EVALUATION OF POTENTIAL WATER-RESOURCE IMPACTS FROM BLM PROPOSED RESOURCE MANAGEMENT PLAN AMENDMENT FOR FEDERAL FLUID MINERALS LEASING AND DEVELOPMENT IN THE SALT BASIN, NEW MEXICO

prepared by

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prepared for

Otero Mesa Coalition

February 6, 2004

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1.0 INTRODUCTION

John Shomaker & Associates, Inc. (JSAI) was contracted by the Otero Mesa Coalition to provide a technical opinion on the U.S. Department of Interior Bureau of Land Management (BLM) proposed resource management plan for the Otero Mesa area. The BLM document is titled *Proposed Resource Management Plan Amendment and Final Environmental Impact Statement for Federal Fluid Mineral Leasing and Development in Sierra and Otero Counties* (BLM, 2003).

The primary area of concern and review is the Otero Mesa and surrounding area within the Salt basin, New Mexico (Fig. 1). As stated in the Resource Management Plan (RMP), some of the criteria in developing the plan included (but was not limited to) the following:

1. Provide for the protection of water resources
2. Maintain public health and safety
3. Consider social and economic effects

1.1 BLM Proposed Plan

According to the proposed plan, the majority of public land in the Salt Basin part of Otero County would remain open to fluid mineral leasing. The BLM (public land) in the Salt Basin is shown on Figure 1, and comprises more than 70 percent of the basin (approximately 850,000 acres). The proposed plan leaves approximately 70 percent of the public land open with standard lease terms and conditions and no special provisions for protection of ground-water resources (public water supply). Proposed activities may include oil and gas exploration and development, with the potential for injection wells to dispose waste. Proposed activities and protection of identified water resources (public water reserves) would be regulated under standard lease terms and conditions (BLM, 2003).

1.2 Objective and Purpose

The objective and purpose of this report is to address the following issues:

- Identify water resources underlying Otero Mesa that the BLM has not recognized or adequately addressed
- Identify areas of the aquifer that could potentially be impacted from surface disturbances (i.e., recharge zones)
- Identify activities and methods related to oil and gas exploration and development that could affect the existing aquifer(s)

2.0 DESCRIPTION OF REGIONAL AQUIFER(S)

The Salt basin is a large, internally drained basin covering about 5,900 square miles, of which 4,000 square miles are in Texas and the remaining 1,900 square miles are located just across the state line in New Mexico (Bjorklund, 1957). The water in the Salt Basin originating in New Mexico flows toward Texas. The portion of the Salt Basin in New Mexico includes Crow Flats and Otero Mesa. The Crow Flats portion of the basin drains to a series of alkali flats or playas to the south, just above the state line (Bjorklund, 1957). Irrigation with ground water has occurred in the Salt Basin near the New Mexico-Texas border, an extension of the agricultural area referred to as the Hudspeth County Underground Water District No. 1 (HCUWD#1) in Dell City, Texas.

Major watersheds within the New Mexico portion of the Salt Basin include the Sacramento River, Piñon Creek, and Shiloh Draw (Fig. 1). The Sacramento River drains the southern end of the Sacramento Mountains, where elevations of the upper watershed range from 8,000 ft to 9,500 ft.

Depth to water in the central part of the basin is around 200 ft, and many of the wells have depth to water less than 100 ft (see well data in Appendix A).

2.1 Structure and Framework

The Salt Basin is an extensional basin that widens to the south and is bordered on the east by the Guadalupe and Brokeoff Mountains and on the west by the Hueco Mountains and Otero Mesa. The Salt Basin is a block-faulted graben bounded by faults that extends 260 miles from the Sacramento River south into Texas (Fig. 1). The Crow Flat area is at lower elevation than the surrounding mesas, plateaus, and mountains, and is the site of the salt flats where ground-water discharges and evaporates.

Faults and associated folds on the eastern side of the basin represent the eastern extent of the Rio Grande Rift portion of the Basin and Range physiographic province. A good description of the hydrogeologic setting for the Salt Basin can be referenced from TWDB/NMWRRI (1997).

Ground-water flow in the limestone rocks of the Salt Basin is largely controlled by regional fracture systems (Mayer and Sharp, 1998). The most significant regional fracture system in the Salt Basin area is referred to as the Otero Break, trending from the Sacramento River to Dell City, Texas.

The Otero Break structural feature "graben" formed in late Paleozoic time along a northwest fault zone from right-lateral shear and extensional forces (Mayer, 1995). This fault zone was reactivated during the development of Basin and Range extension (Salt Basin), and extensively fractured the Permian-age carbonate rocks (Yeso Fm., San Andres Fm., etc) that occupy the majority of the Salt Basin and Otero Mesa area (Fig. 2).

2.2 Geologic Units

A summary of the geologic units found in the study area is presented as Table 1, and shown on Figures 2 through 4. Tertiary igneous intrusions of both andesitic and basaltic composition are present in the Cornudas Mountains and Dell City area (Dietrich et al. 1995). Quaternary-age basin fill in the form of alluvium and piedmont deposits, as well Santa Fe Group sediments, can be more than 500 ft thick, but in most places range from 25 to 300 ft thick (Bjorklund, 1957).

The principal bedrock aquifer units in the New Mexico portion of the Salt Basin are the San Andres Limestone, Yeso Formation, and Abo (Hueco) Formation, which together make up the bulk of the water bearing strata. In the Dell City area, the carbonate rock aquifer is referred to as the Victorio Peak-Bone Spring. Older formations (pre-Permian-age rocks), such as the Fusselman Dolomite, are water bearing and may possibly contain a viable public water supply.

Table 1. Summary of geologic units for the Salt Basin

age	symbol	stratigraphic unit	thickness, ft	description
Quaternary	Qal	alluvium	200 - 500	basin fill - unconsolidated clay, silt, sands, and gravels
	Qts	Upper Santa Fe Group	500 - 2000	basin fill - silts, sands, and gravels
Tertiary	Ti	intrusives	10 - 100	igneous intrusives - dikes and sills
Permian	P	Permian undivided	2000 - 5000	shale, limestone, mudstone, gypsum
	Psa/ Pvp	San Andres/ Victorio Peak	200 - 1000	limestone
	Pbs	Bone Spring	900 – 1,700	limestone
	Py	Yeso Formation	1200 - 1800	interbedded limestones and shales
	Pa/ Ph	Abo/ Hueco Formations	200 - 500	mudstones and conglomerates
	Pb	Bursum Formation	400 - 600	interbedded siltstones, sandstones, shales and conglomerates
Pennsylvanian	IPh	Holder Formation	500 - 900	interbedded limestones and conglomerates
		Gobbler Formation	1200 - 1600	sandstones and conglomerates
Mississippian	M	Lake Valley Formation	350 - 450	interbedded limestones and shales
Devonian	D	Percha Shale	40 - 80	black noncalcareous shale
Silurian	Sf	Fusselman Dolomite	20 - 100	massive dolomite with chert
Ordovician	Om	Montoya Formation	190 - 225	massive dolomite
Cambrian	Ce	El Paso Formation	350 - 450	dolomitic sandstone
		Bliss Sandstone	100 - 150	quartz sandstone
Precambrian	pC	granite	--	granites and granodiorites

Figure 2 is a map showing the distribution of major geologic units that make up the aquifer(s) in the study area. On Figure 2, the basin-fill deposits (Qal) refer to alluvium and Upper Santa Fe Group listed in Table 1; other Permian-age rocks are equivalent to Permian undivided. Cretaceous rocks refer to the Cox Sandstone and other overlying and underlying rocks of similar age.

The upper sequence of Permian-age rocks, Yeso, San Andres, Bone Spring, and Victorio Peak Formations, were deposited in a shallow sea environment behind the reef margin of the Delaware Basin. These carbonate rocks typically become more permeable toward the reef margin (Capitan reef in the Guadalupe Mountains), which would suggest increasing permeability to the southeast in the New Mexico portion of the Salt Basin. The lower member of the San Andres Formation grades to the southeast toward the Permian reef facies into the Victorio Peak Formation (Black, 1975). Therefore, the Victorio Peak is equivalent, in time of deposition, to the upper Yeso and lower San Andres. Cross-sections showing the relationship of major geologic units from west to east, across the New Mexico portion of the Salt Basin, are provided as Figures 3 and 4.

The San Andres Limestone and Yeso Formation cover most of the upper portion of the Salt Basin (Fig. 2). The San Andres Formation is composed of limestone, with sandstone at the base of the formation. The Yeso consists of sandstone, limestone, dolomite, siltstone, shale, and evaporites (Pray, 1961). The Yeso Formation is approximately 1,000 ft thick in the southern Sacramento Mountains (Kelly, 1971). Many of the springs in the southern Sacramento Mountains discharge from the contact between the San Andres and Yeso Formations. Most wells that yield water from the Yeso Formation are completed in the upper 500 ft of the formation in fractured limestone and dolomite where the permeability has been enhanced by solution. In the Timberon area, wells drilled into the lower Yeso Formation are typically low yielding (<5 gpm) as compared with wells in the upper Yeso, which produce more than 100 gpm.

The Bone Spring-Victorio Peak aquifer extends from Crow Flat in an arc to the south around the edge of the Permian-age Delaware Basin. The Bone Spring-Victorio Peak aquifer is present under most of the east part of the Diablo Plateau (Fig. 2). High-yield irrigation wells that produce from the Bone Spring-Victorio Peak aquifer commonly intercept fractures that have been opened by the percolation of ground water from overlying alluvium (Scalapino, 1950; Bjorklund, 1957). Scalapino (1950) reported that approximately 50 percent of the wells drilled are high-yield (> 1,000 gpm) and the other half are low-yielding (< 500 gpm).

Rocks older than Permian include (1) Pennsylvanian- and Mississippian-age limestone and shale, (2) shale, dolomite, and sandstone of Devonian-, Silurian-, Ordovician-, and Cambrian-age, and (3) Precambrian-age granite and metamorphic rocks (see Table 1).

Exploration drilling has indicated biogenic gas is associated with the Pennsylvanian- and Mississippian-age organic shale, which is formed by decomposition of organic matter by fresh water microbes.

The Silurian-age Fusselman Dolomite has been reported by the oil and gas exploration industry as having "fresh" water in the Otero Mesa and Diablo Plateau areas. The Fusselman Dolomite is generally found at depths greater than 2,000 ft below land surface (Black, 1975; Pearson, 1980; Harder, 1982).

2.3 Recharge

Due to the absence of perennial streams in the basin center, ground-water recharge is mainly infiltration of precipitation from melting snowpack and during flash flooding of ephemeral channels (Bjorklund, 1957). Most of the water for recharge originates from the higher elevations of the Sacramento River and Piñon Creek watersheds. The total annual average yield of these watersheds is approximately 35,000 ac-ft/yr (Table 2). The area of these watersheds is approximately 20-percent of the total area for the New Mexico portion of the Salt Basin.

Table 2. Watersheds in the Salt Basin, and summary of watershed data and estimated yield

name	mean annual precipitation, in./yr	mean elevation, ft amsl	area, mi^2	estimated watershed yield, ac-ft/yr
Sacramento River	22.8	7,795	135	17,580
Piñon Creek	20.0	7,100	99	8,872
small un-named watersheds and mountain front on Otero Mesa and Cornudas and Brokeoff Mountains	17.2	6,500	124	8,626
Salt Basin total			358	35,078

in./yr inches per year
mi^2 square miles
ft amsl feet above mean sea level
ac-ft/yr acre-feet per year

The watershed yield analysis was performed by evaluating monthly precipitation and potential evaporation data collected from weather stations in the region (Livingston Associates and John Shomaker & Associates, Inc., 2001).

The watershed yield analysis indicates that aerial recharge does not occur below an elevation of 5,860 ft, although below an elevation of 5,860 ft recharge from storm-water runoff occurs along arroyos and highly fractured rock where infiltration rates are high. Total watershed yield calculated for the Salt Basin area is 35,000 ac-ft/yr (Table 2), with approximately one-half originating from the Sacramento River Watershed.

Due to the fractured conditions of the rocks, all of the 35,000 ac-ft/yr plus storm-water runoff infiltrates into the ground-water system and can be considered as recharge.

Mayer (1995) estimated a total average annual rate of recharge at 58,000 ac-ft/yr for the Salt Basin, which included part of the Diablo Plateau in Texas.

2.4 Direction of Ground-Water Flow

Ground-water elevation contour maps for only parts of the study area have been developed by Ashworth (1995), Mayer (1995), and TWDB/NMWRRI (1997). The water-level contour maps from Ashworth (1995) and TWDB/NMWRRI (1997) are limited to the Dell City area and are representative of near present pumping conditions. The water-level contouring by Mayer (1995) was limited to a few data points in New Mexico, and implied a relatively flat hydraulic gradient throughout the study area.

The ground-water elevation contour map shown as Figure 5 was constructed from data from existing reports, the Texas Water Development Board (TWDB) database, and the New Mexico Office of the State Engineer (NMOSE) WATERS database. There are several areas where water-level data are absent, and extrapolation between data points 10 to 20 miles apart was made. Additional data are needed for Otero Mesa, Diablo Plateau, and the northern fringes of Otero Break to have a more accurate ground-water elevation contour map of the study area.

Regional ground-water flow is from the northern Salt Basin, Otero Mesa, and Diablo Plateau toward the Salt Flats near Dell City (Fig. 5). Ground-water elevation contours along the northern watershed boundary of the Salt Basin, between Timberon and Piñon, indicate ground-water flow from the Peñasco Basin to the Salt Basin.

The direction of ground-water flow from Otero Mesa and the Sacramento watershed area is toward the highly fractured region referred to as Otero Break. The fractured rocks of Otero Break have very high permeability and, as a result, effectively transport water to the

Dell City area and Salt Flats. Figure 6 is an aerial photograph of a portion of the Otero Break area (T23S, R16E), showing the visibility and northwest orientation of the regional fracture system.

Ground-water flows radially away from the Cornudas Mountains, presumably as a result of recharge there. Mayer (1995) suggested the water levels in the Cornudas Mountains indicate a perched water table, but data from nearby deep wells still show radial flow from the Cornudas Mountains.

2.5 Current and Historic Use

The primary uses of ground water in the New Mexico portion of the Salt Basin have been for domestic supply, stock watering, and irrigation. Irrigation has primarily been in the Crow Flat area. Bjorklund (1957) reported 3,000 acres of irrigated land from 17 wells in 1956, all in the Crow Flats area with most of it near the New Mexico-Texas state line.

Stock wells are scattered throughout the Salt Basin, and several of them are converted oil and gas exploration wells. A list of well data from the NMOSE WATERS database is provided in Appendix A. Existing wells are shown on the map provided as Figure 7.

Timberon Water & Sanitation District has approximately 1,500 ac-ft/yr of surface-water rights associated with Carriza Spring, tributary to the Sacramento River. Table 3 summarizes the declared water rights in the Salt Basin.

Table 3. Summary of declared water rights in Salt Underground Water Basin, New Mexico

use	declared water rights, ac-ft/yr
domestic	80
stock	566
municipal	1,499
irrigation*	47,595
total	49,740

* Hunt Development Corp. has declared 35,290 ac-ft/yr for irrigation of 3,600 acres
ac-ft/yr acre-feet per year

The majority of pumping from the Salt Basin occurs in the Dell City area, in Texas. Ashworth (1995) and Scalapino (1950) have summarized the acre-feet pumped for the HCUWD#1 (Dell City area), as listed in Table 4. Irrigation in the Dell City area began in 1947, and approximately 26,000 acres are currently irrigated for growing alfalfa, cotton, and chile. The HCUWD#1 claims 36,000 acres can potentially be irrigated, which would require about 180,000 ac-ft/yr of pumping at the current application rate of about 5 acre-feet per acre. Wilson and Lucero (1997) estimated a total pumping for irrigation in the New Mexico side of the Salt Basin at 10,171 ac-ft/yr in 1995.

Table 4. Summary of historic pumping for irrigation in the Dell City area

year	acre-feet pumped
1948[a]	7,500
1949[a]	18,000
1958[b]	67,000
1964[b]	91,500
1974[b]	132,700
1979[b]	144,600
1984[b]	102,000
1989[b]	94,700
1994[c]	100,000
1999[c]	100,000

[a] from Scalapino (1950)
[b] from Ashworth (1995)
[c] from HCUWD#1

2.6 Future Use

Recognizing the importance of the public ground-water reserve, the New Mexico State Engineer declared the Salt Underground Basin in September 13, 2000. After the basin was declared, several applications have been filed to further develop the water resources in Crow Flat and Otero Break (Fig. 7).

The Tularosa-Salt Basin Regional Water Plan was adopted by the New Mexico Interstate Stream Commission in May 2002, which defines the water resources of the Salt Basin and outlines current and future use. Even though the Salt Basin is sparsely populated and remote, the vast water supply in the Salt Basin is an important alternative resource for the future of New Mexico. Alternatives include development and importation to areas of need, as well as, preservation for use beyond the 40-year planning horizon.

The State Water Plan for New Mexico (selected pages in Appendix C) contains the following discussion on the Salt Basin and associated water resources:

- The availability of safe and adequate drinking water supplies for all New Mexicans is of paramount importance to the health and safety of the State's citizens (pg 6).
- Little development of the Salt Basin has occurred in New Mexico, but pressure to develop this resource is growing (appendix A, A-36)
- Steps must be taken to ensure that water from the basin is preserved to meet growing demands in southern New Mexico (appendix A, A-37)

3.0 DEFICIENCIES IN BLM RMP AND EIS

3.1 Identification of Water Resources and Potential Impacts

The BLM RMP and EIS did not review and include key publications on the water resources for the impact assessment (see references Section 5.0, and Appendix B).

- The majority of the Salt Basin is underlain by limestone (carbonate) rock that is fractured, and considered a regional aquifer (Mayer, 1995; Mayer and Sharp, 1998). Detailed description of this regional aquifer can be obtained from the references provided in Appendix B.
- The shallow alluvial aquifer is localized to arroyo and stream channels where recharge occurs. The alluvial aquifer is used for domestic and stock purposes. Depth to water is shallow in the alluvial aquifer rendering it susceptible to contamination from surface disturbances.
- There are potentially significant fresh water resources above and below the target formations for oil and gas development.
- The full extent of the water resources in the Salt Basin has not been defined.

3.2 Characterization of Aquifer(s) and Sensitivity to Management Alternatives

The BLM RMP and EIS did not identify the regional fractured carbonate rock aquifer beneath the Salt Basin and its susceptibility to surface disturbances related to oil and gas development.

- The regional aquifer is similar to the Edwards Aquifer in Texas, where the recharge zone is sensitive to contamination and requires controlled surface use for protection.
- The majority of the Salt Basin has fractured Permian-age carbonate rocks exposed at the surface, which is part of the regional aquifer. The fracture density has been quantified by Mayer and Sharp (1998), in which fracture density can be as high as 15,800 ft per square mile; in some cases fractures are no more than one meter apart (see discussion and photographic documentation by Mayer (1995) in Appendix B). Fractures are exposed at the land surface and potentially provide pathways for contaminant migration to the regional aquifer.
- The hydraulic conductivity for the Otero Break area is estimated to average 100 ft/d, and the hydraulic gradient estimated from Figure 5 is 0.002 ft/ft. Using Darcy's Law to calculate the tracer velocity, an average value of 20 ft/d was calculated for the fractured part of the aquifer at Otero Break (assuming an effective porosity of 0.01). With in a particular facture, the tracer velocity may be several orders of magnitude greater. This indicates how rapid contaminants could travel once introduced into the aquifer.

3.3 Ground-Water Protection Measures

Additional ground-water protection measures need to be implemented to insure protection of water resources in the Salt Basin.

- The possibility of injection wells should be omitted from the RMP given the widespread distribution of fresh "public ground water beneath the Salt Basin, and the fractured nature of the aquifer(s)."
- The fracture density study performed by Mayer (1995) could provide guidance for determining areas of the aquifer susceptible to contamination from surface disturbances. It is likely a more detailed fracture evaluation will need to be undertaken before land management decisions are made.

3.4 Economic and Ranking Evaluation of Resources

The BLM RMP and EIS should review existing water plans for the Salt Basin and incorporate those into resource evaluation and protection of water resources identified for future use. (excerpts from the State Water Plan can be referenced in Appendix C).

- The value of the water resources and fluid mineral resources should be evaluated, and appropriate methods should be used to rank resources based on impacts, value, and sustainability.

4.0 CONCLUSIONS AND FINDINGS

1. The proposed plan leaves approximately 70 percent of the public land open with standard lease terms and conditions and no special provisions for protection of ground-water resources (public water supply). Proposed activities may include oil and gas exploration and development, with the potential for injection wells to dispose waste. Proposed activities and protection of identified water resources (public water reserves) would be regulated under standard lease terms and conditions (BLM, 2003).
2. Depth to water in the central part of the basin is around 200 ft, and many of the wells that produce from shallow perched ground water may have depth to water less than 100 ft (see well data in Appendix A). The BLM RMP and EIS does not include the shallow depth to water data in the analysis of water-resource impacts.
3. The majority of the Salt Basin is underlain by limestone (carbonate) rock that is fractured, and considered as a regional aquifer (Mayer, 1995; Mayer and Sharp, 1998).
4. The regional aquifer is similar to the Edwards Aquifer in Texas, where the recharge zone is sensitive to contamination and requires controlled surface use for protection.

5. The Silurian-age Fusselman Dolomite has been reported by the oil and gas exploration industry as having "fresh" water in the Otero Mesa and Diablo Plateau areas. The Fusselman Dolomite is generally found at depths greater than 2,000 ft below land surface (Black, 1975; Pearson, 1980; Harder, 1982).

6. The possibility of injection wells should be omitted from the RMP given the widespread distribution of fresh "public ground water beneath the Salt Basin, and the fractured nature of the aquifer(s)."

