Final Technical Report

Investigation of the Snyder Field Site, Howard County, Texas

Volume I—Technical Report

by

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INTRODUCTION

The Snyder field study area (the site) consists of salt-impacted soils and springs located southeast of the town of Coahoma, Howard County, Texas (fig. 1). The impacted area is located within the Snyder Oil Field on Susie B. Snyder and O.D. and M. H. O'Daniel leases. At least four separate ground-water seeps are discharging saltwater to the ground surface, resulting in two separate barren areas. The discharge area has been ditched to contain the flow, which is routed to a former stock tank. This tank drains to an unnamed tributary, which joins Beals Creek approximately 2 mi downstream. Although surface flow in the tributary is ephemeral, there is concern that the site may be impacting Beals Creek and, subsequently, surface-water impoundments downstream.

The oil field has been developed in the study area primarily since 1953. A "no-pit" order for Snyder field was issued in July 1959 (memorandum dated March 10, 1992; appendix I, from Charles Ross to Felix Dailey) by the Railroad Commission of Texas (RRC). Currently, produced water is reinjected at a series of injection wells throughout the oil field to maintain oil production. The RRC has used state funds to investigate the source of the saltwater at the site. A number of producing oil wells and injection wells were tested for casing integrity by the RRC in 1997. A number of wells in the area were plugged by operators before and during 1995.

The Bureau of Economic Geology (BEG) investigated this site on behalf of the RRC to (1) delineate the general extent of subsurface saltwater at the site and identify the stratigraphic units conducting saltwater beneath the unnamed tributary, (2) characterize the general salinity and hydrochemistry of ground water at the site, and (3) attempt to constrain or identify possible sources of saltwater. This report is a summary of the results of these preliminary studies. The reader is referred to the attached appendices for more detailed data analyses.

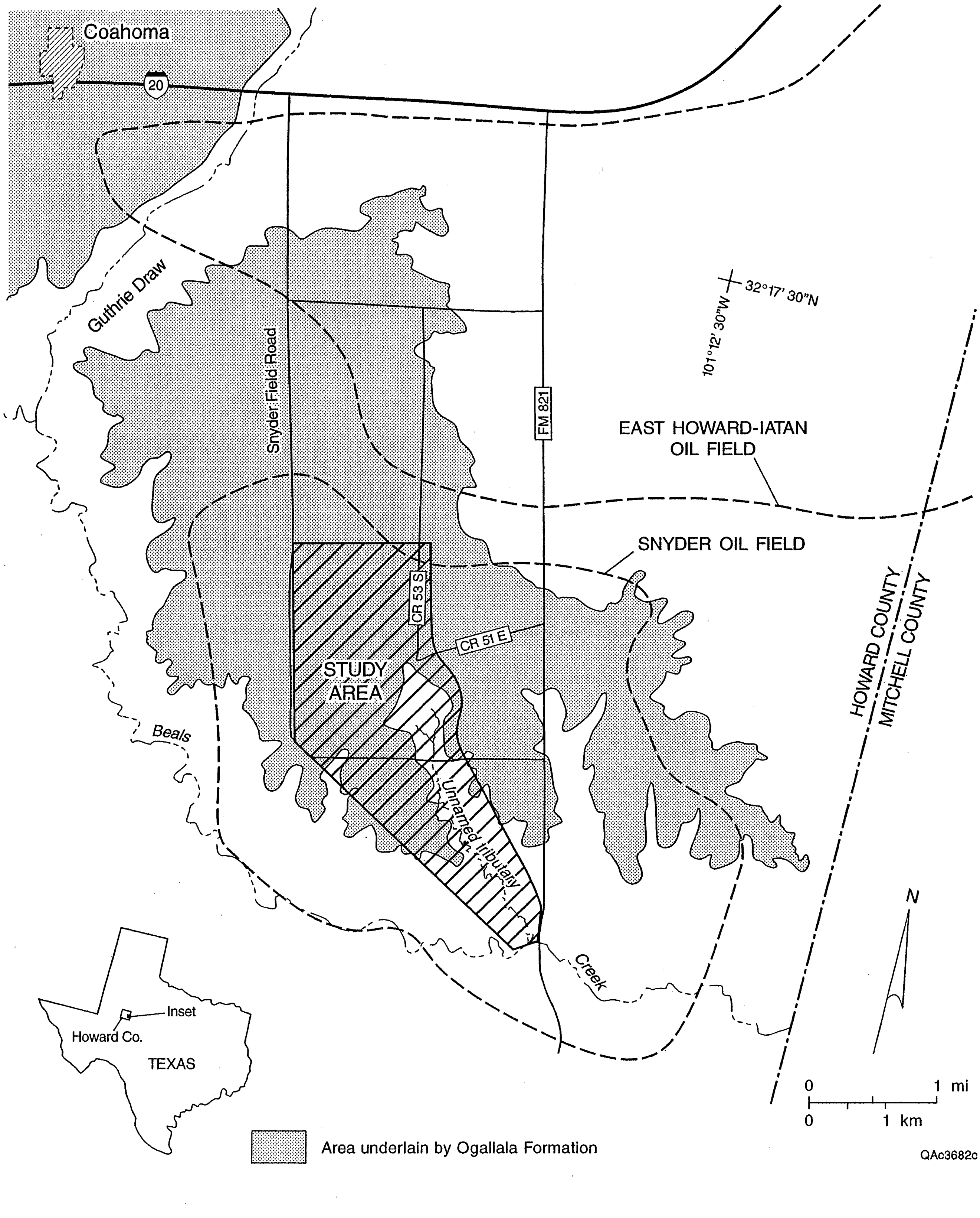

Figure 1. Snyder field study area, Howard County, Texas. Also showing subcrop of Ogallala Formation (Eifler and others, 1994) and outline of Snyder Oil Field.

SITE DESCRIPTION

The Snyder field site, consisting of a seepage area, a larger main, barren area, and a second smaller barren area, is located approximately 5.5 mi southeast of the town of Coahoma and 1 mi west of FM 821 (fig. 1). It is shown on the Hyman U.S. Geological Survey 7.5-minute quadrangle about 0.25 mi north of the east-west segment of Snyder Field Road and west of the unnamed tributary. The main part of the site is composed of approximately four seeps/springs, which have an approximate flow of 3 to 5 gpm each (Tim Prude, RRC Region 8 Office, personal communication, July 1998) and an associated barren area (fig. 2). A number of pits and ditches have been dug to control the flow and route it through culverts under a site road. The flow is then routed to a stock pond (referred to herein as the West Tank) on the west side of the unnamed tributary. The pond dam was breached by the property owner in 1997 to allow drainage. Drainage from the pond enters the unnamed tributary, but surface flow is normally not visible downstream beyond approximately 0.25 mi, unless rainfall has produced local runoff. A second stock pond (North Tank) exists to the northeast of the West Tank; it also has been reported to have increased salinity.

A second, separate barren area (fig. 2) was noted approximately 0.25 mi west of the main seep area, along a drainage that crosses Snyder Field Road. Although no surface seepage was noted at the time of the study, this barren area was investigated along with the main seep area because of the possibility that they could be related.

METHODOLOGY

The BEG reviewed project files located at the RRC office in Austin and the RRC district office in Midland, including sample-analysis results and information about the operational history of the site, such as well reports, plugging and abandonment reports, field-inspection documentation, Underground Injection (UIC) and H15 fluid-level data bases, and limited

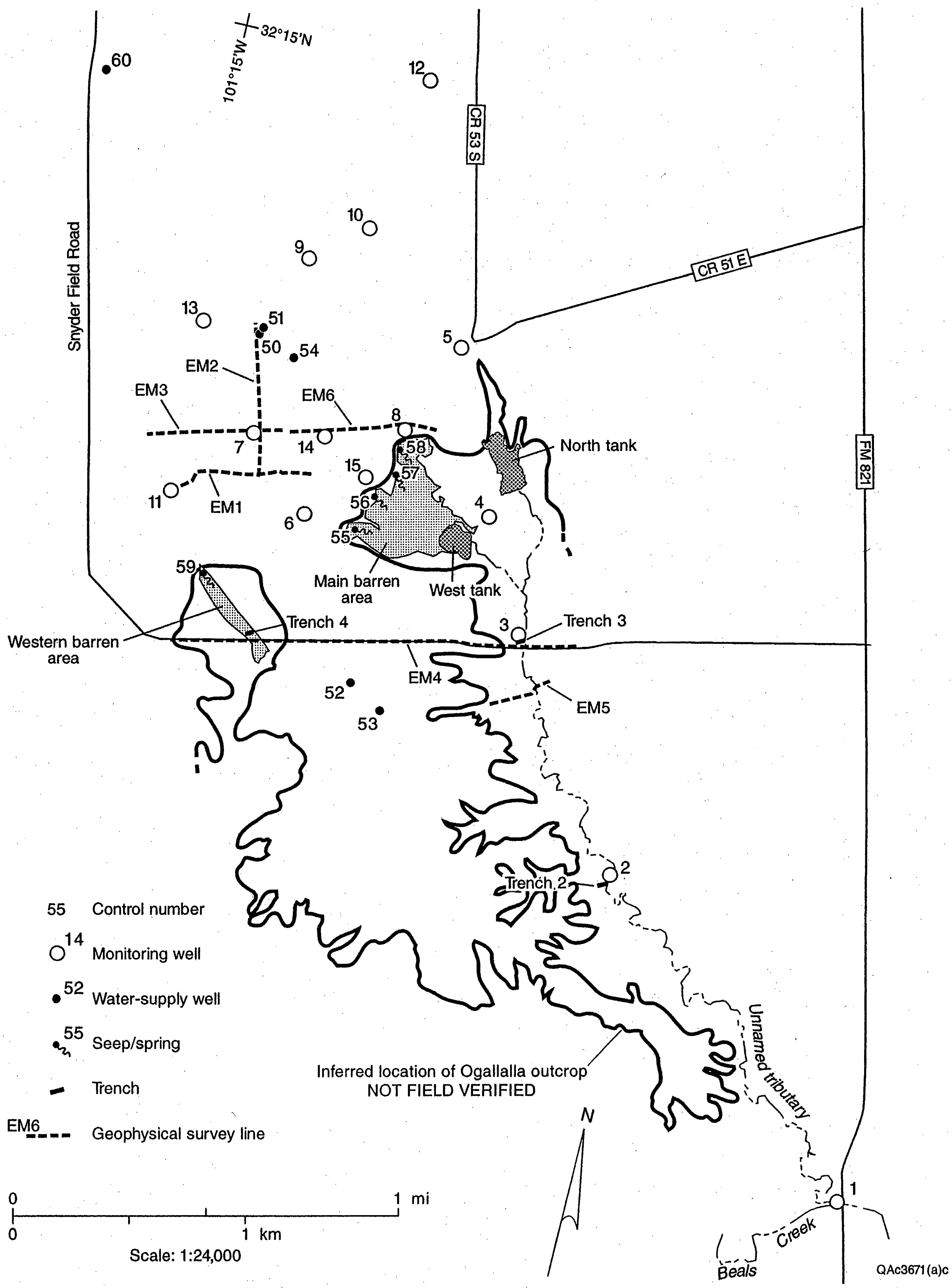

Figure 2. Sampling and measurement points.

correspondence. BEG staff visited the site on July 15, 1998, and conducted field work through October 1998.

Site field activities included:

- an electromagnetic induction (EM) geophysical survey using a Geonics EM 34-3 meter, including spot checks and linear surveys.
- a global positioning survey (GPS) to map site features, monitoring wells, and geophysical lines accurately,
- drilling 15 borings,
- installing and sampling 13 monitoring wells,
- measuring water levels in these monitoring wells and several water supply wells
- down-hole EM logging of two monitoring wells using a Geonics EM 39 meter,
- trenching and sampling of two locations within the unnamed tributary valley and one location in the western barren area,
- sampling of four (of five identified) seeps, and
- sampling of five water-supply wells.

The purpose of the geophysical survey was to look for evidence of saltwater contamination in subsurface soil and ground water. Electromagnetic induction methods measure apparent ground conductivity as an indicator of pore-water conductivity and are an indirect measure of pore-water salinity. Areas of increased salinity are delineated by mapping areas of elevated ground conductivity.

We measured 7 linear geophysical transects (fig. 2) and spot-checked 20 additional locations in two separate mobilizations using the Geonics EM 34-3 meter (Appendix II). An initial mobilization was used to help target well locations, predict depth to the water table and predict depth of the base of the Ogallala Formation; the second mobilization was to help define areas of salt contamination in the subsurface between and beyond well-control points. Several transects were run northwest and north of the main barren area, with particular emphasis on areas where extreme gradients in conductivity were noted in the water quality. The Geonics EM 34-3 ground-conductivity meter supports 10-, 20-, and 40-m (33-, 66-, and 131-ft) transmitter and receiver-coil separations and two principal coil orientations (horizontal and vertical dipoles). The conductivity value represents the "bulk" conductivity, or an average conductivity of the soil volume beneath the transmitter and receiver coils. All three coil separations were used, resulting in an effective penetration depth of 6 to 25 m (20 to 82 ft) for the horizontal-dipole orientation and 12 to 50 m (39 to 164 ft) for the vertical-dipole orientation. A detailed discussion of the EM results is included in appendix II. Information from this appendix is referred to in the following discussions.

The GPS survey was used in conjunction with aerial photographs to generate a base map of the site with accurate locations of significant features such as wells, roads, and seeps. The GPS points were also used to rectify several air photographs from 1939, 1957, 1963, 1970, 1979, 1991, and 1996. This time period spans the development of most of the Snyder Oil Field, including before and after the no-pit order and the onset of waterflooding. The air photos were compared for the presence of natural features such as springs and other features such as tanks, oil wells, injection wells, mud and saltwater disposal pits, and development of barren areas. All positional data were organized, evaluated for accuracy, and transferred to ArcView Geographic Information System (GIS) software. A GIS data base of the site was then developed.

Borings were drilled following ASTM Standard method D 5784 for drilling, using 7.5-inch O.D. hollow-stem augers (ASTM, 1997). Boring locations are shown in figure 2. Continuous core was extracted from 7 out of 15 total boreholes and archived following BEG Specific Work Instructions 2.1 and 3.4. Highly cemented intervals within the Ogallala were drilled without core recovery. No water was encountered in boreholes 3 and 4 after 24 h. These borings were tremie grouted. Cuttings were spread on the ground surrounding the well; 1:1 field conductivity tests indicated that no cuttings were above background values.

