments across the Montague site (appendix 1 and fig. 4) to locate highly conductive ground indicative of salinization. In these surveys, a Geonics EM34-3 ground conductivity meter was used to measure apparent conductivity (McNeill, 1980b). The EM34-3 supports a 10-, 20-, or 40-m transmitter and receiver coil separations and two principal coil orientations (horizontal dipole and vertical dipole). Most measurements were taken with the 20-m coil separation, which has an exploration depth of 12 m for the horizontal dipole orientation and 25 m for the vertical dipole orientation. The conductivity values represent "bulk" conductivities, or an average conductivity of the soil volume within the exploration range of the transmitter and receiver coils.

Conductivity measurements were taken as follows: (1) the transmitter coil was placed on the ground in the horizontal dipole orientation; (2) the receiver coil was placed on the ground 20 m from the transmitter coil (or 40 m from the transmitter coil at the 40-m setting); (3) apparent conductivity was logged on a digital data logger; (4) both coils were realigned in the vertical dipole orientation at the same locations and coil separation; (5) apparent conductivity for the vertical dipole orientation was digitally logged; and (6) the transmitter and receiver coils were each moved forward 20 m. The process was repeated until the end of the line was reached.

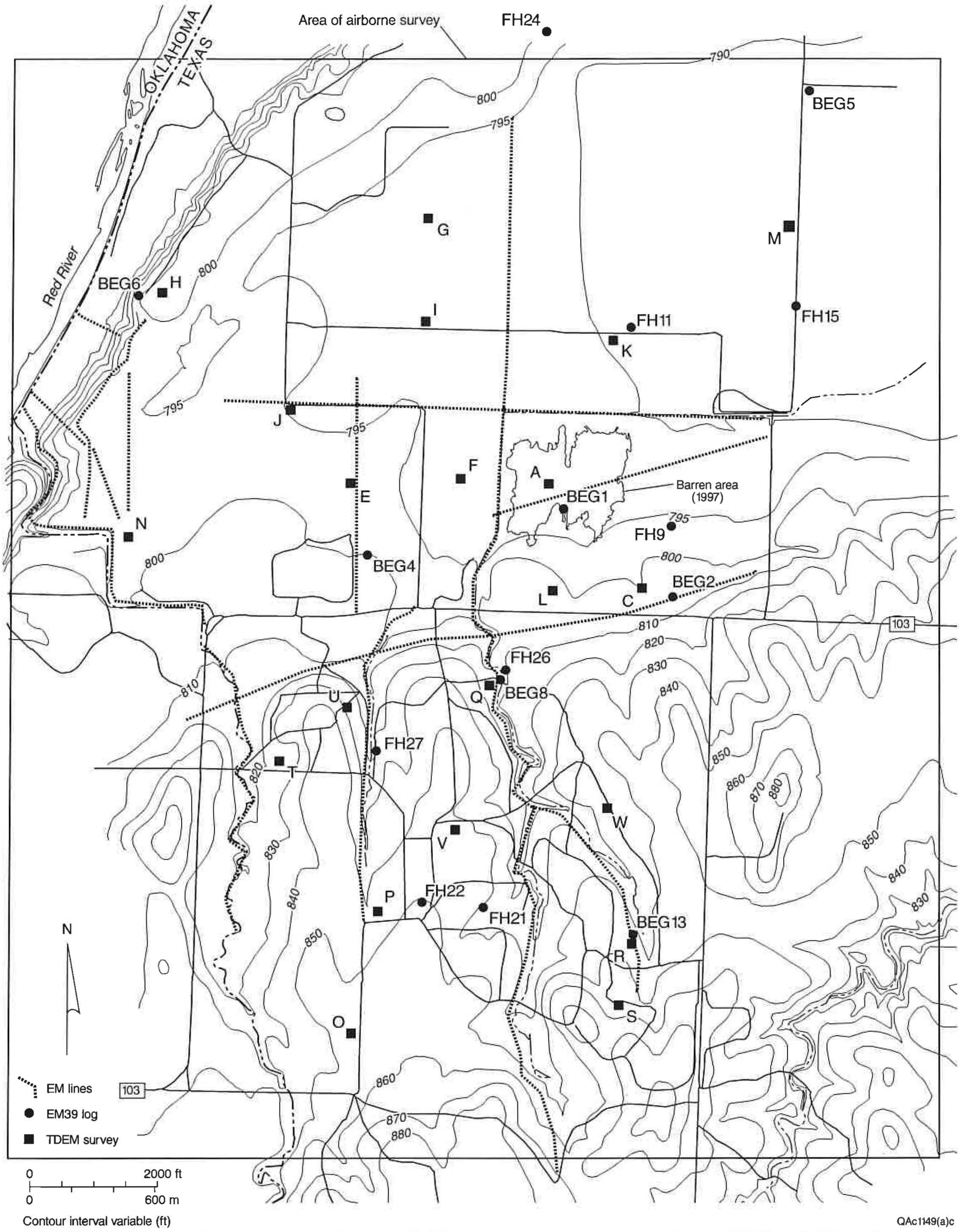


Figure 4. Map showing reconnaissance EM lines, airborne survey boundaries, BEG and FH wells for which EM39 logs were collected, and locations of TDEM soundings.

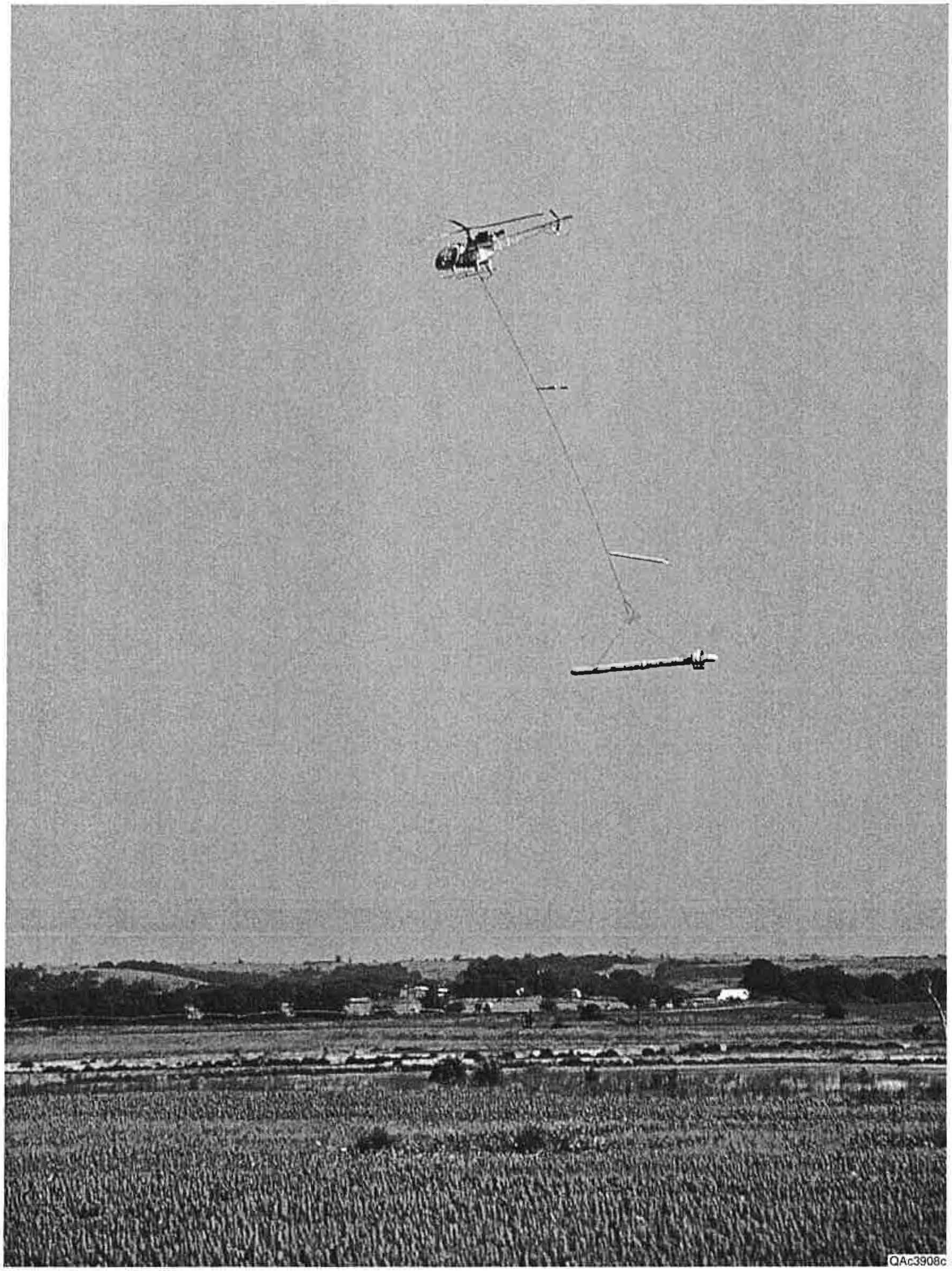
Airborne Survey

Geoterrex–Dighem, a Canadian geophysical contractor, surveyed the Montague study area with helicopter-borne geophysical instruments in July 1997 (Garrie, 1997). Principal instruments mounted on or towed by the Aerospatiale SA315B helicopter were the multicoil, multifrequency DIGHEM^V EM induction system used to measure ground conductivity, and a Picodas Cesium vapor magnetometer for measuring magnetic field strength. The EM coils and the magnetometer were towed beneath the helicopter at nominal heights of 30 m for the coils and 40 m for the magnetometer (fig. 5). The helicopter maintained a height of 60 m and flew at an average speed of 120 km/hr (Garrie, 1997). Supporting instruments included a differential GPS navigation system with locational accuracy to better than 5 m, a radar altimeter, and a video camera that recorded the ground along the flight lines.

Flight lines were oriented east–west, were spaced at 100-m intervals, and covered a total length of 261 km within a 25 km^2 area that measured 4.5 km east–west by 5.5 km north–south (fig. 4). Samples from the EM coils and the magnetometer were acquired at 0.1-s intervals, which corresponds to a sample spacing of about 3 m along each flight line. Lateral resolution was thus better by a factor of 33 in the east–west direction than in the north–south direction.

Raw EM and magnetometer data were recorded digitally and processed by Dighem I-Power in the months following the airborne survey (Garrie, 1997). Preliminary conductivity maps were supplied to BEG to enable us to select priority field sites and begin field investigations. Final products delivered by Dighem included maps of ground conductivity at three coil frequencies, maps of total and enhanced magnetic field strength, cross sections showing lateral and vertical conductivity changes along east–west flight lines, a flight-line track map and videotapes, and digital-map images that were imported into a geographic information system data base.

Figure 5. View looking north from Fm 103 showing helicopter towing EM coils (lower instrument) and magnetometer (upper instrument) over the Montague barren area.



Time-Domain EM

Ground-based, time-domain EM (TDEM) soundings were used to measure the thickness of the saltwater plume and examine changes in ground conductivity in depths deeper than those reached by the airborne and ground-based, frequency-domain methods. TDEM soundings (Kaufman and Keller, 1983; Spies and Frischknecht, 1991) were acquired with the Geonics PROTEM 47/D instrument. These soundings produced multilayer conductivity profiles to a maximum depth of 75 to 100 m. Rather than employing multiple frequencies and coil separations to vary exploration depth along surveyed lines as we did for the reconnaissance EM34 measurements and the airborne survey, we used the TDEM instrument at selected sites to measure the decay of a secondary EM field (the "transient") produced by the termination of an alternating primary EM field. At a TDEM site, the decay of a secondary field produced by an electrical current flowing in the ground is measured after the electric current is shut off in a transmitter wire laid out at the ground surface. Secondary field strength at early times gives information about conductivity in the shallow subsurface; field strength at later times is governed by conductivity at depth. The computer program TEMIX, by Interpex, was used to construct model conductivity profiles that best fit the observed transient decay for each site.

In October 1997, TDEM soundings were collected at 23 sites to (1) supplement borehole data and (2) define the vertical bounds of the saltwater plume as revealed by the airborne EM results (fig. 4). At each site, two TDEM soundings were collected using a 40- × 40-m transmitter loop. For the first sounding at each site, the receiver coil was placed 10 m outside the transmitter loop. For the second sounding, the receiver coil was moved to the center of the transmitter loop. Outside-the-loop receivers reduce potential interference from metallic objects within the transmitter loop, but cause interpretation difficulties related to EM-field propagation velocities in conductive ground. Inside-the-loop receivers record transient decay curves that are easier to interpret, but these curves can be distorted by the presence of the receiver coil within the transmitter loop when loop dimensions are small. Because comparisons of decay curves for the two soundings showed no significant difference between conductivity models, all conductivity profiles presented in this report were calculated from inside-the-loop soundings.

Existing Wells

Our search through the Texas Water Development Board (TWDB) data base identified 42 domestic water-supply wells within 6.6 mi (10.6 km) of the site having data on water levels or analyses of chemical composition of ground waters (fig. 6; table 1). We sampled three of the wells listed in the TWDB chemical-composition data base and six additional water-supply wells that were accessible to within approximately 2 mi (~3.3 km) of the site. Sampling information is included in appendix 2. In the months before we began our work, Fox Hollow Consultants (FH) of Ardmore, Oklahoma, drilled 27 monitoring wells at 20 locations in the study area (fig. 7). Seven pairs of wells are twinned and completed at different depths. Fox Hollow Consultants made these wells available for water-level measurements, water sampling, and downhole EM logging during this study.

Piezometer Nests

Two groups of piezometers (PNA and PNB) were installed in the barren area (MBA) using the BEG Giddings probe. The piezometers were used to estimate the local vertical gradient in hydraulic head near ground surface at the barren zone. The piezometers consisted of 3/4- and 1-inch steel pipe constructed using a chisel-edge drive point and drilled perforations across the bottom foot. The piezometers were installed to depths ranging from 4.4 to 20.2 ft.

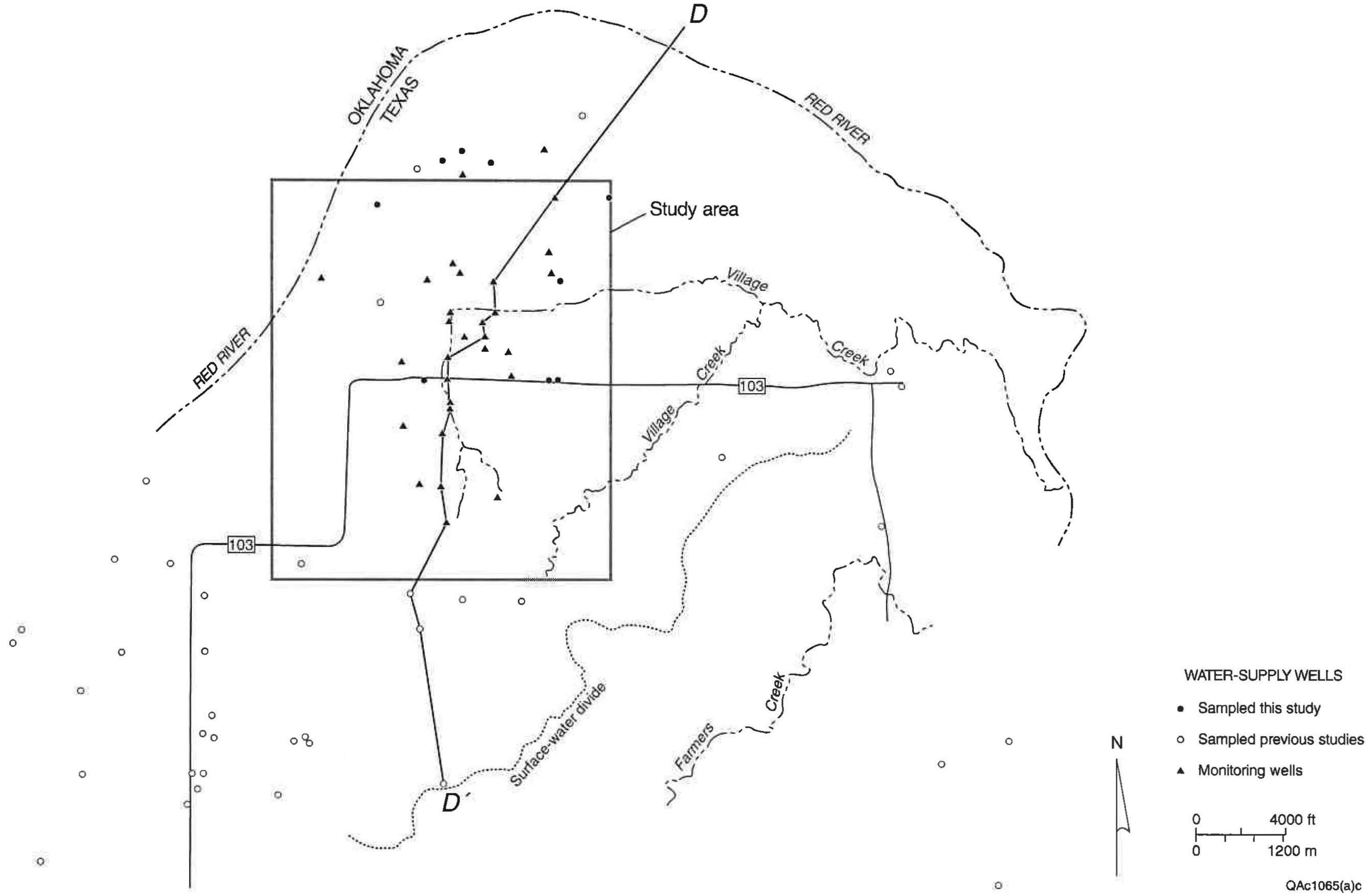


Figure 6. Location of water-supply wells within and near the study area sampled during this and previous studies. Data on well construction in table 1. Location of monitoring wells for comparison. Section D–D′ shown in figure 10.

Table 1. Construction data on water-supply wells.*

TWDB well no.	Latitude (°)	Longitude (°)	Aquifer code**	Date drilled	Land surface elevation (ft)	Well depth (ft)	Diameter (inches)
1903201	97.6886	33.9719	2	1963	801	150	5
1903301	97.6636	33.9783	2	1955	800	219	8
1903402	97.7297	33.9333	1	1930	809	67	8
1903403	97.7344	33.9236	2	1916	831	60	6
1903404	97.7261	33.9231	2	nr	848	72	6
1903405	97.7211	33.9189	5	nr	879	75	6
1903501	97.6967	33.9564	2	1930	812	175	7
1903502	97.6842	33.9283	5	1955	850	125	7
1903503	97.6678	33.9578	2	nr	788	100	6
1903504	97.6681	33.9456	2	1928	832	99	5
1903505	97.6681	33.9456	1	1948	832	40	10
1903506	97.7067	33.9228	5	nr	868	70	7
1903507	97.6903	33.9189	5	1953	890	108	6
1903508	97.6736	33.9178	5	nr	850	150	7
1903509	97.6825	33.9181	5	1959	885	200	5
1903601	97.6431	33.9356	3	1974	842	172[1]	6
1903701	97.7483	33.9150	2	1919	818	125	8
1903702	97.7497	33.9133	1	1959	794	72	7
1903707	97.7211	33.9119	5	nr	887	100[2]	6
1903710	97.7203	33.9039	5	nr	900	100	6
1903711	97.7397	33.9072	5	1938	857	119	6
1903712	97.7397	33.8967	5	1900	872	173	6
1903713	97.7461	33.8858	5	nr	828	280	6
1903714	97.7217	33.9017	5	1960	896	112	6
1903715	97.7200	33.9011	5	1954	927	145	6
1903717	97.7233	33.8967	5	1948	902	150	6
1903718	97.7217	33.8967	5	nr	902	200	5
1903719	97.7225	33.8947	5	1941	885	129	6
1903720	97.7242	33.8928	5	1929	869	225	7
1903721	97.7336	33.9119	5	1925	893	134	7
1903722	97.7106	33.8939	5	1955	885	137	6
1903803	97.7081	33.9006	5	1961	905	111	6
1903804	104.0342	33.9011	5	1920	923	126	6
1903806	97.6889	33.9144	5	1956	914	120	7
1903809	97.6858	33.8950	5	1955	900	360	4
1903810	97.7081	33.9006	5	nr	905	120[3]	4
1904401	97.6175	33.9461	5	1960	785	205	6
1904402	97.6192	33.9267	5	1962	824	205	7
1904403	97.6158	33.9442	5	1964	786	212	5
1904701	97.6106	33.8967	5	nr	826	268	6
1904702	97.6003	33.8994	4	1944	768	388	9
1904703	97.6022	33.8814	5	1951	820	150	7

* Compiled from ftp://rio.twdb.state.tx.us/gwdata/Montague/

** Aquifer code: 1 = Quaternary alluvium; 2 = Alluvium and Wichita Group; 3 = Paleozoic; 4 = Wichita and Cisco Groups; 5 = Wichita Formation or Group

nr not reported

[1] Well screen from depths of 138 to 160 ft

[2] Well screen from depths of 65 to 97 ft

[3] Well screen from depths of 100 to 120 ft

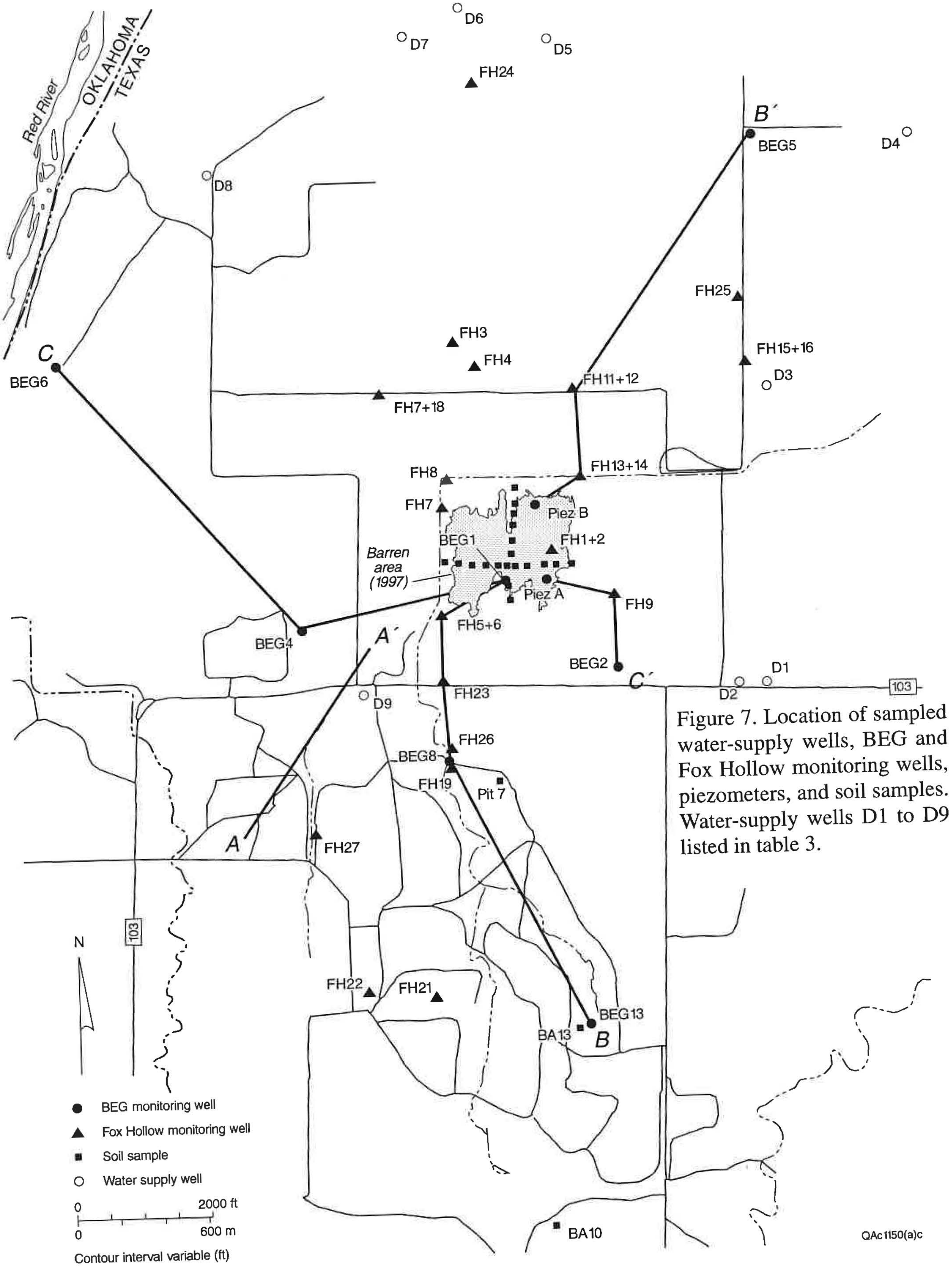


Figure 7. Location of sampled water-supply wells, BEG and Fox Hollow monitoring wells, piezometers, and soil samples. Water-supply wells D1 to D9 listed in table 3.

Well and Borehole Construction

Our strategy was to drill in various parts of the saline plume as well as areas with uncontaminated background characteristics to collect representative sediment and water samples at several different depths and over the geographic area of the plume. We used the airborne and TDEM surveys for guidance to target plume and background borehole and well locations. An initial list of 26 numbered possible sites was prepared, listed by approximate priority. The final selection of drilling locations was dependent on obtaining property-owner permission and having a substrate firm enough to support the truck-mounted drilling rig. We avoided siting drill holes in pit areas where surface oil contamination was observed because the scope of our study was focused on salinization.

We drilled seven boreholes using the BEG's CME Mobile 75 drilling rig. Various coring and drilling techniques were required to drill and sample boreholes in each part of the study area. In alluvial areas, we used hollow-stem auger coring as our preferred method to recover core having no contamination by drilling fluid. However, thick sections of saturated unconsolidated sand as well as intervals containing coarse gravel required a variety of drilling techniques, including mud rotary and auguring with a pilot bit in the core barrel (no core recovery), as summarized in table 2. In the upland, we push-cored the upper 10 feet, set temporary casing, and drilled with mud rotary through the indurated bedrock. Recovery was poor in unconsolidated sediments and poorly cemented bedrock. Monitoring well BEG 8 was reamed to create a nominal 8-inch hole to allow multiple completions.

BEG 1 was sited in the large barren area (MBA) on the Pleistocene terrace. The location was selected along the fence row where slightly higher elevation gave improved access across the loose sand for the drill rig. BEG 2 was located in a cropped field east of the barren area in an area of background conductivity, as shown on the airborne conductivity mapping. This borehole was intended to test background conditions and therefore was not completed as a monitoring

Table 2. BEG well construction.

Well number	Date completed	Drilling method	Total depth (ft bgl)	Screened intervals (ft bgl)	Filterpack intervals (ft bgl)	Bentonite seal (ft bgl)	Comments
BEG Montague 1	10/16/97	Hsa 0 to 18.8; pilot bit to 28.5; mud rotary to 34.4; drill to 53; mud rotary to 70.6	65.3	S 12–22 D 40–50	11–22 38–55	0–9 22–24 35–37	Hole collapse 52 to 70.6
BEG Montague 2	10/19/97	Hsa 0 to 33.6; pilot bit to 59.5; hsa 65.4; pilot bit to 76.0	76.0				Plugged and abandoned after coring, logging, and water sampling
BEG Montague 4	11/9/97	Hsa 0 to 18.5; pilot bit to 29; hsa to 39.0, hsa to 40; pilot bit to 44, hsa to 45, pilot bit to 54.0	54.1	S 10. 1–15.1 D 44.1–54.1	9.2–15.1	0–9.2 15.1–17.1	Hole collapsed around pipe to 17.1 ft
BEG Montague 5	11/7/97	Hsa 0 to 42.3, pilot bit to 54.5, hsa to 68.6	68.6	S 15.4–20.4 D 38.2–48.2	13.5–20.4 natural pack	0–13.5 22.4–20.4	Hole collapsed around pipe to 22.4 ft
BEG Monague 6	11/11/97	Hsa	28.7				Plugged and abandoned after coring, logging, and water sampling
BEG Montague 8	11/6/97	Push 0 to 10; mud rotary 94.9, ream 117.3	117.3	S 15.1–25.1 M 68.7–78.7 D 99.5–104.5	14.0–30.2 62.9–78.8 90.4–104.5	0–14.0 30.2–31.7 58.5–62.9 88.3–90.4	Drilled to 99.5 10/18/97; reamed to 117.3 11/6/97; collapsed to 104.5
BEG Montague 13	11/11/97	Push 0 to 10.5; mud rotary to 75.2	75.2	64.1–74.1	22–74.1	0–22	4-inch borehole, 10 ft to TD

well. BEG 4 was located over the west part of the conductive area identified by the airborne conductivity survey and is within the north part of the North Nocona field and beneath the Pleistocene terrace. The area is covered by grass and scrub vegetation. BEG 5 was located at the edge of a cropped field near the north end of the conductivity plume. BEG 6 was drilled above the William's seep near the west end of the conductive area identified by the airborne survey and is located in a plowed field on dunes rimming the Red River valley. The purpose of this borehole was to assess conditions in the source area of the spring. Access was limited because of soft ground in the cropped area and steep slopes on the Red River bluff. Drilling was terminated at auger refusal when bedrock was encountered and the borehole was plugged and abandoned. BEG 8 was located at the north edge of the Permian upland to examine the possible flow pathways in an area of conductive ground between the Permian upland and the Pleistocene terrace. Salt crusts were visible in the alluvium and bedrock was exposed in the drainage near BEG 8. BEG 13 was located in the upland several hundred feet downslope and presumably down gradient from a pit seen on the 1966 photograph.

One water sample was bailed from each borehole when water was first encountered. We put recovered core in flexible plastic tubing in core boxes and used standard BEG quality-assurance (QA) procedures for core labeling and recording recovery. Core and cuttings were examined in the field and detailed sediment and lithologic logs were prepared in the laboratory. Cores are stored at BEG Core Research Center and core logs are included in appendix 3. Well-registration forms are included as appendix 4.

In all boreholes, we installed new 2-inch schedule 40 PVC casing and slotted screen to total depth in order to maintain the hole. Field core and cutting descriptions were used to determine the depths of sand and gravel zones, and 5- or 10-ft-long screened sections were placed to sample the selected intervals. The casing was installed down the center of the hollow-stem auger flights because of the risk of hole collapse as the augers were removed.

Five boreholes were selected to be completed as monitor wells. Well design followed standard environmental drilling procedures and included a sand filter pack installed from 2 ft below to 2 ft above the screened interval, 2 ft of a bentonite seal above the sandpack, and bentonitic cement to ground surface (appendix 5). We completed four monitor wells within the plume at multiple depths by installing the deepest screen, sandpack, and overlying bentonite seal, then backfilling the borehole with cuttings to a shallower permeable interval, setting a bentonite seal, and installing additional 2-inch schedule 40 PVC pipe with a 5- or 10-ft-long screened interval and sandpack at the bottom (table 2; appendix 5). Bentonite was used to isolate each screened interval within the borehole. The purpose of these multiple completions was to obtain water samples from several depths within the plume and to investigate the vertical connection between several sand layers at several depths. In boreholes BEG 4 and 5, the collapse of unconsolidated sediments after the augers were removed constrained the placement of shallow screen. BEG 13 was not reamed and was completed with a 10-ft-long screened interval at the well's bottom with a sandpack to 20 ft below surface. After logging and sampling was complete, boreholes BEG 2 (outside of the plume area) and BEG 6 (a shallow borehole in a plowed area near the Williams complaint) were plugged and abandoned following procedures that meet TNRCC regulations.

Cuttings were temporarily stored on plastic sheets before being hauled off for disposal. Cuttings from the most saline areas were composited, analyzed, and taken for disposal to the Nunneley Ranch commercial pit disposal facility. Cuttings from areas of low or background salinity were disposed of downhole and any remaining cuttings were spread.

Downhole EM Logging

Borehole induction logs were acquired in October and November 1997 in seven BEG monitor wells and boreholes and nine FH monitor wells (appendix 5 and fig. 4) using the Geonics EM39 induction probe. The EM39 has a 50-cm transmitter-receiver coil separation, an operating frequency of 39.2 kHz, and a formation-penetration radius of about 1 m. Conductivity measurements were taken at 2.5-cm intervals in the borehole.

Downhole conductivity is a function of water content, water conductivity, pore volume and structure, and ion-exchange capacity of clay minerals (McNeill, 1980a; Schlumberger, 1989). Owing to their high cation-exchange capacity and large surface area per unit volume, clay-rich deposits typically have higher conductivities than do sand-rich deposits (McNeill, 1980a) in unsaturated conditions, or in saturated conditions when pore fluids are relatively resistive. When conductive fluids (for example, saline water) fill the pore volume, electrolytic conductivity (movement of ions in pore fluid) dominates all other sources of electrical conductivity. This effect causes sand-rich zones to have higher conductivities than clay-rich deposits despite the fact that the clay is more conductive than the sand.

Hydrological Measurements and Tests

Water levels were measured in the BEG and FH monitoring wells and in the two sets of drive-point piezometers. Water levels were measured using standard electrical probes.

We made hydrologic measurements of transmissivity and hydraulic conductivity at seven BEG monitoring wells in conjunction with collecting water samples for chemical analysis. The hydrologic tests consisted of unsteady-state drawdown and recovery tests with water-level changes measured in the pumping well. Before conducting a test, pumping rate was varied to determine an appropriate rate. Water level was allowed to recover before the drawdown phase of the test began. Discharge rate during the test was measured using a 5-gallon (18.9-L) bucket and a stopwatch. Water levels were recorded using a pressure transducer and programmable data logger attached to a laptop computer. After we completed the drawdown phase of the test, ground-water samples were collected and then the pump was turned off and water-level recovery was monitored. Produced water was pumped into drums or a storage tank on a vacuum truck and hauled off site for disposal. Tests were curtailed once the rate of change of water levels had nearly stabilized in order to minimize the cost of fluid disposal. The duration of the pumping phase of the tests was therefore short and generally ranged from 30 to 75 min; the first test in well BEG 1D lasted 130 minutes, whereas a repeated test ran 9 min. None of the tests showed evidence of a vertical hydrologic connection between completion zones.

We evaluated hydrologic test data by comparing them to standard type curves such as the Theis curve. The equation of the Theis curve describes an idealized transient response of water level that results from pumping a well, assuming that (1) the aquifer is homogeneous, isotropic, and of infinite extent, (2) the well fully penetrates the aquifer and has an infinitesimally small diameter, (3) water removed from storage is instantly discharged, and (4) water movement in the aquifer is only horizontal. If these assumptions are not met by actual conditions, water levels observed during a test will not match those predicted by the Theis equation. Comparing hydrologic test data to standard type curves and evaluating these assumptions can yield insight into hydrologic conditions affecting a test.

Comparing the test data to the type curves showed that in all cases drawdown was less than that predicted by the Theis equation. Information about subsurface stratigraphy, water-level change during drilling, and the hydrologic setting suggests that the drawdown response might partly reflect the leakage of water from water-bearing deposits with a permeability lower than that of the main aquifer zone. Accordingly, data were analyzed through comparison with standard type curves for a leaky (semi-confined) aquifer (Walton's method [Kruseman and De Ridder, 1990, p. 81]). Early-time drawdown data from tests in unconfined aquifers follow essentially the same type curve as data from leaky confined aquifers. Since leakage apparently was significant, transmissivity could not be accurately estimated on the basis of specific capacity or semi-log approximation techniques, such as the Jacob-Cooper or Theis-recovery methods. We relied accordingly on the curve-matching technique to interpret the test data.

Water-Chemical Composition

Analysis of water-chemical composition is based on (a) samples collected during this study from BEG and FH monitoring wells and from water-supply wells (fig. 7), and (b) results compiled from the TWDB data base (fig. 6). Most ground-water samples from BEG monitoring wells were collected at the end of the drawdown periods of the hydrologic tests, during which temperature and specific conductance were measured. At least 5 to 10 well-bore volumes (for monitoring wells BEG 5S, 8M, 8D) to more than 30 well-bore volumes (for monitoring wells 1S, 1D, 5D, 8S) of water were removed in these drawdown tests prior to the collection of water samples. The sample from BEG 6 was collected by a bailer after three well-bore volumes had been bailed. Three successive samples from BEG 13 were collected after four, six, and eight well-bore volumes were pumped out into drums. Ground-water samples from FH monitoring wells were collected after at least three well-bore volumes of water were produced. For FH monitoring wells that had only a small water column or low yield, water samples were bailed by a disposable bailer. FH monitoring wells with a greater water column or greater yield were sampled using a purge pump powered by a car battery. Samples from domestic water-supply wells were collected at faucets close to the well head and prior to water treatment. Domestic-well samples were collected after less than one well-bore volume of water was purged but most wells were being used; sampled domestic wells are shown in figures 6 and 7 and listed as D1 to D9 in table 3.

Temperature, pH, and specific conductance were measured at well sites. Alkalinity was also measured at well sites, or later in the day of sample collection, by potentiometric titration of unfiltered samples with a standard dilute (approximately 0.16 N) H_2SO_4 solution using a Hach digital titrator. Where a well pump was used, samples for the analysis of ionic constituents and dissolved metals were filtered through an in-line 0.45-mm cartridge filter attached at a tee to the discharge line. In addition, samples for the analysis of cations and metals were acidified using 1 mL of 6N HNO_3 per 125 mL sample (~1 percent by volume). Where a bailer was used, samples were filtered in the laboratory.

Ionic analyses were performed at the RRC Surface Mining and Reclamation Division Laboratory (RRC) and at DHL Analytical Laboratory (DHL) in Austin, Texas. Charge balance for ionic analyses was ±5 percent for 52 percent of BEG and FH water samples and ±10 percent

Table 3. Chemical composition of ground waters from water-supply wells.

Map no.	Sample code	Well name	Date sampled	Temp. (°C)	pH	Ca	Mg	Na	K	Sr	Ba	Cl	SO_4	HCO_3	SiO_2	NO_3	Br	TDS	Charge balance (%)
		1903201	06/17/64	20	8.1	2.8	2.1	386	0	0	nr	62	30	854	10	nr	nr	1,356	0.8
		1903301	03/05/64	25	8.5	1.4	1.4	450	0	0	nr	186	75	747	9	nr	nr	1,495	-0.4
		1903402	09/02/76	25	8.1	30	6	199	0	0	nr	230	12	253	12	nr	nr	742	-1.3
		1903403	10/07/63	21	7.3	94	25	58	0	0	nr	126	24	283	16	nr	nr	648	1.1
		1903404	10/10/63	19	7.2	49	16	17	0	0	nr	11	23	232	16	nr	nr	365	-1.6
		1903405	10/10/63	19	7	42	14	19	0	0	nr	42	20	149	15	nr	nr	301	0.2
		1903501‡	08/20/63	20	7.5	173	97	170	0	0	nr	620	75	336	11	nr	nr	1,482	-1.2
		1903502	02/20/64	16	7.8	82	25	49	0	0	nr	26	114	321	9	nr	nr	628	-0.9
D3	St8027	1903503†‡	10/23/97	23.1	7.79	86	21	417	<5	1.7	0.13	578	66	328	7	<1	4	1,504	2.5
	St8018	1903503*†‡	10/23/97	23.1	nm	101	24	441	<5	2.4	0.35	577	65	468	7	<1	3	1,686	1.9
		1903503	04/18/64	19	7.9	14	3	204	0	0	nr	34	61	446	10	nr	nr	774	1.1
D2	Ro8024	1903504†	10/23/97	17.1	7.14	99	19	131	<5	0.3	0.6	157	23	390	14	6	<1	835	4.1
		1903504	04/18/64	19	7.5	63	12	81	0	0	nr	69	13	317	15	nr	nr	583	0.2
D1	Ra8020	1903505†	10/23/97	23.5	8.2	17	5	164	<5	0.9	0.1	73	47	422	7	<1	<1	742	-9.1
		1903505	04/18/64	20	7.5	56	11	53	0	0	nr	48	13	258	16	nr	nr	471	-1
		1903506	10/10/63	22	7.4	105	27	120	0	0	nr	343	16	159	15	nr	nr	785	0.2
		1903507‡	10/31/63	20	7.4	308	48	57	0	0	nr	630	25	211	13	nr	nr	1,293	0.1
		1903508	02/11/64	18	7.5	128	30	116	0	0	nr	35	360	330	14	nr	nr	1,013	-0.1
		1903509	03/21/91	20	7.27	59	17	32	2.2	0.7	0.058	16	44	288	0	nr	<0.1	459	-2.7
		1903601	10/14/75	25	7.8	84	6	65	0	0	nr	21	80	332	19	nr	nr	607	-1.5
		1903701‡	09/25/63	25	7.7	26	10	1,020	0	0	nr	1,360	24	464	9	nr	nr	2,915	-0.1
		1903702‡	10/03/63	25	7.5	69	20	1,270	0	0	nr	1,810	162	330	7	nr	nr	3,668	0.4
		1903707	10/10/63	20	7.2	66	19	43	0	0	nr	143	16	132	17	nr	nr	437	1.3
		1903710	10/10/63	27	7	54	16	31	0	0	nr	98	25	120	17	nr	nr	361	0.9
		1903711	10/10/63	21	7.2	82	20	63	0	0	nr	26	60	398	17	nr	nr	667	-0.4
		1903712	10/10/63	25	7.8	46	11	237	0	0	nr	97	219	388	10	nr	nr	1,009	-0.7
		1903713	10/04/63	25	8.5	2.8	0.1	227	0	0	nr	37	41	483	10	nr	nr	811	-0.6
		1903714	10/14/63	25	7.6	100	13	26	0	0	nr	23	100	256	18	nr	nr	537	1.6
		1903715	10/14/63	20	7.3	95	12	25	0	0	nr	24	90	251	21	nr	nr	519	0.9
		1903717	10/14/63	20	7.3	94	27	99	0	0	nr	42	187	383	16	nr	nr	849	-0.8
		1903718	10/14/63	20	7.6	74	24	109	0	0	nr	49	133	378	16	nr	nr	784	0.2
		1903719	10/14/63	24	7.6	35	13	136	0	0	nr	41	99	334	15	nr	nr	675	-0.2
		1903720	10/17/63	25	7.8	52	17	160	0	0	nr	44	156	386	13	nr	nr	828	0.6

Table 3 (cont.)

Map no.	Sample code	Well name	Date sampled	Temp. (°C)	pH	Ca	Mg	Na	K	Sr	Ba	Cl	SO_4	HCO_3	SiO_2	NO_3	Br	TDS	Charge balance (%)
		1903721	10/31/63	19	7.1	35	10	20	0	0	nr	21	20	144	17	nr	nr	268	0.7
		1903722	10/14/63	20	7.7	129	33	263	0	0	nr	53	494	510	12	nr	nr	1,495	1.1
		1903803	10/14/63	21	7.4	181	50	75	0	0	nr	328	96	312	16	nr	nr	1,059	-0.1
		1903804	10/11/63	27	7	66	15	39	0	0	nr	94	69	129	21	nr	nr	439	-0.8
		1903806	10/18/63	19	7.2	115	25	42	0	0	nr	55	112	354	17	nr	nr	721	-0.8
		1903809‡	02/11/64	25	8.1	16	5	1,060	0	0	nr	1,320	116	514	8	nr	nr	3,041	-0.9
		1903810	03/26/91	20	7.35	57	16	25	1.3	0.5	<0.02	27	22	244	0	nr	<0.1	396	0
		1904401	02/10/64	10	8.7	2.2	0.38	188	0	0	nr	12	9	461	9	nr	nr	695	-1.3
		1904402	02/10/64	25	7.3	96	22	98	0	0	nr	72	76	439	19	nr	nr	823	0.1
		1904403	04/18/64	20	8.4	0.8	0.85	186	0	0	nr	16	24	442	10	nr	nr	685	-1.1
		1904701	02/06/64	25	8.8	1.6	0.1	202	0	0	nr	25	18	448	10	nr	nr	721	-0.6
		1904702	02/06/64	18	8.8	1.6	0.74	205	0	0	nr	25	20	434	10	nr	nr	714	1.2
		1904703	02/11/64	25	8.8	2	0.5	215	0	0	nr	50	26	427	9	nr	nr	747	-0.2
D4	8042	Lavy†	10/23/97	18.8	7.31	162	52	126	<5	0.82	0.03	264	92	465	14	68	1	1,245	-0.7
D5	8030	Pittman†	10/23/97	17.8	8.76	<5	<5	341	<5	0.07	<0.05	39	41	761	6	<1	<1	1,226	0.4
D6	8033	Brown No. 1†	10/23/97	16.8	7	<5	<5	221	<5	0.1	<0.05	51	84	703	7	<1	<1	1,087	-19.2
D7	8036	Brown No. 2†	10/23/97	17.7	8.81	<5	<5	226	<5	0.05	<0.05	39	107	397	7	<1	<1	798	1.3
D8	8039	Koontz†	10/23/97	17.7	8.35	6	<5	147	<5	0.23	0.06	28	63	313	7	<1	<1	573	-1.7
D9	8045	Goolsby†	10/24/97	nm	7.39	147	41	159	<5	2.5	<0.05	226	227	376	11	<1	<1	1,189	1.4

*	Duplicate
†	Sample collected by Bureau of Economic Geology; all others from Texas Water Development Board
‡	Sample with elevated chlorinity and salinity
nr	not reported
nm	not measured

for 94 percent of the samples. Charge balance for all analyses taken from water-supply wells reported by TWDB was ±2 percent. Four blind duplicates and six sample splits were analyzed for waters collected from BEG and FH monitoring wells and one water-supply well. Error in total dissolved solids (TDS) for blind duplicates ranged from 2 to 12 percent. The amount of error for split samples analyzed at different laboratories varied with TDS and ranged from 0.3 to 18 percent.

Soil Sampling

The salt content of the unsaturated soil and sediment was assessed by sampling the upper parts of cores. In the laboratory, core samples were cleaned by removing the surface-smeared zone and cutting a 0.1- to 0.2-ft-long core section at 0.5- to 5-ft intervals. Sample spacing was based on observed changes in lithology, soil profile, and evidence of salinity observed when sampling the core.

Limited surface soil analysis was done in selected barren areas and pits to assess the concentration of salts and document the reason for sparse vegetation. In the largest observed main barren area (MBA) in the cropped part of the Pleistocene terrace, soil was sampled at 200-ft intervals along a north-south and an east-west transect (fig. 7). The upper 5 inches of soil was sampled using a shovel. The purpose of this analysis is to measure the near-surface accumulation of salt and compare the soil to brine chemistry. In the upland areas within the North Nocona oilfield, the locations of former saltwater disposal pits can be identified using the 1966 air photograph (appendix 6). Inspection of these former pit sites showed that berms and ponds evident in the 1966 photograph appear to have been leveled with a bulldozer. Remaining evidence of pits includes irregular topography, local crusts of oxidized oil or tank bottom material, local gullying, sparse vegetation, and minor debris. Representative soil or sediment grab samples were collected using a shovel at depths of 0- to 0.5- and 0.5- to 1-ft depths from the soil within former pits and associated barren areas (Pit7, BA10, and BA13, fig. 7) to document the salinity and oil content in these areas.

Core and surface samples were labeled with abbreviations signifying location and depth, bagged, and submitted to the RRC Surface Mining and Reclamation Division Laboratory for analyses of water soluble components from 1:1 extracts. Samples in which evidence of oil contamination was observed were also submitted for TPH. Because salinity was the focus of our study, we did not systematically sample or analyze to document the extent of oil contamination in pits.

GIS and GPS Analyses

We prepared site maps by merging various data sets using ESRI ARC/INFO and Arcview Geographic Information System (GIS) software. Roads, topography, and creeks and drainage were digitized from the USGS Prairie Valley School 1:24,000-scale quadrangle (appendix 7). Location and types of oil and gas wells were imported from digital files supplied by the RRC; digital water-supply well locations were supplied by the TWDB. A 1966 black-and-white air photograph from BEG files was digitized (appendix 6) and used for a historic base map. The 1966 photo shows the location of many former pits. The photograph was georeferenced using DGPS (Differential Global Positioning System) locations on prominent features, corrected for distortion, and imported into Arcview. DGPS was also used to collect locations for BEG and FH wells, boreholes, piezometer nests, and surface samples. Ground elevation at boreholes was then interpreted from the USGS Prairie Valley School 1:24,000-scale quadrangle. A 1995 color-infrared photograph of the area was scanned to examine the distribution of vegetation and the extent of the barren area.

RESULTS

Stratigraphy

Bedrock

The outcropping and shallow subsurface Permian units of the Nocona Formation (Wichita Group) in the study area are composed of continental redbeds containing stacked sequences of chert granule conglomerate, cross-bedded sandstone, siltstones, mudstones, and shale. Correlation of commercial wireline SP and resistivity logs of oil wells shows that fresh water (resistivity >20 ohm-m) extends to depths of 150 to 200 ft below land surface in sandstones of the Nocona Formation (fig. 3). Oil wells were cased in the upper 100 ft, therefore providing no information about the near surface salinity; however, they document the thickness and continuity of the fresh-water aquifer overlying natural saline water across the North Nocona field. At more than 200 ft below surface, SP deflection and resistivities greater than 20 ohm-m in sandstones indicate that pore fluids are saline. Log quality in the fresh-water section, and truncation of log traces at surface casing, preclude interpretation of detailed sandstone geometry in this unit.

Six cores collected during our study penetrated Permian bedrock (figs. 8 and 9). In addition, several bedrock outcrops in the study area were examined. Lithologies include poorly indurated chert granule conglomerate, and strongly to poorly cemented sandstone, siltstone, mudstone, and nonfissile shale. Cross bedding, mud rip-up clasts, and lignite fragments are abundant in coarser (granule to medium sand) units interpreted as fluvial channel facies. Decimeter-scale fining-upward sequences and sharp contacts composed of finer grained medium-to-fine sand, silt, and clay are interpreted as upper point-bar channel fill or overbank channel-margin facies.

Thick sections of claystone and mudstone regionally interpreted as mud-flat deposits (Hentz, 1988) were encountered in BEG 5. Sedimentary structures include mottles, lamination, mudcracks, and fabric resembling pedogenic carbonate.

The north-south cross section (fig. 8) shows that channel facies complexes are laterally equivalent to mudstone deposits, a characteristic typical of these facies regionally (Hentz, 1988). Fluvial channel facies having coarse grain size and probably having high permeability interfinger with bedded sandstone and siltstone channel fill and overbank deposits of lower permeability. Wireline log quality and core density are insufficient to map the geometry of channel facies in the Nocona Formation in the area.

Core examination shows that surface processes, including oxidation to red colors observed in outcrop, precipitation of limonite cements forming nodules and thick rims on clay chips, and possible dissolution of calcite cements, have altered bedrock and possibly enhanced permeability in the upper 50 ft of the section. Poor core recovery is interpreted as evidence of cement dissolution. Below the altered interval, sandstones are generally gray, mud clasts are soft and gray, and sand and gravel appear to be better cemented. Well-cemented low-permeability sandstone was found in thin intervals in several cores. Several high angle fractures were observed in shales and in sandstones. Some of the fractures were mineralized in sandstone and slickensided in shale, suggesting that natural fracturing may enhance permeability in the subsurface.

Alluvium

All seven cores collected during this study recovered Quaternary sediments. The major lithologies are cobble-to-granule-sized gravel with variable amounts of admixed silt and clay, well sorted to poorly sorted sand, and clay with admixed gravel, sand, and silt.

Quaternary and Permian gravels are compositionally distinct; the former contain large cobbles of milky vein quartz in addition to reworked Permian material. Gravel is found in the subsurface Pleistocene terrace deposits in two wells—BEG 1 and BEG 4 (fig. 9). Recovery of gravel and cobbles was poor and bed thickness was inferred from drilling speed, cuttings, and core recovery. The amount and type of matrix in the gravel is unknown.

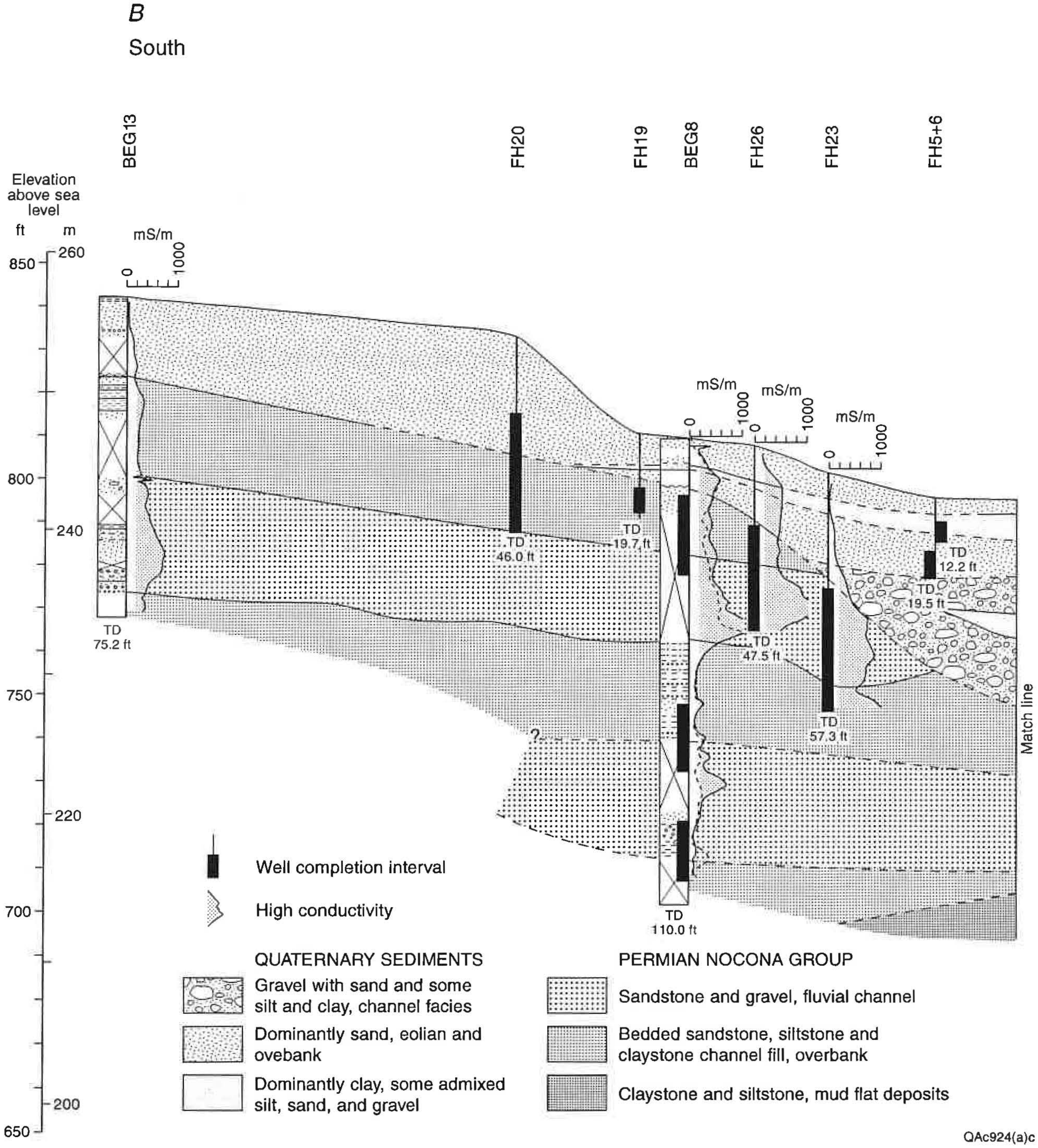


Figure 8. Site north–south stratigraphic cross section. Line of section B–B′ shown in figure 7.