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ILLUSTRATIONS

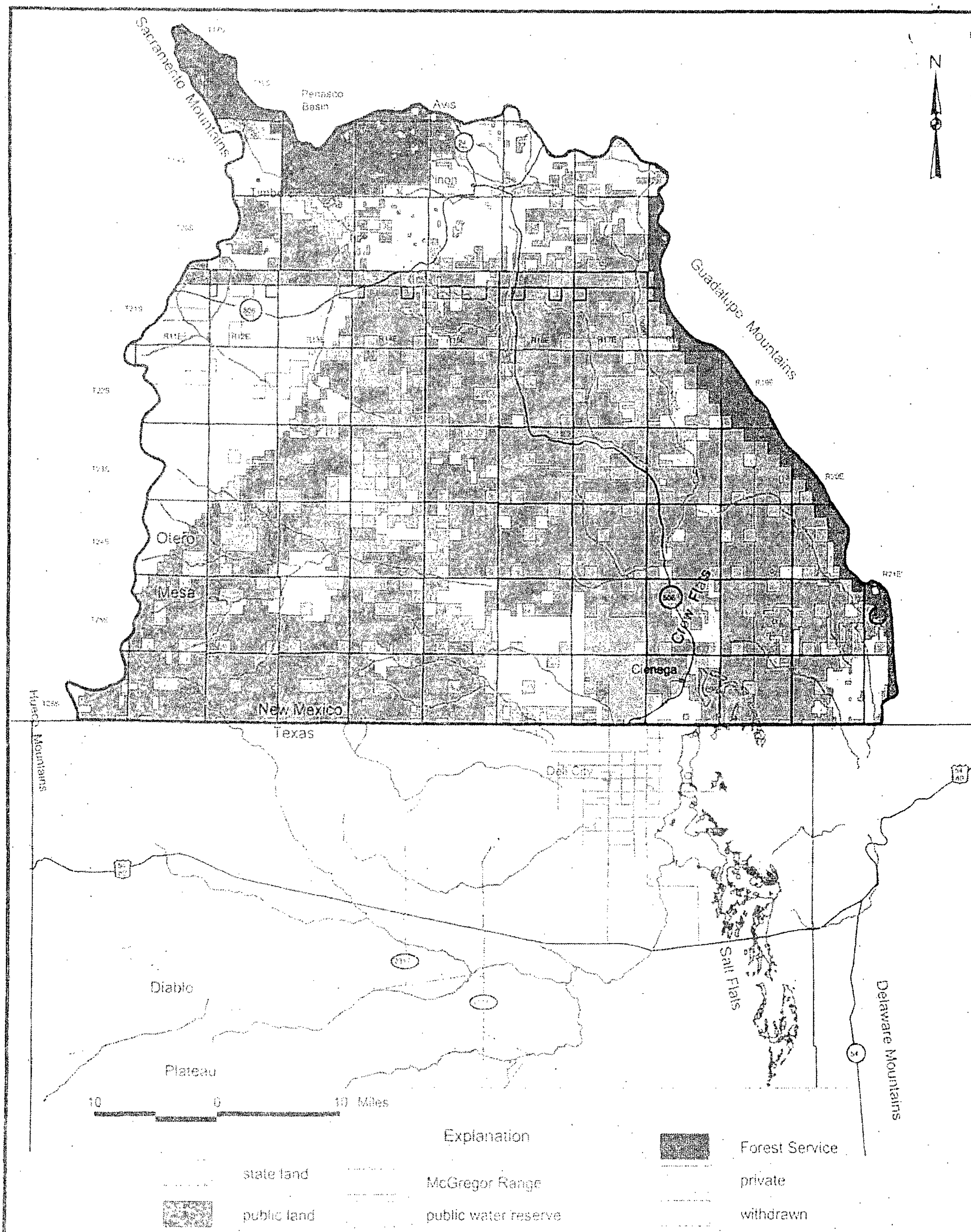

Figure 1. Map showing location of study area, land ownership, and geographic features within the Salt Basin and Diablo Plateau.

JOHN SHOMAKER & ASSOCIATES, INC.

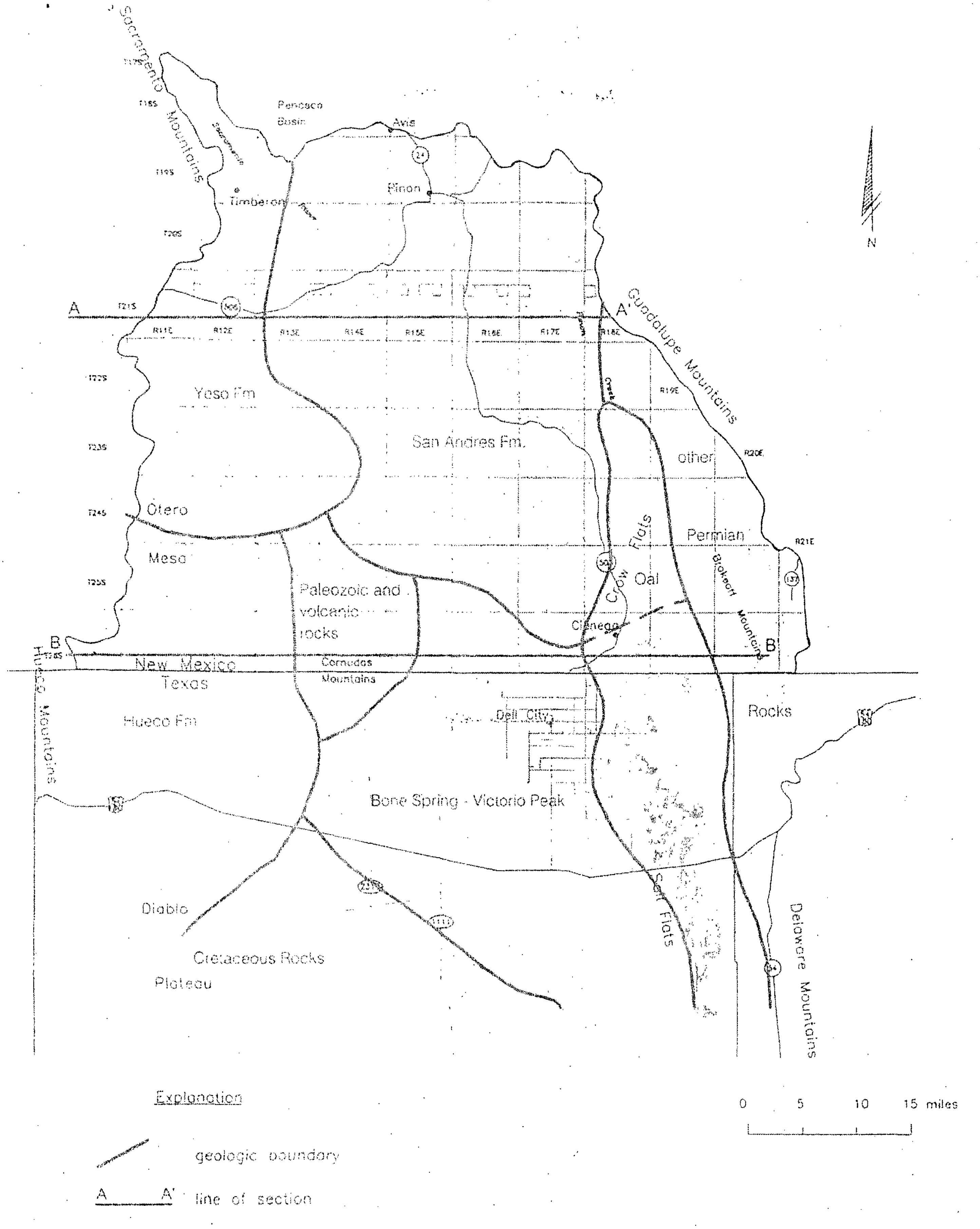

Figure 2. Map showing regional geology of the Northern Salt Basin and Diablo Plateau.

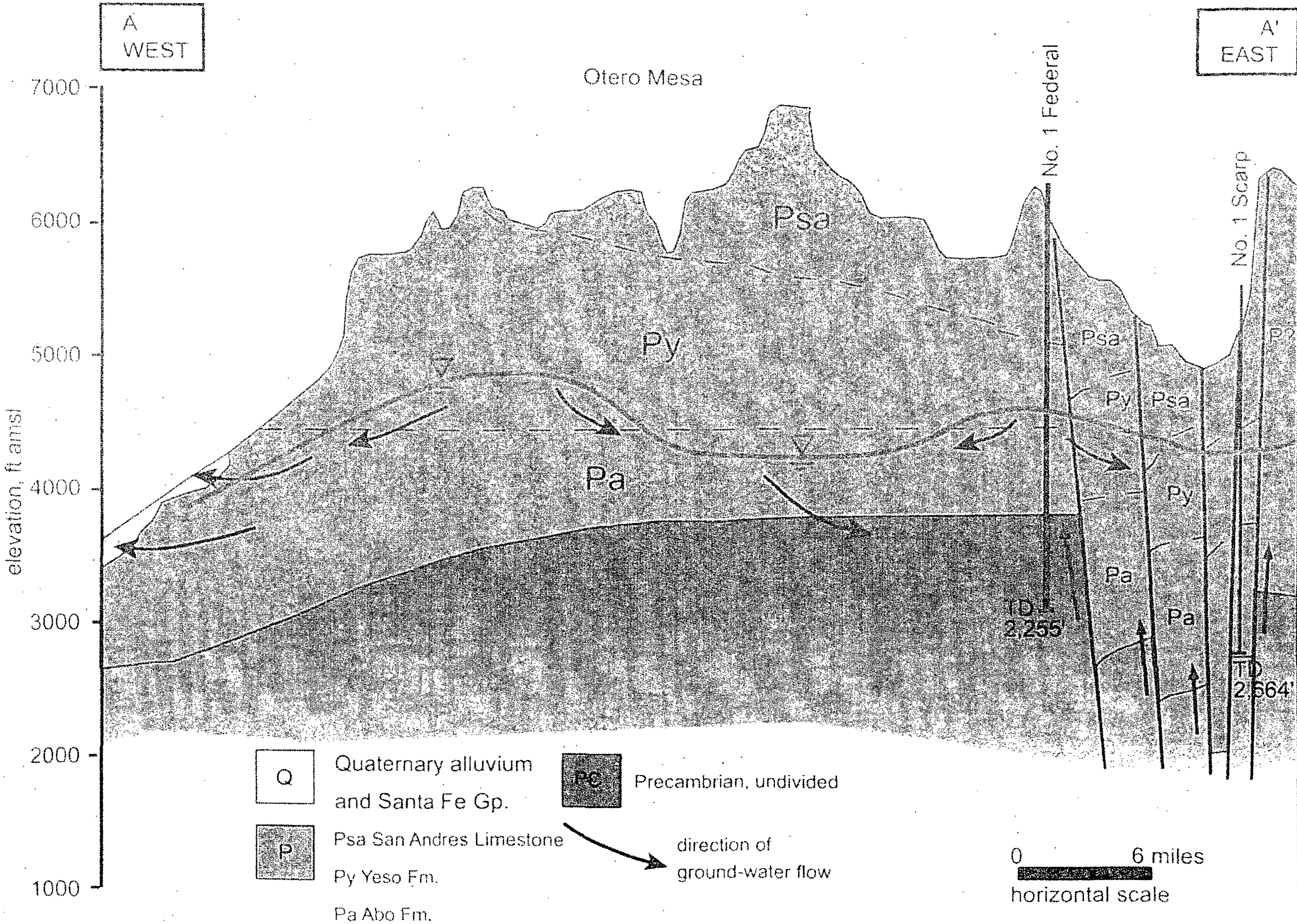

Figure 3. Hydrogeologic cross-section, A-A', Salt Basin.

JOHN SHOMAKER & ASSOCIATES, INC.
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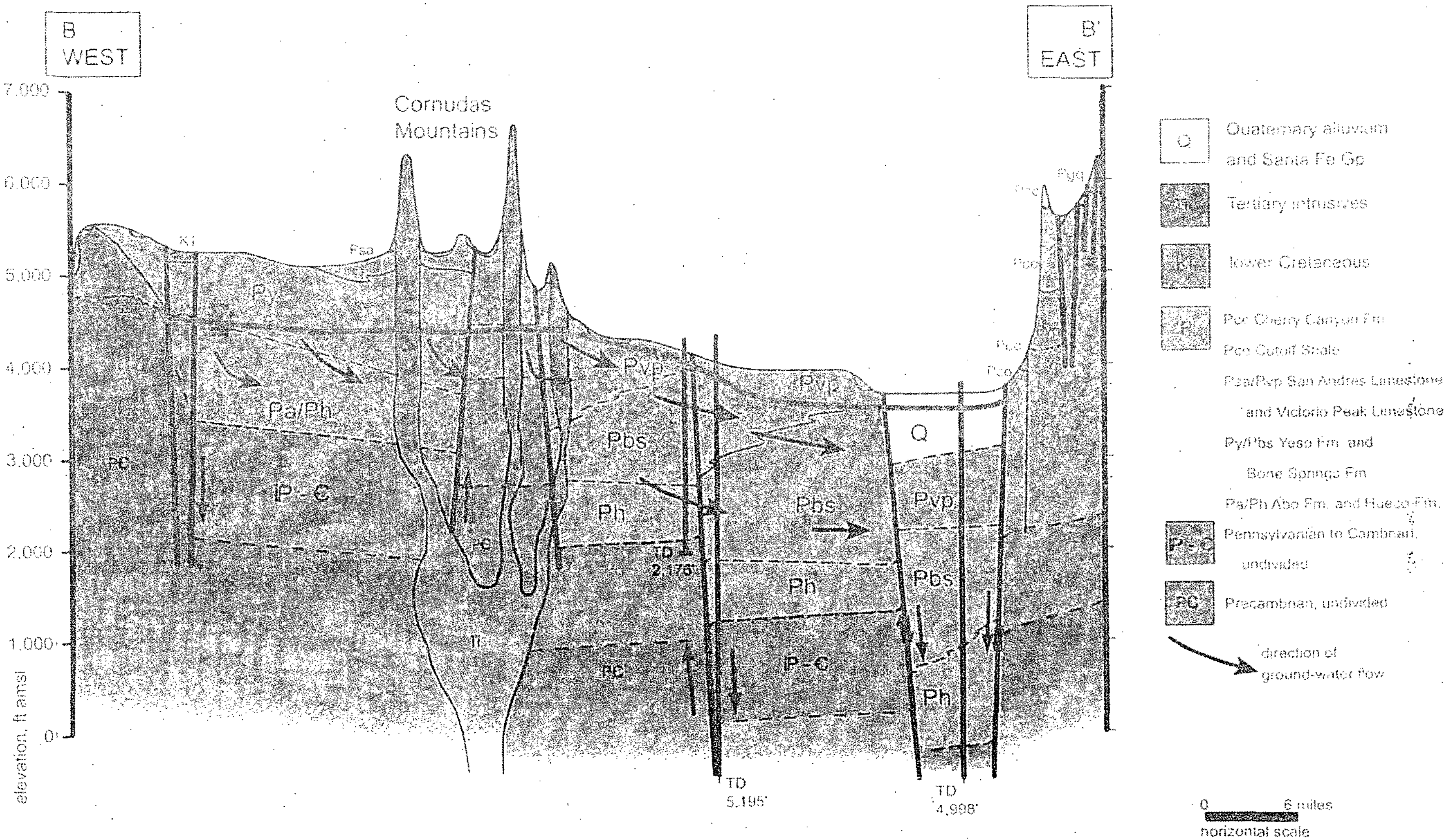

Figure 4. Hydrogeologic cross-section, B-B', Salt Basin.

JOHN SHOMAKER & ASSOCIATES, INC.
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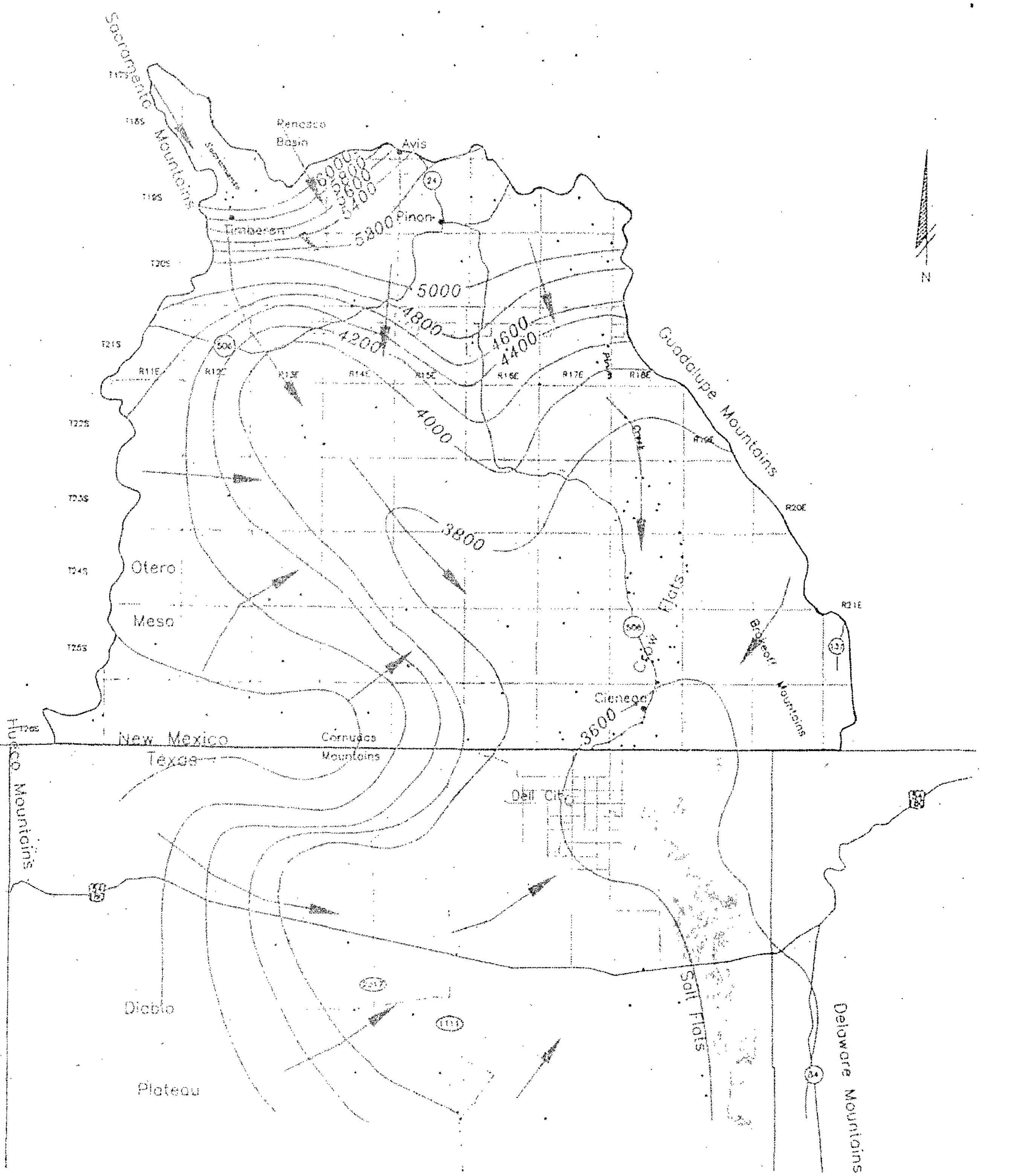

Explanation

predevelopment ground-water elevation contour, ft msl

flow direction

data point

0 5 10 15 miles

Figure 5. Predevelopment ground-water elevation contours and direction of ground-water flow for the study area.

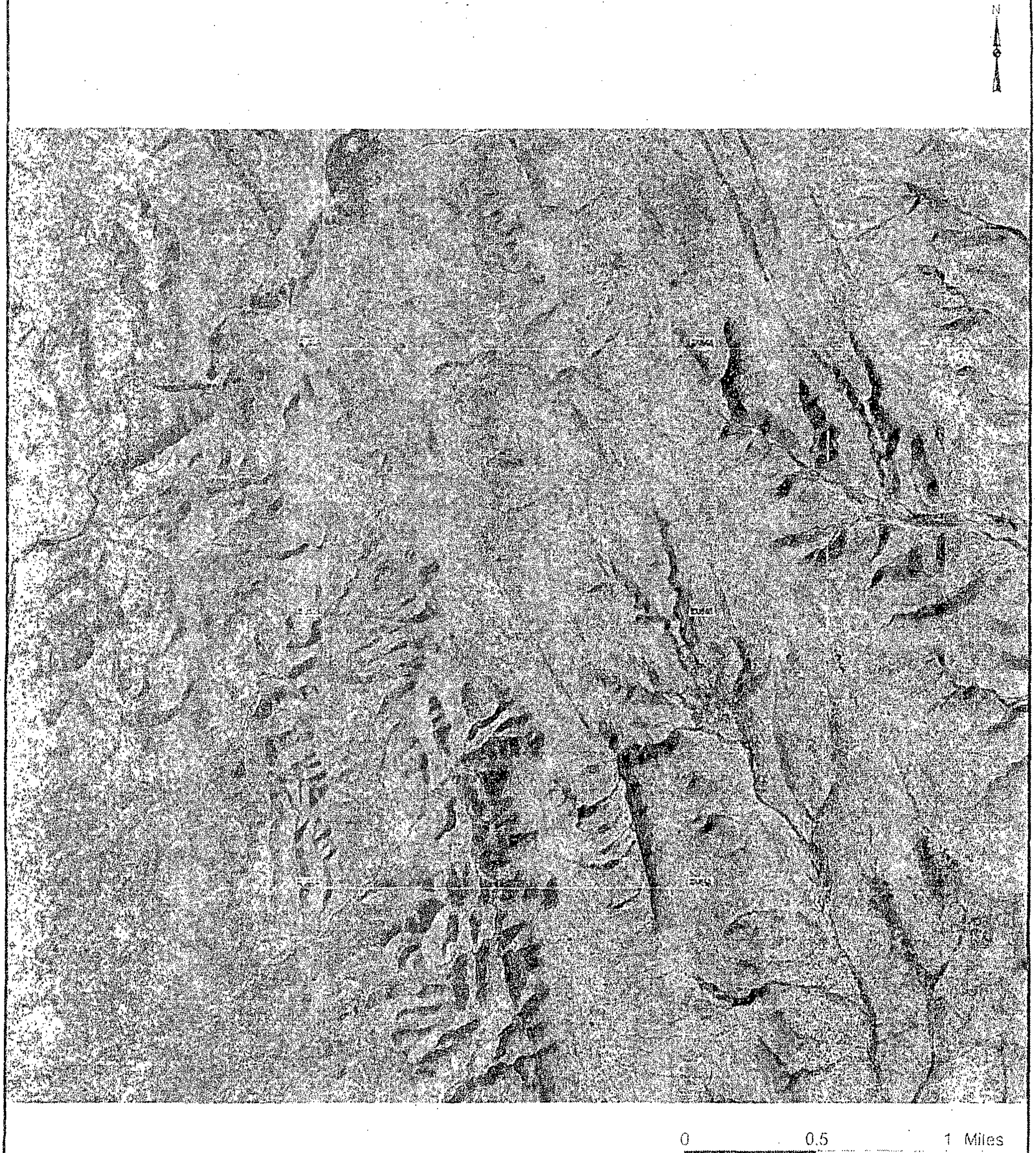

Figure 6. Aerial photograph mosaic from September 21, 1996, of southeastern Otero Mesa, showing system of northwest-trending lineaments.