Monitoring wells were installed in the remaining boreholes following ASTM standard D 5092-90 for monitoring-well installation (ASTM, 1997). All wells were constructed of 2-inch I.D. PVC screen and riser. Monitoring wells were developed to clarity and constant conductivity and temperature. Details of monitoring-well construction and depths and water depths and elevations are presented in appendix III. Well logs and construction data are also included in appendix III. Synoptic ground-water elevations were measured on August 28, 29 and September 9, 10, 1998.

Two trenches were excavated in the unnamed tributary bed, and one trench was excavated in the western barren area to characterize subsurface sediments and to detect ground water. Trenches were excavated by a backhoe tractor equipped with a 16-inch bucket. The trenches were approximately 3 ft wide × 8 ft deep and as much as 50 ft long. Water was found at one discrete interval in each of the trenches. Grab samples of trench water and soil were taken at each location. Results of trench sampling and cross sections of the trenches are shown later.

Ground water at the site was characterized for a range of inorganic parameters and for some volatile organic parameters. Both were used to help evaluate possible source areas for brine contamination in the Ogallala aquifer and to determine the quality of water moving in the alluvium of the unnamed tributary. Because the study did not include sampling of surface flow outside of the seep area, it does not indicate surface-water quality in either the unnamed tributary or Beals Creek. Ground-water and seep/surface water sampling was conducted August 27 through 29, 1998. Organic compounds analyzed included benzene, toluene, ethylbenzene, and xylenes (BTEX). These samples were taken from the monitoring wells, one abandoned water supply well (number 50), and four seeps. General inorganic cations analyzed included sodium, calcium, magnesium, lithium, iron (total), potassium, and strontium. Anions included bicarbonate, carbonate, bromide, chloride, fluoride, nitrate, and sulfate. Additional metals analyzed that may be related to oil-field activities included barium, chromium, vanadium, and nickel. All well and seep samples were analyzed for the inorganic constituents. A detailed listing of all results is included in appendix IV.

Well sampling was conducted following ASTM D 4448-85a guidelines (ASTM, 1997). Each inorganic sample was filtered by a GeoTech preanalyzed 0.45-micron high-flow filter. BTEX samples were not filtered. Seeps were sampled at the point of origin by filling a plastic filtration container and then filtering each inorganic sample from this container. BTEX samples were filled directly from the seep flow. All samples were submitted to the RRC Surface Mining and Reclamation Laboratory for inorganic analysis. Selected split samples and all BTEX samples were submitted to DHL Analytical for analysis. Summary results and analytical reports are given in appendix IV.

SITE HISTORY

The Snyder Oil Field, discovered in 1926, encompasses several square miles (fig. 1). The study area is located in the northwest part of the field. The producing zones are the Permian San Angelo Formation and the Clear Fork Group at depths of 2,600 to 2,900 ft below ground (appendix III). The initial reservoir energy was solution-gas drive. Field-spacing rules are one well per 10 acres. The first producing well in the Snyder Oil Field was completed in 1927, and some documented wells were drilled near the study area in 1938. Systematic development of the reservoir in the study area began around 1953. As of January 1, 1991, cumulative crude-oil production from Snyder field was 39,225,853 bbl (RRC 1990 Annual Report). Between 1993 and 1997, crude-oil production in Snyder field ranged from 388,202 to 456,218 bbl/yr (RRC ACTI Production Reports).

Within the study area, our review of oil-field activities focused on the south half of Section 20 and the north half of Section 29, Block 30, T & P RR Survey T-1-S (fig. 3). Six leases are within this study area: Susie B. Snyder (lease numbers 06208 and 29697), O. D. O'Daniel, M. H. O'Daniel No. 12, M. H. O'Daniel Estate, and O'Daniel B. Data available through September 1995 for the O'Daniel B lease and both Susie B. Snyder leases show cumulative total crude-oil production of 3,033,875 bbl and produced-water volumes of 5,482,409 bbl for these three leases combined (RRC ACTI Production Reports, 1995).

A no-pit order for the Snyder Oil Field was issued in 1959, several years before the statewide order. Complaints regarding saltwater impact on shallow water were documented in the area at this time. File information generally refers to the historic use of surface saltwater disposal pits, and

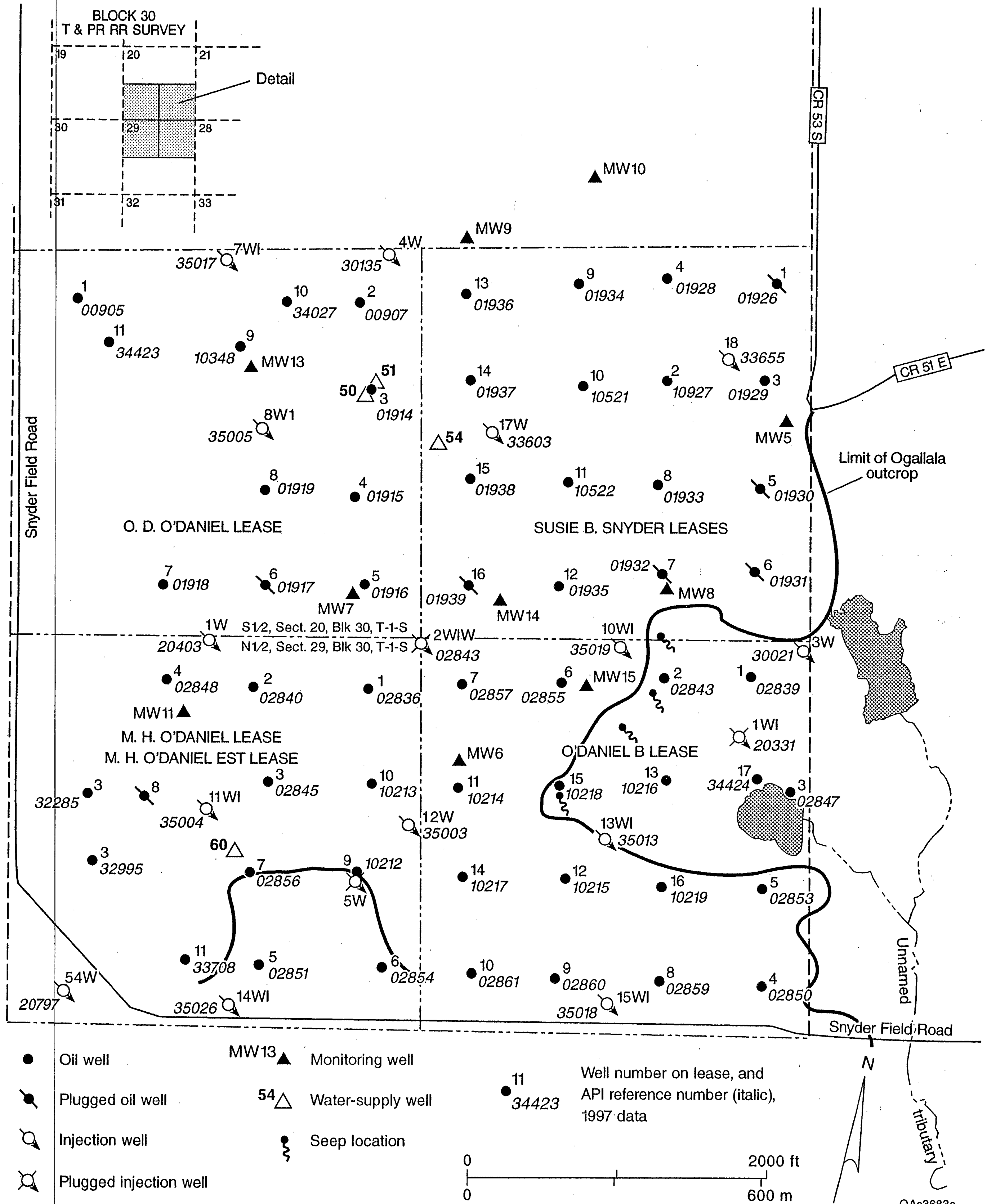

Figure 3. Oil and injection wells in study area. Oil-field data from RRC (1997 and earlier).

some pits can be seen on historical aerial photos. Some operators were using injection wells for disposal of produced water as early as 1959. A 1967 map shows at least 10 injection wells in the study area (Samedan Oil, 8/3/67). At least seven of these wells were oil wells drilled in the 1950's and converted to injection.

In 1998, secondary recovery from waterflooding was ongoing in the Snyder Oil Field. Data from the RRC's underground injection control (UIC) department indicate the first injection well in the Snyder Oil Field was authorized in 1959. For the leases in the study area, injection wells were first authorized in 1967.

Table 1 lists wells located in the south half of Section 20 and the north half of Section 29, Block 30, T & P RR Survey T-1-S. RRC project files contain more information for the O'Daniel B lease and the Susie B. Snyder leases than for the O. D. O'Daniel or M. H. O'Daniel leases. Some additional record searching is recommended for the latter leases.

SITE HYDROGEOLOGY

Hydrologic Units

The site is underlain by the Quaternary Blackwater Draw Formation, the Tertiary Ogallala Formation, and the Triassic Dockum Group (fig. 1). The main water-bearing zone is in the Ogallala, which is composed of fine-grained quartz sands and gravels, a buried caliche caprock, and a distinctive, basal, coarse-grained quartz gravel. The Ogallala is as much as 12 m (40 ft) thick in this area and unconformably overlies the Dockum Group, which is composed of as much as 366 m (1,200 ft) of red to reddish-brown clay, silt, fine-grained sand, and coarse-grained sand stringers. The contact between the Ogallala and Dockum is exposed in areas of topographic relief. Above the Ogallala, the Quaternary Blackwater Draw Formation is composed of fine-grained eolian and alluvial sand. This unit is rarely more than 6 m (20 ft) thick, although it covers as much as 80 percent of the Ogallala present in the area. Most of the surface materials appear to be permeable

Table 1. Oil-well identification, status, and casing depths, sections 20 and 29, Snyder Oil Field.

Lease name	Well no.	Section	Status	Completion date	TD	Surface casing depth (ft)	Production casing depth(ft)	API Number	Notes:
Snyder, Susie B. (06208)	1	20	P&A (1/22/88)	1954	2600	132	2500	42227019260000	Shown as injection well on 1967 map
Snyder, Susie B. (06208)	2	20		1954	2615	150	2525	42227019270000	Shown as injection well on 1967 map
Snyder, Susie B. (06208)	3	20		1955	2684	100	2530	42227019290000	Shown as injection well in 1967. H15 level at surface 5/26/94.
Snyder, Susie B. (06208)	4	20			2610	95	2550	42227019280000	Reentered and deepened to 2635' in 1991.
Snyder, Susie B. (06208)	5	20	P&A (1/10/95)	1955	2685	100	2548	42227019300000	H15 level at surface on 5/26/94.
Snyder, Susie B. (06208)	6	20	P&A (1/12/95)	1955	2686	100	2555	42227019310000	Shown as injection well in 1967. H15 level at surface 5/26/94.
Snyder, Susie B. (06208)	7	20	P&A (1/13/95)	1955	2619	120	2550	42227019320000	H15 level at surface on 5/26/94.
Snyder, Susie B. (06208)	8	20		1955	2616	103	2550	42227019330000	Reentered and deepened to 2665' in 1991.
Snyder, Susie B. (06208)	9	20		1955	2633	87	2550	42227019340000	Reentered and deepened to 2844' in 1991.
Snyder, Susie B. (06208)	10	20		1966	2885	128	2885	42227105210000	
Snyder, Susie B. (06208)	11	20		1966	2810	128	2810	42227105220000	
Snyder, Susie B. (06208)	12	20	Inactive	1956	2617	150	2568	42227019350000	H15 level at 1420' on 2/14/96
Snyder, Susie B. (06208)	13	20		1956	2618	150	2558	42227019360000	Shown as injection well in 1967. Deepened to 2873' in 1991.
Snyder, Susie B. (06208)	14	20		1956	2617	156	2560	42227019370000	Reentered and deepened to 3043' in 1991.
Snyder, Susie B. (06208)	15	20		1956	2644	150	2560	42227019380000	Reentered and deepened to 3020' in 1991.
Snyder, Susie B. (06208)	16	20	P&A (1/16/95)	1956	2620	150	2566	42227019390000	Shown as injection well in 1967. H15 level at surface 5/26/94.
Snyder, Susie B. (06208)	20	20						42227809770000	Not shown on RRC well map.
Snyder, Susie B. (29697)	17/17W	20	Injection	1984	3140		3138	42227336030000	Not listed in UIC database.
Snyder, Susie B. (29697)	18/18W	20	Injection	1985	3202		3202	42227336550000	Not listed in UIC database.
O'Daniel "B" (06218)	1	29		1955	2680	120	2560	42227028390000	
O'Daniel "B" (06218)	2	29		1955	2716	120	2560	42227028430000	
O'Daniel "B" (06218)	3	29		1955	2679	125	2553	42227028470000	
O'Daniel "B" (06218)	4	29		1955	2692	107	2602	42227028500000	
O'Daniel "B" (06218)	5	29		1956	2695	100	2548	42227028530000	
O'Daniel "B" (06218)	6	29		1956	2686	110	2550	42227028550000	May correspond to injection well 6W, UIC 19898
O'Daniel "B" (06218)	7	29		1956	2687	120	2576	42227028570000	
O'Daniel "B" (06218)	8	29		1956	2675	123	2560	42227028590000	
O'Daniel "B" (06218)	9	29		1957	2691	128	2600	42227028600000	
O'Daniel "B" (06218)	10	29		1957	2691	128	2592	42227028610000	
O'Daniel "B" (06218)	11	29		1963	2696	128	2690	42227102140000	
O'Daniel "B" (06218)	12	29		1963	2698	126	2695	42227102150000	
O'Daniel "B" (06218)	13	29		1963	2694	128	2694	42227102160000	UIC Well No. 70994 (permitted 8/13/73)
O'Daniel "B" (06218)	14	29		1964	2695	128	2694	42227102170000	
O'Daniel "B" (06218)	15	29		1964	2695	127	2695	42227102180000	
O'Daniel "B" (06218)	16	29		1964	2685	117	2684	42227102190000	UIC Well No. 49717 (permitted 10/27/83)
O'Daniel "B" (06218)	17	29		1989	2945	N/D	2710	42227344240000	
O'Daniel "B" (06218)	10W1	29				120	2800	42227350190000	UIC Well No. 84205 (permitted 1/30/96)
O'Daniel "B" (06218)	13W1	29				120	2800	42227350130000	UIC Well No. 84206 (permitted 1/30/96)
O'Daniel "B" (06218)	15W1	29				120	2800	42227350130000	UIC Well No. 84207 (permitted 1/30/96)
O'Daniel "B" (06218)	1A	29	Injection	1960	1500			42227040070000	Injection well
O'Daniel "B" (06218)	2WIW	29	P&A (11/13/91)					42227028430000	
O'Daniel "B" (06218)	3W	29		1969	3015		3014	42227300210000	UIC Well No. 19897 (permitted 7/14/89)
O'Daniel "B" (06218)	6W	29						42227028550000	
O'Daniel "B" (06218)	6W	29						42227102160000	UIC Well No. 19898; Same API No. is well 13/UIC 70994
O'Daniel "B" (06218)	8W1	29				120	2800	No API No.	UIC Well No. 84202 (permitted 1/30/96). Not on well map.
O'Daniel "B" (06218)	9W1	29				120	2800	No API No.	UIC Well No. 84204 (permitted 1/30/96). Not on well map.
O'Daniel "B" (06218)	WI2	29	Injection	1967	2830			42227108650000	

Table 1. Oil-well identification, status, and casing depths, sections 20 and 29, Snyder Oil Field.