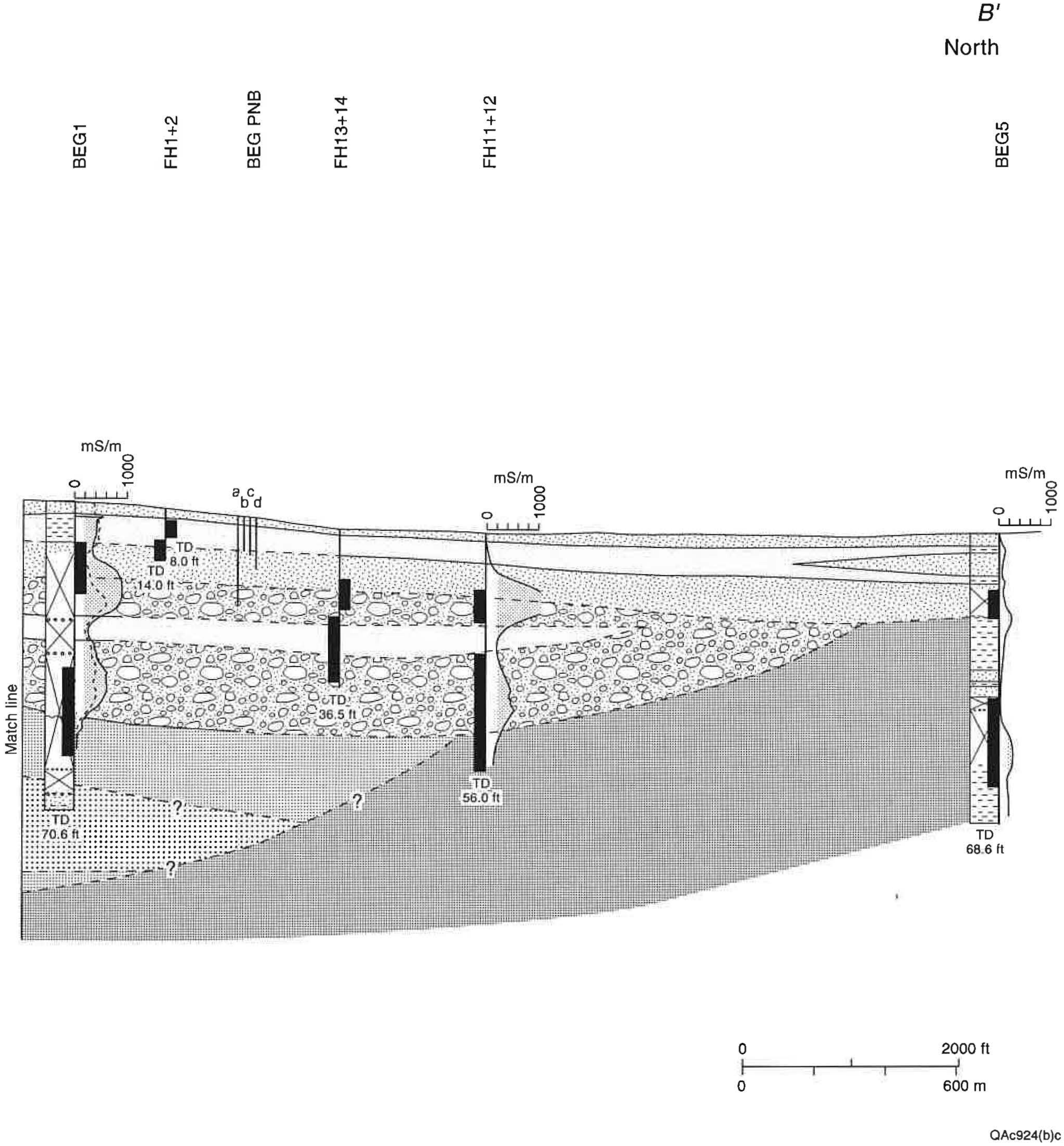


Figure 8. (cont.)

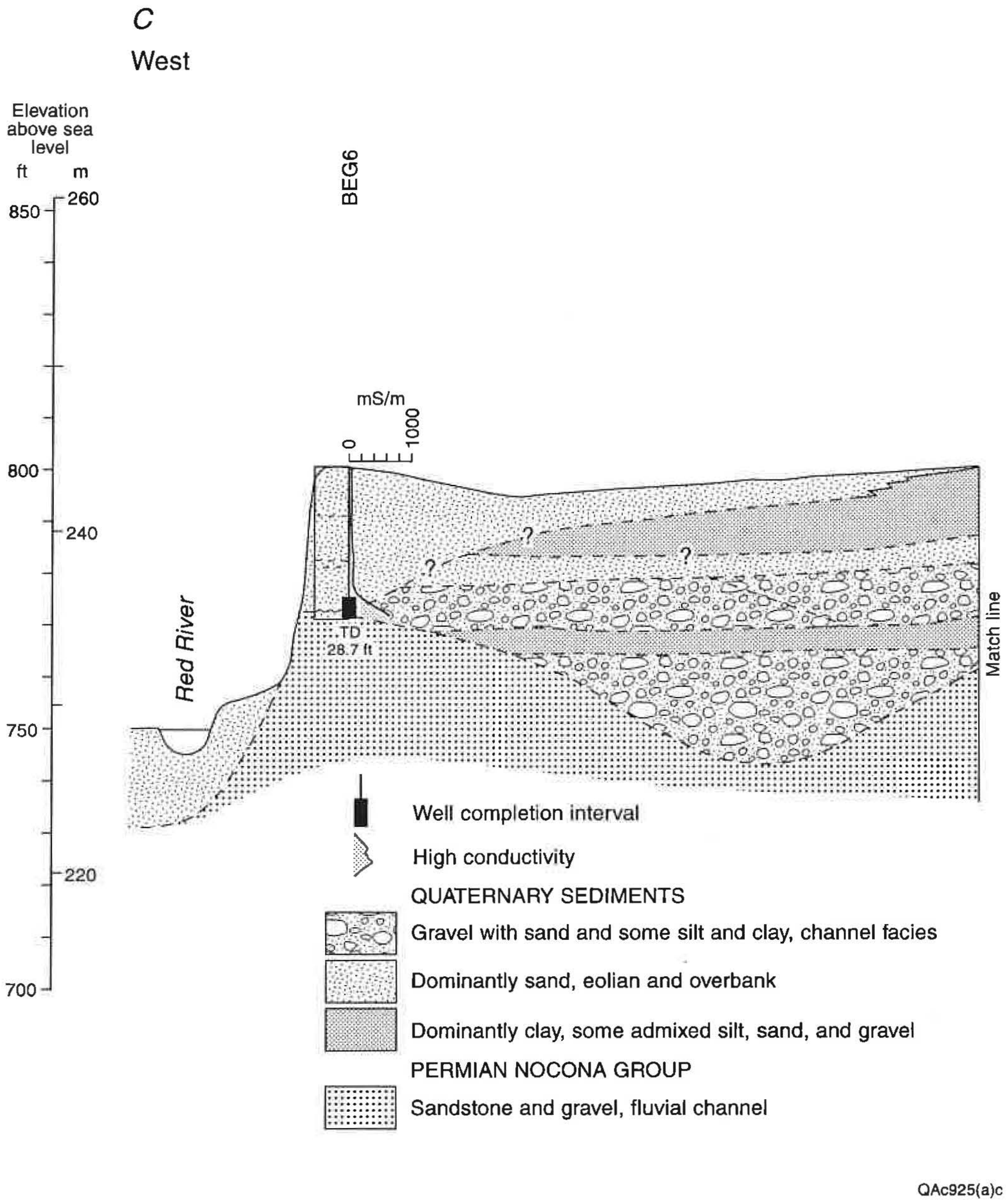


Figure 9. Site east–west stratigraphic cross section. Line of section C–C′ shown in figure 7.

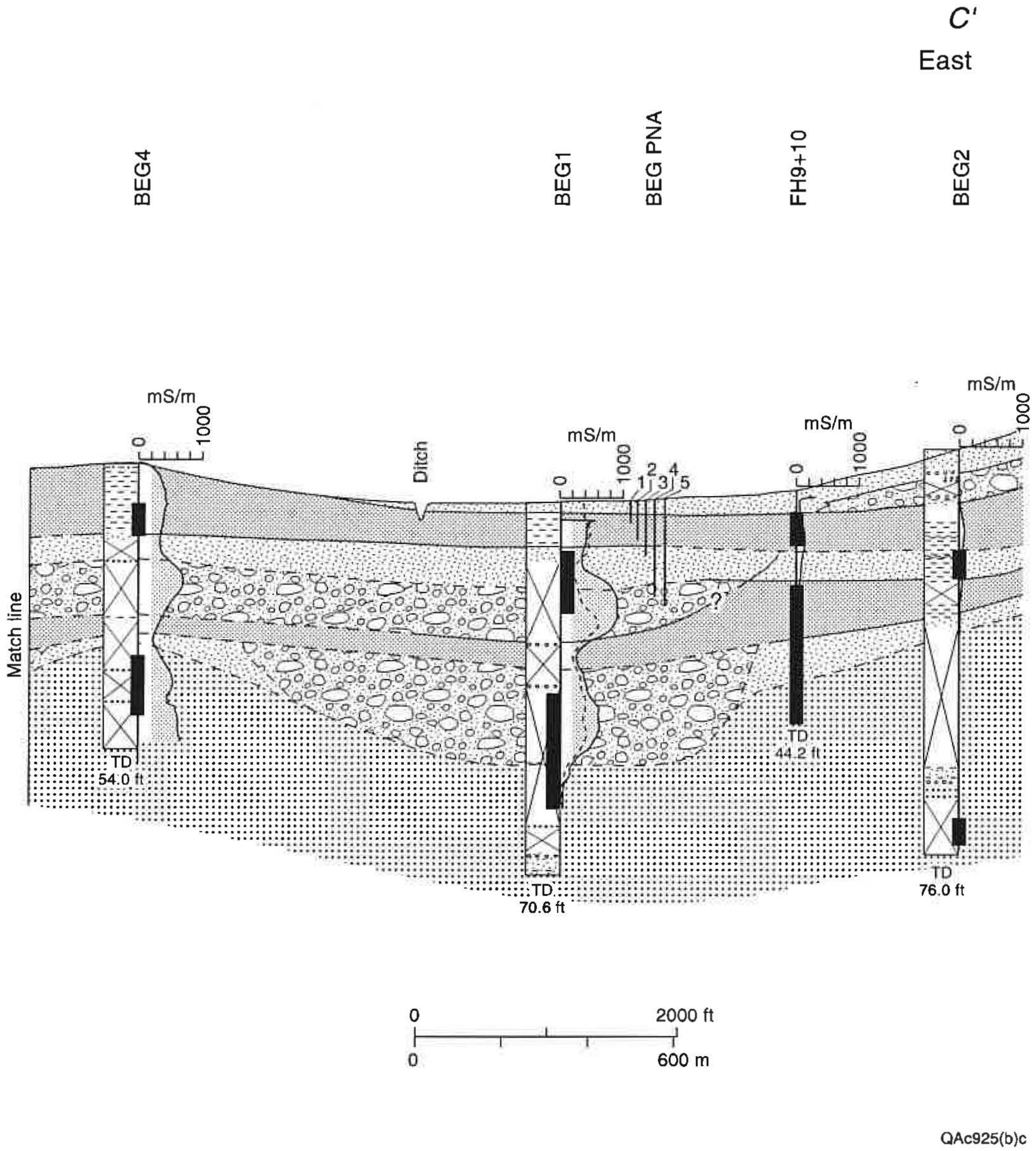


Figure 9 (cont.)

Composition and texture of the sand in the area suggests that it is derived from admixtures of sand from three sources: (1) weathering of local Permian sandstone, (2) sand transported down the paleo-Red River and deposited in channel bars, and (3) sand reworked from modern and paleo-Red River channel bars and deposited as dune and eolian sheet sands. Sand derived from local weathering of Permian bedrock is found in the uplands and is characterized by poor sorting with abundant clay and pebbles. Increases in thickness and extent of surficial deposits toward the Red River obscure local bedrock geology shown on aerial photographs; eolian sand may also make up part of these deposits. Local high gravels are found as surficial deposits in the area (Frye and Leonard, 1963). The BEG 8 well cored 0.5 ft of porous clayey carbonate interpreted as a spring deposit formed at the base of the upland bedrock.

Sand transported by dominantly eolian processes is well sorted with fine to very fine grain size. Thick intervals of dominantly eolian sand of Pleistocene age were cored at BEG 5 (fig. 8) and BEG 6 (fig. 9) near the modern Red River. This homogeneous permeable material has been slightly modified by pedogenic processes that have added minor amounts of clay, carbonate, and manganese, and have created features such as root tubules and weak peds.

Poorly sorted, generally fine-grained fluvial-overbank deposits having strong pedogenic overprints were cored at depths beneath 5 ft in cores from BEG 1, 2, and 4. The section at BEG 4 contains several stacked depositional units, one having a preserved A-soil horizon at the top. The recovered upper 15 feet, however, is all fine grained and dominated by clay. At BEG 1 and 2, the fine-grained interval composed of interbedded sand and clay is overlain by 2 to 5 ft of fine silt and sand of possible eolian origin at the surface.

Hydrologic Head

Two predominant hydrogeologic units or aquifers are distinguished in the study area. One is composed of Permian bedrock and the other of Pleistocene and Holocene alluvium. The Permian bedrock aquifer underlies the entire study area and is covered locally by the alluvial aquifer beneath the terrace and the Red River floodplain. Stratigraphic horizons within these aquifers differ in their hydrologic properties but are not broken out as distinct aquifers.

Hydraulic heads measured in monitoring wells during this study are listed in table 4. Older hydraulic-head data reported for water-supply wells are also included in table 4. The shallowest ground water tends to be unconfined. For example, ground water is unconfined in test zones at wells BEG 1S, 5S, and 8S. The water table in these zones lies within the permeable zone that makes up the flow unit at those sites. Ground water at greater depths occurs under varying degrees of confinement depending on the depth, thickness of local confining layers, and stratigraphy. For example, ground water at depths of 33 to 55 ft at BEG 1D appears to be confined by a clay bed within the alluvial aquifer, and rises to a height of 26 ft above the top of the permeable zone. This interval is in hydrostatic equilibrium with the unconfined ground water measured in BEG 1S.

Figure 10 presents a regional cross section that extends from the Red River to beyond the surface-water divide in the upland area south of the site. The cross section includes the BEG and FH monitoring wells and deeper domestic water-supply wells that lie near or along the line of the section (table 4). The profile of the water table marks the top of the saturated zone. Depth to water is greater beneath the upland area than beneath the terrace underlain by Quaternary sediments. Hydraulic head decreases from more than 870 ft beneath the upland area to between 790 and 770 beneath the terrace. Hydraulic head beneath the Holocene terrace along the Red River is projected to be less than 740 ft, but no measurements were made there in this study. The horizontal gradient in hydraulic head is greater beneath the upland area than beneath the relatively flat-lying terrace. Inclination of the equipotential contours indicates that hydraulic head decreases with depth, so there are both downward vertical and lateral components of ground-water movement beneath the upland area and adjacent to the Red River floodplain. This implies that ground water is recharged in the upland area in Permian bedrock, moves generally north, and passes into Quaternary sediments beneath the terrace.

Table 4. Hydraulic-head data.

Monitoring well	Ground-level elevation (ft)	Well depth (ft)	Well-bottom elevation (ft)	Date measured	Depth to water bgl (ft)	Hydraulic head (ft)
Monitoring Wells						
BEG-1S	794	23.52	770.5	10/17/97	5.82	788.18
				10/24/97	6.54	787.46
				11/10/97	6.62	787.38
				11/11/97	6.73	787.27 *
				03/03/98	2.4 †	791.6
BEG-1D	794	62.45	731.6	10/17/97	5.82	788.18
				10/24/97	5.84	788.16
				11/10/97	6.44	787.56
				11/11/97	6.75	787.25
				03/03/98	2.2 †	791.8
BEG-2	804	75	729	10/19/97	16.93	787.07 *
BEG-4S	798	15.1	782.9	11/13/97	7.75	790.25 *
				3/3/98	4.9 †	793.1
BEG-4D	798	54.1	743.9	11/13/97	11.02	786.98
				3/3/98	4.2 †	793.8
BEG-5S	789	20.4	768.6	11/13/97	11.39	777.61 *
				11/14/97	11.70	777.30
BEG-5D	789	48.2	740.8	11/13/97	11.61	777.39
				11/14/97	11.59	777.41
BEG-6	800	30.85	769.2	11/12/97	24.21	775.79 *
BEG-8S	810	25	785	11/12/97	16.97	793.03
BEG-8M	810	78.7	731.3	11/12/97	8.73	801.27 *
BEG-8D	810	104.5	705.5	11/12/97	9.41	800.59
BEG-13	843	77.5	765.5	11/13/97	25.68	817.32 *
FH-1	793	13.99	779	10/22/97	5.45	787.55
				11/11/97	5.37	787.63 *
FH-2	793	8	785	10/22/97	5.38	787.62
				11/11/97	5.43	787.57
FH-3	791	15.97	775	10/22/97	8.90	782.10 *
FH-4	792	15.07	776.9	10/22/97	7.97	784.03 *
				11/13/97	11.34	780.66
FH-5	795	19.5	775.5	10/22/97	7.68	787.32 *
FH-6	795	12.23	782.8	10/22/97	7.68	787.32
FH-7	793	13.95	779.1	10/22/97	6.48	786.52
				11/11/97	6.43	786.57 *
FH-8	793	14.37	778.6	10/22/97	6.03	786.98
				11/11/97	6.00	787.00 *
FH-9	796	46.34	749.7	10/15/97	7.60	788.40
				10/22/97	7.30	788.70
				11/11/97	6.93	789.07
FH-10	796	12.38	783.6	10/22/97	7.26	788.74
				11/11/97	6.96	789.04 *

Table 4. (cont.)

Monitoring well	Ground-level elevation (ft)	Well depth (ft)	Well-bottom elevation (ft)	Date measured	Depth to water bgl (ft)	Hydraulic head (ft)
FH-11	789	58.29	730.7	10/15/97	7.41	781.59
				10/22/97	6.62	782.38
FH-12	789	22.55	766.5	10/22/97	6.94	782.06 *
FH-13	790	38.69	751.3	10/22/97	5.43	784.57
FH-14	790	21.17	768.8	10/22/97	5.47	784.53 *
FH-15	786	26.77	759.2	10/22/97	7.14	778.86
				11/13/97	6.93	779.07
FH-16	786	10.92	775.1	10/22/97	7.01	778.99
				11/13/97	6.65	779.35 *
FH-17	793	15.38	777.6	10/22/97	9.67	783.33
				11/13/97	9.55	783.45 *
FH-18	793	40.84	752.2	10/22/97	9.46	783.54
				11/13/97	9.29	783.71
FH-19	810	19.69	790.3	10/22/97	7.47	802.53
				11/11/97	7.43	802.57 *
FH-21	839	36.87	802.1	10/15/97	19.05	819.95
				10/22/97	19.19	819.81
				11/11/97	19.29	819.71 *
FH-22	851	60.03	791	10/15/97	35.67	815.33
				10/22/97	35.70	815.30 *
FH-23	802	59.69	742.3	10/14/97	12.60	789.40
				10/22/97	12.80	789.20
				11/11/97	12.89	789.11 *
FH-24	800	41.34	758.7	10/15/97	20.79	779.21
				10/22/97	20.77	779.23
				11/13/97	20.92	779.08 *
FH-25	787	11.79	775.2	10/22/97	8.36	778.64
				11/13/97	8.25	778.75 *
FH-26	809	47.49	761.5	10/15/97	10.06	798.94
				10/22/97	10.12	798.88
				11/11/97	10.10	798.90 *
FH-27	820	39.95	780.1	10/15/97	11.71	808.29
				10/22/97	11.96	808.04
				11/11/97	12.08	807.92 *
			Water-supply wells			
1903201	801	150	651.0		65.00	736.00
1903301	800	219	581.0		30.00	770.00
1903503	788	100	688.0		9.00	779.00
1903501	812	175	637.0		73.10	738.90
1903502	850	125	725.0		37.50	812.50
1903506	868	111	757.0		0.00	868.00
1903806	914	120	794.0		40.00	874.00
1903509	885	200	685.0		64.98	820.02
1903508	850	150	700.0		50.00	800.00

† Measured by R. Horton, RRC District 9 Office

* Used in mapping potentiometric surface

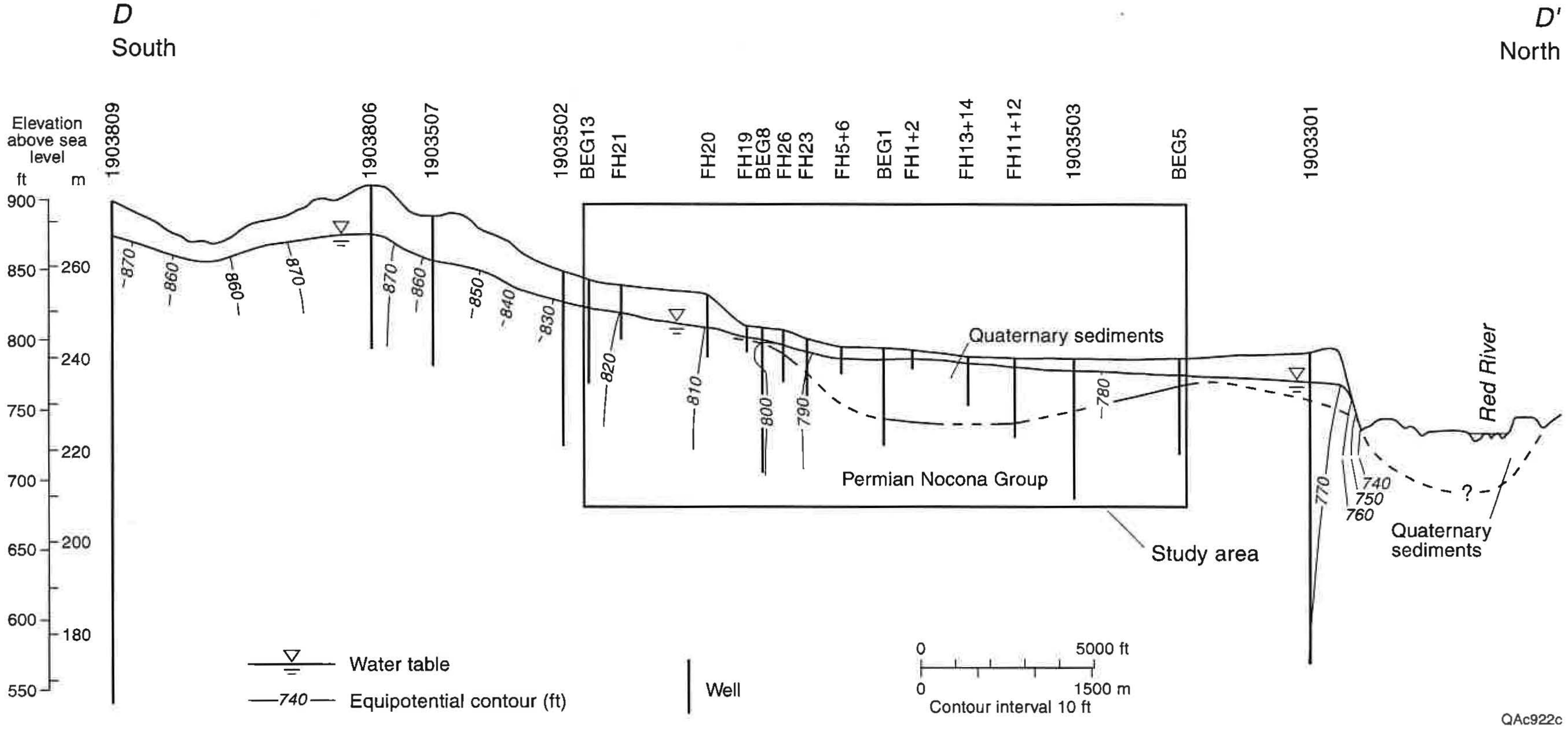


Figure 10. Regional north–south cross section of hydraulic head. Box shows area detailed in figure 11. Line of section D–D′ shown in figure 13. Data on hydraulic head in table 4. Data on well construction in tables 1 and 2.

Figures 11 and 12 show in greater detail the variations in hydraulic head beneath the study area. The equipotential or hydraulic head contours in figures 10 to 12 measured hydraulic head and are consistent with standard conceptual models (Hubbert, 1940; Tóth, 1963, 1978; Freeze and Witherspoon, 1967). There is little vertical gradient in hydraulic head beneath the Quaternary terrace measured in several paired wells. Equipotential contours beneath the terrace, therefore, are drawn without an inferred upward or downward gradient. One exception is the paired measurement of head at wells 4S and 4D, at which a local downward-directed gradient is evidenced. Another exception is the below-hydrostatic hydraulic head measured at BEG 8S; hydraulic head at that well might be influenced by the adjacent incised drainage. Thus, hydraulic-head data imply predominantly horizontal movement of shallow ground water beneath the terrace, both above and beneath the clay bed. These data alone show no strong evidence for much recharge taking place locally across the terrace. As will be shown, some recharge is suggested by data on water chemical composition.

The hydrologic section E–E′ (fig. 11) is aligned approximately with a possible ground-water flow path. The west end of section F–F′ (fig. 12) might also be aligned with a local flow path. The hydraulic-head gradient drawn in the vicinity of well BEG 6 (fig. 12) near the Red River implies a potential for downward flow. The east end of section F–F′, between wells BEG 1 and BEG 2, shows no lateral gradient because the section in that area is perpendicular to the regional flow path.

Figures 13 and 14 are regional and study-area representations, respectively, of the potentiometric surface, and are drawn on the basis of measured water levels from BEG and FH wells (table 4) and have some interpretation guided by local topography. A plan-view potentiometric surface is commonly used to infer directions of horizontal movement of ground water, although this assumes that vertical gradient in hydraulic head is insignificant and hydraulic conductivity is homogeneously distributed. Vertical variations in hydraulic head, suggested in the cross sections (figs. 10 through 12), insignificantly affect the plan-view maps, given the latters' contour intervals of 5 to 10 ft. Contouring of the potentiometric surface across

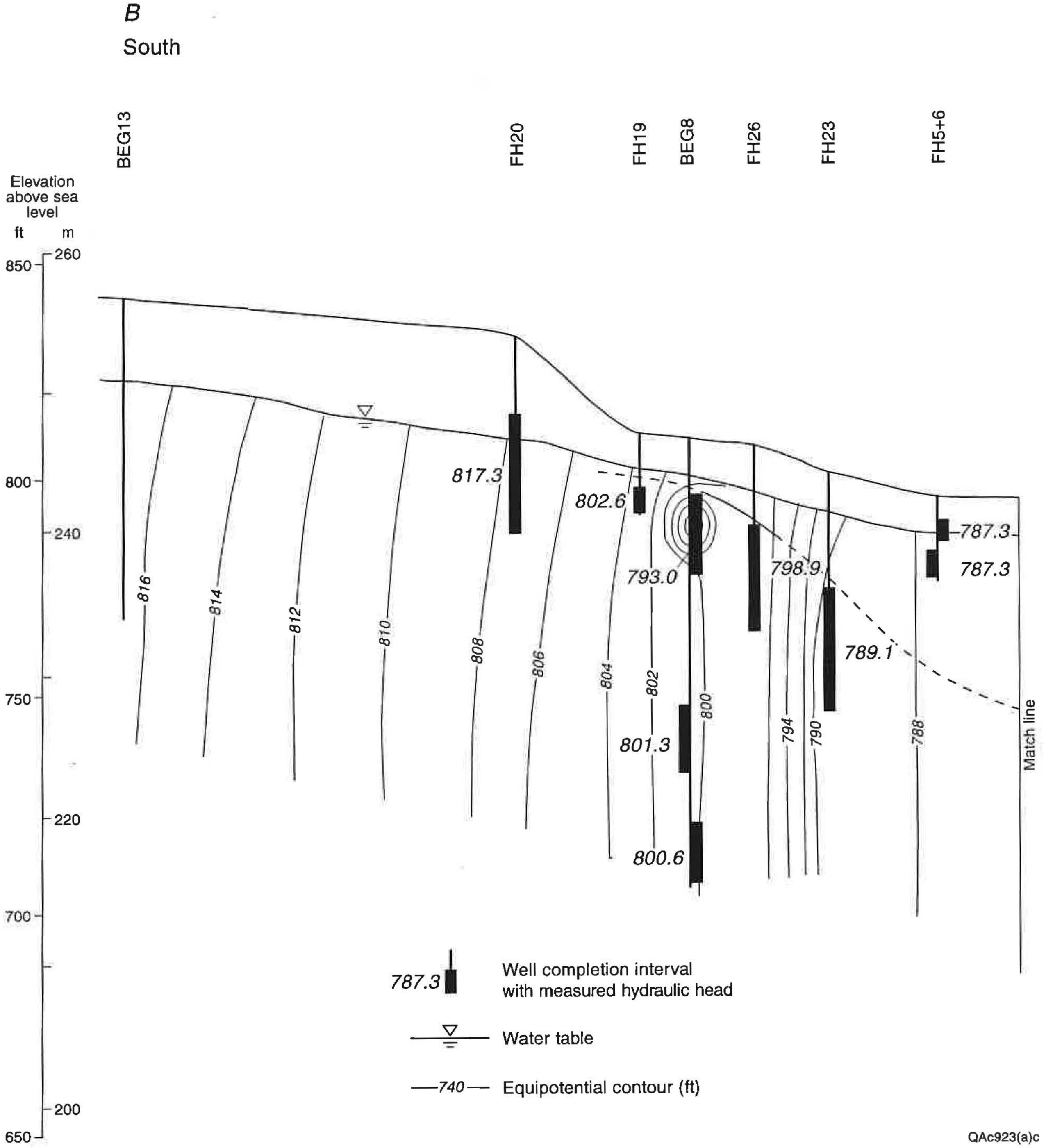


Figure 11. Study area north–south cross section of hydraulic head. Line of section B–B′ shown in figure 7.

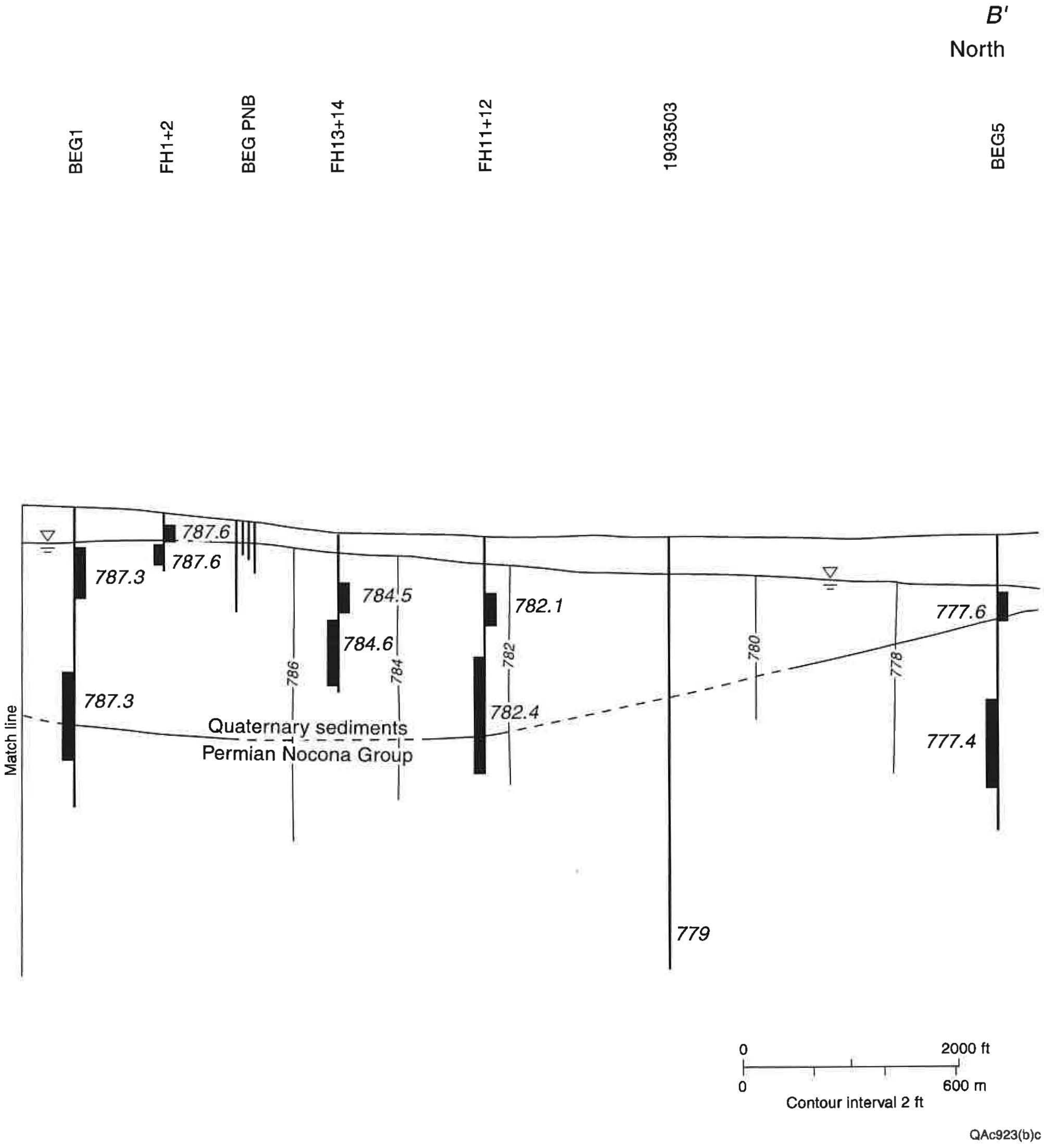


Figure 11 (cont.)

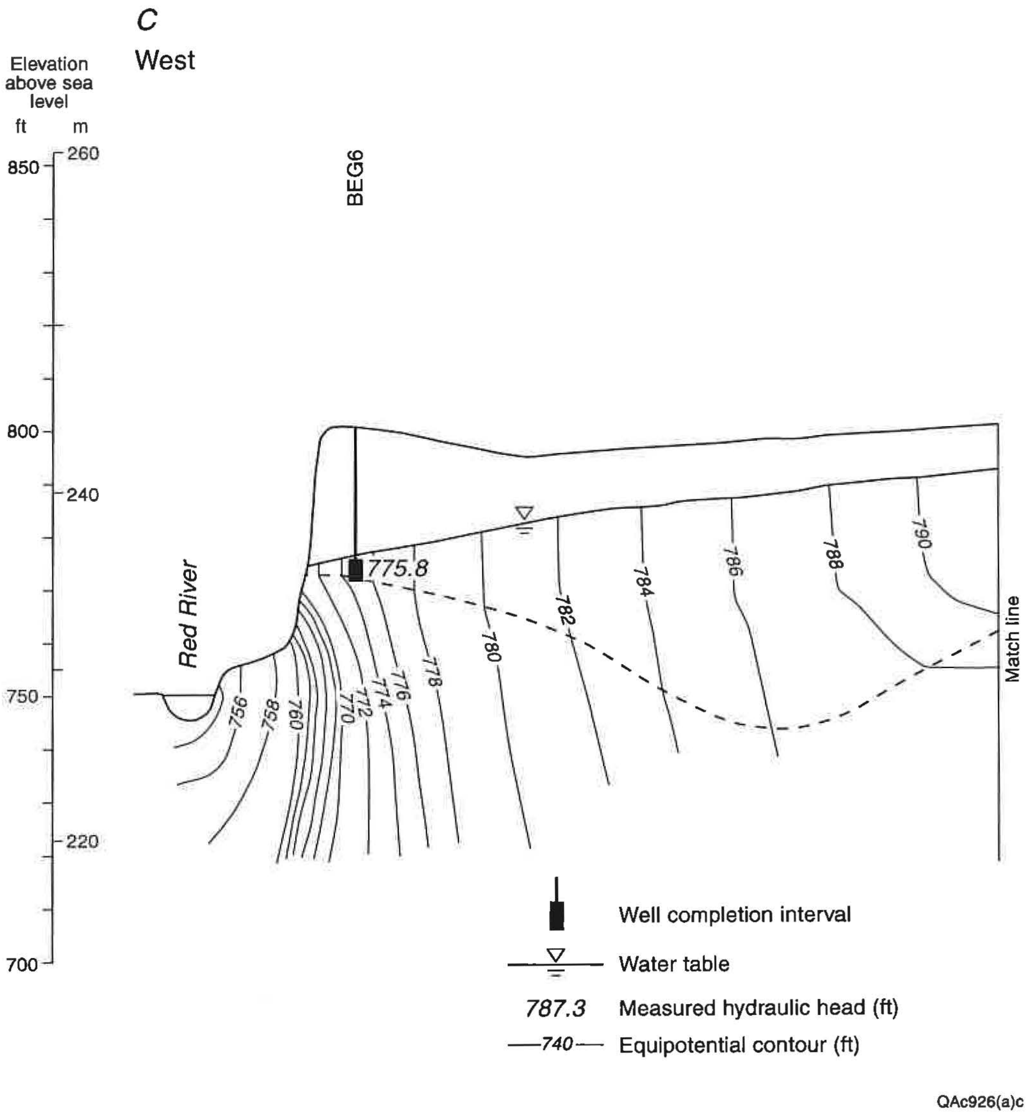


Figure 12. Study area east–west cross section of hydraulic head. Line of section C–C′ shown in figure 7.

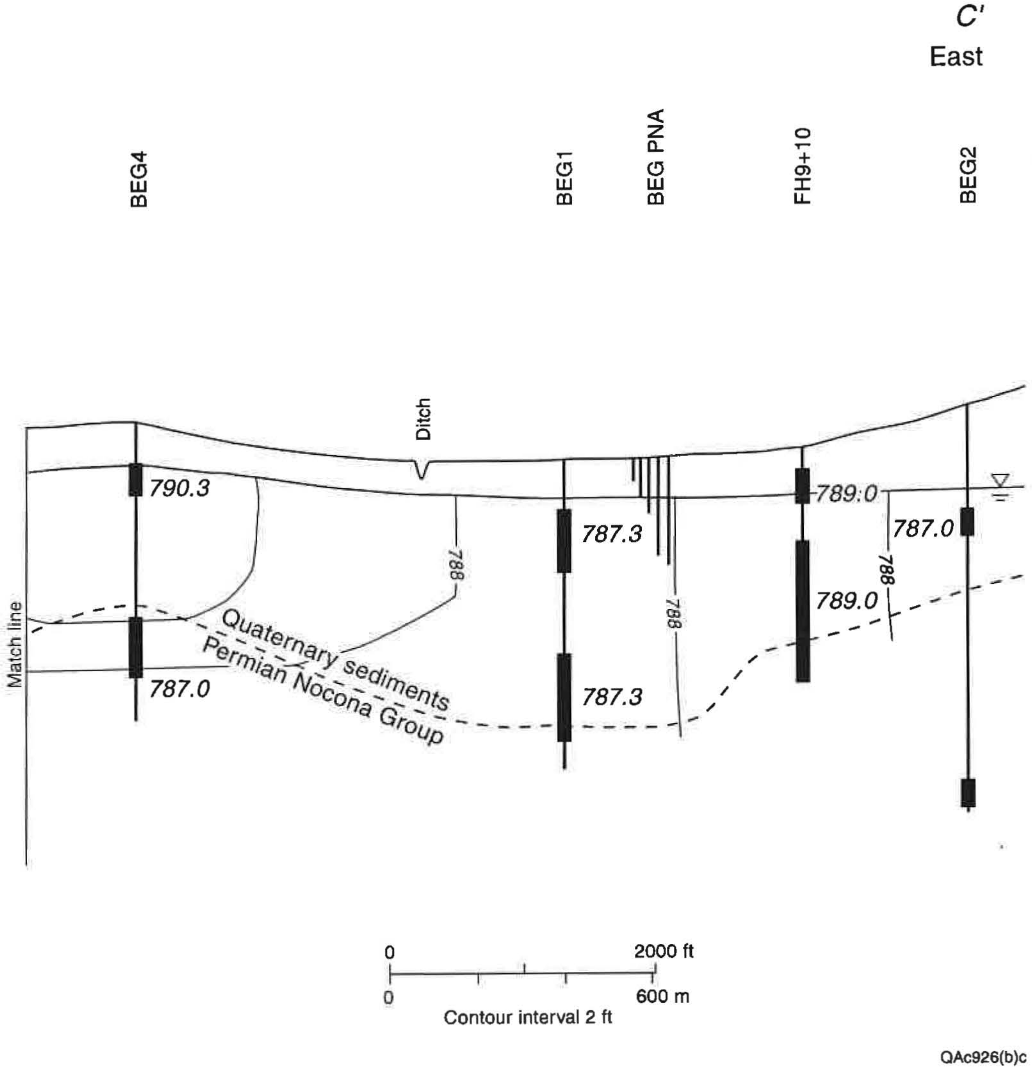


Figure 12 (cont.)

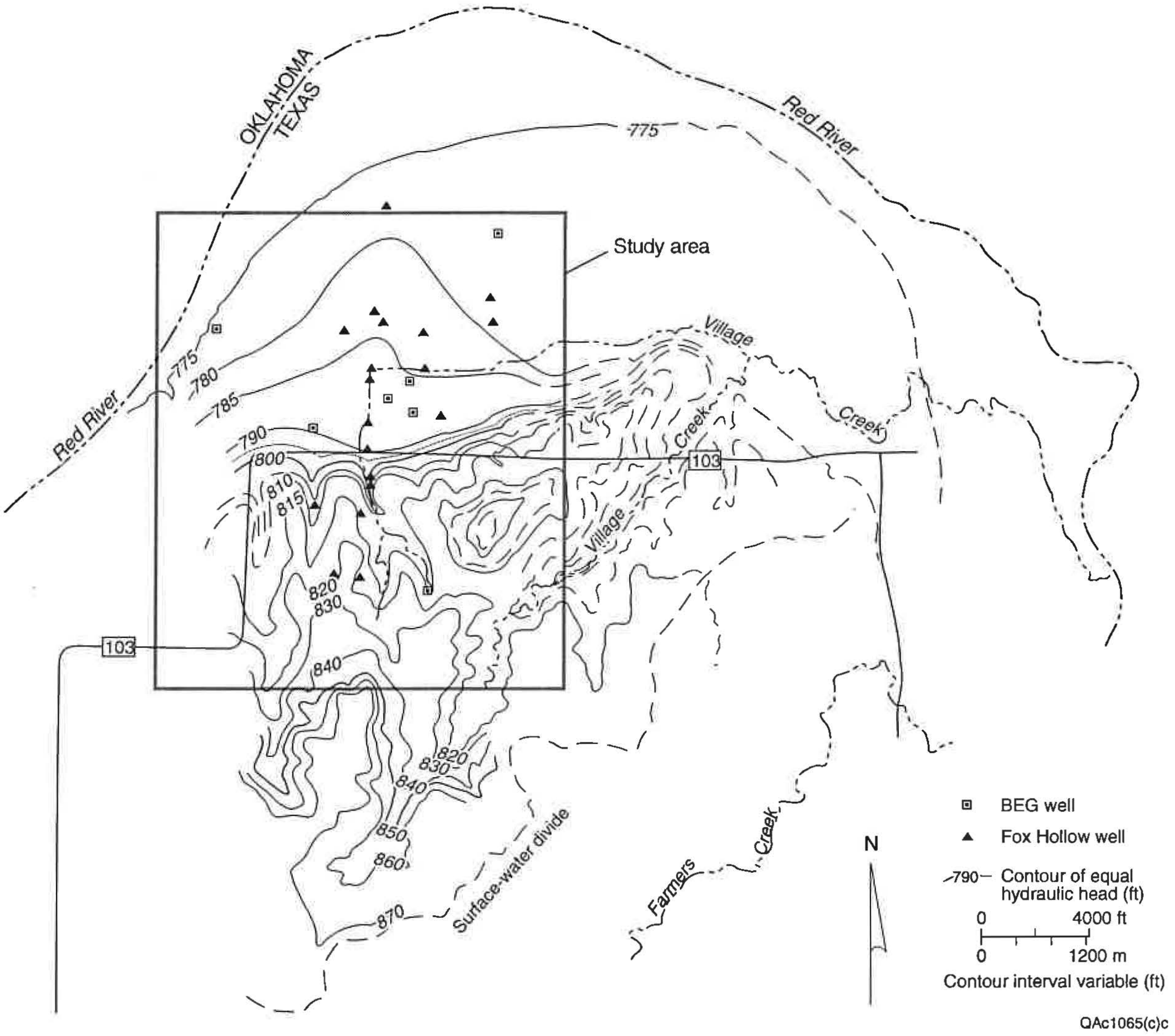
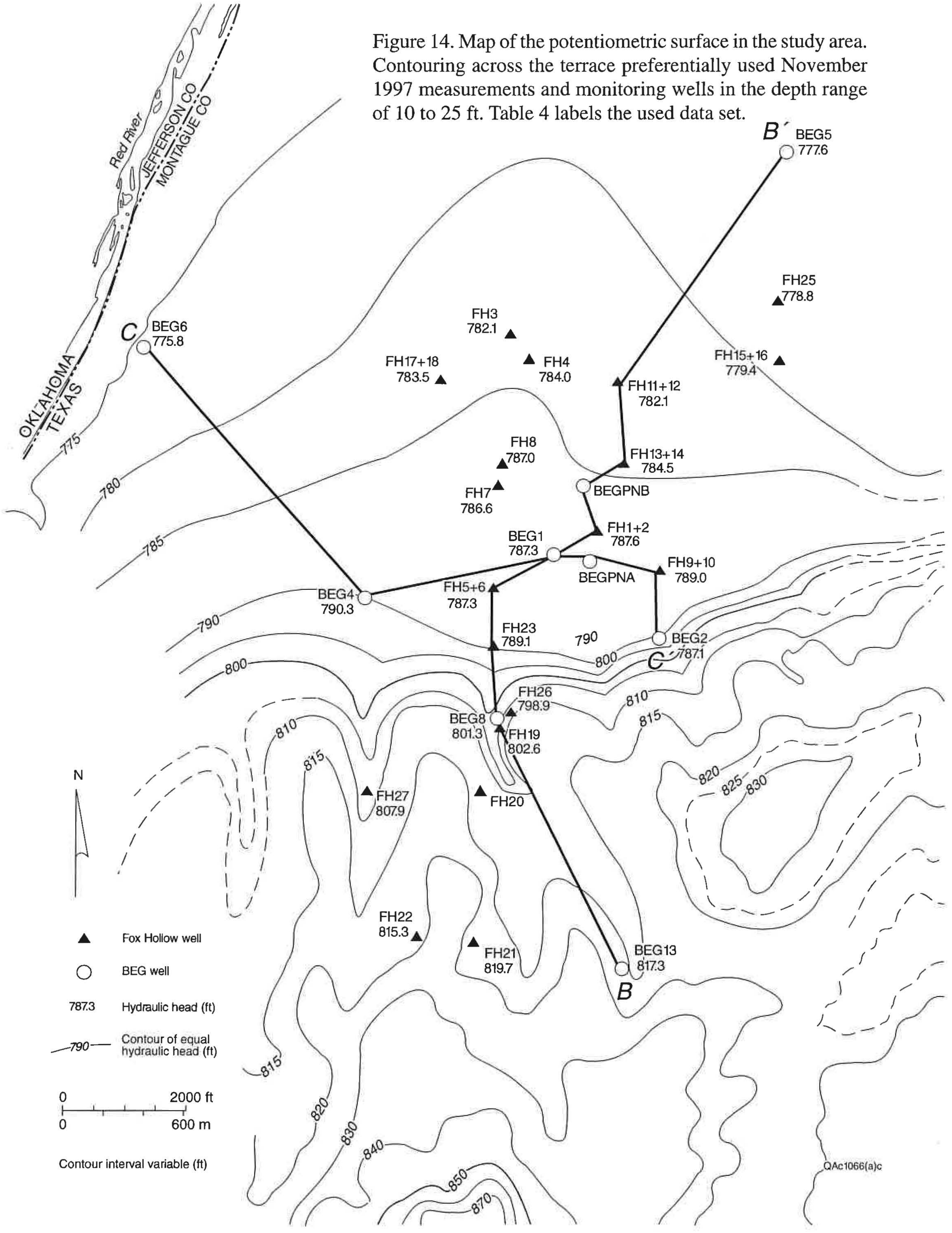


Figure 13. Map of regional potentiometric surface of shallow (8- to 79-ft depth) ground water in the vicinity of the study area contoured on the basis of data from monitoring wells (table 4) and topography. Water levels in water-supply wells, constructed in deeper zones than the monitoring wells, were not used in contouring. The 775-ft contour approximates the bluff along the Red River. Box shows area detailed in figure 14.

Figure 14. Map of the potentiometric surface in the study area. Contouring across the terrace preferentially used November 1997 measurements and monitoring wells in the depth range of 10 to 25 ft. Table 4 labels the used data set.



the terrace preferentially used November 1997 measurements but included some October 1997 data where the former were not collected. Contouring also preferentially used data from paired monitoring wells in the depth range of 10 to 25 ft. Several points are particularly notable:

- A regional ground-water divide to the south of the site most likely coincides with the surface-water divide between Village Creek and Farmers Creek (fig. 13). Ground water beneath the terrace in the study area is probably derived from recharge occurring north of the surface-water divide.
- Hydraulic head decreases from approximately 870 ft in the upland area south of Highway 103 to less than 790 ft across the Quaternary terrace (fig. 14).
- The potentiometric surface beneath the Quaternary terrace in the study area has the shape of a broad fan or nose pointing north, its north-south axis aligned with a surface-water drainage in the vicinity of wells BEG 8 and FH 19.
- The 775-ft contour drawn at the bluff and dividing the Quaternary from the Holocene terraces is consistent with both the measurement of 775.8 ft at well BEG 6 and the elevation of seeps observed in the bluff. The drop in hydraulic head to base level along the Red River (figs. 11 and 12) is not shown on the plan-view maps because of a lack of data.

Typical gradients in hydraulic head range from 0.008 beneath the upland area to 0.002 beneath the terrace (fig. 14). The average gradient beneath the slope break between the upland and terrace is 0.014. The gradient beneath the flat-lying terrace seems unusually low for an unconfined aquifer. Vertical gradients in hydraulic head, measured in piezometers in the shallow subsurface beneath the barren ground, are variable, ranging from -0.37 (directed upward) to 0.55 (directed downward) (table 5). Fluctuation in magnitude and direction of the vertical gradient results from the transient effects of precipitation, infiltration, and evaporation.

Depth to ground water reflects the difference in elevation of the ground surface and the water table. Beneath the upland area, depth to water varies from 12 ft to more than 30 ft (fig. 15). Beneath the Quaternary terrace, however, depth to water can be less than 6 ft. The nose on the

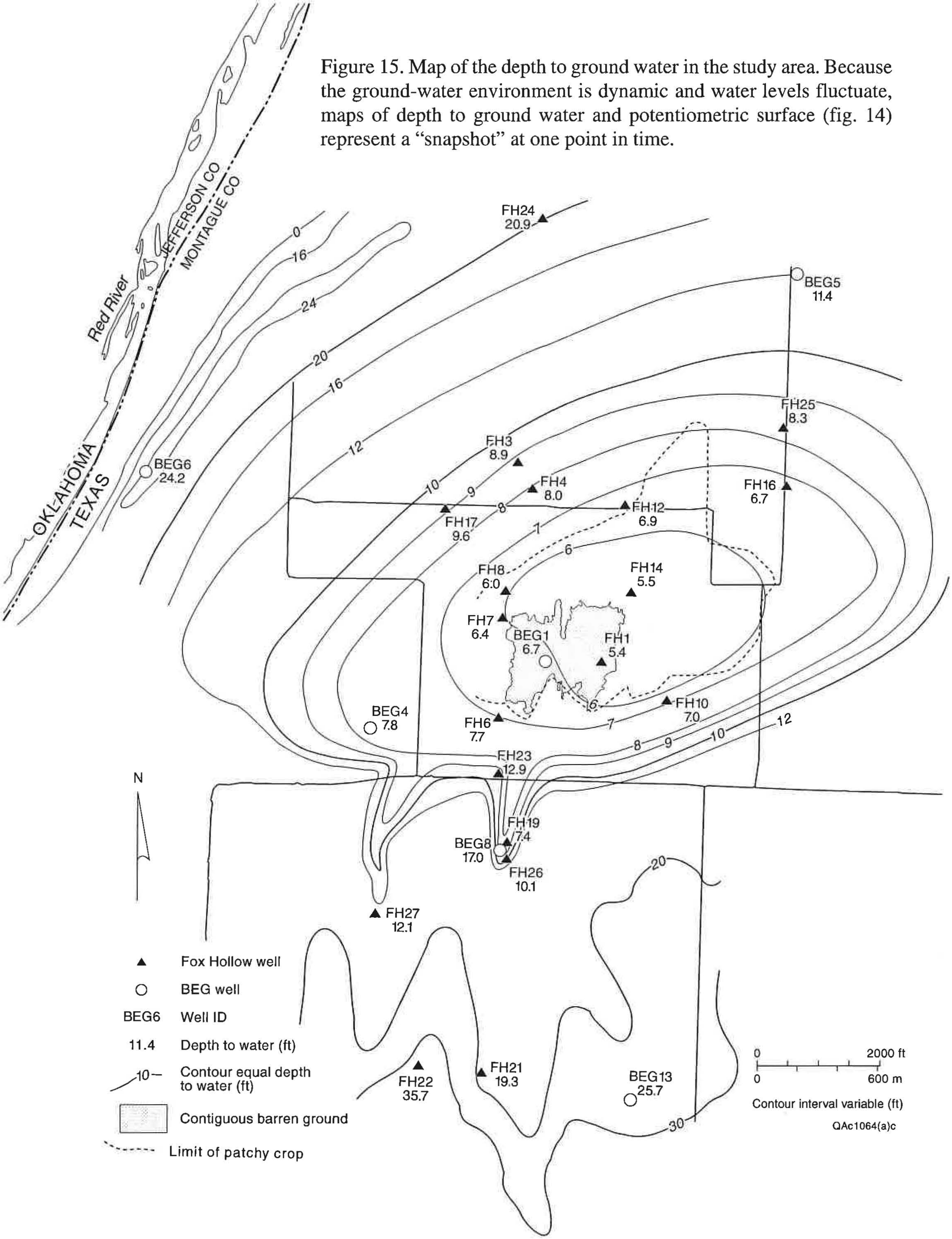
Table 5. Hydraulic-head data from piezometer nests in barren ground.