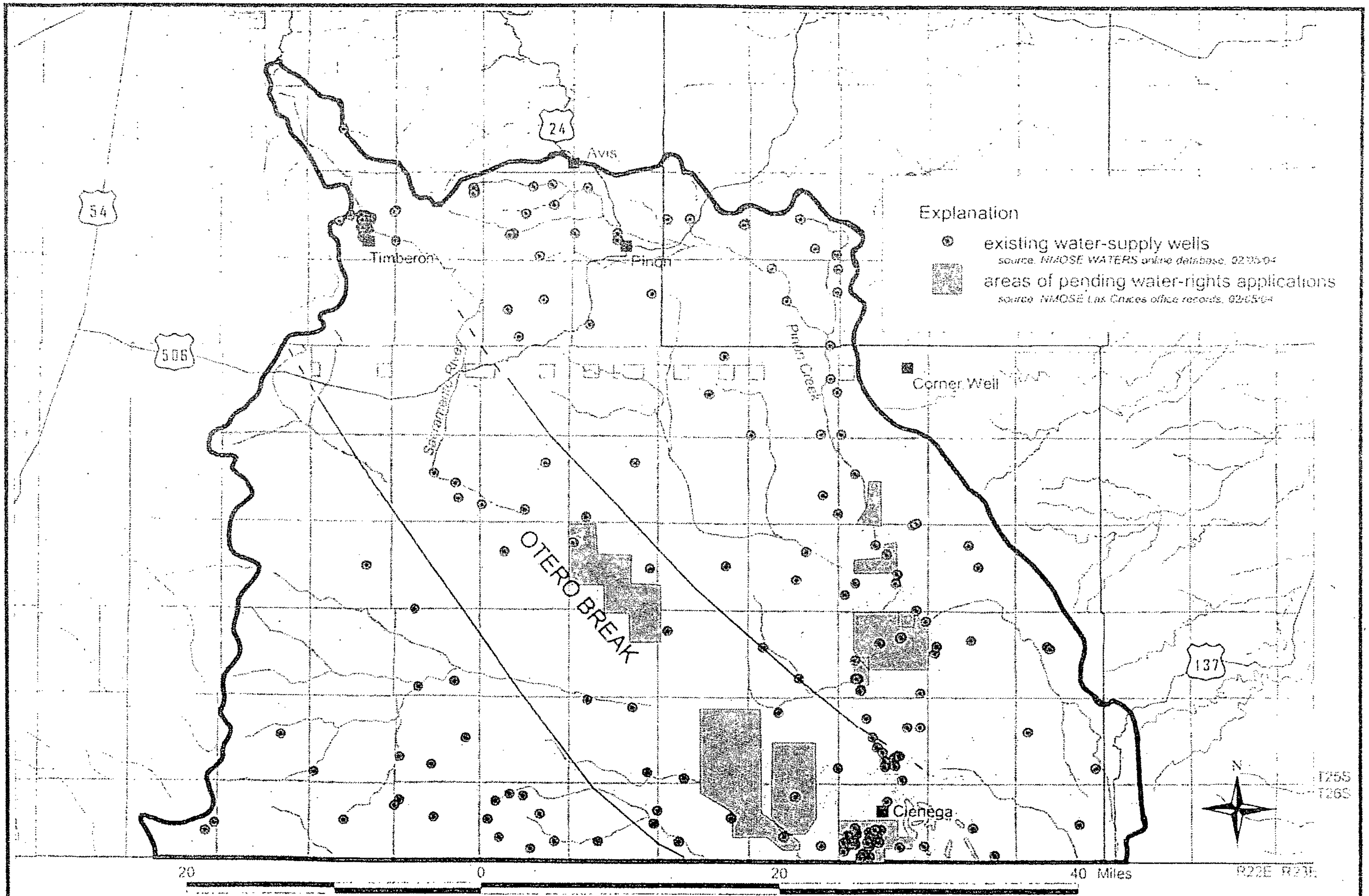

Figure 7. Map of Salt Basin, southern New Mexico, showing existing wells and locations of pending water-right applications.

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APPENDICES

Appendix A.

List of Water-Supply Wells in the Salt Basin

Appendix A. List of wells in Salt Basin from NMOSE WATERS online database 02/05/04.

1

Well Number	Use	Diversion (ac-ft/yr)	Owner	Tws	Rng	Sec	q q q	Easting	Northing	Date Completed	Well Depth (ft bgl)	Water Depth (ft bgl)
ST 00001	STK	3	J.P. CAUHAPE, INC.	19S	17E	36	4 1 4	485546	3607919	12/31/1929	15	4
ST 00002	STK	3	J.P. CAUHAPE, INC.	20S	17E	1	4 2 3	485746	3606310	7/31/1957	450	300
ST 00003	STK	3	J.P. CAUHAPE, INC.	20S	17E	5	3 2	478599	3606417	12/31/1914	1100	1020
ST 00004	STK	3	J.P. CAUHAPE, INC.	20S	17E	16	3 4	480207	3602796	12/31/1918	650	550
ST 00005	DOM	3	IRA DEE & BARBARA ELAINE TIDWE	19S	17E	22	1	481623	3611849	12/31/1940	1150	1000
ST 00006	STK	3	IRA DEE & BARBARA ELAINE TIDWE	19S	17E	35	1	483230	3608626	12/31/1965	860	600
ST 00007	STK	3	OLIN D. JR. & DOROTHY A. HAMMA	20S	17E	13	2	485640	3603796	12/31/1965	585	460
ST 00008	STK	3	VAN CLEVE FAMILY TRUST	19S	16E	20	2	469835	3611813	12/31/1929	975	935
ST 00009	STK	3	VAN CLEVE FAMILY TRUST	19S	16E	19	1	467425	3611767	12/31/1946	1210	1150
ST 00010	STK	3	DREW OR CINDY GOSLIN	19S	16E	24	4 1 1	475813	3611359	12/31/1984	120	60
ST 00011	DOM	3	JAMES O. OR JEANETTE R. COUPLA	20S	15E	29	3 1 2	459089	3600142	12/31/1939	1040	150
ST 00012	DOM	5	GLENN OR MINNIE STEVENSON	19S	16E	24	3 2	475604	3611202	12/31/1927	350	
ST 00013	STK	3	W.W.JR. OR ORA MCDANIELS	19S	16E	24	3 2	475604	3611202	12/31/1944	35	30
ST 00014	DOM	6	ELDO LEWIS	23S	18E	29	1 1 1	487613	3571455	12/31/1906	300	110
ST 00015	STK	3	ELDO LEWIS	24S	18E	11	3 3	492536	3565319	12/31/1905	180	100
ST 00016	STK	3	ELDO LEWIS	23S	18E	30	3 4	486508	3570154	12/31/1950	300	140
ST 00017	STK	2	ELDO LEWIS	23S	17E	22	3 3	481221	3571776	12/31/1961	660	450
ST 00018	STK	3	J.P. CAUHAPE, INC.	21S	16E	2	1 4 3	473525	3596629	6/30/1954	1280	1150
ST 00019	STK	3	J.P. CAUHAPE, INC.	21S	17E	31	3 3	476414	3587873	7/31/1947	1035	950
ST 00020	STK	3	VAN CLEVE FAMILY TRUST	19S	14E	34	4	453734	3607679	12/31/1964	1080	650
ST 00021	DOM	3	SAM TOM LEWIS	20S	15E	13	1 4 3	465743	3603531	12/31/1952	1430	1400
ST 00022	DOM	3	TOM WOODS RUNYAN	21S	16E	22	1 2 1	471907	3592408	12/31/1961	2700	1390
ST 00023	DOM	3	TOM WOODS RUNYAN	21S	16W	18	3 2 2	168307	3598778	12/31/1914	1440	1400
ST 00024	STK	0	CAMBALACHIE ENTERPRISES	26S	13E	7	1	438219	3547223	12/31/1966	560	535
ST 00025	STK	0	CAMBALACHIE ENTERPRISES	25S	11E	14	3	425153	3554603	12/31/1965	540	500
ST 00026	STK	0	CAMBALACHIE ENTERPRISES	25S	13E	30	1	438279	3552047	12/31/1959	200	150
ST 00027	STK	0	CAMBALACHIE ENTERPRISES	25S	13E	28	4	441859	3551227	12/31/1948	550	490
ST 00028	STK	140651	CAMBALACHIE ENTERPRISES	25S	13E	13	3 3 3	445590	3554122	12/31/1946	200	185
ST 00029	STK	3	WILLIAM T. JONES	26S	15E	29	2 2 2	459867	3542590	12/31/1959	700	670
ST 00030	STK	3	WILLIAM T. JONES	26S	14E	27	3 2 2	452570	3541812	12/31/1963	317	300
ST 00031	DOM	3	WILLIAM T. JONES	26S	14E	25	1 1 1	455193	3542611	12/31/1947	150	116
ST 00032	STK	3	WILLIAM T. JONES	26S	14E	14	1 1 3	453595	3545633	12/31/1961	310	186
ST 00033	IRR	75	COLQUET WARREN	25S	18E	27	2 2 2	492226	3552145	1/31/1956	300	40

Well Number	Use	Diver-sion (ac-ft/yr)	Owner	Tws	Rng	Sec	q q q	Easting	Northing	Date Completed	Well Depth (ft bgl)	Water Depth (ft bgl)
ST 00034	DOM	3	THOMAS S. COOPER	26S	14E	20	3 4 1	449159	3543034	12/31/1945	600	550
ST 00035	DOM	0	SNOW LAND AND CATTLE, INC.	23S	15E	24	1 2 4	465541	3573042	12/31/1916	650	600
ST 00036	DOM	0	SNOW LAND AND CATTLE, INC.	24S	16E	7	2 3 3	467409	3566080	12/31/1961	550	480
ST 00037	STK	0	JOHN V. WHITE	24S	19E	16	2 2 2	500056	3565008	8/21/1963	900	707
ST 00038	DOM	3	ALTON JONES	25S	15E	5	1	458784	3558365	12/31/1908	1000	600
ST 00039	STK	3	ALTON JONES	26S	14E	8	1 3 1	448775	3547065	12/31/1947	350	280
ST 00040	STK	3	ROBERT A. JONES	25S	16E	32	4 1 4	469167	3549592	12/31/1920	600	500
ST 00041	DOM	0	ROBERT A. JONES	26S	14E	4	3 3 1	450387	3547863	12/31/1952	300	250
ST 00042	STK	3	ROBERT A. JONES	25S	15E	2	3	463609	3557547	12/31/1915	600	500
ST 00043	DOM	0	ROBERT A. JONES	25S	15E	36	1	465211	3550310	12/31/1906	800	600
ST 00044	STK	3	JAMES W. BENNETT	26S	15E	12	4 4 4	466306	3545981	12/31/1961	800	488
ST 00045	DOM	3	JAMES W. BENNETT	26S	15E	13	4 3 2	465899	3544574	12/31/1963	860	350
ST 00046	STK	3	JAMES W. BENNETT	26S	16E	14	2 4 3	474196	3545151	12/31/1900	425	350
ST 00047	STK	3	JAMES W. BENNETT	26S	16E	29	1 2 1	468548	3542556	12/31/1908	420	390
ST 00048	STK	2	JAMES RAY EVRAGE	24S	18E	1	4 2 3	495254	3567220	12/31/1904	112	95
ST 00049	STK	2	JAMES RAY EVRAGE	24S	18E	36	3 2 4	494645	3559187	12/31/1921	90	83
ST 00050	STK	2	JAMES R. EVRAGE	24S	19E	18	4 3 3	496235	3563604	12/31/1904	200	
ST 00051	STK	3	ELMER CLIFFORD AKERS	26S	14E	4	4 4 4	451795	3547655	7/15/1976	260	205
ST 00052	STK	3	ELDO LEWIS PARTNERSHIP	22S	18E	36	3 3 4	494255	3578071	12/31/1960	450	400
ST 00052	STK	2	ELDO LEWIS	22S	18E	36	3 3 4	494255	3578071	12/31/1960	450	400
ST 00053	STK	3	ELDO LEWIS	23S	18E	22	2 4 4	492242	3572447	12/31/1973	330	185
ST 00053				23S	18E	22	2 4 4	492242	3572447	12/31/1973	330	185
ST 00054	DOM	0	PEARL P. LEWIS FAMILY TRUST	25S	18E	21	2 3 3	490013	3553159	12/31/1952	300	75
ST 00055	STK	0	PEARL P. LEWIS RANCH, LLC	22S	13E	23	1 4	444603	3582444	12/31/1959	1018	920
ST 00055	STK	0	PEARL P. LEWIS FAMILY TRUST	22S	13E	23	1 4	444603	3582444	12/31/1959	1018	920
ST 00056	STK	0	PEARL P. LEWIS RANCH, LLC	22S	14E	30	3 3	447402	3580022	9/30/1960	900	775
ST 00056	STK	0	PEARL P. LEWIS FAMILY TRUST	22S	14E	30	3 3	447402	3580022	9/30/1960	900	775
ST 00057	IRR	5000	CIMARRON AGRICULTURAL, LTD	26S	18E	21	2 2 3	490393	3543903	12/31/1949	156	78
ST 00057 S				26S	18E	21	2 2 3	490393	3543903	12/31/1949	93	70
ST 00058	IRR	8000	CIMARRON AGRICULTURAL, LTD.	26S	18E	21	4 1 1	489987	3543299	12/31/1949	430	73
ST 00058 S				26S	18E	21	4 1 1	489987	3543299	12/31/1949	430	73
ST 00058 S-2				26S	18E	28	2 1 2	490184	3542493	12/31/1949	130	
ST 00059	IRR	11000	CIMARRON AGRICULTURAL, LTD	26S	18E	21	1 3 1	489183	3543704	12/31/1949	430	81

Well Number	Use	Diver-sion (ac-ft/yr)	Owner	Tws	Rng	Sec	q q q	Easting	Northing	Date Completed	Well Depth (ft bgl)	Water Depth (ft bgl)
ST 00059 S				26S	18E	28	1 3 1	489176	3542092	12/31/1949	430	81
ST 00059 S-2				26S	18E	21	3 3 1	489180	3542898	12/31/1949		
ST 00059 S-3				26S	18E	21	3 3 4	489380	3542698	12/31/1949	1008	70
ST 00060	IRR	8500	CIMARRON AGRICULTURAL, LTD	26S	18E	29	1 1 3	487567	3542299	12/31/1950	520	81
ST 00060 S				26S	18E	29	1 1 3	487567	3542299	12/31/1950	520	81
ST 00060 S-2				26S	18E	29	1 1 1	487567	3542499	12/31/1950	550	85
ST 00061	IRR	2000	CIMARRON AGRICULTURAL, LTD.	26S	18E	33	1 3 3			12/31/1950	300	65
ST 00061 S				26S	18E	33	1 1 1	489170	3540881	12/31/1949	86	46
ST 00062	DOM	3.25	RICHARD LESSENTINE	18S	12E	21	1 2 1	432181	3621776	6/30/1980	290	224
ST 00062	DOM	0	RICHARD P. LESSENTINE	18S	12E	21	1 2 1	432181	3621776	6/30/1980	290	224
ST 00064	STK	3	THE DIAMOND A CATTLE CO.	26S	19E	35		502566	3541090	12/31/1946		
ST 00065	STK	3	THE DIAMOND A CATTLE CO.	26S	18E	26	1 3 3	492400	3541884	12/31/1963		
ST 00066	STK	3	THE DIAMOND A CATTLE CO.	26S	19E	22	1 1 1	500254	3544081	12/31/1946	72	
ST 00067	DOM	0	T.A. TANNER	21S	17E	13	4 4	485672	3592683	12/31/1947	228	203
ST 00068	DOM	0	T.A. TANNER	21S	17E	13	4 4	485672	3592683	12/31/1947	244	219
ST 00069	STK	7	GEORGE WESLEY RAUCH	23S	19E	9	2 4 3	499834	3575648	12/31/1982	940	900
ST 00070	STK	20	GEORGE WESLEY RAUCH	23S	19E	15	3 4 4	500845	3573238	12/31/1961	750	725
ST 00071	IRR	800	GEORGE W. RAUCH	23S	18E	15	1 1 2	491038	3574663	12/31/1968	600	225
ST 00072	IRR	0	GEORGE W. RAUCH	23S	18E	2	2 2 2	493854	3577866	12/31/1968	500	300
ST 00073	STK	5	GEORGE W. RAUCH	23S	18E	36	3 3 4	494248	3568426	12/31/1961	500	450
ST 00074	IRR	3520	GEORGE W. RAUCH	24S	19E	18	2 3 4	496435	3564407	12/31/1954	450	148
ST 00075	STK	10	GEORGE W. RAUCH	22S	18E	17	3 1 1	487621	3583522	12/31/1940	500	400
ST 00076	STK	5	GEORGE W. RAUCH	23S	18E	27	2 2 1	492040	3571442	12/31/1961	600	500
ST 00077	STK	5	GEORGE W. RAUCH	24S	20E	16	1 3 4	508261	3564389	12/31/1978	1250	1100
ST 00078	DOM	10	GEORGE W. RAUCH	23S	18E	9	1 4 4	489831	3575671	12/31/1902	300	225
ST 00079	DOM	2.02	WILLIAM J. & DORTHEY BUDAGHER	20S	15E	29	3 1 2	459089	3600142	12/31/1939	1000	150
ST 00080	STK	16.13	WESTERN BANK	20S	14E	33	1 4 4	451456	3598756	12/31/1948	1150	1130
ST 00081	STK	8.06	BRYAN & JUDY L. PRATHER	22S	14E	11	3 4 4	454340	3584720	12/31/1950	650	635
ST 00083	IRR	7	JOHN G. SCHAFER	24S	18E	29	3 1 4	487796	3560800	2/13/1967	200	110
ST 00084	IRR	0	JOHN G. OR L. JANE SCHAFER	24S	18E	29	3 1 4	487796	3560800	6/7/1982	235	110
ST 00085	STK	2	JOHN G. OR L. JANE SCHAFER	24S	18E	29	3 2 3	487999	3560800	12/31/1932	100	110
ST 00086	STK	4	JOHN G. OR L. JANE SCHAFER	24S	18E	11	3 3 2	492635	3565418	12/31/1958	180	110
ST 00087	DOM	5	JOHN G. OR L. JANE SCHAFER	24S	18E	29	3 1 3	487596	3560800	7/10/1964	200	110

Appendix A. List of wells in Salt Basin from NMOSE WATERS online database 02/05/04.

Well Number	Use	Diversion (ac-ft/yr)	Owner	Tws	Rng	Sec	q q q	Easting	Northing	Date Completed	Well Depth (ft bgl)	Water Depth (ft bgl)
ST 00088	IRR	1260	JOHN G. OR L. JANE SCHAFER	24S	18E	20	1 3 3	487598	3562810	6/3/1974	350	110
ST 00089	IRR	560	JOHN G. OR L. JANE SCHAFER	24S	18E	29	3 2 3	487999	3560800	7/1/1964	425	110
ST 00090	STK	3	CAMBALACHIE ENTERPRISES	26S	10E	13	4 4 3	417933	3544699	12/31/1930	200	160
ST 00091	STK	3	CAMBALACHIE ENTERPRISES	26S	10E	24	1 3 4	416921	3543902	12/31/1967	900	710
ST 00092	DOM	3	CAMBALACHIE ENTERPRISES	24S	13E	35	1 2 1	444414	3560430	12/31/1900	800	600
ST 00093	DOM	4	DOROTHY G. LEWIS	25S	18E	27	2 1 4	491823	3551947	12/31/1963	130	
ST 00094	IRR	574	DOROTHY G. LEWIS	25S	18E	27	2 2 2	492226	3552145	12/31/1958	152	
ST 00095	STK	3	HFR CORP.	24S	20E	16	3 2	508563	3564086	12/31/1975	1050	
ST 00096	STK	3	HFR CORP	25S	20E	25	3 4	513407	3550798	12/31/1975	1750	
ST 00097	STK	46	CAMBALACHIE ENTERPRISES	24S	13E	32	2 4 3	440393	3559861	12/31/1900	500	90
ST 00098	STK	3	KENNETH TIDWELL TRUST	20S	14E	20	4 1 2	450263	3601773	12/31/1950	930	
ST 00099	STK	3	BOB JONES	26S	14E	18	4 1 1	447962	3545055	12/31/1982	200	150
ST 00100	STK	3	CAMBALACHIE ENTERPRISE	25S	13E	13	3 3 3	445590	3554122	12/31/1945	190	170
ST 00101	STK	19	CAMBALACHIE ENTERPRISES	26S	13E	16	2 4 4	442132	3545293	12/31/1950	800	610
ST 00102	STK	16	CAMBALACHIE ENTERPRISES	23S	12E	23	1 1 2	434625	3573349	12/31/1916	550	490
ST 00103	STK	48	CAMBALACHIE ENTERPRISES	24S	13E	5	2 1 1	440026	3568508	12/31/1915	560	490
ST 00104	IRR	429	CAMBALACHIE ENTERPRISES	24S	13E	32	2 4 3	440393	3559861	12/31/1978	400	90
ST 00105	STK	77	CAMBALACHIE ENTERPRISES	24S	13E	32	2 4 3	440393	3559861	12/31/1960	400	90
ST 00106	STK	3	THOMAS S. COOPER	26S	12E	12	4 2 2	437711	3546602	7/6/1963	570	420
ST 00107	STK	3	THOMAS S. COOPER	25S	12E	31	1	428753	3550403	8/1/1962	380	280
ST 00108	STK	3	THOMAS S. COOPER	26S	12E	16	3 2 2	432067	3545038	12/31/1945	610	540
ST 00110	IRR	45	JOHN V WHITE	25S	18E	27	2 3 2	491824	3551745	12/31/1966	500	45
ST 00111	MDW	1499	TIMBERON WATER CO., INC.	19S	12E	23	1	435249	3611861	2/13/2001	490	110
ST 00111	EXP	0	TIMBERON WATER & SAN DISTRICT	19S	12E	23	1	435249	3611861	2/13/2001	490	110
ST 00111 S				19S	12E	23	1 3 4	435147	3611559	9/14/2000	400	50
ST 00111 S	MDW	0	TIMBERON WATER & SANTIATION DT	19S	12E	23	1 3 4	435147	3611559	9/14/2000	400	50
ST 00112	EXP	0	TIMBRON WATER & SANITATION DIS	19S	12E	13	4 2 4	437974	3612658	3/28/2001	100	25
ST 00113	EXP	0	TIMBERON WATER & SANITATION	19S	12E	25	4 4 2	437946	3609312	2/3/2001	600	
ST 00114	EXP	0	TIMBERON WATER & SANITATION	19S	12E	13	4 2 4	437974	3612658	1/29/2001	400	
ST 00115	STK	10.61	PINON CATTLE COMPANY	19S	14E	28	1 1 3	450906	3610180		700	
ST 00115 S				19S	13E	12	1 4 2	446708	3614798		700	
ST 00115 S-10				19S	13E	12	1 2 1	446510	3615199	5/13/2003	1005	740
ST 00115 S-2				19S	13E	12	1 4 3	446508	3614598		700	

Well Number	Use	Diver-sion (ac-ft/yr)	Owner	Tws	Rng	Sec	q q q	Easting	Northing	Date Completed	Well Depth (ft bgl)	Water Depth (ft bgl)
ST 00115 S-3				19S	14E	28	1 3 1	450837	3609983		700	
ST 00115 S-4				19S	14E	3	3 4 3	453042	3615369		700	
ST 00115 S-5				19S	14E	16	4 4 1	452257	3612358		700	
ST 00115 S-6				19S	14E	2	4 3 1	455105	3615607		700	
ST 00115 S-7				19S	15E	7	2 2 2	458891	3615291		700	
ST 00115 S-8				19S	14E	14	2 1 4	455316	3613358		700	
ST 00115 S-9				19S	14E	29	2 4 1	450454	3609982		700	
ST 00116	IRR	760.5	LOLA BETH BULLARD	26S	18E	19	4 2 4	487368	3543106	5/31/1950	180	110
ST 00116 A	IRR	1320	CIMARRON AGRICULTURAL, LTD.	26S	18E	19	4 2 4	487368	3543106	12/31/1950	180	110
ST 00116 A	IRR	0	L.N. SAUL	26S	18E	19	4 2 4	487368	3543106	12/31/1950	180	110
ST 00116 A-S				26S	18E	19	4 3 3	486764	3542704	12/31/1958	120	110
ST 00116 B				26S	18E	20	1 3 4	487772	3543508	1/31/1996	253	113
ST 00116 S				26S	18W	19	4 3 3	148674	3548957	5/31/1958	120	110
ST 00118	DOM	3	CIMARRON AGRICULTURAL, LTD.	26S	18E	19	4 1 1	486765	3543308	12/31/1950		
ST 00119	DOM	3	JAMES P. & CYNTHIA D LIVERS	19S	15E	28	2 2	462031	3610256		1500	
ST 00120	IRR	874.5	VIRGINIA L BROWNFIELD	26S	18E	30	2 3 1	486760	3542098	12/31/1950	250	90
ST 00121	IRR	0	HUNT BUILDING CORP.	26S	18E	21	3 1 3	489181	3543101			
ST 00123	STK	40	CIMARRON AGRICULTURAL, LTD.	26S	18E	21	1 2 4	489788	3543906	12/31/1949	234	70
ST 00125	DOM	14.8	HUNT BUILDING CORP.	26S	18E	29	2 2 2	488975	3542496	12/31/1949		170
ST 00127	IRR	3	CIMARRON AGRICULTURAL, LTD.	26S	18E	29	4 3 1	488367	3541288	12/31/1949		
ST 00129	IRR	12.9	CAMBALACHIE ENTERPRISES	24S	13E	35	1 2 1	444414	3560430	12/29/1890	710	647
ST 00130	EXP	0	TIMBERON WATER & SAN DISTRICT	19S	12E	13	4 4 1	437770	3612511	3/29/2001	60	25
ST 00131	STK	8.46	LAHEETA L. HARVEY	22S	13E	16	4 2 4	442296	3583559	12/31/1970	1080	
ST 00132	STK	8.46	LAHEETA L. HARVEY	22S	13E	26	2 3 3	444896	3580734	12/31/1970	925	877
ST 00133	STK	9.94	LAHEETA L. HARVEY	22S	14E	34	1 1 3	452103	3579501	12/31/1970	600	475
ST 00134	STK	8.96	LAHEETA L. HARVEY	22S	15E	11	3 4 4	463957	3584709	12/31/1950	635	
ST 00135	STK	16.44	LAHEETA L. HARVEY	22S	15E	32	3 1 4	458711	3578679	12/31/1900	480	
ST 00136	STK	25.35	LAHEETA L. HARVEY	23S	14E	17	2 1 2	449872	3574887	12/31/1970	730	
ST 00137	STK	9.94	LAHEETA L. HARVEY	23S	15E	7	1 4 3	457305	3575866	12/31/1970	445	
ST 00138	STK	3	MARTHA W. SKEEN	25S	20E	18	2 4	506164	3554844	12/31/1971	2800	
ST 00138	STK	0	MILTON A. HUGHES	25S	20E	18	2 4	506164	3554844	12/31/1971	2800	
ST 00141	IRR	525	ELMER W. HEPLER	24S	18E	32		488296	3559494	2/28/1964	900	
ST 00141 S				24S	18E	32	2 3			4/30/1966	350	