Lease name	Well no.	Section	Status	Completion date	TD	Surface casing depth (ft)	Production casing depth(ft)	API Number	Notes:
O.D. O'Daniel (06192)	1							42227009050000	
O.D. O'Daniel (06192)	2							42227009070000	
O.D. O'Daniel (06192)	3							42227019140000	
O.D. O'Daniel (06192)	4							42227019150000	Shown as injection well on 1967 map
O.D. O'Daniel (06192)	5							42227019160000	
O.D. O'Daniel (06192)	6	20	P&A (6/20/85?)					42227019170000	H15 level at 0' in 1997
O.D. O'Daniel (06192)	7							42227019180000	
O.D. O'Daniel (06192)	8							42227019190000	
O.D. O'Daniel (06192)	9							42227103480000	
O.D. O'Daniel (06192)	10							42227340270000	
O.D. O'Daniel (06192)	11							42227344230000	
O.D O'Daniel (06192)	4W						2998	42227301350000	Note: UIC Well No. 19895 (permitted 2/13/70)
O.D. O'Daniel (06192)	7W1						2800	42227350170000	Note: UIC Well No. 84201 (permitted 1/30/96)
O.D. O'Daniel (06192)	8W1						2800	42227350050000	Note: UIC Well No. 87017 (permitted 1/30/96)
O.D. O'Daniel (06192)	16W						2800	No API No.	Note: UIC Well No. 84203 (permitted 1/30/96)
M.H. O'Daniel (08963)	1	29		1957	2665			42227028360000	
M.H. O'Daniel Est.	1	29		1981	8990			42227322850000	
M.H. O'Daniel (08963)	2	29		1956	2675			42227028400000	
M.H. O'Daniel (08963)	3	29		1956	2660			42227028450000	
M.H. O'Daniel Est.	3	29		1983	8963			42227329950000	
M.H. O'Daniel (08963)	4	29		1956	2670			42227028480000	
M.H. O'Daniel (08963)	5	29		1958	2673			42227028510000	
M.H. O'Daniel (08963)	6	29		1958	2665			42227028540000	
M.H. O'Daniel (08963)	7	29		1958	2660			42227028560000	
M.H. O'Daniel (08963)	8	29	P&A (6/20/74)	1958	2710			42227028580000	
M.H. O'Daniel (08963)	9	29	P&A (11/26/91)	1963	2675			42227102120000	Shown as injection well in 1967. UIC Well No. 70993 (permitted 8/13/73)
M.H. O'Daniel (08963)	10	29		1964	2695			42227102130000	
M.H. O'Daniel (08963)	10			1965	2820			42227103430000	
M.H. O'Daniel (08963)	11	29		1985	3265			42227337080000	
M.H. O'Daniel (08963)	12WI	29			2800			42227350030000	Note: UIC Well No. 84209 (permitted 1/30/96)
M.H. O'Daniel (08963)	11WI				2800			42227350040000	Note: UIC Well No. 84208 (permitted 1/30/96)
M.H. O'Daniel (08963)	1W				2821			42227204030000	Note: UIC Well No. 19899 (permitted 8/14/67)
M.H. O'Daniel (08963)	1W1				2821			42227028360000	Note: UIC Well No. 86621 (permitted 8/20/97)
M.H. O'Daniel (08963)	5W		P&A (11/26/91)		2674			42227102120000	Note: UIC Well No. 19900 (permitted 8/14/67)
M.H. O'Daniel B (11318)	14W1				2800			42227350260000	Note: UIC Well No. 84210 (permitted 1/30/96)
M.H. O'Daniel B (11318)	54W				2775			42227007970000	Note: UIC Well No. 19874 (permitted 3/27/67)
M.H. O'Daniel B (11318)	55							42227007990000	

fine sands, and drainage in the area is rapid. The unnamed tributary is floored by stratified clay, sand, and gravel reworked from the just-named formations.

The site lies at the southeast edge of the Caprock Escarpment of the Southern High Plains (Mullican and others, 1997, and others cited therein). Topography of the area to the northwest, north, and west of the site area is gently sloping toward the east and south. Some poorly developed drainages run south and southeast along this elevated area. Eolian dunes have developed along old fence and section lines, which are now topographic high points.

Flow units differentiated at the site include the saturated and unsaturated parts of the Ogallala Formation and overlying deposits in the upland area, alluvium in the floor of the unnamed tributary, and the saturated and unsaturated parts of the Dockum Group that underlies the entire site. Recharge to the Ogallala occurs on the upland part of the plateau northwest of the springs. Rainfall collects in playas, man-made low areas such as road cuts, or in natural drainages and infiltrates into the subsurface (Wood and Osterkamp, 1987; Mullican and others, 1997). Because the plateau is eroded on all sides, recharge is limited to recharge on the plateau only. Guthrie Draw separates the study area from the main part of the Ogallala to the north (Knowles and others, 1984) (fig. 1). No horizontal inflow from the main body of the Ogallala reaches the site. The Dockum Formation acts as a confining layer to vertical downward flow, so that ground water stored in the Ogallala exists in a thin saturated zone, flowing horizontally within basal gravels and sands, discharging only to the springs, evapotranspiring at the outcrop, and discharging from water-supply wells. A very dry unsaturated zone exists above the saturated portion of the Ogallala. The Dockum appears to contain no available ground water at shallow depths, according to core observations and geophysical data. Flow of water in the Ogallala appears to be controlled both by gradient and by the topography of the surface of the Dockum Formation, rather than surface topography, judging from observations of ground-water gradients in monitoring wells.

The seeps and springs occur along the edge of the escarpment, at and above the contact between the Ogallala and the Dockum (figs. 1 and 2). The Dockum Group at ground surface at the site is predominantly low permeability clay. The contact becomes a seepage face, and most of the spring water flows above ground for some distance within the barren area before reaching the unnamed tributary. Surface flow from the seeps eventually infiltrates into the alluvium; no surface-water base flow (that is, no precipitation runoff) from the seeps reaches Beals Creek. Observation of historic air photos and interviews with local residents indicate that these springs/seeps exist naturally in the area and have not always been salt impacted. The only times that surface flow was observed in the unnamed tributary was during and as much as 1 day after rainfall events of about .5 inch or more.

The water table in the Ogallala Formation in the study area is inclined generally to the east-southeast at a gradient of approximately 0.005, becoming somewhat steeper near the outcrop limit of the Ogallala (fig. 4). The water-table gradient in the Ogallala steepens across the neck between the two seep areas where the Ogallala has been eroded laterally (fig. 1). The saturated zone of the Ogallala was generally 1.5 to 3 m (5 to 10 ft) thick during August and September 1998 (fig. 5). Although the elevation of the water table might fluctuate seasonally, it is assumed that the direction of the gradient remains fairly constant. Saturated thickness of the Ogallala Formation is influenced by the structure of the base of the formation as much as by the height of the water table or the position of the outcrop limits of the formation (fig. 6). Depressions in the base of the Ogallala Formation exist toward the northeast and southeast of the site and are superposed on a slightly eastward tilt.

Evidence from monitoring wells and trenches indicates that there is a thin, perched zone of ground water in alluvial sand and gravel lenses and channel deposits along the unnamed tributary. Two trenches dug in August 1998 (figs. 2 and 7) showed a sandy gravel that extended to a depth of 4 to 5 ft beneath ground surface. The trenches also showed that the saturated zone within the gravel was only about 2 ft thick. The ground water was perched on top of Dockum Group clay, which appeared unsaturated. The gravel lens appeared to thin to the edge of the tributary valley (fig. 7).

The perched zone was encountered in borehole 2, which at first appeared dry, as if there was negligible inflow of water from the alluvium to the well. At borehole 3, the core was unsaturated,

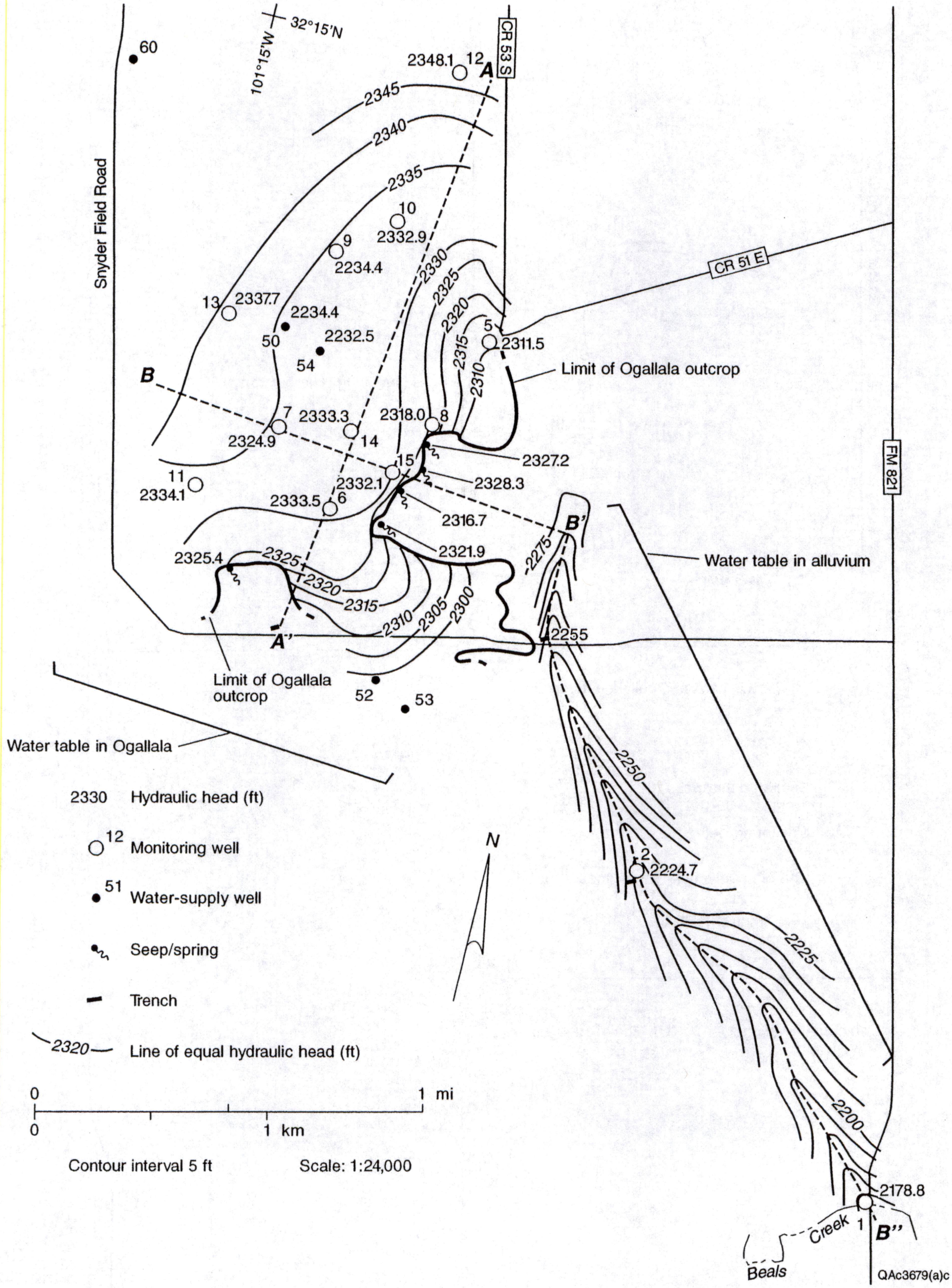

Figure 4. Separate water tables in Ogallala Formation and Quaternary alluvium (9/98 data). Hydrologic sections A–A′ and B–B′–B″ shown in figure 8.

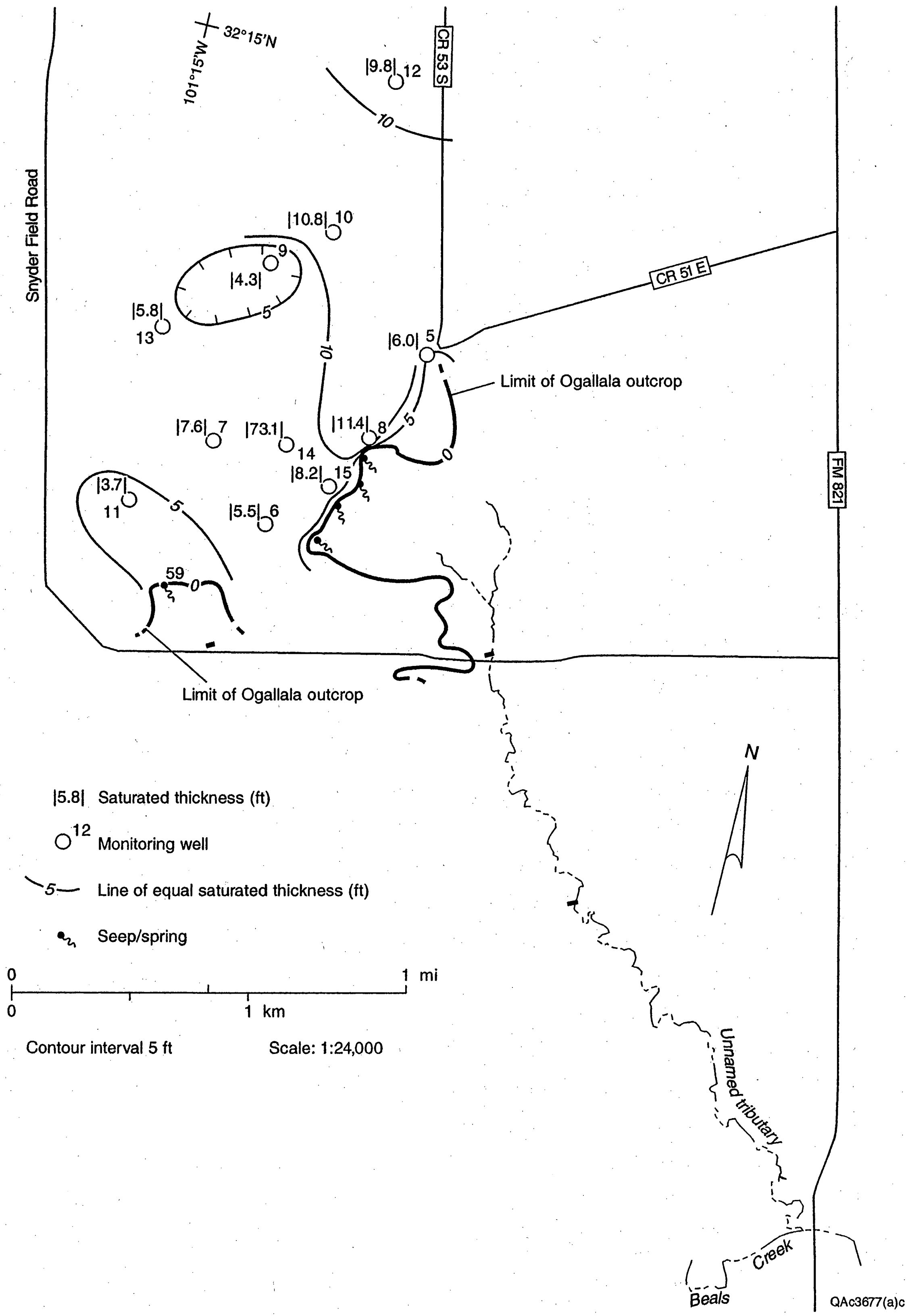

Figure 5. Saturated thickness of the Ogallala Formation (9/98 data). Magnitude of seasonal fluctuation undetermined.