ID	Ground elevation (ft)	Piezometer depth (ft)	Measurement date	Measurement time	Depth to water (ft)	Hydraulic head (ft)	Gradient* (– up; + down)
Piezometer nest A							
PNA–1	794	4.42			dry	nd	
PNA–2	794	7.46			dry	nd	
PNA–3	794	10.88	7/23/97	14:25	6.83	787.2	
PNA–3	794	10.88	10/23/97	8:00	5.16	788.8	
PNA–3	794	10.88	10/24/97	9:20	5.14	788.9	
PNA–3	794	10.88	10/24/97	15:00	5.19	788.8	
PNA–3	794	10.88	10/25/97	8:05	5.14	788.9	
PNA–4	794	17.52	7/23/97	14:25	4.35	789.6	–0.37
PNA–4	794	17.52	10/23/97	8:00	5.10	788.9	–0.01
PNA–4	794	17.52	10/24/97	9:20	5.12	788.9	0.00
PNA–4	794	17.52	10/24/97	15:00	5.07	788.9	–0.02
PNA–4	794	17.52	10/25/97	8:05	5.32	788.7	0.03
PNA–5	794	20.21	7/23/97	14:25	4.27	789.7	–0.03
PNA–5	794	20.21	10/23/97	8:00	5.10	788.9	0.00
PNA–5	794	20.21	10/24/97	9:20	5.20	788.8	0.03
PNA–5	794	20.21	10/24/97	15:00	5.11	788.9	0.01
PNA–5	794	20.21	10/25/97	8:05	5.12	788.9	–0.07
Piezometer nest B							
PNB–b	792	4.38	10/23/97	8:45	2.01	790.0	
PNB–b	792	4.38	10/24/97	9:00	2.28	789.7	
PNB–b	792	4.38	10/24/97	15:30	2.27	789.7	
PNB–b	792	4.38	10/25/97	8:05	3.45	788.6	
PNB–c	792	9.67	10/23/97	8:45	4.93	787.1	0.55
PNB–c	792	9.67	10/24/97	9:00	4.81	787.2	0.48
PNB–c	792	9.67	10/24/97	15:30	4.37	787.6	0.40
PNB–c	792	9.67	10/25/97	8:05	4.48	787.5	0.20
PNB–d	792	12.91	10/23/97	8:45	5.43	786.6	0.15
PNB–d	792	12.91	10/24/97	9:00	5.08	786.9	0.08
PNB–d	792	12.91	10/24/97	15:30	4.93	787.1	0.17
PNB–d	792	12.91	10/25/97	8:05	5.37	786.6	0.27
PNB–a	792	16.77	10/23/97	8:45	5.34	786.7	–0.02
PNB–a	792	16.77	10/24/97	9:00	4.63	787.4	–0.12
PNB–a	792	16.77	10/24/97	15:30	4.65	787.4	–0.07
PNB–a	792	16.77	10/25/97	8:05	4.72	787.3	–0.17

nd not determined

* Gradients are read between the measuring-point depth of a piezometer and the next shallower piezometer measured at the same time

Figure 15. Map of the depth to ground water in the study area. Because the ground-water environment is dynamic and water levels fluctuate, maps of depth to ground water and potentiometric surface (fig. 14) represent a “snapshot” at one point in time.



potentiometric surface is the highest in approximately the same place that ground surface (fig. 14) is the lowest, along the ditch leading from the upland drainage tributary of Village Creek (figs. 2, 6). The local high on the potentiometric surface approximately underlies the local low on the ground surface, resulting in a closed contour with a minimum depth to ground water of less than 6 ft (fig. 15).

Hydrologic Properties

The results of matching hydrologic test data to type curves are shown in figures 16 through 18. On the left-hand side of figure 16, for example, are hydrographs of water levels monitored during the tests in wells BEG 1S and 1D. The fact that there was no change in water level in one zone when the other zone was being pumped during the October 1997 test (compare figs. 16a and 16c) indicates there was negligible vertical hydrologic connection between wells 1S and 1D within the well bore. Well-bore conditions affected the results of the October test in BEG 1D and that type-curve match was ambiguous (fig. 16d). The test in well 1D was repeated with a greater pumping rate in an attempt to improve the match of field data and the type curve. The higher pumping rate of the short-duration November test yielded more data that could be matched to the type curve with less ambiguity (fig. 16f).

The various r/B curves shown in figures 16 through 18 represent a departure from the assumptions that underlie the Theis type curve, as discussed in the Methods section. Data lie along r/B curves when water-level change is not as great as expected under the ideal assumptions for the Theis curve. This is usually taken to indicate water leakage in confined aquifers or delayed yield in unconfined aquifers.

Similar to the tests conducted at wells BEG 1S and 1D, those conducted at wells BEG 5S and 5D show no evidence of vertical hydrologic connection between the two completion zones within the well bore (fig. 17a, b). Because the water level in well BEG 5S fluctuated with pumping rate, the pumping rate was repeatedly changed (in order to keep the well from

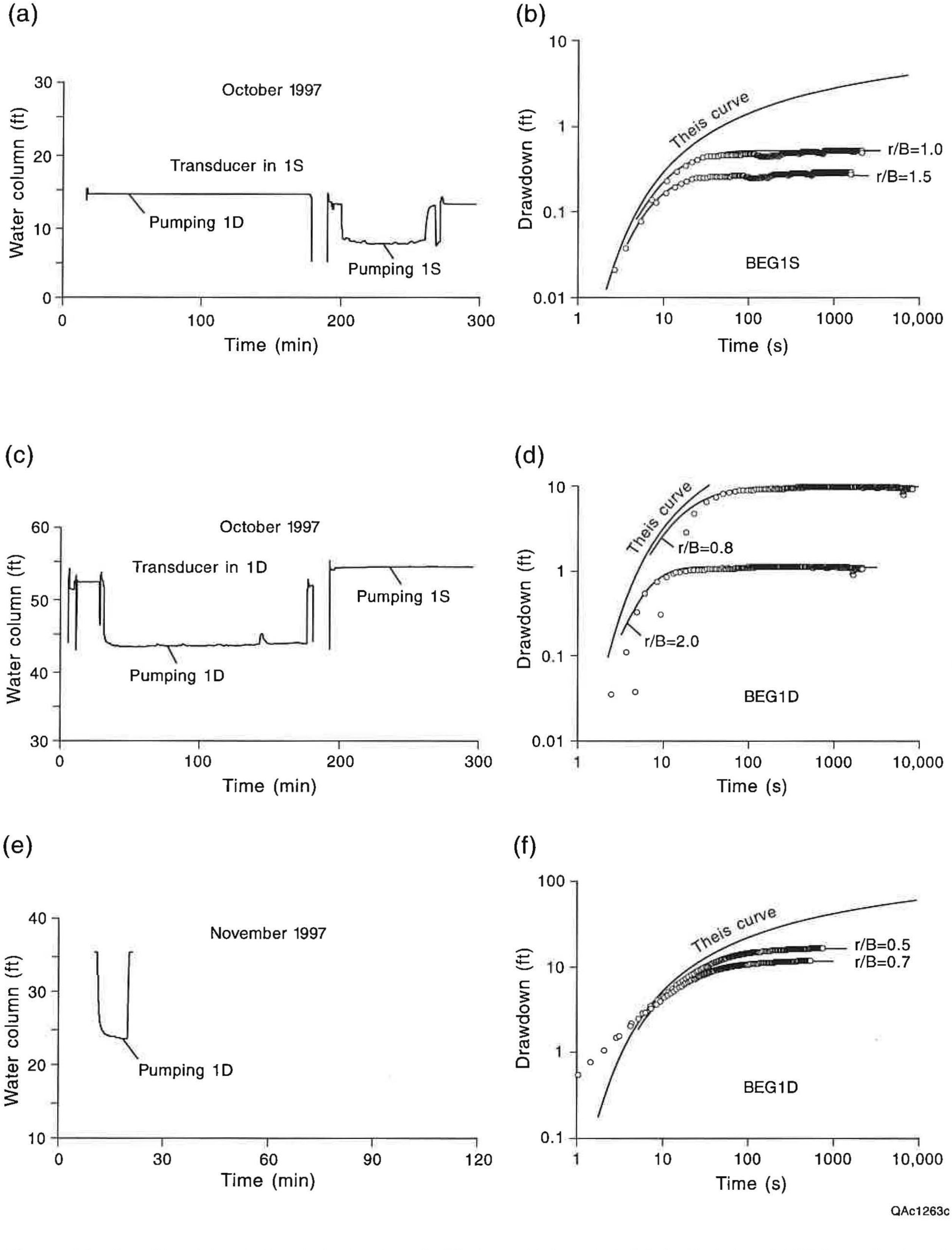


Figure 16. Results of hydrologic tests at well 1S (a and b) and at 1D in October 1997 (c and d) and November 1997 (e and f). Hydrographs a, c, and e show water-level changes during the tests. Type-curve matches b, d, and f form the basis of estimating transmissivity.

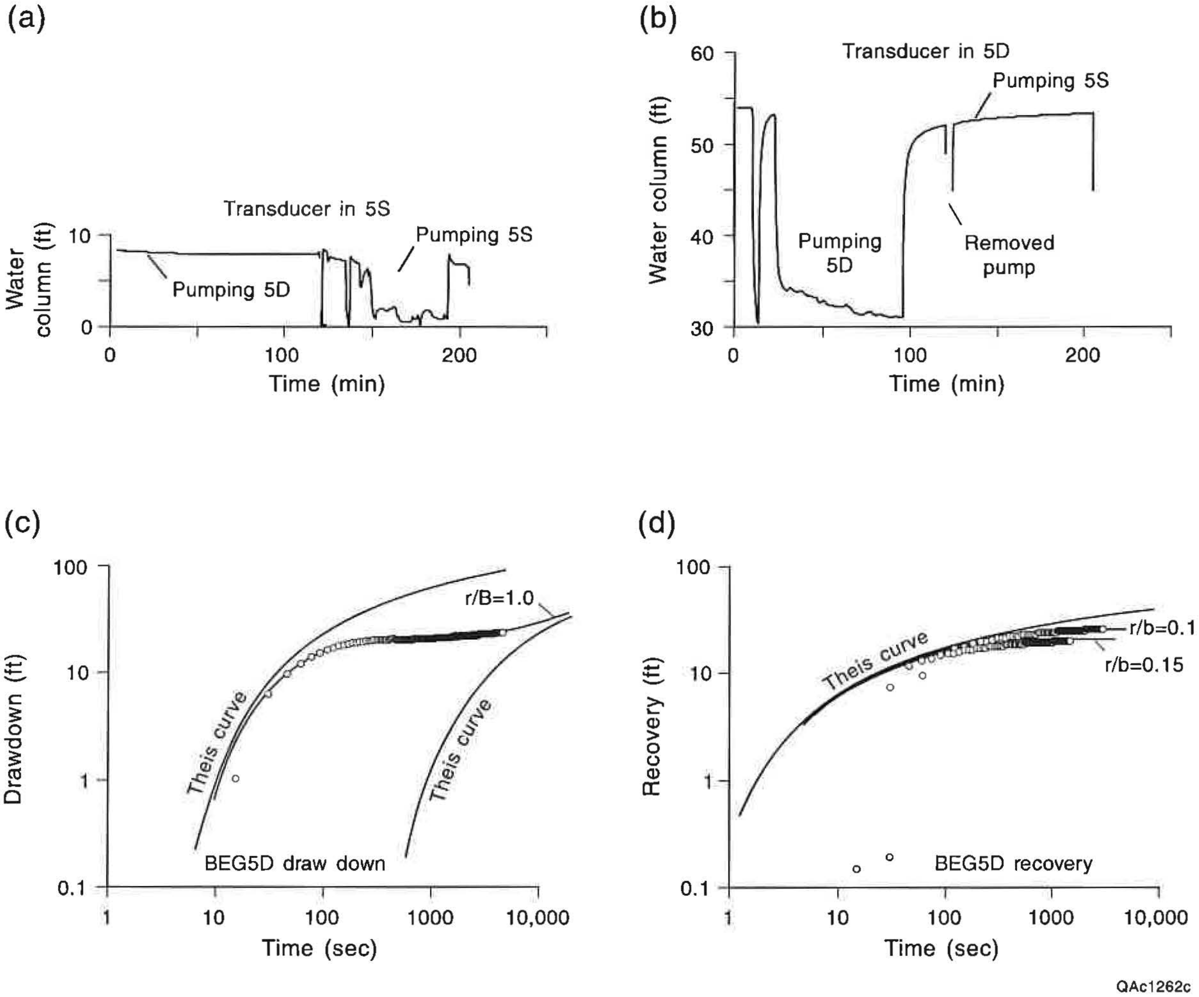


Figure 17. Results of hydrologic tests at well 5S a and 5D b to d. Hydrographs a and b show water-level changes during the tests. Type-curve matches c and d form the basis of estimating transmissivity.

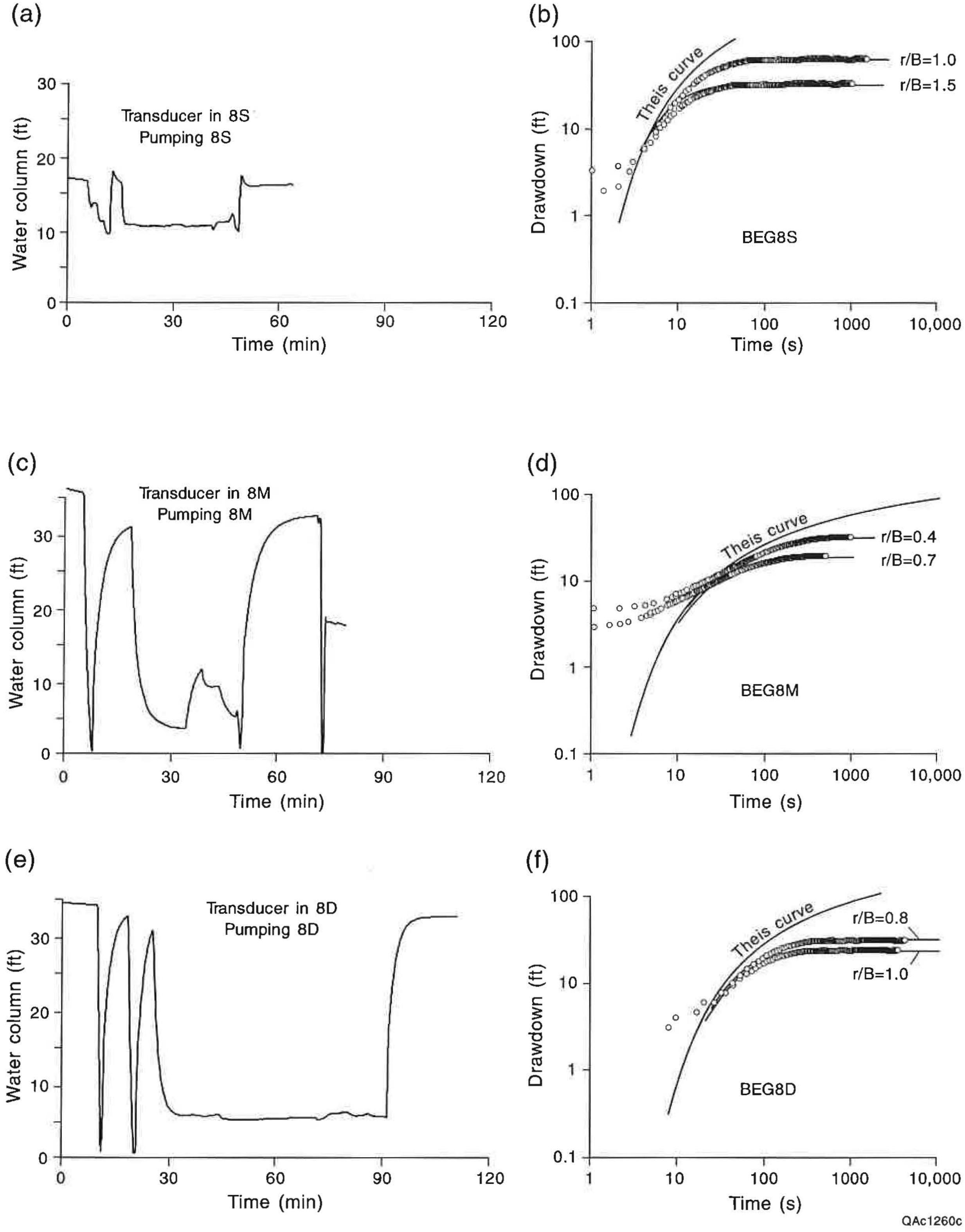


Figure 18. Results of hydrologic tests at well 8S (a and b), 8M (c and d), and 8D (e and f). Hydrographs a, c, and e show water-level changes measured in each well during the tests. Type-curve matches b, d, and f form the basis of estimating transmissivity.

dewatering before a water sample was collected [fig. 17a]), and hydraulic conductivity was not estimated for this test. Specific capacity in well BEG 5S, however, was less than that in BEG 5D.

The hydrographs for wells BEG 8S, 8M, and 8D are plotted relative to the start of each test (fig. 18a, c, and e). No evidence of hydrologic connection between the zones was observed during these tests. The hydrographs show the preliminary adjustment of pumping rates and the recovery of water levels before hydrologic tests began. The match between field data and type curves was not unique, so multiple possible matches are shown in figures 16 through 18 and in table 6. In most cases, however, the range of possible matches is small, which constrains the estimation of transmissivity.

Estimates of transmissivity and hydraulic conductivity are tabulated in table 6. Hydraulic conductivity is estimated from transmissivity by dividing the latter by the thickness of the flow unit. We determined the thickness for the test zones on the basis of the conductivity logs run before and after well development (figs. 8 and 9). The geometric mean of hydraulic conductivity for all test results is 0.2 ft/d; the geometric mean for tests in alluvium is 0.4 ft/d. The maximum measured hydraulic conductivity is 0.8 ft/d, measured at well 1D. These are typical values for silty sand or clean sand but appear low when compared to typical values of hydraulic conductivity for gravel.

Chemical Composition of Ground Water

Samples Associated with Coproduced Brine

RRC file information identifies two brine samples from near the study area that were collected as part of a separate RRC investigation. One sample was a coproduced brine from an oil well, and the other brine sample was collected from a seep. The samples have a TDS of 106,000 and 116,000 mg/L and are of sodium-chloride facies (table 7; fig. 19). These two samples are listed here as a possible comparison with the monitoring-well samples.

Table 6. Data on hydrologic properties estimated from field tests.

Well	Test period	Discharge (gal/d)	r/B value	Flow-unit thickness* (ft)	Trans-missivity (ft^2/d)	Hydraulic conductivity** (ft/d)
1S †	Drawdown	2.49	1.0 to 1.5	18.0	3.2 to 6.0	0.2 to 0.3
1D	Drawdown	7.70	0.5 to 0.7	22.0	12.8 to 18.5	0.6 to 0.8
5S	Not interpreted					
5D	Drawdown	3.16	0.8 to 1.0	13.5 to 36.0	1.9 to 2.0	~0.1
5D	Recovery	3.16	0.07 to 0.15	22.0	9.3 to 12.1	0.4 to 0.55
8S	Drawdown	1.99	1.0 to 1.5	39.0	2.1 to 4.3	~0.1
8M	Drawdown	1.91	0.4 to 0.7	14.8	1.3 to 2.1	~0.1
8D	Drawdown	2.08	0.8 to 1.0	6.6	0.9 to 1.2	0.1 to 0.2

* Flow-unit thickness inferred from borehole conductivity logs

** Hydraulic conductivity determined by dividing transmissivity by flow-unit thickness

† October 1997 test, all other results from November 1997 tests

Table 7. Chemical composition of oil-field brine samples.*

Well name	Date sampled	Temp. (°C)	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SIO_2	Sr	TDS	Charge balance (%)
Produced brine sample	nr	nr	nr	7,750	7,475	33,850	35	66,640	5	nr	nr	nr	115,864	1.3
Road ditch seep	nr	nr	7.03	7,500	1,410	33,750	120	63,040	15	136	nr	nr	105,971	1.1

nr not reported
* From RRC file documents.

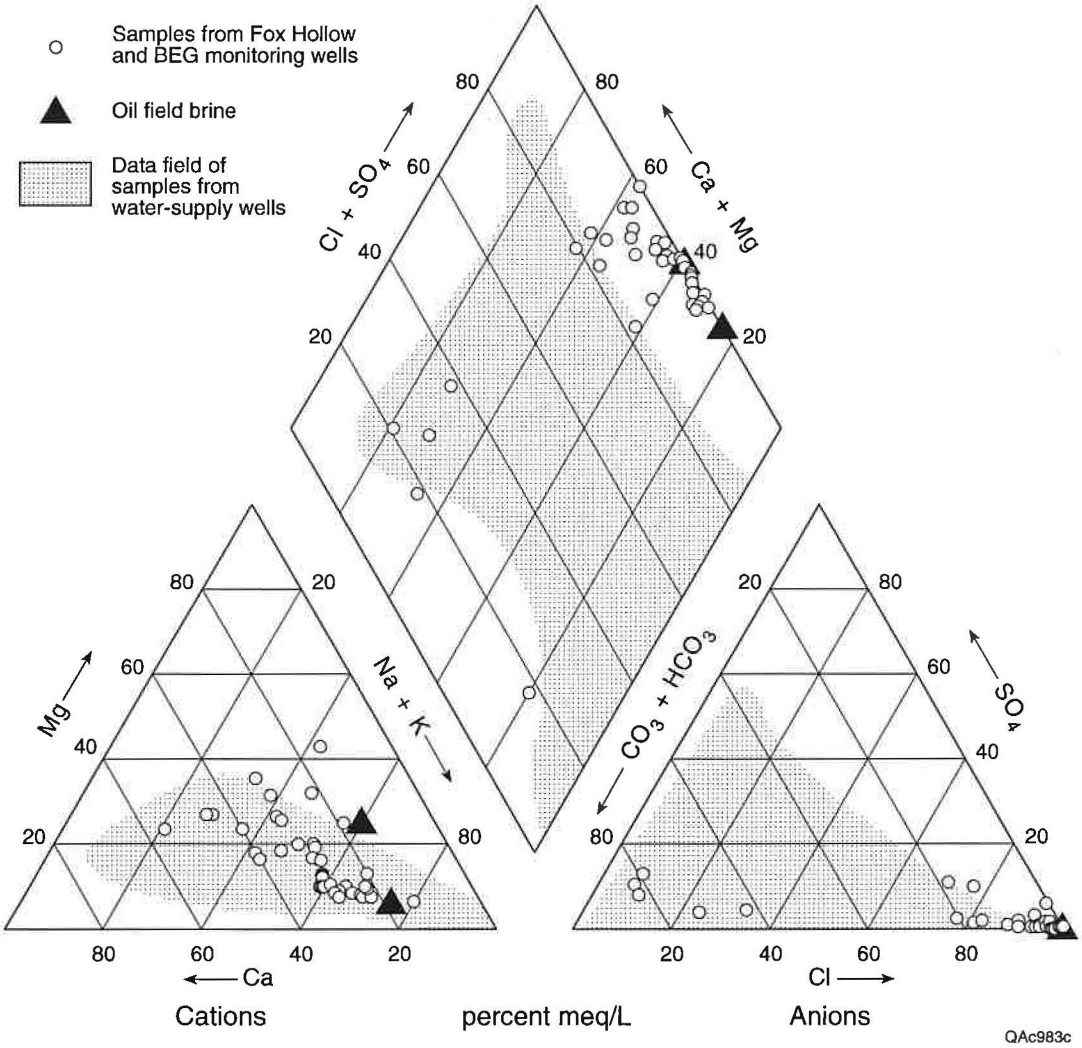


Figure 19. Trilinear diagram showing hydrochemical variation of ground waters.

Samples from Water-Supply Wells

Table 3 presents analyses of ground water from domestic water-supply and stock wells from this study (1997) and from the TWDB data base (1963–64 and 1975–76). The water-supply wells in the terrace and upland parts of the study area average approximately 135 ft in depth (table 1). In addition to the water-supply wells sampled in this study, those wells within 6.6 mi (10.6 km) of the site sampled in previous studies (fig. 6) provide a greater data base with which to identify typical background chemical composition of natural ground waters in the area.

The total dissolved solids (TDS) content of ground water from the water-supply wells averages 793 mg/L and varies from 270 to 3,670 mg/L (fig. 20b). Chloride concentration in 9 of the 48 wells exceeds 250 mg/L, the EPA secondary water-quality standard, and in 6 samples exceeds 500 mg/L (labeled in table 3). De Zuane (1990, p. 121) stated that the 250 mg/L limit was not based on either health or taste; salty taste is mostly related to sodium ions. Plants are more sensitive than animals to high chloride concentrations and the 250 mg/L limit remains a good standard for chlorides (De Zuane, 1990). The predominant chemical composition of these waters (see stippled area of fig. 19) is of either (1) calcium-bicarbonate hydrochemical facies (Back, 1966), (2) sodium-bicarbonate hydrochemical facies, or (3) low-salinity calcium-chloride and sodium-chloride hydrochemical facies. Ionic exchange between ions dissolved in water and adsorbed on clay minerals is probably the main geochemical reaction controlling the natural evolution of calcium-bicarbonate waters into sodium-bicarbonate facies, which results in the increase in the sodium/calcium ratio.

TDS exceeds 1,000 mg/L in 16 of the water-supply wells (table 3). Water having TDS of more than 1,000 mg/L is referred to as brackish. In half of the 16 wells, TDS is elevated because of bicarbonate concentration or bicarbonate and sulfate concentrations, not because of elevated chloride concentration. In the other eight wells (labeled in table 3), TDS is elevated owing to high chloride (C1 >250 mg/L). One (1903506) of the nine wells with elevated chloride has TDS

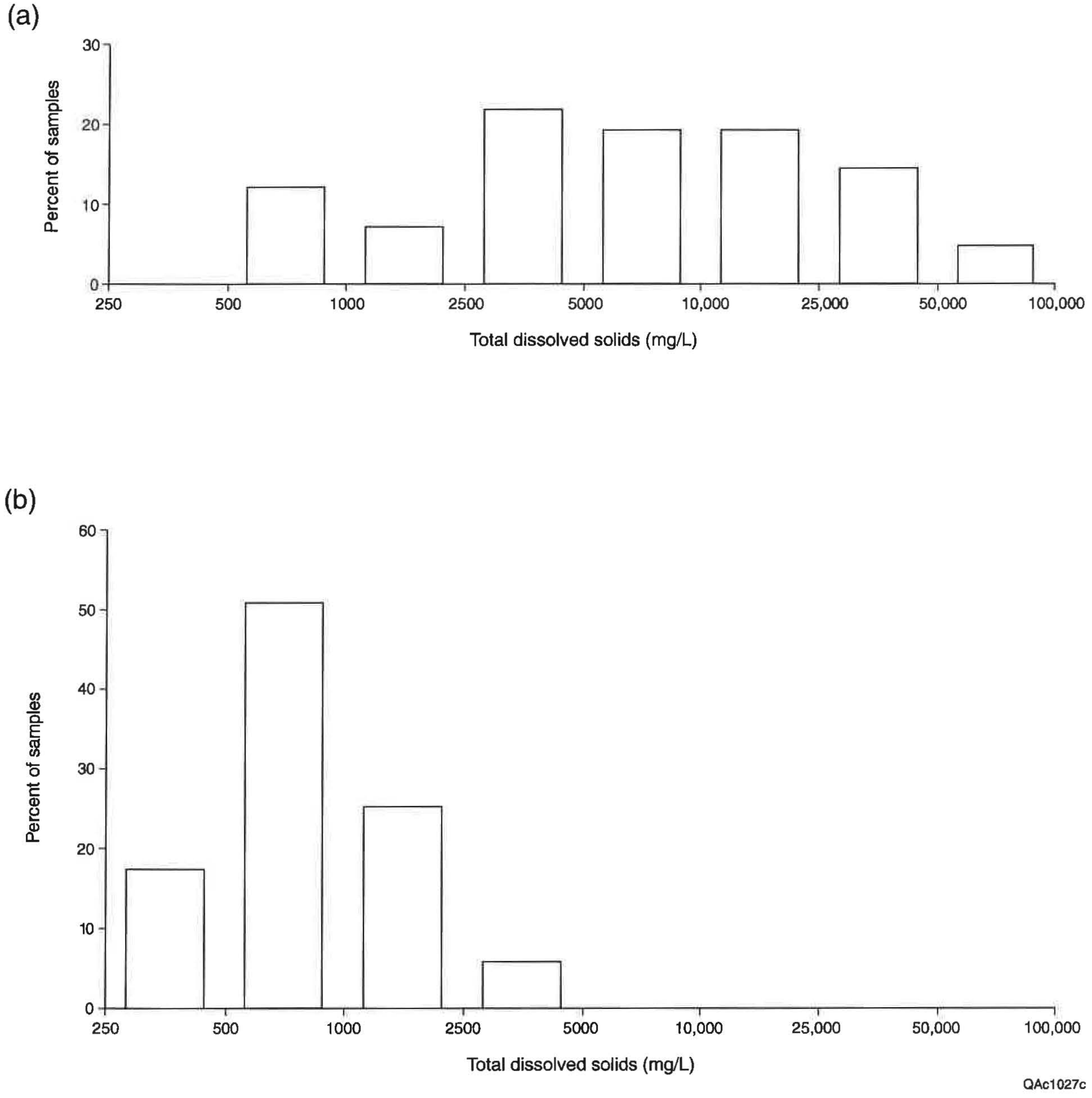


Figure 20. Histograms of total dissolved solids in (a) ground-water samples from BEG and FH monitoring wells (data from tables 8 and 9) and (b) water-supply wells (data from table 3).

less than 1,000 mg/L. Only two (1903501 and 1903503) of the wells with elevated chloride and TDS, however, lie within the study area. Well 1903501 had been sampled in 1964, but when visited during this study it had apparently been abandoned since then and did not have a working pump, and so it was not resampled. It lies within the footprint of the subsurface salinity plume measured in 1997 (fig. 21). Well 1903503 was sampled in 1964 and resampled in 1997 during this study. It lies just east of the mapped edge of the salinity plume (well labeled D3, fig. 21). Depths of these wells are 175 and 100 ft, respectively (table 1).

Another water-supply well sampled in 1997 that lies within the footprint of the subsurface salinity plume (labeled D9, unknown depth, fig. 21, table 3) has a TDS of approximately 1,200 mg/L; this well, however, does not have an elevated chlorinity (Cl=226 mg/L). Its TDS is influenced by calcium, bicarbonate, and sulfate, as well as chloride.

Two other wells in the TWDB data base (1903504 [D2, 99-ft depth] and 1903505 [D1, 40-ft depth]) were resampled along with 1903503 (tables 1 and 3; figs. 7 and 21). The previously reported analyses were made in 1964. Neither of these resampled wells lie within the footprint of the subsurface salinity plume, nor do the wells have elevated chlorinity. Salinity increased by 27 to 118 percent for the three resampled wells, however, from 1964 to 1997. TDS of water from well 1903503 increased from 470 to 1,690 mg/L. TDS of water from wells 1903504 and 1903505, however, was still less than 900 mg/L. Possible sources of salinity that might account for these changes between 1964 and 1997 are (a) inflow of naturally occurring, poor-quality water from lower permeability zones within the aquifer while these wells are being operated, and (b) inflow of poor-quality surface-water runoff owing to problems in well completion.

Samples from Monitoring Wells

In contrast to the water-supply wells, TDS of samples of ground water from BEG and FH monitoring wells averages 6,990 mg/L and ranges from 540 to 74,310 mg/L (fig. 20a). These wells average 36 ft in depth and sample a much more shallow zone than the water-supply wells. Tables 8 and 9 give chemical analyses of water samples from BEG and FH wells, respectively,

Figure 21. Plan view map of total dissolved solids (TDS) in the subsurface saltwater plume drawn on the basis of water samples from monitoring wells guided by maps of ground conductivity imaged from airborne geophysical data (1 g/L = 1,000 mg/L). Data used in contouring listed in tables 8 and 9. TDS of water-supply wells shown for comparison.

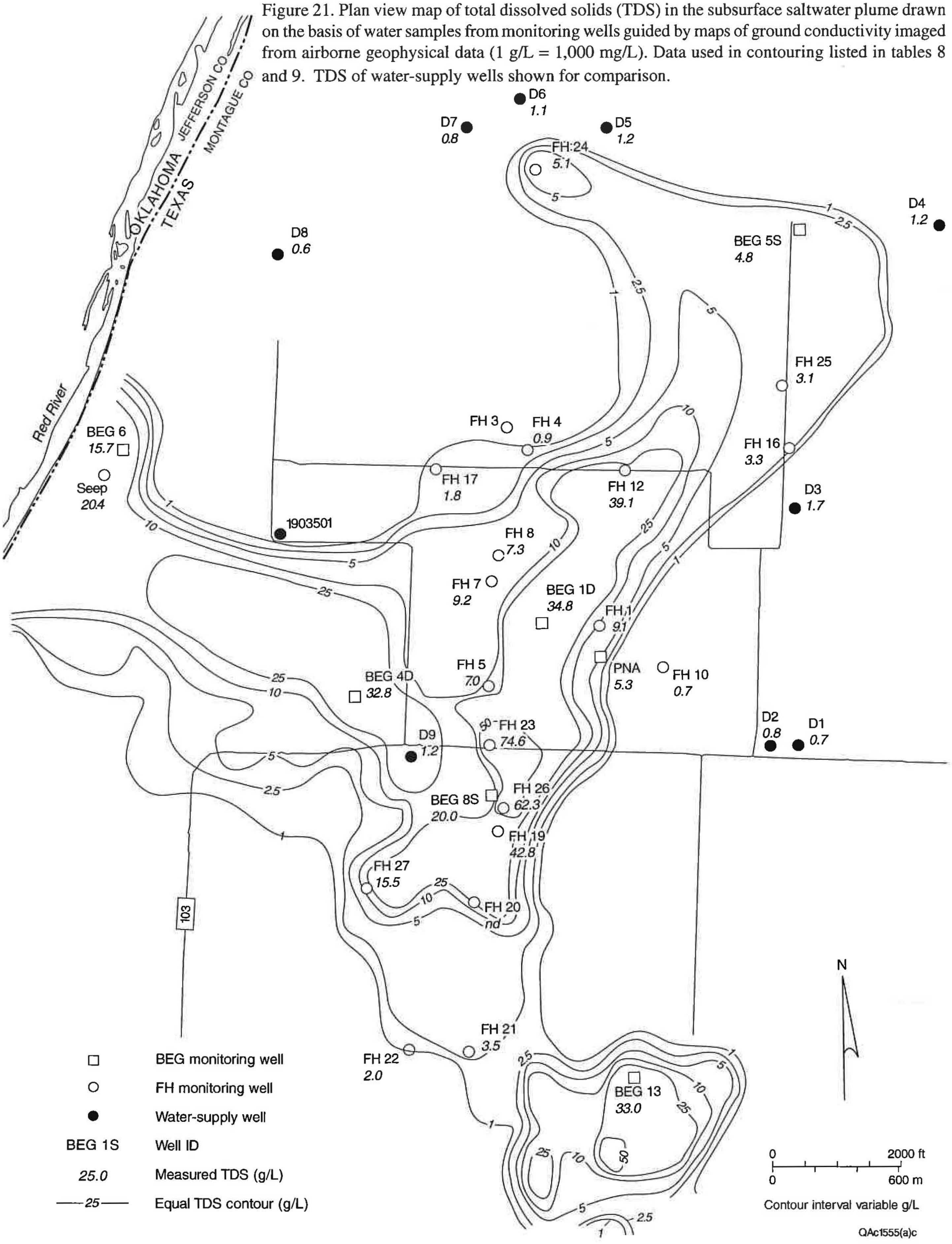


Table 8. Chemical composition of ground waters from BEG monitoring wells.

Sample code	Well name	Date sampled	Temp. (°C)	Cond. (mS/m)	pH	Ca	Mg	Na	K	Sr	Ba	Cl	SO_4	HCO_3	SiO_2	NO_3	Br	TDS	Charge balance (%)
8048	BEG1D	10/24/97	nm	5,510	6.69	3,389	734	8,661	62	75	6.4	21,477	32	221	10	<5	139	34,806 *	0.0
8061	BEG1D**	10/24/97	nm	5,510	6.69	3,415	742	8,798	60	82	6.4	21,940	34	216	10	<1	143	35,446	-0.4
8054	BEG1S	10/24/97	nm	3,810	9.94	2,824	491	7,034	24	45	6.4	14,415	74	31	6	<1	74	25,024	8.9
8063	BEG 2 (20 ft)‡	10/21/97	nm	nm	nm	nm	nm	nm	nm	nm	nm	48	nm	nm	nm	nm	nm	nm	–
8064	BEG 2 (19-24 ft)‡	10/21/97	nm	nm	nm	nm	nm	nm	nm	nm	nm	38	nm	nm	nm	nm	nm	nm	–
8065	BEG 2 (69-74 ft)‡	10/21/97	nm	nm	nm	nm	nm	nm	nm	nm	nm	25	nm	nm	nm	nm	nm	nm	–
8067	BEG4 ‡	11/08/97	nm	2,160	6.77	1,079	289	3,855	12	22	3.8	7,053	23	337	11	3	40	12,728	9.1
	BEG 4S	12/03/97	nm	24,100	nm	nm	nm	nm	nm	nm	nm	7,906	nm	nm	nm	nm	nm	nm	–
8086	BEG4D	11/13/97	nm	5,300	nm	3,625	730	9,429	99	92	3.9	20,470	91	113	7	<1	112	34,772 *	6.1
	BEG4D	12/03/97	nm	24,000	nm	nm	nm	nm	nm	nm	nm	7,911	nm	nm	nm	nm	nm	nm	–
8079	BEG5D†	11/13/97	nm	87	7.63	29	8	188	<5	0.3	0.08	32	36	481	10	<1	<1	784	3.8
8080	BEG5S	11/13/97	nm	867	6.99	626	205	962	<5	8	1.3	2,488	70	384	14	66	15	4,839 *	6.5
8068	BEG6	11/12/97	18	2,400	6.98	1,694	455	3,807	11	27	4.8	9,325	22	300	11	42	44	15,743 *	3.4
8088	BEG6**	11/12/97	nm	2,390	6.98	1,752	465	3,808	12	33	5	8,246	22	296	12	44	46	14,741	10.1
8069	BEG8D	11/12/97	19.5	2,340	7.13	1,492	236	3,830	26	41	3.1	8,246	59	185	10	<1	45	14,173	5.1
	BEG8D	12/03/97	nm	19,760	nm	nm	nm	nm	nm	nm	nm	6,645	nm	nm	nm	nm	nm	nm	–
8070	BEG8M	11/12/97	nm	2,590	8.33	1,614	229	4,385	28	41	3	9,691	127	38	<5	<1	50	16,206	2.7
8070	BEG8M**‡‡	11/12/97	nm	nm	nm	1,178	186	2,870	42.6	44.3	2.92	8,810	0.1	38	6.9	nm	nm	13,179	-10.4
	BEG8M	12/03/97	nm	98,100	nm	nm	nm	nm	nm	nm	nm	42,571	nm	nm	nm	nm	nm	nm	–
8071	BEG8S	11/12/97	nm	3,180	6.6	1,775	330	5,813	40	48	4.1	11,767	45	201	10	4	58	20,095 *	4.9
	BEG8S	12/03/97	nm	42,200	nm	nm	nm	nm	nm	nm	nm	14,998	nm	nm	nm	nm	nm	nm	–
8083	BEG13 ††	11/13/97	nm	4,200	nm	3,351	678	7,406	<5	58	1.2	15,339	1,362	173	9	1	86	28,464	8.1
8084	BEG13 ††	11/13/97	nm	5,000	nm	3,985	790	8,683	25	75	2.1	18,795	68	179	9	<1	95	32,706	9.2
8085	BEG13 ††	11/13/97	nm	5,170	6.41	3,913	779	8,850	27	86	2.3	19,079	72	175	9	<1	107	33,099 *	8.7
	BEG13	12/04/97	nm	51,700	nm	nm	nm	nm	nm	nm	nm	19,830	nm	nm	nm	nm	nm	nm	–
	PNA 3	07/25/97	nm	700	6.91	419	180	912	<5	3.1	nm	1,995	100	175	<5	nm	10	3,794	10.3
	PNA4	07/25/97	nm	859	6.98	519	186	1,089	<5	2.8	nm	2,531	79	96	<5	nm	13	4,516	8.5
	PNA5	07/25/97	nm	1,008	6.76	562	202	1,284	<5	6.3	nm	2,992	89	171	<5	nm	15	5,321 *	6.0
	Seep	12/04/97	nm	3,330	7.38	2,156	545	5,676	23	44	6	11,570	22	255	8	19	61	20,385 *	9.5

*	Used in mapping subsurface salinity plume
†	Low salinity sample
**	Duplicate
‡	Sampled during borehole drilling
‡‡	Sample analyzed by DHL, Inc.; all others by RRC Surface Mining and Reclamation Laboratory
††	Three successive samples at BEG 13 taken after 4, 6, and 8 well-bore volumes were pumped out
nr	not reported
nm	not measured

Table 9. Chemical composition of ground waters from FH monitoring wells.

Sampl e code	Well name	Date sampled	Temp. (°C)	Cond. (mS/m)	pH	Ca	Mg	Na	K	Sr	Ba	Cl	SO_4	HCO_3	SiO_2	NO_3	Br	TDS	Charge balance (%)
8060	FH1	11/11/97	25	1,576	6.92	750	204	2,653	<5	11	0.99	5,054	41	319	21	<5	31	9,085 *	6.5
8061	FH2	11/11/97	18.2	1,735	7.08	789	316	3,051	<5	8	0.9	5,815	38	364	12	<5	33	10,427	7.3
8074	FH4†	11/13/97	20	123	7.18	104	37	71	<5	0.5	0.81	139	26	452	14	25	1	870 *	-4.0
8010	FH5	10/22/97	nm	1,281	6.96	827	410	1,300	<5	10	2	4,046	34	328	18	46	26	7,047 *	4.2
8012	FH5**	10/22/97	nm	1,244	nm	808	416	1,238	<5	7.6	2	3,976	33	407	18	48	25	6,979	3.2
8008	FH6	10/22/97	nm	870	7.16	435	382	1,038	<5	4.2	1.6	2,764	24	336	14	26	18	5,043	7.5
8062	FH7	11/11/97	20.8	1,585	6.97	961	426	2,108	<5	8.3	1.6	5,269	79	282	16	5	30	9,186 *	5.9
8063	FH8	11/11/97	21	1,116	7.23	462	370	1,570	<5	4.1	0.67	4,442	77	343	16	31	19	7,335 *	-4.5
8059	FH9†	11/11/97	18.5	65	7.32	78	20	33	<5	0.3	0.12	19	43	335	16	<1	<1	544	0.4
8058	FH10†	11/11/97	nm	80	7.52	55	38	67	<5	0.5	0.07	23	44	439	30	9	<1	706 *	-0.6
8004	FH11	10/22/97	18	5,340	6.83	3,519	800	8,546	79	71	5.8	21,704	33	261	9	<5	137	35,165	0.0
8006	FH12	10/22/97	19.7	6,460	6.38	3,195	742	8,926	67	92	7.6	25,609	20	223	10	<5	160	39,052 *	-8.5
8075	FH15	11/13/97	19.75	333	7.11	270	68	333	<5	1.4	0.17	834	179	360	14	<1	4	2,064	0.6
8075	FH15**‡	11/13/97	nm		7.11	289	64.1	258	7.46	1.8	0.16	748	185	356	19.1	1.3	4.3	1,934	0.8
8087	FH15**	11/13/97	nm	334	7.11	242	63	334	<5	2	0.16	825	174	363	15	<1	4	2,022	-1.6
8076	FH16	11/13/97	nm	517	7.01	446	123	530	<5	1.7	0.25	1,446	256	438	16	<1	8	3,265 *	1.9
8076	FH16**‡	11/13/97	nm		7.01	378	102	378	8.44	2.15	0.19	1,300	227	447	19.5	0.9	6.6	2,870	-4.9
8073	FH17	11/13/97	nm	308	7.12	235	83	245	<5	1.2	0.47	732	30	339	13	164	4	1,847 *	-0.5
8073	FH17**‡	11/13/97	nm		7.12	237	81.4	181	5.63	1.51	0.39	639	38.9	314	16.6	163	3.6	1,682	0.2
8072	FH18†	11/13/97	19	90	7.37	78	29	58	<5	0.7	0.22	78	18	414	15	<1	<1	691	-3.0
8055	FH19	11/11/97	nm	6,310	6.55	3,546	739	13,030	104	94	8.4	24,943	19	271	17	<5	154	42,821 *	6.4
8057	FH21	11/11/97	20.1	588	7.01	372	90	842	<5	4.6	0.43	1,767	29	371	14	6	8	3,504 *	5.0
8056	FH22	11/11/97	18.3	349	7.24	194	51	437	<5	2	0.68	936	20	352	12	8	5	2,018 *	0.2
8056	FH22**‡	11/11/97			7.24	233	60.7	430	10	2.64	0.66	882	18.5	359	15.9	7.15	4.5	2,024	6.9
8064	FH23	11/11/97	18.3	10,220	6.38	6,609	1,333	21,630	91	181	23	44,246	18	154	8	<1	268	74,561 *	5.1
8082	FH24	11/13/97	19.25	926	6.9	586	231	1,094	<5	10	2.2	2,604	26	443	14	30	15	5,055 *	8.0
8081	FH25	11/13/97	nm	531	6.95	318	203	459	<5	2	0.47	1,514	51	493	16	54	9	3,119 *	-0.2
8081	FH25**‡	11/13/97	nm		6.95	319	188	348	5.9	2.54	0.46	1,400	81.8	498	20.4	69.2	8.25	2,942	-3.8
8065	FH26	11/11/97	19	8,830	6.29	5,604	1,004	18,710	127	148	14	36,261	18	166	9	4	210	62,275 *	7.1
8066	FH27	11/11/97	20.5	2,480	6.65	1,401	289	4,120	25	34	25	9,131	24	333	12	10	49	15,453 *	2.1

*	Used in mapping subsurface salinity plume
†	Low salinity sample
**	Duplicate
‡	Sample analyzed by DHL, Inc.; all others by RRC Surface Mining and Reclamation Laboratory
nr	not reported
nm	not measured

that were collected during this study. Chloride concentration exceeds the 250 mg/L standard in all but five of the BEG and FH samples. These five low-salinity samples (TDS<900 mg/L; Cl<150 mg/L; tables 8 and 9) are of the calcium-bicarbonate hydrochemical facies; these five are assumed to represent the "background" ground water at shallow depth and come from wells outside the footprint of the saltwater plume. The rest of the BEG and FH samples are of sodium-chloride or mixed-cation-chloride facies (fig. 19). The gradation in ionic dominance from calcium to sodium in these samples most likely results from the mixing of calcium-bicarbonate with sodium-chloride waters, rather than from ionic exchange.

Concentrations of sodium and chloride in samples from BEG and FH wells are directly related and plot along a line between (1) the two oilfield brine samples, and (2) low-salinity waters from water-supply wells (fig. 22a). The Na/Cl mass ratio of many BEG and FH samples (having an average of 0.42 and ranging from 0.25 to 0.55) is slightly less than that of the two oilfield brines (0.51 to 0.54). Some of the fresh-water (TDS<1,000 mg/L) samples from the water-supply wells have a higher Na/Cl ratio (fig. 22a). This is typical of low-salinity natural waters in which there are a number of sources of dissolved sodium, including ionic exchange and partial solution of sodium-bearing minerals. The linear (log scale) increase in sodium with chloride is typical of the mixing of low-salinity water with a sodium-chloride brine (Kreitler and others, 1977; Richter and others, 1990). Chloride is a good predictor of TDS at salinities greater than 1,000 mg/L (fig. 22b).

The Br ($\times 10^4$)/Cl ionic ratio has been demonstrated as a useful tool for comparing oilfield brine and dilute ground waters (Whittemore and Pollock, 1979; Whittemore, 1995). There is no significant change in the Br ($\times 10^4$)/Cl ratio, however, with increase in chlorinity among samples; the Br ($\times 10^4$)/Cl ratio of the BEG and FH samples averages 55 (fig. 23a). While the concentration of bromide was not measured in the previous analyses of the two oilfield brine samples reported in table 7, Br × 10^4/cl of a typical oilfield brine from the site might be expected to lie between 43 and 68, on the basis of the reported data from BEG and FH wells and assuming that variation in salinity is owing to the mixing of fresh-water and oilfield brine. This

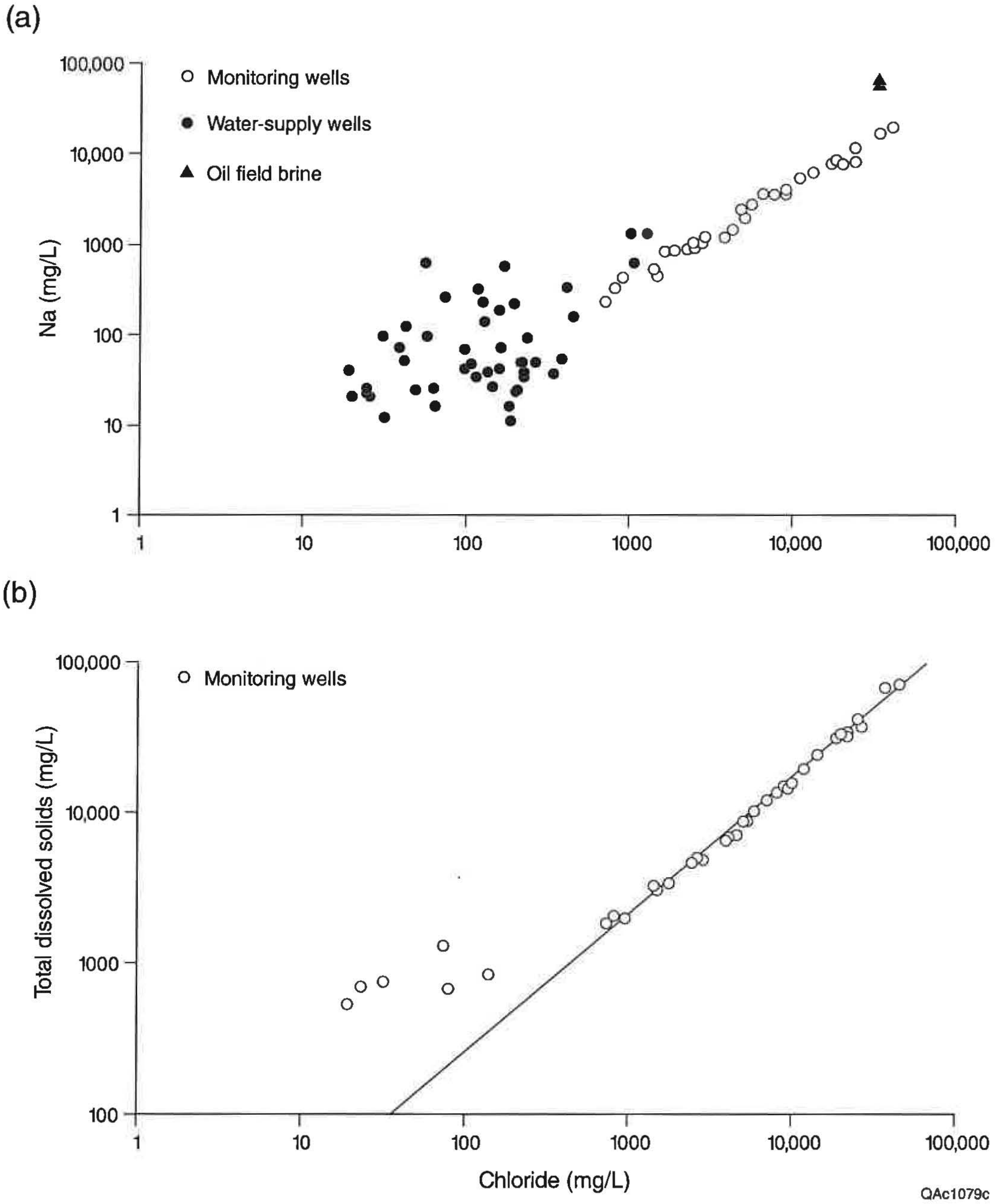


Figure 22. Graph showing covariations of dissolved chloride with (a) dissolved sodium and (b) total dissolved solids in ground waters.

