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Using δ^{87}Sr values to identify sources of salinity to a freshwater aquifer, Greater Aneth Oil Field, Utah, USA

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Abstract

Salinity increases in water from the freshwater Navajo aquifer in the Aneth area have been documented in recent years. Previous studies during the 1980s in the Aneth area suggested that brines associated with oil production and their subsequent re-injection were the probable source of salinity in the Navajo aquifer. Differences in the delta strontium-87 (δ^{87}Sr) composition of ground-water samples from southeastern Utah were used to determine if oil-field brine or water from the upper Paleozoic aquifer is a plausible source of salinity to the Navajo aquifer. The δ^{87}Sr values of the oil-field brine samples (mean = −0.95‰, range = −1.06 to −0.79‰, $n = 5$) are substantially more negative than the values in water samples from wells completed in the Navajo aquifer (mean = 0.73, range = −0.85 to 2.02‰, $n = 48$), indicating that oil-field brine is not a source of salinity. The δ^{87}Sr values in water samples from wells completed in the upper Paleozoic aquifer (mean = 0.80‰, range = 0.34 to 1.10‰, $n = 4$) are similar to the mean isotopic composition of the more saline water from the Navajo aquifer. The δ^{87}Sr values in water from the Navajo aquifer confirm that two distinct flow areas are present. Mixing models using the δ^{87}Sr values and Sr concentrations of non-saline water from the Navajo aquifer and saline water from the upper Paleozoic aquifer indicate that water from the upper Paleozoic aquifer is a plausible source of saline water to the Navajo aquifer. Most Navajo aquifer wells that contain water with a δ^{87}Sr signature similar to water from the upper Paleozoic aquifer are located within or adjacent to an area where the hydraulic gradient is favorable for upward movement of water from the upper Paleozoic aquifer into the Navajo aquifer. © 1997 Elsevier Science B.V.

Keywords: isotopes; strontium; Utah; ground water; salinity

1. Introduction

The most widespread contaminant of ground water is salinity (Richter and Kreitler, 1991). The saline source(s) leading to increases in dissolved-solids concentrations can be difficult to identify when more than one potential source exists; however, this type of information is needed by regulatory agencies to develop proper mitigation strategies to prevent continued or future dissolved-solids concentration increases in freshwater aquifers.

Numerous geochemical techniques have been used to identify sources of salinity in ground-water systems (Richter and Kreitler, 1991). Heavy isotopes, such as strontium-84 (^{84}Sr), strontium-86 (^{86}Sr), and