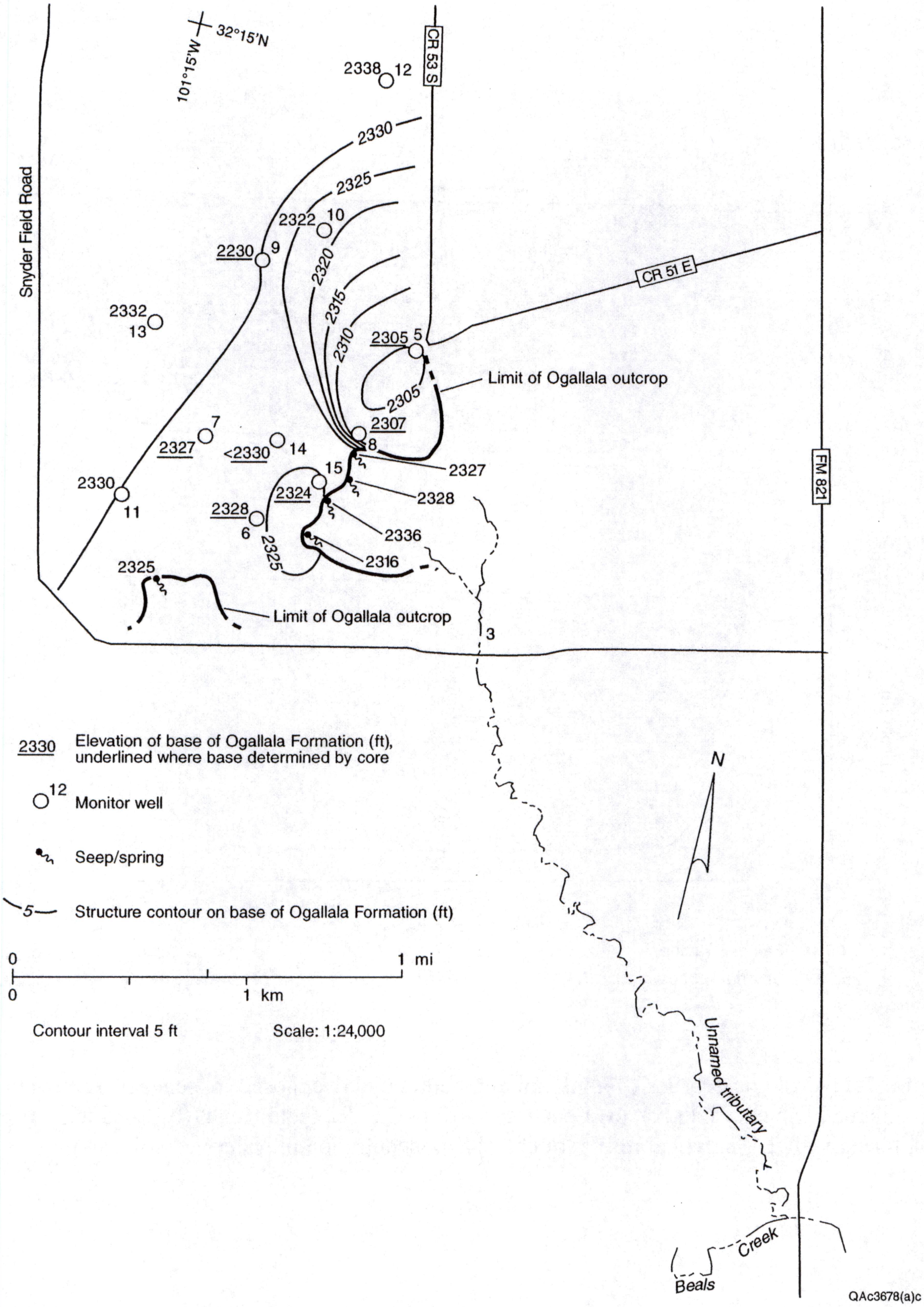

Figure 6. Elevation of the base of the Ogallala Formation inferred from core and cuttings. Underlined numbers signify core control.

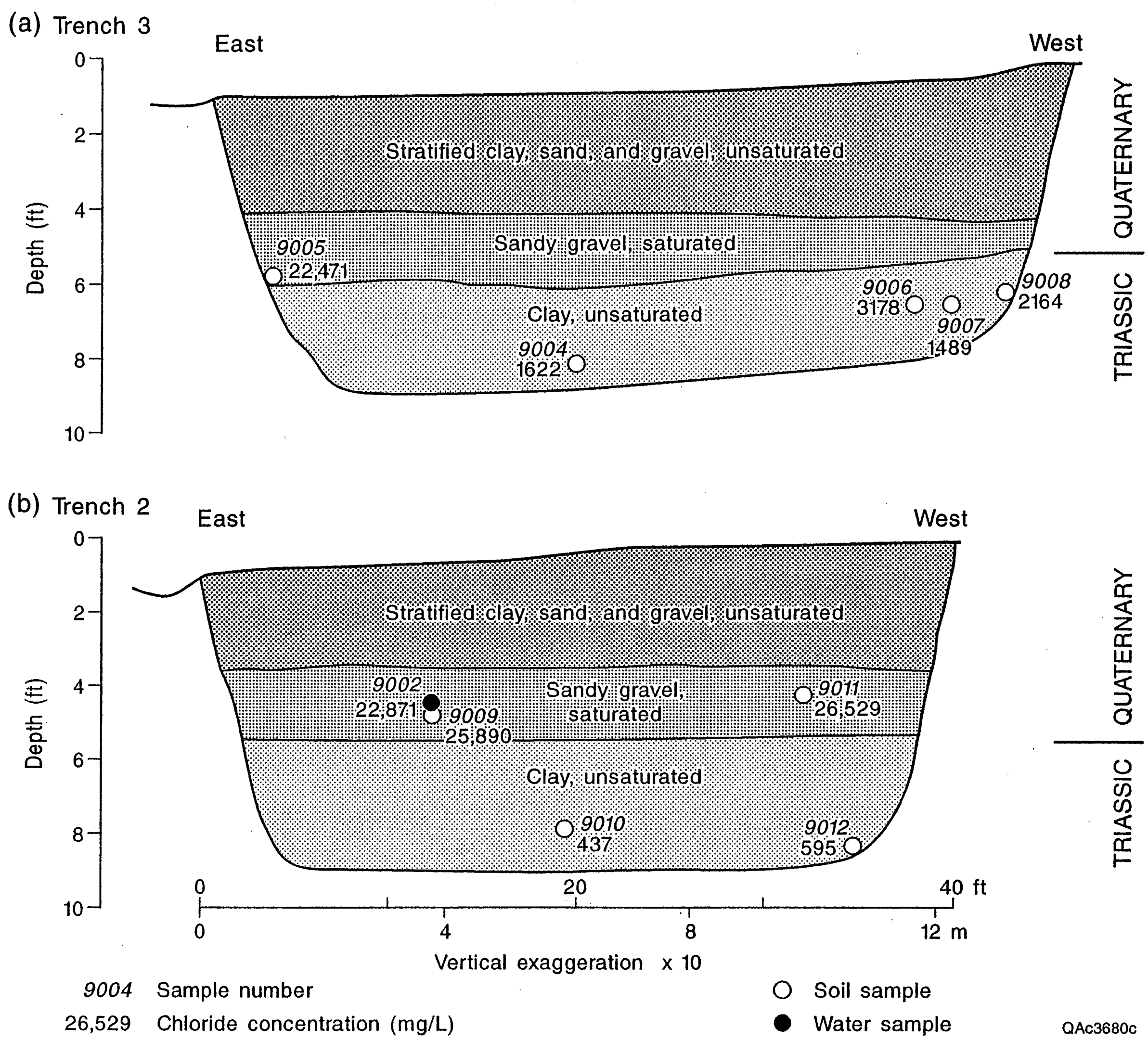

Figure 7. Hydrologic profiles of alluvium and bedrock clay exposed in trenches excavated along the unnamed tributary (fig. 2). (a) Location north of Snyder Field Road. (b) Location adjacent to monitoring well 2. Analytical results of chloride concentration in water and soil samples.

and no water was observed in the borehole in the week after it was drilled. On the basis of water-level elevations measured at monitoring wells 1 and 2 and sighted in the trenches, the gradient in the alluvium was estimated to be approximately 0.008.

As previously mentioned, the Dockum clay underlying the alluvium beneath the unnamed tributary valley appeared to be unsaturated at a depth of 5 to 8 ft below ground surface. The depth at which the bedrock clay beneath the channel becomes saturated was not investigated in this study. The bedrock Dockum clay beneath the Ogallala in the upland area, however, appeared to be much wetter than the Dockum clay beneath the alluvium. The difference in saturation between bedrock clay beneath the Ogallala and the tributary alluvium most likely reflects the hydrology of the overlying flow units. The Ogallala is perennially saturated, although the alluvium underlies an intermittently flowing stream.

Figure 8 profiles general hydrogeologic sections at the site. Section B–B′ is approximately parallel to the gradient in hydraulic head, and section A–A′ is oriented perpendicular to the gradient. The flow units in the Ogallala and tributary alluvium are shown to be separate and distinct (figs. 4 and 8b).

Discharge Estimation

Darcy's law provides a foundation for estimating ground-water velocity at the site. As previously stated, the gradient (i) of the Ogallala water table averages approximately 0.005. Hydraulic conductivity (K) of the Ogallala has not been measured in the study area, but hydraulic conductivity in the main part of the Ogallala in Howard County to the north of the site ranges from 500 to 1,000 gal/d/ft^2 or 67 to 134 ft/d (Knowles and others, 1984).

Assuming that this range of values applies to the site, the calculated seepage velocity,

$$q = K \cdot i, \qquad (1)$$

is 0.3 to 0.4 ft/d. RRC measurements of seepage from the Ogallala provide a check on this calculated velocity. Total discharge (Q) from seeps in the vicinity of control points 55 to 58 RRC

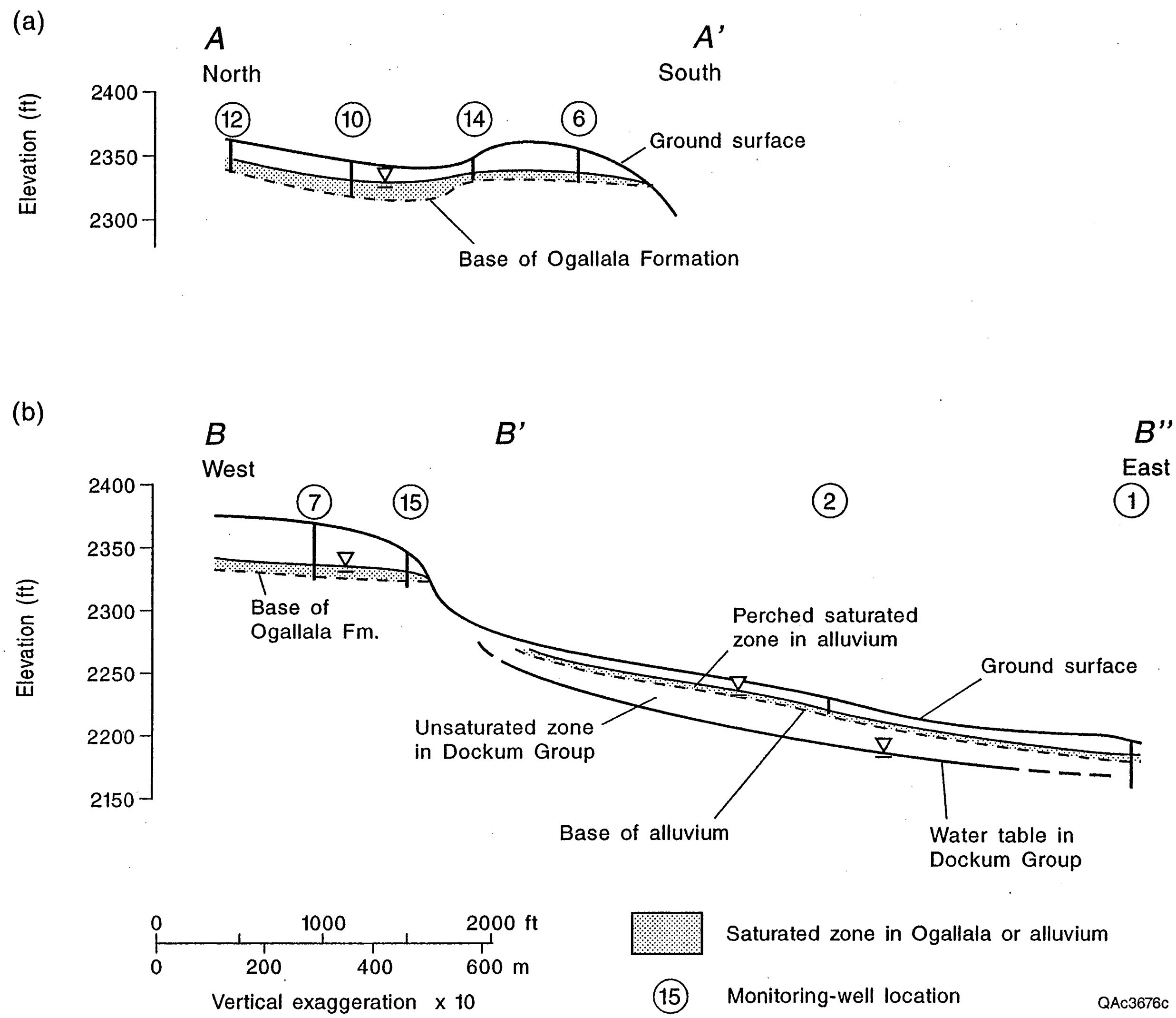

Figure 8. Generalized hydrogeologic sections (a) A–A′ across the upland Ogallala section and (b) B–B′–B″ across the upland Ogallala section and unnamed tributary. See figure 4 for section locations.