Well Number	Use	Diver-sion (ac-ft/yr)	Owner	Tws	Rng	Sec	q q q	Easting	Northing	Date Completed	Well Depth (ft bgl)	Water Depth (ft bgl)
ST 00142	DOM	3	GARRY R & BONNIE G STARR	19S	12E	22	2 3 3	434132	3611573	7/20/2001	400	172
ST 00143	DOM	0	STUART C BROWN	19S	12E	26	1 1 1	434919	3610544		600	
ST 00144		0	TIMBERON WATER & SANITATION	19S	12E	22	4 3 3	434118	3610761		450	
ST 00145		0	TIMBERON WATER & SANITATION	19S	12E	27	4 1 2	434262	3609755		450	
ST 00146	IRR	480	LENDAL C. BARKER	26S	18E	30	3 2 1	486355	3541696	4/30/1955	446	
ST 00146 S				26S	18E	30	3 2 3	486355	3541496	4/30/1955	178	
ST 00147	IRR	0	B.V. BALLARD, JR.	25S	18E	16	3	489509	3554267	12/31/1957	472	
ST 00148	IRR	0	B.V. BALLARD, JR.	24S	18E	16	2	490320	3564718	8/31/1957	600	
ST 00149	DOM	3	JOHN PAUL FAIN	26S	18E	30	1 2 1	486359	3542502	12/31/1956	150	
ST 00150	IRR	420	JOHN PAUL FAIN	26S	18E	30	1 2 1	486359	3542502	12/31/1956	376	
ST 00151	IRR	705	CHARLES W. DICE	25S	18E	27	1 3 3	490819	3551548	7/31/1962	500	
ST 00152	IRR	20	ANDY A. LEWIS	25S	18E	21	4 4 2	490616	3552553	12/31/1934	250	
ST 00152 S				25S	18E	21	4 4 2	490616	3552553	12/31/1936	100	
ST 00153	STK	0	ANDY A. LEWIS	25S	17E	25	4 4 4	485729	3550766	12/31/1961	500	
ST 00154	STK	0	VIRGINIA LEWIS	26S	18E	10	1	491110	3547022	12/31/1908	70	
ST 00155	STK	0	VIRGINIA LEWIS	25S	18E	27	4	491926	3551042	12/31/1917	60	
ST 00156	STK	0	VIRGINIA LEWIS	25S	18E	35	3	492726	3549431	12/31/1917	50	
ST 00157	STK	0	VIRGINIA LEWIS	25S	18E	27	4	491926	3551042	12/31/1955	60	
ST 00158	STK	0	VIRGINIA LEWIS	25S	18E	35	3	492726	3549431	12/31/1956	60	
ST 00159	IRR	300	RAY LEWIS	26S	18E	25	2 3 2	495016	3542080	12/31/1955	500	
ST 00160	STK	3	MILTON A. HUGHES	26S	20E	14	3 4 1	511713	3544466	12/31/1964	2880	2510
ST 00161	STK	0	W.L. "PETE" LEWIS	24S	17E	18	4 2 2	477685	3564245	12/31/1948	810	500
ST 00162	STK	0	W.L. "PETE" LEWIS	24S	17E	27	3 2 3	481503	3560813	12/31/1958	448	400
ST 00163	STK	0	W.L. "PETE" LEWIS	25S	17E	8	2 2 2	479287	3556996	12/31/1945	505	450
ST 00164	STK	0	W.L. "PETE" LEWIS	25S	18E	8	2 4 3	488802	3556377	12/31/1903	125	67
ST 00165	STK	3	SPRING MESA LTD PARTNERSHIP	19S	15E	30	1 1 3	457516	3610173	12/31/1947	1425	1080
ST 00166	DOM	0.5	SPRING MESA LTD PARTNERSHIP	19S	15E	28	4 2	462034	3609436	12/31/1945	1370	1150
ST 00168	EXP	0	TIMBERON WATER & SANITATION DT	19S	12E	22	2 2 1	434545	3612170	9/5/2001	600	374
ST 00169	EXP	0	TIMBERON WATER & SANITATION DT	19S	12E	21	2 2 1	432925	3612185			
ST 00172				19S	12E	22	4 4 4	434728	3610756	8/30/2001	440	158
ST 00172	EXP	0	TIMBERON WATER & SANITATION DI	19S	12E	22	4 4 4	434728	3610756	8/30/2001	440	158
ST 00173	EXP	0	TIMBERON WATER & SAN DIST	19S	12E	22	2 1 1	434139	3612179	9/6/2002	1200	540
ST 00180 S	AGR	0	CHESTER WALKER	24S	18E	32	3 2 2	488196	3559392	12/31/1963	600	70

Appendix A. List of wells in Salt Basin from NMOSE WATERS online database 02/05/04.
7

Well Number	Use	Diver-sion (ac-ft/yr)	Owner	Tws	Rng	Sec	q q q	Easting	Northing	Date Completed	Well Depth (ft bgl)	Water Depth (ft bgl)
ST 00182	IRR	960	BRYAN ODIE PRATHER	25S	18E	26	1 1 1	492428	3552144	12/31/1957	150	50
ST 00183	EXP	0	TIMBERON GOLF ASSOCIATION	19S	12E	22	4 3 3	434118	3610761			
ST 00184	EXP	0	TIMBERON GOLF ASSOCIATION	19S	12E	22	4 3 4	434318	3610761	9/19/2002	700	560
ST 00185	DOM	3	ROSS AND LINDA L DORAN DURANT	19S	12E	21	1 3 3	431708	3611547		600	
ST 00186	IRR	77	L.N. SAUL	26S	18E	20	1 1 3	487574	3543912	12/31/1910	250	110
ST 00186 S				26S	18E	20	1 1 1	487574	3544112	11/7/1954	275	191
ST 00187	STK	3.46	L. N. SAUL	26S	17E	21	3 2 3	479863	3543123	7/28/1914	250	174
ST 00187 S				26S	17E	3	3 3 3	481094	3547555	1/4/1954	342	273
ST 00187 S-2				26S	17E	26	2 4 1	483885	3542103	1/12/1958	392	242
ST 00187 S-3				26S	17E	21	3 2 3	479863	3543123	12/31/1914		
ST 00187 S-4				26S	17E	26	2 4 1	483885	3542103	12/31/1958		
ST 00188	IRR	0	L. N. SAUL	26S	18E	32	1 2 2	488163	3540886	2/10/1953	260	55
ST 00189	DOM	3	CHARLES A & DONNA S RANDLEMAN	19S	12E	21	1 3 3	431708	3611547		400	
ST 00190	DOM	3	WILLIAM J & GERTRUDE C MERCHAN	19S	12E	22	2 2 3	434545	3611970	1/20/2003	167	60
ST 00191	IRR	700	BETTY ANN OLSEN	25S	18E	13	1 2 2	494642	3555359	12/31/1959	300	61
ST 00192	IRR	400	BETTY ANN OLSEN	25S	18E	14	2 1 1	493234	3555361	12/31/1959	300	61
ST 00194	STK	8	PAUL L. OR YVONNE R. MOTT	21S	17E	12	3 4 4	484967	3594192	12/31/1930		150
ST 00194 S				20S	17E	36	3 4 3	484926	3597862	12/30/1980	900	850
ST 00194 S-2				21S	17E	12	3 4 4	484967	3594192	12/31/1982		150
ST 00195	STK	3	FRANK D STEWART, II	22S	17E	26	2 2 2	484148	3581118	12/31/1918	450	439
ST 00196	STK	3	FRANK D STEWART, III	21S	18E	31	3 3 2	486169	3587953	12/31/1961	767	740
ST 00197	STK	3	FRANK D STEWART, II	23S	17E	10	4 4 3	482329	3574888	12/31/1946	550	525
ST 00198	STK	3	FRANK D STEWART, II	22S	17E	36	2 4 2	485753	3579106	12/31/1948	371	350
ST 00199	STK	3	FRANK D STEWART, II	23S	16E	14	3 4 4	473662	3573302	12/31/1960	800	775
ST 00200	STK	3	FRANK D STEWART, II	21S	17E	35	4 4 1	483958	3587956	12/31/1985	720	700
ST 00201	DOM	3	DAVID C PIETZ	19S	12E	27	4 2 3	434472	3609541		300	
ST 00205	DOM	3	ROY AND VIRGINIA SMITH	19S	12E	22	2 3	434233	3611674		300	
ST 00208	MUL	3	MARJORIE FLEMING	20S	14E	14	3 3	454174	3602885		800	
ST 00212	PRO	0	DAVID E. DICE	25S	18E	27	3 3 1	490820	3550943		500	
ST 00213	PRO	0	JANE SCHAFER	24S	18E	29	3 1 4	487796	3560800		235	

Appendix B.

Selected Pages and Figures from Mayer, 1995

THE ROLE OF FRACTURES IN REGIONAL GROUNDWATER FLOW: FIELD EVIDENCE AND MODEL RESULTS FROM THE BASIN-AND-RANGE OF TEXAS AND NEW MEXICO

by

JAMES ROGER MAYER, B.S., M.S.

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT AUSTIN

December, 1995

THE ROLE OF FRACTURES IN REGIONAL GROUNDWATER FLOW: FIELD EVIDENCE AND MODEL RESULTS FROM THE BASIN-AND-RANGE OF TEXAS AND NEW MEXICO

Publication No.______________

James Roger Mayer, Ph.D.
The University of Texas at Austin, 1995

Supervisor: John M. Sharp, Jr.

This study integrates fracture mapping and groundwater flow modeling to assess the role of fractures in regional groundwater flow. This is an important topic because fractures play a prominent role in groundwater flow in many aquifers. Furthermore, few studies have addressed quantitatively the regional hydrogeological implications of fractures.

The study area is located in west Texas and southern New Mexico, between the Salt Basin and the Tularosa Valley. The region is largely undeformed, but the Permian carbonate bedrock is cut by many extensional faults and fractures. Air-photo analysis and field mapping reveal a broad fracture zone extending from the Sacramento Mountains to the Salt Basin near Dell City, Texas. Most fractures roughly parallel major normal faults and are oriented

approximately N20W. The most intense fracturing coincides with a prominent trough in the potentiometric surface and an apparent "plume" of relatively fresh groundwater. Flow simulation and chemical modeling suggest that fracturing has created a high permeability zone that funnels recharge from the Sacramento Mountains at least 80 km southeastward to discharge points in the Salt Basin and the Dell City irrigation district.

To estimate the regional transmissivity and to test the role of fractures in regional flow, a steady-state finite-element flow model was constructed in which fracture data are used to constrain a spatially distributed transmissivity. Given the probable range of recharge, discharge and other hydrologic parameters, fractures are the most important single constraint on the configuration of the potentiometric surface.

Major results include: (1) fracturing can control groundwater flow over large (>1000 km^2) areas, (2) effective recharge areas and regional groundwater chemistry trends are strongly influenced by fractures, and (3) through fracture studies, *a priori* inferences about aquifer properties and regional flow are possible. Finally, this study demonstrates one mechanism by which the timing and nature of tectonic events can affect regional subsurface fluid flow and, perhaps more importantly, related processes such as hydrothermal mineralization, diagenesis, and hydrocarbon transport and entrapment.

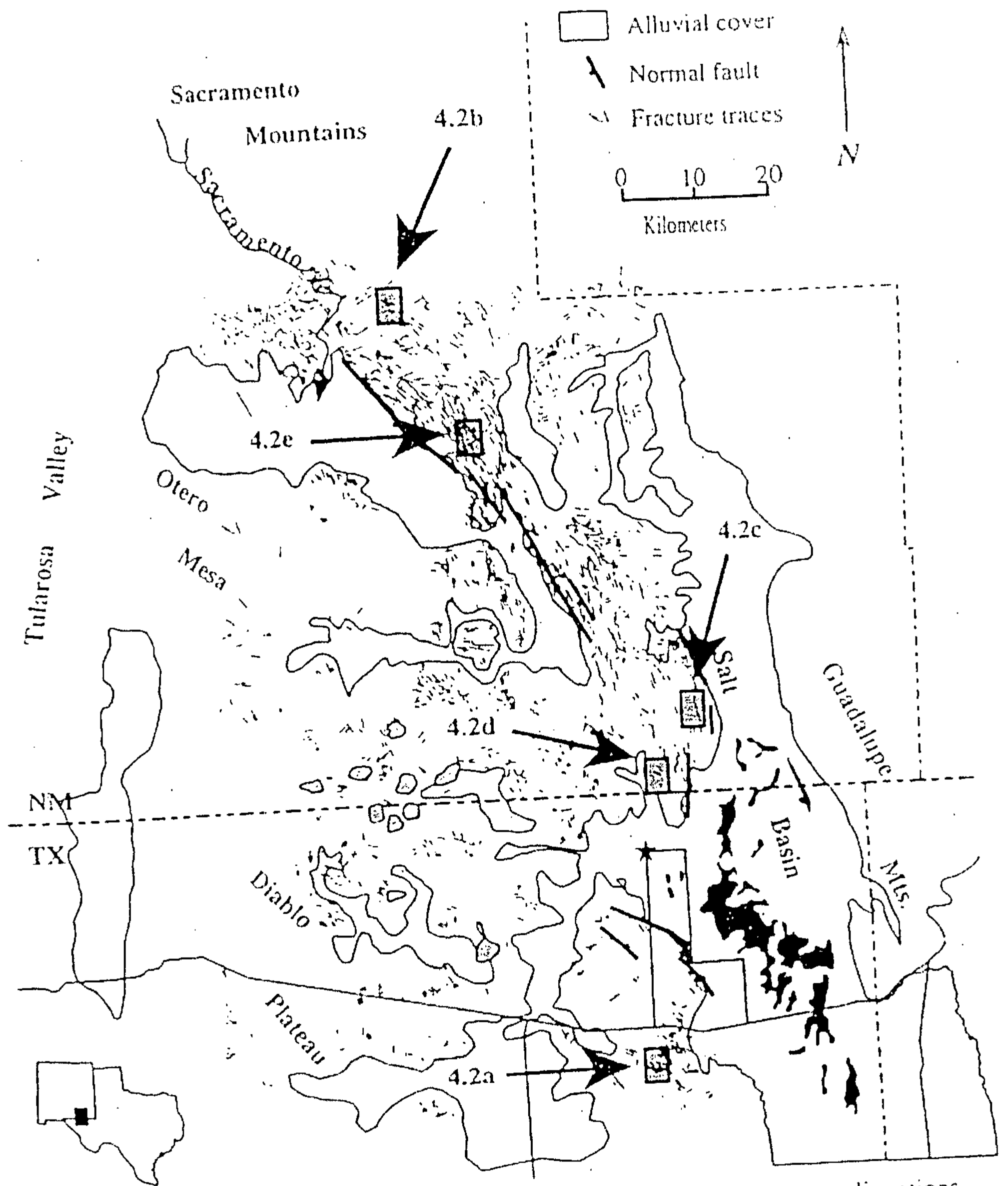

Figure 4.3: Locations of photographs of figure 4.2. Fine line segments represent lineations identified in this study. Note that very few lineations occur in areas covered by alluvium.

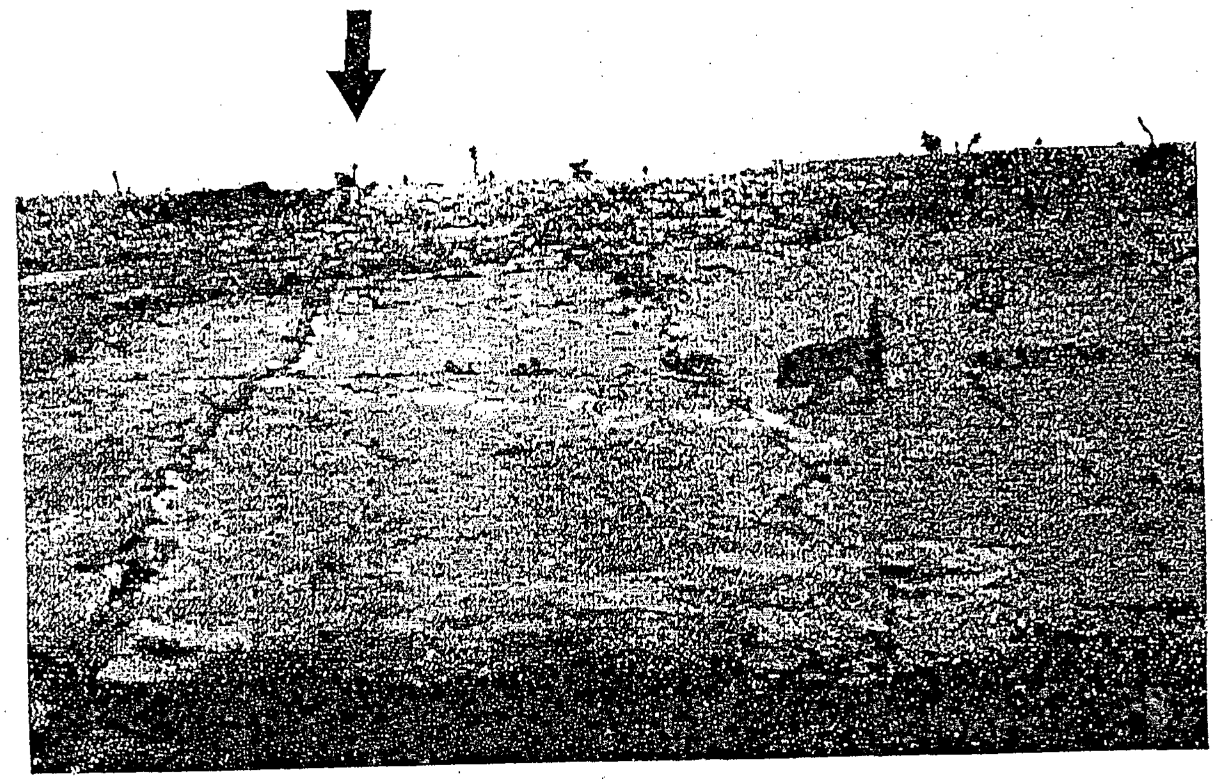

Figure 4.4: A fracture zone in the Otero Mesa. Picture is taken looking toward the southeast; 45-lb dog for scale. Note the alignment of large yucca plants along the left-most fracture trace (arrow) where soil covers the bedrock.

in the western Otero Mesa is probably lithologically controlled. The western Otero Mesa is underlain by the gypsum-rich Yeso Formation, and therefore it is less prone to fracturing than the more brittle strata of the carbonate-dominated units present throughout the rest of the area. The correlation between fractures and normal faults suggests that they formed as the result of the same tectonic events.

Fracture Zones

Based primarily on fracture density, but also on fracture orientation, the study area may be divided into distinct fracture zones (Figure 4.10). The boundaries of these zones are used to constrain hydraulic conductivity in a groundwater flow model in Chapter 6. Zone 1 is located along the Otero Break and is the most heavily fractured zone. There is a very strong preferred fracture orientation within this zone of approximately N20W, parallel with the normal faults of the Otero Break. Zones 2 and 3 each have significant fracture density and a dominant fracture orientation similar to Zone 1. In Zone 3 there appear to be two additional fracture sets not observed elsewhere. These are oriented approximately N40W and N50E. Zone 4 includes primarily the western Otero Mesa and Diablo Plateau and is characterized by relatively sparse fractures and no single, dominant fracture orientation. In this zone there are either additional fracture sets, or a largely random component of orientation. Zone 5 is composed of Salt Basin alluvium and no lineaments were mapped there.

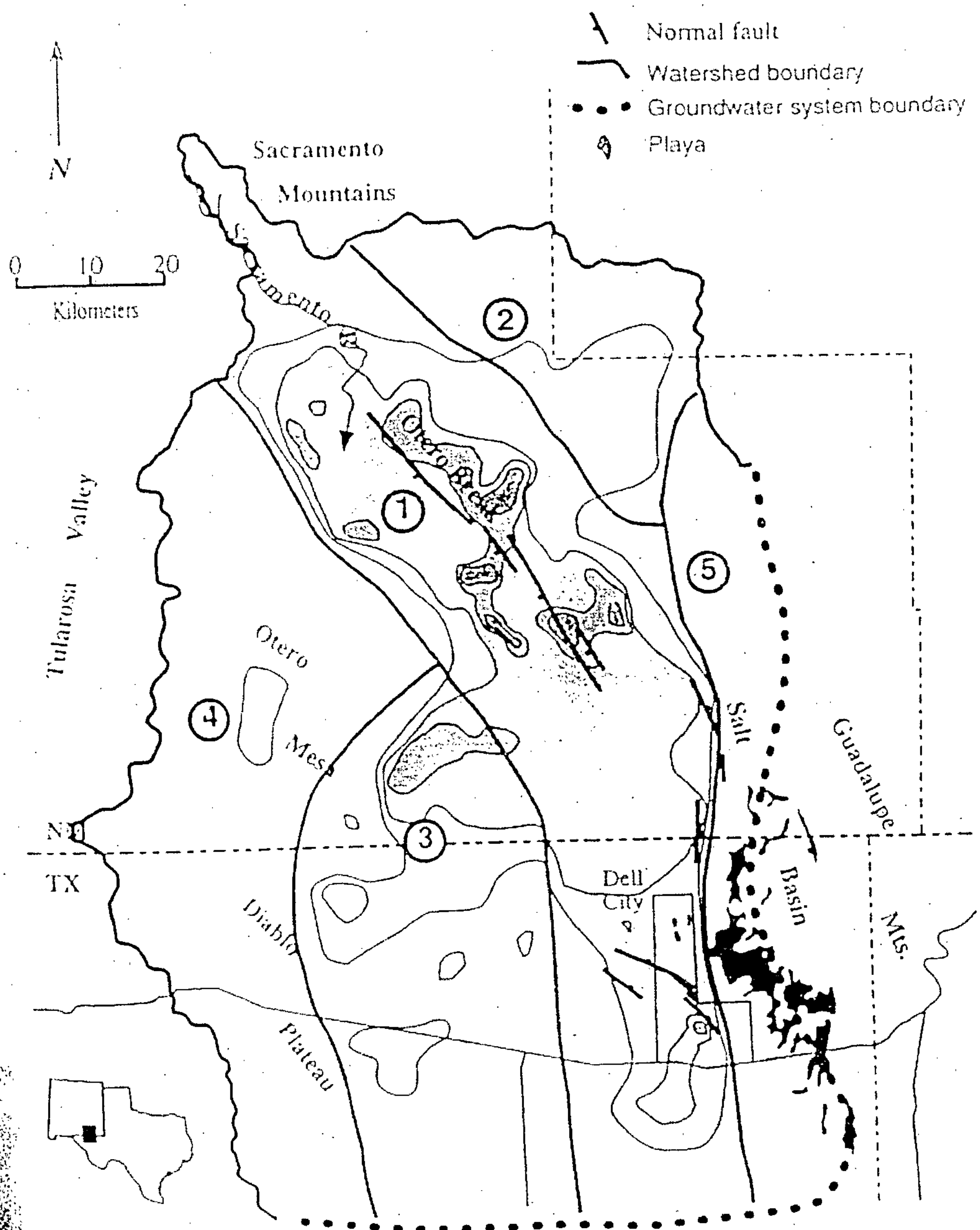

Figure 4.13: Fracture zones.