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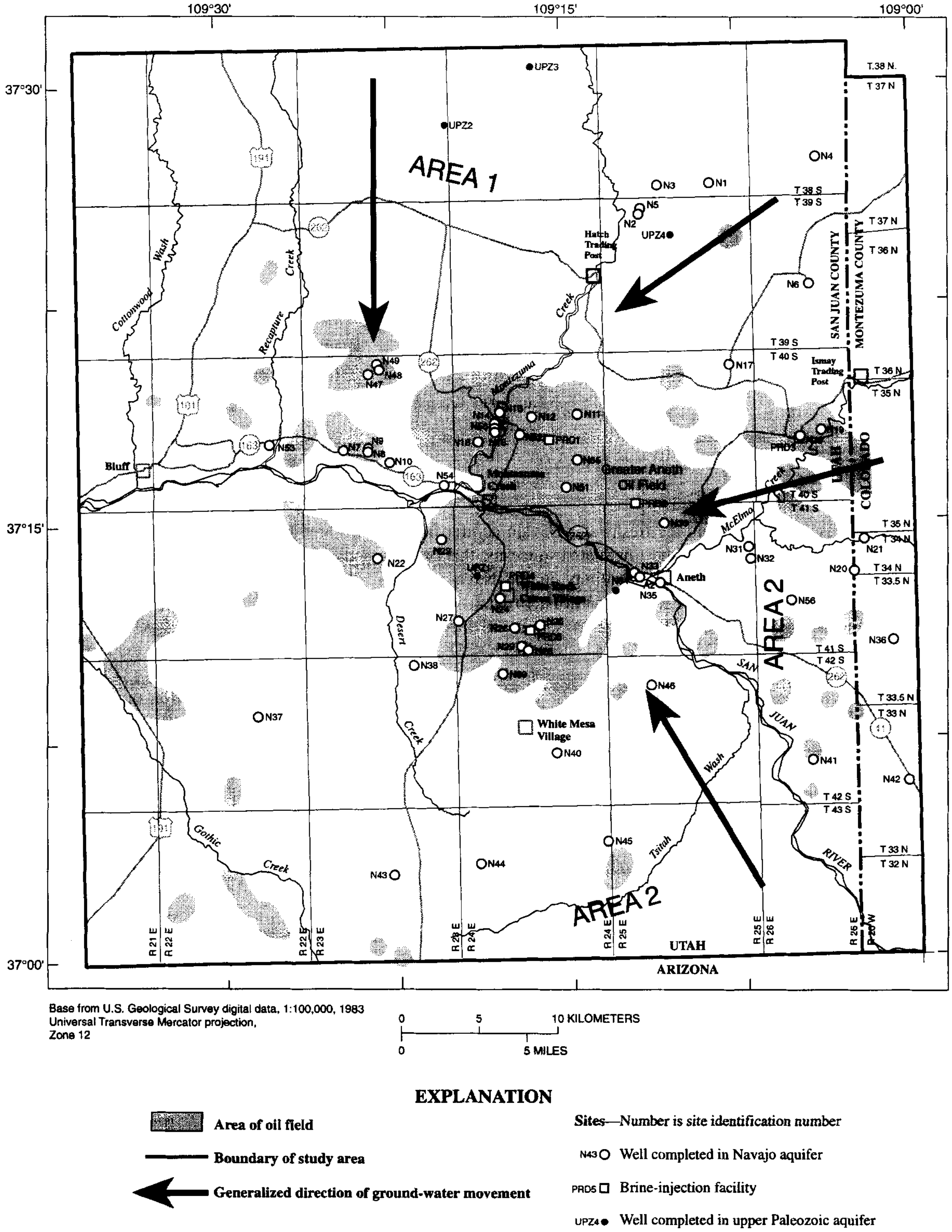
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AREA 1
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UPZ3
UPZ2
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N1
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N47
N48
N49
N53
N54
N56
PRD1
PRD5
Hatch Trading Post
Ismay Trading Post
Bluff
Aneth
Greater Aneth Oil Field
White Mesa Village
SAN JUAN COUNTY
MONTEZUMA COUNTY
UTAH
COLORADO
ARIZONA
Cottonwood Wash
Recapture Creek
Montezuma Creek
McElmo Creek
Desert Creek
Gothic Creek
Tsitah Wash
SAN JUAN RIVER
T.38 N.
T 37 N
T 36 N
T 35 N
T 34 N
T 33.5 N
T 33 N
T 32 N
T 38 S
T 39 S
T 40 S
T 41 S
T 42 S
T 43 S
R 21 E
R 22 E
R 23 E
R 24 E
R 25 E
R 26 E
Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection,
Zone 12
0 5 10 KILOMETERS
0 5 MILES
EXPLANATION
Area of oil field
Boundary of study area
Generalized direction of ground-water movement
Sites—Number is site identification number
N43 Well completed in Navajo aquifer
PRD5 Brine-injection facility
UPZ4 Well completed in upper Paleozoic aquifer

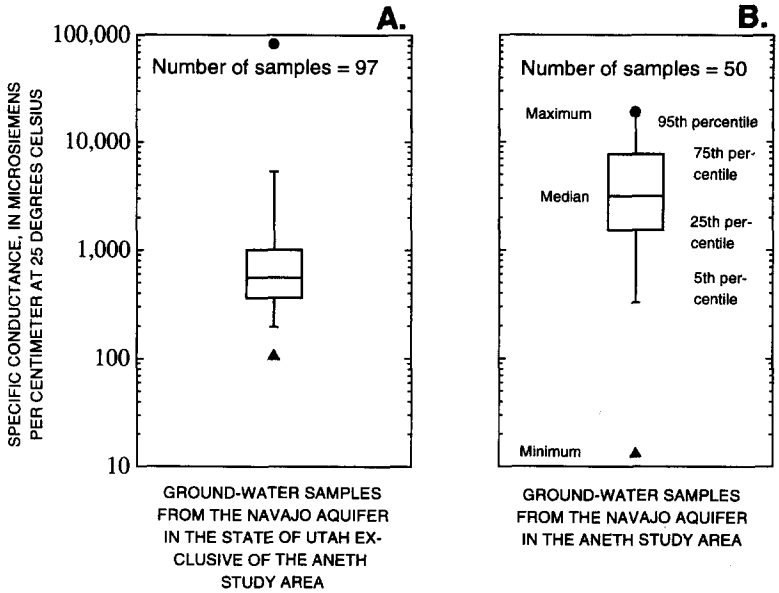


Fig. 2. Box plots comparing the specific conductance of water samples from the Navajo aquifer. (A) Water samples from wells and springs in the state of Utah exclusive of the Aneth study area. (B) Water samples from wells and springs in the Aneth study area. For wells and springs with multiple values, only the most recently determined value was selected.