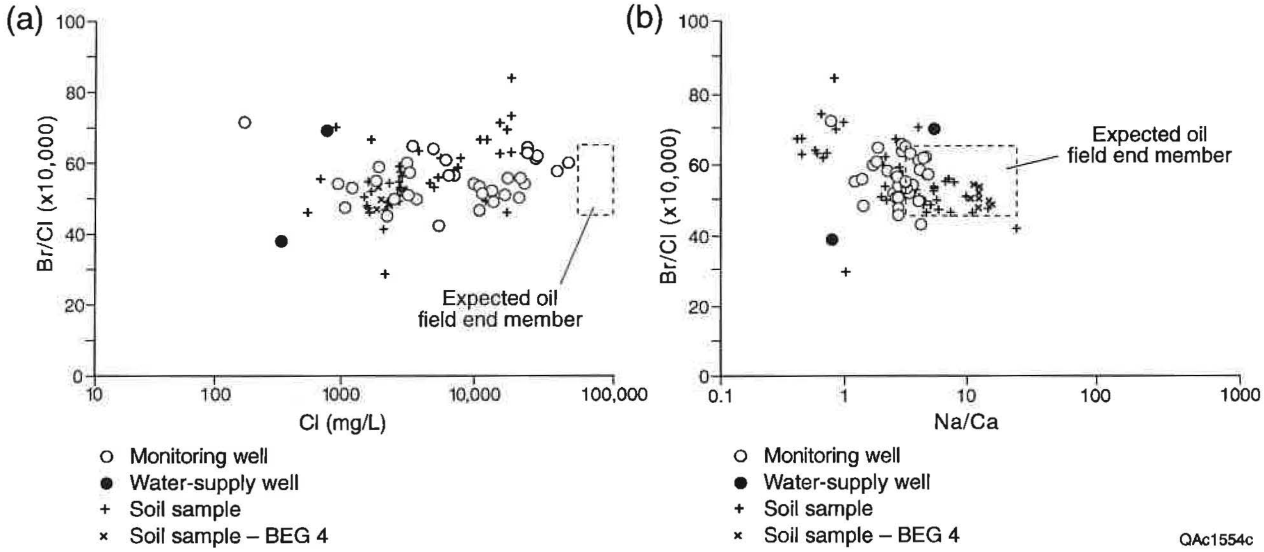


Figure 23. Graph showing variation in Br (x104)/Cl with (a) chloride and (b) Na/Ca ratio in water and soil. Field of expected oilfield end member based on Br (x104)/Cl ratio extrapolated from data field and composition of two oilfield brine samples from the study area (table 7).

Br ($\times 10^4$)/Cl ratio would be somewhat more enriched in bromide, compared to oilfield brines from Pennsylvanian reservoirs in the Permian Basin in West Texas, and much more enriched compared to brines from Permian reservoirs (Richter and others; 1990). The ratio would be approximately the same as the typical ratio of dilute water.

The Na/Ca ratio varies with salinity because of the influence of (a) partial dissolution of sodium- and calcium-bearing minerals, and (b) variation in ion exchange with salinity owing to change in ion adsorption selectivity. Simple dilution of an oilfield brine would not result in a change in Na/Ca ratio. Possible Na/Ca ratios of the expected brine end member are bounded by the two samples from the study area and the extrapolation of trends in water and soil data (table 7; fig. 24). Na/Ca and Cl/SO_4 ratios of BEG and FH samples plot between (1) oilfield brine samples, and (2) low-salinity waters from water-supply wells, especially those with a Na/Ca ratio of less than 10 (fig. 24a). Ground waters with a Na/Ca ratio of more than 10 are located mainly east and south of the study area but also include a few deep wells north of the study area. The trend in Na/Ca and Cl/SO_4 ratios of waters from BEG and FH wells is consistent with mixing between oilfield brine, as defined by the two samples from RRC files, and dilute ground waters occurring at and near the study area (fig. 24a).

The maximum contaminant level (MCL) for barium in drinking water is 2 mg/L. Barium concentration in samples from BEG and FH monitoring wells is correlated with chloride concentration and TDS. Barium concentration averages 3.5 mg/L and ranges from 0.07 mg/L to 25 mg/L (tables 8 and 9). Other ions, of course, are also correlated with salinity. There is not a MCL set for strontium, for example, but its drinking-water health advisory levels are 25 mg/L for a 10-kg (22-lb) child and 90 mg/L for a 70-kg (154-lb) adult (U.S. Environmental Protection Agency, October 1996, Drinking water regulations and health advisories, EPA 822-B-96-002, http://www.epa.gov/docs/ostwater/Tools/dwstds0.html). Strontium concentration averages 30 mg/L and ranges from 0.3 mg/L to 181 mg/L in the BEG and FH samples; five samples exceed 90 mg/L and 15 samples exceed 25 mg/L (tables 8 and 9).

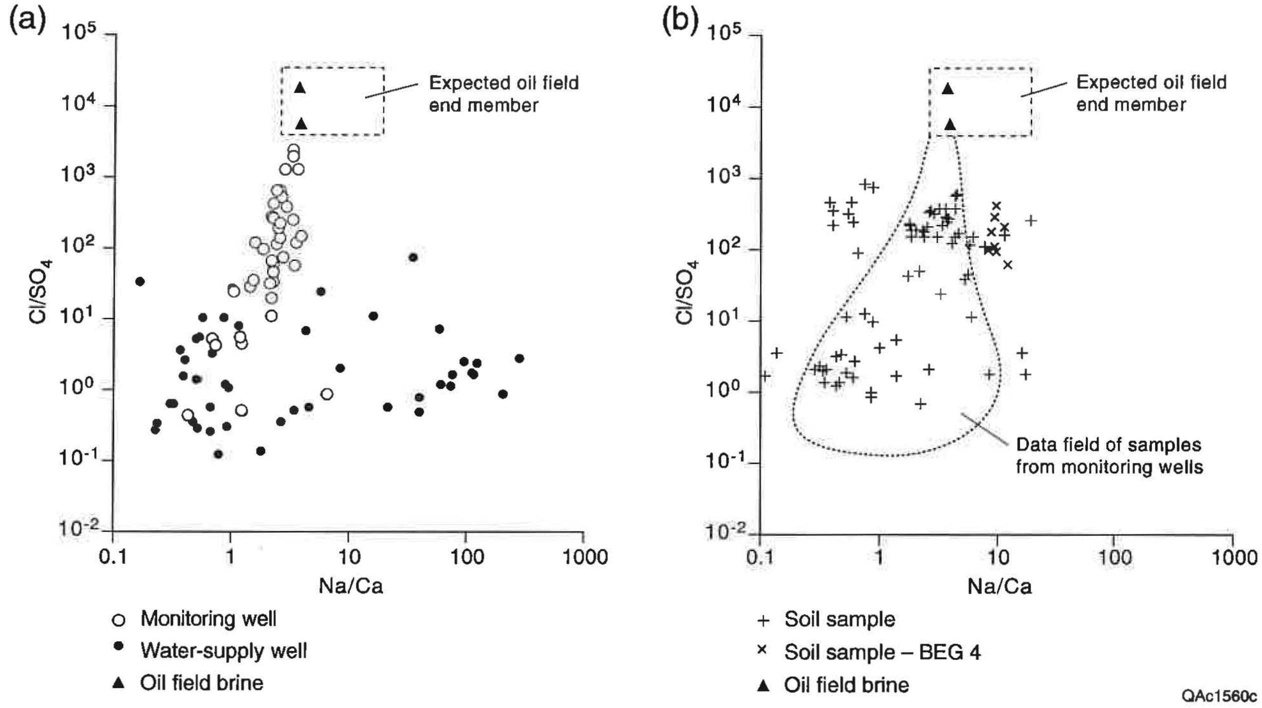


Figure 24. Graph showing variation in ionic ratios (meq/L) of Cl/SO_4 and Na/Ca for samples from monitoring and water-supply wells, soil, and oil-field brine. In (b) the data field for water samples from monitoring wells is compared to soil data.

Cross Sections and Map of Subsurface Salinity Plume

Figures 25 and 26 present cross sections of the subsurface saltwater plume on the basis of measured TDS, and follow the same hydrologic sections shown in figures 11 and 12. The base of the plume is estimated partly on the basis of geophysical (TDEM) profiles. TDS varies along the sections in part because section lines do not exactly follow flow paths but instead cut across the main axes of the saltwater plume. Figure 26 is especially idealized because it shows the plume to be continuous between wells BEG 1 and BEG 16, although the line of section does not exactly follow the main plume axis.

Figure 21 shows a plan-view map that approximates the footprint and concentrations of the subsurface saltwater plume on the basis of measured salinity. Spatial variations in ground conductivity measured by 7,000-Hz and 900-Hz EM coils during the airborne survey were used to guide mapping of the edge of the saltwater plume. Concentration contours consistently follow ground conductivity contours.

The cross sections and salinity map show several important features:

- The salinity plume has a northwest and northeast lobe beneath the Quaternary terrace. The northwest lobe extends toward well BEG 6 and the northeast lobe extends toward well BEG 5S (figs. 21, 25, and 26).
- The saltwater plume appears thicker and salinity is higher beneath the upland area than beneath the terrace (figs. 21 and 25). The TDS of 74,561 to 62,275 mg/L from wells FH 23 and 26, respectively, in the upland area, is 54 to 70 percent of the TDS of two oilfield brine samples from the area.
- The main lobes of the saltwater plume beneath the Quaternary terrace have a TDS of 25,000 to 35,000 mg/L (figs. 21, 25, and 26).
- The leading edge of the northeast lobe of the saltwater plume appears just north of well BEG 5 (figs. 21 and 25); the sample from BEG 5S having TDS of 4,800 mg/L is assumed

to be affected by the saltwater plume, whereas the sample from BEG 5D having TDS of 800 mg/L is not.

- The east side of the saltwater plume is well defined on the section by the decrease in TDS from more than 34,800 mg/L at well BEG 1 to less than 1,000 mg/L at wells FH 9 and FH 10 (fig. 26).

As the saltwater plume is carried north, we infer that it moves from Permian bedrock beneath the upland area into the Quaternary sediment package beneath the terrace. Monitoring-well data and geophysical results indicate that in most areas beneath the terrace the saltwater plume lies within the Quaternary sediments and does not extend significantly downward into the underlying Permian bedrock (figs. 25 and 26). Well BEG 4 is in the transition zone between the upland and terrace areas and here the base of the plume appears to lie within Permian bedrock (fig. 26). The airborne geophysical survey shows a gap in conductivities between the main northwest lobe beneath the terrace and elevated conductivity in the vicinity of BEG 6, as discussed in the following sections. We interpret this gap to be an artifact of increasing depth to water and interpret that the northwest lobe of the salinity plume is continuous between BEG 4 and BEG 6.

Elevated salinity beneath the Red River and adjacent Holocene terrace (figs. 21 and 26) is inferred to include (a) saltwater moving northeastward through alluvium along the river reach beneath the floodplain, and (b) saltwater discharging from the plume at the study area. In this study, however, we did not collect data on ground-water salinity beneath the Holocene terrace in the Williams seep area.

Barren Areas and Saline Seeps

Field observation of barren areas and surface salinization involved inspection of some of the barren areas and former pit sites identified on the 1966 photograph (appendix 6), plotting the

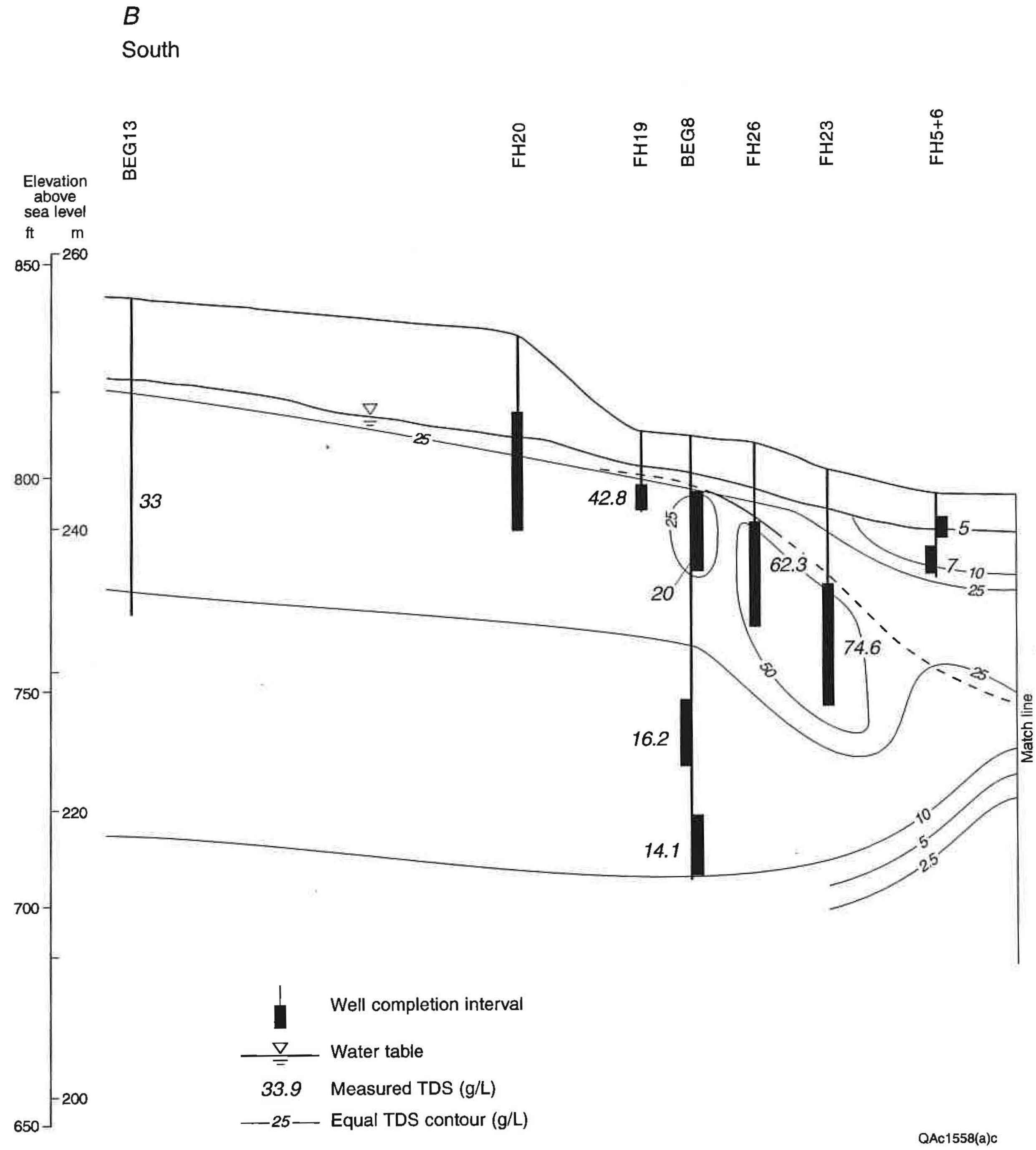


Figure 25. Study area north–south cross section of total dissolved solids. Line of section E–E′ shown in figure 7.

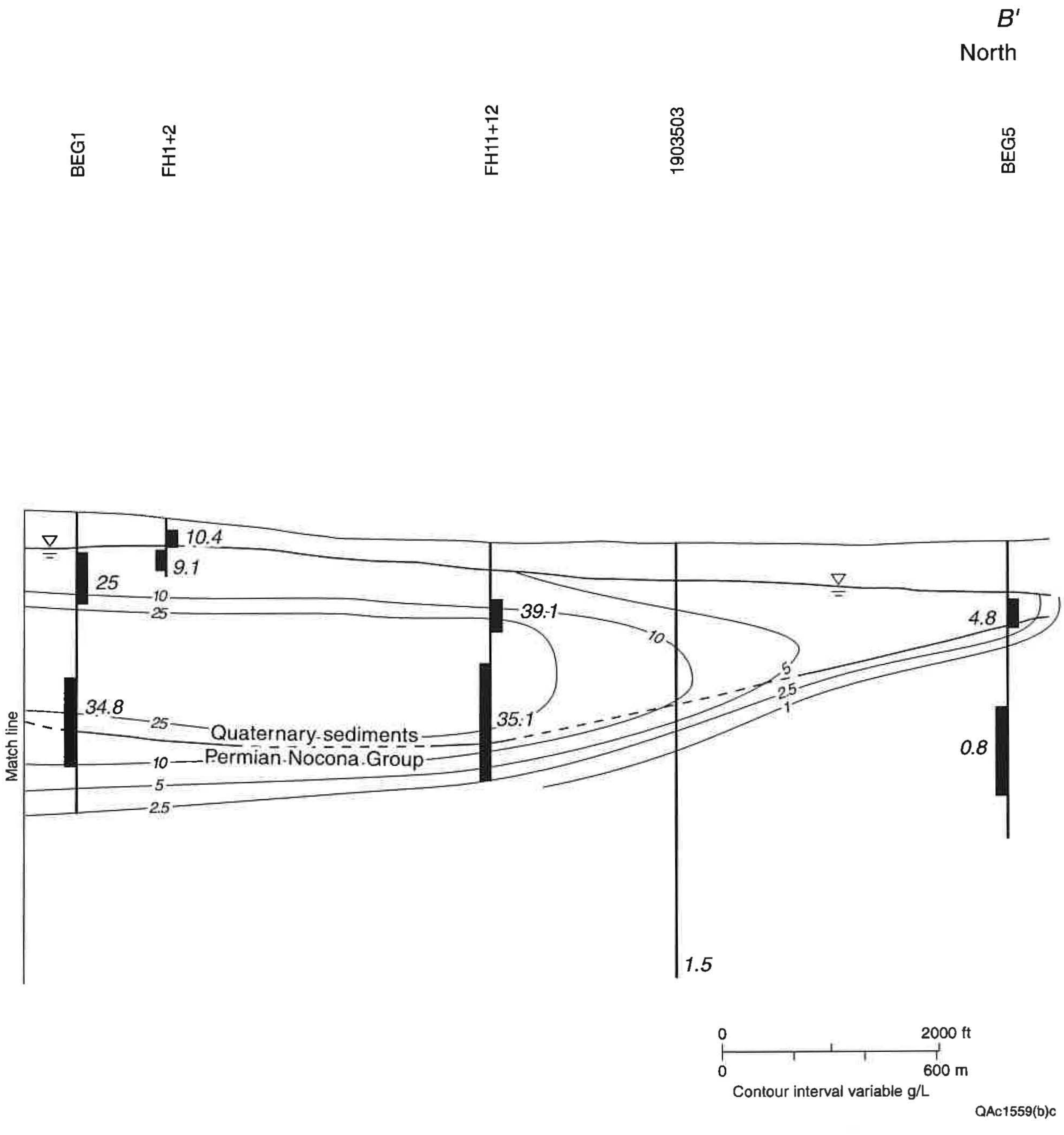


Figure 25 (cont.)

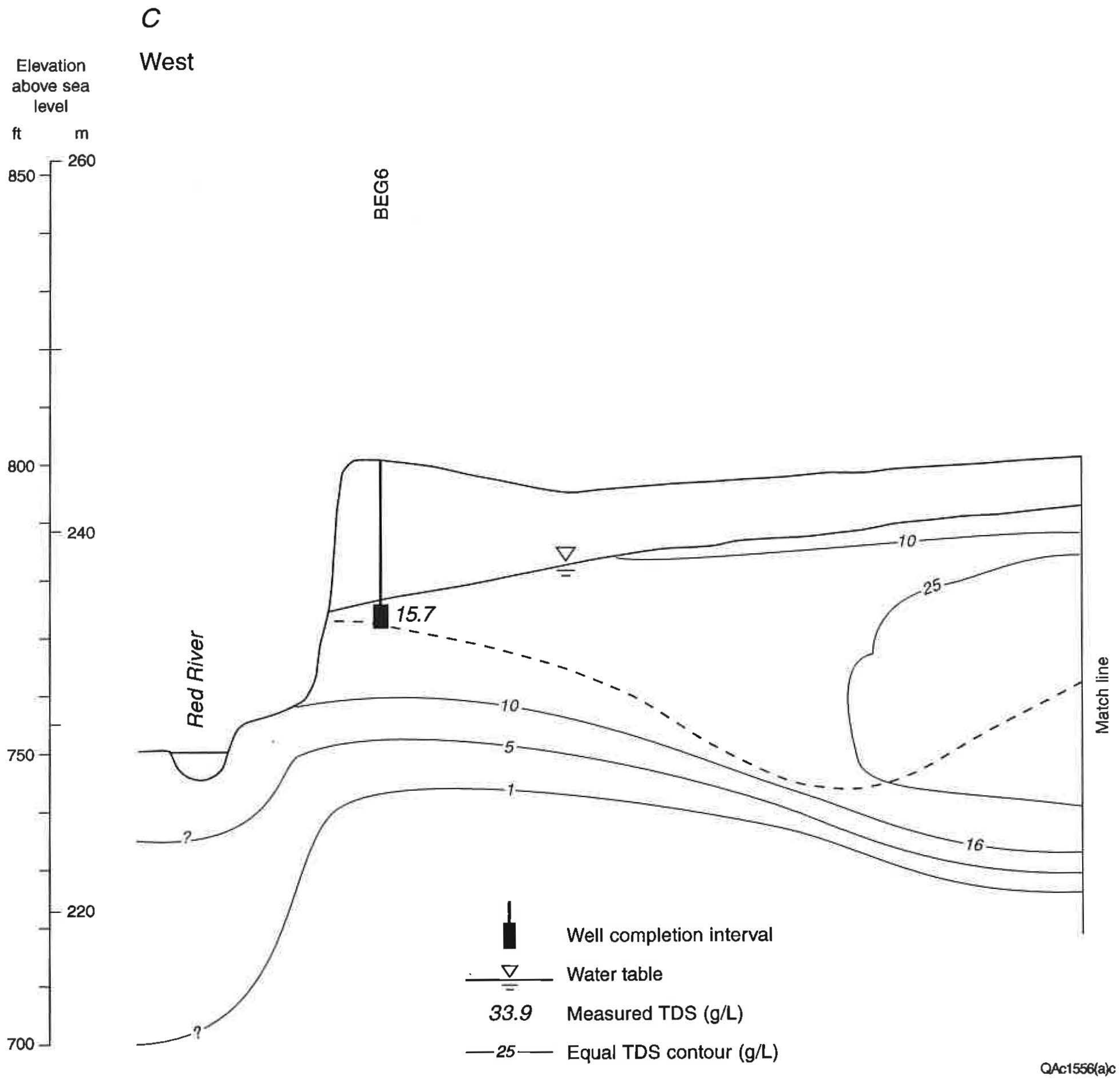


Figure 26. Study area east–west cross section of total dissolved solids. Line of section F–F′ shown in figure 7.

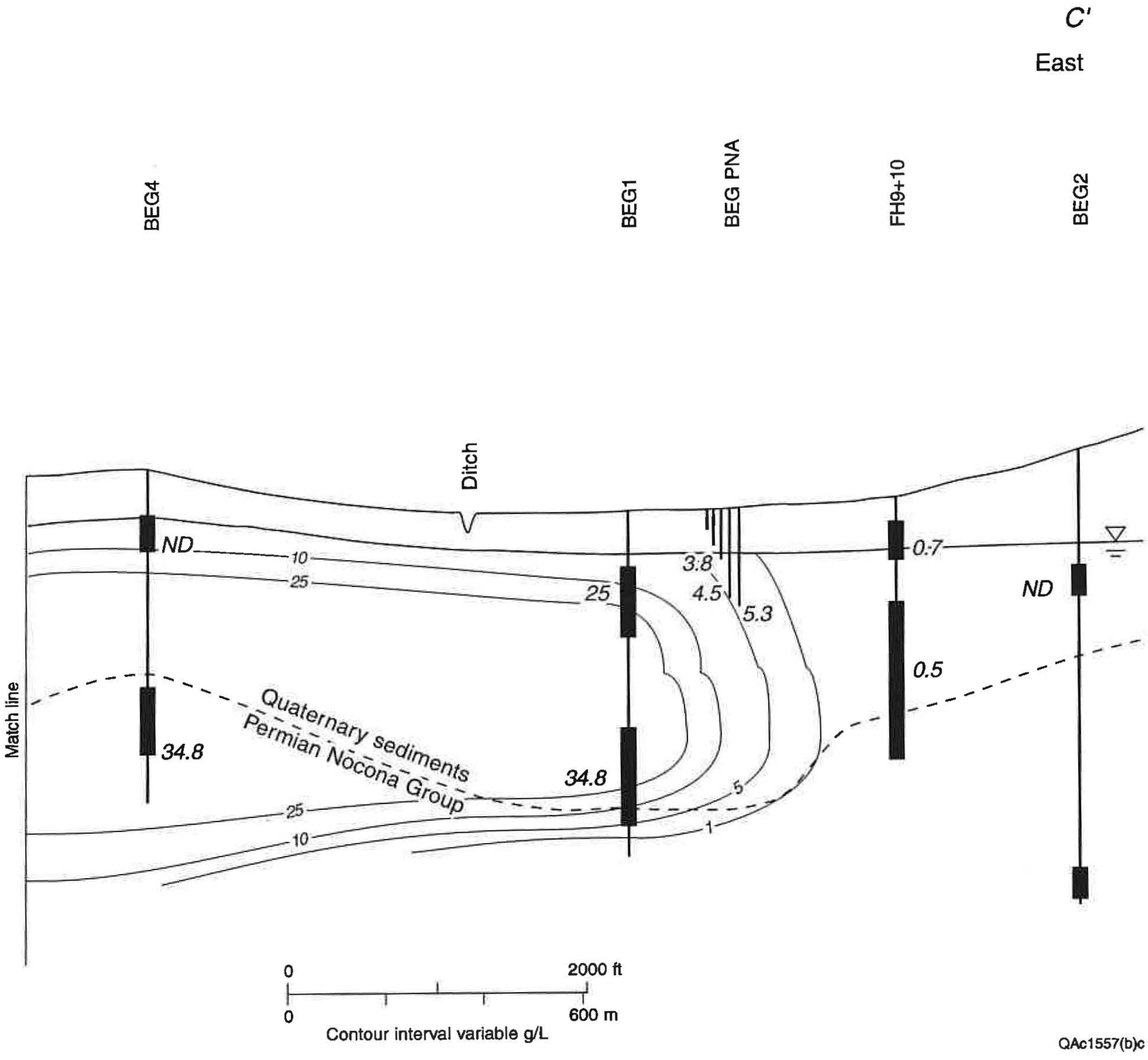


Figure 26 (cont.)

extent of the large barren area on the terrace (fig. 2), and reconnaissance exploration of the seep at the Williams complaint.

Barren areas and former pit sites identified on the 1966 photograph were located by navigating to the identified coordinates using GPS. Former pit sites were also identified by matching current oilfield roads and equipment to the photograph. All of the pits visited have been breached and flattened by bulldozing, although some areas of hummocky and disrupted surface remain. Shallow gullies are cut though some former pit areas. Weathered crusts of oil and tank bottom material on the surface and minor amounts of debris were observed in some former pit areas. Some of the former pit areas are sparsely vegetated and, therefore, grab samples were collected in the pit floors to determine soil salinity and TPH. Other former pit areas are now vegetated and there is no visible evidence of the former pit. Several former pit sites have been obscured by newer constructions.

Examination of the large barren area (MBA) included circumnavigation of the contiguous barren area carrying a backpack-mounted GPS receiver. This produced an accurate measurement of the extent of the barren area in fall 1997 against which future changes can be compared. The ground surface of the barren area was lightly crusted by salt. Soil over most of the barren area is sandy and surface textures suggest that the area is being erroded and deflated. Slightly higher areas along the north-south fenceline across the barren area are partly vegetated and appear to be less saline. Evidence of ponding is observed in low-lying muddy areas at the north and northwest edge of the barren area.

Other impacted ground is found north and east of the main barren area, but because of the scattered nature of the barren spots, the best sense of the impact is seen in air photographs. The extent of impacted ground can be seen in a 1995 color-infrared image (appendix 8). Poor crop growth in this photograph could be a result of salinization, ponding or high water table without salinization, or other land-use impacts; therefore, the outlined area is the maximum extent of impacted ground at the time it was taken.

The saltwater seeps of the Williams complaint are 1.2 mi west-northwest of the main barren area. No surface drainage connects the two saline areas across intervening productive farm land. Past and present-day oil-production wells, tank batteries, and injection wells are found in the immediate area of the Williams seep. One part of this investigation was to evaluate the relationship between the main barren area and the saltwater seeps.

The Williams seep is in the 40-ft-high bluff between the Pleistocene and Holocene terraces of the Red River. Permian sandstone crops out in the middle of the bluff. Vegetated dunes mantle the surface and create a topographic high on the bluff edge. The Holocene terrace is used for agriculture and lies above a 10-ft-high cutbank of the modern river.

An area of saline seeps marked by dead brush and trees extends about a half of a mile along the bluff. A number of earth dams have been constructed at the base of the bluff to impound saline water. At the time of our field work, overflow from these dams was sourcing several small flowing streams that discharged across the field before seeping into the Holocene terrace. Recently dead large pecan trees were noted on the terrace in the area of the seeps. A grab sample of water from an impoundment had TDS of 20 g/L (table 8).

Soil Chemistry

Concentration of water-soluble components extracted by 1:1 dilution in core samples vary regionally and with depth (fig. 27; table 10). Soluble salt content is the lowest in BEG 2, at a Quaternary terrace setting outside of the saline plume, defined by airborne conductivity and ground-water chemistry. Concentrations in soils at BEG 13 are also relatively low. This borehole was sited to examine soils and water near a drainage a few hundred feet downhill from a former pit site. Low chloride in these soils suggest that a large amount of chloride is not stored in surficial soils in the upland. High concentrations of chloride and total salt were measured at depths of 5 to 10 feet at BEG 8. These soils are alluvial deposits along drainage and are observed to have white surface crusts where they crop out in the modern arroyo walls. A bedrock outcrop

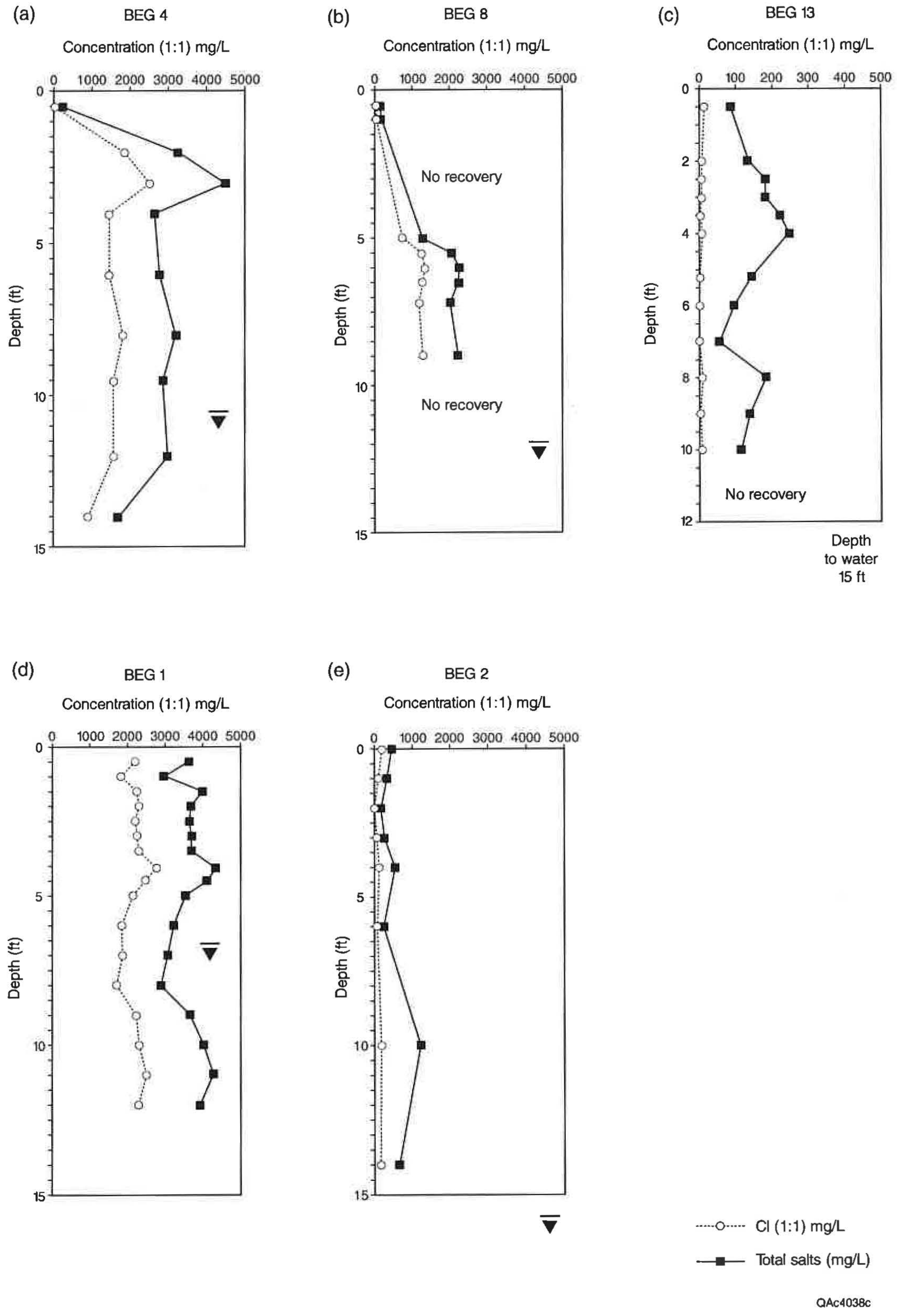


Figure 27. Vertical profile of chloride in unsaturated soils.

near this site also has white salt crusts, suggesting that saline water discharges and evaporates from bedrock in the arroyo.

The highest concentrations of total salt and of chloride were measured beneath the barren area at BEG 1 and in soils over the west part of the plume at BEG 4. High salinity was expected beneath the barren area because of vegetation kill. High salinity in surficial soils was not expected at BEG 4, which is in an area covered by scrub vegetation. Depth to ground water was more than 10 ft below surface in this area. The relationship between salinity in this unsaturated soil and saline ground water is not well understood. It is possible that the salinity in the soil is related to past or seasonally higher water levels. Alternatively, salinity in the soils may be related to local oilfield activities such as former pits or spills, because this area is at the north edge of the North Nocona field.

Surface soils collected along two transects across the barren area showed that highest salinity is toward the center of the barren area (fig. 28). Soils collected from the surface of abandoned pits had moderate to high salinity of 1277 to 15,000 m/L from 1:1 dilutions (table 10). Oxidized oil or tank bottom material on the surface and in shallow soils was observed in some of the pit areas. Grab samples from pits 7 and 13 (table 10; fig. 7) contained 7.1 percent and 3.4 percent TPH. In the 10 grab samples of soil or sediment from the floor of former pits, TCLP metal analyses were all below detection limits except for barium (table 11). Barium TCLP concentrations of 0.3 to 0.7 mg/L indicate low mobility of barium and are indicative of low total concentration.

Soil chemical composition is generally similar to that of water samples from the affected area (figs. 23 and 24b). The Br (x10^4)/Cl ratio of soils matches that of ground water from monitoring wells (fig. 23). Soil data also generally match ground-water composition in Cl/SO_4 and Na/Ca ratios (fig. 24b). Exceptions include (1) soil samples from the barren area, which have a great deal of scatter and include data plotting to the upper left (high Cl/SO_4 and low Na/Ca ratios) of the data field defined by samples from monitor wells (fig. 24b); and (2) core samples from the BEG 4 borehole (shown as "x" in fig. 24b). The anomalous core samples from above

Table 10. Chemical composition of water-soluble fraction in soils.

Site	Depth (ft)	Date	Matrix	HCO3 (1:1) mg/L	Br (1:1) mg/L	Ca (1:1) mg/L	CO3 (1:1) mg/L	Cl (1:1) mg/L	Diluted cond. mmhos/cm	EC (1:1) mmhos/cm	Mg (1:1) mg/L	NO3 (1:1)mg/L	pH (1:1)	K (1:1) mg/L	Na (1:1) mg/L	SO4 (1:1) mg/L	Total Salts mg/L	CEC g	Exchangable Na meq/100g
BEG1	0.5–0.7	10/14/97	soil	-	13	350	0	2,193	8.4	7	266	54	6.22	16	713	13	3,618	5.9	n.d.
BEG1	1.0–1.2	10/14/97	soil	-	9	271	0	1,820	6.7	5.6	217	25	6.65	14	581	16	2,953		
BEG1	1.5–1.7	10/14/97	soil	-	12	353	0	2,241	8.7	7.3	278	23	7.3	<5	744	16	3,975.3	12	n.d.
BEG1	2.0–2.2	10/14/97	soil	-	13	334	0	2,293	8.2	6.9	252	18	7.62	<5	785	17	3,681		
BEG1	2.5–2.7	10/14/97	soil	-	12	319	0	2,190	8.1	7	250	12	6.66	<5	844	16	3,619		
BEG1	3.0–3.2	10/14/97	soil	-	13	314	0	2,248	8	7	248	10	6.66	<5	859	17	3,686	17	0.24
BEG1	3.5–3.7	10/14/97	soil	15	12	309	0	2,274	8.3	7	239	6	7.07	<5	847	20	3,689		
BEG1	4.1–4.2	10/14/97	soil	17	14	258	0	2,764	9.4	7.8	277	7	7.03	<5	1,007	17	4,323		
BEG1	4.5–4.7	10/14/97	soil	-	13	332	0	2,475	9	7.7	303	7	6.46	<5	976	16	4,102		
BEG1	5.0–5.2	10/14/97	soil	-	11	276	0	2,155	7.5	6.4	254	5	6.42	<5	827	9	3,521		
BEG1	6.0–6.2	10/14/97	soil	-	10	263	0	1,839	7.1	6.1	241	1	6.64	<5	868	8	3,219		
BEG1	7.0–7.2	10/14/97	soil	-	9	196	0	1,863	6.3	5.4	174	<1	6.95	<5	817	7	3,057		
BEG1	8.0–8.2	10/14/97	soil	-	8	158	0	1,702	6	5.3	135	<1	6.97	<5	861	14	2,870		
BEG1	9.0–9.2	10/14/97	soil	-	11	230	0	2,230	7.5	6.6	176	1	7.18	<5	997	11	3,644		
BEG1	10.0–10.2	10/14/97	soil	-	13	286	0	2,296	8.5	7.3	201	2	6.94	<5	1,201	11	3,995		
BEG1	11.0–11.2	10/14/97	soil	-	13	337	0	2,484	8.8	7.6	205	2	6.92	<5	1,221	9	4,256		
BEG1	12.0–12.2	10/14/97	soil	-	12	349	0	2,289	8.5	7.3	191	2	6.61	<5	1,076	9	3,914		
BEG2	0.0–0.2	10/19/97	soil	-	<1	9	0	17		0.36	5	113	5.45	66	5	7	43		
BEG2	1.0–1.2	10/19/97	soil	-	<1	7	0	8		0.08	7	6	6.28	<5	5	4	31		
BEG2	2.0–2.2	10/19/97	soil	-	-	5	0	-		0.07	5	-	6.46	<5	5	-	15		
BEG2	3.0–3.2	10/19/97	soil	-	<1	5	0	5		0.07	<5	7	6.54	<5	<5	7	24.07		
BEG2	4.0–4.2	10/19/97	soil	-	<1	10	0	10		0.12	<5	17	6.75	<5	5	11	53.12		
BEG2	6.0–6.2	10/19/97	soil	-	<1	5	0	5		0.09	<5	5	6.77	<5	<5	8	23.09		
BEG2	10.0–10.2	10/19/97	soil	-	<1	11	0	15		0.23	5	31	6.88	<5	28	30	120.23		
BEG2	14.0–14.2	10/19/97	soil	-	<1	10	0	14		0.17	<5	12	7.21	<5	16	11	63.17		
BEG4	0.5–0.6	11/8/97	soil	-	<1	45	0	56		0.32	55	<1	6.62	65	71	14	241		
BEG4	2.0–2.1	11/8/97	soil	-	9	88	0	1,864	6.3	5.5	18	2	6.23	<5	1,246	42	3,258		
BEG4	3.0–3.2	11/8/97	soil	-	13	158	0	2,527	8.4	7.8	35	2	6.14	<5	1,746	32	4,498		
BEG4	4.0–4.1	11/8/97	soil	-	7	94	0	1,484		4.7	20	<1	6.39	<5	1,039	7	2,644		
BEG4	6.0–6.2	11/8/97	soil	-	8	99	0	1,502		4.7	46	1	7.57	<5	1,134	5	2,786		
BEG4	8.0–8.1	11/8/97	soil	57	9	93	0	1,832	6.1	5.5	32	3	7.62	<5	1,250	12	3,219		
BEG4	9.5–9.6	11/8/97	soil	60	8	101	0	1,600	6	5.3	39	3	7.46	<5	1,123	23	2,886		
BEG4	12.0–12.1	11/8/97	soil	-	8	126	0	1,602	6	5.4	57	4	7.22	<5	1,213	22	3,020		
BEG4	14.0–14.1	11/8/97	soil	-	5	66	0	930		3.4	30	1	7.53	<5	674	7	1,707		
BEG4	0.5–1.0	10/15/97	soil	-	<1	39	0	10		0.11	36	<1	6.35	45	5	8	98		
BEG4	1.0–1.1	10/15/97	soil	-	<1	50	0	13		0.1	51	<1	6.71	54	8	5	127		
BEG4	5.0–5.2	10/15/97	soil	27	5	103	0	712		2.6	24	<1	7.22	20	396	40	1,275		
BEG4	5.5–5.7	10/15/97	soil	11	6	137	0	1,249	3.8		38	1	6.68	<5	647	14	2,085		
BEG4	6.0–6.2	10/15/97	soil	-	7	144	0	1,342		4.1	41	3	6.14	<5	728	12	2,267		
BEG4	6.5–6.7	10/15/97	soil	-	6	117	0	1,295		4.1	32	3	6.16	<5	793	15	2,252		
BEG4	7.2–7.4	10/15/97	soil	7	6	81	0	1,189		3.9	22	3	6.6	<5	730	15	2,037		
BEG4	9.0–9.2	10/15/97	soil	7	6	67	0	1,268		4	17	<1	6.82	<5	883	11	2,246		
BEG13	0.5–0.7	11/10/97	soil	14	<1	15	0	15		0.07	15	<1	6.49	26	<5	10	87.56		
BEG13	2.0–2.2	11/10/97	soil	-	<1	38	0	10		0.06	65	<1	6.31	89	15	7	135		
BEG13	2.5–2.7	11/10/97	soil	-	<1	53	0	9		0.07	93	<1	6.28	147	22	6	183		
BEG13	3.0–3.2	11/10/97	soil	-	<1	49	0	10		0.09	89	<1	6.51	122	26	10	184		
BEG13	3.5–3.7	11/10/97	soil	-	<1	67	0	7		0.07	116	<1	6.6	151	27	7	224		
BEG13	4.0–4.2	11/10/97	soil	-	<1	74	0	12		0.06	130	<1	6.86	139	27	7	250		

Table 10 (cont.)

Site	Depth (ft)	Date	Matrix	HCO3 (1:1) mg/L	Br (1:1) mg/L	Ca (1:1) mg/L	CO3 (1:1) mg/L	Cl (1:1) mg/L	Diluted cond. mmhos/cm	EC (1:1) mmhos/cm	Mg (1:1) mg/L	NO3 (1:1)mg/L	pH (1:1)	K (1:1) mg/L	Na (1:1) mg/L	SO4 (1:1) mg/L	Total Salts mg/L	CEC g	Exchangable Na meq/100g
BEG13	5.2–5.7	11/10/97	soil	-	<1	41	0	7		0.08	69	2	7.26	66	25	5	147		
BEG13	6.0–6.2	11/10/97	soil	-	<1	26	0	6		0.07	45	2	7.24	51	18	5	100		
BEG13	7.0–7.2	11/10/97	soil	-	<1	9	0	6		0.13	14	<1	7.63	20	27	4	60		
BEG13	8.0–8.2	11/10/97	soil	-	<1	45	0	12		0.18	75	<1	7.71	123	52	4	188		
BEG13	9.0–9.2	11/10/97	soil	-	<1	<5	0	8		0.35	<5	<1	8.1	21	99	6	142.45		
BEG13	10.0–10.2	11/10/97	soil	-	<1	<5	0	13		0.33	7	<1	8.16	<5	94	5	119.33		
MBA0		10/14/97	soil	8	<1	10	0	14		0.16	7	23	5.12	29	<5	6	89	5.1	0.06
MBA1		10/14/97	soil	5	20	1,009	0	3,150	12	9.7	448	49	5.31	39	611	381	5,707	4.5	0.05
MBA2		10/14/97	soil	10	41	1,761	0	6,636	25	19	1,342	25	6.43	29	1,235	38	11,107	4.7	n.d.
MBA3		10/14/97	soil	6	63	2,735	0	9,421	36	26	1,766	51	5.34	30	1,310	60	15,436	6.1	n.d.
MBA4		10/14/97	soil	10	84	3,224	0	13,364	49	34	2,888	80	6.55	17	2,024	59	21,740	5.7	0.8
MBA5		10/14/97	soil	10	120	3,364	0	16,287	62	40	3,748	61	6.56	23	2,276	48	25,927	6.9	1.7
MBA6		10/14/97	soil	6	104	4,404	0	16,496	64	43	2,664	109	5.87	89	3,330	248	27,444	14	5
MBA7		10/14/97	soil	5	61	2,154	0	12,106	43	33	1,672	187	5.35	38	4,245	379	20,842	11	n.d.
MBA8		10/14/97	soil	6	106	3,328	0	15,258	62	39	3,266	524	5.36	28	2,913	1640	27,063	12	3.2
MBA9		10/14/97	soil	69	<1	19	0	148		0.74	8	<1	7.91	<5	133	18	326	15	0.98
MBA10		10/14/97	soil	11	9	237	0	1344		4.3	151	19	6.56	<5	601	36	2,378	8.7	0.23
MBA11		10/14/97	soil	162	2	45	4	432		2.3	18	<1	8.49	<5	445	328	1,274	5.4	0.75
MBA12		10/14/97	soil	66	3	49	0	537		1.9	17	9	7.78	<5	322	16	944	6.6	0.51
MBA13		10/14/97	soil	11	29	820	0	4,689	17	14	444	22	6.51	12	1,714	29	7,759	8.8	3.5
MBA15		10/14/97	soil	8	72	2,719	0	10,759	41	29	2,221	70	6.19	19	1,206	32	17,098	6.8	0.01
MBA16		10/14/97	soil	10	115	3,080	0	14,719	54	37	2,988	132	6.28	25	1,510	43	22,612	6.5	n.d.
MBA17		10/14/97	soil	8	97	3,533	0	13,582	51	35	1,492	92	6.15	21	3,597	25	22,439	6.5	n.d.
MBA18		10/14/97	soil	7	139	4,097	0	16,548	62	42	1,929	113	5.74	14	3,508	27	26,375	10	n.d.
MBA19		10/14/97	soil	7	130	5,198	0	20,746	79	50	3,906	287	5.68	33	2,478	79	32,857	11	n.d.
MBA20		10/14/97	soil	6	5	401	0	1,722	6.4	5.4	158	78	5.29	25	415	237	3,041	13	0.3
Pit7-1	0.0–0.5	8164	Pit7-1	13	7	125	0	1,277		4.2	24	16	5.38	25	756	45	2,275	7.9	0.32
Pit7-2	0.5–1.0	8165	Pit7-2	16	8	110	0	1,457		4.6	21	<1	6.16	21	803	13	2,433	8.7	0.5
Pit7-4	0.0–0.5	8166	Pit7-4	4	7	49	0	1,686			9	52	5.14	11	1,073	9	2,896	9.7	1.4
BA10-1	0.0–0.5	8167	BA10-1	5	52	1,224	0	10,497	38	29	241	99	5.65	28	6,466	24	18,631	21	n.d.
BA10-2	0.5–1.0	8168	BA10-2	6	49	921	0	9,304	34	26	173	71	5.83	24	4,694	22	15,258	22	9.8
BA10-3	0.0–0.5	8169	BA10-3	6	70	2,056	0	15,178	53	39	426	169	6.05	24	9,073	75	27,071	32	0.86
BA13-1	1"–0.5	8170	BA13-1	6	25	585	0	4,446	17	14	109	33	4.86	31	2,547	25	7,801	n.d.	0.9
BA13-2	0.5–1.0	8171	BA13-2	8	22	501	0	4,123	15	13	92	12	5.4	28	2,527	15	7,320	12	n.d.
BA13-3	1"–0.5	8172	BA13-3	9	37	1,174	0	6,269	26	20	187	55	5.43	37	3,177	46	10,982	11	1.9
BA13-4	0.5–1.0	8173	BA13-4	9	21	585	0	3,853	15	12	91	16	5.65	28	2,065	35	6,694		
BA13-5		11/12/97	soil														0		
BA7-3		11/12/97	soil														0		

insufficient sample amount
n.d. not detected

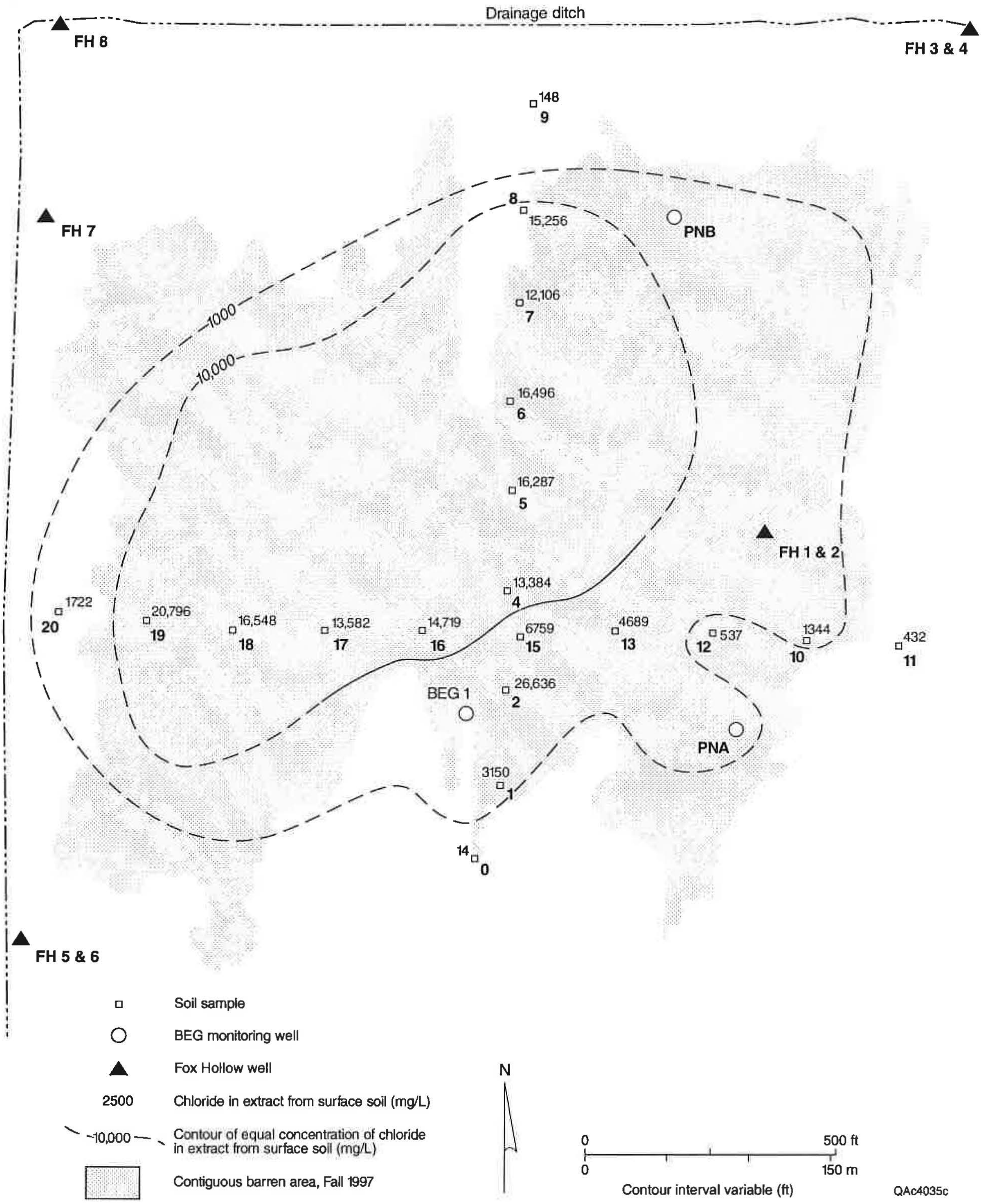


Figure 28. Map showing chloride in 1:1 dilution in surface soils in the barren area.

Table 11. TLCP metals in soils.

Sample ID	Site	Depth (ft)	Matrix	Arsenic TCLP	Barium TCLP	Cadmium TCLP	Chromium TCLP	Lead TCLP	Mercury	Selenium TCLP	Silver TCLP
8164	Pit7-1	0.0–0.5	soil	<.01	0.52	<.01	<.05	<.01	<.0002	<.01	<.01
8165	Pit7-2	0.5–1.0	soil	<.01	0.68	<.01	<.05	<.01	<.0002	<.01	<.01
8166	Pit7-4	0.0–0.5	soil	<.01	0.31	<.01	<.05	<.01	<.0002	<.01	<.01
8167	BA10-1	0.0–0.5	soil	<.01	0.3	<.01	<.05	<.01	<.0002	<.01	<.01
8168	BA10-2	0.5–1.0	soil	<.01	0.56	<.01	<.05	<.01	<.0002	<.01	<.01
8169	BA10-3	0.0–0.5	soil	<.01	0.48	<.01	<.05	<.01	<.0002	<.01	<.01
8170	BA13-1	1"–0.5	soil	<.01	0.83	<.01	<.05	<.01	<.0002	<.01	<.01
8171	BA13-2	0.5–1.0	soil	<.01	0.58	<.01	<.05	<.01	<.0002	<.01	<.01
8172	BA13-3	1"–0.5	soil	<.01	0.64	<.01	<.05	<.01	<.0002	<.01	<.01
8173	BA13-4	0.5–1.0	soil	<.01	0.77	<.01	<.05	<.01	<.0002	<.01	<.01

the water table at BEG 4 do not match the ground-water samples from BEG 4; the latter plot within the tight cluster of data from monitor wells (fig. 24a).