(fig. 1) was measured to be 10 bbl/hr (1,350 ft^3/d, 0.016 cfs) (Tim Prude, RRC Region 8 Office, personal communication, July 1998). We estimated the length of the seepage face from a topographic map to be 1,575 to 2,360 ft (W) and the height of the seepage face to be 2 ft (H). The seepage velocity, q, is then calculated from

$$q = Q/(W \times H). \qquad (2)$$

This yields a value of q between 0.3 and 0.4 ft/d, which matches well with the ground-water seepage velocity calculated earlier from Darcy's law. The observed seeps are the most obvious manifestations of ground water. There might also be some subsurface discharge from the Ogallala into the Dockum clay in the immediate vicinity of the seeps. The flux of water in the bedrock clay, however, is assumed to be small in comparison with the surface-water discharge.

To compare discharge from the Ogallala to flow in the alluvium we made the following calculations. As previously stated, the average gradient (i) in hydraulic head beneath the tributary is approximately 0.008, which is 1.6 times the gradient in the Ogallala. Hydraulic conductivity (K) of the alluvium at the site has not been measured; for convenience we assumed it to be the same as the hydraulic conductivity of the sandy gravel that makes up the Ogallala. The seepage velocity (q) in alluvium is calculated from equation 1, yielding a value of q between 0.5 and 1.1 ft/d. Total discharge (Q) of water in the alluvium is of interest because of the potential for transport of saltwater. Assuming the permeable, saturated alluvium is 100 ft wide (W) and 4 ft thick (H), total discharge is calculated from equation 2, where Q is then 200 to 400 ft^3/d (5,700 to 11,300 L/d; 0.08 to 0.15 cfs).

As previously stated, the unnamed tributary is an intermittent stream. It is also a losing stream. RRC base-flow measurements found that the 10 bbl/hr (0.016 cfs) discharge measured near the seeps had decreased to 3 bbl/hr (0.005 cfs) by crossing under Snyder Field Road and was nil a short distance downstream (Tim Prude, RRC Region 8 Office, personal communication, July 1998). The calculated ground-water flow rate in the alluvium of 0.08 to 0.15 cfs has enough capacity to take in the 0.016 cfs discharge from the seeps. Discharge from the Ogallala in seeps and springs along the length of the tributary undoubtedly contributes to the base flow of ground water in the alluvium, and additional flow comes from stream losses from runoff following rainfall events.

SITE HYDROCHEMISTRY AND PLUME DEFINITION

Background Water Quality

Both the Rankin well and BEG MW 12 were considered to be good examples of background water quality in the Ogallala in the study area. These wells are located upgradient of most of the oil-field activity in the area, as much as 1.5 mi from the main seep area. Background chloride values in the Ogallala at the site fell between 100 and 700 mg/L (fig. 9), a range typical for the Ogallala in this part of Howard County (Knowles and others, 1984).

Results of BTEX sampling are shown in table 2. The BTEX values for MW 12 were below detection limits (fig. 10). BTEX was analyzed to detect recent contamination by produced water, which typically contains significant concentrations of BTEX compounds. However, water from 30-year-old evaporation-pit sources is unlikely to contain much, if any, BTEX due to aeration, sorption, and biodegradation processes. No BTEX was expected in the background well locations.

Stiff diagrams illustrated the pattern of major cations and anions in these background wells and other lower-chloride-concentration wells (fig. 11a, 11b). RRC Laboratory data were used for these diagrams (appendix IV). MW 12 and MW 11 showed a similar chemical pattern, although the Rankin well contained slightly greater amounts of calcium and sulfate. MW 11 also contained no BTEX above method-detection limits.

Seep Water Quality

Stiff diagrams (fig. 12a) were used to compare major cations and anions in Saga produced water, ground water in MW 15, and seep locations 55, 56, and 57 (seeps 1, 2, and 3 on chain-of-custody forms). Note the change in axes scale from the previous figure. The Saga produced-water

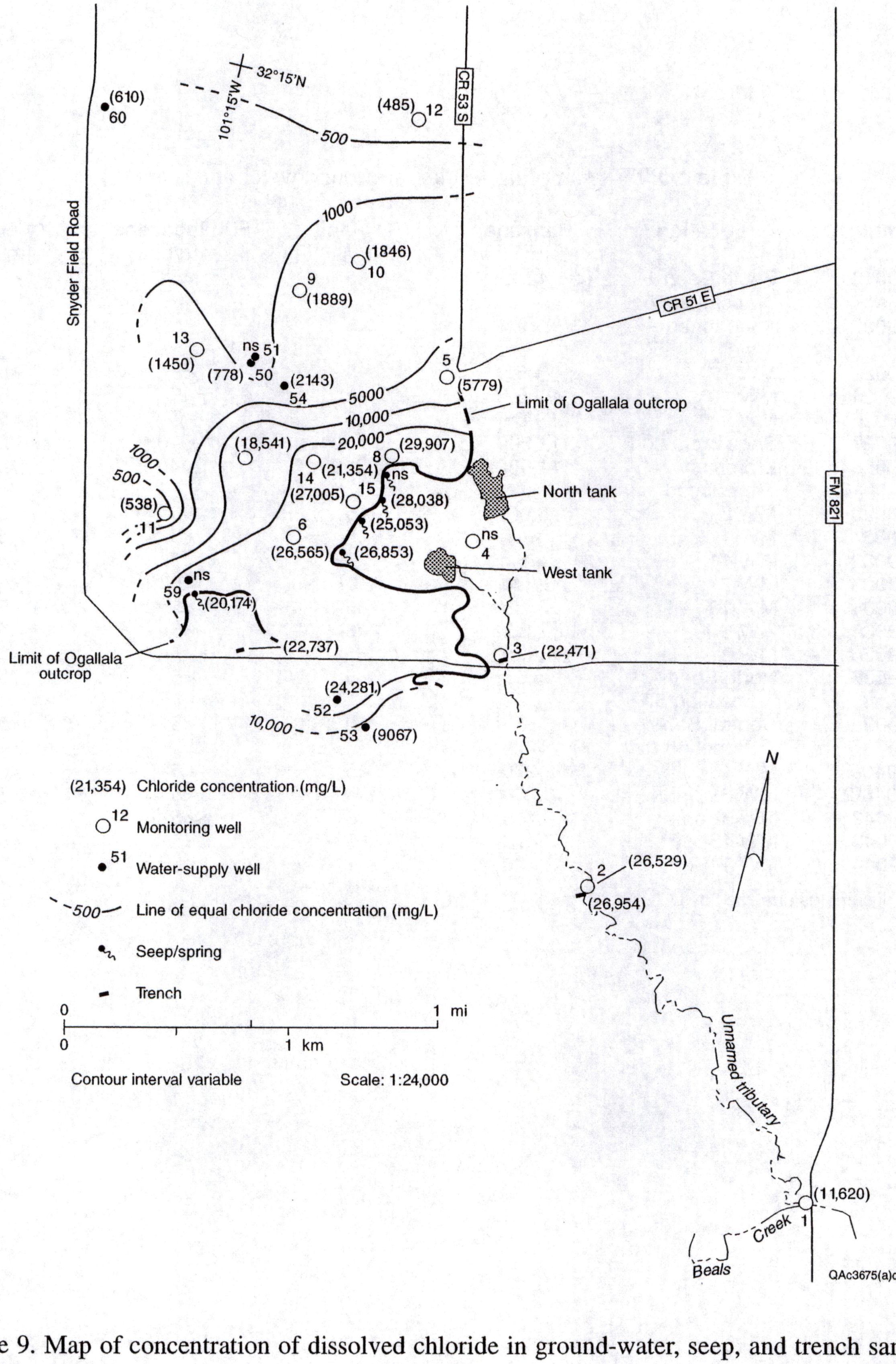

Figure 9. Map of concentration of dissolved chloride in ground-water, seep, and trench samples (9/98 data).

Table 2. BTEX sampling results for ground water and seeps.

Sample ID	Location	Benzene µg/L	Toluene µg/L	Ethylbenzene µg/L	Xylenes µg/L
9019	South Seep 1- Location 55	42.7	<5	<5	<5
9020	Abandoned well- loc. 50	<5	<5	<5	<5
9022	MW 12	<5	<5	<5	<5
9024	MW 10	<5	<5	<5	<5
9026	MW 9	<5	<5	<5	<5
9027	Saga produced	12,300	6,460	1,910	827
9028	Brammer produced	11,500	4,250	1,040	541
9029	MW 2	5.05	<5	<5	<5
9031	MW 1	<5	<5	<5	<5
9032	MW 11	<5	<5	<5	<5
9033	MW 7	6,260	13.1	<5	<5
9034	MW 13	34.2	<5	<5	<5
9035	MW 5	7.36	<5	<5	<5
9036	MW 8	1,120	<5	<5	<5
9037	North Seep- Location 57	<5	<5	<5	<5
9038	Central Seep 2-Loc. 56	<5	<5	<5	<5
9040-1	MW 15	2,270	<5	<5	<5
9040-2	MW 6	6,930	14.8	<5	<5
9042	MW 6-rep.	7,750	<5	<5	<5
9043	MW 15-rep.	2,470	<5	<5	<5
9044	MW 14	3,420	8.97	<5	<5

Note: All samples analyzed by DHL Analytical.

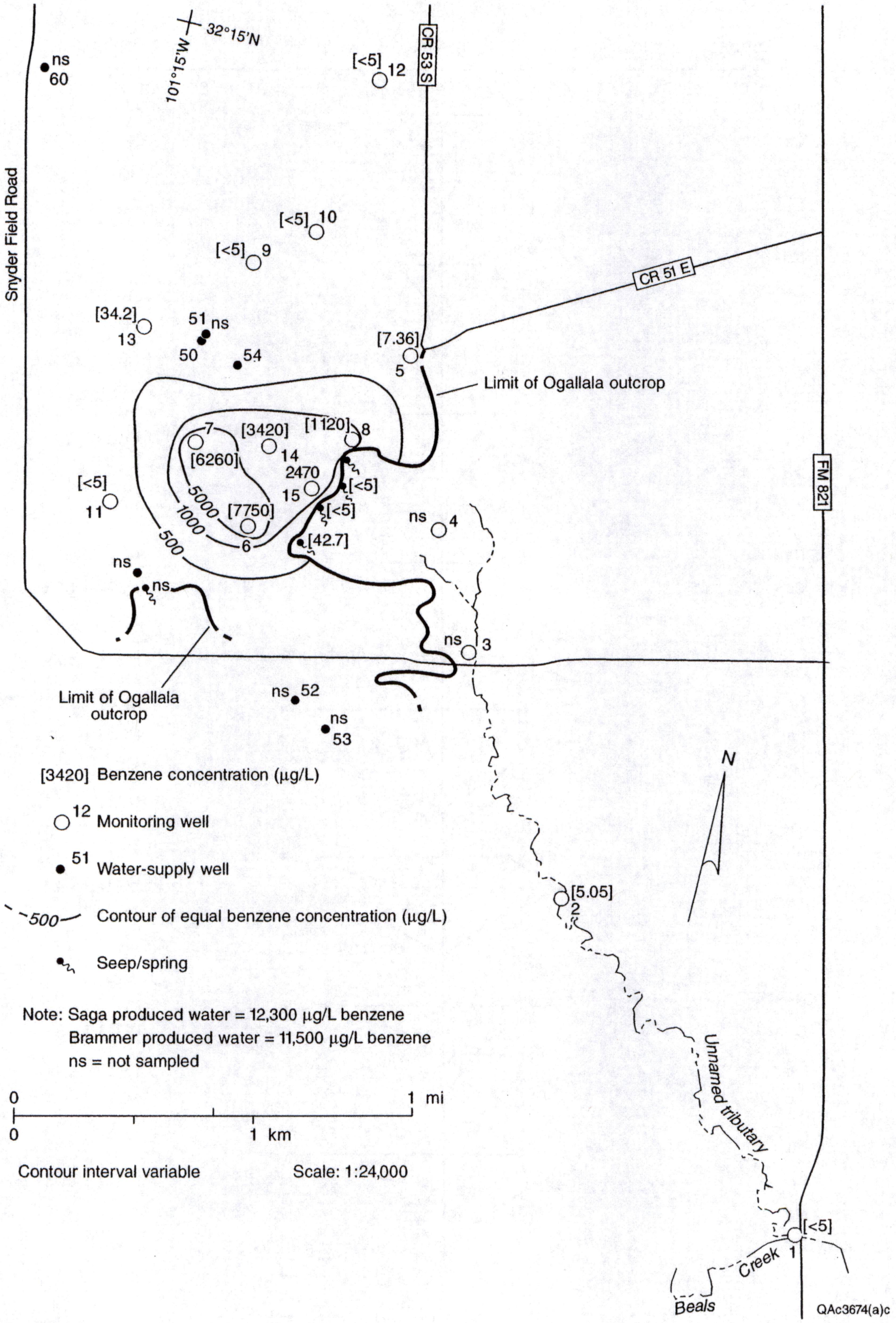

Figure 10. Map of concentration of dissolved benzene in ground-water, seep, and trench samples (9/98 data).