strontium-87 (^{87}Sr) are becoming increasingly important in studies of surface- and ground-water systems, including the identification of saline sources. Unlike the stable isotopes of oxygen and hydrogen that have long been used in hydrology, Sr isotopes do not measurably fractionate in nature. Instead, the proportion of radiogenic ^{87}Sr relative to the nonradiogenic isotopes will vary from the decay of the parent nuclide rubidium-87 (^{87}Rb). Ground water acquires dissolved Sr at the recharge area during infiltration and percolation and along the flow path by dissolution of minerals or through ion exchange with such minerals as clays and zeolites. Thus, Sr is not conservative, but rather provides an integrated flow-path signal of rock–water interaction. Previous studies of Sr isotopes in runoff (Wadleigh et al., 1985; Jacks et al., 1989; Krishnaswami et al., 1992; Pande et al., 1994), precipitation (Herut et al., 1993), and ground water (Chaudhuri et al., 1987; Banner et al., 1989; Franklyn et al., 1991; Peterman and Stuckless, 1992; Smalley et al., 1992; Stueber et al., 1993; Lyons et al., 1995) demonstrate the usefulness of this tracer in hydrologic applications.

The Aneth study area in southeastern Utah (Fig. 1), where numerous wells penetrate the freshwater Navajo aquifer, provides an excellent field site to evaluate the application of Sr isotopes in differentiating potential sources of salinity. Salinity increases in water from the Navajo aquifer in the Aneth area have been documented in recent years (Kimball, 1992; Spangler, 1992; Naftz and Spangler, 1994; Naftz et al., 1995), and specific-conductance values of water samples from the Navajo aquifer are higher than in other parts of Utah (Fig. 2). Substantial quantities of oil are produced in this part of Utah, and brines associated with oil production and re-injection have been suggested as the potential source of salinity (Kimball, 1992); however, recent results

Fig. 1. Location of the study area, sites where $\delta^{87}Sr$ values were determined, and generalized ground-water flow areas and directions in the Navajo aquifer. Primary recharge areas to the Navajo aquifer in flow area 1 are north and northeast of the study area. Recharge areas to the Navajo aquifer in flow area 2 are east and south of the study area.

using bromide, iodide, chloride, delta oxygen-18 ($\delta^{18}O$), and delta deuterium (δD) data have indicated that oil-field brines are not the source of salinity (Naftz and Spangler, 1994). Although oil-field brines have been eliminated as the source of salinity, an alternative source(s) of salinity has not been identified. This paper presents Sr isotope data from the study area in an attempt to determine the source(s) of salinity to water in the Navajo aquifer in southeastern Utah.

2. Hydrogeology of the Navajo aquifer

The hydrogeology of the study area and adjacent areas has been investigated by Goode (1958), Cooley et al. (1969), Sumsion (1975), Whitfield et al. (1983), Avery (1986), Thomas (1989), Howells (1990), and Freethey and Cordy (1991). The Wingate, Kayenta, Navajo, and Entrada Sandstones of Triassic to Jurassic age, along with intervening semiconfining units, are included in the Navajo aquifer (Fig. 3). The Navajo aquifer ranges from 154 to 256 m in thickness and generally is fully saturated in the study area. Most wells finished in the Navajo aquifer are artesian because elevation of the hydraulic head in the wells is higher than the elevation of the land surface at the well.

Lateral and vertical hydraulic-head differences in the Navajo aquifer indicate that ground water moves from highland recharge areas north, south, and east of the study area toward the San Juan River (Fig. 1). Ground-water flow within the Navajo aquifer was separated into two flow areas (Fig. 1) that have distinctly different directions of ground-water flow and sources of recharge. Primary recharge areas to the Navajo aquifer in flow area 1 are north of the study area along the flanks of the Abajo Mountains, and possibly mountain ranges to the northeast in Colorado (Freethey and Cordy, 1991). Recharge areas to the Navajo aquifer in flow area 2 are east of the study area along the flanks of Sleeping Ute Mountain in Colorado, and south of the study area along the Carrizo Mountains in Arizona. Wells completed in the Navajo aquifer north of McElmo Creek and north of the San Juan River after its confluence with McElmo Creek are included in flow area 1 (Fig. 1). Wells completed in the Navajo aquifer south of McElmo Creek and south of the San Juan River after its confluence with McElmo Creek are included in flow area 2 (Fig. 1).