A variety of soil processes might account for the anomalous ionic ratios of some of the barren ground soils, including ionic exchange, evaporative concentration, and precipitation of gypsum or other salts. The anomalous soil chemical composition from BEG 4 is more difficult to explain but might be related to the unique profile of salinity with depth.

Plume Geometry

Lateral Extent

Reconnaissance measurements obtained with a ground conductivity meter across the Montague site (appendix 1) revealed that apparent conductivities ranged from less than 50 mS/m in areas having no evidence of salinization, to 200 mS/m or more across saltwater seeps and barren areas. These surveys also indicated that

- there is a conductivity anomaly associated with the barren area on the Pleistocene terrace,
- the conductivity anomaly underlies an area that is much larger than the barren area,
- several conductivity anomalies exist along the streams that cross the oilfield south of the terrace, suggesting multiple sources of saline water, and
- the salinity sources and salinization are bound by an area that is about 4.5 km east–west by about 5.5 km north–south (fig. 4). This area was subsequently surveyed with airborne instruments.

Maps of ground conductivity, as measured by the airborne 56,000-, 7,200-, and 900-Hz induction coils, are similar, and each clearly shows the extent of highly conductive ground (figs. 29, 30, and 31). Exploration depths for the 56,000-Hz coils, calculated from the known frequency and from the observed conductivity range of 25 to 3,000 mS/m, range from about 1 m for the most conductive ground to about 14 m for the least conductive ground (fig. 32). Conductivities measured by the 7,200-Hz coils, ranging from 25 to 1,500 mS/m (fig. 30), are

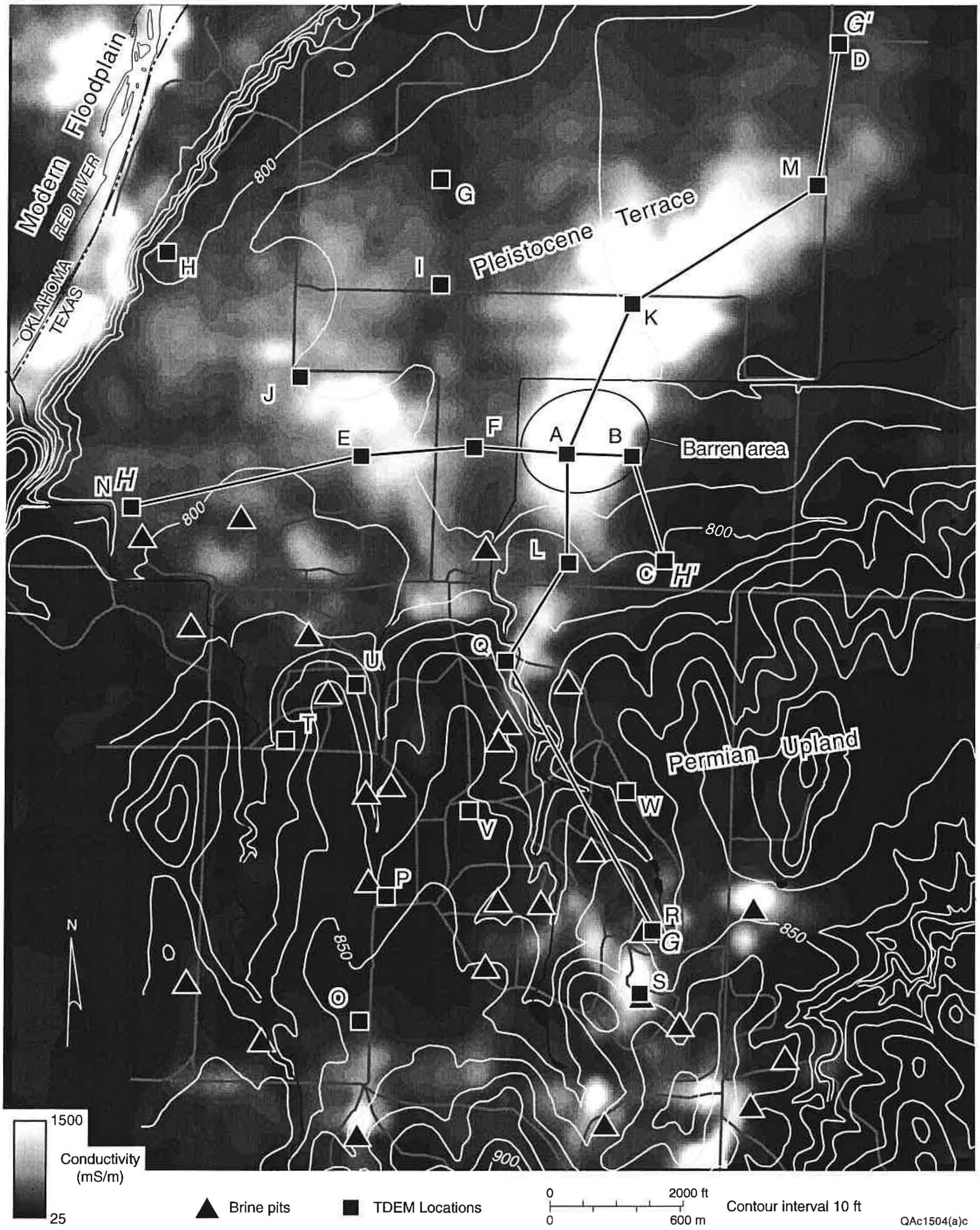


Figure 29. Map of the Montague site superimposed on a gray-scale image of apparent conductivity measured with 56,000-Hz airborne-induction coils.

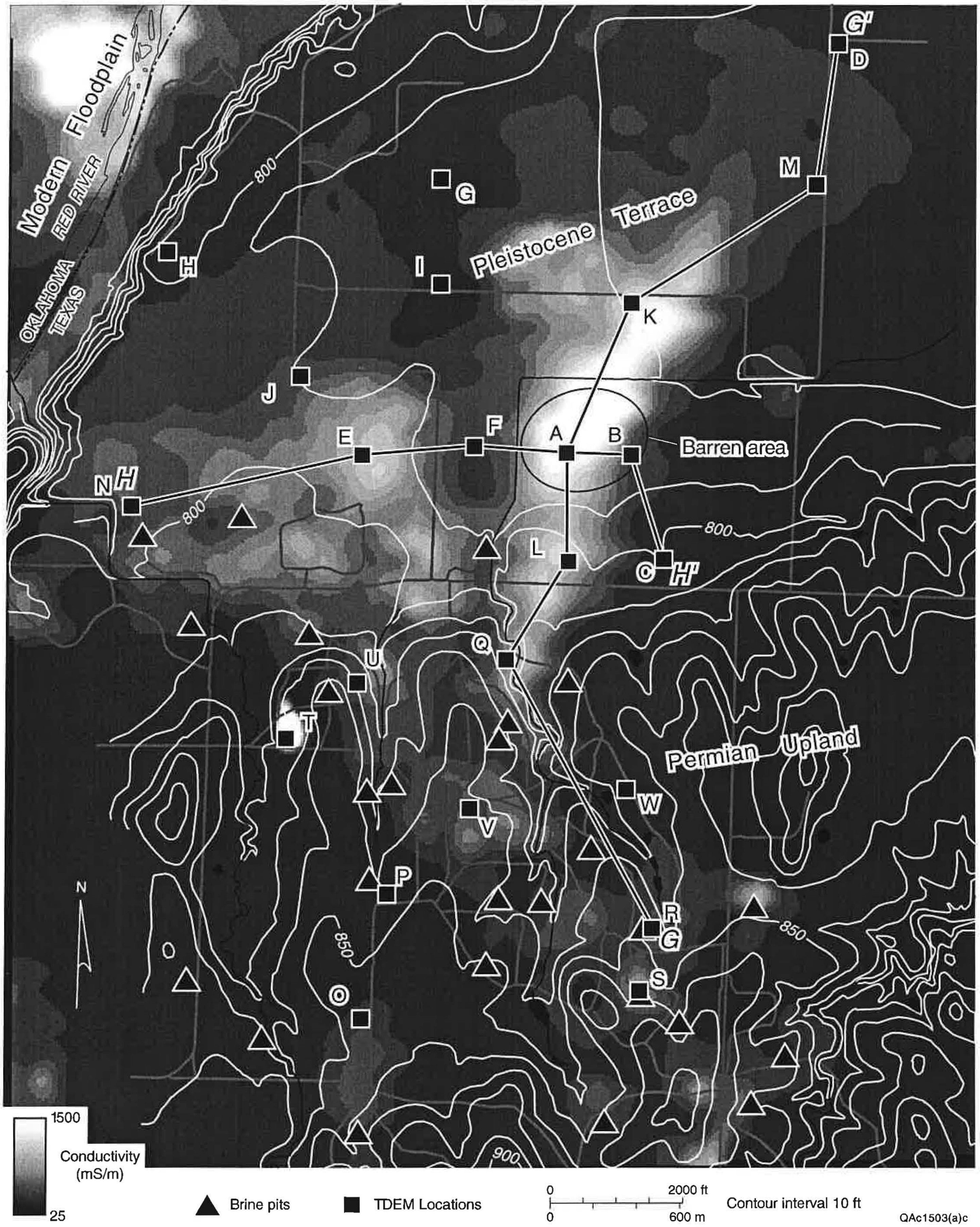


Figure 30. Apparent conductivity at the Montague site measured with 7,200-Hz airborne induction coils.

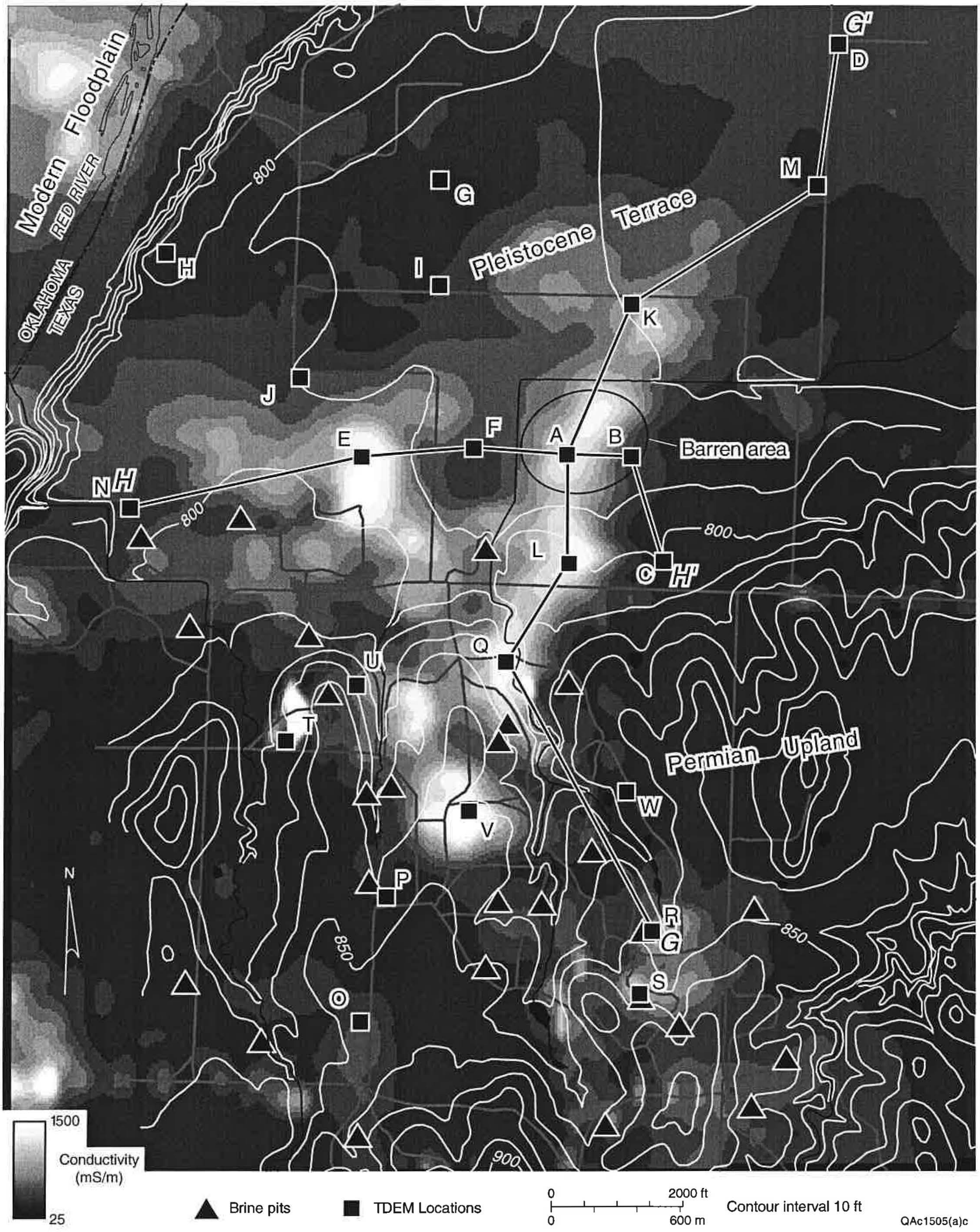


Figure 31. Apparent conductivity at the Montague site measured with 900-Hz airborne induction coils.

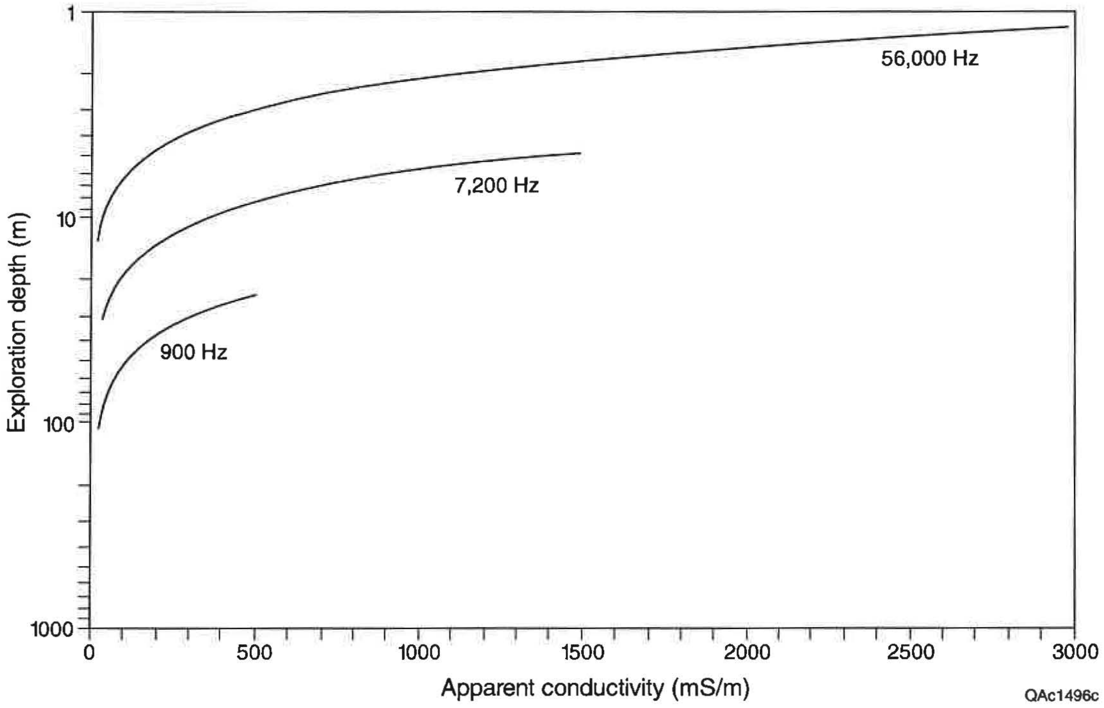


Figure 32. Changes in estimated exploration depth (skin depth) with ground conductivity for 900-Hz, 7,200-Hz, and 56,000-Hz airborne-coil configurations. Line extent indicates conductivity range observed for each frequency at the Montague site.

lower than those measured by the 56,000-Hz coils. Exploration depths for this frequency are between 5 and 38 m, decreasing with increasing conductivity. At 900 Hz, airborne coils measured conductivities that ranged from 25 mS/m to 500 mS/m (fig. 31). Exploration depths for this frequency are between 25 m for the most conductive ground to more than 75 m for the least conductive ground.

Particularly at the two higher frequencies, many conductivity anomalies in the oilfield on the Permian upland coincide with known brine-pit locations identified from 1966-vintage aerial photographs taken before pit closure (figs. 29 and 30). Each of these anomalies is several hundred meters across and, as exploration depth increases, the connection between adjacent anomalies increases. The barren area on the Pleistocene terrace falls within a larger conductivity anomaly that has conductivities ranging from just above background values (about 50 mS/m), to the highest conductivities observed for each frequency. This large anomaly has

- a sharp eastern boundary that might be controlled by the permeability contrast between Pleistocene channel deposits and Permian bedrock,
- a bifurcation into a northeast-trending branch, and a west-trending branch that intersects the Red River and includes the Williams seep, and
- a diffuse northern boundary.

Parts of the modern floodplain of the Red River, and the Red River itself, are also highly conductive (fig. 29), reflecting the naturally high chloride concentrations in the river and its alluvium (Red River Authority of Texas, 1996, p. 97).

Because the shape of the area characterized by above-background conductivities is irregular, we calculated the total area of conductive ground to be most likely related to Montague-site salinization by (1) drawing a boundary around the area of the saltwater plume originating in the upland oilfield to exclude other highly conductive areas, and (2) calculating a conductivity distribution for the area inside the boundary. The conductivity distribution is expressed as the total area above threshold conductivities between 10 and 500 mS/m (at 10 mS/m increments) for the deep-exploring 900-Hz airborne data (fig. 33). Including both

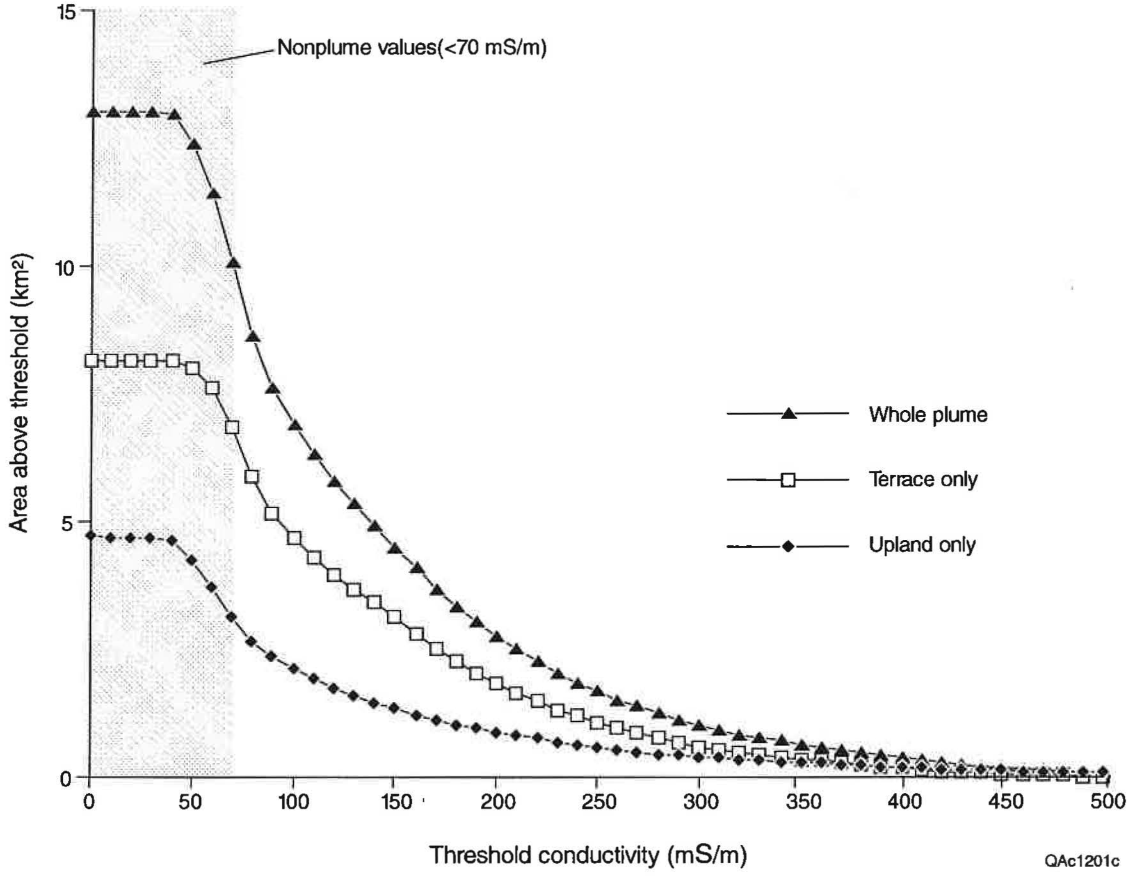


Figure 33. Cumulative area with conductivities measured by the 900-Hz airborne EM coils above indicated threshold values for the Montague saltwater plume as a whole and for the parts of it that are beneath the Pleistocene terrace and the Permian upland. Conductivities below 70 mS/m are excluded from the salt-water plume.

the Pleistocene terrace and Permian upland, 10.1 km^2 is underlain by ground having an apparent electrical conductivity greater than 70 mS/m. Of this total conductive ground, 6.9 km^2 lies in the Pleistocene terrace and 3.1 km^2 lies in the Permian upland. Conductive areas outside the boundaries of this plume, such as those visible in the northwest and southwest parts of the airborne survey (figs. 29, 30, and 31), are likely to be caused by other natural and oilfield salinity sources in Texas and Oklahoma.

Thickness

Much as results from the reconnaissance ground-based surveys were used to design the airborne survey, results from the airborne survey were used to determine optimal borehole locations and follow-up geophysical sites. Because the number of independent conductivity measurements is limited in the airborne EM survey, its vertical resolution is poor and other methods must be employed to determine an accurate vertical conductivity distribution. Borehole induction logs acquired at seven BEG boreholes and at nine FH monitor wells in upland and terrace settings provided the best vertical resolution, clearly showing the upper and lower boundaries of highly conductive ground as well as highly conductive individual stratigraphic units (appendix 5). Vertical resolution obtained by these logs is within a few centimeters.

We supplemented borehole information on the vertical distribution of conductive ground with TDEM soundings acquired at 23 sites, selected on the basis of airborne survey results (fig. 4; appendix 9). Although these soundings do not achieve the high vertical resolution obtained by borehole logs, they produce conductivity models consisting of several layers that are adequate to portray the material above, within, and below the saltwater plume. Models constructed to fit these data represent simplified versions of the actual subsurface conductivity distribution at a given site that have an estimated accuracy better than a few meters.

The relative merits of borehole induction logs and surface TDEM soundings are evident when we compare an induction log acquired at well BEG 1 with the best-fit conductivity model obtained from a TDEM sounding acquired adjacent to the monitor well (fig. 34). The borehole log shows clearly the base of the saltwater plume and the stratigraphic detail, allows us to determine which subsurface stratigraphic zones are likely to contain saltwater, guides borehole water and soil sampling, and allows us to calibrate chloride content in sampled water to ground conductivity measured by the borehole log. The TDEM sounding locates the base of the plume relatively well, produces a good average fit to measured borehole conductivities, and is noninvasive and more easily acquired than a borehole log. TDEM soundings also explore more deeply, and allowed us to determine optimum drilling depths where boreholes were needed and ensured that we reached the base of the saltwater plume in a given borehole.

Transient signatures from TDEM soundings acquired at saltwater plume and nonplume sites across the Permian upland and the Pleistocene terrace clearly differ (fig. 35). Transients observed in background areas have short durations (less than 0.001 s) and high apparent resistivities (above 10 ohm-m), whereas transients observed over the saltwater plume have longer durations (more than 0.001 s) and lower apparent resistivities (a few ohm-m). Increases in apparent resistivities observed at late times in transients acquired over the saltwater plume confirm that the soundings penetrated the base of the plume (fig. 35). Three- to five-layer models constructed for each sounding fit these transients better than a 7-percent fitting error (appendix 9). The three-layer model that fits the transient acquired at TDEM site E (figs. 29 and 35) indicates the presence of conductive ground (less than 10 ohm-m or more than 100 mS/m) from the surface to a depth of 23 m; the most conductive zone (1 ohm-m or 1,000 mS/m) is between 5- and 23-m depth. Conversely, the model that fits the transient acquired at TDEM site C (figs. 29 and 35), located outside of the saltwater plume, indicates the presence of resistive ground (more than 15 ohm-m or less than 70 mS/m) at similar depths.

Cross sections constructed from TDEM soundings show good agreement with ground conductivity images from airborne data. Where conductivity images from the airborne data show elevated conductivities, TDEM soundings show conductive layers in the near surface. Where conductivity images from the airborne data show low conductivities, TDEM soundings show

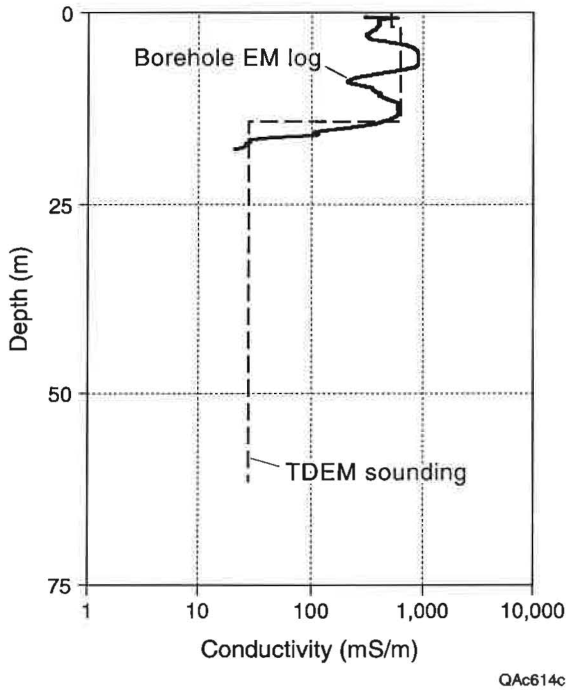


Figure 34. Comparison of a conductivity profile acquired at monitoring-well BEG 1 using a borehole conductivity meter with a profile derived from a TDEM sounding acquired adjacent to the borehole at TDEM site A (fig. 29).

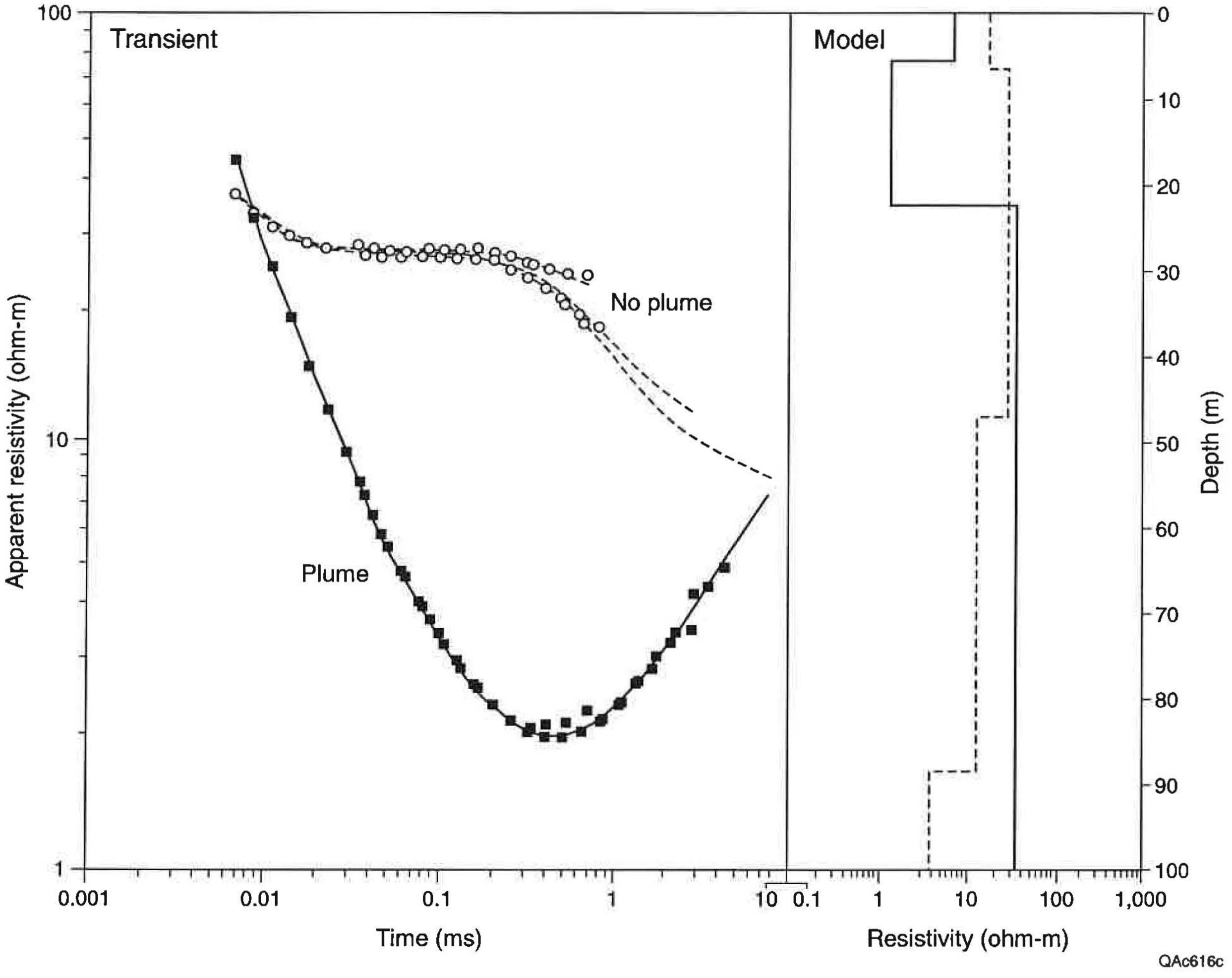


Figure 35. Comparison of transient signals (left) and best-fit conductivity models (right) from TDEM soundings acquired over the saltwater plume at TDEM site E (fig. 29) and in a background area outside of the plume at TDEM site C.

resistive layers in the near surface. Section G–G′, constructed from best-fit conductivity models for soundings acquired along the main axis of the saltwater plume (figs. 29 and 36), illustrates that moderately conductive (100 to 300 mS/m) and highly conductive (300 to 1,000 mS/m) layers that represent salinized ground are thickest beneath the oilfield on the Permian upland (33 to 38 m thick at soundings R and Q). These layers thin northward across the Pleistocene terrace from 15 m at sounding A to 7 m at sounding M, and are not present at sounding D.

Section H–H′, constructed from six TDEM soundings on the Pleistocene terrace that cross the main axis of the saltwater plume (figs. 29 and 37), shows that conductive ground coincides with that detected by the airborne survey, and reaches depths of 15 to 23 m in the central part of the plume (soundings E, F, and A). Conductive ground thins eastward to less than 15 m at sounding B and is absent at sounding C. Conductive ground also thins westward to less than 15 m at sounding N. Where highly conductive near-surface layers are thin or absent, TDEM exploration depth is sufficient to detect a moderately conductive layer at a depth of 58 m at sounding N and 89 m at sounding C. These moderately conductive layers are separated from the surface layers by one or more intervening layers of low conductivity, indicating little or no communication between shallow and deep conductive layers. The deeper layers probably represent the base of potable water.

Conductivities in the moderately and highly conductive layers in both TDEM cross sections best match values measured by the more deeply penetrating (7,200- and 900-Hz) airborne coils. Background conductivities of 10 to 100 mS/m, which underlie the highly conductive near-surface layers, are similar to those measured beneath the saltwater plume by borehole instruments, and are similar to those measured beyond the boundaries of the saltwater plume by airborne induction coils.

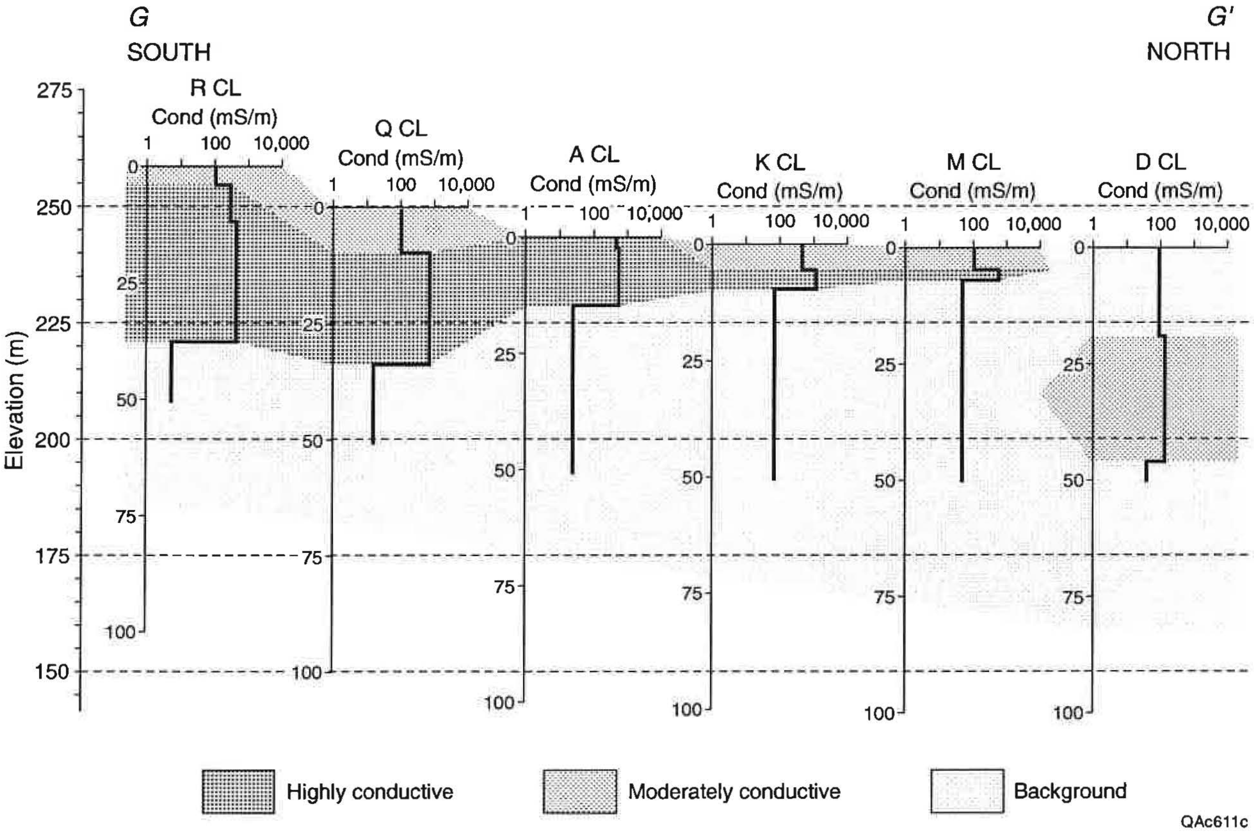


Figure 36. TDEM cross section G–G′ along main axis of saltwater plume (fig. 29). Highly conductive layers have conductivities greater than 300 mS/m, moderately conductive layers have conductivities between 100 and 300 mS/m, and background layers have conductivities below 100 mS/m.

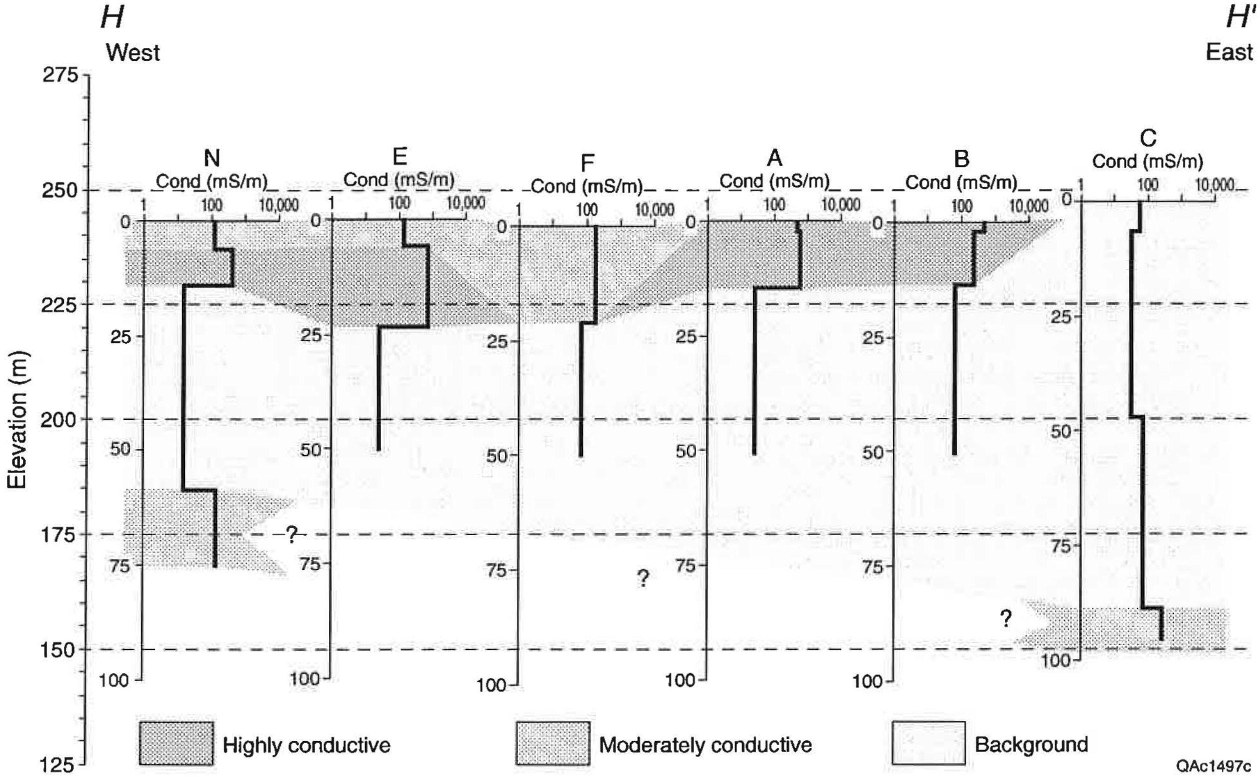


Figure 37. TDEM cross section H–H′ crossing main axis of saltwater plume (fig. 29). Highly conductive layers have conductivities greater than 300 mS/m, moderately conductive layers have conductivities between 100 and 300 mS/m, and background layers have conductivities below 100 mS/m.

Volume

Detailed information on the lateral extent of highly conductive ground, obtained from the airborne EM survey, can be combined with data on the vertical extent of conductive ground, obtained from TDEM soundings and borehole induction logs, in order to estimate the total volume of highly conductive soil at the Montague site. Assuming that conductivities above background values are caused by the infiltration of saline water, the volume of highly conductive soil represents the volume of salinized ground. This assumption is addressed in the contaminant assessment section.

Within the 6.9-km^2 area on the Pleistocene terrace that is considered to be within the saltwater plume, there are nine TDEM soundings that have combined thicknesses of moderately and highly conductive near-surface layers ranging from 7 to 23 m (table 12). Using an average thickness for the conductive layers of 13.6 m, we estimate the volume of the conductive area beneath the Pleistocene terrace to be 93,840,000 m^3.

Beneath the Permian upland, where 3.1 km^2 is underlain by conductive ground, five TDEM soundings reveal combined thicknesses of moderately and highly conductive layers ranging from 10 to 43 m (table 12). Multiplying an average combined thickness of 32.0 m by 3.1 km^2 results in an estimated conductive volume beneath the upland of 99,200,000 m^3. Total estimated volume of conductive ground within the saltwater plume area on the Permian upland and Pleistocene terrace is 193,040,000 m^3.

Contaminant Assessment

Relationship between EM and Chloride Concentration

Comparisons of borehole induction logs and chemical analyses of water samples taken from the same boreholes and monitor wells show that there is a strong correlation between the

Table 12. Total combined thickness of moderately and highly conductive near-surface layers within saltwater plume boundary on Permian upland and Pleistocene terrace. Data from Appendix 9.

Permian upland soundings (n=5)

Sounding	Thickness (m)
O	36
P	43
Q	33
R	38
U	10
Upland average	32.0

Pleistocene terrace soundings (n=9)

Sounding	Thickness (m)
A	15
B	13
E	23
F	21
H	9
J	10
K	10
M	7
N	14
Terrace average	13.6

measured electrical conductivity of the water and the peak electrical conductivities indicated by the borehole induction log (fig. 38). As the measured conductivity of the water sample increases, the conductivity recorded by the borehole induction logger for the sampled interval also increases. A similar relationship is observed when measured chloride content in the water samples is compared with peak conductivity measured by the borehole induction logger (fig. 39). Because chloride is the most abundant ion in waters sampled from BEG and FH wells (tables 8 and 9), and because borehole induction logs correlate well with measured water conductivity and chloride content, we infer that chloride is a robust predictor of conductivity as measured in water samples as well as of conductivity measured by borehole, airborne, and ground-based EM instruments.

Chemical analyses of 40 water samples taken from the Montague site reveal an empirical relationship between chloride concentration and measured electrical conductivity of the water samples (fig. 40). Chloride concentrations in analyzed samples range from 19 mg/L to 44.2 g/L; measured electrical conductivities for these samples increase from 65 to 10,220 mS/m. Over this concentration range, the ratio of chloride concentration to measured conductivity increases with chloride concentration, averaging 3.42 mg/L of chloride per mS/m of conductivity for the most commonly observed chloride values (fig. 41). Because measured ground conductivity has been shown to be linearly related to chloride content at the Montague site, this chloride-to-conductivity ratio can be used in conjunction with airborne conductivity measurements to estimate total chloride mass within the exploration range of the airborne induction coils.

Chloride Mass

As we have shown by comparing the chloride content of water samples with conductivities measured by a borehole induction logger, measured ground conductivities increase linearly with chloride content of ground water. Because measured ground conductivity in excess of observed background values is related to the presence of chloride in the saturated and unsaturated zone, we

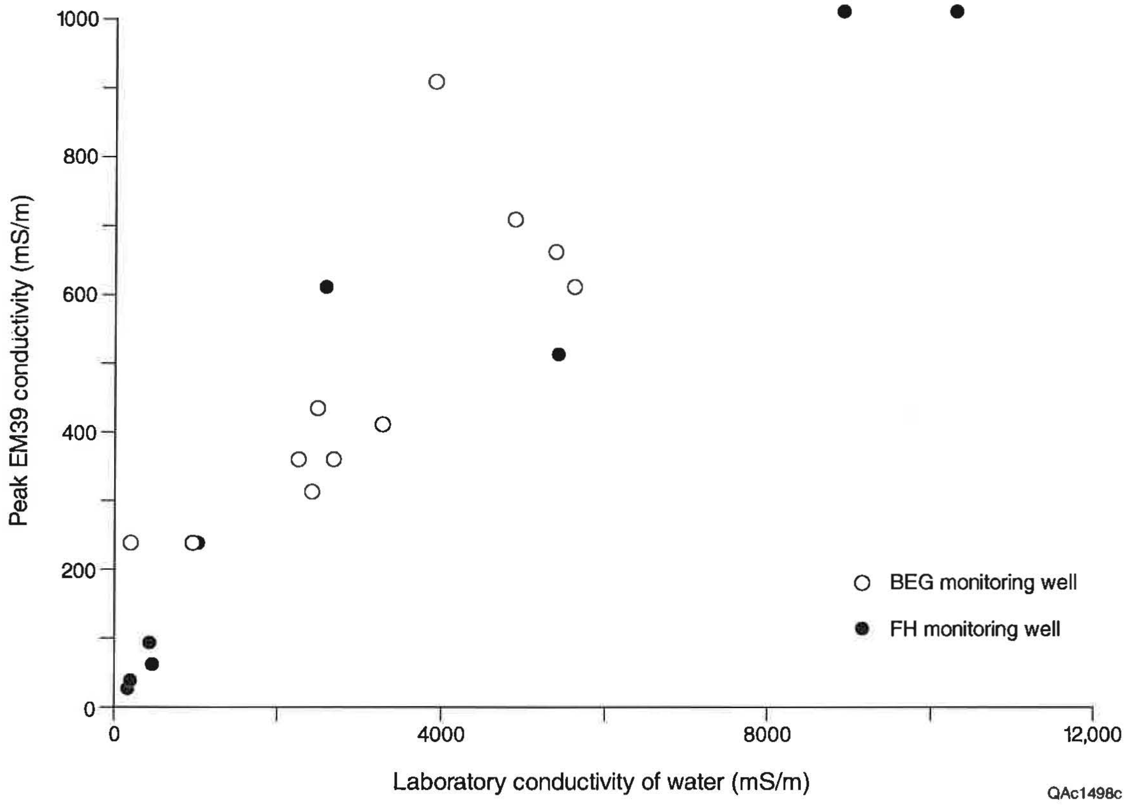


Figure 38. Relationship between electrical conductivity of water samples taken from BEG and FH monitoring wells and peak electrical conductivity measured by a Geonics EM39 borehole induction logger in the borehole.

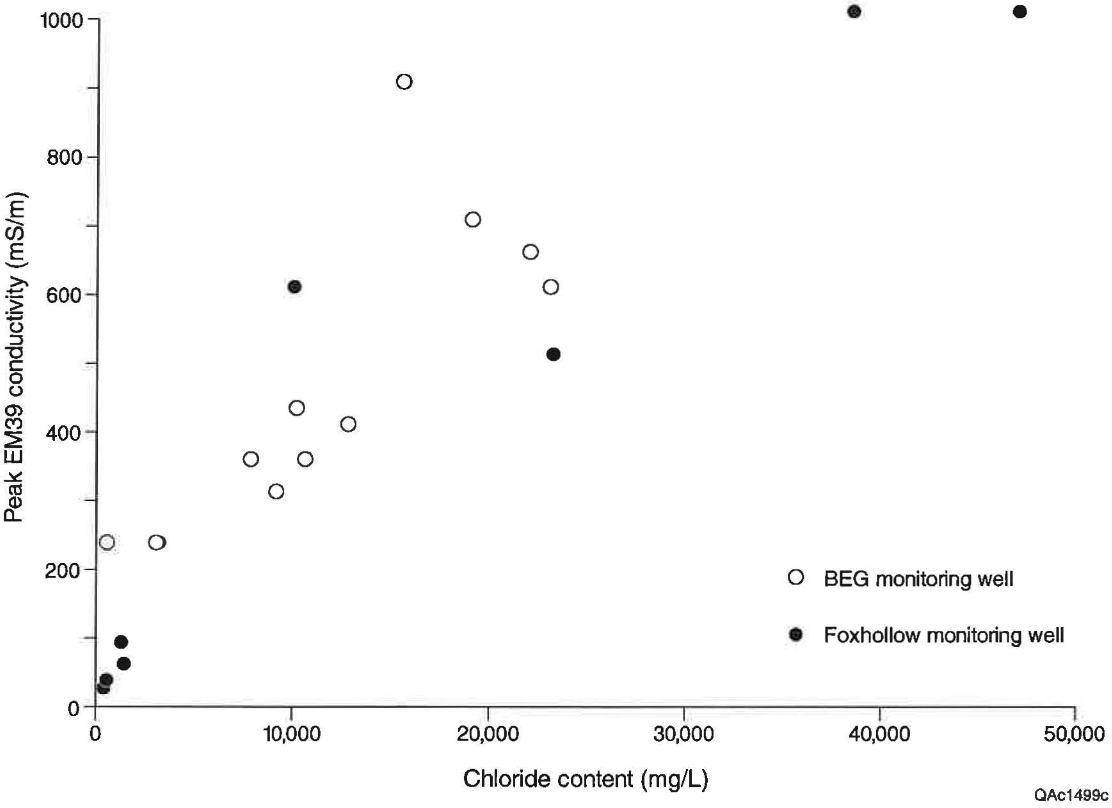


Figure 39. Relationship between chloride content of water samples taken from BEG and FH monitoring wells and peak electrical conductivity measured by a Geonics EM39 borehole induction logger in the borehole.

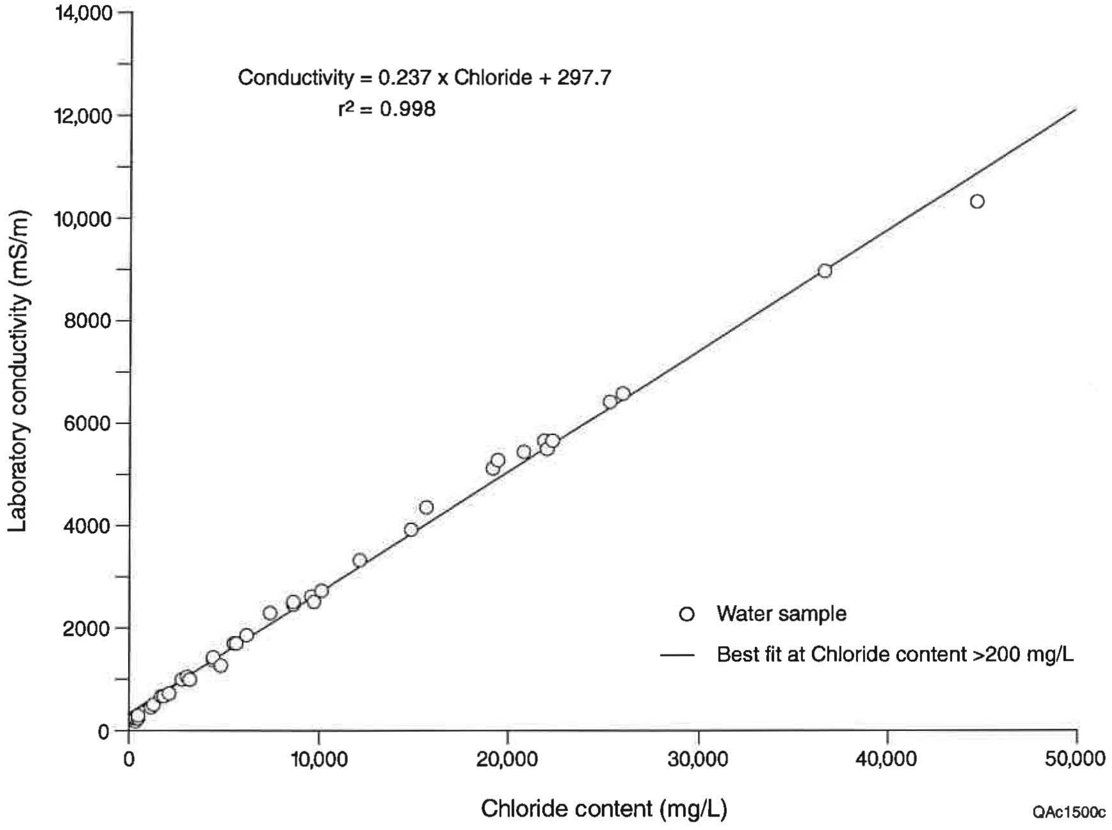


Figure 40. Relationship between chloride content and measured electrical conductivity of water samples taken from BEG and FH monitoring wells.

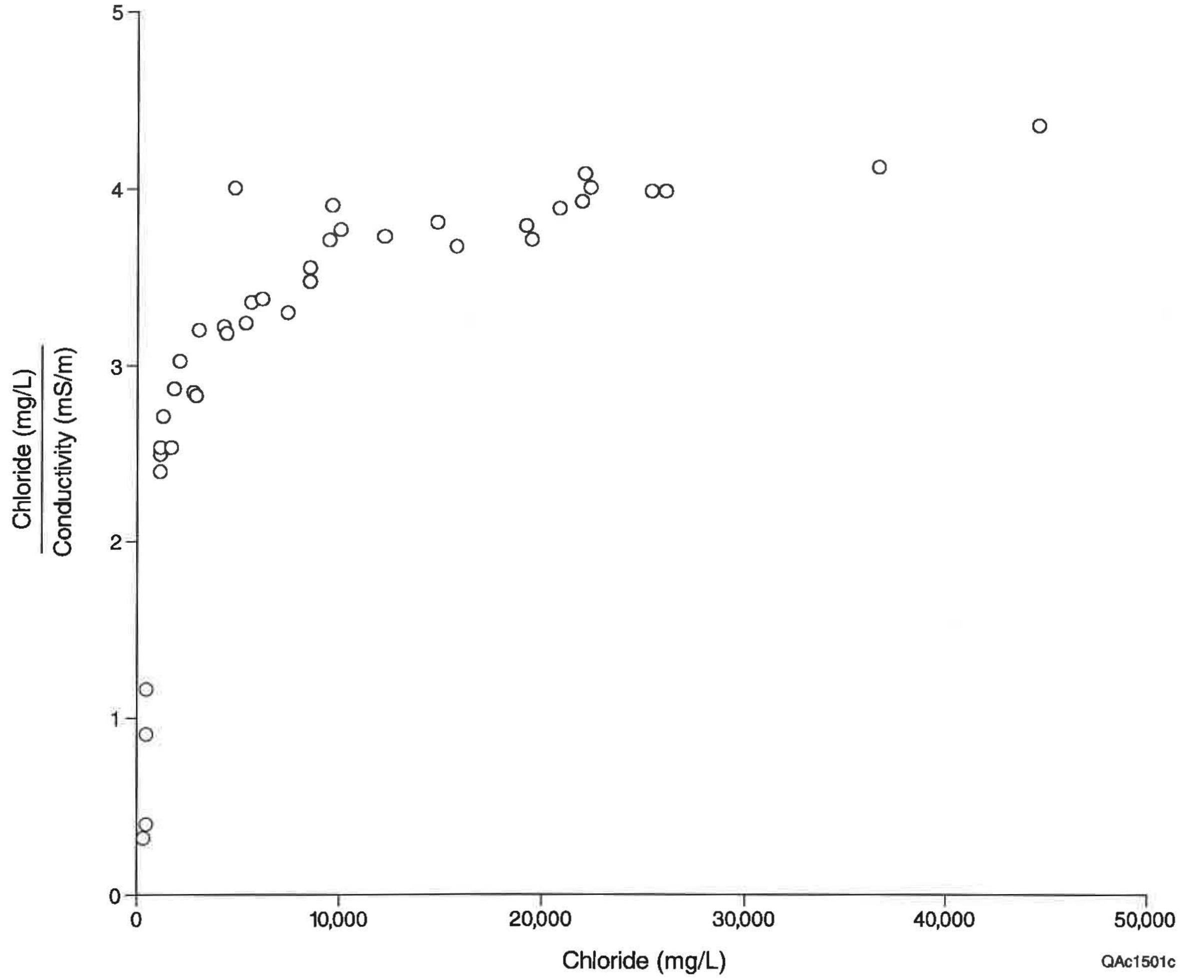


Figure 41. Increase in chloride/conductivity ratio observed over range of chloride concentrations measured for Montague site samples.

can estimate a mass of chloride per unit area from the chloride-to-conductivity relationship established from water samples. This number represents the total mass of chloride within the exploration range of a given coil frequency and will be higher for a given ground conductivity as the EM frequency decreases.