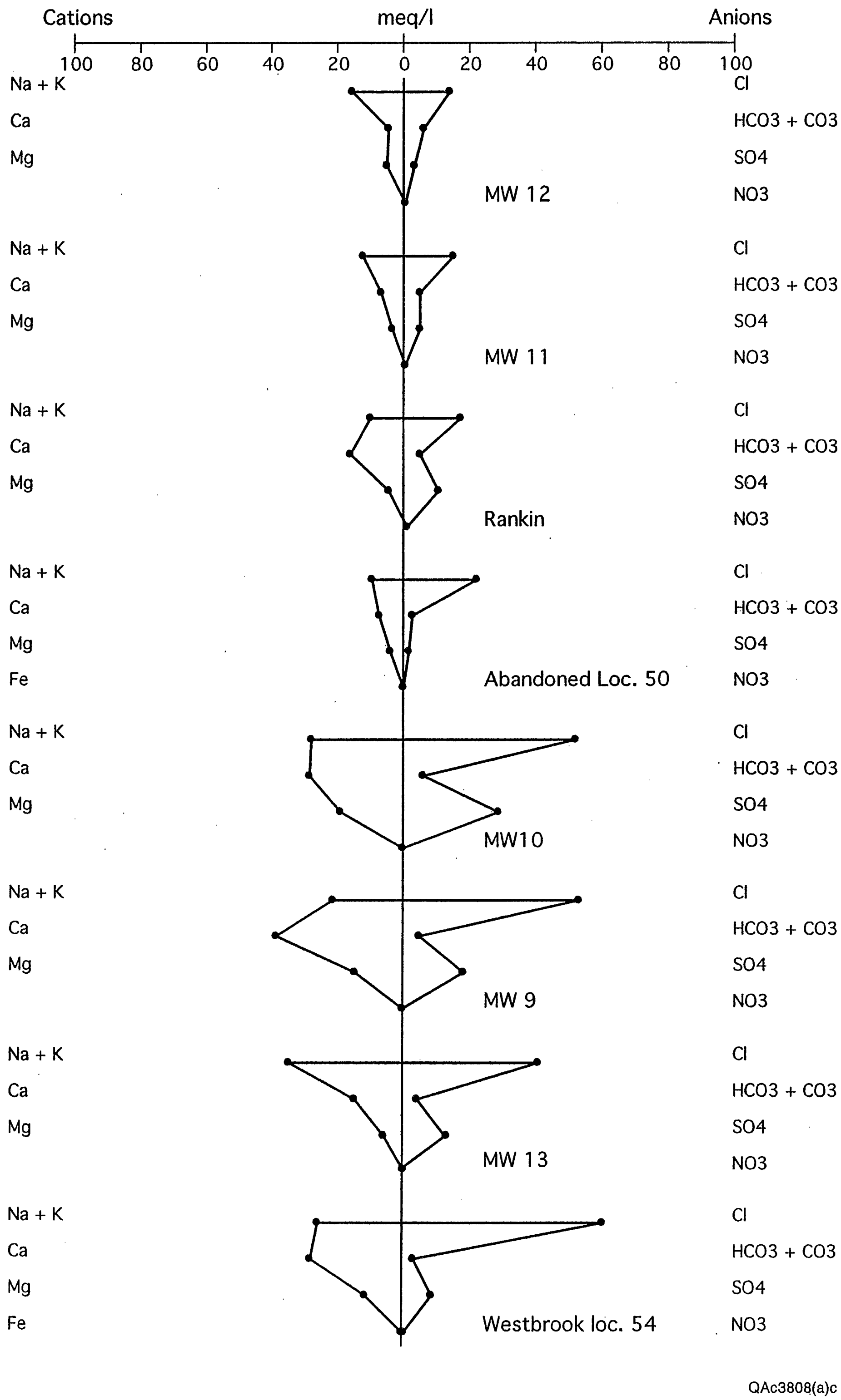

Figure 11. Stiff diagrams of chemical composition of low-chloride water samples 12, 11, Rankin, 50 (abandoned well), 10, 9, and 13.

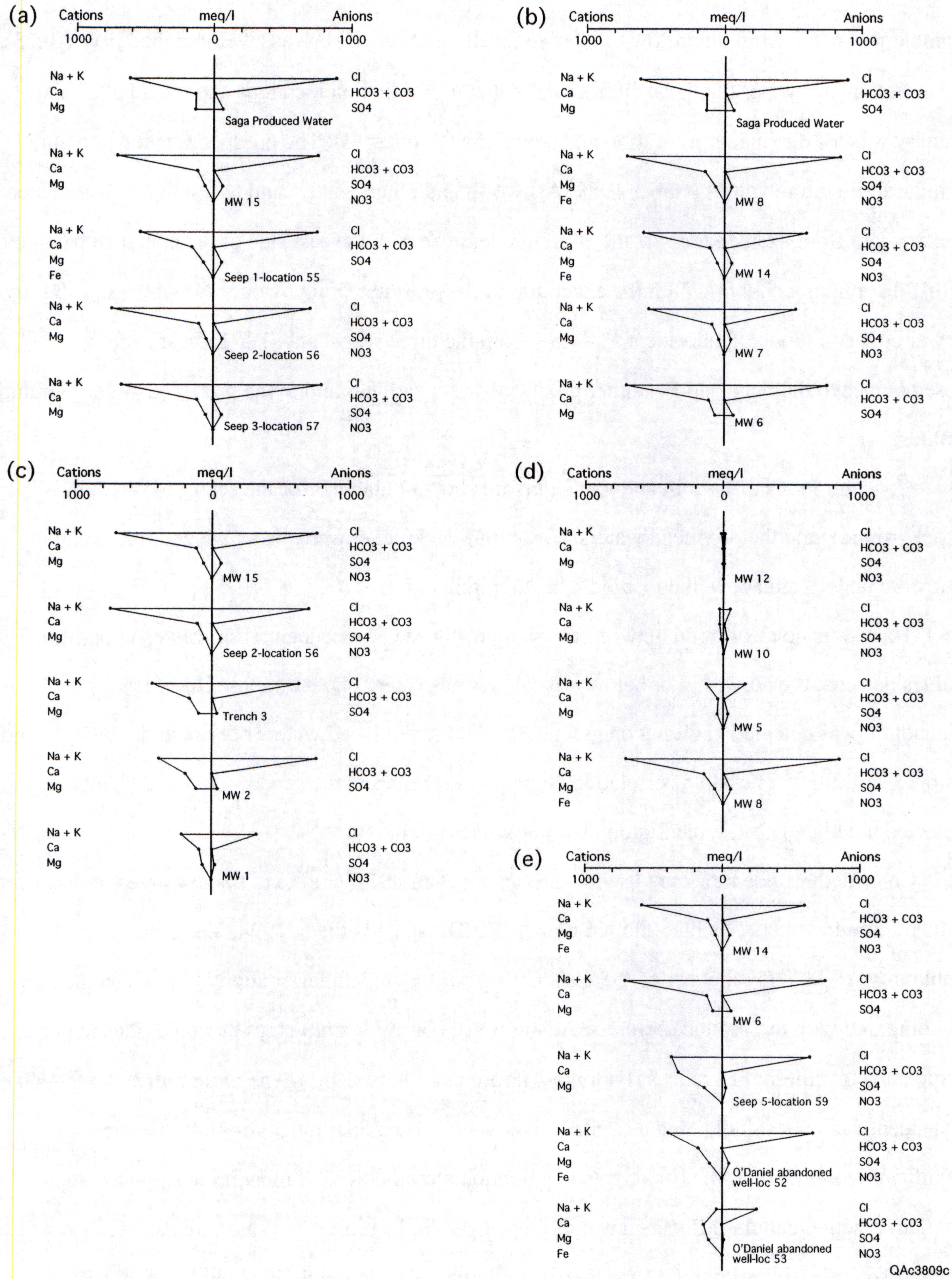

Figure 12. Stiff diagrams of chemical composition of intermediate- and high-chloride water samples.

sample was taken from the inflow to injection well on O'Daniel B lease well number 13W (fig. 3). This well injects water that is taken from a number of production locations and mixed at a tank battery west of the injection location and south of MW 6 (fig. 3). The produced-water signature is similar to literature values (Nativ, 1988; Ashworth and others, 1991) and to a sample of produced water taken from a tank battery at the Brammer lease area on the east side of the unnamed tributary (Stiff diagram not shown). With the exception of the presence of low values of nitrate and slightly lower concentrations of chloride, the waters from the three seeps and MW 15 bear a strong resemblance to the Saga and Brammer produced-water samples and to the produced-water literature values.

Concentrations of barium and vanadium are shown in table 3 for the seeps, MW 15, MW 12 (background), and the produced waters. Chromium and nickel were also analyzed for all samples, but were undetected above the method-detection limits (5 mg/L).

There was no clear trend between the samples for the low-concentration values in barium. The values detected are all within or below typical ground-water concentrations (Hem, 1992). Vanadium was detected in all but one seep (57) and the produced waters but not in the background sample, indicating a possible correlation between the seeps and the produced water. The values detected are higher than typical ground-water values (Hem, 1992).

Chloride:bromide ratios are used widely in geochemical literature to track sources of dissolved salts in ground waters (Richter and Kreitler, 1991; Davis and others, 1998; Vengosh and Pankratov, 1998; and others cited therein). Cl:Br ratios were similar or slightly higher in the seeps as compared with the produced waters. Adsorption of bromide onto clays or iron oxides may be responsible for these differences (Fabryka-Martin and others, 1991). The two produced waters had near-identical values, indicating a similar brine source. The Cl:Br ratios for all brines were significantly higher than the background well ratio, a trend noted for most brine samples when compared with Ogallala-influenced waters (see appendix IV). If DHL values are used for comparison, the background Cl:Br ratio is even lower. This low ratio is possibly a function of

Table 3. Selected metals, chloride:bromide ratios, and summed BTEX values for three seeps, MW 15, a background location (MW 12), and two produced-water samples. All inorganic values in mg/L. BTEX values in μg/L.

Sample location	Sample number	Barium[1]	Vanadium[1]	Chloride: bromide[3]	BTEX[2] (sum of B ,T, E, X)
MW 12 (background)	9022	0.07	<0.05	547 (322)	<5
Seep 55	9019	0.06	1.7	1,026	42.7
Seep 56	9038	0.2	2.4	869	<5
Seep 57	9037	<.05	<0.05	1,003	<5
MW 15	9043	0.1	2.2	869	<5
Saga produced	9027	0.09	5.3	842	21,497
Brammer produced	9028	<0.05	3.9	840	17,331

[1]Source of data: RRC Laboratory.
[2]Source of data: DHL.
[3]All data from RRC, except for Sample no. 9022 (DHL).

more accurate quantitation at lower chloride concentrations. DHL replicates were made for lower and midconcentration samples as a quality-assurance check.

BTEX concentrations in all seeps were low, which is expected of aerated surface waters and indicates that even if BTEX from produced waters reaches the seeps, then BTEX compounds are unlikely to travel to the unnamed tributary. This fact is corroborated by the nearly nondetectable BTEX values measured in wells MW 2 and MW 1 (appendix IV).

Water Quality in Areas of Elevated Salinity

Because typical background levels of chloride vary from 100 to1,000 mg/L regionally in the Ogallala in Howard County, wells exceeding 1,000 mg/L chloride were noted to be of intermediate quality. Of these wells, a number exceeded 10,000 mg/L chloride, an arbitrary designation chosen to indicate elevated salinity levels. All sampled seeps, three trench samples, one abandoned water supply well (number 52), and monitoring wells 8, 14, 7, 6, 15, and 2 had chloride exceeding 20,000 mg/L, although wells 1 and 5 exceeded 5,000 mg/L. These values and the resulting chloride-concentration contours in the Ogallala are shown in figure 9. Geophysical survey transects marked the transition between wells from low to high conductivity owing to saltwater impact, particularly along EM lines 2 between MW 7 and water-supply well 50, EM line 3 west of MW 7, and EM line 6 between MW 14 and MW 8.

Figure 12b is a comparison of Stiff diagrams for wells 8, 14, 7, and 6 with Saga produced water (also similar to Brammer produced water, not shown). As with the seeps, there is a distinct similarity between the produced-water profile and the major cation/anion profiles in the wells, with the exception of the presence of small nitrate concentrations and slightly less magnesium. MW 15, shown in figure 12c, was also similar.

Selected metals, chloride:bromide ratios, and BTEX content are shown in table 4 for the high-chloride-content well locations. As before, there was little correlation or distinction between barium concentrations. There appears to be some correlation between vanadium detected in the produced

Table 4. Selected metals, chloride:bromide ratios, and summed BTEX values for selected high-chloride well locations, a background location (MW 12), and two produced-water samples. All metal/ion values in mg/L. BTEX values in μg/L.

Sample location	Sample number	Barium[1]	Vanadium[1]	Chloride: bromide[3]	BTEX[2] (sum of B ,T, E, X)
MW 12 (background)	9022	0.07	<0.05	547 (322)	<5
MW 8	9036	<0.05	0.49	963	1,120
MW 14	9044	0.12	1.9	859	3,429
MW 7	9033	0.08	1.5	889	6,273
MW 6	9042	0.15	2.7	921	7,750
MW 15	9043	0.1	2.2	869	2,470
MW 2	9029	0.19	4.1	964	5.05
Saga produced	9027	0.09	5.3	842	21,497
Brammer produced	9028	<0.05	3.9	840	17,331

[1]Source of data: RRC Laboratory.
[2]Source of data: DHL.
[3]All data from RRC, except for bracketed value for Sample no. 9022.

waters and the high-chloride wells, particularly because vanadium was not detected in the background well.

Chloride:bromide ratios for all these well samples were similar to or slightly higher than that for the produced water. Again, sorption of bromide onto clays or mixing with other waters may account for these small differences. The waters have been mixed to some extent; chloride concentrations are lower in the monitoring-well samples than in the produced waters. As expected, the Cl:Br ratios of produced water and chloride-impacted ground waters are higher than the ratios in the background water samples.

BTEX concentrations, particularly benzene, were high in produced waters before reinjection, even after being routed through a tank battery. The hydrocarbons result from equilibration and dissolution of crude oil in the produced water while it resides in the reservoir formation. Produced water that enters the shallow ground-water environment is expected to retain significant concentrations of hydrocarbons over relatively short times (months to a few years) on the basis of typical degradation rates for benzene (see appendix IV). The highest benzene concentrations appear to be centered between MW 6 and MW 7 and extend toward the seep area (fig. 10). This center of concentration overlaps but is slightly west and south of the apparent center of the highest chloride concentration (fig. 9).

Quality of Intermediate Waters

Monitoring locations MW 1, MW 5, MW 9, MW 10, and MW 13 have intermediate chloride contents of between 1,000 and 20,000 mg/L. Figure 11a shows the Stiff diagrams for wells 10, 9, and 13. Although wells 9 and 10 are similar, they have elevated chloride, calcium, magnesium, and sodium over background locations. MW 13 has elevated sodium and chloride similar to the produced-water patterns discussed earlier, albeit at much lower concentrations. The Stiff pattern for MW 1 (fig. 12c) is similar in pattern to, but smaller in magnitude than, waters at the seeps or MW 15.