An increase in base flow of the San Juan River in the study area has been attributed to seepage from the Navajo and other overlying aquifers (Avery, 1986). Analysis of discharge records from U.S. Geological Survey gaging stations on the San Juan River and McElmo Creek during November 1980 indicate the net gain in San Juan River discharge (along about a 95-km reach) from bedrock aquifers was about 1870 l/s (Avery, 1986). Hydraulic-head differences indicate that movement of saline water from the upper Paleozoic aquifer (Cutler Formation and DeChelly Sandstone Member) upward into the Navajo aquifer is possible in some areas (Freethey and Cordy, 1991; Weiss, 1991) (Fig. 3). For example, pump-test data from a site within the study area indicate that hydraulic head in the upper Paleozoic aquifer at a depth of about 510 m below land surface exceeded that in the Navajo aquifer by 65 m, thus confirming a potential for upward vertical movement (Taylor et al., 1986). Upward leakage of saline water from the middle Paleozoic aquifer (Leadville Limestone) and upper Paleozoic aquifer and confining units (Hermosa Group) to the Navajo aquifer, however, is not likely (Weiss, 1987; Kimball, 1992).

3. History of oil-field production

Substantial drilling activities were begun in the study area during the early 1950s (Clem and Brown, 1984). Producing zones in the Greater Aneth Oil Field and vicinity are primarily in carbonate units of the Pennsylvanian-age Paradox Formation at depths generally ranging from 1520 to 1830 m below land surface. Since the early 1960s, a large quantity of oil-field brine has been re-injected into the oil-producing zones to enhance oil recovery. This re-injection process potentially provides a human-induced mechanism for movement of oil-field brine into the Navajo aquifer.

4. Sampling and analytical procedures

Water samples from flowing wells were collected and processed immediately. Water from wells that