To illustrate and test this method, we can calculate chloride mass for the area near monitor well BEG 1, where we can also independently calculate chloride mass from borehole data alone. From airborne EM data, we know that the conductivity measured by the 900-Hz coils is 325 mS/m. Assuming a background conductivity of 50 mS/m, this site has 275 mS/m of "excess" conductivity that can be attributed to the presence of chloride within the exploration range. Because we know empirically that about 3.4 mg/L chloride concentration is required to account for a 1-mS/m increase in conductivity, this area must have an equivalent chloride concentration (chloride concentration in water that produces an equivalent observed ground conductivity) of 275 × 3.4 mg/L, or 941 mg/L, distributed over the entire exploration range for that frequency. For a representative 1-m^3 volume of water at this concentration, the total chloride mass is 941 g. At 325 mS/m and 900 Hz, the exploration depth is about 29 m (fig. 32). We thus have a chloride mass per unit area of 29 × 941 g, or 27.7 kg/m^2, calculated from 900-Hz airborne data at well BEG 1.

At this same site, we know from borehole data that (1) saltwater has infiltrated from the water table at 2 m to a total depth of 14 m (fig. 34), and (2) the average chloride concentration of water samples from this well is 17,960 mg/L (table 8). Per square meter at the surface, we have an infiltrated volume of 12 m^3 (12,000 L). We do not know the porosity of the sediments beneath the Pleistocene terrace, but if we assume a reasonable porosity value of 15 percent, we arrive at a pore fluid volume of 1.8 m^3 (1,800 L). Total chloride mass estimated from borehole data is 1,800 L × 17,960 mg/L, or 32.3 kg beneath a 1-m^2 area. To match the airborne estimate exactly, a porosity of 13 percent should be used.

Similar calculations of estimated chloride mass per unit area can be made for the range of observed conductivities for the 900-, 7,200-, and 56,000-Hz airborne coils (fig. 42). To estimate

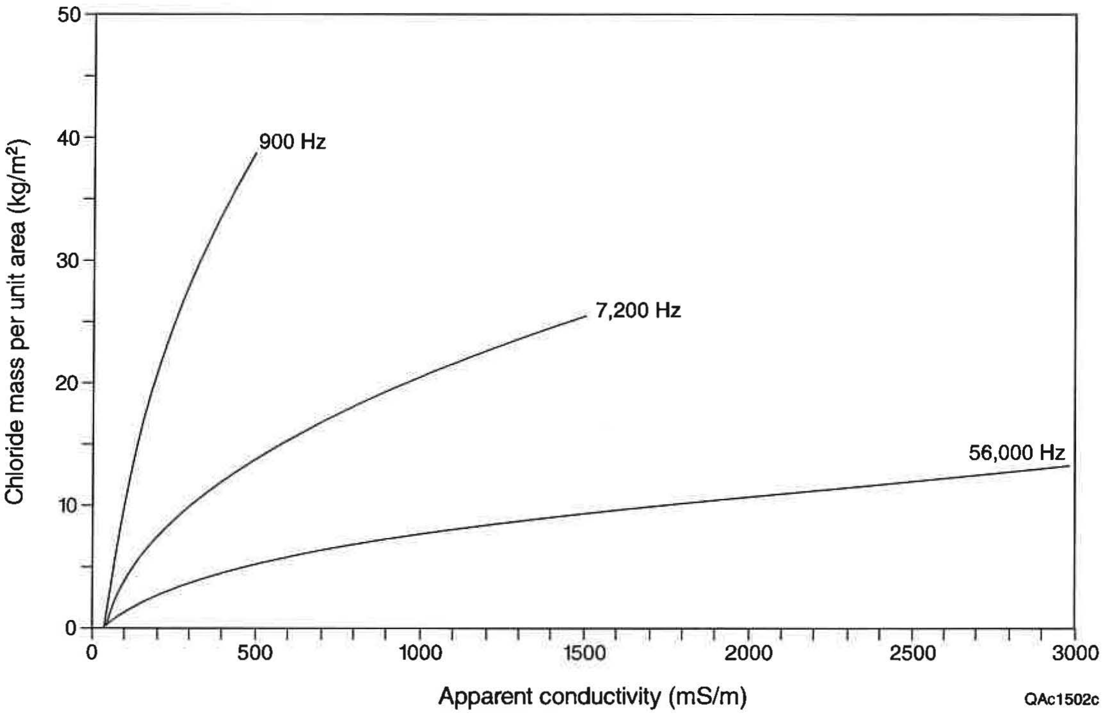


Figure 42. Chloride mass per unit area calculated for 900-, 7,200-, and 56,000-Hz airborne coils assuming background conductivity values of 50 mS/m and a chloride-to-conductivity ratio of 3.42 mg/L chloride per mS/m of conductivity.

total chloride mass within the exploration range of a given coil frequency, we must determine the incremental areas that have a given conductivity range, multiply those areas by the calculated chloride per unit area value for that conductivity and frequency, and then add each mass value to all others for that coil frequency.

Because lower frequencies have greater exploration depths for a given ground conductivity, the choice of coil frequency for chloride mass calculations is important. At the Montague site, TDEM soundings show that conductive ground reaches maximum depths of 7 to 43 m (table 12), which are beyond the exploration depth of the 56,000-Hz, and to a lesser extent, the 7,200-Hz coils when operating over conductive ground. Calculations made from the 900-Hz airborne data provide the greatest exploration depths at all observed conductivities and should give the best estimate of total chloride mass at the Montague site.

The distribution of ground conductivity values by land area can be calculated from the cumulative land-surface area above conductivity threshold values obtained from the 900-Hz airborne EM data (fig. 33). These areas are calculated for the whole plume, the upland only, and the terrace only at 10 mS/m increments (fig. 43). Areal values within each 10-mS/m conductivity range were multiplied by the calculated chloride mass per unit area for that conductivity range to obtain chloride-mass estimates for each conductivity range (fig. 44), which were then added together to estimate total chloride mass. These calculations indicate that total chloride mass in the Montague saltwater plume is about 1.48×10^8 kg (table 13), which is equivalent to the amount of chloride contained in 14×10^6 bbl of brine with a concentration of 65,000 mg/L (fig. 45), the reported concentration of produced brine in the oilfield (table 7). Of this total chloride mass, we infer that 0.47×10^8 kg remains beneath the Permian upland and 1×10^8 kg is beneath the Pleistocene terrace (table 13).

Chloride concentrations have been diluted from original brine concentrations to the wide range of concentrations observed in BEG and FH test wells (tables 8 and 9), increasing the total volume of saline water within the plume to near 100×10^6 bbl (fig. 45).

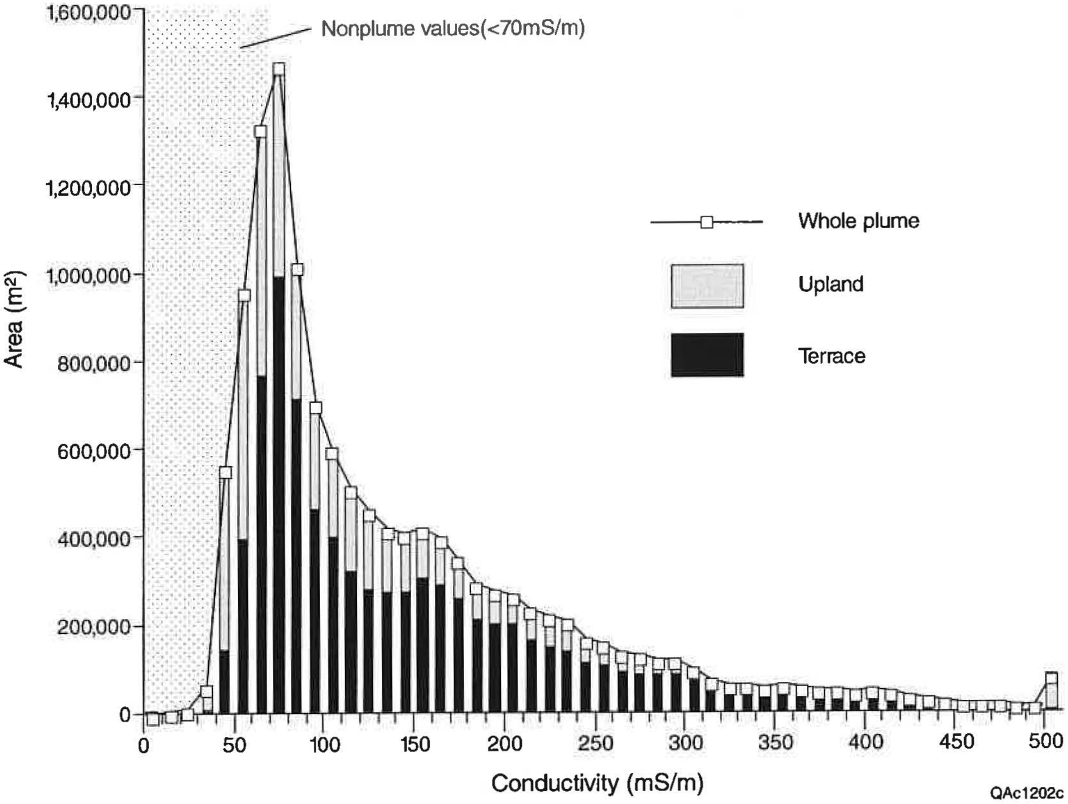


Figure 43. Areal distribution of conductivities measured by the 900-Hz airborne EM coils over the Montague saltwater plume as a whole and for the parts of it that are beneath the Pleistocene terrace and the Permian upland. Conductivities below 70 mS/m are excluded from the plume.

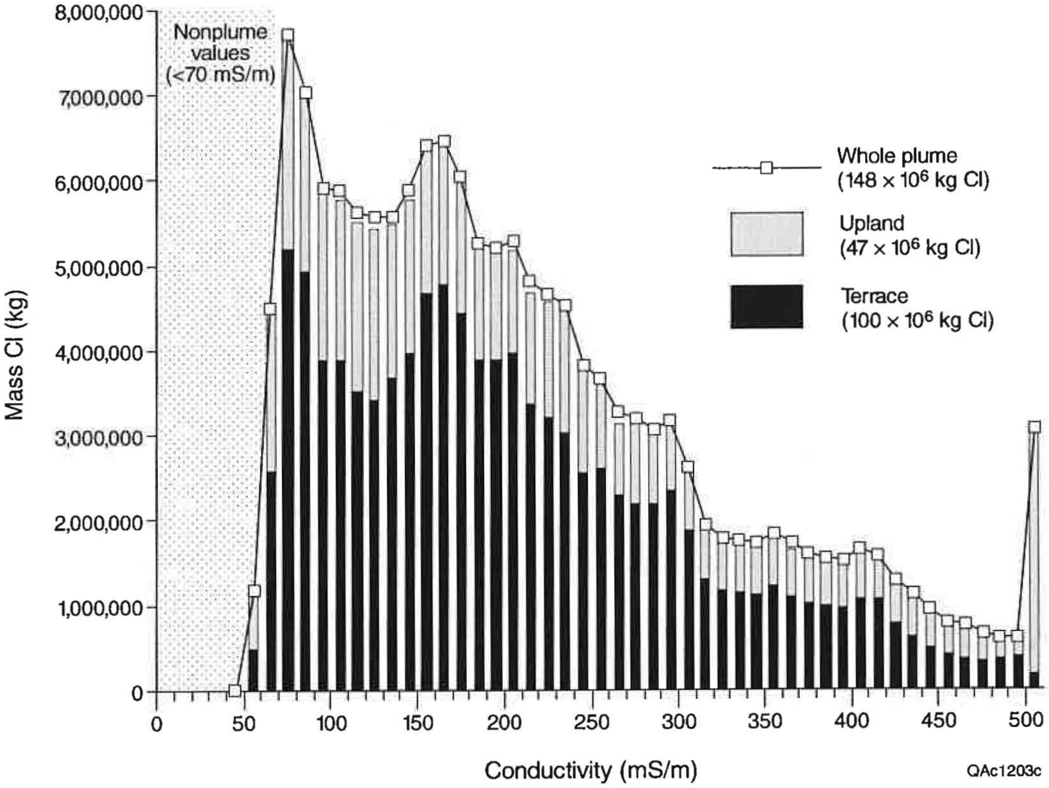


Figure 44. Estimates of chloride mass within conductivity ranges measured by the 900-Hz airborne EM coils. Values below 70 mS/m are considered to be outside the saltwater plume.

Table 13. Surface area, estimated chloride mass, and equivalent volume of brine (at chloride content of 65,000 mg/L) for the Montague site saltwater plume. Plume areas are those above 70 mS/m threshold conductivities from 900-Hz airborne data. Sums of upland and terrace area, mass, and brine-equivalent values do not equal whole plume values because of boundary losses during contouring.

Unit	Area (km^2)	Mass Cl (kg)	Brine equivalent (bbl)
Whole plume	10.10	148,912,750	14,410,400
Permian upland	3.14	47,052,500	4,553,300
Pleistocene terrace	6.85	100,051,100	9,682,000

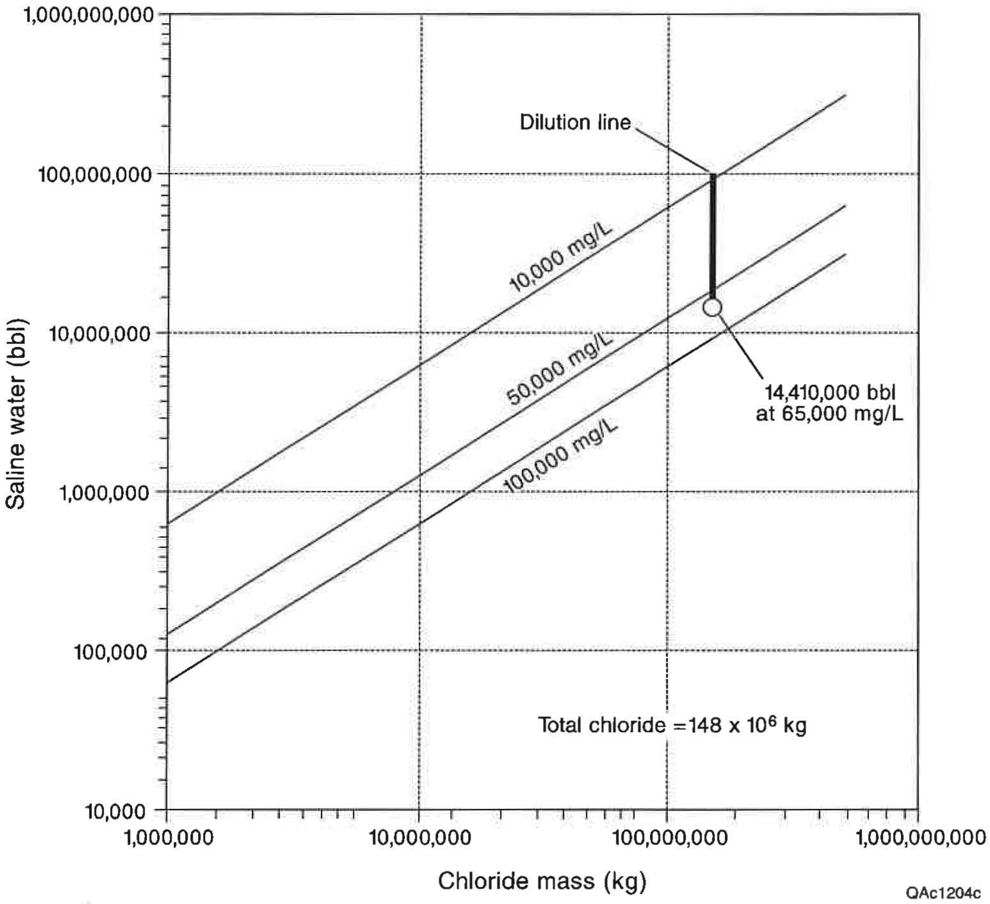


Figure 45. Estimated volume of original brine (at 65,000 mg/L chloride concentration) beneath the Permian upland and Pleistocene terrace at the Montague site and equivalent volumes of saline water at diluted chloride concentrations.

ENVIRONMENT ASSESSMENT

Possible Saltwater Sources

Possible saltwater sources include:

- leakage of saltwater from injection or production wells,
- natural discharge of saltwater from subsurface formations,
- agricultural practices that result in the accumulation of dissolved salt in the shallow subsurface,
- percolation of saltwater discharged into disposal pits,
- leaching of residual salt from soil beneath former saltwater pits, and
- runoff of saltwater spilled in the vicinity of production wells or disposal pits or both.

Such saltwater sources have been identified in other areas of Texas (for example, in the Concho River valley) (Dutton and others, 1989; Richter and others, 1990; Paine and others, in press). These possible sources, however, are not equally likely for the Montague County study area for the following reasons:

- Ionic ratios (fig. 24) indicate the saltwater plume is a mixture of locally produced oilfield brine and shallow ground waters.
- Natural discharge of saltwater from subsurface formations does not appear to be a factor at the Montague County site because (a) TDEM geophysical profiles and commercial resistivity logs indicate there is a 150- to 200-ft-thick high resistivity section of fresh water throughout the area between the near-surface contaminated zone and a regional saline zone at depth, and (b) fresh ground water (sampled from water-supply wells) underlies the saltwater plume beneath all parts of the study area.
- There is no major feedlot or significant cropland agriculture in the oilfield area, so agricultural practices are unlikely to be the source of salinity in the upland source areas.

- Injection and production wells are not a likely source for the large volume of water present in the regional saltwater plume because producing horizons have low formation pressure that does not generally favor discharge to shallow depths through leaking casing strings. Typical reported injection pressures in the field between 120 and 290 psi (RRC file data) are too low to cause invasion of the fresh-water zone. In two areas, airborne and TDEM profiles show that salinity occurs relatively deep in the fresh-water section. In one of these areas, several wells (API #33781118, 37781126, 33730405, 33730406) reported historic injection pressures as high as 700 psi. Another isolated conductivity anomaly is in the area of an injection well (API #3373102).
- Techniques that have been used successfully in other areas (Paine and others, in preparation) for identifying leaking casing at injection and production wells using combined magnetic and conductivity anomalies are not very useful in the North Nocona oilfield. Permeable sandstone and conglomerate have transmitted saline water laterally and down gradient away from sources and, therefore, areas of high conductivity are found in many parts of the oilfield. In addition, close well spacing and other oilfield equipment causes amalgamation of magnetic anomalies. In most of the oilfield, any contribution from leaking casings would be masked by overall high salinity.
- Formation water, coproduced with oil, is a likely source of the saltwater contamination, but the exact pathway leading to the subsurface saltwater plume is ambiguous. Coproduced water can equal from 25 to 90 percent of produced hydrocarbons, with the water/oil ratio generally increasing through the life of a field. Unknown volumes of coproduced formation water were discharged to surface disposal pits.
- In this study, soils directly beneath pits were not cored because of observed minor surface-oil contamination in these areas. Residual salt that remains in soil beneath pits for

some time after pits are abandoned, however, can continue to be leached to ground water as a secondary contamination source, and this has been observed in other areas of the United States (Pettyjohn, 1982, cited in Richter and others, 1990).

- It is also possible that before the no-pit order, brine might have spilled, or that pits might have overflowed, with runoff of the excess saltwater down the drainages to the north. There might have been some contribution to the saltwater plume from losing sections of the drainages and because of infiltration downward to the water table beneath the upland area. There also might have been surface transport and discharge of saltwater onto the terrace, where it soaked into the shallow subsurface.
- It is possible that both pathways—(a) subsurface percolation from beneath disposal pits and (b) runoff down surface drainages—contributed saltwater to the present subsurface plume in the past.

Fate of Saline Water

Active Sources

A secondary salinity source of residual salt in soils probably remains in the upland area beneath (a) abandoned or regraded pits, and (b) drainage courses. Such secondary sources have the potential to persist and, with every infiltration event, to release additional salinity pulses to ground water (Pettyjohn, 1982). While persistent, the impact of such secondary sources decreases gradually with time and repeated flushing.

Plume Evolution

Lateral Migration

The velocity of the subsurface saltwater plume can be estimated from either:

(a) dimensions and history of the plume, or

(b) a Darcy's law calculation using estimates of hydraulic conductivity, hydraulic gradient, and porosity.

Velocity undoubtedly varies between different Permian bedrock units and facies of Quaternary sediments. The estimate based on dimensions and history can give an average velocity that integrates all the variations in flow rate encountered along a pathway. Its precision and accuracy, however, are limited by errors in estimating the development and path of the plume. On the other hand, the estimate of average linear velocity on the basis of a Darcy's law calculation typically uses the geometric mean of hydraulic-conductivity measurements. Error in the calculation depends on how well that geometric mean and assumed values of porosity represent the range of hydrologic properties encountered along the flow path.

Velocity estimated from the dimensions and history of the plume ranges from 110 to 150 ft/yr (0.3 to 0.4 ft/d), assuming

- a plume length of 8,000 ft, the distance between the midpoint of the upland recharge area and the midpoint of the front of the plume (defined by the C=35,000 mg/L TDS [C/C_O=0.3 to 0.33] contour), and
- the duration of the plume is 53 to 75 yr (since 1922 or 1944).

This is a reasonable range of average velocity in coarse granular material such as the Quaternary sediments beneath the terrace.

Velocity calculated from Darcy's law and field test data ranges from 0.1 to 20 ft/yr (0.003 to 0.06 ft/d), assuming

- hydraulic conductivity values of 0.4 to 0.8 ft/d on the basis of average and maximum measured values for alluvium (table 6),
- hydraulic gradients of 0.002 to 0.014 (fig. 14), and
- a porosity of 0.1 to 0.3.

The latter estimate of velocity is probably too low (by a factor of 15 to 20) and does not adequately reproduce the apparent size of the saltwater plume within the past 100 yr. Possible errors are that the interpreted hydraulic-conductivity tests in Quaternary alluvium underestimated mean hydraulic-conductivity, or did not adequately characterize the range of actual values, or both. We consider the estimate of plume velocity made on the basis of plume size and site history, therefore, to be the better estimate.

Vertical Migration

The areas where vertical migration of the saltwater plume appear possible include:

- the upland area beneath the former disposal pits, which is inferred to have been the source of saltwater and across which is a downward-directed gradient (fig. 10),
- the topographic break bordering the Red River floodplain where ground water beneath the Quaternary terrace moves downward toward probable discharge points in the Holocene alluvium along the Red River, and
- certain water-supply or oil wells that lie within the footprint of the subsurface saltwater plume that lack adequate surface casing cement to prevent downward leakage of saltwater along the annulus.

There is a potential for vertical movement of saltwater in the vicinity of the topographic break between the upland area and the Quaternary terrace. This potential reflects (a) the subcrop of permeable Permian beds adjacent to permeable Quaternary sediments, and (b) changes in topography. As previously mentioned, there appears to be a potential for the movement of water from Quaternary sediments downward into shallow bedrock near the toe of the upland area, on the basis of hydraulic-head measurements made at well BEG 4. In most areas of the terrace, however, the saltwater plume appears to be present almost exclusively within the Quaternary sediments and not within the underlying Permian bedrock.

Potential for Impact on Ground-Water Resources

Where water-supply wells lack adequate surface casing cement and lie within the footprint of the subsurface saltwater plume, there is a risk for downward leakage of saltwater along the annulus of the well. Most wells are constructed to provide protection from an influx of surface-water runoff at the well head; few are constructed to protect against an influx of shallow ground water. Although there are three wells for which chemical analyses suggest increases in salinity from 1964 to 1997, none of the three lie within the footprint of the subsurface saltwater plume. This suggests that there might be explanations for those changes in salinity other than the impact from the saltwater plume. The two water-supply wells that lie within the footprint of the saltwater plume beneath the terrace (1903501 and Goolsby [D9] [table 3; fig. 21]) have TDS in excess of 1,000 mg/L; the former was analyzed in 1964 and the latter in 1997. There is some basis for concern, therefore, that these wells are at risk for having been impacted by downward movement of water along the well casing. The Goolsby well nonetheless does not have elevated chloride (Cl <250 mg/L); its salinity is more complex than a Na-Cl impact. There are also two wells (1903507 and 1903809) having 1964-vintage analyses in the upland area that appear to have elevated salinity (table 3) and that lie within the footprint of the saltwater plume. Whether these wells are still being used for water supply is unknown; they were not resampled during this study.

Barren Zone Development and Potential for Impact on Agriculture

The nose on the potentiometric surface beneath the Quaternary terrace in the study area (fig. 14) most likely represents (1) additional water in that part of the aquifer compared to adjacent parts to the northwest and northeast, and (2) variations in transmissivity caused by differences in the thickness of Quaternary sediments and the permeability contrast between alluvium and bedrock. There is no obvious evidence that the local buildup in hydraulic head is caused either by recharge from precipitation across the whole terrace or by upward discharge of ground water from the underlying Permian bedrock beneath the whole terrace (figs. 10 through 12). The source of the additional water appears to be to the south in the upland area. Three possible explanations include:

- surface-water runoff that is carried from the upland out onto the terrace and soaks into the ground, causing local recharge in excess of that which occurs from direct precipitation across the rest of the terrace;
- ground water that is recharged in the upland area moves across a narrow front northward from Permian bedrock and then laterally into the Quaternary sediments beneath the terrace, where one flow path follows a northwestward arc toward the closest point of the Red River, and another flow path follows an arc to the northeast and east. The east-northeast flow path beneath the Quaternary terrace is somewhat obstructed by the thinning of sediments lying over a bedrock high (fig. 8); and
- the leakage of water from previously used disposal pits in the upland area that caused additional recharge to ground water in Permian bedrock along a north-south trend and, therefore, the alignment of those point sources of recharge has concentrated a lateral flow of additional ground water from the upland to the terrace.

The first two explanations might exist under steady-state conditions; that is, they may occur naturally and for a long time. The second explanation is questionable because (a) there is no obvious reason why flow should be focused across a narrow front, and (b) there is no present evidence for a mound or ridge in the potentiometric surface in the upland area. The third explanation implies that a transient mound in the potentiometric surface could have developed between the 1920's and 1960's, but has dissipated since disposal pits were abandoned. It also implies that the nose on the potentiometric surface will eventually decay as that additional recharge water moves through the aquifer. Otherwise there is little evidence for distinguishing between these three explanations.

The coincidence of the main barren area and the shallow depth to ground water (fig. 15) suggests a physical relationship. One possible explanation is that evaporation and plant transpiration (evapotranspiration [ET]) have the potential to draw water up from the water table where the water table is not too deep, and when weather conditions are favorable. Saltwater that thus contaminates the unsaturated zone can continue to be drawn to the ground surface even when the water table falls. Figure 46 illustrates how the ground-water-flow computer code MODFLOW simulates evapotranspiration as a function of depth to water. The maximum rate of evapotranspiration (Q_{ETM}) would occur if the water table was at the ground surface (head = h_S) or if there was standing water. The ET potential decreases as the depth to water increases. At a certain depth (called the extinction depth or cutoff depth), the evapotranspiration of water becomes zero. Wickham (1991) simulated evapotranspiration from an aquifer in Quaternary alluvium in Ellis County, Texas. He determined the best estimate of cutoff depth to be 6 ft, and found simulation results to be more sensitive to cutoff depth than to maximum ET rates. Larkin and Bomar (1983) estimated potential evapotranspiration (gross lake-surface evaporation) to be approximately the same in both Montague and Ellis Counties, so Wickham's (1991) findings might reasonably be applied to the study area.

Thus, evaporation of saltwater from a water table is a reasonable and plausible explanation for the location of the main barren area. Minimum depth to water measured during this survey was about 5.4 ft. The limit of patchy crop, a somewhat larger area than the main barren area, coincides with the 6-ft depth-to-water contour (fig. 15). The water table most likely fluctuates seasonally and annually so that during some seasons the water table might be more shallow and, during others, deeper than that measured during this study. Even when the water table is lower, as previously stated, pore water above the water table might contain saltwater from some previous highstand. Upward movement of saltwater either from the water table or from within the unsaturated zone could account for the location of the barren ground. This also suggests that

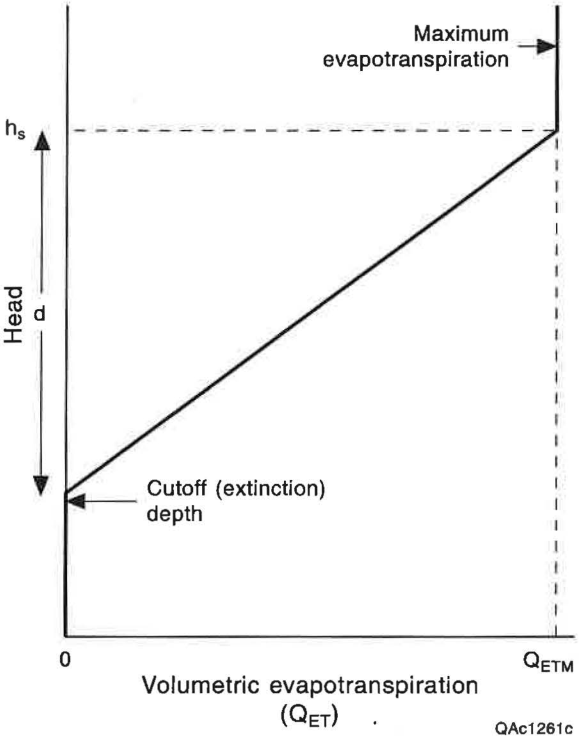


Figure 46. Model of evapotranspiration as a function of depth (d) beneath ground surface. Modified from McDonald and Harbaugh (1988).

(1) the potential for the barren ground to further expand is limited by depth to water, and
(2) lowering the water table beneath the barren ground might be a possible means to control the barren ground.

Williams Seep

Reconnaissance examination and surface and subsurface water sampling at the saline discharge and vegetative kill area cited in the Williams complaint show that saline water having a composition similar to the subsurface plume is being discharged. Surface discharge appears to be focused at the contact between the Holocene dune sands and Permian bedrock. One exploratory borehole, sited on the Pleistocene terrace bluff at the southern extent of the bluff road, encountered 28 ft of nearly homogeneous, well-sorted fine sand above indurated Permian sandstone. Water level was at 24.2 ft below surface, so that in this area about 4 ft of loose sand was saturated. TDEM in an area slightly north of the borehole showed the water level to be about 21 ft below the surface. High conductivity ground was measured by TDEM to depths of about 54 ft. This suggests that in this area, saline water has moved into Permian sandstones. The seeps are observed along the bluff for about 0.5 mi south of the area of the reconnaissance investigations. Airborne conductivity mapping (fig. 29) shows near-surface areas of high conductivity across the Holocene terrace below the seeps. This is probably related to shallow saline water recharged into this terrace below the seeps, and indicates that brine is moving from the seeps through the alluvium to the Red River. Impacted vegetation on the terrace supports this interpretation. The airborne conductivity mapping shows a trend of moderately elevated conductivity between the Williams seep and the main plume. Samples from BEG 6 and the seep had TDS of 14 to 20 g/L, indicating that the concentration of the salt in the Williams seep area is high. We therefore interpret the decrease in the airborne conductivity in the west part of the plume to result from an increase in thickness of the unsaturated zone beneath the dune sands, not dilution of the plume. The base of the saline plume also occurs at shallower depths toward the

Red River, decreasing the thickness of the saline-water mass. The combination of a thicker unsaturated section and a thinner plume decreases the bulk conductivity of the section. The volume of water observed at the seep, the salinity and composition of the brine, and the geometry of the conductive ground indicate that the source for the saline discharge at the Williams complaint is the same subsurface saline plume responsible for the main barren area.

Potential for Discharge to Red River

Upstream from Lake Texoma, the normal chloride concentration in the Red River exceeds the drinking-water standard of 250 mg/L (table 14) (Red River Authority of Texas, 1996, p. 97). The river segment (0205) above Lake Texoma is not designated for public water supply (Red River Authority of Texas, 1996, p. 68). The Red River carries an average chloride load of 3,600 tons (3,970 metric tons) of chloride per day (Red River Authority of Texas, 1996, p. 97). A long-term average and range of chloride in the river can be estimated by dividing the average chloride load by the volume of river flow. Dougherty (1980) gives average, maximum, and minimum estimates of sustained flow as 1.6 million acre-ft/yr, 7.0 million acre-ft/yr, and 0.45 million acre-ft/yr, respectively. Dividing the number of average flow into the estimates of 3,600 tons (3,970 metric tons) of chloride per day and then converting units gives an average chloride content of 735 mg/L.

Two estimates of the potential impact of additional saltwater discharge to the Red River can be made by:

- estimating the total amount of salt in the subsurface plume that goes into the Red River in 1 year, which gives a maximum, although unrealistic, impact scenario, and
- estimating the annual discharge of saltwater and comparing it to the annual saltwater transport by the river.

The total mass of dissolved chloride in the subsurface plume was previously estimated at 148,900 metric tons (table 13). This is approximately 10 percent of the average annual chloride

Table 14. Chloride loading of the Red River near the site.

		Baseline Chlorinity	Incremental loading of surface-water chloride		
Condition	Flow (cfs)	(mg/L)	(%)		(mg/L)
Average	~2,200	735	0.02 to 0.2	(annual)	<2
Sustained minimum	~620	1,260	0.04 to 0.5	(daily)	~6
Minimum monthly	~4	2,630	3.4 to 38	(daily)	~1,000

load in the Red River (Red River Authority of Texas, 1996, p. 97). Of course, not all of the chloride in the subsurface plume will discharge in a given year; 10 percent is an uppermost bound on any possible annual impact.

Estimates of possible rates of discharge of saltwater from ground water at the site range from 160 to 1,800 metric tons of chloride per linear mile of river reach per year, assuming (1) a ground-water velocity of 110 to 150 ft/yr (0.3 to 0.4 ft/d), (2) a porosity of 10 to 20 percent, (3) a seepage face height of 10 to 20 ft, and (4) a chlorinity of 10,000 mg/L (as at BEG 6) to 20,000 mg/L (as at BEG 1 and BEG 4). It is not clear when, or along what reach, the northeast limb of the plume (sampled at BEG 5) would impact the river. The northwest limb (sampled at BEG 6) is already close to the river and has the most imminent impact. Given the dimensions of the plume, it seems reasonable to assume that with no action, the northwest limb of the saltwater plume would encounter the Red River alluvium along as much as a 2-mi reach, giving a total incremental loading of 320 to 3,600 metric tons of chloride per year. Estimates of incremental impact can be based on a comparison with the amount of surface-water chloride given average annual flow conditions, minimum sustained flow, and minimum monthly flow having a 5-percent frequency or return period (table 14).

For the 37-yr period between 1960 and 1997, only 5 percent of the total months had a minimum flow in the Red River (gauged at U.S. Geological Survey's Burkburnett, Texas, station, no. 07308500) of less than 4 cfs. Since the minimum flow is not sustained for the whole month, the calculated 38-percent incremental loading is expressed on a daily basis.

CONCLUSIONS

Site investigation of the Montague saltwater seep was conducted using a multidisciplinary investigation involving cores and borehole logs, hydrological tests and water-level measurements, geophysical data, and analyses of the chemical composition of soil and ground water, in order to interpret the hydrogeology of the subsurface saltwater plume at the site and its relationship to saltwater seeps and barren areas at the surface. The cause of the complaint is a large area, barren of vegetation, that lies on agricultural acreage on a Pleistocene alluvial terrace of the Red River just north of the Nocona North–Spanish Fort part of the Montague County Regular Field. This investigation also documents the relationship between the saltwater plume and the Williams complaint, which is a related area of saltwater discharge and barren ground along the bluff separating the Holocene terrace of the Red River from the higher Pleistocene terrace.

The area underlain by saline water (apparent electrical conductivity greater than 70 mS/m) is about 10 km^2, and lies beneath the oilfield in the upland and agricultural areas on the terrace. The volume of salt-contaminated water is approximately 100 MMbbl (TDS ranging from 2.5 to 74 g/L), and saline water has penetrated to depths of 30 m below the surface beneath the upland area. Saline water has moved from source areas in the upland, down hydrologic gradient, and into Pleistocene terrace sand and gravel. The plume appears to bifurcate, forming a north lobe and a west lobe, possibly reflecting heterogeneous permeability distribution producing preferential flow in fluvial channel sediments in the terrace. The plume geometry and saltwater volume were determined from airborne conductivity measurements that were calibrated and confirmed using time-domain EM soundings, ground-based EM transects, core analysis, water samples, and downhole conductivity logs from seven newly drilled monitor wells, as well as water samples and downhole conductivity logs of monitor wells recently drilled by Fox Hollow Consultants.

The conclusion of this study is that produced water discharged into unlined disposal pits is the dominant source of salt in the plume. Fourteen million barrels of 65 g/L brine could produce the observed volumes of chloride. Saltwater disposal pits visible on a 1966 air photograph coincide with the present upgradient portion of the salinity plume. High-conductivity ground is beneath many of the former disposal pits, as well as over a broad area down the mapped hydrologic gradient toward the Red River, indicating that saltwater percolated out of the pits into the soil and bedrock, and then moved laterally down the hydrologic gradient to the north. It is possible that saline runoff from saltwater spilled into the vicinity of production wells, or disposal pits flowing down surface drainages contributed in the past to subsurface plume. Ionic ratios indicate the saltwater plume is a mixture of a locally produced oilfield brine and shallow ground waters. The primary source of saltwater contamination was ended by the no-pit order, but an inferred secondary source remains with salt in storage in the unsaturated zone beneath pits and above the water table.

Other possible sources of salinity are eliminated as major contributors. Natural discharge of saltwater from subsurface formations does not appear to be a factor at the Montague County site because fresh ground water was sampled or measured using TDEM underneath the saltwater plume beneath all parts of the study area. Therefore, there appears to be no flow path along which saline water at depth discharges into shallow aquifers or at the surface. With the exception of a few past incidences, pressure increase because of injection of saline water during oilfield activities appears to be inadequate to cause brine to move upward along either natural conduits or improperly cased boreholes. Agricultural practices are unlikely to be a significant source of salinity in the upland source areas because of present and historic use as rangeland.

The impacts of saltwater on the environment can be observed where the saline plume lies at shallow depth below the surface in the main barren area and where it discharges at the Williams seep. The impact of saline plume on drinking-water-supply wells and on water quality in the Red River is also assessed.

The barren area has formed where the saltwater plume has moved into an area of probable naturally shallow ground water (6 to 7 ft below ground surface). This minimum depth to water is controlled by the coincidence of a topographic low along a drainage tributary of Village Creek and a water-table high related to locally focused recharge from upland surface-water runoff. We propose that vertical flux of saltwater from the water table is controlled by the range in water-table fluctuation and by the effective depth limit of evapotranspiration. This mechanism suggests that surface salinization in areas underlain by the plume is limited to areas of shallow ground water. Salinization is unlikely to expand over the entire area underlain by the saline plume.

Mapping of depth to ground water during one field season is probably inadequate to characterize the natural variations in water level; it is possible that surface soil salinization during high water levels may increase the size of the barren area.

At least two deep drinking-water-supply wells (one of which is abandoned) lie within the footprint of the subsurface saltwater plume and are at risk of contamination if the surface casing does not cement off the upper 50 ft of the wells.

The subsurface saltwater plume is continuous with and genetically related to the salinity complaint on the Holocene terrace of the Red River floodplain (Williams complaint). Flow through seeps and bedrock into Holocene terrace poses a potential impact to the Red River. The Red River has already elevated salinity having an average chloride content of 735 mg/L (calculated from a long-term average of chloride load and flow volume). Total incremental loading from a discharge of the northwest lobe of the saltwater plume would add another 0.02 to 0.2 percent to the annual average chloride load in the Red River, or less than 1 mg/L of chloride under average flow conditions. Under low flow conditions, saltwater discharge could add 0.5 to 38 percent of the minimum chloride flux on a daily basis.

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Appendix 1. Reconnaissance EM lines.

APPENDIX 1: RECONNAISSANCE EM LINES

Major reconnaissance EM lines acquired with Geonics EM34-3 ground conductivity meter. Locations shown on fig. 4. Coil configuration refers to separation between transmitter and receiver coil and orientation of coils (HD=horizontal dipole; VD=vertical dipole).

Line #	Description	Coil configuration	Measurement sites	Line length (m)
1	Southwest–northeast along base of Permian bluff	20 m HD, VD	130	2,580
2	North–south along main branch of drainage A and extension across Pleistocene terrace	20 m HD, VD	44	860
2a	Along east branch of drainage A from head to main branch intersection	20 m HD, VD	309	6,160
2b	Minor branch of drainage A near tank battery at head of drainage	20 m HD, VD	5	80
3	Along top of bluff at Williams seep	40 m HD, VD	61	1,200
4	Along drainage B from lease road at head of drainage to FM 103	20 m HD, VD	89	1,760
5	Along drainage C to Red River	20 m HD, VD	187	3,720
6	Southwest–northeast across barren area	20 m HD, VD	74	1,460
7	East–west across modern Red River floodplain on Williams property	20 m HD, VD 40 m HD, VD	9	160
8	East–west along ditch north of barren area	20 m HD, VD	130	2,580
9	North–south from FM103 across Pleistocene terrace	20 m HD, VD	50	980

Appendix 2. Sampling information from water wells.

Water Well Survey

Map#D1

Note: If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration, Label each sample accordingly.

WATER SAMPLE ID(s): 8020 - 8022

Time Collected: 1249 Date: 10/23/97

RRC Sample Collector: A. Dutton

Resident Name: E. Rackley Phone Number: (940) 966 - 3291

Street address of water well: (FM 103 - E. of Valley View)
Rt 3 Box 790
Nocona TX 76255

Length of time at residence:

Have you experienced any problems with water quality, taste, smell?(*if so, explain*) NO

Are there any additional wells present on the property?(*if yes, are they plugged or open*) None known

Water Well Data:

GPS Coordinates: Latitude Longitude

Well pipe construction(circle one): PVC [✓ Steel] Unknown

Diameter of well: 4"

Depth of well(if known): 195' Date of construction:

Driller Name(if known):

Is the water used for drinking No [✓ Yes]

Is the water used for cooking No [✓ Yes]

Is the water used for bathing No [✓ Yes]

Is the water used for washing dishes No [✓ Yes]

Is there a pressure tank No [✓ Yes] (*if yes, estimate volume*) 50 Gal.

Is there a water softener [✓ No] Yes

Is there a reverse osmosis filter [✓ No] Yes (*if yes, is filter in kitchen only*)

Is there a septic field on site No [✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID________mg/l Sample ID________mg/l

Water Well Survey

Map # D2

Note: If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration, Label each sample accordingly.

WATER SAMPLE ID(s): 8024-26
Time Collected: 1314 Date: 10/23/97
RRC Sample Collector: A Dutton

Resident Name: Mrs. Zella Rose Phone Number: (940) 966-3317
Street address of water well: (FM 130 across from church)
Rt 3 Box 794
Nocona TX 76255
Length of time at residence:
Have you experienced any problems with water quality, taste, smell? (*if so, explain*) no

Are there any additional wells present on the property? (*if yes, are they plugged or open*) None known

Water Well Data:
GPS Coordinates: Latitude Longitude
Well pipe construction (circle one): PVC [✓ Steel] Unknown
Diameter of well: possibly large hand-dug.
Depth of well (if known): 40' Date of construction: 1941
Driller Name (if known):

Is the water used for drinking	No	[✓ Yes]
Is the water used for cooking	No	[✓ Yes]
Is the water used for bathing	No	[✓ Yes]
Is the water used for washing dishes	No	[✓ Yes]
Is there a pressure tank	No	[✓ Yes] (*if yes, estimate volume*) 15 Gal.
Is there a water softener	[✓ No]	Yes
Is there a reverse osmosis filter	[✓ No]	Yes (*if yes, is filter in kitchen only*)
Is there a septic field on site	No	[✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID______ mg/l Sample ID______ mg/l

Water Well Survey

Map # D3

Well 1903503 (sampled 10/23/97) is a stock well. No survey information was collected.

Water Well Survey

Map #D4

Note: If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration, Label each sample accordingly.

WATER SAMPLE ID(s): 8042 – 8044
Time Collected: 1731 Date: 10/23/97
RRC Sample Collector: A. Dutton

Resident Name: Brandy Lavy & Patrick Derrick Phone Number: (940) 966 – 3378
Street address of water well: Rt 3 Box 706
Nocona TX 76255

Length of time at residence:
Have you experienced any problems with water quality, taste, smell? (*if so, explain*) NO

Are there any additional wells present on the property? (*if yes, are they plugged or open*) old well, may be plugged.

Water Well Data:
GPS Coordinates: Latitude Longitude
Well pipe construction (circle one): [✓ PVC] Steel Unknown
Diameter of well: 4'' or >
Depth of well (if known): Date of construction: < 5 yrs old
Driller Name (if known):
Is the water used for drinking No [✓ Yes]
Is the water used for cooking No [✓ Yes]
Is the water used for bathing No [✓ Yes]
Is the water used for washing dishes No [✓ Yes]
Is there a pressure tank No [✓ Yes] (*if yes, estimate volume*) 20 Gal.
Is there a water softener [✓ No] Yes
Is there a reverse osmosis filter [✓ No] Yes (*if yes, is filter in kitchen only*)
Is there a septic field on site No [✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID _____ mg/l Sample ID _____ mg/l

Water Well Survey

Map # DS

Note: If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration. Label each sample accordingly.

WATER SAMPLE ID(s): 8030 - 8032
Time Collected: Date: 10/23/97
RRC Sample Collector A. Dutton

Resident Name Ricky Pittman Phone Number (940) 966 - 3372
Street address of water well: (on Map @ intersect of Russel Rd N. of unnamed N-S Ro
Rt 3 Box 638
Nocona, TX 76255

Length of time at residence:
Have you experienced any problems with water quality, taste, smell? (*if so, explain*) Slight sulfur odor

Are there any additional wells present on the property? (*if yes, are they plugged or open*) None known

Water Well Data:
GPS Coordinates: Latitude Longitude
Well pipe construction (circle one): PVC [✓ Steel] Unknown
Diameter of well: 4" or greater
Depth of well (if known): Date of construction: > 30 yrs old
Driller Name (if known):
Is the water used for drinking No [✓ Yes]
Is the water used for cooking No [✓ Yes]
Is the water used for bathing No [✓ Yes]
Is the water used for washing dishes No [✓ Yes]
Is there a pressure tank [✓ No] Yes (*if yes, estimate volume*) Gal.
Is there a water softener [✓ No] Yes
Is there a reverse osmosis filter [✓ No] Yes (*if yes, is filter in kitchen only*)
Is there a septic field on site No [✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID mg/l Sample ID mg/l

Water Well Survey

Map # D6

Note: If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration, Label each sample accordingly.

WATER SAMPLE ID(s): 8033 - 8035
Time Collected: 1600 Date: 10/23/97
RRC Sample Collector: A. Dutton

Resident Name: Matt Brown Phone Number: (940) 966-3241
Street address of water well: Rt 3 Box (Main House)
Nocona TX 76255

Length of time at residence:
Have you experienced any problems with water quality, taste, smell? (*if so, explain*) NO

Are there any additional wells present on the property? (*if yes, are they plugged or open*) windmill, not operational. also 2nd house on ranch property

Water Well Data:
GPS Coordinates: Latitude Longitude
Well pipe construction (circle one): PVC [✓ Steel] Unknown
Diameter of well:
Depth of well (if known): Date of construction:
Driller Name (if known):
Is the water used for drinking No [✓ Yes]
Is the water used for cooking No [✓ Yes]
Is the water used for bathing No [✓ Yes]
Is the water used for washing dishes No [✓ Yes]
Is there a pressure tank No [✓ Yes] (*if yes, estimate volume*) 60 Gal.
Is there a water softener [✓ No] Yes
Is there a reverse osmosis filter [✓ No] Yes (*if yes, is filter in kitchen only*)
Is there a septic field on site No [✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID______ mg/l Sample ID______ mg/l

Water Well Survey

Map # D7

Note:If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration, Label each sample accordingly.

WATER SAMPLE ID(s): 8036 - 8038

Time Collected: 1615 Date: 10/23/97

RRC Sample Collector: A. Dutton

Resident Name: M. Brown Phone Number (940) 966-3241

Street address of water well: Rt 3 Box (Brown house trailer)
Nocona TX 76255

Length of time at residence:

Have you experienced any problems with water quality, taste, smell?(*if so, explain*) NO

Are there any additional wells present on the property?(*if yes, are they plugged or open*) yes, see other sheets → main house well

Water Well Data:

GPS Coordinates: Latitude Longitude

Well pipe construction(circle one): PVC Steel [✓ Unknown]

Diameter of well: UK

Depth of well(if known): Date of construction:

Driller Name(if known):

Is the water used for drinking No [✓ Yes]

Is the water used for cooking No [✓ Yes]

Is the water used for bathing No [✓ Yes]

Is the water used for washing dishes No [✓ Yes]

Is there a pressure tank No [✓ Yes] (*if yes, estimate volume*) 40 Gal.

Is there a water softener [✓ No] Yes

Is there a reverse osmosis filter [✓ No] Yes (*if yes, is filter in kitchen only*)

Is there a septic field on site No [✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID____ mg/l Sample ID____ mg/l

WatrSurv.doc
10/06/97

Water Well Survey

Map #D8

Note: If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration, Label each sample accordingly.

WATER SAMPLE ID(s): 8039- 8041

Time Collected: Date: 10/23/97

RRC Sample Collector: A. Dutton

Resident Name: Ken Koontz Phone Number (940) 966-3362

Street address of water well: Rt 3 Box 629
Nocona TX 76255

Length of time at residence:

Have you experienced any problems with water quality, taste, smell?(*if so, explain*) excellent quality

Are there any additional wells present on the property?(*if yes, are they plugged or open*)
Supplies 2 houses

Water Well Data:

GPS Coordinates: Latitude Longitude

Well pipe construction(circle one): PVC Steel Unknown

Diameter of well:

Depth of well(if known): Date of construction:

Driller Name(if known):

Is the water used for drinking No [✓ Yes]

Is the water used for cooking No [✓ Yes]

Is the water used for bathing No [✓ Yes]

Is the water used for washing dishes No [✓ Yes]

Is there a pressure tank No [✓ Yes] (*if yes, estimate volume*) 30 Gal.

Is there a water softener [✓ No] Yes

Is there a reverse osmosis filter [✓ No] Yes (*if yes, is filter in kitchen only*)

Is there a septic field on site No [✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID________mg/l Sample ID________mg/l

Map #D9

Water Well Survey

Note: If a water filtration/purification system is being used, please collect one sample before filtration and one after filtration, Label each sample accordingly.

WATER SAMPLE ID(s): 8045 - 8047
Time Collected: 1335 Date: 10/24/97
RRC Sample Collector: Sullivan / Smyth

Resident Name: O.K. Goolsby Phone Number (940) 966-3221
Street address of water well: Rt 3 Box 624
Nocona TX 76255

Length of time at residence:
Have you experienced any problems with water quality, taste, smell?(*if so, explain*) yes - Sulfur smell. has "Culligan purifier" at well head. Sample taken before purifier in line.