Fracture control of regional ground-water flow in a carbonate aquifer in a semi-arid region

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ABSTRACT

We integrate fracture mapping and numerical modeling to assess the role of fractures in regional ground-water flow. Although the importance of fractures in ground-water flow and solute transport is accepted generally, few studies have addressed quantitatively the regional hydrogeological implications of fractures. The field-study area in west Texas and southeastern New Mexico consists primarily of subhorizontal Permian carbonate rocks cut by extensional faults and fractures. Air-photo analysis and field mapping reveal a broad fracture zone extending from the Sacramento Mountains of New Mexico to the Salt Basin near Dell City, Texas. Most fractures are subparallel to major normal faults. The most intense fracturing coincides with a prominent trough in the potentiometric surface and an apparent "plume" of relatively fresh ground water. Flow models, corroborated by geochemical data, indicate that fracturing has created a high-permeability zone that funnels recharge from the Sacramento Mountains at least 80 km southeastward to its discharge zone.

A steady-state finite-element flow model uses fracture data to predict the spatial transmissivity distribution. Given the probable range of recharge, discharge, and other hydrologic parameters, fractures are the most important factor affecting the potentiometric surface configuration. Our study implies that: (1) fractures can control ground-water flow over large (>1000 km^2) areas; (2) effective recharge areas and regional ground-water chemistry trends are strongly influenced by fractures; and (3) a priori inferences about aquifer properties and regional flow are possible by means of fracture studies. This study demonstrates that the timing and nature of fracturing can affect regional subsurface fluid flow, as well as related processes such as hydrothermal mineralization, diagenesis, and hydrocarbon transport and entrapment.

INTRODUCTION

Fluid flow in fractures is important in ground-water resource development, the isolation, disposal, and cleanup of hazardous waste, petroleum migration, and hydrothermal mineral formation. Although the reservoir-scale hydraulics and the regional structural implications of fractures have been extensively studied, few studies address the regional hydrogeological implications of fractures (Mayer and Sharp, 1995) and fewer use fracture data when modeling regional flow and solute transport.

The main contribution of this study is to show that fracture data can improve our understanding of regional ground-water flow, especially in areas for which there are sparse hydrogeologic data. This is important because fractures commonly provide the only significant effective porosity and permeability of carbonate rocks, igneous and metamorphic rocks, and shales. In some aquifers, ground-water flow direction is determined as much by fracture-related anisotropy as by hydraulic gradient. In these situations, many common assumptions about flow and transport are inappropriate. In addition, high-permeability trends caused by preferential fracturing can create large-scale variations in flow rates and can determine if and where interbasin flow will occur and, thus, the extent of regional flow systems.

At the regional scale, fractured aquifers are typically modeled as equivalent porous media, and fracture data are ignored. For example, the Edwards aquifer in central Texas, a fractured carbonate aquifer that has been extensively studied, is generally modeled as a homogeneous (and often isotropic) system, even though fracture-related anisotropy is clearly indicated (Slade et al., 1985; Senger and Kreitler, 1984; McKinney and Sharp, 1995; Uliana and Sharp, 1996). On the other extreme, discrete fracture models (e.g., Dershowitz and Einstein, 1988), widely used for reservoir-scale modeling, require a level of subsurface characterization not normally feasible at the regional scale. For example, studies in mine tunnels (e.g., Long and Billaux, 1987) show that even if fracture orientation and apertures are known, we cannot predict a priori which fractures are conductive, perhaps because of their connectedness or channeling.

The goals of this study are to evaluate how regional fracture systems affect regional ground-water flow and to develop a conceptual framework for regional ground-water flow in fractured aquifers that allows use of fracture data. Specifically, we evaluate: (1) if regionally pervasive fracture systems create permeability trends and regional anisotropy that are manifest through hydraulic potential and water chemistry trends; (2) if fractured aquifers can be conceptualized in terms of fracture domains, each domain defined by internally consistent fracture patterns and hydraulic properties; and (3) if a priori fracture analysis significantly improves the predictive power of regional ground-water flow models.

STUDY AREA

The study area includes 9000 km^2 in Hudspeth County, Texas, and Otero County, New Mexico (Fig. 1). We refer to the study area as the Otero-Diablo region because most of it is on the Otero Mesa and the Diablo Plateau. Study-area boundaries generally coincide with the watersheds of the northern Salt Basin and the Sacramento River. Important physical features include the Sacramento Mountains, the Sacramento River, the Otero Mesa–Diablo Plateau, and the Salt Basin. Elevations range from 1095 m in the Salt Basin

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to more than 2750 m in the Sacramento Mountains. In the vicinity of Dell City, Texas, there is extensive irrigation where there is arable land.

The Otero-Diablo region is within the Basin and Range physiographic province. There are several distinct morphologic subdivisions within the study area (Fig. 2), the largest of which is the Diablo Plateau-Otero Mesa, which is a gently eastward-sloping plateau at an elevation between 1250 and 1500 m. Within the Diablo Plateau–Otero Mesa are Tertiary igneous intrusive rock bodies, including the Cornudas Mountains, that form distinctive, isolated landmarks on the otherwise low-relief plateau.

The Salt Basin is a major Basin and Range graben extending from south of Van Horn, Texas, north into New Mexico, where it terminates between the Sacramento and Guadalupe Mountains. The topographic floor of the Salt Basin is nearly planar and slopes gently to the south. The Salt Basin contains alluvial fill as thick as 750 m that is overlain by evaporites, primarily gypsum (Veldhuis and Keller, 1980). The Sacramento Mountains occupy the northernmost portion of the study area where they rise steeply from the Otero Mesa to elevations greater than 2750 m.

The Otero-Diablo region is characterized by a subtropical arid climate; most of the area is within the northern Chihuahuan Desert (Dick-Peddie, 1975). Summers are hot and dry; winters are generally mild, although short periods of severe winter weather are common. Weather and climate vary considerably across even small areas; most variation is a function of elevation. As elevation increases, precipitation increases, whereas potential evaporation and temperature decrease.

Annual precipitation varies from less than 25 cm in the Salt Basin to greater than 90 cm in the Sacramento Mountains (Fig. 3). Most precipitation occurs during violent but short-lived thunderstorms during July and August. Estimating average annual precipitation in the Otero-Diablo region is problematical because of the paucity of climate recording stations. However, precipitation is strongly dependent upon elevation. In Figure 4, precipitation values in the vicinity of recording stations are based on recorded values; far from recording stations, where most of this study is located, precipitation is based on elevation using the regression shown in Figure 3. Annual potential evaporation ranges from 190 cm at high elevations to 250 cm at low elevations (Hydrosphere Data Products, Inc., 1992). Because precipitation is greater and potential evapotranspiration is less, the most intense recharge occurs in the Sacramento Mountains.

The Sacramento River is the only perennial surface water in the region. It originates in the Sacramento Mountains and disappears into alluvial fans adjacent to the Otero Mesa (Fig. 5). There is a well-developed system of ephemeral streams throughout the region. Salt Basin playas are primarily ground-water discharge areas, but short-duration floods generated by storm runoff from surrounding areas occasionally fill them (Boyd and Kreitler, 1986). There are several Pleistocene lake beds in the Otero Mesa (Hawley, 1993) attesting to the effects of climate change in this region.

STRATIGRAPHY

The study area is composed almost exclusively of Permian carbonate rocks and associated clastic and evaporite rocks (Fig. 6). There are minor outcrops of pre-Permian sedimentary rocks, Tertiary and Precambrian igneous rocks, and Cretaceous sedimentary rocks, and there is a thin veneer of unconsolidated Quaternary deposits. The following discussion focuses on Permian stratigraphy.

The lower Permian Hueco Formation is the oldest unit that crops out extensively in the study area. It crops out in the western part of the Diablo Plateau and is composed primarily of limestone, dolomite, sandstone, mudstone, and conglomerate (Barnes, 1975).

The Yeso, Victorio Peak, and Bone Spring Formations are equivalent Leonardian to earliest Guadalupian formations that record deposition in the

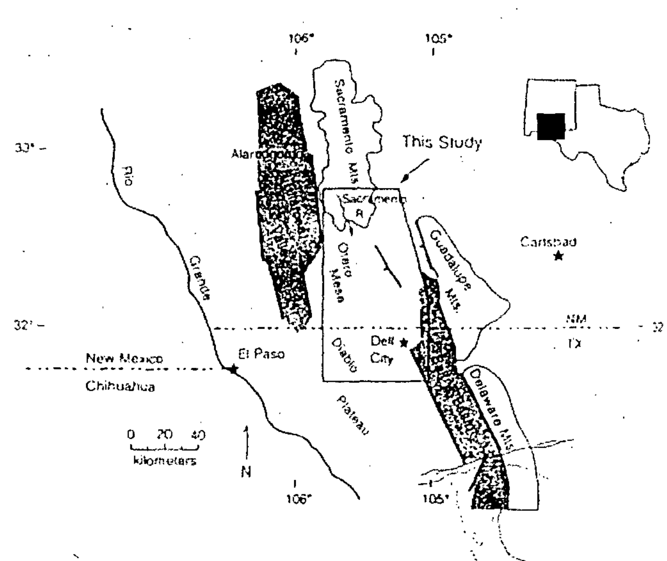

Figure 1. The Otero-Diablo study region. Salt Basin and Tularosa Valley are grabens of the Basin and Range physiographic province. Most of region occupies Otero Mesa and Diablo Plateau and is within the northern Chihuahuan Desert.

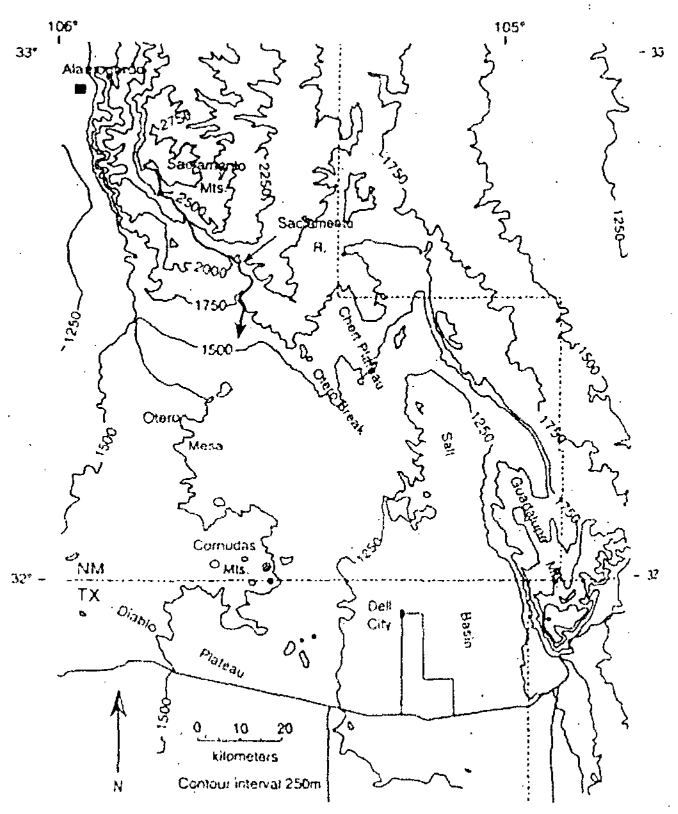

Figure 2. Geomorphological regions and topographic map of Otero-Diablo region. Elevations range from more than 2750 m in the Sacramento Mountains to 1095 m in the Salt Basin. The Sacramento River rises from base flow in the Sacramento Mountains and sinks into alluvial fans at base of the mountains.

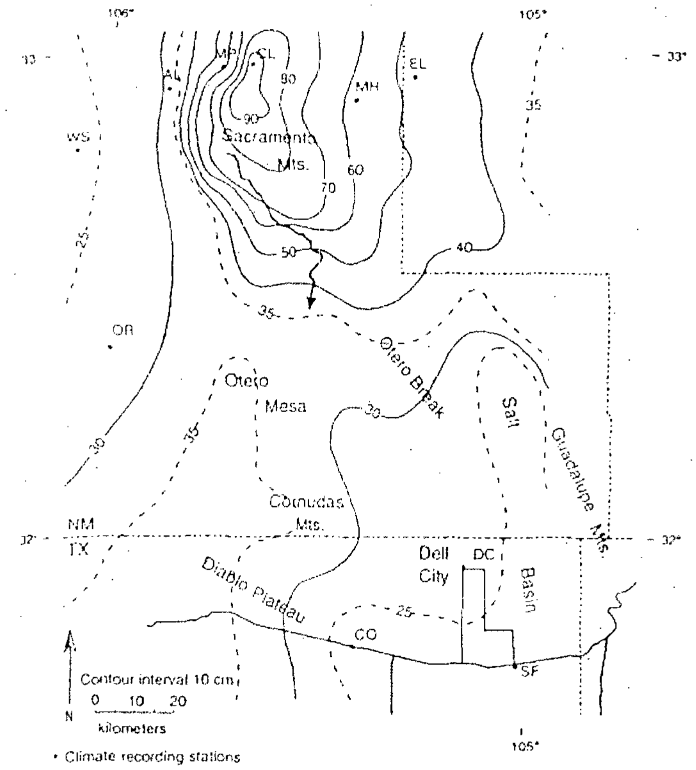

Figure 3. Precipitation (centimeters) in the Otero-Diablo region. Data distant from recording stations are calculated by elevation relationship illustrated in Figure 3. Note that the greatest precipitation by far (and thus the most intense recharge) occurs in the Sacramento Mountains. Recording stations: AL—Alamogordo; CL—Cloudcroft; CO—Cornudas; DC—Dell City; EL—Elk; MH—Mayhill; MP—Mountain Park; OR—Orogrande; SF—Salt Flat; WS—White Sands.

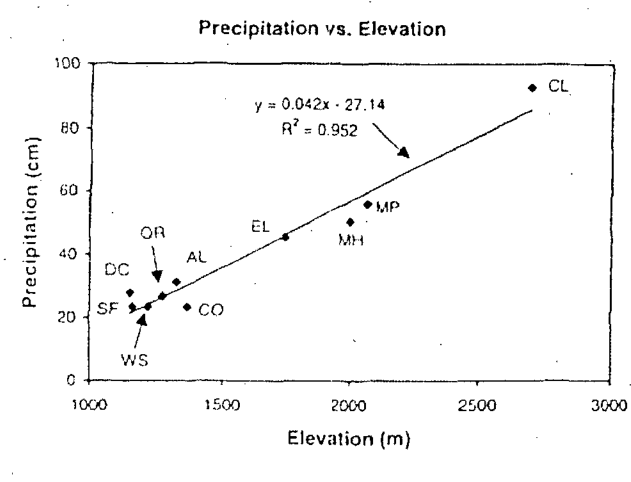

Figure 4. Precipitation (centimeters) as function of elevation (meters) from recording stations in and near the study area. Note strong dependence of precipitation on elevation. This relationship is used to calculate precipitation at points distant from recording stations. Recording station abbreviations as for Figure 3.

Delaware basin and the northwest shelf of the Delaware basin. The Bone Spring Formation is a deep-water limestone unit that crops out primarily to the south and east of the study area. However, there are minor outliers that crop out near the Cornudas Mountains; the formation is also present in the subsurface. The Bone Spring Formation is a thin-bedded, dark gray limestone unit, in part cherty, and has interbedded dolomite, sandstone, and shale. The Victorio Peak Formation, the shelf equivalent of the basinal Bone Spring Formation, crops out in the eastern Diablo Plateau and consists of limestone, dolomite, sandstone, and siltstone (Barnes, 1975).

The Yeso Formation is a heterogeneous unit of limestone, shale, gypsum, dolomite, sandstone, and minor halite; and was deposited in a transitional marine-terrestrial environment (Pray, 1961). The Yeso Formation is hydrogeologically significant because it contains abundant evaporites, primarily gypsum. Because of this, ground water in the Yeso Formation generally has a higher salinity than in other strata. Furthermore, the Yeso Formation is less fractured than other Permian carbonate formations.

The Leonardian–lower Guadalupian San Andres Formation is the most extensive unit to crop out in the study area. It is a gray, massive to thin-bedded limestone with increasing amounts of dolomite and gypsum to the

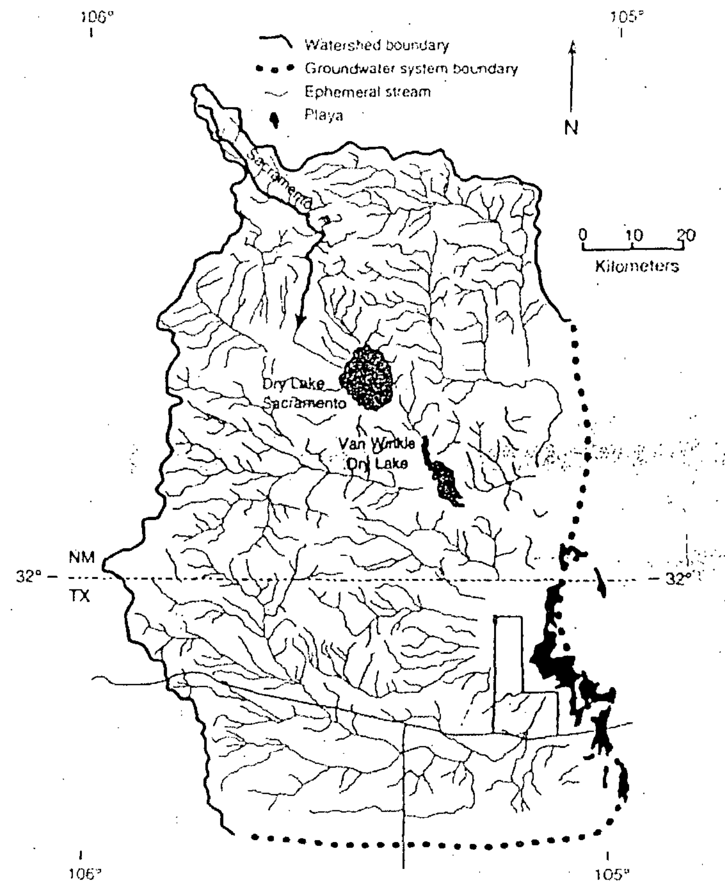

Figure 5. Hydrogeologic features of the Otero-Diablo region. Southern and eastern boundaries of the figure are symmetry boundaries defined by ground-water flow; other boundaries correspond to surface water divides. The only perennial surface water is the Sacramento River. Playas, dry lakes, and streams hold water only after heavy rains. Natural discharge for ground water is through evapotranspiration in Salt Basin playas; a significant amount of ground water is also withdrawn for irrigation in the Dell City area.

north. The lowermost San Andres is equivalent to the upper Victorio Peak (Lucia et al., 1992), and a poorly defined transitional boundary is present between the two formations on the west flank of the Salt Basin near the Texas–New Mexico border. In Figure 6, strata north of the Texas–New Mexico border are mapped primarily as San Andres Formation; strata to the south are mapped primarily as Victorio Peak.

STRUCTURAL GEOLOGY

The most prominent structural feature of the Otero-Diablo region is the Salt Basin, a 420-km-long north-northwest–trending graben (Fig. 7), which is the easternmost margin of the Basin and Range structural province (Goetz, 1977). The structural floor of the graben dips to the southwest and is buried by as much as 750 m of alluvium (Veldhuis and Keller, 1980). There were two phases of deformation: right-lateral shear and extension during late Paleozoic time along a northwest-oriented fault zone; and west-oriented extension, beginning in the Tertiary (Goetz, 1985; Dickerson, 1985). The second phase of deformation created the Basin and Range province and was widespread over a large area of southwestern North America. Fault scarps in recent alluvium suggest that Basin and Range extension is still active (Goetz, 1985).

The Sacramento Mountains consist of a large, east-tilted fault block with gentle folds and numerous normal faults (Black, 1975; Pray, 1961). Extending southeastward from the Sacramento Mountains is a prominent topographic and structural feature, herein named the Otero Break, consisting of a series of down-to-the-west normal faults and a zone of intense fracturing (Fig. 7). It extends from just north of Dell City, Texas, to the Sacramento Mountains, where a series of faults defines the course of the Sacramento River. The Otero Break roughly parallels major Paleozoic structures in Texas and New Mexico, including the Babb flexure, Kelley's shear, and the subsurface Otero fault, which is probably a reactivated Paleozoic feature (Black, 1976).

HYDROGEOLOGY

Previous hydrogeological studies in this region address either irrigation water quantity and quality or the suitability of the area for hazardous waste disposal. Scalapino (1950) documented the early ground-water irrigation development in the Dell City area, and he speculated that the Sacramento River drainage area might be a significant source of recharge for Dell City. Bjorklund (1957) compiled water-level data in the vicinity of Crow Flats in the northern Salt Basin in Texas and New Mexico, but at that time, elevation data for wells were not available and he was unable to map the hydraulic head. Davis and Leggat (1965), Sharp et al. (1993), and Mayer and Sharp (1994) documented water-level and water-quality changes in the Dell City

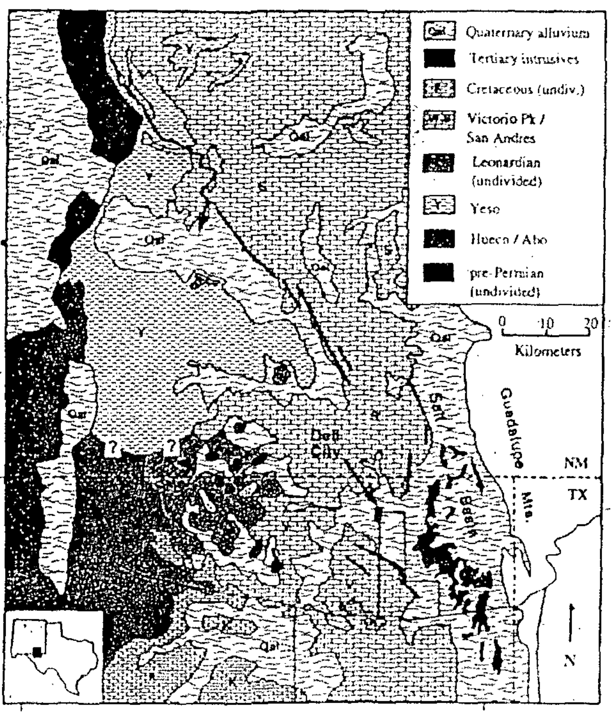

Figure 6. Simplified geologic map (adapted from many sources, including Barnes, 1975; New Mexico Geological Society, 1982; Pray, 1961; Kerans et al., 1994; and Muehlberger and Dickerson, 1989). The region is dominated by carbonate rocks and variable amounts of interbedded clastic and evaporite rocks. Note that the area receiving the most intense recharge (Sacramento Mountains) and the natural discharge area (Salt Basin playas) are at opposite ends of a prominent northwest-southeast–aligned fault trend (Otero Break). This arrangement appears to be the result of conduit flow along fractures, which are concentrated along the Otero Break fault trend. Thus, fracturing appears to exert a major control over the gross geometry of the regional flow system.