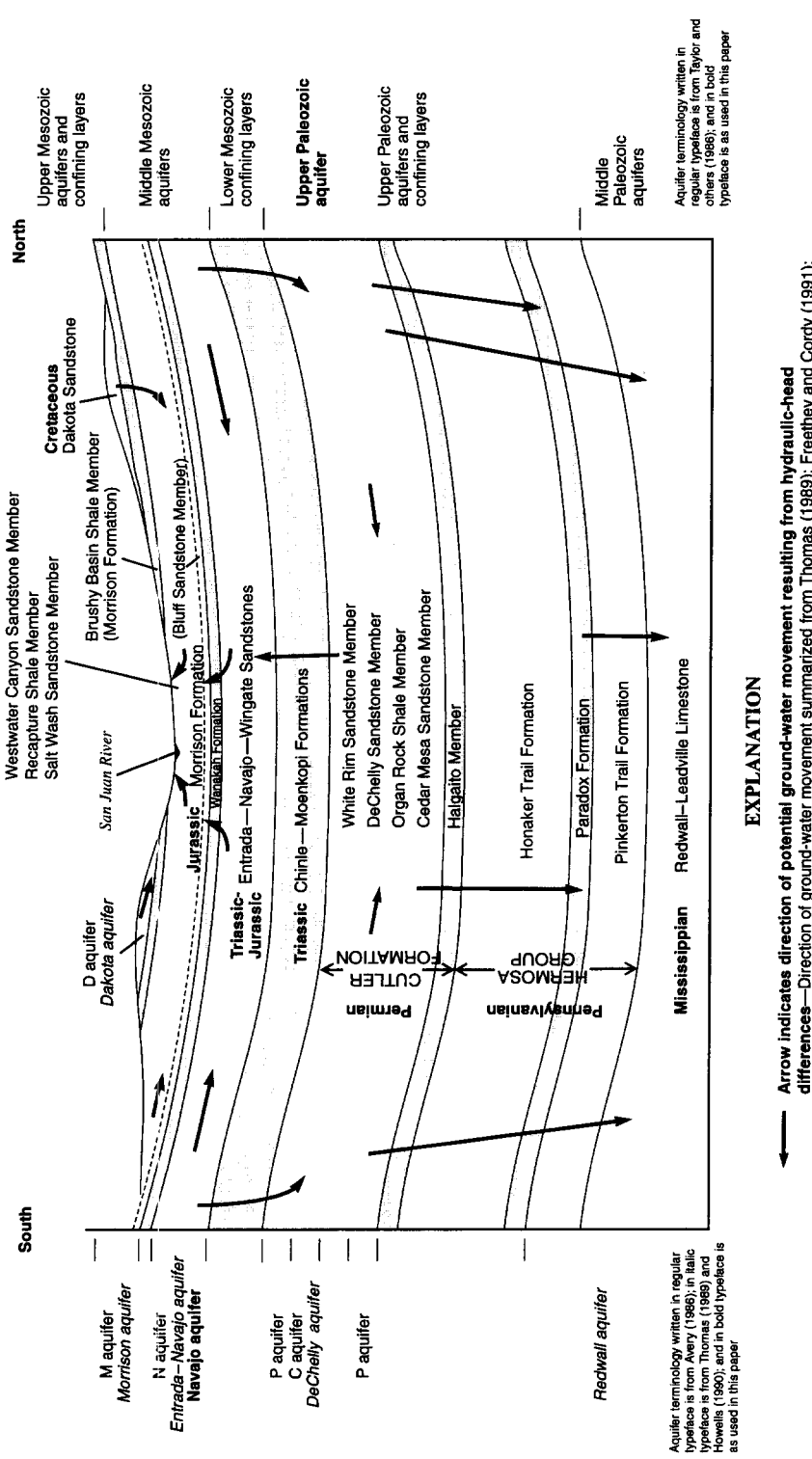


Fig. 3. Schematic cross-section showing hydrogeologic units in the vicinity of the Greater Aneth Oil Field, Utah.

Table 1
Chemical data from ground-water samples collected in the study area

Field site	Sampling date	$\delta^{87}Sr$	$\delta^{87}Sr$ (‰)	Sr (mg/l)	Cl (mg/l)	Dissolved-solids conc. (mg/l)
Navajo aquifer						
N43	06-15-93		−0.85	1.4	3.8	150
N44	11-04-93		−0.79	0.03	3.6	367
N45	08-29-92		−0.64	1.5	360	2,840
N40	11-17-92		−0.24	11	1,700	11,400
N31	08-27-92		−0.01	0.60	110	2,160
N38	06-15-93		0.03	0.05	20	473
N41	11-16-92		0.06	1.1	100	2,140
N39	10-06-89		0.08	0.40	130	1,290
N20	11-18-92		0.10	0.70	240	2,030
N53	08-26-92		0.11	0.20	6.9	261
N25	10-11-89		0.13	11	2,000	8,860
N28	08-28-92		0.16	0.30	95	1,050
N29	08-28-92		0.17	0.80	200	1,560
N56	09-23-94		0.27	0.94	100	2,510
N46	04-01-93		0.30	6.1	1,100	5,760
N42	06-26-92		0.35	9.1	890	4,860
N36	11-18-92		0.38	11	4,200	11,800
N27	05-05-93		0.38	0.20	53	818
N24	06-18-93		0.41	0.60	240	1,890
N35	08-23-89		0.48	12	3,600	8,730
N33	04-06-93		0.51	1.2	2,900	6,990
N21	08-31-92		0.52	9.0	1,900	11,500
N34	04-02-93		0.54	18	3,200	7,620
N47	04-03-93		0.56	1.6	240	998
N32	10-10-89		0.64	8.5	3,500	9,110
N19	06-26-92		0.78	20	4,700	12,200
N18	09-21-94		0.93	11	4,900	17,000
N10	08-25-92		0.97	2.5	460	1,870
N30	06-26-92		0.99	3.7	610	2,780
N54	09-23-94		0.99	6.4	1,300	4,470
N49	06-24-92		1.14	4.8	360	1,970
N15	06-23-92		1.18	1.8	160	1,300
N22	09-24-94		1.20	0.31	52	850
N23	06-25-92		1.24	10	1,200	6,240
N17	09-21-94		1.27	4.8	3,100	10,200
N8	08-28-92		1.35	1.1	180	986
N50	06-23-92		1.41	2.5	520	2,400
N7	10-03-89		1.42	0.80	160	946
N52	04-02-93		1.45	4.0	1,100	3,740
N48	06-24-92		1.47	0.60	19	359
N2	08-26-93		1.48	1.2	190	1,000
N51	06-25-92		1.54	5.9	1,100	4,600
N14	06-23-92		1.65	2.8	760	2,430
N12	06-20-89		1.69	2.6	470	2,170
N6	10-07-89		1.71	2.3	20	907
N16	10-09-89		1.75	2.7	520	2,230
N13	08-25-92		1.85	1.5	6.8	380
N1	08-26-93		2.02	0.56	57	704