Values for selected metals, chloride:bromide ratios, and BTEX for the samples with intermediate chloride contents are given in table 5. Barium concentrations are again inconclusive in correlating the well-water quality with either background or produced waters. Vanadium in MW 1 and MW 5 is slightly elevated, indicating a possible correlation with the produced water. Cl:Br ratios were difficult to compare in these cases because of the difference between RRC and DHL ratios. DHL bromide values tended to be greater than the RRC values, thus lowering the Cl:Br ratios considerably. Assuming that RRC values are consistent in their variation, then MW 9, MW 10, and MW 13 correlate best with background Ogallala water as their main source of dissolved salt. MW 1 and MW 5 appear to have mixed brine/Ogallala components.

The presence of low levels of BTEX in MW 5 and MW 13 indicates either that a more recent source of BTEX is distant or diluted or that BTEX has been degraded over time at that location. Although MW 5 is immediately downgradient of two older pit locations (see later discussion), it could also be influenced by water flowing from a more westerly location, judging from estimated flow directions (figs. 4 and 13) and the influence of the slope at the base of the Ogallala (fig. 6).

Ground Water within the Tributary

As described earlier, ground water at the site flows east-southeast in the Ogallala, to discharge at the seeps; base flow in the alluvium is fed by runoff from the seeps. Little water enters the alluvium from the Dockum Group. The southernmost point of surface-water entry to the unnamed tributary was observed at the breach in the West Tank dam during dry weather and only about 100 yd downstream, at the confluence of the west and north unnamed branches during wet weather.

Results of a preliminary geophysical transect along the length of the unnamed tributary (appendix II, not shown in fig. 2) indicated uniformly high ground-conductivity values at relatively shallow depths, decreasing with depth. EM line 5 was run perpendicular to the stream channel south of the Snyder Field Road culvert (fig. 2, appendix II). This line indicated near-surface

Table 5. Selected metals, chloride:bromide ratios, and summed BTEX values for intermediate-chloride concentration wells, a background location (MW 12), and two produced-water samples. All metal/ion values in mg/L. BTEX values in μg/L.

Sample location	Sample number	Barium[1]	Vanadium[1]	Chloride: bromide[3]	BTEX[2] (sum of B ,T, E, X)
MW 12 (background)	9022	0.07	<0.05	547 (322)	<5
MW 1	9031	0.05	1.8	903 (307)	<5
MW 5	9035	0.06	1.0	724 (212)	7.36
MW 9	9024	0.05	<0.05	473	<5
MW 10	9026	<0.05	0.74	462	<5
MW 13	9034	<0.05	<0.05	654 (314)	34.2
Saga produced	9027	0.09	5.3	842	21,497
Brammer produced	9028	<0.05	3.9	840	17,331

[1]Source of data: RRC Laboratory.
[2]Source of data: DHL.
[3]All data from RRC, except for bracketed values, which are from DHL data.

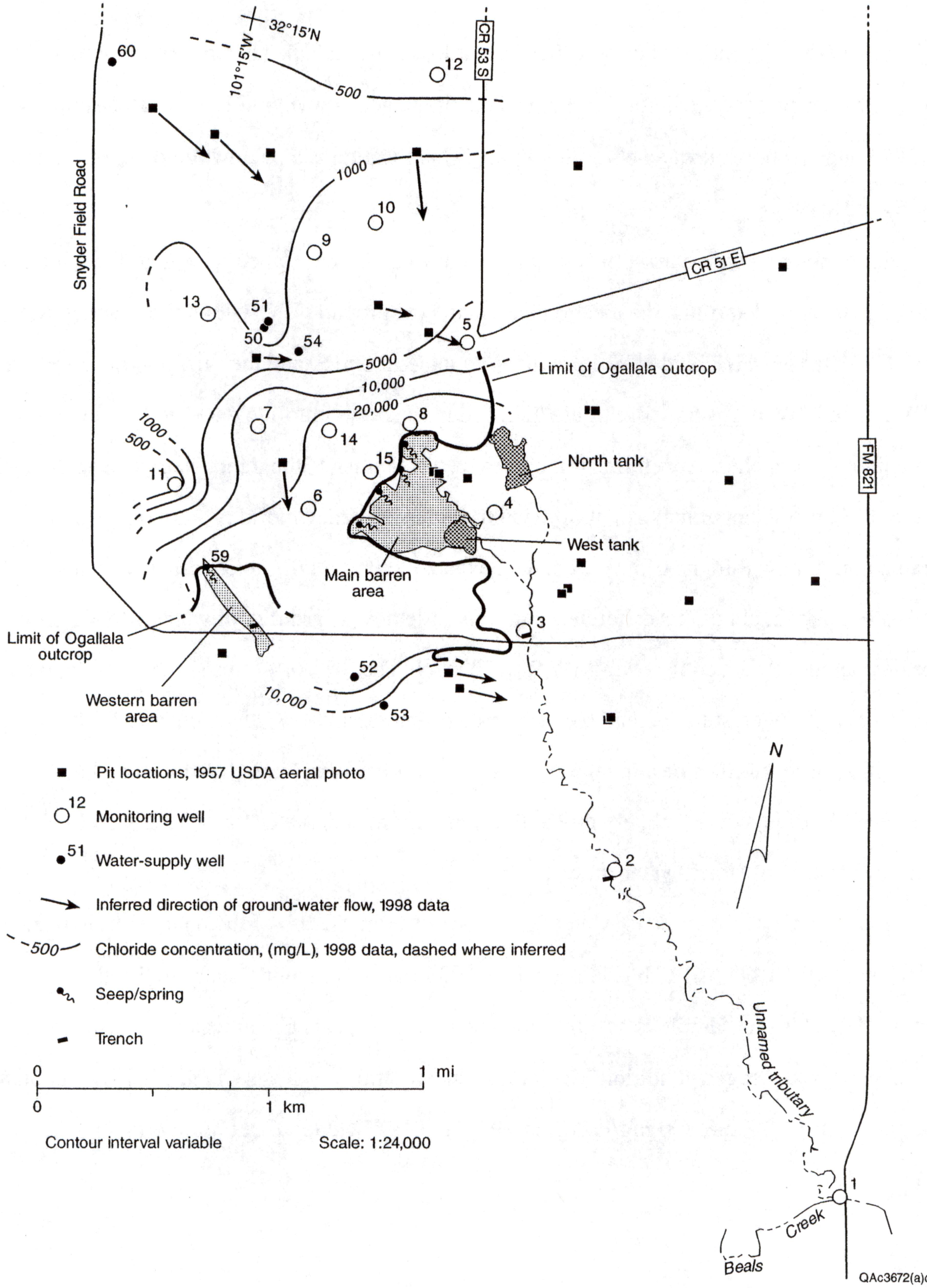

Figure 13. Surface pits identified in 1957 aerial photo, ground-water flow directions from pit areas inferred from water table map (fig. 4), and selected contours of dissolved chloride concentrations (fig. 9).

salinization across the entire tributary valley at that location. The line also indicated salinization of a drainage, which enters the tributary channel. This drainage is downgradient of water-supply wells 52 and 53, which show elevated chloride impact. This location is also downgradient of a former pit area (fig. 13).

Two monitoring wells, two trenches, and one boring were installed in or near the unnamed tributary channel to determine the location and quality of ground water within the channel. Metal and BTEX data for MW 2 and MW 1 are given in tables 2 and 3, and the Stiff diagrams for trench 3, MW 2, and MW 1 are shown in figure 12c. Figure 7 shows chloride data for various samples taken within the trenches. Appendix IV includes the remainder of the trench-sample data. Trench data indicate that the horizontal extent of the alluvium is limited. Chloride concentrations in saturated alluvium within the tributary channel exceed 20,000 mg/L, much less than in the underlying Dockum clay. This difference suggests little downward flux of water into the clay. Chloride content is reduced between MW 2 and MW 1. The Stiff diagrams show a similar pattern between MW 15 (nearest the potential source area of interest), Seep 2, Trench 3, and MW 2, with the exception of low values of nitrate. MW1 shows a similar pattern, with reduced quantities of sodium and chloride, which is likely due to dilution with fresher water from Beals Creek alluvium or from infiltration of storm-water runoff.

A grab sample of Beals Creek water taken about 1 mi upstream of the unnamed tributary by RRC in August 1998 had a chloride content of 938 mg/L (remaining analytes listed in appendix IV). This one sample is not fully representative of Beals Creek water because it was not taken under flow-averaged conditions. Chloride concentrations in Beals Creek at CRMWD Station 17 ranged from 1,300 to 3,800 mg/L during 1996 and 1997 (letter, C. L. Wingert to J. Tintera, 11/25/97).

North Pond Area

According to the property lease holder (Mr. Lane, personal communication, July 1998) the North Tank has become increasingly saline over several years. Ground water flowing toward the North Tank is monitored at MW 5 (fig. 2), which is approximately 100 yd northwest of the tank. MW 5 is located within a drainage that runs south from the area of MW 12 to the North Tank. There is evidence of a vegetated seepage area between MW 5 and the North Tank. Figure 12e shows a series of Stiff water-quality diagrams for a generalized flow path from MW 12 to MW 5 and contrasts the quality with MW 8, where the Stiff pattern of the produced-water end member is clearly developed. Chloride concentrations at MW 5 are much lower than at MW 8, which may be because the source is more dilute or distant or older and has been cut off. Potential sources include old pits that existed northwest of MW 10 (fig. 13) or an area of interest west of MW 8. EM spot locations (981006-SP2 and -SP3, appendix II) measured upgradient of MW 5 along the drainage indicated some areas of salinization. The BTEX values for MW 5 total 7.36 μg/L, which tends to indicate a more recent, but diluted, source or a combination of sources. It therefore seems more likely that the area of interest west of MW 8 is impacting the north tank.

Areas South of Snyder Field Road

The expansion of the western barren area since 1996, high salinities in two abandoned water-supply wells (52 and 53), and the measured water-table gradient indicate that there is a southward component to the movement of the saline plume. Water from the trench at location 59 (Pat O'Daniel trench) had a chloride concentration of 22,737 mg/L within 2 ft of the surface. The barren area in this location has nearly doubled in length since the most recent air photo taken in 1996.

Two wells on the O'Daniel property, wells 52 and 53, have chloride concentrations of 24,281 and 9,067 m/L, respectively. These wells, screened within the Ogallala Formation, were reported to have "gone bad" in 1994 (RRC files, July 1994) within a 2-week time frame. Figure 12f shows the Stiff diagrams for well 52 (O. D. O'Daniel abandoned water-supply well) and the seep 59 sample. Although both show similarities to the produced water profile, the chloride concentration diminished with distance south.

Geophysical data, discussed earlier and in appendix II, corroborate that subsurface salinization has developed along Snyder Field Road, where it crosses the western barren area (EM line 4). EM line 5 also indicates subsurface salinization in a drainage leading from the area of wells 52 and 53. This salinization, along with earlier information, indicates that the saline plume is moving south with the ground-water gradient within the Ogallala.

POTENTIAL SOURCES OF SALTWATER

Pit Disposal

One potential source of salt contamination is historical disposal of saltwater to evaporation pits. Although a significant amount of evaporation most likely occurred in this part of Texas, it is generally recognized that this method of disposal also led to subsurface recharge of saltwater. Residual salt in soil underlying pits may also be available for remobilization during times when natural recharge is significant (Pettyjohn, 1982). Pit disposal in Snyder field was banned in 1959, before development of some areas of the field.

Historical air photos were examined to determine the sequence of oil-field development and the locations of pits in relation to the current seep area. This information, in conjunction with the known ground-water gradient in the area (generally east-southeast), was used to determine an area where pits could influence the seep area, either directly by recharging saltwater or indirectly by remobilization of residual salts.

Figure 13 shows locations of pits identified on air photos from 1957, before the no-pit order, and from 1963, after the no-pit order. The pits identified include pits used for other purposes, such as drilling mud storage; however, because several were located near tank batteries, they were likely evaporation pits. The 1963 air photo shows that many former pit features were removed or filled in; some features remain that appear to be mud pits located near oil wells. These latter types of pits are not thought to be significant sources of saltwater.

Because monitoring wells 9, 10, 5, and 6 are located downgradient of noted pits (fig. 13), they may be impacted by residual salt from these locations. Many pits are downgradient of the seep area and, thus, do not impact the seeps. These locations may have influenced water quality in the unnamed tributary. Assuming that flow velocities in the area have been relatively constant at 0.9 to .12 m/d (0.3 to 0.4 ft/d), the distance from the farthest pit to the seepage face (1,600 m [1 mi]) could be covered in 36 to 48 yr, which is the average time that it would take for the last pit waters to travel to the seepage face. This does not account for the effects of dispersion, dilution, or incomplete flushing of pore space, which have both positive and negative effects on the displacement of the chloride plume.

The geochemistry of waters in wells 9 and 10 (see previous sections, figures 9 through 11, tables 3 and 4) in particular seem to correlate well with what might be expected to be an old plume of produced water. The chloride values are slightly elevated above background, indicating dilution over time. The Stiff patterns indicate increased calcium and magnesium, which could occur as sodium concentrations in the water decrease. Sulfate is elevated above background levels, possibly from oxidation of residual sulfide compounds. BTEX is low, indicating no new source of produced water in this area. This type of pattern appears to be, as one might expect, from redissolution of salts or flushing of contaminated pore waters by native Ogallala water.

In contrast, the chemistry of the ground water immediately northwest of the seeps (such as at MW 6) indicates recently produced water rather than aged, aerated pit-recharge water. Recently produced water has significant concentrations of volatile organic compounds. Two produced-water samples, numbers 9027 and 9028, were taken during the field investigation (table 2). Their combined BTEX concentrations were 21,497 μg/L (benzene at 12,300 μg/L) and 17,331 μg/L (benzene 11,500 μg/L), respectively. Aeration normally reduces volatile organic concentrations significantly, and adsorption and biodegradation over 30 yr should also produce large reductions in volatile constituents. Monitoring-well samples (MW 6, MW 14, and MW 15) immediately upgradient of the seeps, however, show concentrations of benzene that are closer to those of produced-water values (7,750, 3,420, and 2,470 μg/L, respectively), a single order of magnitude reduction. In contrast, aeration at the seeps has reduced benzene at two seeps to less than the detection limit of 5 μg/L, more than four orders of magnitude, a reduction similar to what might be expected in an open pit.