Are there any additional wells present on the property?(*if yes, are they plugged or open*) No

Water Well Data:
GPS Coordinates: Latitude Longitude
Well pipe construction(circle one): PVC [✓ Steel] Unknown
Diameter of well: Not known
Depth of well(if known): 120' Date of construction:
Driller Name(if known):

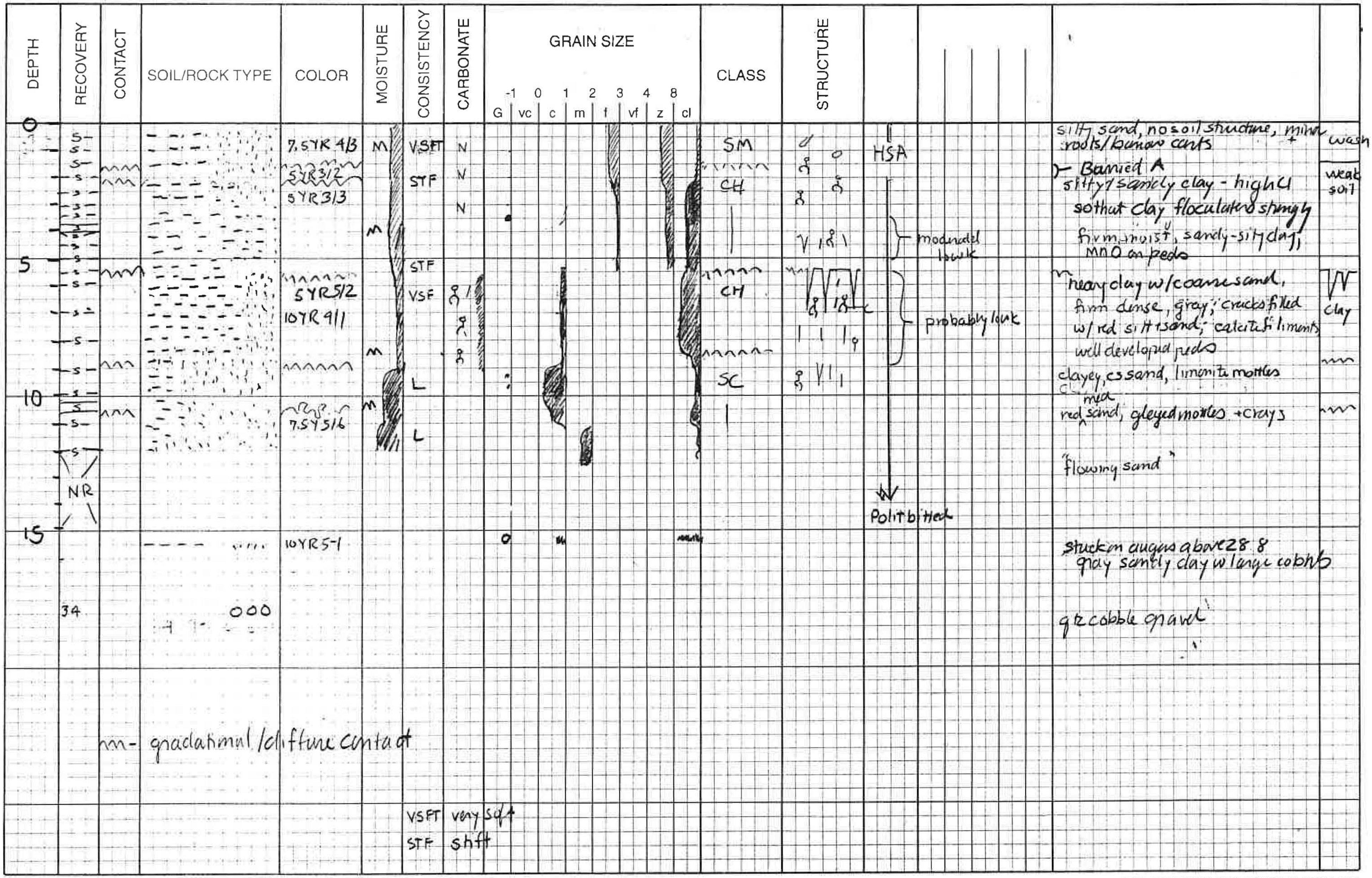
Is the water used for drinking	No	[✓ Yes]
Is the water used for cooking	No	[✓ Yes]
Is the water used for bathing	No	[✓ Yes]
Is the water used for washing dishes	No	[✓ Yes]
Is there a pressure tank	No	[✓ Yes] (*if yes, estimate volume*) 20 Gal.
Is there a water softener	No	[✓ Yes] → "Culligan purifier"
Is there a reverse osmosis filter	No	[✓ Yes] (*if yes, is filter in kitchen only*)
Is there a septic field on site	No	[✓ Yes] (*if yes, estimate volume*)

Chloride Concentration from titration kit in milligrams per liter (mg/l)
Sample ID______ mg/l Sample ID______ mg/l

Appendix 3. Core logs.

BORING BEG/Mont #1 COUNTY Montague DATUM est GL per topo '794' ft FORMATION alluvium/Permian P 1 /2

LOGGED BY SDH DATE 10/28/97 DRILLING METHOD mixed - auger/polit bit SAMPLING METHOD



silty sand, no soil structure, minor roots/burrow casts

Buried A
silty/sandy clay - high Cl so that clay flocculated strongly
firm, moist, sandy-silty clay, MnO on peds

heavy clay w/coarse sand, firm dense, gray; cracks filled w/red silt+sand; calcite filaments well developed peds

clayey, cs sand, limonite mottles

red med sand, gleyed mottles + clays

"flowing sand"

stuck on augers above 28.8
gray sandy clay w large cobbles

qtz cobble gravel

~~~ gradational/diffuse contact

VSFT very soft
STF stiff

BEG ENVIRONMENTAL LOGGING FORM 6/97
~~~

BORING BEG/Mont #1 COUNTY Montague DATUM ______ FORMATION Permian P 2/2

LOGGED BY SDH DATE 10/28 DRILLING METHOD mud rotary SAMPLING METHOD ______

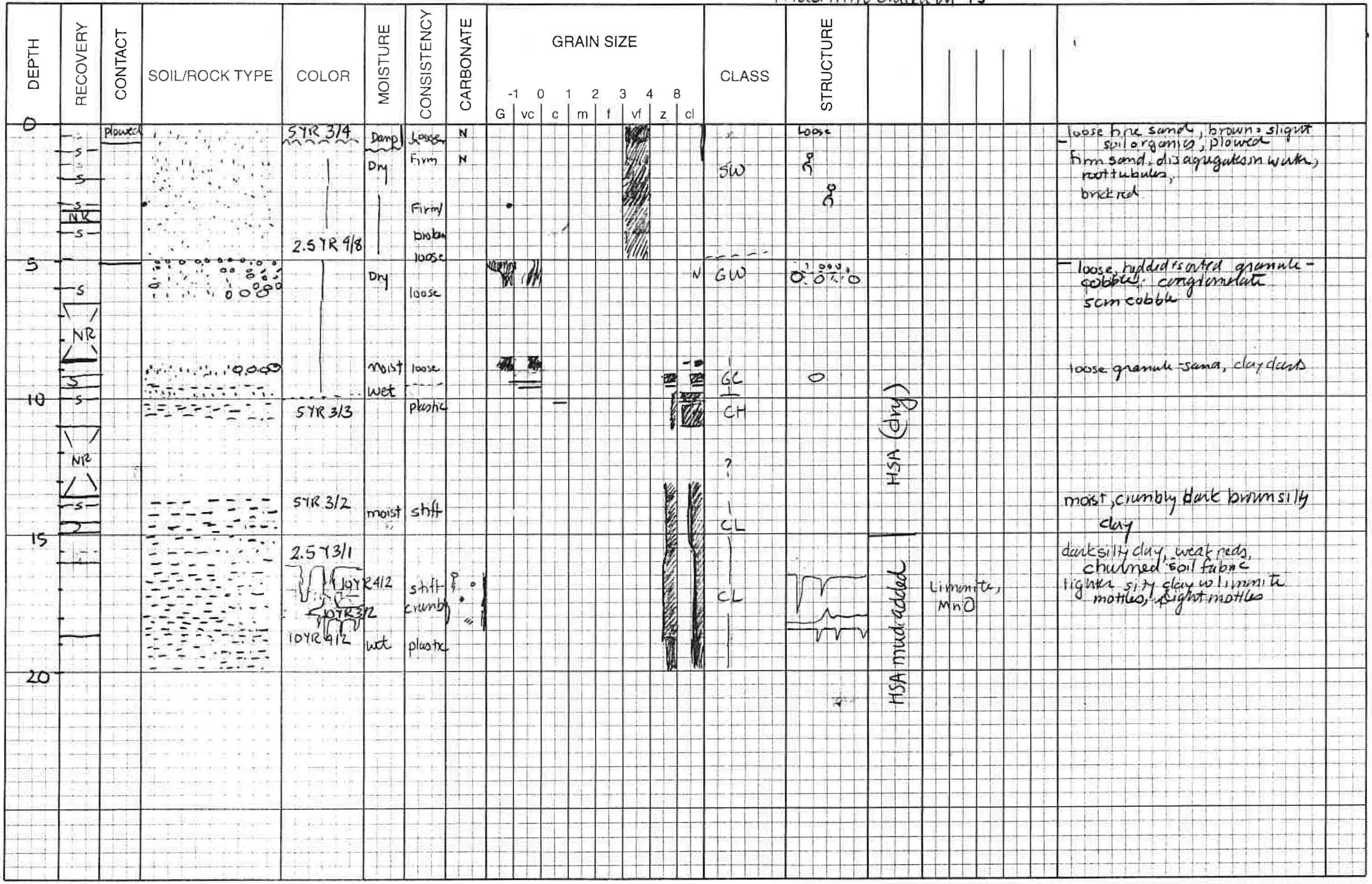
DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G vc c m f vf z cl	CLASS	STRUCTURE				
60				5Y5/1		H	N		sandstone				indurated x bedded gray sandstone	
						?								
65				5Y5/1		H					mud rotary		indurated x bedded gray sandstone and granule conglomerate	
70	TD 70.6													

BEG ENVIRONMENTAL LOGGING FORM 6/97

est GL per topo

BORING BEG/MONT #2 COUNTY Montague DATUM 804 FORMATION alluvium P 1 / 4

LOGGED BY SDH DATE 10/29/97 DRILLING METHOD hollow stem auger. mud introduced at 15' SAMPLING METHOD



DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE (-1 0 1 2 3 4 8; G vc c m f vf z cl)	CLASS	STRUCTURE			
0		Plowed		5YR 3/4	Damp	loose	N			loose			loose fine sand, brown: slight soil organics, plowed
	S				Dry	Firm	N		SW				firm sand, disaggregates in water, root tubules,
	S												brick red
	S NR S					Firm							
				2.5YR 4/8		broken loose							
5	S				Dry	loose		N	GW				loose, bedded/sorted granule-cobble conglomerate 5cm cobble
	NR												
	S				moist	loose			GC				loose granule-sand, clay clasts
					wet								
10	S			5YR 3/3		plastic			CH		HSA (dry)		
	NR								?				
	S			5YR 3/2	moist	stiff			CL				moist, crumbly dark brown silty clay
15				2.5Y 3/1							HSA mud added		dark silty clay, weak peds, churned soil fabric
				10YR 4/2 10YR 3/2		stiff crumbly			CL			Limonite, MnO	lighter silty clay w/ limonite mottles, slight mottles
				10YR 4/2	wet	plastic							
20													

BORING BEG/MONT #2 COUNTY Montague DATUM FORMATION alluvium P2/4

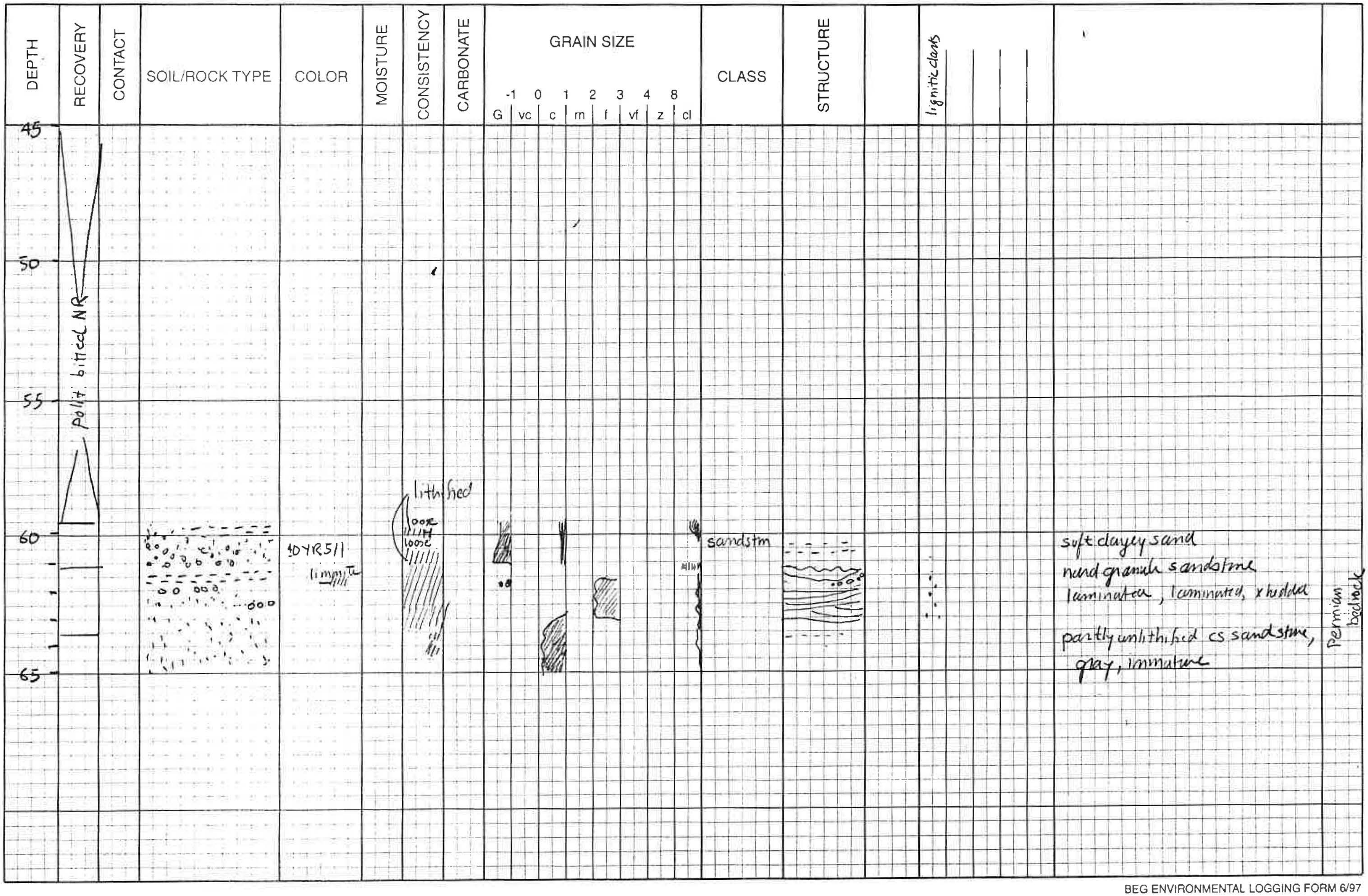
LOGGED BY SDH DATE 10/29/97 DRILLING METHOD hollowstem auger SAMPLING METHOD

DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G vc c m f vf z cl	CLASS	STRUCTURE				
20				5YR4/6	wet	plastic			CH	mottled, reduced on vertical conduits minor MnO			red silty clay, localy strongly reduced along vertical fingers a conduits, wet, plastic minor soil fabrics, root tubules weak ped dev	
25	NR?													
				5YR4/6	wet	plastic			CL				wet plastic red sandy clay fairly massive, minimal soil fabrics	FILL
30														
	NR			5YR5/4		loose			SW				loose, wet medium sand	
35	polit bitted NR													
40														
45														

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING BEG/Mont 2 COUNTY Montague DATUM — FORMATION P 3/4

LOGGED BY SDH DATE 10/29/97 DRILLING METHOD hollow stem auger SAMPLING METHOD



soft clayey sand

nend granule sandstone

laminated, laminated, x bedded

partly unlithified cs sandstone, gray, immature

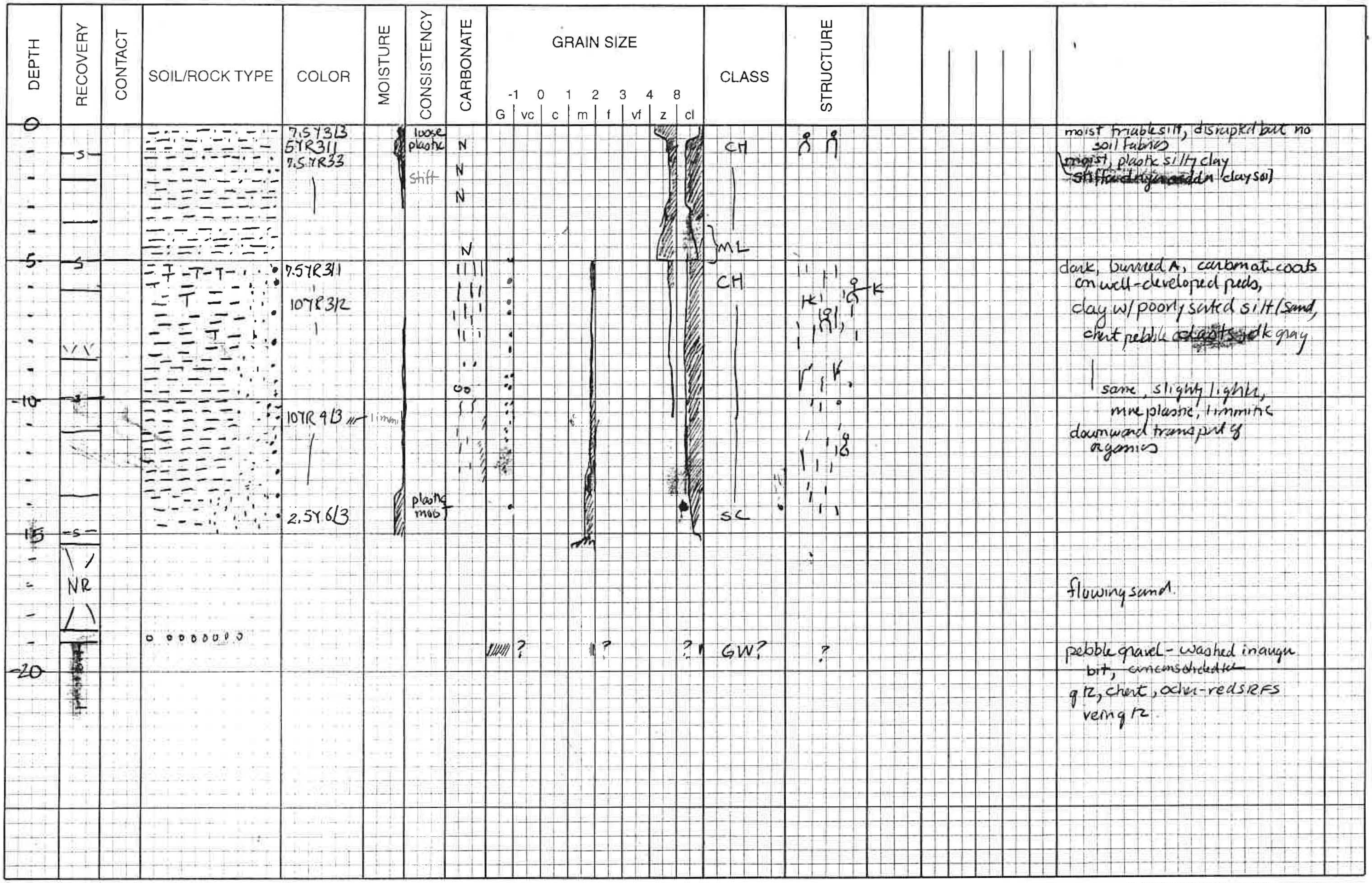
BORING BEG/Montague #2 COUNTY Montague DATUM FORMATION P 4 14

LOGGED BY SDH DATE 10/29/97 DRILLING METHOD SAMPLING METHOD

DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G vc c m f vf z cl	CLASS	STRUCTURE			
65													
70	po/it bited IVR												
75													
	TD	76.0											

BORING MONT 4 COUNTY Montague DATUM FORMATION Quaternary P 1 /3

LOGGED BY SDH DATE 12/2/97 DRILLING METHOD hollowstem auger SAMPLING METHOD



DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G vc c m f vf z cl	CLASS	STRUCTURE	
0	S			7.5Y3/3 5YR3/1 7.5YR3/3		loose plastic stiff	N N N N		CH ML		moist friablesilt, disrupted but no soil fabrics moist, plastic silty clay ~~stiff[illegible]~~dn clay soil]
5	S			7.5YR3/1 10YR3/2					CH		dark, burried A, carbonate coats on well-developed peds, clay w/ poorly sorted silt/sand, chert pebble ~~clasts~~ dk gray same, slightly lighter, more plastic, limonitic downward transport of organics
10				10YR4/3 — 1mm 2.5Y6/3		plastic mod			SC		
15	S NR										flowing sand.
			o o o o o o o o					? ? ?	GW?	?	pebble gravel - washed in auger bit, ~~unconsolidated~~ qtz, chert, ocher-red SRFS vein qtz
20											

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING Mont 4 COUNTY Montague DATUM ______ FORMATION ______ P 2/3

LOGGED BY SDH DATE 12/2/97 DRILLING METHOD hollowstem auger SAMPLING METHOD ______

DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G vc c m f vf z cl	CLASS	STRUCTURE				
-20	NR													
-25													flowing sand	
	pilot bitted NR												stuck to auger 25-29 blue clay, gravel clasts	
-30														
-35														
				2.5Y5/1					SC				sandy clay blue, limonite mottles indurated sandstone = Permian bedrock	
-40														

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING Mont 4 COUNTY Montague DATUM ____ FORMATION ____ P 3/3

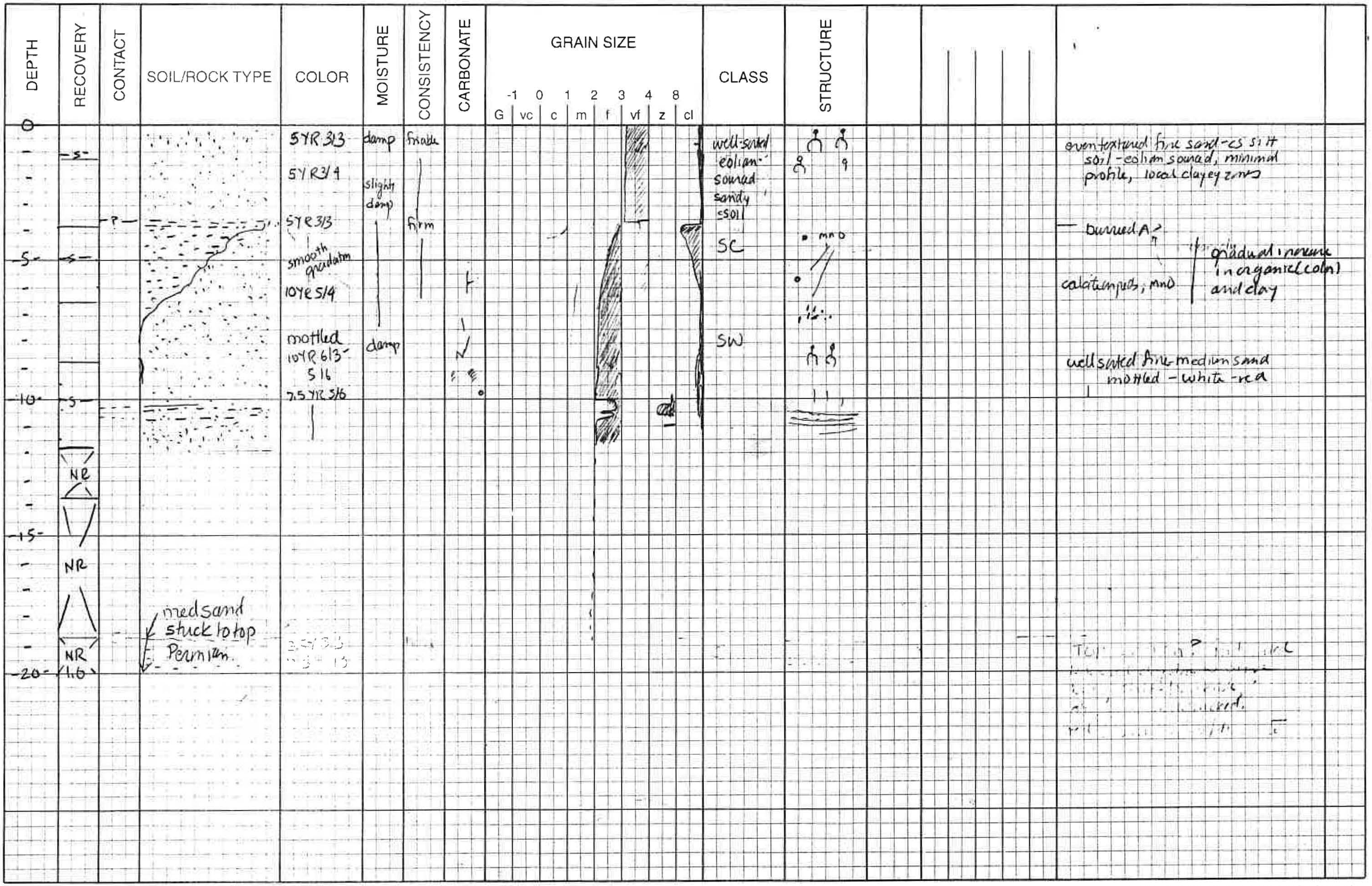
LOGGED BY SDH DATE 12/2/97 DRILLING METHOD ____ SAMPLING METHOD ____

DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G | vc | c | m | f | vf | z | cl	CLASS	STRUCTURE			
40	pilot bit												
45					wet	loose							gravel, clay beds, bedrock clasts somewhat disrupted during coring. possibly Quaternary gravel
50	pilot bitted												
	TD 54.0												

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING Mont 5 COUNTY Montague DATUM FORMATION Qal/ Permian P 1/3

LOGGED BY SDH DATE 11/24/97 DRILLING METHOD HSA SAMPLING METHOD



5YR 3/3 damp friable

5YR 3/4 slightly damp

5YR 3/3 firm

smooth gradation

10YR 5/4

mottled 10YR 6/3-5/6 damp

7.5YR 5/6

well-sorted eolian-sourced sandy soil

SC

SW

even textured fine sand-cs silt soil-eolian sourced, minimal profile, local clayey zones

buried A?

calcite nodules, MnO

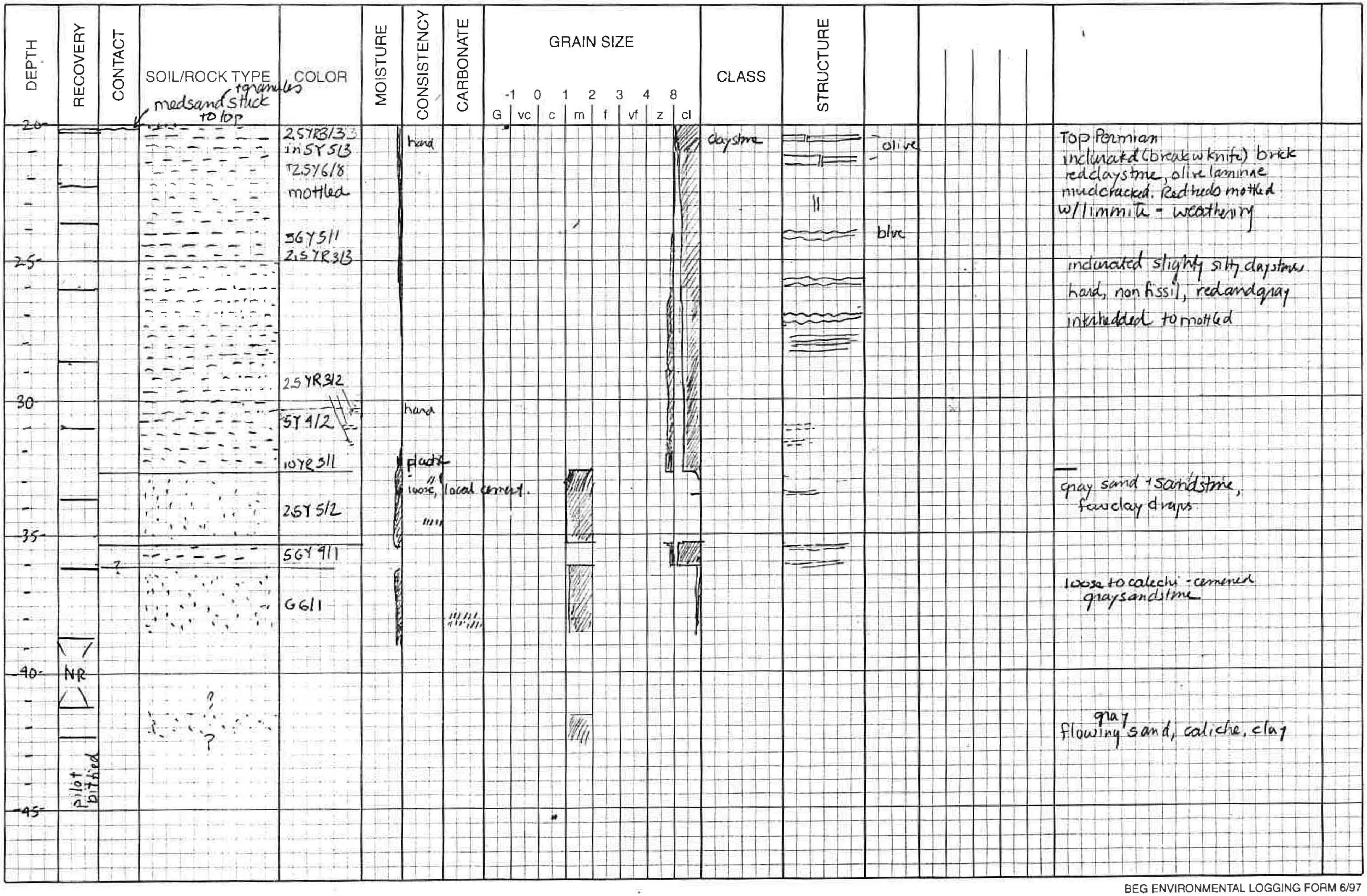
gradual increase in organic (color) and clay

well sorted fine-medium sand mottled - white-red

med sand stuck to top Permian.

BORING Monts 5　COUNTY Montague　DATUM　FORMATION Qal/Permian　P 2/3

LOGGED BY SDH　DATE 11/24/97　DRILLING METHOD HSA　SAMPLING METHOD



medsand + granules stuck to top

2.5YR3/3 in 5Y5/3 + 2.5Y6/8 mottled

5GY5/1

2.5YR3/3

2.5YR3/2

5Y4/2

10YR5/1

2.5Y5/2

5GY4/1

G6/1

hard

hard

plastic

loose, local cement.

claystone

Top Permian
indurated (break w knife) brick red claystone, olive laminae mudcracked. Red beds mottled w/limonite - weathering

indurated slightly silty claystone hard, nonfissil, red and gray interbedded to mottled

gray sand + sandstone, few clay drapes

loose to caliche-cemented gray sandstone

flowing gray sand, caliche, clay

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING RRC Mont 6 COUNTY Montague DATUM ______ FORMATION ______ P 2/2

LOGGED BY SDH DATE 12/18/97 DRILLING METHOD ______ SAMPLING METHOD ______

DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 G	vc 0	c 1	m 2	f 3	vf 4	z 8	cl	CLASS	STRUCTURE				
20				7.5YR 7/4			N					▨									
	NR											▨									
25					wet	loose														Wet, loose sand.	
	NR?	?																		<? not clear what core loss was	
				2.5Y 4/6		hard	N					▨								Permian bedrock - well indurated olive sandstone	
			TD 28.7																		
30																					

est GL fr topo

BORING BEG Mont 8

COUNTY Montague

DATUM 810

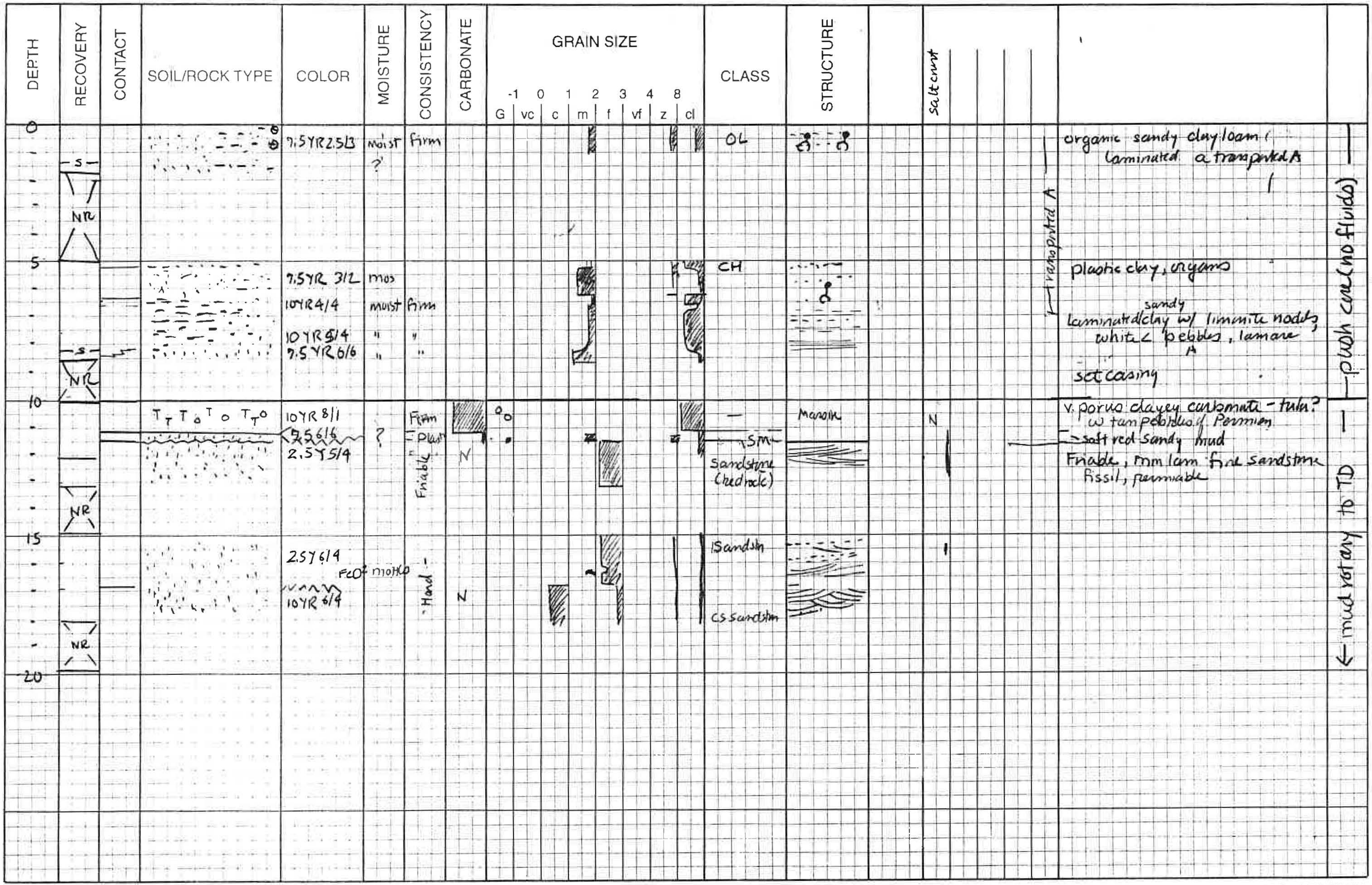
FORMATION alluvium - Permian Noc P 1/5

LOGGED BY SDH

DATE 11/17/97

DRILLING METHOD 0-10' push core 10-10 mud rotary

SAMPLING METHOD



DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G vc c m f vf z cl	CLASS	STRUCTURE	Salt crust			
0	S NR			7.5YR2.5/3	moist ?	firm			OL			transported A	organic sandy clay loam (laminated a transported A	push core (no fluids)
5	S NR			7.5YR 3/2 10YR4/4 10YR 5/4 7.5YR 6/6	mos moist " "	firm " "			CH				plastic clay, organs laminated sandy clay w/ limonite nodes, white pebbles, lamare set casing	
10	NR			10YR 8/1 7.5 6/6 2.5Y 5/4	?	Firm Plast Friable	N		— SM Sandstone (bedrock)	Massive	N		v. porus clayey carbonate - tufa? w tan pebbles of Permian → soft red sandy mud Friable, mm lam fine sandstone fissil, permeable	mud rotary to TD
15	NR			2.5Y 6/4 FeO? mottle 10YR 6/4		Hard	N		fSandstn cs Sandstn					
20														

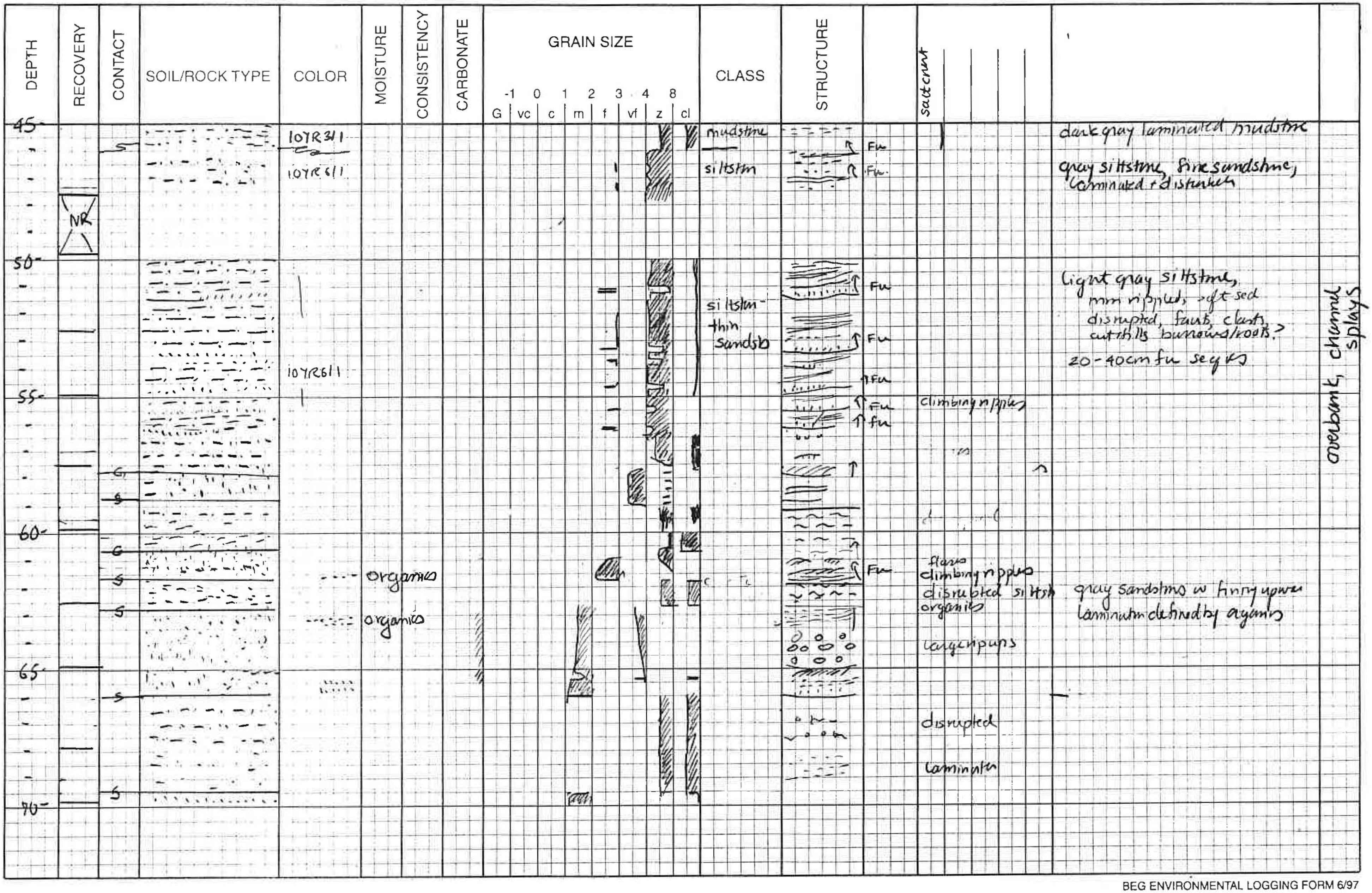
BORING BEG Mont 8 COUNTY Montague DATUM – FORMATION Permian Nocona Gp P2 /5

LOGGED BY SDH DATE 11/17/97 DRILLING METHOD mud rotary SAMPLING METHOD

DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE -1 0 1 2 3 4 8 G vc c m f vf z cl	CLASS	STRUCTURE				
20			granule sand cuttings											
25	NR													
30			"	some oxidized chips - 10YR 6/3 on cutting										
35														
40	NR													
45			see next page											

BORING BEG Mont 8 COUNTY Montague DATUM - FORMATION Permian Nocona Gp P 3 15

LOGGED BY SDH DATE 11/17/97 DRILLING METHOD mud rotary SAMPLING METHOD



climbing ripples

flasers climbing ripples

disrupted siltsh organics

largerippups

disrupted

laminatn

dark gray laminated mudstne

gray siltstne, fine sandstne, laminated + disturbed

light gray siltstne, mm rippled, soft sed disrupted, faults, clasts, cutfills burrows/roots?

20-40cm fu seqs

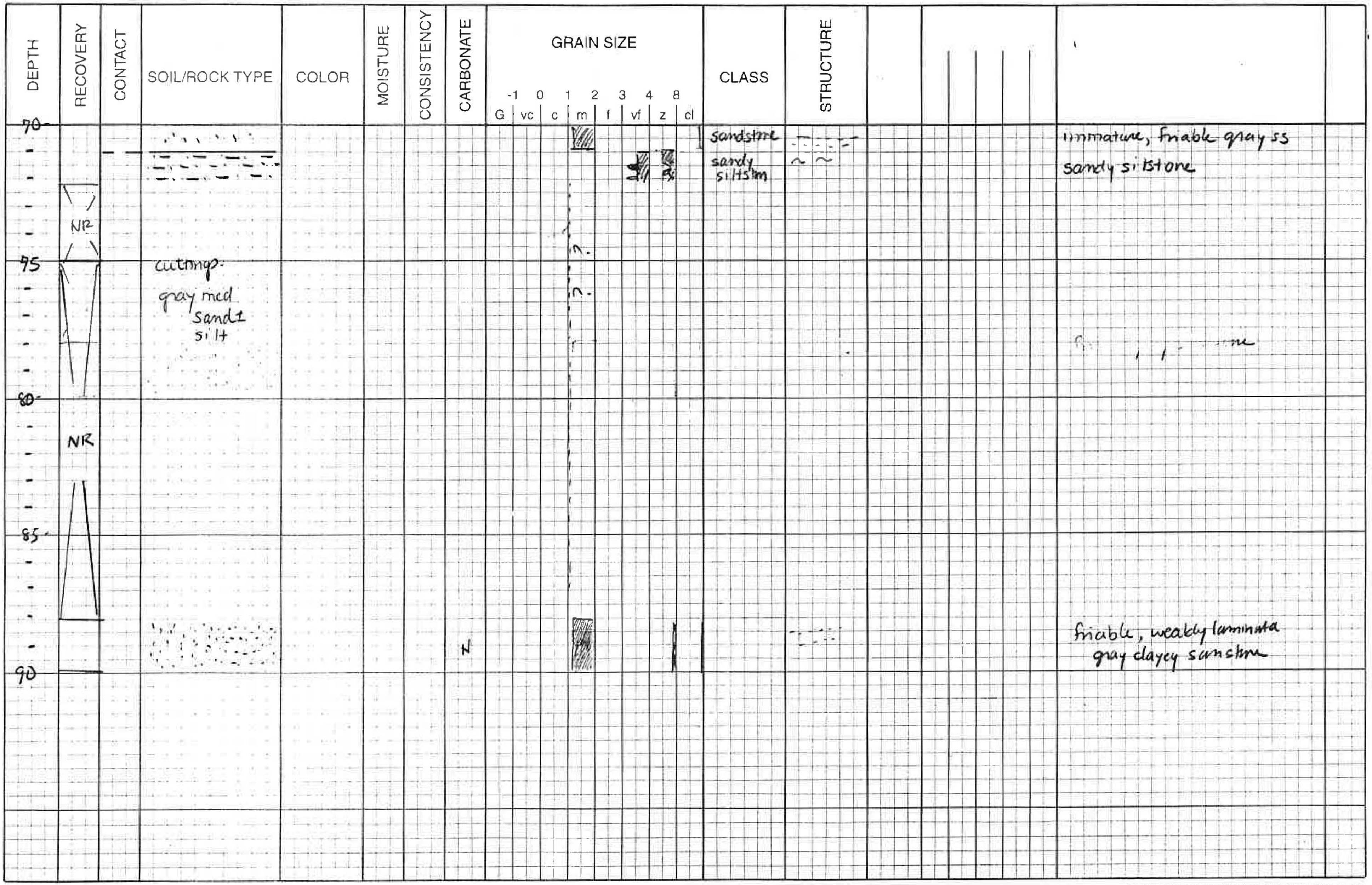
gray sandstns w finingupward laminatn defined by organics

overbank, channel splays

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING BEG Mont 8 COUNTY Montague DATUM ______ FORMATION Permian Nocona Gp P 4/5

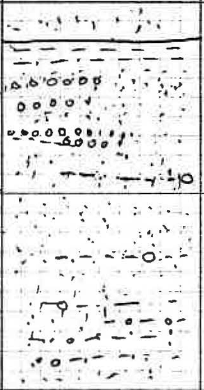
LOGGED BY SDH DATE 11/17/97 DRILLING METHOD ______ SAMPLING METHOD ______

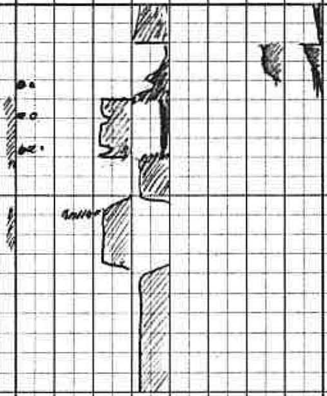


DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE	CLASS	STRUCTURE				
70									sandstone				immature, friable gray ss	
									sandy siltstn	~ ~			sandy siltstone	
	NR													
75			cuttings: gray med Sand/ silt											
80	NR													
85														
							N						friable, weakly laminata gray clayey sanstone	
90														

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING BEG Mont 8
COUNTY Montague
DATUM
FORMATION Permian Nocona
P5 /5
LOGGED BY SDH
DATE 11/17/97
DRILLING METHOD mud rotary
SAMPLING METHOD



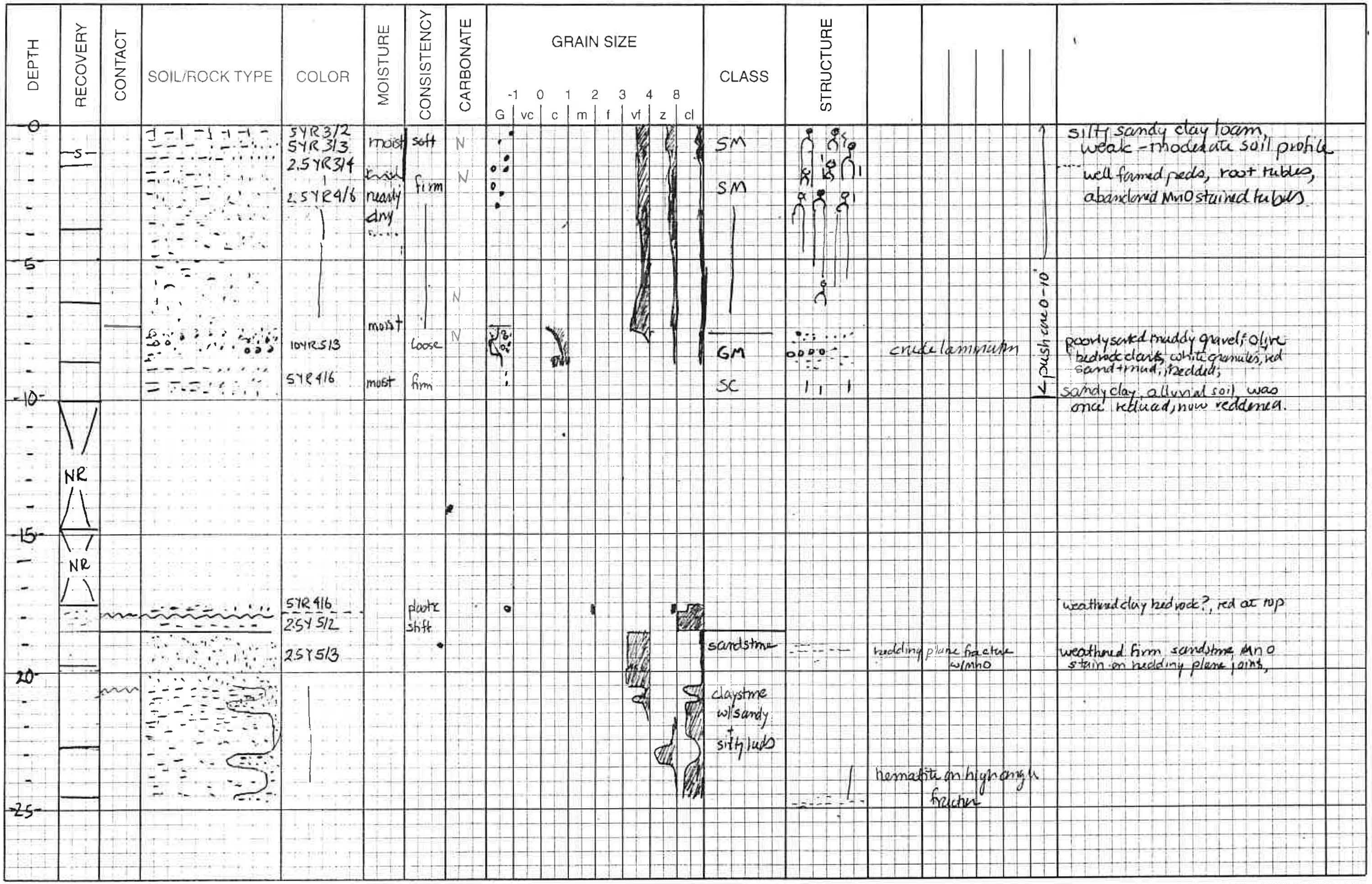


DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE	CLASS	STRUCTURE			
90				lt gray		Friable	N		sandstn	↑	Fu		med gray sandstone, poorly indurated
		s		dk gray					mudstne	↑	Fu		
				lk gray			N						
						Hard							calcite cemented (tight) xbedded granual-pebble conglomerate
				orgens		friable						brown discoloration below tight zone	high∠ xbedded med sand, dark organics
95				lt gray		hard							well cemented (calcite) cs sands cement is preferentially in coarser zones
				organics ↓									
						friable							friable med sandstn, abundant lignite fragments
100	drilled w 8" bit to sample below saline	per sounding											
105													
110													

BEG ENVIRONMENTAL LOGGING FORM 6/97

BORING Mont 13 COUNTY Montague DATUM ______ FORMATION alluvian/ P.Nocona P 1 /3

LOGGED BY SDH DATE 11/20/97 DRILLING METHOD push 0-10; mud rotary TD SAMPLING METHOD ______



DEPTH	RECOVERY	COLOR	MOISTURE	CONSISTENCY	CARBONATE	CLASS	STRUCTURE			
0	S	5YR3/2 5YR3/3 2.5YR3/4 2.5YR4/6	moist ~~moist~~ nearly dry	soft firm	N N	SM SM			push core 0-10	silty sandy clay loam, weak-moderate soil profile well formed peds, root tubles, abandoned MnO stained tubes
5					N					
8		10YR5/3	moist	loose	N	GM		crude lamination		poorly sorted muddy gravel; olive bedrock clasts, white granules, red sand+mud, bedded;
9		5YR4/6	moist	firm		SC				sandy clay, alluvial soil was once reduced, now reddened.
10	NR									
15	NR									
17.5		5YR4/6 2.5Y5/2		plastic stiff						weathered clay bedrock?, red at top
19		2.5Y5/3				sandstone		bedding plane fracture w/MnO		weathered firm sandstone, MnO stain on bedding plane joints,
20						claystone w/sandy + silty beds				
24								hematite on high angle fracture		

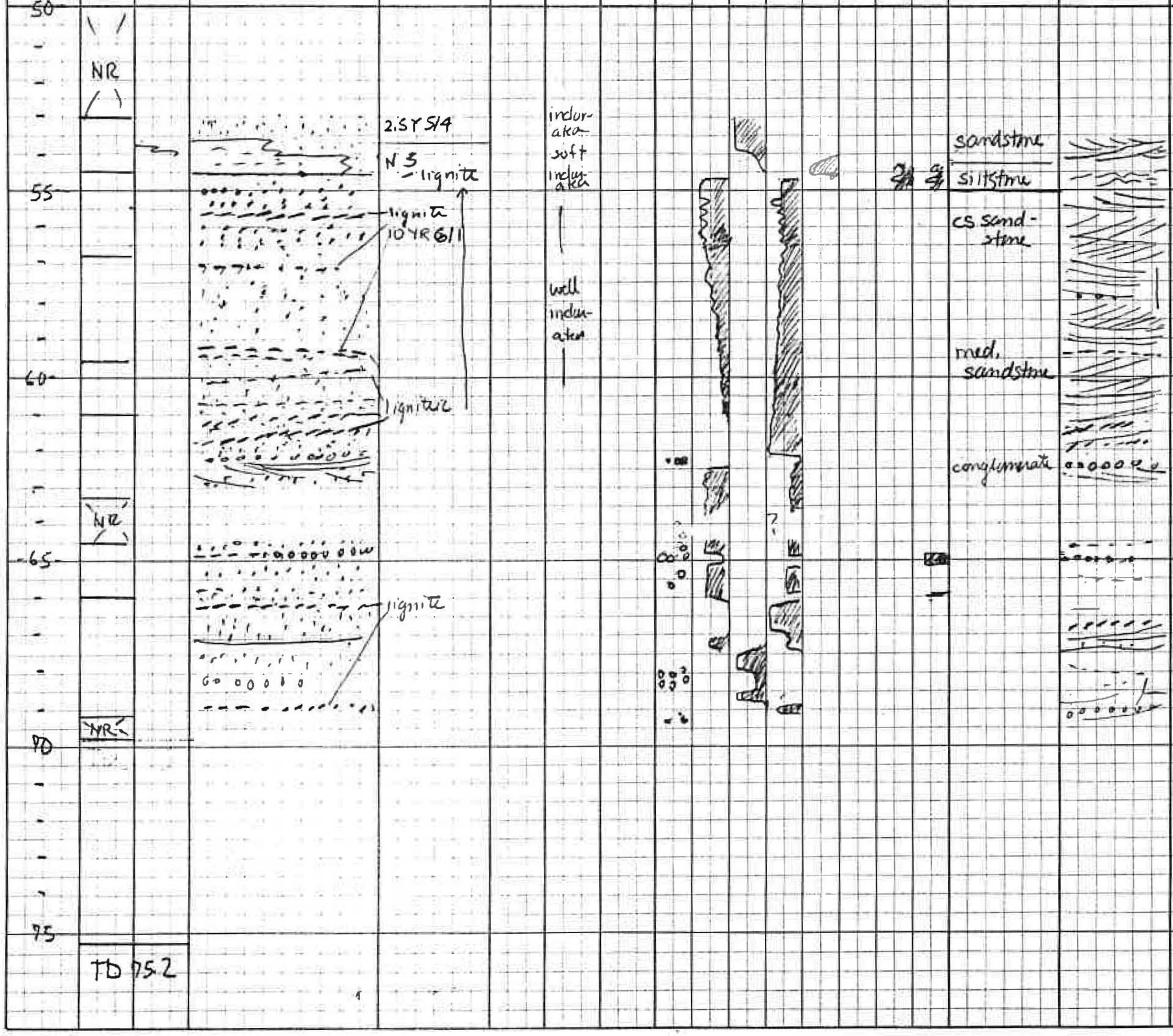
BORING Mont 13 COUNTY Montague DATUM ______ FORMATION Permian Nocona P 2/3

LOGGED BY SD Hovorka DATE 11/20/97 DRILLING METHOD mud rotary SAMPLING METHOD ______

DEPTH(FT)	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE	CLASS	STRUCTURE			
25				2.5Y 6/6					claystn-siltstn				ripple laminated + burrowed siltstone and claystone, sandstone beds.
				7.5YR 5/6 2.5Y 5/4					sandstne		Fe		limonite nodules in sandstn. cross bedded well indurated-slightly friable sandstn
	NR												
30	NR		rounded sandstne fragments only recovery										
35	NR												
				5YR 3/3		broken friable					core broken		
40	?			2.5Y 5/4		well indurated			sandstne		friable		iron oxide nodules-mottles in med.-cs sandstone
	NR												
45				2.5Y 4/3		well indur-ated loose			sandstne conglomerate				iron stained granual-med sandstne, well indurated. Reduced where lignitic iron-replaced mudclast conglomerate, olive lignitic sandstne, red leached pebbles. more reduced in lignitic areas
	NR												
50	NR												

BORING Mont 13 COUNTY Montague DATUM FORMATION Permian Nocona P 3/3

LOGGED BY SDH DATE 11/20/97 DRILLING METHOD SAMPLING METHOD



DEPTH	RECOVERY	CONTACT	SOIL/ROCK TYPE	COLOR	MOISTURE	CONSISTENCY	CARBONATE	GRAIN SIZE	CLASS	STRUCTURE			
50	NR												
				2.5Y 5/4		indur-ated			sandstone				cross bedded ironstained sandstone
				N 3 – lignite		soft			siltstone				gray siltstone
						indur-ated							
55				lignite 10YR 6/1					cs sand-stone				very coarse sandstone, friable
											vertical fracture, not mineralized		soft blue clay clasts – 5G 7/2 ! precoursor of weathered clasts
						well indurated			med. sandstone				lignitic do fines mantle x bed sets.
60				lignite									imbricate lignite clasts
									conglomerate				10cm lag conglomerate
	NR												
65											poorly defined bedding poor sorting		conglomerate w plastic gray clay matrix
				lignite									
													bedded + crossbedded medium - sandstone - conglomerate. coarse zones are poorly indurated.
											soft sed fault coated w/lignite		
70	NR												
75													
	TD 75.2												

BEG ENVIRONMENTAL LOGGING FORM 6/97

Appendix 4. Well-registration forms.