Table 1 (continued)

Field site	Sampling date	$\delta^{87}Sr$	$\delta^{87}Sr$ (‰)	Sr (mg/l)	Cl (mg/l)	Dissolved-solids conc. (mg/l)
Upper Paleozoic aquifer						
UPZ1	04-17-94		1.10	87	1,000	6,760
UPZ2	04-21-94		0.82	11	6,000	12,900
UPZ3	04-21-94		0.94	6.4	1,200	2,540
UPZ4	04-19-94		0.34	11	15,000	25,500
Oil-field brine						
PRD1	06-22-89		−0.82	180	48,000	78,800
PRD2	11-20-92		−1.06	200	44,000	71,700
PRD3	10-09-89		−1.06	200	110,000	184,000 [a]
PRD4	08-31-92		−1.03	160	48,000	82,400
PRD5	08-25-93		−0.79	153	48,000	75,900

Field site location shown in Fig. 1.

[a] Dissolved-solids concentration determined by residue on evaporation at 180°C (Fishman and Friedman, 1989).

had to be pumped or that had valves to control free flow were allowed to flow for 1 to 2 h or until temperature and specific conductance stabilized before samples were collected. The Sr samples (including the isotopes ^{87}Sr and ^{86}Sr) were collected in 250-ml, acid-rinsed polyethylene bottles and were filtered (0.45 μm) in the laboratory prior to analysis. Samples collected for chloride were filtered on-site through a 0.45-μm filter using a peristaltic pump and collected in field-rinsed, 250-ml polyethylene bottles.

The $^{87}Sr/^{86}Sr$ ratios and Sr concentrations of water samples were determined at the U.S. Geological Survey, Yucca Mountain Project Branch Isotope Laboratory in Lakewood, Colorado. The Sr isotopic values and Sr concentrations were determined by thermal ionization mass spectrometry using a fully automated Finnigan MAT 262 [1] instrument. Aliquots of the ground-water samples were commonly between 10 and 100 ml. To these aliquots, a known amount of enriched ^{84}Sr spike was added prior to evaporation to dryness. The Sr was purified with conventional ion-exchange columns. Measured $^{87}Sr/^{86}Sr$ ratios are precise to better than ±0.01% of the ratio at 2-σ (external precision). The $^{87}Sr/^{86}Sr$ ratio of ground-water samples was converted to the permil deviation from modern seawater using the following formula:

$$\delta^{87}Sr = \{[(^{87}Sr/^{86}Sr)_m/(^{87}Sr/^{86}Sr)_{sw}] - 1\} \times 1000 \quad (1)$$

where $\delta^{87}Sr$ is the sample deviation from seawater expressed in units of permil, $(^{87}Sr/^{86}Sr)_m$ is the isotope ratio of the sample, and $(^{87}Sr/^{86}Sr)_{sw}$ is the isotope ratio of modern seawater (0.70920). The isotope composition of dissolved Sr in seawater is used as the reference because it is globally uniform. Chloride concentrations were determined by ion-exchange chromatography (Fishman and Friedman, 1989) at the U.S. Geological Survey National Water Quality Laboratory in Arvada, Colorado. Dissolved-solids concentrations were calculated as the sum of major constituents (Fishman and Friedman, 1989).

5. Results and discussion

5.1. Distribution of $\delta^{87}Sr$ in ground-water samples

The analytical data shown in Table 1 include 48 samples from wells completed in the Navajo aquifer, 4 samples from wells completed in the upper Paleozoic aquifer, and 5 samples of oil-field brine collected from injection facilities in the study area. Histograms of $\delta^{87}Sr$ values of samples of potential saline end-member water sources (oil-field brine and

[1] Use of brand names in this article is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