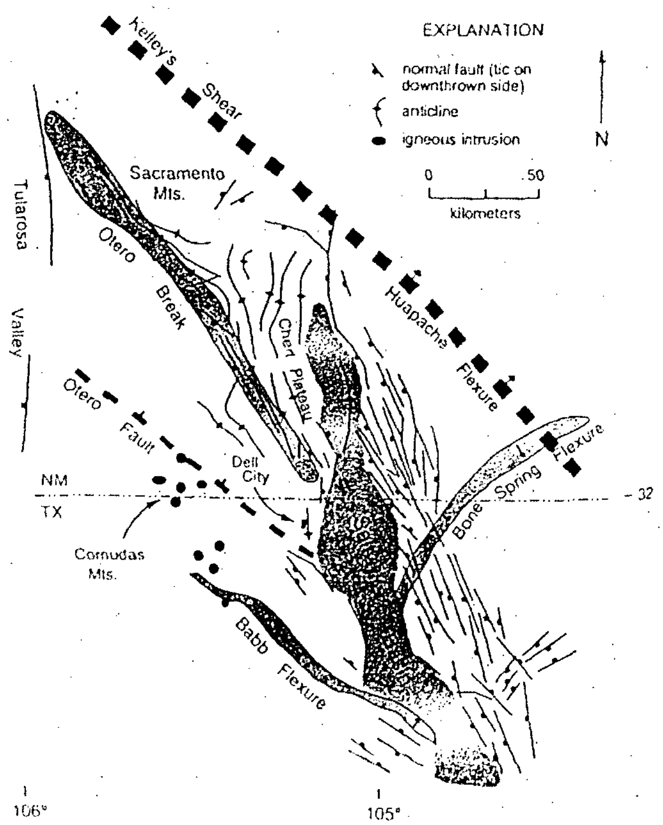

Figure 7. Tectonic features map of Otero-Diablo region (after Goetz, 1985; Black, 1976).

area created by irrigation. Ashworth (1995) provided a review of the water resources of the Dell Valley area. Regional studies by Hiss (1980) and Motts (1968) examined the role of facies and highlighted the role of Permian carbonate facies in channeling regional flow. An implied common theme in these studies is the role of geologic structure and stratigraphy in controlling regional ground-water flow.

Kreitler et al. (1987) mapped the regional potentiometric surface in northern Hudspeth County, Texas, and sampled wells for major ions, trace constituents, tritium, and ^{14}C to assess the feasibility of two potential low-level radioactive waste disposal sites on the Diablo Plateau. Sharp (1989) mapped regional ground-water flow systems in Hudspeth, Culberson, and Reeves Counties, Texas. Boyd (1982), Boyd and Kreitler (1986), and Chapman and Kreitler (1990) studied the Salt Basin unsaturated zone and concluded that sediments there were deposited primarily by ground-water discharge and mineral precipitation and not by a preexisting lake, as had been suggested by King (1948).

Hydrostratigraphy

The Otero-Diablo aquifer consists primarily of Victorio Peak, San Andres, and Yeso Formations strata (Fig. 8). The prolific Dell City irrigation district obtains its water from undifferentiated Bone Spring–Victorio Peak rocks (Scalapino, 1950). Hydrostratigraphic details are not known; in particular, there is little known about aquifer thickness. Most wells penetrate only tens of meters to approximately 100 m of saturated thickness. Several wells near Dell City penetrate as much as 430 m of aquifer. In the central part of the region the San Andres Formation overlies the less-permeable Yeso Formation. Here the Yeso Formation probably serves as the base of the flow system. In other areas there is no clear basal unit.

Ground-Water Recharge and Discharge

Recharge in the Otero-Diablo region is from areal infiltration of precipitation (Kreitler et al., 1987); infiltration of the Sacramento River (Scalapino, 1950); and irrigation return flow in the Dell City irrigation district (Logan, 1984). Recharge other than irrigation return flow is assumed to be negligible within the Salt Basin because soil permeability is low and potential evaporation is more than 10 times greater than precipitation (Boyd and Kreitler, 1986).

The Salt Basin is the natural discharge area for regional ground-water flow. Evaporation occurs directly from the water table, which is located at a depth of between 0.8 and 1.8 m (Boyd and Kreitler, 1986). Since about 1950, however, pumping in the Dell City irrigation district has discharged significant volumes of ground water. According to Texas Water Development Board figures (Ashworth, 1995), total annual discharge for the period 1958 to 1992 averaged approximately 1.0×10^8 m^3 (85 000 acre ft).

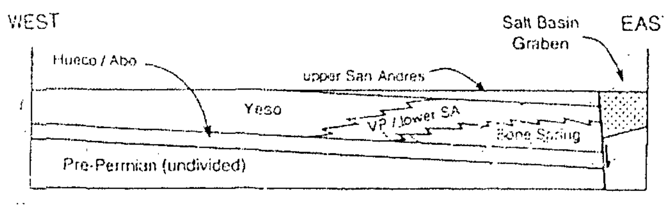

Figure 8. Schematic cross section showing relationships among major formations of the Otero-Diablo region (adapted from Black, 1975; Lucia et al., 1992). VP—Victorio Peak Formation; SA—San Andres Formation.

Potentiometric Surface

Data in Texas were compiled from published reports and from records kept by the Texas Water Development Board. Data for New Mexico were obtained from records of the U.S. Department of the Interior, Bureau of Land Management; the New Mexico State Engineer's Office; and from individual well owners. Well locations and water depths in wells were translated to elevation above mean sea level using wellhead elevations estimated from U.S. Geological Survey 7.5 minute topographic maps. Therefore potentiometric data are accurate only to plus or minus several meters. Because the data are widely spaced and potentiometric surface relief is large, this uncertainty does not appreciably affect the interpretation.

The potentiometric surface slopes generally eastward from the Diablo Plateau and Otero Mesa, and southward from the Sacramento Mountains toward Dell City and the Salt Basin (Fig. 9). There is a broad, shallow cone of depression around Dell City. In the west, the potentiometric surface mimics topography. However, near the Otero Break it appears to be almost independent of topography, and in the central part of the study, it is nearly flat. Together with the large amount of water discharged in the Dell City irrigation district, this suggests very high transmissivity. Regional ground-water flow is southward from the Sacramento Mountains and eastward from the Diablo Plateau–Otero Mesa toward the Salt Basin and the Dell City irrigation district.

Ground-Water Chemistry

Ground-water chemistry is only briefly summarized here. Details and data tables are in Mayer (1995). Other data sources include Kreitler et al. (1987), Ashworth (1995), and the Texas Water Development Board for the Dell Valley and Diablo Plateau regions of Texas; and Bjorklund (1957), Hudson and Borton (1980), and the U.S. Department of the Interior, Bureau of Land Management, for the New Mexico regions. Ground water in most of the region is fresh to brackish. Total dissolved solids (TDS) concentrations range from a low of 400 mg/L in the Sacramento River to a local high of 3500 mg/L in the central Otero Mesa (Fig. 10). In the Salt Basin, where ground water discharges by evapotranspiration, TDS concentrations can exceed 250 000 mg/L (Boyd, 1982). Note that in the Dell City area we use only pre-1950 data because more recent data are strongly influenced by irrigation return flow and do not accurately reflect regional trends.

A key observation is the prominent low-salinity trend extending from the Sacramento Mountains southeastward along the Otero Break, terminating near Salt Basin playas and Dell City. Within this corridor TDS concentrations range from less than 500 mg/L to 2000 mg/L. Salinities on either side of this zone increase by as much as several thousand milligrams per liter over short distances (Fig. 10). Hydrochemical facies vary from $Ca\text{-}SO_4$ and $Ca\text{-}Mg\text{-}SO_4\text{-}HCO_3$ in the Otero Mesa, Otero Break, and Crow Flats regions, to $Ca\text{-}Mg\text{-}Na\text{-}SO_4$ facies in Dell Valley and the Diablo Plateau. There are also local occurrences of Na-Cl facies in Dell Valley and the Diablo Plateau (Mayer, 1995, p. 60).

FRACTURE CHARACTERIZATION

The Otero-Diablo region is an excellent setting for mapping geologic features through aerial photo analysis. Vegetation is sparse; there are extensive areas of outcrop; and soils, where present, are generally thin. To identify major fracture trends, lineaments were mapped from U.S. Geological Survey black and white, infrared aerial photographs at a scale of 1:58 000. The air-photo database for this study consists of 112 stereo photos covering approximately 6000 km^2.

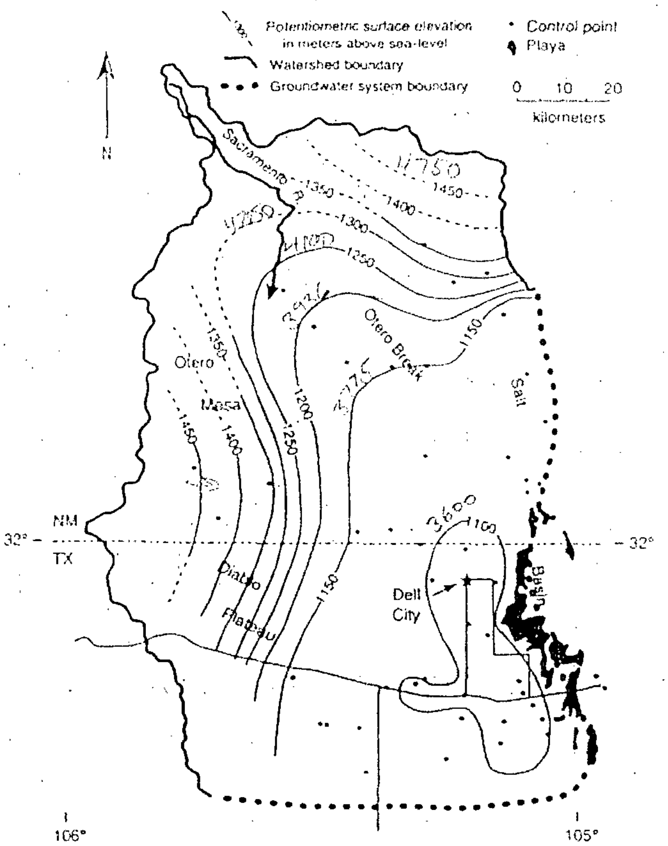

Figure 9. Regional potentiometric surface map. Note low hydraulic gradient in southeastern part of region, and broad, northwest-trending potentiometric trough, coincident with Otero Break. These features correspond to areas of relatively intense fracturing and suggest that fracturing plays a major role in determining ground-water flow in this area. TDS—total dissolved solids.

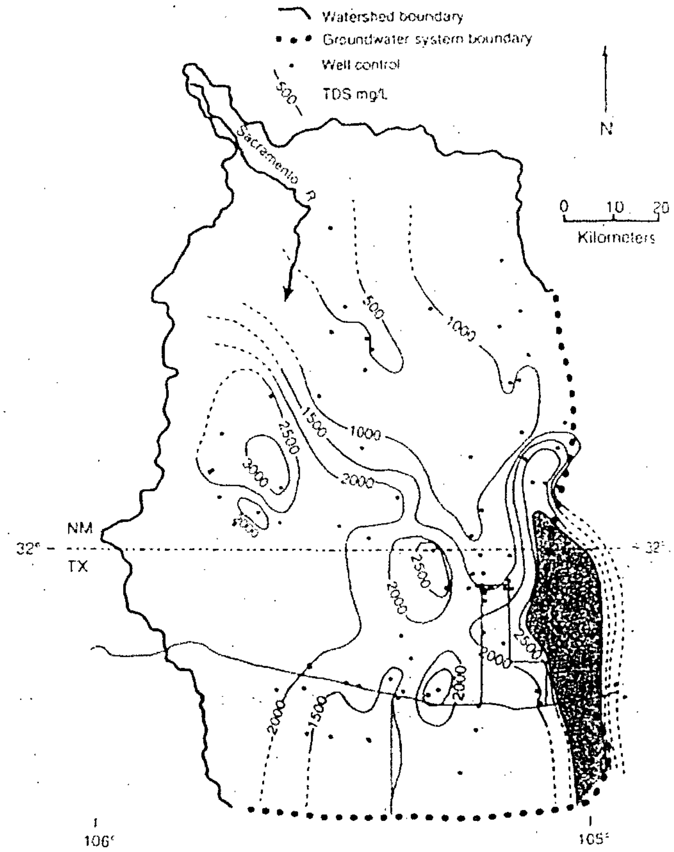

Figure 10. Contour map of total dissolved solids (milligrams per liter). Note apparent plume of fresh water extending from the Sacramento Mountains toward Dell City. Plume is coincident with potentiometric trough shown in Figure 9. It suggests that relatively fresh Sacramento Mountains recharge is funneled along the Otero Break, ultimately to discharge in the Salt Basin, more than 80 km distant. If not for the Otero Break fracture zone, the discharge point for system would probably be much closer to the Sacramento Mountains.

FRACTURE MAPPING

Several classes of lineaments are considered indicative of fracturing. They are summarized here and depicted in Figure 11. The classes are as follows.

1. Sharply defined features cut across and in some cases appear to offset bedding. These features are prominent fracture zones that are directly visible on air-photos (Fig. 11A).

2. Thin, anomalously colored bands are normally darker than surrounding materials. These features appear to be weathered zones overlying fractures and are inferred to be filled with thicker soil than surrounding, less-weathered, unfractured rock (Fig. 11B).

3. Because of thicker soil overlying some fracture zones, vegetation commonly grows preferentially over fractured bedrock (Fig. 11C) and produces linear vegetation trends.

4. Linear depressions or aligned sinkholes apparently formed from preferential dissolution along fractures (Fig. 11D).

5. Additional lineaments are linear stream courses, especially those forming a trellis or rectangular drainage pattern (Fig. 11E).

To establish the feasibility of air-photo mapping in the Otero-Diablo region, we conducted a pilot study to field check probable fracture zones identified on air photos. In every case, lineaments identified on the photos could be correlated with fractures on the ground. It is important to note that individual fractures are not visible on air photos. Fracture-zone (lineament) spacing varies from tens to thousands of meters. Figure 12 shows a fracture zone on the Otero Mesa. Fracture spacing is approximately 2.5 m; adjacent fracture zones are approximately 500 m distant. Figure 13 shows a fracture zone on the Diablo Plateau. Fracture spacing is approximately 1 m; adjacent fracture zones are 150 m distant.

That lineaments represent subvertical fracture zones is supported by observations in the field and on air photos. Fractures observed in cliff-face exposures on the Otero Break are within 10° of vertical. In addition, lineaments maintain a linear trace, even across rugged terrain (Fig. 11B).

Air-photo analyses and field observations demonstrate that the Otero-Diablo region is heavily fractured, and there are many indications that ground-water flow is fracture-dominated. Specific capacities of wells in the Dell City area within 30 m of each other commonly vary by more than an order of magnitude (Scalapino, 1950). This suggests that the high-capacity wells intersect open fractures, whereas the low-capacity wells do not. Ground-water recharge wells drilled in conjunction with a U.S. Soil Con-

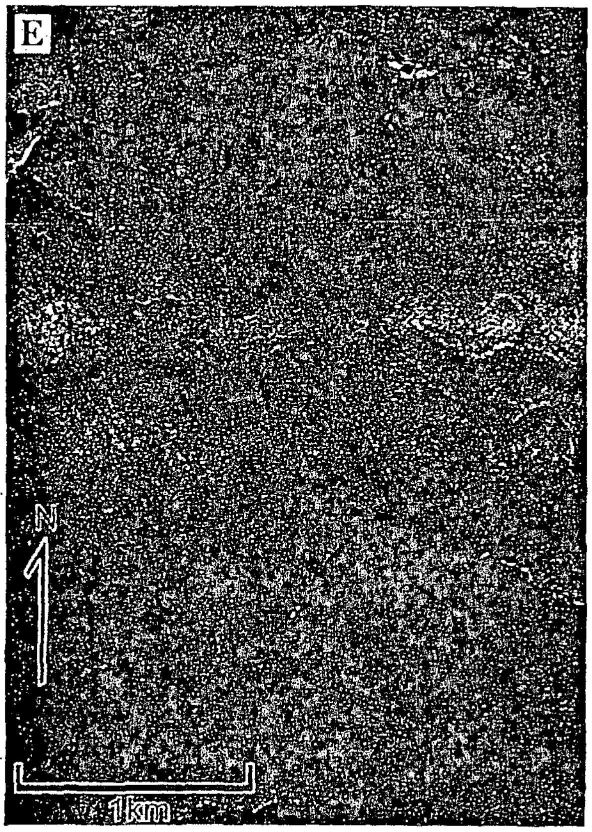

Figure 11. (E) Trellis drainage patterns developed in horizontal, fractured strata. Major streams are aligned north-northwest along the most prominent fracture sets; their tributaries are nearly perpendicular, along less prominent fracture sets.

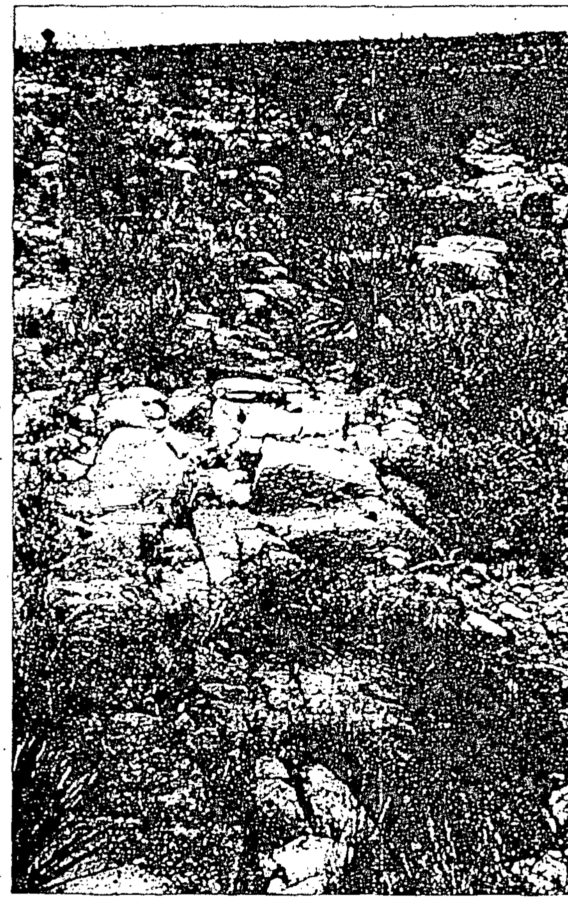

Figure 13. Fracture zone on Diablo Plateau, looking northwestward. Individual fractures spaced approximately 1 m apart; adjacent fracture zones are approximately 150 m distant. Field book on left measures 22 by 30 cm.

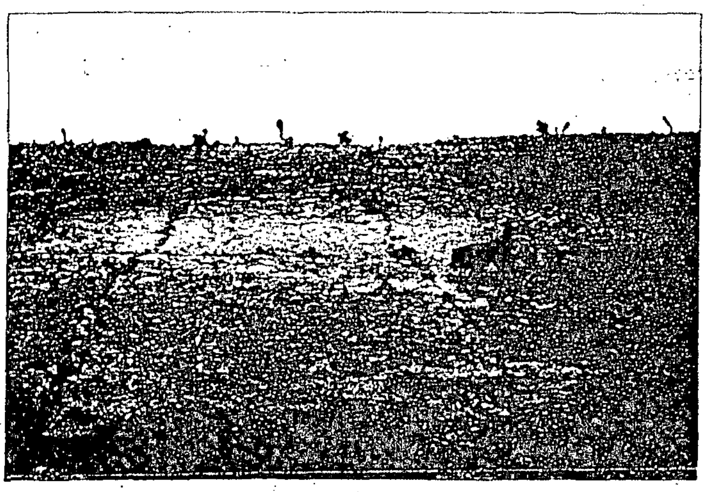

Figure 12. Fracture zone on Otero Mesa, looking southeastward. Individual fractures are not visible on air photos but zones of relatively closely spaced fractures are. Fracture spacing within fracture zone is approximately 2.5 m; adjacent fracture zones are approximately 500 m distant. Note alignment of yucca plants along leftmost fracture where soil covers bedrock. Dog (for scale) measures 0.65 m high at shoulder.

servation Service flood-control project west of Dell City were sited with the aid of air-photo analysis and were drilled at the intersections of major lineaments (Logan, 1984). Of 12 wells drilled, 11 had specific capacities greater than 24.8 m^3/min/m (2000 gal/min/ft). This success rate is contrasted to a rate of only 44% for irrigation wells drilled in Dell Valley without the aid of lineament analysis (Scalapino, 1950).

E. McCutcheon (1992, personal commun.) noted linear trends within the irrigation district aligned subparallel to nearby faults, along which ground-water conductivity, temperature, and pH are nearly identical and distinct from nearby wells. This suggests that these wells produce from the same fault or fracture zone. Furthermore, local well drillers reported numerous incidences of lost circulation that indicate large, open fractures or dissolution features.

These observations were confirmed by video well logs that show open fractures intersecting wells (Logan, 1984). Although the rest of the Otero-Diablo region is less suitable for agriculture and has not been drilled as extensively as Dell Valley, local drillers reported indications of fracture-dominated flow throughout the region (L. Perry, 1994, personal commun.). Because most of the region is geologically similar to the Dell City area, and because extensive fracturing is widespread throughout the region, it is reasonable to assume that fracture flow dominates the Otero-Diablo system.

FRACTURE DATA REDUCTION

Discretization

Lineaments were marked on one half of a stereo-photo pair and then transferred to U.S. Geological Survey 7.5 minute topographic maps. Lineaments were then digitized at the University of Texas, Department of Geological Sciences Geographic Information Systems (GIS) lab with the GIS package, Arcinfo. To create a single fracture map, forty 7.5 minute topographic maps were digitized and assembled.

Gridding and Contouring

The study area was overlain with a 3 km by 3 km grid. Fracture density was determined by summing the total length of fractures within a grid cell and dividing by the area of the cell. The cell-wide value of fracture density was then assigned to the center point of the grid cell, and these values were contoured. Some areas of the study are covered by enough alluvium to obscure fractures (Fig. 6). These areas were subtracted from the area of the grid cell. Thus, fracture density represents fracture length per unit area of outcrop rather than per unit area of land surface. Fracture orientations were analyzed similarly; rose diagrams depict fracture orientations.

FRACTURE SYSTEM CHARACTERISTICS

Fracture Geometry

Approximately 2400 lineaments were mapped. Contoured fracture density (Fig. 14) ranges from 0 to 1850 m/km^2, which corresponds to average fracture spacing of 540 m to greater than 3 km. Because the mapped fractures are actually fracture zones (made up of closely spaced individual fractures), the true fracture density is greater than Figure 14 suggests. We assume that fracture density is proportional to fracture-zone density; thus, this figure illustrates relative fracture density. An absolute fracture density cannot be resolved at this scale. Fracture orientations are depicted in Figure 15 by rose diagrams for representative subareas.