Send original copy by certified mail to: **TNRCC, P.O. Box 13087, Austin, TX 78711-3087** *Please use black ink.*

ATTENTION OWNER: *Confidentiality Privilege Notice on Reverse Side*

State of Texas
WELL REPORT

Texas Water Well Drillers Advisory Council
P.O. Box 13087
Austin, Texas 78711-3087
512-239-0530

Montague #1

1) OWNER Railroad Commission of Texas (Name) **ADDRESS** 1701 N. Congress (Street or RFD) Austin (City) Texas (State) 78711-2967 (Zip)

2) ADDRESS OF WELL:
County Montague North of County Road 103 (Street, RFD or other) Nocona (City) Texas (State) 76755 (Zip) **GRID #**

3) TYPE OF WORK (Check):
☒ New Well ☐ Deepening
☐ Reconditioning ☐ Plugging

4) PROPOSED USE (Check): ☒ Monitor ☒ Environmental Soil Boring ☐ Domestic
☐ Industrial ☐ Irrigation ☐ Injection ☐ Public Supply ☐ De-watering ☐ Testwell
If Public Supply well, were plans submitted to the TNRCC? ☐ Yes ☐ No

5)
Longitude: 97.68048
97° 40 min. 50 sec.
Latitude: 33.94843
33° 56 min. 54 sec.
N

6) WELL LOG:
Date Drilling:
Started 10/15 1997
Completed 10/16 1997

DIAMETER OF HOLE

Dia. (in.)	From (ft.)	To (ft.)
7 7/8	Surface	28.8
5 7/8"	28.8	60.6
2 7/8"	60.6	70.6

7) DRILLING METHOD (Check): ☐ Driven
☐ Air Rotary ☒ Mud Rotary ☐ Bored
☐ Air Hammer ☐ Cable Tool ☐ Jetted
☐ Other Augar & Reamed

From (ft.)	To (ft.)	Description and color of formation material
0.0	3.8	Topsoil clay & sand
3.8	8.8	Sandy clay
8.8	13.8	Sandy clay & flowing sand
13.8	28.8	Sand & chunks of rocks
28.8	34.9	Chunks of rocks
34.9	60.6	No recovery
60.6	70.6	Gray sandstone

(Use reverse side if necessary)

8) Borehole Completion (Check): N/A ☐ Open Hole ☐ Straight Wall
☐ Underreamed ☐ Gravel Packed ☐ Other
If Gravel Packed give interval . . . from ft. to ft.

CASING, BLANK PIPE, AND WELL SCREEN DATA: N/A

Dia. (in.)	New or Used	Steel, Plastic, etc. Perf., Slotted, etc. Screen Mfg., if commercial	Setting (ft.) From	Setting (ft.) To	Gage Casting Screen
2	N	PVC Riser	0.0	12	
2	N	PVC Riser	0.0	40	
2	N	PVC Slotted Screen	12	22	
2	N	PVC Slotted Screen	40	50	

9) CEMENTING DATA: [Rule 338.44(1)] N/A
Cemented from ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
Method used
Cemented by
Distance to septic system field lines or other concentrated contamination ft.
Method of verification of above distance

10) SURFACE COMPLETION N/A
☐ Specified Surface Slab Installed [Rule 338.44 (2) (A)]
☐ Specified Steel Sleeve Installed [Rule 338.44 (3)(A)]
☐ Pitless Adapter Used [Rule 338.44 (3)(b)]
☐ Approved Alternative Procedure Used [Rule 338.71]

11) WATER LEVEL: N/A
Static level ft. below land surface Date
Artesian flow gpm. Date

12) PACKERS: N/A Type Depth

13) TYPE PUMP: N/A
☐ Turbine ☐ Jet ☐ Submersible ☐ Cylinder
☐ Other
Depth to pump bowls, cylinder, jet, etc., ft.

14) WELL TESTS: N/A
Type test: ☐ Pump ☐ Bailer ☐ Jetted
Yield: gpm with ft. drawdown after hrs.

15) WATER QUALITY: N/A
Did you knowingly penetrate any strata which contained undesirable constituents?
☐ Yes ☐ No If yes, submit "REPORT OF UNDESIRABLE WATER"
Type of water? Depth of strata
Was a chemical analysis made? ☐ Yes ☐ No

I hereby certify that this well was drilled by me (or under my supervision) and that each and all of the statements herein are true to the best of my knowledge and belief. I understand that failure to complete items 1 thru 15 will result in the log(s) being returned for completion and resubmittal.

COMPANY NAME University of Texas/Bureau of Economic Geology (Type or Print) WELL DRILLER'S LICENSE NO. 3187-M

ADDRESS P.O. Box X University Station (Street or RFD) Austin (City) Texas (State) 78701 (Zip)

(Signed) James Doss (Licensed Well Driller) **(Signed)** Jordan Forman (Registered Driller Trainee)

Please attach electric log, chemical analysis, and other pertinent information, if available.

TNRCC-0199 (Rev. 11-01-94) TRNCC COPY

Send original copy by certified mail to: **TNRCC, P.O. Box 13087, Austin, TX 78711-3087** *Please use black ink.*

ATTENTION OWNER: *Confidentiality Privilege Notice on Reverse Side*

State of Texas
WELL REPORT

Texas Water Well Drillers Advisory Council
P.O. Box 13087
Austin, Texas 78711-3087
512-239-0530

Montague #2

1) OWNER Railroad Commission of Texas (Name) **ADDRESS** 1701 N. Congress (Street or RFD) Austin (City) Texas (State) 78711-2967 (Zip)

2) ADDRESS OF WELL:
County Montague North of County Road 103 (Street, RFD or other) Nocona (City) Texas (State) 76755 (Zip) **GRID #**

3) TYPE OF WORK (Check) :
☒ New Well ☐ Deepening
☐ Reconditioning ☐ Plugging

4) PROPOSED USE (Check) : ☒ Monitor ☒ Environmental Soil Boring ☐ Domestic
☐ Industrial ☐ Irrigation ☐ Injection ☐ Public Supply ☐ De-watering ☐ Testwell
If Public Supply well, were plans submitted to the TNRCC? ☐ Yes ☐ No

5)
Longitude: 97.67487
97° 40 min. 30 sec.

Latitude: 33.94452
33° 56 min. 40 sec.

N

6) WELL LOG:
Date Drilling:
Started 10/19 1997
Completed 10/19 1997

DIAMETER OF HOLE

Dia. (in.)	From (ft.)	To (ft.)
7 7/8	Surface	76.0

7) DRILLING METHOD (Check): ☐ Driven
☐ Air Rotary ☐ Mud Rotary ☐ Bored
☐ Air Hammer ☐ Cable Tool ☐ Jetted
☐ Other Augar

From (ft.)	To (ft.)	Description and color of formation material
0.0	3.6	Topsoil, sandy loam & clay
3.6	13.6	Silty clay & sand, gravel
13.6	28.6	Silty sandy clay
28.6	33.6	Sandy clay & sand
33.6	59.5	No recovery
59.5	65.4	Sand & gravel
65.4	76.0	No recovery

(Use reverse side if necessary)

8) Borehole Completion (Check): ☐ Open Hole ☐ Straight Wall
☐ Underreamed ☐ Gravel Packed ☒ Other Plugged
If Gravel Packed give interval . . . from ft. to ft.

CASING, BLANK PIPE, AND WELL SCREEN DATA: N/A

Dia. (in.)	New or Used	Steel, Plastic, etc. Perf., Slotted, etc. Screen Mfg., if commercial	Setting (ft.)		Gage Casting Screen
			From	To	

9) CEMENTING DATA: [Rule 338.44(1)]
Cemented from 0.0 ft. to 3.0 ft. No. of Sacks Used 4
ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
Method used Handpoured
Cemented by Drill crew
Distance to septic system field lines or other concentrated contamination ft.
Method of verification of above distance

10) SURFACE COMPLETION N/A
☐ Specified Surface Slab Installed [Rule 338.44 (2) (A)]
☐ Specified Steel Sleeve Installed [Rule 338.44 (3)(A)]
☐ Pitless Adapter Used [Rule 338.44 (3)(b)]
☐ Approved Alternative Procedure Used [Rule 338.71]

11) WATER LEVEL: N/A
Static level ft. below land surface Date
Artesian flow gpm. Date

12) PACKERS: N/A Type Depth

13) TYPE PUMP: N/A
☐ Turbine ☐ Jet ☐ Submersible ☐ Cylinder
☐ Other
Depth to pump bowls, cylinder, jet, etc., ft.

14) WELL TESTS: N/A
Type test: ☐ Pump ☐ Bailer ☐ Jetted
Yield: gpm with ft. drawdown after hrs.

15) WATER QUALITY: N/A
Did you knowingly penetrate any strata which contained undesirable constituents?
☐ Yes ☐ No If yes, submit "REPORT OF UNDESIRABLE WATER"
Type of water? Depth of strata
Was a chemical analysis made? ☐ Yes ☐ No

I hereby certify that this well was drilled by me (or under my supervision) and that each and all of the statements herein are true to the best of my knowledge and belief. I understand that failure to complete items 1 thru 15 will result in the log(s) being returned for completion and resubmittal.

COMPANY NAME University of Texas/Bureau of Economic Geology (Type or Print) **WELL DRILLER'S LICENSE NO.** 3187-M

ADDRESS P.O. Box X University Station (Street or RFD) Austin (City) Texas (State) 78701 (Zip)

(Signed) James Doss (Licensed Well Driller) **(Signed)** Jordan Forman (Registered Driller Trainee)

Please attach electric log, chemical analysis, and other pertinent information, if available.

TNRCC-0199 (Rev. 11-01-94) TRNCC COPY

Send original copy by certified mail to: **TNRCC, P.O. Box 13087, Austin, TX 78711-3087** *Please use black ink.*

ATTENTION OWNER: *Confidentiality Privilege Notice on Reverse Side*

State of Texas
WELL REPORT

Texas Water Well Drillers Advisory Council
P.O. Box 13087
Austin, Texas 78711-3087
512-239-0530

Montague #4

1) OWNER Railroad Commission of Texas (Name) **ADDRESS** 1701 N. Congress (Street or RFD) Austin (City) Texas (State) 78711-2967 (Zip)

2) ADDRESS OF WELL:
County Montague North of County Road 103 (Street, RFD or other) Nocona (City) Texas (State) 76755 (Zip) **GRID #**

3) TYPE OF WORK (Check) :
☒ New Well ☐ Deepening
☐ Reconditioning ☐ Plugging

4) PROPOSED USE (Check) : ☒ Monitor ☒ Environmental Soil Boring ☐ Domestic
☐ Industrial ☐ Irrigation ☐ Injection ☐ Public Supply ☐ De-watering ☐ Testwell
If Public Supply well, were plans submitted to the TNRCC? ☐ Yes ☐ No

5)
Longitude: 97.66067
97° 57 min. 38 sec.
Latitude: 33.94665
33° 56 min. 5 sec.

N

6) WELL LOG:
Date Drilling:
Started 11/8 1997
Completed 11/8 1997

DIAMETER OF HOLE

Dia. (in.)	From (ft.)	To (ft.)
7 7/8	Surface	54.0

7) DRILLING METHOD (Check): ☐ Driven
☐ Air Rotary ☐ Mud Rotary ☐ Bored
☐ Air Hammer ☐ Cable Tool ☐ Jetted
☐ Other Augar & Reamed

From (ft.)	To (ft.)	Description and color of formation material
0.0	3.5	Topsoil, clay & sand
3.5	8.5	Clay
8.5	13.5	Gray sandy clay
13.5	18.5	Sand & clay
18.5	39	No recovery
39	40	No recovery
40	44.0	No recovery
44	45.7	No recovery
45.7	54	No recovery

(Use reverse side if necessary)

8) Borehole Completion (Check): N/A ☐ Open Hole ☐ Straight Wall
☐ Underreamed ☐ Gravel Packed ☐ Other
If Gravel Packed give interval . . . from ft. to ft.

CASING, BLANK PIPE, AND WELL SCREEN DATA:

Dia. (in.)	New or Used	Steel, Plastic, etc. Perf., Slotted, etc. Screen Mfg., if commercial	Setting (ft.)		Gage Casting Screen
			From	To	
2	N	PVC Riser	0.0	10.1	
2	N	PVC Riser	0.0	44.1	
2	N	PVC Slotted Screen	10.1	15.1	
2	N	PVC Slotted Screen	44.1	54.1	

9) CEMENTING DATA: N/A [Rule 338.44(1)]
Cemented from ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
Method used
Cemented by
Distance to septic system field lines or other concentrated contamination ft.
Method of verification of above distance

13) TYPE PUMP: N/A
☐ Turbine ☐ Jet ☐ Submersible ☐ Cylinder
☐ Other
Depth to pump bowls, cylinder, jet, etc., ft.

10) SURFACE COMPLETION N/A
☐ Specified Surface Slab Installed [Rule 338.44 (2) (A)]
☐ Specified Steel Sleeve Installed [Rule 338.44 (3)(A)]
☐ Pitless Adapter Used [Rule 338.44 (3)(b)]
☐ Approved Alternative Procedure Used [Rule 338.71]

14) WELL TESTS: N/A
Type test: ☐ Pump ☐ Bailer ☐ Jetted
Yield: gpm with ft. drawdown after hrs.

11) WATER LEVEL: N/A
Static level ft. below land surface Date
Artesian flow gpm. Date

15) WATER QUALITY: N/A
Did you knowingly penetrate any strata which contained undesirable constituents?
☐ Yes ☐ No If yes, submit "REPORT OF UNDESIRABLE WATER"
Type of water? Depth of strata
Was a chemical analysis made? ☐ Yes ☐ No

12) PACKERS: N/A Type Depth

I hereby certify that this well was drilled by me (or under my supervision) and that each and all of the statements herein are true to the best of my knowledge and belief. I understand that failure to complete items 1 thru 15 will result in the log(s) being returned for completion and resubmittal.

COMPANY NAME University of Texas/Bureau of Economic Geology (Type or Print) WELL DRILLER'S LICENSE NO. 3187-M

ADDRESS P.O. Box X University Station (Street or RFD) Austin (City) Texas (State) 78701 (Zip)

(Signed) James Doss (Licensed Well Driller) **(Signed)** Jordan Forman (Registered Driller Trainee)

Please attach electric log, chemical analysis, and other pertinent information, if available.

TNRCC-0199 (Rev. 11-01-94) TRNCC COPY

Send original copy by certified mail to: **TNRCC, P.O. Box 13087, Austin, TX 78711-3087** *Please use black ink.*

ATTENTION OWNER: *Confidentiality Privilege Notice on Reverse Side*

State of Texas
WELL REPORT

Texas Water Well Drillers Advisory Council
P.O. Box 13087
Austin, Texas 78711-3087
512-239-0530

Montague #5

1) OWNER Railroad Commission of Texas (Name) **ADDRESS** 1701 N. Congress (Street or RFD) Austin (City) Texas (State) 78711-2967 (Zip)

2) ADDRESS OF WELL:
County Montague North of County Road 103 (Street, RFD or other) Nocona (City) Texas (State) 76755 (Zip) **GRID #** ______

3) TYPE OF WORK (Check) :
☒ New Well ☐ Deepening
☐ Reconditioning ☐ Plugging

4) PROPOSED USE (Check) : ☒ Monitor ☒ Environmental Soil Boring ☐ Domestic
☐ Industrial ☐ Irrigation ☐ Injection ☐ Public Supply ☐ De-watering ☐ Testwell
If Public Supply well, were plans submitted to the TNRCC? ☐ Yes ☐ No

5)
Longitude: 97.70251
97° 42 min. 9 sec.
Latitude: 33.95806
33° 57 min. 29 sec.

6) WELL LOG:
Date Drilling:
Started 11/7 1997
Completed 11/7 1997

DIAMETER OF HOLE

Dia. (in.)	From (ft.)	To (ft.)
7 7/8	Surface	68.6

7) DRILLING METHOD (Check): ☐ Driven
☐ Air Rotary ☐ Mud Rotary ☐ Bored
☐ Air Hammer ☐ Cable Tool ☐ Jetted
☐ Other Augar

From (ft.)	To (ft.)	Description and color of formation material
0.0	3.6	Topsoil, fine sand, silty clay
3.6	8.6	Inorganic clay & calcite, mud
8.6	13.6	Fine to Medium sand
13.6	18.6	Sand
18.6	23.6	Sand & claystone
23.6	28.6	Silty claystone
28.6	33.6	Silty claystone & sand, sandstone
33.6	41.1	Calcite & sandstone
41.1	42.3	Sand, calcite & clay
42.3	54.5	No recovery
54.5	58.6	Claystone & mudstone
58.6	68.6	Claystone & slickensided

(Use reverse side if necessary)

8) Borehole Completion (Check): N/A ☐ Open Hole ☐ Straight Wall
☐ Underreamed ☐ Gravel Packed ☐ Other ______
If Gravel Packed give interval . . . from ______ ft. to ______ ft.

CASING, BLANK PIPE, AND WELL SCREEN DATA: N/A

Dia. (in.)	New or Used	Steel, Plastic, etc. Perf., Slotted, etc. Screen Mfg., if commercial	Setting (ft.)		Gage Casting Screen
			From	To	
2	N	PVC Riser	0.0	15.4	
2	N	PVC Riser	0.0	38.2	
2	N	PVC Slotted Screen	15.4	20.4	
		PVC Slotted Screen	38.2	48.2	

9) CEMENTING DATA: N/A [Rule 338.44(1)]
Cemented from ______ ft. to ______ ft. No. of Sacks Used ______
______ ft. to ______ ft. No. of Sacks Used ______
______ ft. to ______ ft. No. of Sacks Used ______
Method used ______
Cemented by ______
Distance to septic system field lines or other concentrated contamination ______ ft.
Method of verification of above distance ______

10) SURFACE COMPLETION N/A
☐ Specified Surface Slab Installed [Rule 338.44 (2) (A)]
☐ Specified Steel Sleeve Installed [Rule 338.44 (3)(A)]
☐ Pitless Adapter Used [Rule 338.44 (3)(b)]
☐ Approved Alternative Procedure Used [Rule 338.71]

11) WATER LEVEL: N/A
Static level ______ ft. below land surface Date ______
Artesian flow ______ gpm. Date ______

12) PACKERS: N/A Type Depth

13) TYPE PUMP: N/A
☐ Turbine ☐ Jet ☐ Submersible ☐ Cylinder
☐ Other ______
Depth to pump bowls, cylinder, jet, etc., ______ ft.

14) WELL TESTS: N/A
Type test: ☐ Pump ☐ Bailer ☐ Jetted
Yield: ______ gpm with ______ ft. drawdown after ______ hrs.

15) WATER QUALITY: N/A
Did you knowingly penetrate any strata which contained undesirable constituents?
☐ Yes ☐ No If yes, submit "REPORT OF UNDESIRABLE WATER"
Type of water? ______ Depth of strata ______
Was a chemical analysis made? ☐ Yes ☐ No

I hereby certify that this well was drilled by me (or under my supervision) and that each and all of the statements herein are true to the best of my knowledge and belief. I understand that failure to complete items 1 thru 15 will result in the log(s) being returned for completion and resubmittal.

COMPANY NAME University of Texas/Bureau of Economic Geology (Type or Print) WELL DRILLER'S LICENSE NO. 3187-M

ADDRESS P.O. Box X University Station (Street or RFD) Austin (City) Texas (State) 78701 (Zip)

(Signed) James Doss (Licensed Well Driller) **(Signed)** Jordan Forman (Registered Driller Trainee)

Please attach electric log, chemical analysis, and other pertinent information, if available.

TNRCC-0199 (Rev. 11-01-94)

TRNCC COPY

Send original copy by certified mail to: **TNRCC, P.O. Box 13087, Austin, TX 78711-3087** *Please use black ink.*

ATTENTION OWNER: *Confidentiality Privilege Notice on Reverse Side*

State of Texas
WELL REPORT

Texas Water Well Drillers Advisory Council
P.O. Box 13087
Austin, Texas 78711-3087
512-239-0530

Montague #6

1) OWNER Railroad Commission of Texas (Name) **ADDRESS** 1701 N. Congress (Street or RFD) Austin (City) Texas (State) 78711-2967 (Zip)

2) ADDRESS OF WELL:
County Montague North of County Road 103 (Street, RFD or other) Nocona (City) Texas (State) 76755 (Zip) **GRID #**

3) TYPE OF WORK (Check):
☒ New Well ☐ Deepening
☐ Reconditioning ☐ Plugging

4) PROPOSED USE (Check): ☒ Monitor ☒ Environmental Soil Boring ☐ Domestic
☐ Industrial ☐ Irrigation ☐ Injection ☐ Public Supply ☐ De-watering ☐ Testwell
If Public Supply well, were plans submitted to the TNRCC? ☐ Yes ☐ No

5)
Longitude: 97.6838
97° 41 min. 2 sec.
Latitude: 33.94106
33° 56 min. 28 sec.
N

6) WELL LOG:
Date Drilling:
Started 11/1 1997
Completed 11/1 1997

DIAMETER OF HOLE

Dia. (in.)	From (ft.)	To (ft.)
7 7/8	Surface	28.7

7) DRILLING METHOD (Check): ☐ Driven
☐ Air Rotary ☐ Mud Rotary ☐ Bored
☐ Air Hammer ☐ Cable Tool ☐ Jetted
☐ Other Augar

From (ft.)	To (ft.)	Description and color of formation material
0.0	3.7	Topsoil & sand
3.7	8.7	Sand with some clay
8.7	18.7	Sand & clay
18.7	23.7	Sand
23.7	28.7	Sandstone & bedrock

(Use reverse side if necessary)

8) Borehole Completion (Check): ☐ Open Hole ☐ Straight Wall
☐ Underreamed ☐ Gravel Packed ☒ Other Plugged
If Gravel Packed give interval . . . from ft. to ft.

CASING, BLANK PIPE, AND WELL SCREEN DATA: N/A

Dia. (in.)	New or Used	Steel, Plastic, etc. Perf., Slotted, etc. Screen Mfg., if commercial	Setting (ft.) From	Setting (ft.) To	Gage Casting Screen

9) CEMENTING DATA: [Rule 338.44(1)]
Cemented from 0 ft. to 3.0 ft. No. of Sacks Used 4
ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
Method used Hand poured
Cemented by Drill crew
Distance to septic system field lines or other concentrated contamination ft.
Method of verification of above distance

13) TYPE PUMP: N/A
☐ Turbine ☐ Jet ☐ Submersible ☐ Cylinder
☐ Other
Depth to pump bowls, cylinder, jet, etc., ft.

10) SURFACE COMPLETION N/A
☐ Specified Surface Slab Installed [Rule 338.44 (2) (A)]
☐ Specified Steel Sleeve Installed [Rule 338.44 (3)(A)]
☐ Pitless Adapter Used [Rule 338.44 (3)(b)]
☐ Approved Alternative Procedure Used [Rule 338.71]

14) WELL TESTS: N/A
Type test: ☐ Pump ☐ Bailer ☐ Jetted
Yield: gpm with ft. drawdown after hrs.

11) WATER LEVEL: N/A
Static level ft. below land surface Date
Artesian flow gpm. Date

15) WATER QUALITY: N/A
Did you knowingly penetrate any strata which contained undesirable constituents?
☐ Yes ☐ No If yes, submit "REPORT OF UNDESIRABLE WATER"
Type of water? Depth of strata
Was a chemical analysis made? ☐ Yes ☐ No

12) PACKERS: N/A Type Depth

I hereby certify that this well was drilled by me (or under my supervision) and that each and all of the statements herein are true to the best of my knowledge and belief. I understand that failure to complete items 1 thru 15 will result in the log(s) being returned for completion and resubmittal.

COMPANY NAME University of Texas/Bureau of Economic Geology (Type or Print) **WELL DRILLER'S LICENSE NO.** 3187-M

ADDRESS P.O. Box X University Station (Street or RFD) Austin (City) Texas (State) 78701 (Zip)

(Signed) James Doss (Licensed Well Driller) **(Signed)** Jordan Forman (Registered Driller Trainee)

Please attach electric log, chemical analysis, and other pertinent information, if available.

TNRCC-0199 (Rev. 11-01-94) TRNCC COPY

Send original copy by certified mail to: **TNRCC, P.O. Box 13087, Austin, TX 78711-3087** *Please use black ink.*

ATTENTION OWNER: *Confidentiality Privilege Notice on Reverse Side*

State of Texas
WELL REPORT

Texas Water Well Drillers Advisory Council
P.O. Box 13087
Austin, Texas 78711-3087
512-239-0530

Montague #8

1) OWNER Railroad Commission of Texas (Name) **ADDRESS** 1701 N. Congress (Street or RFD) Austin (City) Texas (State) 78711-2967 (Zip)

2) ADDRESS OF WELL:
County Montague North of County Road 103 (Street, RFD or other) Nocona (City) Texas (State) 76755 (Zip) **GRID #**

3) TYPE OF WORK (Check) :
☒ New Well ☐ Deepening
☐ Reconditioning ☐ Plugging

4) PROPOSED USE (Check) : ☒ Monitor ☒ Environmental Soil Boring ☐ Domestic
☐ Industrial ☐ Irrigation ☐ Injection ☐ Public Supply ☐ De-watering ☐ Testwell
If Public Supply well, were plans submitted to the TNRCC? ☐ Yes ☐ No

5)
Longitude: 97.68377
97° 41 min. 2 sec.

Latitude: 33.94108
33° 56 min. 28 sec.

N

6) WELL LOG:
Date Drilling:
Started 10/16 1997
Completed 11/06 1997

DIAMETER OF HOLE

Dia. (in.)	From (ft.)	To (ft.)
2 7/8	Surface	99.9
5 7/8	0	117.3

7) DRILLING METHOD (Check): ☐ Driven
☐ Air Rotary ☒ Mud Rotary ☐ Bored
☐ Air Hammer ☐ Cable Tool ☐ Jetted
☐ Other

From (ft.)	To (ft.)	Description and color of formation material
0.0	10	Topsoil, sandy clay, loam
10	13.4	Gray clay sand & tan sand
13.4	14.9	Tan sandstone
14.9	19.9	Multi colored sandstone
19.9	44.9	No recovery
44.9	64.9	Shale
64.9	74.9	Shale & claystone
74.9	84.9	No recovery
84.9	99.9	Sandstone & shale
0	117.3	Reamed, no recovery

(Use reverse side if necessary)

8) Borehole Completion (Check): ☐ Open Hole ☐ Straight Wall
☐ Underreamed ☐ Gravel Packed ☐ Other Reamed
If Gravel Packed give interval . . . from ft. to ft.

CASING, BLANK PIPE, AND WELL SCREEN DATA: See schematic

Dia. (in.)	New or Used	Steel, Plastic, etc. Perf., Slotted, etc. Screen Mfg., if commercial	Setting (ft.)		Gage Casting Screen
			From	To	

9) CEMENTING DATA: N/A [Rule 338.44(1)]
Cemented from ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
Method used
Cemented by
Distance to septic system field lines or other concentrated contamination ft.
Method of verification of above distance

10) SURFACE COMPLETION N/A
☐ Specified Surface Slab Installed [Rule 338.44 (2) (A)]
☐ Specified Steel Sleeve Installed [Rule 338.44 (3)(A)]
☐ Pitless Adapter Used [Rule 338.44 (3)(b)]
☐ Approved Alternative Procedure Used [Rule 338.71]

11) WATER LEVEL: N/A
Static level ft. below land surface Date
Artesian flow gpm. Date

12) PACKERS: N/A Type Depth

13) TYPE PUMP: N/A
☐ Turbine ☐ Jet ☐ Submersible ☐ Cylinder
☐ Other
Depth to pump bowls, cylinder, jet, etc., ft.

14) WELL TESTS: N/A
Type test: ☐ Pump ☐ Bailer ☐ Jetted
Yield: gpm with ft. drawdown after hrs.

15) WATER QUALITY: N/A
Did you knowingly penetrate any strata which contained undesirable constituents?
☐ Yes ☐ No If yes, submit "REPORT OF UNDESIRABLE WATER"
Type of water? Depth of strata
Was a chemical analysis made? ☐ Yes ☐ No

I hereby certify that this well was drilled by me (or under my supervision) and that each and all of the statements herein are true to the best of my knowledge and belief. I understand that failure to complete items 1 thru 15 will result in the log(s) being returned for completion and resubmittal.

COMPANY NAME University of Texas/Bureau of Economic Geology (Type or Print) WELL DRILLER'S LICENSE NO. 3187-M

ADDRESS P.O. Box X University Station (Street or RFD) Austin (City) Texas (State) 78701 (Zip)

(Signed) James Doss (Licensed Well Driller) **(Signed)** Jordan Forman (Registered Driller Trainee)

Please attach electric log, chemical analysis, and other pertinent information, if available.

Send original copy by certified mail to: **TNRCC, P.O. Box 13087, Austin, TX 78711-3087** *Please use black ink.*

ATTENTION OWNER: *Confidentiality Privilege Notice on Reverse Side*

State of Texas
WELL REPORT

Texas Water Well Drillers Advisory Council
P.O. Box 13087
Austin, Texas 78711-3087
512-239-0530

Montague #13

1) OWNER Railroad Commission of Texas (Name) **ADDRESS** 1701 N. Congress (Street or RFD) Austin (City) Texas (State) 78711-2967 (Zip)

2) ADDRESS OF WELL:
County Montague North of County Road 103 (Street, RFD or other) Nocona (City) Texas (State) 76755 (Zip) **GRID #**

3) TYPE OF WORK (Check) :
☒ New Well ☐ Deepening
☐ Reconditioning ☐ Plugging

4) PROPOSED USE (Check) : ☒ Monitor ☒ Environmental Soil Boring ☐ Domestic
☐ Industrial ☐ Irrigation ☐ Injection ☐ Public Supply ☐ De-watering ☐ Testwell
If Public Supply well, were plans submitted to the TNRCC? ☐ Yes ☐ No

5)
Longitude: 97.67708
97° 40 min. 37 sec.
Latitude: 33.92968
33° 55 min. 47 sec.
N

6) WELL LOG:
Date Drilling:
Started 11/9 1997
Completed 11/11 1997

DIAMETER OF HOLE

Dia. (in.)	From (ft.)	To (ft.)
7 7/8	Surface	10.5
2 7/8	10.5	75.2

7) DRILLING METHOD (Check): ☐ Driven
☐ Air Rotary ☒ Mud Rotary ☐ Bored
☐ Air Hammer ☐ Cable Tool ☐ Jetted
☐ Other Augar

From (ft.)	To (ft.)	Description and color of formation material
0.0	3.6	Silty sand clay loam
3.6	8.6	Silty sandy clay muddy gravel
8.6	10.5	Sand clay
10.5	14.5	No recovery
14.5	24.5	Clay, sandstone, & bedrock
24.5	29.5	Sand, silt & claystone
29.5	34.5	Sandstone
34.5	39.5	Washout
39.5	44.5	Sandstone
44.5	53.0	Sandstone, conglomerate & siltstone
53.0	59.5	Sandstone
59.5	64.5	Conglomerate & clay
64.5	75.2	Sandstone

(Use reverse side if necessary)

8) Borehole Completion (Check): N/A ☐ Open Hole ☐ Straight Wall
☐ Underreamed ☐ Gravel Packed ☐ Other
If Gravel Packed give interval . . . from ft. to ft.

CASING, BLANK PIPE, AND WELL SCREEN DATA: N/A

Dia. (in.)	New or Used	Steel, Plastic, etc. Perf., Slotted, etc. Screen Mfg., if commercial	Setting (ft.)		Gage Casting Screen
			From	To	
2	N	PVC Riser	0.0	64.1	
2	N	PVC Slotted Screen	64.1	74.1	

9) CEMENTING DATA: N/A [Rule 338.44(1)]
Cemented from ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
ft. to ft. No. of Sacks Used
Method used
Cemented by
Distance to septic system field lines or other concentrated contamination ft.
Method of verification of above distance

10) SURFACE COMPLETION N/A
☐ Specified Surface Slab Installed [Rule 338.44 (2) (A)]
☐ Specified Steel Sleeve Installed [Rule 338.44 (3)(A)]
☐ Pitless Adapter Used [Rule 338.44 (3)(b)]
☐ Approved Alternative Procedure Used [Rule 338.71]

11) WATER LEVEL: N/A
Static level ft. below land surface Date
Artesian flow gpm. Date

12) PACKERS: N/A Type Depth

13) TYPE PUMP: N/A
☐ Turbine ☐ Jet ☐ Submersible ☐ Cylinder
☐ Other
Depth to pump bowls, cylinder, jet, etc., ft.

14) WELL TESTS: N/A
Type test: ☐ Pump ☐ Bailer ☐ Jetted
Yield: gpm with ft. drawdown after hrs.

15) WATER QUALITY: N/A
Did you knowingly penetrate any strata which contained undesirable constituents?
☐ Yes ☐ No If yes, submit "REPORT OF UNDESIRABLE WATER"
Type of water? Depth of strata
Was a chemical analysis made? ☐ Yes ☐ No

I hereby certify that this well was drilled by me (or under my supervision) and that each and all of the statements herein are true to the best of my knowledge and belief. I understand that failure to complete items 1 thru 15 will result in the log(s) being returned for completion and resubmittal.

COMPANY NAME University of Texas/Bureau of Economic Geology (Type or Print) WELL DRILLER'S LICENSE NO. 3187-M

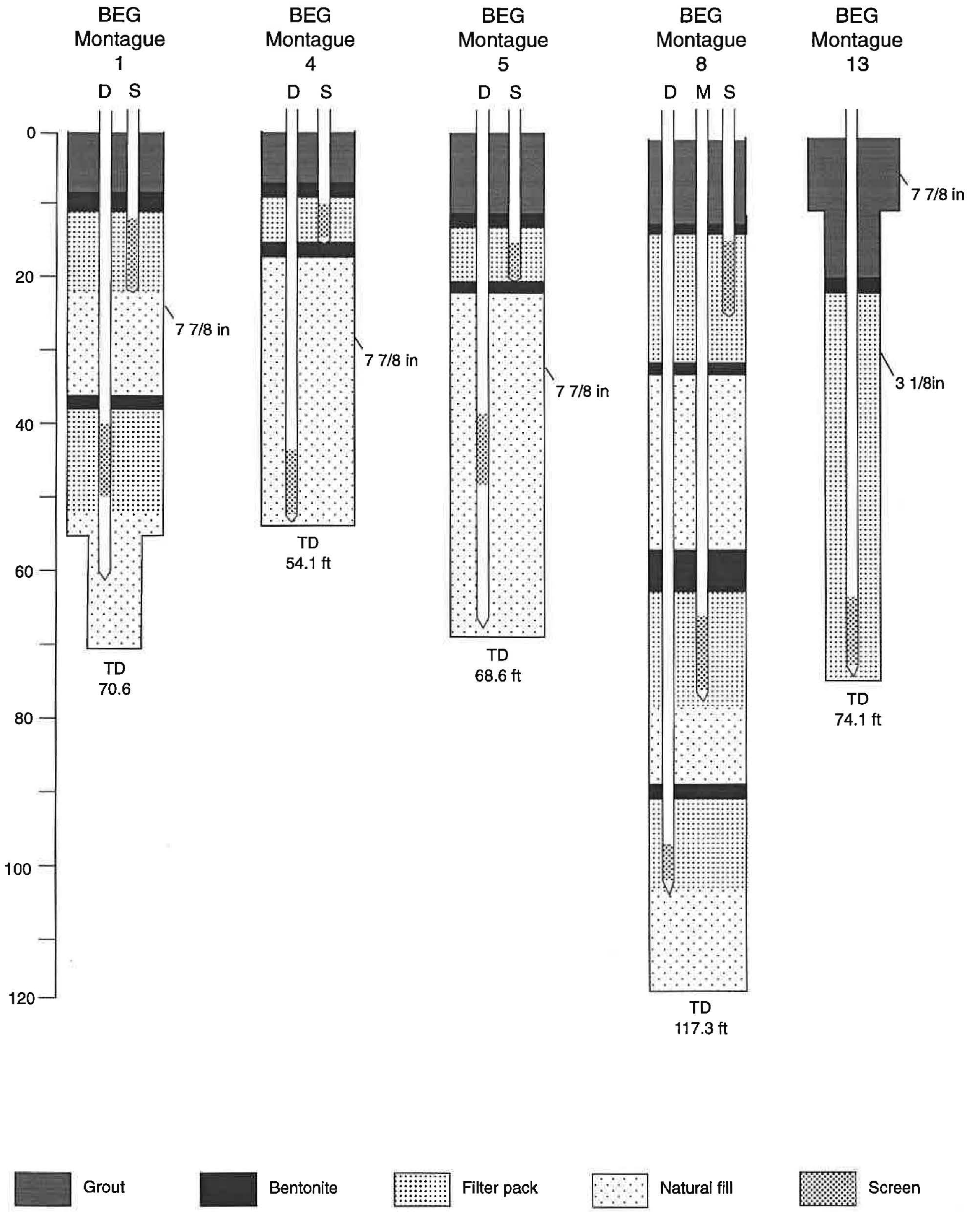
ADDRESS P.O. Box X University Station (Street or RFD) Austin (City) Texas (State) 78701 (Zip)

(Signed) James Doss (Licensed Well Driller) **(Signed)** Jordan Forman (Registered Driller Trainee)

Please attach electric log, chemical analysis, and other pertinent information, if available.

TNRCC-0199 (Rev. 11-01-94) TRNCC COPY

Appendix 5. Well construction.


BEG Montague 1
D S
BEG Montague 4
D S
BEG Montague 5
D S
BEG Montague 8
D M S
BEG Montague 13
0
20
40
60
80
100
120
7 7/8 in
7 7/8 in
7 7/8 in
7 7/8 in
3 1/8in
TD 70.6
TD 54.1 ft
TD 68.6 ft
TD 117.3 ft
TD 74.1 ft
Grout
Bentonite
Filter pack
Natural fill
Screen

QAc4118c

Appendix 6. Borehole induction logs.

APPENDIX 6: BOREHOLE INDUCTION LOGS

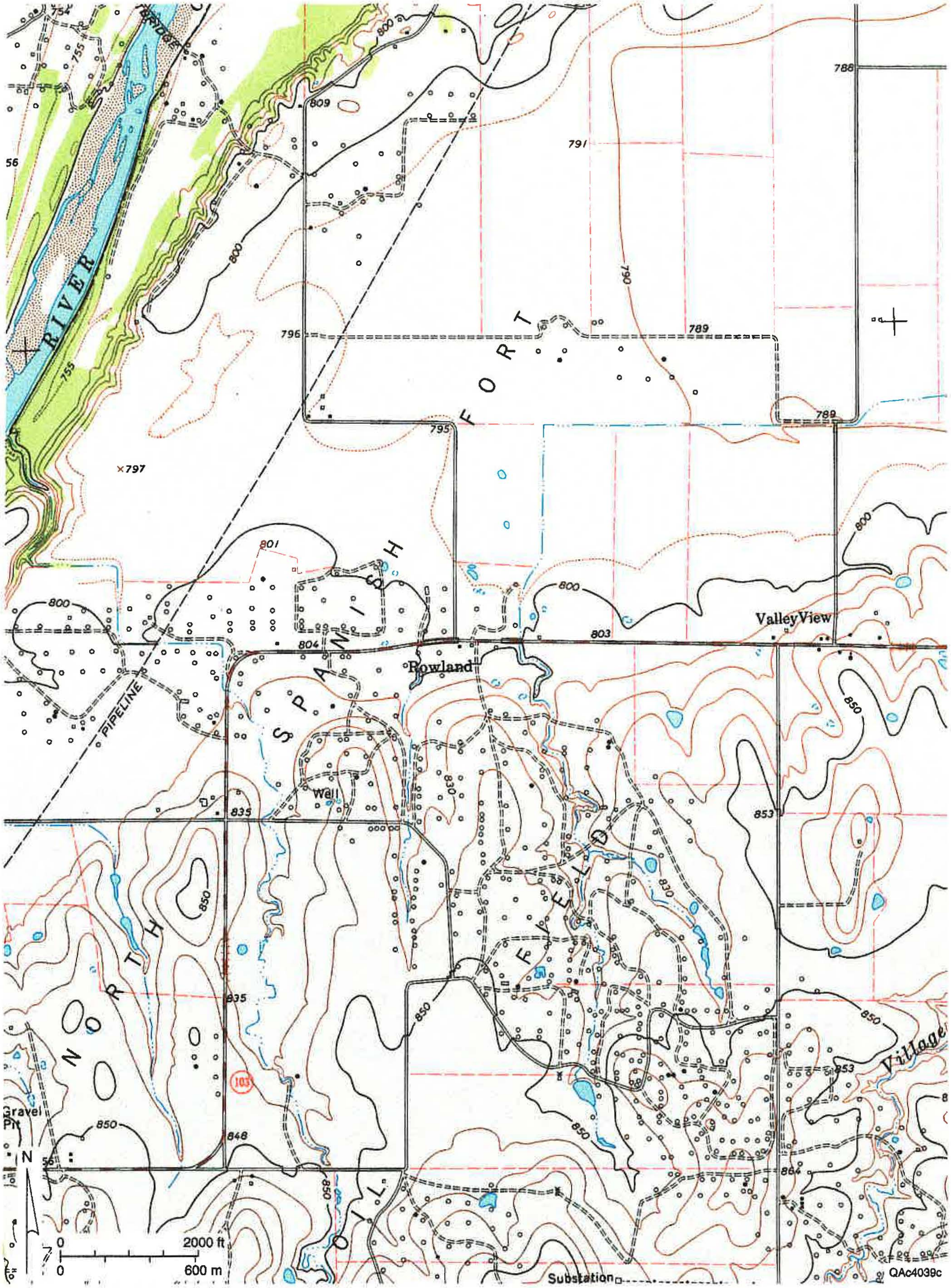
Montague site boreholes logged with Geonics EM39 induction probe. Borehole locations shown on fig. 4.

Borehole	Well completion date	Logging date	Depth logged (m)	Logging notes
BEG1	10/16/97	10/16/97	17.7	Logged shortly after drilling
		11/9/97	18.0	Higher conductivities in sandy zones
		12/3/97	17.7	Conductivity decreasing in upper 3 m
BEG2	10/19/97	10/19/97	21.5	Conductivities below 100 mS/m
BEG4	11/9/97	11/9/97	16.0	Conductivities below 750 mS/m
		12/3/97	15.8	Conductivities below 750 mS/m
BEG5	11/7/97	11/8/97	20.5	Conductivities below 250 mS/m
BEG6	11/12/97	11/12/97	8.0	Hit top of salt-water plume; increasing above 400 mS/m
BEG8	11/5/97	11/9/97	32.0	Conductivities below 1000 mS/m; base at 15 m
		12/3/97	31.7	Clipped at 1000 mS/m; conductive zones at 25 and 30 m
BEG13	11/11/97	11/11/97	22.5	Conductivities below 750 mS/m
		12/4/97	22.1	Conductivities below 750 mS/m
FH9		10/15/97	13.0	Conductivities below 150 mS/m
FH11		10/15/97	16.5	Conductivities above 1000 mS/m; clipped
		11/13/97	16.5	Conductivities above 1000 mS/m; clipped
FH15		11/13/97	7.0	Conductivities below 150 mS/m
FH18		11/13/97	11.0	Conductivities below 300 mS/m
FH22		10/15/97	17.0	Conductivities below 150 mS/m
FH23		11/11/97	17.5	Conductivities below 1000 mS/m; bottom not reached
FH24		10/15/97	11.0	Conductivities below 250 mS/m
FH26		10/15/97	13.0	Conductivities above 1000 mS/m; clipped
		11/11/97	13.0	Conductivities above 1000 mS/m; clipped
FH27		10/15/97	11.0	Conductivities 700 mS/m and climbing
		11/11/97	11.0	Conductivities 700 mS/m and climbing

Appendix 7. 1966 air photograph showing pit locations.

QAc4037c

Appendix 8. Scan of USGS 1:24,000-scale Prairie Valley School quadrangle.



754
755
BRIDGE
RIVER
56
809
800
791
788
790
796
789
795
FORT
SPANISH
NORTH
FIELD
OIL
×797
801
800
804
803
Valley View
Rowland
PIPELINE
Well
835
830
850
853
103
Gravel Pit
848
864
Village
Substation
N
0
2000 ft
600 m
QAc4039c

Appendix 9. Color-infrared photograph of the large barren area MBA showing extent of patchy crop north and east of the barren area. Patchy crop may be a result of salinization or other causes, such as high but not saline ground water.


?
MBA
?
N
0
2000 ft
0
600 m
Limit of patchy crop
QAc4036c

Appendix 10. TDEM soundings.

APPENDIX 10: TDEM SOUNDINGS

Summary of TDEM soundings collected at the Montague site in October 1997. All soundings acquired with a Geonics 47D instrument, 40 by 40 m transmitter loop, and a high frequency receiver coil at the center of the transmitter loop. Data processed using the software TEMIX from Interpex. Locations on fig. 4.

Sounding	Depth (m)	Resistivity (ohm-m)	Elevation (m)	Conductivity (mS/m)	Comment
A	0	1.81	242.3	552	
Fit 6.5 %	1.92	1.81	240.4	552	
	1.92	1.50	240.4	667	
	14.26	1.50	228.0	667	
	14.26	33.45	228.0	30	
	50	33.45	192.3	30	boundary not detected
B	0	2.03	242.3	493	
Fit 4.4 %	1.7	2.03	240.6	493	
	1.7	3.89	240.6	257	
	13.57	3.89	228.7	257	
	13.57	14.46	228.7	69	
	50	14.46	192.3	69	boundary not detected
C	0	17.01	246.8	59	
Fit 3.6%	6.28	17.01	240.5	59	
	6.28	29.97	240.5	33	
	46.9	29.97	199.9	33	
	46.9	12.98	199.9	77	
	88.18	12.98	158.6	77	
	88.18	3.66	158.6	273	
	95	3.66	151.8	273	boundary not detected
D	0	9.87	240.2	101	
Fit 2.5 %	18.93	9.87	221.3	101	
	18.93	6.81	221.3	147	
	45.57	6.81	194.6	147	
	45.57	22.70	194.6	44	
	50	22.70	190.2	44	boundary not detected
E	0	6.97	243.2	143	
Fit 3.0 %	5.53	6.97	237.7	143	
	5.53	1.31	237.7	763	
	23.37	1.31	219.8	763	
	23.37	37.89	219.8	26	
	50	37.89	193.2	26	boundary not detected
F	0	5.35	241.7	187	
Fit 2.2 %	20.89	5.35	220.8	187	
	20.89	14.02	220.8	71	
	50	14.02	191.7	71	boundary not detected

H	0	20.72	243.8	48	
Fit 2.5 %	7.09	20.72	236.7	48	
	7.09	6.61	236.7	151	
	16.53	6.61	227.3	151	
	16.53	41.06	227.3	24	
	80.62	41.06	163.2	24	
	80.62	6.41	163.2	156	
	95	6.41	148.8	156	boundary not detected
I	0	23.77	241.7	42	
Fit 4.2 %	3.6	23.77	238.1	42	
	3.6	3.62	238.1	276	
	6.52	3.62	235.2	276	
	6.52	19.04	235.2	53	
	38.12	19.04	203.6	53	
	38.12	3.71	203.6	270	
	50	3.71	191.7	270	boundary not detected
J	0	15.35	242.3	65	
Fit 3.0 %	3.23	15.35	239.1	65	
	3.23	3.32	239.1	301	
	13.29	3.32	229.0	301	
	13.29	15.40	229.0	65	
	50	15.40	192.3	65	boundary not detected
K	0	2.26	240.8	442	
Fit 3.4 %	5	2.26	235.8	442	
	5	0.88	235.8	1,138	
	9.24	0.88	231.6	1,138	
	9.24	14.55	231.6	69	
	50	14.55	190.8	69	boundary not detected
L	0	11.15	245.4	90	
Fit 2.3 %	3.94	11.15	241.5	90	
	3.94	134.50	241.5	7	
	6.87	134.50	238.5	7	
	6.87	1.28	238.5	781	
	18.85	1.28	226.6	781	
	18.85	14.97	226.6	67	
	50	14.97	195.4	67	boundary not detected
M	0	8.10	240.2	123	
Fit 2.7 %	4.7	8.10	235.5	123	
	4.7	1.53	235.5	654	
	6.9	1.53	233.3	654	
	6.9	18.29	233.3	55	
	50	18.29	190.2	55	boundary not detected

N	0	8.52	242.9	117	
Fit 2.3 %	6.12	8.52	236.8	117	
	6.12	2.49	236.8	402	
	14.15	2.49	228.8	402	
	14.15	65.46	228.8	15	
	58.53	65.46	184.4	15	
	58.53	7.50	184.4	133	
	75	7.50	167.9	133	boundary not detected
O	0	8.42	260.0	119	
Fit 2.9 %	8.97	8.42	251.0	119	
	8.97	3.82	251.0	262	
	36.15	3.82	223.9	262	
	36.15	13.47	223.9	74	
	50	13.47	210.0	74	boundary not detected
P	0	37.80	257.6	26	
Fit 3.2 %	19.91	37.80	237.7	26	
	19.91	6.84	237.7	146	
	33.15	6.84	224.5	146	
	33.15	2.18	224.5	459	
	62.41	2.18	195.2	459	
	62.41	81.69	195.2	12	
	75	81.69	182.6	12	boundary not detected
Q	0	9.29	248.4	108	
Fit 3.0 %	8.97	9.29	239.4	108	
	8.97	1.34	239.4	746	
	32.89	1.34	215.5	746	
	32.89	59.69	215.5	17	
	50	59.69	198.4	17	boundary not detected
R	0	8.43	257.6	119	
Fit 2.5 %	3.71	8.43	253.9	119	
	3.71	3.03	253.9	330	
	11.45	3.03	246.2	330	
	11.45	2.00	246.2	500	
	37.37	2.00	220.2	500	
	37.37	162.90	220.2	6	
	50	162.90	207.6	6	boundary not detected
S	0	4.16	260.6	240	
Fit 2.1 %	10.08	4.16	250.5	240	
	10.08	14.69	250.5	68	
	22.56	14.69	238.0	68	
	22.56	2.14	238.0	467	
	50	2.14	210.6	467	boundary not detected
T	0	29.72	251.5	34	

Fit 2.1 %	32.25	29.72	219.3	34	
	32.25	8.95	219.3	112	
	46.19	8.95	205.3	112	
	46.19	4.15	205.3	241	
	50	4.15	201.5	241	boundary not detected
U	0	132.20	249.9	8	
Fit 3.6 %	6.18	132.20	243.7	8	
	6.18	2.41	243.7	415	
	16.16	2.41	233.7	415	
	16.16	32.48	233.7	31	
	50	32.48	199.9	31	boundary not detected
V	0	152.90	256.9	7	
Fit 3.7 %	1.02	152.90	255.9	7	
	1.02	15.17	255.9	66	
	10.38	15.17	246.5	66	
	10.38	100.50	246.5	10	
	14.1	100.50	242.8	10	
	14.1	0.67	242.8	1,484	
	25.42	0.67	231.5	1,484	
	25.42	216.10	231.5	5	
	50	216.10	206.9	5	boundary not detected
W	0	46.73	253.9	21	
Fit 3.9 %	6.77	46.73	247.1	21	
	6.77	8.55	247.1	117	
	25.22	8.55	228.7	117	
	25.22	26.78	228.7	37	
	52.12	26.78	201.8	37	
	52.12	7.91	201.8	126	
	75	7.91	178.9	126	boundary not detected