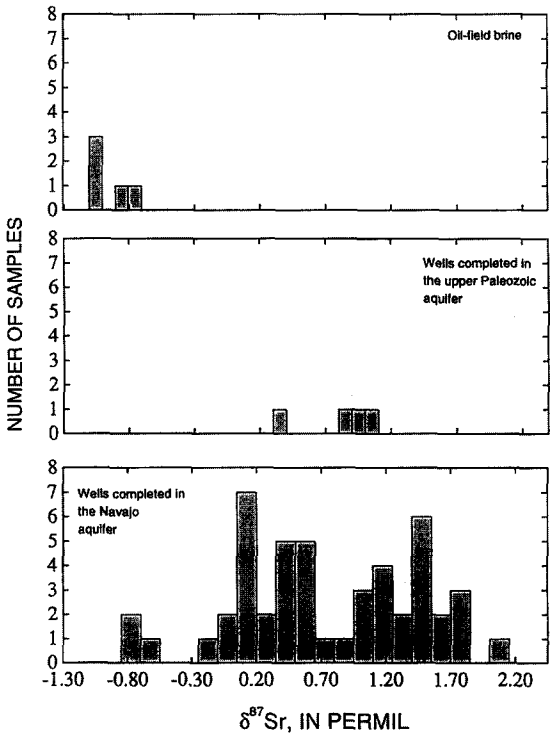


Fig. 4. Histograms of δ^{87}Sr values of oil-field brine samples and water samples from wells completed in the upper Paleozoic and Navajo aquifers.

upper Paleozoic aquifer) were compared with a histogram of δ^{87}Sr values of water samples from the Navajo aquifer (Fig. 4). With the exception of three sites, the δ^{87}Sr values of the five oil-field brine samples are substantially lower than the values of water samples from wells completed in the Navajo aquifer and confirm previous geochemical interpretations that indicate oil-field brine is not a major source of salinity (Naftz and Spangler, 1994). Two of the three water samples collected from the Navajo aquifer with δ^{87}Sr values similar to samples of oil-field brine (Fig. 4) have dissolved-solids concentrations less than 400 mg/l (Table 1) and indicate that oil-field brine is probably not causing the lower isotopic signature. The median δ^{87}Sr value of the oil-field brine data (−1.029‰) is comparable to the δ^{87}Sr value of sea water (approximately −1.269‰) during deposition of the Paradox Formation about 300 million years ago (Burke et al., 1982).

In contrast to the oil-field brine samples, δ^{87}Sr values of water samples from the upper Paleozoic aquifer are higher, about midway in the range of δ^{87}Sr values of water samples from the Navajo aquifer, indicating a possible linkage in isotopic signatures. The bimodal distribution of δ^{87}Sr values in water samples from the Navajo aquifer indicates the presence of two subpopulations. Using a δ^{87}Sr threshold value of 0.75‰, the subpopulation with a δ^{87}Sr value greater than 0.75‰ is composed mostly of water from wells located in flow area 1, and the subpopulation with a δ^{87}Sr value less than 0.75‰ is composed mostly of water from wells in flow area 2 (Fig. 5). The reason for a more radiogenic signature in water from the Navajo aquifer in flow area 1 is not known but may be related to the difference in outcrop lithologies between flow areas 1 and 2 that could impart different δ^{87}Sr values during recharge to the Navajo aquifer.

The δ^{87}Sr values were compared with the Sr concentrations in ground-water samples collected in the study area (Fig. 6). With increasing Sr concentration, the δ^{87}Sr values of water samples from wells in both flow areas 1 and 2 appear to converge to the mean δ^{87}Sr value and mean Sr concentration of four water samples from the upper Paleozoic aquifer (Fig. 6). This convergence indicates that water from the upper Paleozoic aquifer may be a plausible source of salinity to the Navajo aquifer.

5.2. δ^{87}Sr mixing model

Mixing models were constructed to investigate more quantitatively the convergence of δ^{87}Sr values of water from the Navajo aquifer in flow areas 1 and 2 (Fig. 6) to the δ^{87}Sr composition of water from the upper Paleozoic aquifer. The δ^{87}Sr values, in combination with the Sr concentrations, can be used to construct hyperbolic mixing lines to determine if water from the upper Paleozoic aquifer presents a geochemically consistent salinity source to the Navajo aquifer. Mixing lines were constructed using δ^{87}Sr values of water samples from four different end-member wells completed in the Navajo aquifer mixed with the mean Sr data from four wells completed in the upper Paleozoic aquifer (Fig. 6). Two end-member water samples were selected from flow areas 1 (N13 and N1) and 2 (N43 and N44) on the basis of low (less than 60 mg/l) chloride concentra-