Several observations are based on these data. First, except for the western Otero Mesa, there is a strong preferred fracture orientation of approximately N20W. In the western Otero Mesa, there is no single dominant preferred orientation. Second, fractures are most abundant along the Otero Break and least abundant in the western Otero Mesa. Third, fractures closely parallel, and are most abundant near, major normal faults. The scarcity of fractures in the western Otero Mesa may be lithologically controlled. This area is underlain by the gypsum-rich Yeso Formation and may be less prone to fracturing than the carbonate-dominated units present throughout the rest of the Otero Diablo region.

Fracture Domains

On the basis of the above data, the study area may be divided into distinct fracture domains, which are used to develop the numerical model. Domain 1 (Fig. 16) is along the Otero Break. This is the most heavily fractured zone and has a very strong preferred fracture orientation (approximately N20W) parallel to the normal faults of the Otero Break. Domains 2 and 3 have significant fracture densities and dominant fracture orientations similar to those of domain 1. In domain 3 there are two additional fracture sets (oriented approximately N40W and N50E) not observed elsewhere. Domain 4 includes the western Otero Mesa and Diablo Plateau and is characterized by relatively sparse fracturing and no single, dominant fracture orientation. Domain 5 is composed of Salt Basin alluvium. On the basis of fractures observed in nearby outcrops and on abundant subsurface evidence of fractures, the alluvium-covered region surrounding Dell City is included in domain 1.

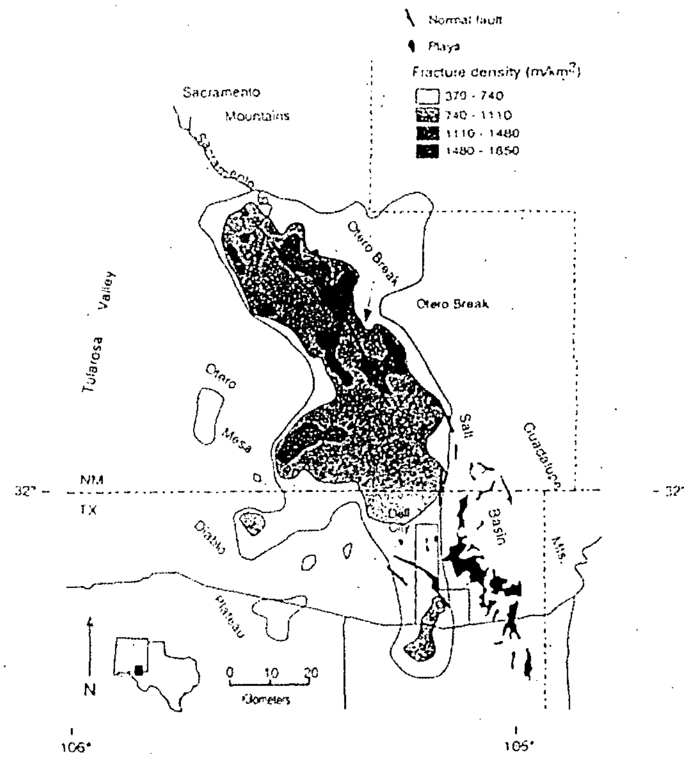

Figure 14. Contour map of fracture density (meters per square kilometer). Note concentration of fractures along Otero Break. Fracture density is least in western Otero Mesa where Yeso Formation crops out. No fractures are mapped in alluvial cover. We hypothesize that fracture distribution is major control of regional ground-water flow.

FINITE-ELEMENT FLOW MODELING

We use a two-dimensional, steady-state finite-element model to test potential configurations of regional transmissivity. The finite-element approach is well suited to analyze the anisotropy and heterogeneity inherent in fractured systems, especially in nonrectangular domains. A Geographic Information System (GIS) interface was used to create the finite-element mesh, discretize input parameters, and display model output. The programs and governing equations were given in their entirety in Mayer (1995). The theory is described in many sources and is not repeated here.

MODEL DEVELOPMENT

The model tests the hypothesis that regional fracture systems control regional ground-water flow by increasing aquifer permeability and creating preferred flow paths. Hence, transmissivity is estimated according to measured fracture properties.

We use an equivalent porous medium/equivalent parallel plate approach (Sharp, 1993). The fractures are assumed to be numerous enough and distributed evenly enough for the effects of individual fractures to be ignored. Thus, transmissivity is modeled as a bulk property of the aquifer; no direct consideration is taken of individual fracture contributions or fracture properties such as aperture, roughness, or length. Implicit in this approach is the un-

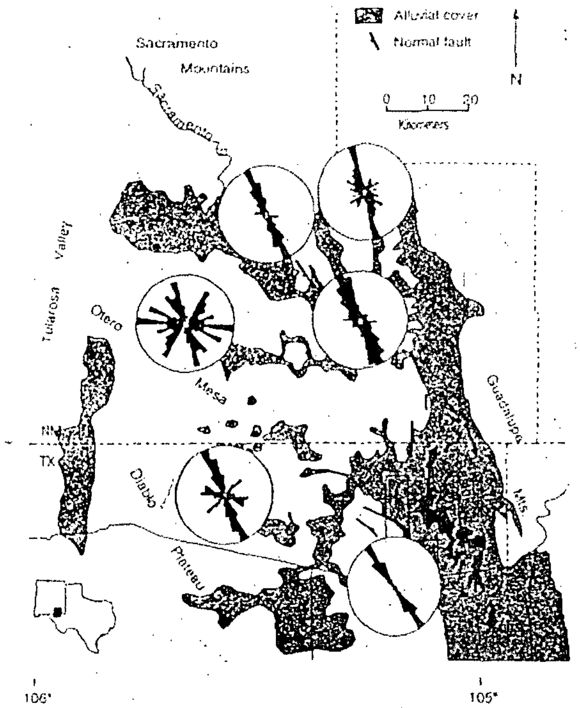

Figure 15. Rose diagrams of fracture orientations. There is a prominent northwest-southeast preferred orientation of fractures across most of region. In Otero Mesa there is no single preferred orientation. Fracture orientation appears to be much less important in regional flow than fracture density.

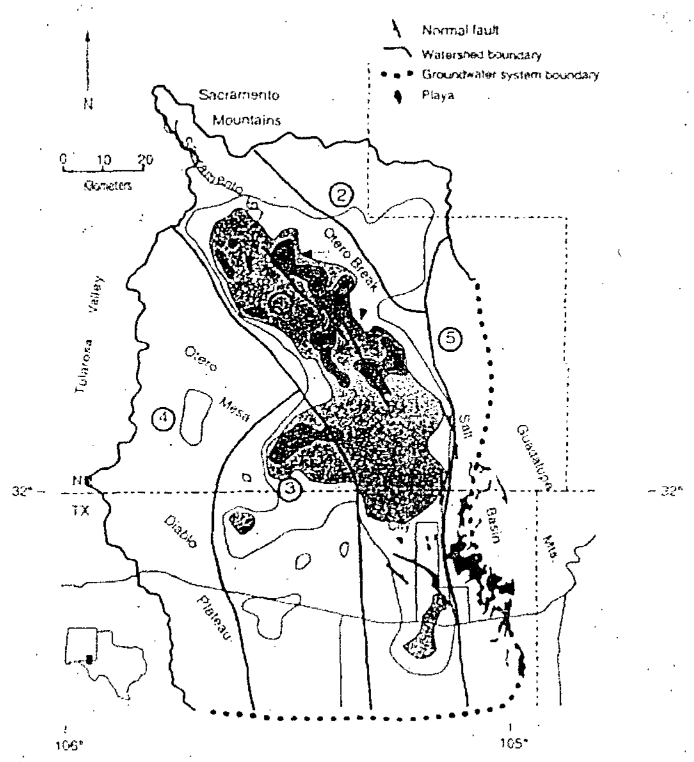

Figure 16. Transmissivity domains defined based on fracture density and orientation. Domain 1 has highest transmissivity; domain 4 has the lowest.

derlying assumption that transmissivity of individual elements in the finite element model can be adequately represented as a symmetric tensor. Given the large study area and the numerous, widely distributed fractures, this may be a reasonable assumption (Long et al., 1982). However, the applicability of porous medium approaches to fractured aquifers is a topic of current debate (e.g., LaPointe et al., 1996).

Mesh Generation

The model boundary was digitized with Arcinfo; the finite-element mesh was generated with Grid Builder 3.0 (McLaren, 1992). The mesh consists of 1134 nodes and 2126 elements; the average element size is 4.5 km^2.

Boundaries

The model is bounded by both constant head and no-flow boundaries (Fig. 17). The western and northern boundaries are the surface-water (and presumed ground-water) divides that delineate the Salt Basin watershed. Coincidence of surface-water and ground-water divides is almost certainly the case on the west because the Otero Mesa and Diablo Plateau drop precipitously into the Tularosa Valley along major normal faults that truncate the aquifer. However, where the ground-water divide separates the Salt Basin from the Rio Penasco watershed (the northern hydraulic boundary) is less certain because in carbonate aquifers of arid regions, ground-water and surface-water divides are less likely to coincide than in more humid climates or in less-permeable aquifers (Maxey and Mifflin, 1966). Because interbasin flow, calculated from water balances, is minimal, we assume that coincidence of ground-water and surface-water divides is reasonable for this boundary.

The eastern no-flow boundary is a symmetry boundary where westward flow from the Guadalupe Mountains and eastward flow from the Otero Mesa converge. The southern no-flow boundary is a symmetry boundary where regional flow is to the east, parallel with the boundary, on the basis of regional potentiometric data (Kreitler et al., 1987). The eastern constant-head boundary corresponds to the water table, which occurs at an elevation of 1095 m (Boyd, 1982), in Salt Basin playas. It is located along the central axis of the Salt Basin.

Transmissivity Domains

Five constant transmissivity domains (Fig. 16) are defined on the basis of fracture domains. Heavily fractured domains are assigned higher transmissivities than less-fractured domains. Transmissivities used in the model are within the range of transmissivities reported for carbonate aquifers (Table 1). Because there are no transmissivity measurements available for most of the study area, transmissivity is estimated by comparing model output to the measured potentiometric surface. However, transmissivity domains are defined, and relative values of transmissivity between zones are predicted, on the basis of mapped fracture domains. Domain 1, the most heavily fractured area, is assigned a transmissivity of 10^{-2} m^2/s, which is in the high transmissivity range of Table 1, but more than an order of magnitude less than the highest values. The other less-fractured domains and domain 5, Salt Basin alluvium, were assigned lower transmissivities.

Recharge and Discharge

Several recharge and discharge processes (summarized in Table 2) operate in the Otero-Diablo region. Recharge from precipitation is distributed over all but the lowest elevations of the study area, and there is significant irrigation return flow in Dell Valley. Discharge occurs by transpiration and evaporation from Salt Basin playas, and since the early 1950s by irrigation

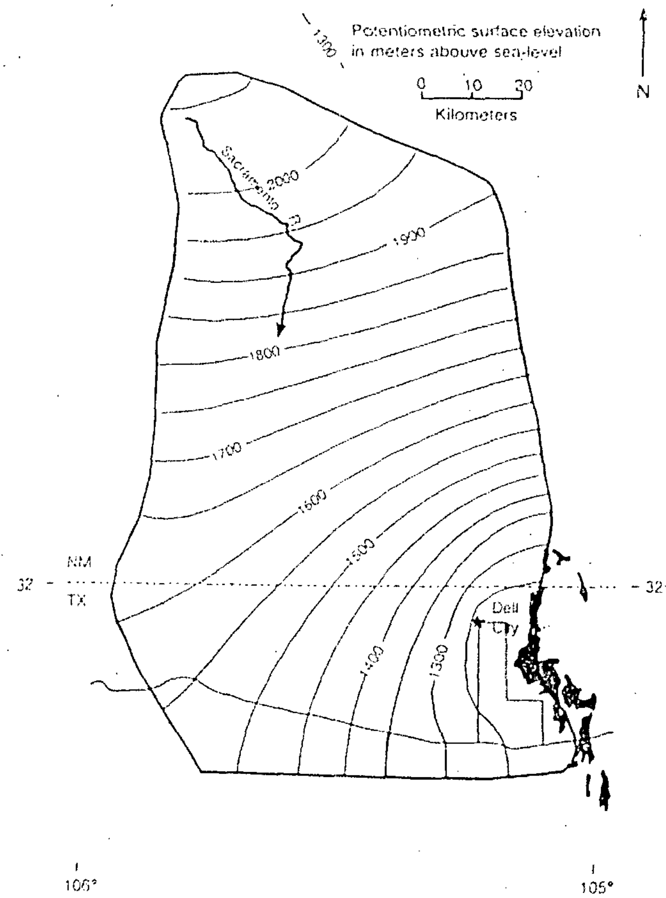

Figure 17. Model-generated potentiometric surface for homogeneous, isotropic transmissivity. By comparison with Figure 9 it is apparent that homogeneous transmissivity is not consistent with the observed hydraulic head distribution, given estimated recharge.

pumping. It is also possible that a small, undetermined amount could discharge through interbasin flow (Davis and Leggat, 1965).

Recharge is strongly elevation dependent; it is estimated by a combination of methods. At relatively low elevations in the central and southern portions of the study area, recharge estimates are based on soil-chloride profiles from the Diablo Plateau. At higher elevations, recharge is based on water-balance studies from similar areas of the Basin and Range province.

In the Salt Basin below an elevation of 1160 m, recharge from direct precipitation is assumed to be negligible. Here, potential evaporation is an order of magnitude greater than precipitation (Boyd, 1982), and soils consist mainly of low-permeability, fine-grained, clay-rich basin-fill deposits (Barnes, 1975). Chapman and Kreitler (1990) reported upward gradients in the unsaturated zone even shortly after significant precipitation events.

Tritium levels and ^{14}C ages of Diablo Plateau ground waters indicate that most wells contain recent, local recharge (Kreitler et al., 1987). Soil chloride profiles from the Diablo Plateau suggest that the main recharge mechanism there is infiltration through fractures in creek beds and closed depressions during occasional flash floods. On the basis of soil chloride profiles, calculated recharge for creek beds and depressions ranges from 0.028 to 0.457 cm/yr, whereas calculated recharge for areas outside creek beds is much less, ranging from 0.005 to 0.020 cm/yr.

The total area of creek beds and closed depressions was calculated on the basis of digitized topography and stream courses, assuming a stream-bed width of 10 m. This gives a total creek bed–depression area of 128 km^2 and an interfluve area of 4713 km^2. Assuming 0.242 cm/yr recharge within creek beds and depressions and 0.0125 cm/yr for the rest of the plateau, the midpoints of the ranges reported by Kreitler et al. (1987), the composite recharge rate for the Otero Mesa–Diablo Plateau is 0.018 cm/yr. This may be lower than the actual recharge for some parts of the Otero Mesa–Diablo Plateau because these data were from a field site at an elevation of approximately 1260 m. Because much of the study region lies at a higher elevation, recharge may be greater.

In the Sacramento Mountains and adjacent high-relief terrain above an elevation of approximately 1675 m, recharge was estimated using techniques established by Maxey and Eakin (1949) for a similar carbonate-dominated regional flow system in the Basin and Range. This technique,

TABLE 1. TRANSMISSIVITY VALUES FOR TEXAS CARBONATE AQUIFERS

Aquifer	Method	Data points	Low	Transmissivity (m^2/s) high	Median	References
Otero-Diablo	Pump tests	4	3.44E–07	2.47E–04	1.24E–04	Kreitler et al., 1987
	Pump tests	2	5.14E–02	5.59E–02	5.37E–02	Logan, 1984
Edwards	Model calibration	21	2.15E–01	2.15E+00	1.18E+00	Maclay and Small, 1980
	Recession curves	6	1.00E–01	4.00E–01	2.50E–01	Senger and Kreitler, 1984
	Specific capacities	525	1.00E–07	1.00E–01	5.57E–03*	Hovorka et al., 1995

*Median value for the Hovorka et al. (1995) study represents a geometric mean of the data.

TABLE 2. RECHARGE AND DISCHARGE MECHANISMS IN THE OTERO-DIABLO REGION

Recharge		(m^3/yr)	
Distributed (Kreitler et al., 1987)		7.20E+07	21,870 AFY
Irrigation return flow (Logan, 1984)		3.7–5.2E+07	
	Total:	1.1–1.2E+08	
Discharge			
Irrigation pumpage (Ashworth, 1995)		1.00E+08	81,000 AFY
Playa evaporation (Almendinger and Titus, 1973)		2.70E+07	21,870 AFY
	Total:	1.27E+08	

which agrees favorably with recharge determined by more rigorous means (Maxey and Robinson, 1947), calculates annual recharge as a percentage of total annual precipitation. Calculated recharge for the Sacramento Mountains is elevation dependent and ranges from 2.1-6.9 cm/yr.

In summary, distributed recharge is assumed to occur over most of the area. It ranges from 0.018 cm in the Diablo Plateau/Otero Mesa to 6.9 cm in the highest parts of the Sacramento Mountains. The Sacramento Mountains receive by far the most intense recharge.

Continuous water-level records (Ashworth, 1995) show that when annual pumpage exceeds approximately 1.24×10^8 m^3 (100 000 acre ft), water levels in the Dell City irrigation district decline. At lower pumping rates, water levels remain constant or increase. The average steady-state flux for the aquifer is 1.24×10^8 m^3 per year.

MODEL RESULTS

Flow simulations tested three main configurations of transmissivity: homogeneous and isotropic; heterogeneous and isotropic; and heterogeneous and anisotropic.

Homogeneous, Isotropic Case

Figure 17 is the output of a homogeneous, isotropic flow system with a transmissivity of $10^{-2.5}$ m^2/s. This is within the range of observed data (Table 1) and was selected by trial and error comparison of model output with the observed potentiometric surface. Although this case presents a theoretically plausible configuration of hydraulic head, there are fundamental discrepancies between observed data and model output. In the central southeastern portions of the study area there is a very low hydraulic gradient of approximately 1 m/km (Fig. 9), whereas this model has a much larger gradient of approximately 5 m/km. This model produces a slight ridge in the potentiometric surface extending from Dell City northwestward, but Figure 9 shows a pronounced trough in the same location. Increasing or decreasing the transmissivity has little effect on the overall configuration of the output; the main effect is to raise or lower the potentiometric surface.

Heterogeneous, Isotropic Case

In simulations 2 and 3 the region is subdivided into transmissivity domains developed according to fracture density (Figs. 15 and 16). More densely fractured areas are assigned higher transmissivities. Transmissivity domain 1 was the highest fracture density of the study area and is assigned a transmissivity of 10^{-2} m^2/s. Domains 2 and 3 (less intensely fractured rock) were assigned a transmissivity of 10^{-3} m^2/s. Domain 4, delineated on the basis of its low fracture density and relatively large variation of fracture orientation, was assigned a transmissivity of 10^{-4} m^2/s. Domain 5 consists of Salt Basin alluvium, and its western boundary coincides with the western bounding fault of the Salt Basin graben. Domain 5 transmissivity is 10^{-4} m^2/s.

Output from the heterogeneous, isotropic case (simulation 2) is shown in Figure 18. This configuration of transmissivity produces a much better match to the observed potentiometric surface than the homogeneous transmissivity case. Note the low hydraulic gradient in the central part of the region, and the potentiometric trough extending from Dell City northwestward—features that are not present in the homogeneous model.

Heterogeneous, Anisotropic Case

In configuration 3 (Fig. 19), domains 1 and 2 are assigned a 10:1 anisotropy ratio, the large value of transmissivity being parallel to the mean fracture direction. This ratio is similar to that used to model the Edwards aquifer (Uliana and Sharp, 1996) and may represent a reasonable estimate of anisotropy in a fractured carbonate aquifer.

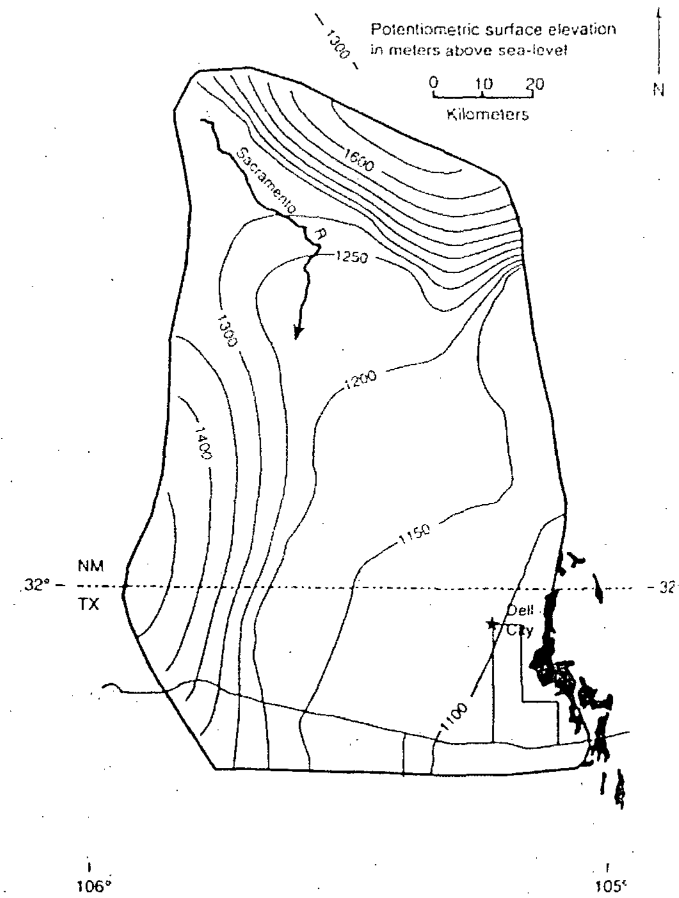

Figure 18. Model-generated potentiometric surface assuming heterogeneous, isotropic transmissivity distribution defined on the basis of fracture density. This transmissivity distribution produces a hydraulic head distribution similar to the observed potentiometric surface. Thus regional potentiometric trends are consistent with a high-transmissivity zone coincident with fracturing along the Otero Break.

Adding anisotropy does not significantly change the model output from configuration 2. This is because the hydraulic gradient is nearly parallel to the direction of maximum transmissivity. The hydraulic gradient and the preferred fracture direction are aligned parallel to the Otero Break. Hence, ground-water flow direction is not strongly affected by anisotropy.