A simple one-dimensional advection-dispersion model (Bear, 1979; see appendix IV for calculations) was used to determine whether biodegradation alone could reduce the concentrations of benzene in produced water over 30 yr or less (the time since pit inflow has stopped). The model includes the effects of first-order biodegradation but no sorption, volatilization, or other mechanisms that could further reduce benzene concentrations. A distance of 800 ft was chosen, roughly the distance from MW 7 to the seeps. If the source concentration is 12,000 μg/L, and the source is continuous, such as a leaking well, then after 10 yr the downgradient source concentration was calculated to be 6,000 μg/L. If the source is a discontinuous "slug," then after 5 yr, the downgradient concentration becomes very small (0.02 μg/L). A pit source is therefore unlikely to produce benzene concentrations such as seen in the just-mentioned wells, particularly when other mechanisms of reducing the benzene concentration are also considered.

In light of the pit locations with relation to the known flow directions upgradient of the main seep area, it seems unlikely that the pits are the source of all of the salinity in the ground water at the site or discharging at the seeps. Pit recharge has most likely had some impact in the area, but it appears from the flow patterns that most of that impact should be to the west and east of the seeps rather than immediately upgradient. In addition, ground-water velocities have been sufficient to allow flushing of at least some of the pit recharge waters within the time since the pit-closure order. Finally, the presence of relatively high concentrations of volatile organic compounds tends to imply a more recent source of produced-water recharge.

Injection and Oil Wells

Geophysical data along EM lines 2 and 3 defined a zone of high conductivity north and west of the seeps (fig. 2, appendix II). The EM data also indicate an area of sharply higher conductivity near the center of EM line 6, which is unrelated to water-table occurrence or stratigraphy. These data, along with geochemical data such as chloride and BTEX, can be used to define a "source area" of interest (fig. 14). This area includes several active and inactive oil wells, injection wells, abandoned wells, and H15-program wells.

A possible source of saline water is a leaking injection well or oil well. Injection wells in Snyder field operate at pressures of as much as 500 psi and may have a subsurface influence as great as 0.25 mi. Saltwater produced at Snyder field is reinjected along with "makeup" water as part of the field's waterflood to maintain oil production. Figure 14 shows both oil and injection wells that are located within the high-chloride (>5,000-mg/L) zone at the site (fig. 9) or the elevated benzene area (>1,000-μg/L) (fig. 10) at the site. A number of these wells have been tested recently for casing integrity or have been converted recently (Tim Prude, RRC Region 8 Office, personal communication, August 1998) and, thus, are not as likely to be sources.

Injection wells are required to have tubing set on a packer, a long string (production casing), and an outer surface casing. The outer casing is intended to isolate the well from fresh-water zones. Corrosion, damage from age and other actions in the well, and inadequate cementing can lead to leaks in the internal casings and connection with the external casing or the fresh-water zone. For contamination to occur, the well must develop (1) tubing or packer failure, (2) one or more leaks in the production casing that allow fluid movement into the annulus between the long string and surface casing, and (3) one or more leaks in the surface casing (or lack of integrity of surface-casing cement) that allow fluid movement outside the surface casing. Wells drilled after January 1, 1983, are required to have high compressive-strength cement in the zone of critical cement along the lower 20 percent of the surface casing. Wells with less than 300 ft of surface casing are

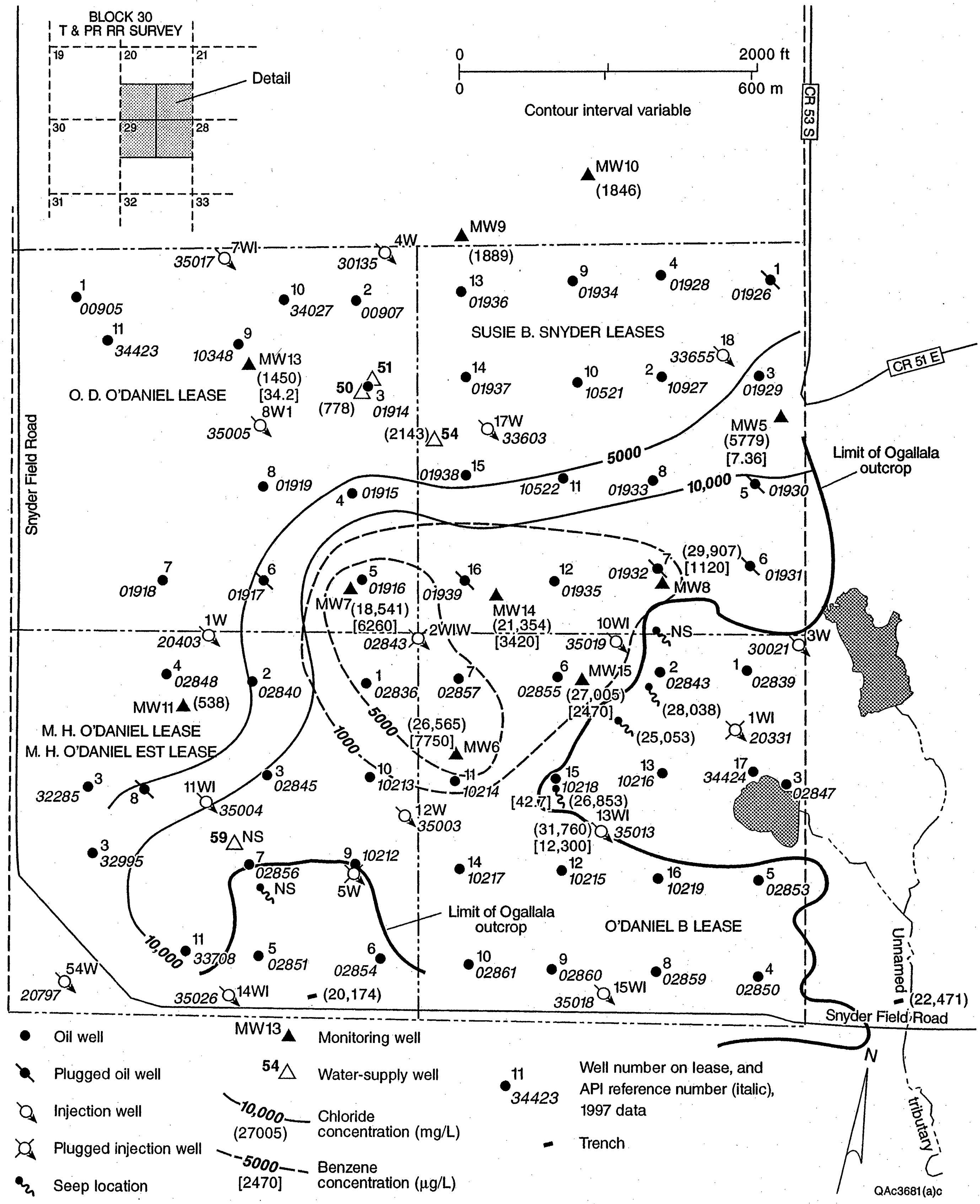

Figure 14. Locations of oil and injection wells in study area (fig. 3) in area of interest for further investigation associated with impacted ground water. Selected contours of dissolved chloride and benzene concentrations from figures 9 and 10, respectively.

required to have high compressive-strength cement along the entire length of the casing. Well reports for oil wells on the O'Daniel B and Susie B. Snyder leases show that typical surface-casing depths are less than 150 ft below ground level (table 1). The base of usable quality water (BUQW) as determined by the Texas Natural Resources Conservation Commission is 100 to 150 ft bgl in the Snyder Oil Field.

Field reports indicated a variety of surface completion problems for several of the oil wells. Some of the wells in the Susie B. Snyder lease, drilled in the period between 1955 and 1956, were reentered and deepened in 1991. In general, the actual BUQW (base of the Ogallala Formation) is about 30 ft below ground surface or less, judging from the monitoring wells drilled for this project. These surface-casing depths should be sufficient to protect ground water as long as the surface casings are properly installed.

In addition to wells drilled and permitted for the purpose of injection, some injection wells were initially oil wells and subsequently permitted as injection wells.

Under RRC Rule 3.14, wells more than 25 yr old that become inactive are to be plugged or tested for mechanical integrity. Operators have the choice of either performing a mechanical integrity test every 5 yr or measuring fluid levels annually. The results of these tests are reported on an H15 form and entered by the RRC into a data base. Information extracted from this data base for annual fluid-level data collected between 1993 and early 1998 was searched for wells in the Snyder Oil Field. Several of the wells in the study area had H15 top-of-fluid levels at the surface. In particular, surface-fluid levels were noted in wells 3, 5, 6, 7 and 16 in 1994 on the Susie B. Snyder lease. Well 3 is an active oil-production well. Four of these wells, Susie B. Snyder wells 5, 6, 7, and 16, were plugged and abandoned in 1995.

Assuming that the H15 top-of-fluid level is an accurate estimate of the static fluid level in the reservoir, the surface-fluid readings are noteworthy. Reservoir fluid, under pressure and seeking static equilibrium, could impact usable-quality water through an improperly abandoned well, a leaky well, or an undocumented open well bore. The source in this scenario does not necessarily correspond to the wells in which fluid levels were measured; their integrity may be intact. Although the elevated fluid level documents the reservoir-fluid mechanism impacting shallow water zones, the actual conduit through which the impact occurs may be another well or borehole.

This scenario, based on the H15 top-of-fluid levels, is inconclusive. In 1996, well 12 on the Susie B. Snyder lease, located between wells 7 and 16, did not have H15 top-of-fluid levels at the surface but rather at a depth greater than 1,400 ft bgl. Furthermore, the assumption that the H15 top-of-fluid levels represent static reservoir-fluid levels may be invalid. The wells may have plugs, and the fluid levels reported may not represent reservoir conditions. Or the measurements may have been erroneous or incorrectly reported. However, five H15 top-of-fluid readings at the ground surface in two different leases near the area of interest do support the scenario of upward-moving reservoir fluid.

Abandoned Wells and Pipelines

Waterflooding and pressuring of the production zone may allow for high levels of fluids in oil-well casings that are not currently used for production. These wells include those in the RRC H15 fluid-level program, wells that have been capped but not abandoned, improperly abandoned wells, and unreported or improperly sealed boreholes. Historical data indicate that the appearance of saltwater in the seeps around 1988 tends to correspond with pressuring of the oil field in the area. One or more boreholes with high fluid levels from the waterflood may be conduits for the saltwater.

Plugged and abandoned injection well 2WIW on the O'Daniel B lease lies within the area of interest (fig. 14). The well was plugged in November 1991. Some difficulty in plugging this well was noted in the field reports, which stated that there was fluid backflow to the surface and that the tubing was corroded below 390-ft depth, and that there was "junk" in the hole below this depth (see app. I). The well is located approximately 1,600 ft northwest of the seep area. If this well was properly plugged, than it would not be an ongoing source.

As in any location where active drilling has occurred for many years, there is a potential for undocumented well locations or wells that were improperly sealed during abandonment to exist. Although the RRC regulates these activities, these types of locations should be considered as possible sources if more obvious potential sources can be ruled out within the area of interest.

RRC district memorandum dated 12/16/94 states that additional research on wells drilled between 1938 and 1994 was performed at Petroleum Information in Midland for Section 29. Only one additional well was found, approximately .5 mi southeast of the seeps. The well was drilled by T. H. McElvain as the Sun-O'Daniel Well No. 1. Because this well is located southeast of the seeps and outside the limits of the Ogallala Formation, it is not considered a potential contributing source to the seeps.

Total discharge from the Ogallala seeps was reported to be about 1,350 ft^3/d (see earlier discussion). Because this measurement has been determined from measurements of both mixed salt and Ogallala waters, the discharge without any contribution from leaking well casings cannot be determined, and relative flow volumes of saline versus fresh waters therefore cannot be compared. Chloride, however, can be used as a conservative tracer to determine whether the expected volume of leakage can produce the salinity observed at the seeps and in monitoring wells. Appendix IV shows calculations for leakage from a single pressured casing, with a starting brine concentration of 30,000 mg/L (RRC sampling results, 1998). Judging from an average saturated thickness in the Ogallala of about 2 m (7 ft), it is clear that one single leaking borehole, leaking at a rate of 1 bbl/d or less over the course of 10 yr, could produce all of the chloride mass observed within the 20,000 mg/L contour of figure 9. If leakage were from more than one source, or if it flowed at a greater rate, then even more of the salinity in the area could be accounted for from a single source, given sufficient time.

Finally the possibility of a surface source, such as a pipeline, was considered. Most pipelines in the area are plastic and run along ground surface. Pipeline damage is usually repaired quickly to prevent losses. Older pipelines were commonly buried steel, which tended to corrode and was harder to maintain. The best way to detect old pipelines is by an EM survey, and there was evidence of buried steel features along EM lines 5, 2, and 1. Although leaking pipelines could be responsible for residual salinization in the area, they are probably not responsible for the continuous flow and high salinities at the seeps. Most old pipelines have been abandoned, and losses from pipelines would be noted by operators who need to maintain the waterflood.

CONCLUSIONS

- The salt-water plume more than likely reflects ongoing sources within the area of interest rather than an inactive source with a historical plume that has moved to its present position. It is possible that corrective measures taken at specific oil or injection wells within the past few years could have fixed the problem. Data collected during this study cannot distinguish an ongoing source from a recently eliminated source.
- A source "area of interest" has been defined on the basis of monitoring-well and geophysical data. Within this area of interest are 3 active injection wells, 15 active oil wells, 5 plugged or abandoned oil wells, and 1 plugged/abandoned injection well. Some of these have already been tested or are recently reworked and, thus, are not top suspects.
- Formation pressure near land surface would create a potential source of the saltwater plume in this area if there are one or more conduits for upward saltwater migration. Near-surface leaks at injection wells owing to failure of surface casing are also possible or have not been eliminated as a possibility.
- The most likely candidates for sources or pathways include injection wells converted from oil wells before 1970 or oil wells with completion problems, improperly sealed abandoned wells, or unreported and improperly sealed boreholes.
- The saltwater plume extends to the south within the Ogallala Formation. This plume extension has impacted the surface at the western seep area, has the potential to impact the surface and

runoff to the southwest of the site, and is a further potential source of saline seeps or subsurface flow to Beals Creek.

- Some amount of water in the unnamed tributary subsurface flow most likely reaches Beals Creek, but dilution from Beals surface and subsurface flow most likely dilutes the concentration of chloride in these waters. Further characterization of Beals Creek and the unnamed tributary surface and subsurface hydrology would be needed to substantiate this hypothesis.

RECOMMENDATIONS

- Further characterize and locate a specific source of saltwater to seeps, in order to cut off the source by well maintenance or better locate an interceptor trench or wells.
- Further define the extent of the plume south of the Snyder Field Road and do a geophysical reconnaissance for possible salt-water discharge points in the area.
- Further ground-truth the Ogallala–Dockum contact, particularly south of the Snyder Field Road.
- Determine fate and impact of saltwater on Beals Creek according to appropriate surface-water flow averaging techniques.

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Appendices Available Upon Request