Sensitivity Analysis

The sensitivity analysis evaluates changes in recharge and transmissivity. One parameter was varied in increments of 10% from −30% to +30% while all other model parameters were held constant (Fig. 20). Model error is measured as root-mean-square (RMS) error. Because there is a high concentration of data points in the Dell City area and there are relatively few data elsewhere, calibration points were selected to provide a more even distribution of measured heads throughout the modeled region for the calculation of RMS error. On a percentage change basis, the model is more sensitive to changes in recharge. However, aquifer transmissivity varies over a

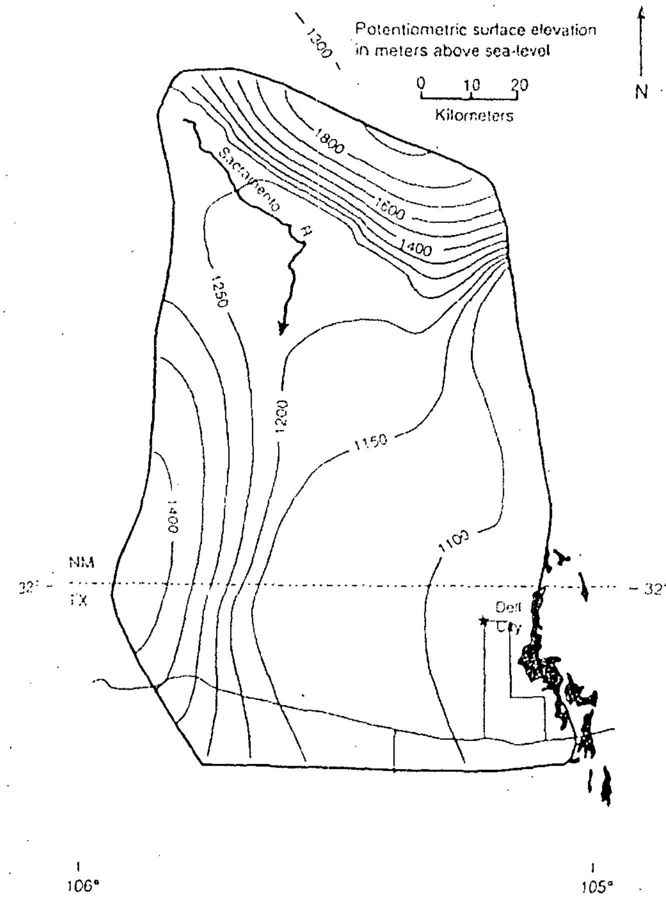

Figure 19. Model-generated potentiometric surface assuming a heterogeneous, anisotropic transmissivity distribution. Domains 1 and 2 are assigned a 10:1 anisotropy ratio, with large value of transmissivity parallel to mean fracture direction. This scenario produces a slightly better match with the observed potentiometric surface; however, the effects are minimal. This suggests that, at least in the Otero-Diablo region, anisotropy is not nearly as important as fracture density in controlling regional ground-water flow in fractured aquifers.

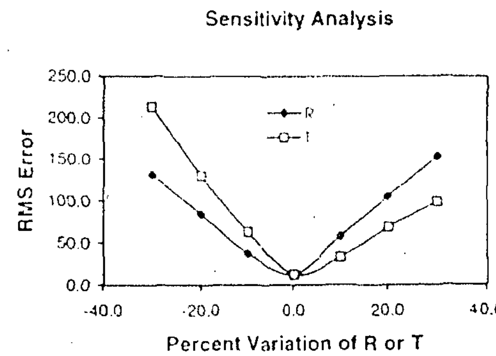

Figure 20. Graph of sensitivity of model to changes in recharge (R) and transmissivity (T). R and T varied in increments of 10% from –30% to +30%, while other model parameters held constant. Error is measured as root mean square (RMS). On a percentage change basis, the model is more sensitive to changes in recharge. However, because the range of variation of transmissivity of geologic materials is much greater than the range of variation of recharge, transmissivity is probably the most critical parameter.

much wider range than recharge; therefore, transmissivity is probably the most important model parameter. Note that we do not evaluate the effects of changing transmissivity domain boundaries, or changing relative transmissivity values between domains. The RMS error could probably be reduced slightly by such an approach.

Integration of Water-Chemistry Results

Numerical flow model results are consistent with a high-transmissivity zone along the Otero Break, extending from the Sacramento Mountains to the Dell City area. This highly fractured zone acts as a drain to the flow system and links the area of most intense recharge (Sacramento Mountains) to the natural discharge areas (Salt Basin playas). This is corroborated by the water-chemistry data including salinity trends, which likewise suggest a conduit along the Otero Break. The low-salinity plume delineated in Figure 10 follows the highly fractured Otero Break. Low salinities extend from the Sacramento Mountains along the length of the Otero Break to Dell City and the Salt Basin. This is consistent with the funneling of relatively fresh Sacramento Mountains recharge along faults and fractures of the Otero Break, ultimately to Dell City and the Salt Basin—a distance of 80 km. Mixing trends also support the existence of high transmissivities along the Otero Break. For example, some Dell City area waters appear to be mixtures of Otero Break and Otero Mesa waters, and in some cases are more similar to distant Otero Break waters than to nearby Diablo Plateau waters (Mayer, 1995, p. 72–75).

DISCUSSION

This study uses readily available geologic data to constrain spatially distributed, two-dimensional transmissivities in a regional carbonate aquifer. Results indicate that a priori analysis of regional fracture systems can significantly improve models of regional ground-water flow, especially in aquifers where fractures are not uniformly distributed. This is significant because geologic controls in regional flow models are normally considered post priori when needed to calibrate the model. Although fracture data are commonly used in reservoir-scale flow characterization, they are rarely used in regional-scale problems.

To incorporate fracture data into regional flow models, we used a finite-element flow model that estimated transmissivity as a function of fracture properties. Transmissivity domains were defined a priori by fracture-density and fracture-orientation trends. Fracture properties were determined from field-checked air-photo analysis and geologic field mapping. The model was calibrated on a 9000 km² fractured carbonate aquifer system in northern Hudspeth County, Texas, and southern Otero County, New Mexico. Although fractures are used to estimate transmissivity, the model employs a porous medium approach to flow simulation.

Modeling supports the hypothesis that in the Otero-Diablo region, fractures are the primary factor controlling transmissivity and regional ground-water flow patterns. There is a high correlation between fracture density and modeled transmissivity. When model transmissivity is based upon fracture density, superior simulations result. Preferred flow paths along fractured, high-transmissivity trends also affect ground-water chemistry. In the Otero-Diablo region, this is manifest as a 80 km "plume" of relatively fresh water extending from recharge areas in the Sacramento Mountains to discharge areas in the Salt Basin and the Dell City irrigation district. This prominent zone of distinct water influences regional water chemistry by delivering relatively fresh water to discharge areas and by providing a "drain" along which adjacent waters converge and mix.

Fractures also determine major aspects of regional flow-system geometry. In the Otero-Diablo region, the heavily fractured Otero Break connects the area of most intense recharge (the Sacramento Mountains) to the natural discharge point of the system (Salt Basin playas). We infer that fracturing has created a large-scale conduit that channels Sacramento Mountains recharge to the southeast along a narrow zone where it eventually emerges in the Salt Basin. Were it not for the fractures of the Otero Break, discharge might be more diffuse (spread over larger areas of the Salt Basin), farther north in the Salt Basin, or even directed to the Tularosa basin, which is closer to areas of concentrated recharge.

The Dell City irrigation district, although 80 km from the Sacramento Mountains, receives a large portion of Sacramento Mountains recharge. If there were no fracture zone linking these areas, Dell City ground water would probably be derived from more brackish, less abundant local sources. In the Otero-Diablo region, hydrologic data are sparse, but geologic data can be used to prepare superior numerical models of this complex system.

CONCLUSIONS

This study demonstrates through several lines of evidence a particular example of fracture-controlled regional ground-water flow. Important points are (1) a priori analysis of regional fracture systems can significantly improve models of regional ground-water flow; (2) fracturing is in some cases the major factor controlling regional transmissivity variations, and thus regional ground-water flow; (3) fracturing can define the overall geometry of regional flow systems by creating large-scale flow conduits that strongly influence the locations of discharge areas; and (4) fracturing can strongly influence regional ground-water chemistry variations. Although fracture data are commonly used in flow calculations at the single-well or reservoir scale, fracture data have been underutilized at the regional scale. This study highlights how the timing and nature of tectonic events may play important roles in subsurface fluid flow, including processes such as diagenesis, hydrothermal mineralization, and petroleum migration.

Further studies of the Otero-Diablo region should include analyses of hydrogen and oxygen stable isotopes, tritium, and ^{14}C. An important question in arid-climate ground-water systems in general, and in the Otero-Diablo region in particular, is how much of the water is recent recharge and how much was recharged during wetter times in the Pleistocene. Because the ground water commonly is a mixture of waters of varying ages, it is difficult to estimate a reliable age. However, by combining isotopic analyses it may be possible to eliminate much of the uncertainty involved with any single method. Ground-water age is fundamentally important for ground-water resource evaluation because if a significant portion of the ground water in the system was recharged in Pleistocene time, under present climate conditions this ground water may be a less-renewable resource, and steady-state models of flow and transport may not be appropriate.

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Appendix C.

Selected Parts of the Regional and State Water Plans

Introduction

Water is the common denominator of New Mexico's future and the indispensable element of quality of life for the state's residents. New Mexico must take control of this vital resource at a time when nature is pinching supplies through a drought, and man-made issues – from endangered species matters to interstate water conflicts – are further threatening or squeezing those already dwindling supplies.

This State Water Plan, prepared at the direction of Governor Bill Richardson in response to a mandate from the 2003 Legislature, is a blueprint to move the State forward into the 21st century with 21st century techniques and technology applied to conserve and to increase the supply of water.

Under the leadership of the State Engineer, who is also Secretary to the Interstate Stream Commission (ISC) and Chairman of the Water Trust Board, a draft plan was presented to the public in a joint meeting of the ISC and Water Trust Board on October 22, 2003 in Santa Fe. After review of that draft document by the public, other State agencies, Tribal governments, other interested stakeholders, and the Governor's Blue Ribbon Task Force on Water, the lead collaborators revised the draft.

This 2003 State Water Plan is therefore the outcome of months of intensive work by the three named agencies, with input from a broad spectrum of New Mexico's citizens and institutions, to develop a vision for strategic management of New Mexico's water resources in the future, in keeping with Section B of the State Water Plan Act. Section B directs that:

The State Water Plan shall be a strategic management tool for the purposes of:

(1) promoting stewardship of the State's water resources;

(2) protecting and maintaining water rights and their priority status;

(3) protecting the diverse customs, culture, environment and economic stability of the State;

(4) protecting both the water supply and water quality;

(5) promoting cooperative strategies, based on concern for meeting the basic needs of all New Mexicans;

(6) meeting the State's interstate compact obligations;

(7) providing a basis for prioritizing infrastructure investment; and

(8) providing statewide continuity of policy and management relative to our water resources.

The State must move aggressively to accomplish these goals. To supply water to grow the New Mexico economy while meeting existing needs, the State must move to expand supplies through desalination, efficiency improvements, and recycling. This State must become a world center in research, development and application of technologies to reclaim and recycle water, both ground water and surface water.

This generation must build a State with rich opportunities for the generations yet to come. As New Mexico moves aggressively forward to build a 21st century economy, the State must move aggressively to put in place the legal and physical structures to provide the water to serve this progress. Growth in population and in industry must be managed for the State's general welfare.

The New Mexico Constitution protects the users of water, with the most senior being first in line. For the 21st century, the State must develop water market and water banking mechanisms that will facilitate the voluntary movement of water from old uses to new, with the marketplace supplying the appropriate rewards and the State providing the necessary safeguards.

The water rights of Indian Pueblos and Tribes will be protected, as will the water rights of members of acequias – community irrigation ditch systems – which rights generally predate the Treaty of Guadalupe Hidalgo which brought American sovereignty to what is now New Mexico. Nothing in the State Water Plan will impair or limit the claims that these senior water rights holders assert.

The role of agriculture in New Mexico's future is recognized, and the water necessary to serve that role must be supplied.

The imperative of securing sufficient water to serve the needs of New Mexico's dynamic urban and industrial areas must remain an objective of water planning. The obligation to restore the ecological balance of our surface watercourses must be recognized and met in the implementation of State water policy. Water quality issues must have equal standing with water quantity issues.

The State will plan and prioritize major water infrastructure improvements to get supplies to where they will serve the greatest good in facilitating economic development and in serving existing and future populations.

The State Engineer will initiate an active management program to assert and maintain administrative authority over the allocation of water. Adjudication of water rights in all basins will be expedited.

New Mexico must establish the physical and legal tools to protect the State's water supplies and maintain administrative authority over the State's water resources. Threats to the State's administrative authority over its water may arise from failure to comply with Interstate Compacts, from failure to protect senior rights, or from failure to provide means for the federal government to meet its Endangered Species Act obligations within the framework of State water law. Cooperation and collaboration in meeting endangered species requirements will be a priority, but the State will go to court where necessary to protect the State's administrative authority over its water.

The State Water Plan will lay the foundation and provide guidance for the State's effort to maintain administrative authority over its water resources. It will be a living document, gaining detail and new emphasis as new technologies and new water needs enter the picture. Its primary objective will always be to protect current water users while allowing continued development of the resource to meet the needs of the future.

The State Water Plan does not attempt to identify and resolve region-specific water management issues, because resolution of those issues must include local decision-makers. Still, the sheer number and variety of issues discussed within the State Water Plan demonstrate the complexity of New Mexico's water situation. What at first glance may appear to be a single issue often reveals a web of interrelated matters, which are in turn part of or affected by other issues.

Without an understanding of the complexity of New Mexico's water situation, developing strong, clear policy statements and implementation strategies for statewide common priorities can be difficult. This State Water Plan articulates the policies that will guide the State's management of its water resources into the future, and presents implementation strategies for doing so.

This 2003 State Water Plan is organized following the provisions contained in Sections C through F of the Act. Each Section includes policy statements and implementation strategies, followed by a brief background discussion and a summary of public opinion expressed during the public involvement process.

Specifics and detail on how the State intends to accomplish these aims is contained in the pages that follow.

- *Completing water rights adjudications.*

The following subsections provide a brief background on each of these fundamental common priorities.

Ensuring that water is available for the continued and future economic vitality of the State

The availability of water has always been and will continue to be inextricably linked to the economic vitality of New Mexico's diverse communities. Early in the State's history, water primarily supported local, subsistence-based economies including hunting and gathering societies as well as subsistence-based agriculture and extractive industries where communal production or barter for the products was the norm. Today, its role has evolved to supporting activities which allow our participation in a global economy characterized by diverse endeavors that span that entire spectrum of economic activity. Our citizens still hunt and gather nature's abundance; they still engage in subsistence agriculture, as well as large-scale commercial agriculture for local, regional and global markets; they produce all manner of products and services; they depend on water to support recreational economies such as fishing, boating, golfing, rafting, skiing and tourism; they play an important role in contributing to the national security of the United States; and they produce high technology products which are used worldwide. All of these activities are directly dependent on the availability of sufficient water of the quality needed for the specific uses.

In addition to being diverse, the State's economy is highly decentralized. People throughout the State contribute to the overall economic picture, with people in rural areas producing agricultural, mineral and other naturally occurring products, and those in urban areas providing goods and services as well as industrial and technological products. The continued viability of the diverse entities that supply water for these economic activities is of vital importance to the State. These include municipal suppliers; community water systems including mutual domestic water consumer associations, water cooperative associations, water and sanitation districts, and privately owned public utilities; acequias; irrigation districts; and conservancy districts.

New Mexico's continued economic vitality is also crucially dependent on its ability to preserve its pristine environment, including its spectacularly scenic wild rivers and wilderness watersheds. Both employers and workers are drawn to live and remain in the State by these environmental features and a comprehensive State Water Plan must recognize the importance of preserving and enhancing New Mexico's rivers and watersheds.

Ensuring a safe and adequate drinking water supply for all New Mexicans

The availability of safe and adequate drinking water supplies for all New Mexicans is of paramount importance to the health and safety of the State's citizens. The provision of adequate safe drinking water supplies for their citizens is primarily the responsibility of local agencies and entities, while the State's role is to support local agencies through the combined efforts of the Environment Department, OSE/ISC, and the Water Trust Board. In addition, a significant number of New Mexicans obtain their drinking water from domestic wells. The State needs to strengthen the institutional protections it provides for these users.

Developing water resources to expand the available supply

New Mexico's surface waters in many parts of the State have been fully appropriated since the early to middle 1900s. Most of the municipal and community water supplies developed since then have relied on the State's substantial potable ground water reserves. However, much of that ground water is in storage in aquifers that are hydrologically connected to the State's rivers and is not available for use because the pumping of that ground water would reduce river flows and impair senior surface rights. Therefore, development of these ground water resources has required the identification, purchase and retirement of surface rights. Continued development of potable water supplies will necessitate further development of both surface and ground water resources. Some alternatives that have been identified include:

- Developing the State's limited remaining unappropriated surface water in those basins where it is practical to do so.
- Developing potable ground water in basins where ground water is not closely connected to river flow.
- Characterizing the State's brackish and saline ground water resources to determine where their development is economically feasible.
- Removing accumulated sediment to increase storage capacity in reservoirs with low evaporation losses.
- Constructing new water storage facilities in areas with low evaporation losses where economically and environmentally feasible.
- Implementing Aquifer Storage and Recovery projects where hydrologically and economically feasible

In some areas of the state surface water is potentially available for appropriation but both the timing of the availability of that water and the need to protect senior rights makes development of these resources difficult. In other areas potable ground water occurs in basins that are not hydrologically connected to a stream system, but these resources are often far removed from areas of potential use and would require expensive pipelines to deliver the water.

Large areas of brackish or saline ground water exist that may provide water to meet some New Mexico demands. In these cases, water treatment plants, sludge disposal plants, and pipelines would likely be needed to make the water available for use. Detailed variation and longevity for specific water purveyors. To plan for a dependable water supply, smaller-scale local analyses are required that take into consideration localized aquifer properties and infrastructure constraints specific to each water purveyor.

Water Quality

The New Mexico Environment Department (NMED) maintains a number of sources of water quality data for both ground and surface water. The U.S. Environmental Protection Agency (USEPA) and the U.S. Geological Survey (USGS) also maintain long-term databases of water quality measurements. Pursuant to Section 305(b) of the federal Clean Water Act, New Mexico, through the NMED and the Water Quality Control Commission, prepares and submits to Congress biennial Water Quality and Pollution Control in New Mexico reports that summarize where designated uses of water are being attained and provide a comprehensive overview of the quality of the State's waters.

According to the latest report, almost 3,080 miles, or 52% of New Mexico's more than 5,875 perennial stream miles, have some level of impairment with respect to designated or attainable uses, and 124,140 out of a total of 148,883 lake acres, or 83%, do not fully support designated uses. Information provided in the report regarding ground water quality indicated that at least 1,200 cases of ground water contamination have been identified in New Mexico since 1927, with 188 public and nearly 2,000 private water supply wells impacted.

The quality of the State's ground water resources has been inventoried in the New Mexico Environment Department's *Ground Water Quality Atlas*, available online at http://www.nmenv.state.nm.us/gwb/GWQ%20Atlas/GWQ_Atlas.html. Ground water quality data in the atlas is listed by county and, where available, by public water supply system within the county. Public drinking water quality reports are already available online in the atlas for 23 municipal and public water supply systems in New Mexico's 33 counties.

About 90 percent of New Mexico's population depends on ground water for drinking, and it is the only source of potable water in many areas of the state. Therefore, protection of ground water is important for public health and welfare. The quality of ground water in New Mexico varies widely. Mountain aquifers, recharged by recent rain and snow melt, often yield high quality water. A tremendous amount of fresh water occurs in the basin-fill aquifers along the Rio Grande, stretching from Colorado to Texas. But ground water in New Mexico often contains naturally occurring minerals that dissolve from the soil and rock that it has flowed through. Some ground water in the southern part of the state is too salty to be used for drinking. High levels of natural uranium, fluoride, and arsenic occur in various areas around the state. Because all water eventually moves through the entire water cycle, pollutants in the air, on land, or in surface water can reach any other part of the cycle, including ground water. The shallow sand-and-gravel aquifers of the river valleys are most vulnerable to contamination. Currently a major source of contamination in these aquifers is septic tanks.

imposed by State administrative constraints to protect existing rights and economic limitations on its recovery and/or treatment.

Table 6. Total ground water in storage and estimated recoverable ground water, by water quality category, for Tularosa basin

Aquifer Category	Water in Storage (ac/ft) by TDS Concentration (mg/L) Range				
	<1,000	1,000-5,000	5,000-10,000	≥10,000	Total
Basin fill, total	32,500,000	232,000,000	238,000,000	26,800,000	529,300,000
Bedrock, total	19,100,000	56,300,000	161,000	0	75,561,000
Basin fill, recoverable	8,120,000	48,000,000	43,700,000	4,700,000	104,520,000
Bedrock, recoverable	9,570,000	28,200,000	81,000	0	37,851,000

The total ground water withdrawn in the Tularosa basin in 1995 was an estimated 47,140 ac-ft. Public water supplies are obtained from both surface water and ground water, while irrigation tends to rely primarily on ground water supplies. Of the surface water withdrawn for public supplies, some is imported from Bonito Lake, in the Rio Hondo watershed of the Lower Pecos basin. Water piped from Bonito Lake provides water to the communities of Nogal, Carrizozo, Alamogordo and Holloman Air Force Base. Combined, these users have rights to a little more than 3,000 ac-ft/yr from Bonito Lake in Lincoln County.

The City of Alamogordo has been very progressive in managing available water resources. An aquifer storage and recovery project is being developed to store the excess winter surface water in the aquifer by well injection and to pump it back during high summer demand. The costs are small (estimated at about $0.15 per ac-ft) because the injection will operate by gravity. Alamogordo has also filed water rights applications to extract saline water and is planning a desalination plant to remove dissolved minerals from ground water. Preliminary cost estimates for a desalination plant in Alamogordo, which could treat 8 million gallons per day, are $15 to $20 million.

Salt Basin

Major Issues

On September 13, 2000, the New Mexico State Engineer declared the Salt UWB to be under his administrative review (ISC/OSE, 2002, Atlas Plate 2). Until the basin was declared, water resource issues were not regulated or monitored. Development pressure within the New Mexico side of the basin has been very modest, less than in Texas. Major issues include:

- Little development of the Salt Basin has occurred in New Mexico, but pressure to develop this resource is growing. Ground water depletions must be managed to prevent mining of the basin's aquifers.

- The Salt basin is being considered by some entities as a water source to augment supplies in southwest Texas. Steps must be taken to ensure that water from the basin is preserved to meet growing demands in southern New Mexico.

Surface Water Hydrology

The Sacramento River, Shiloh Draw and Piñon Creek are the major streams in the Salt basin; all but the Sacramento River are intermittent. There are no surface water reservoirs, other than stock ponds, in the basin. The Sacramento River was gaged from 1985 to 1988, during which time annual flow ranged from about 1,800 to 5,500 ac-ft. Some water from the Sacramento River is diverted for irrigation.

Areal recharge from the Sacramento River and the smaller watersheds around the basin (a total of 358 square miles) is estimated at 35,000 ac-ft/yr.

Ground Water Hydrology

The Salt basin is a complex down-faulted basin, filled with unconsolidated and consolidated sediments. The thickness of Santa Fe Group basin-fill sediments has been reported to be as much as 500 feet, but in most places it is between 25 and 300 feet, and ground water saturation is much less. Bedrock limestone aquifers in the basin are productive where fractured and where solution of minerals has enhanced permeability.

The basin-fill aquifer provides water in the southern Crow Flats, while the bedrock aquifers comprise the main aquifer in the Crow Flats area and other parts of the basin. There are few wells and pumping tests to assess the ground water beneath much of the basin.

Well yields depend on location, depth, and the degree of fracturing in the bedrock aquifer. Reported yields in a few wells reach 6,000 gpm, and irrigation wells can generally produce more than 1,000 gpm. Where bedrock units are less fractured, well yields are generally less than 50 gpm.

Most of the stored and recoverable ground water is in bedrock aquifers (Table 7). The hydrology of the basin is poorly understood, and the estimates in Table 7 are provided for comparison purposes only. The estimates do not reflect legal and State administrative constraints on ground water pumping for protection of existing rights, nor the economic limits to accessing the ground water. Additionally, much of the total ground water is in aquifers that would not support well yields sufficient for economic irrigation. Thorough evaluation of the basin would require many new wells and pumping tests.

Depth to water in the central part of the Salt basin is usually around 200 feet, but is about 400 feet in upland areas surrounding the central basin and about 1,000 feet east of Piñon. Between 1950 and 1995, ground water declines of up to 30 feet have been recorded in the Crow Flats area.