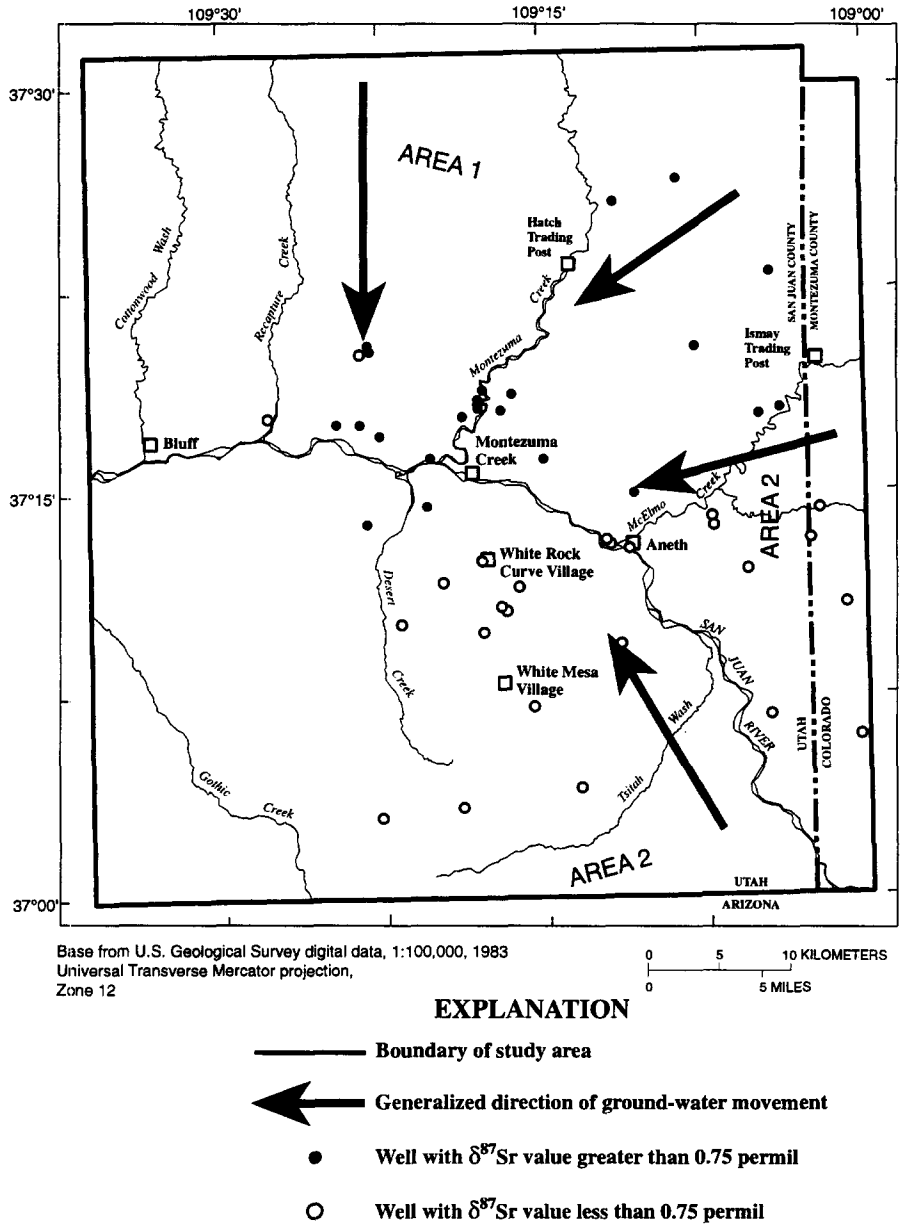


Fig. 5. Location of wells completed in the Navajo aquifer with water containing large (greater than 0.75‰) and small (less than 0.75‰) δ^{87}Sr values.

tions, because these are most representative of ground water not influenced by mixing with saline sources. The δ^{87}Sr value of the water samples was a further consideration in selecting non-saline end-member wells. Water samples from wells N13 and N1 have the highest δ^{87}Sr values of any water samples in flow area 1, and water samples from wells N43 and N44 have the lowest δ^{87}Sr values of any water samples in flow area 2. Mixing lines were constructed using the following equations:

$$C_{mix} = C_1 V + C_2(1 - V) \quad (2)$$

$$\delta^{87}Sr_{mix} = \left[\delta^{87}Sr_1 C_1 V + \delta^{87}Sr_2 C_2 (1 - V)\right] / C_{mix} \quad (3)$$

where C_{mix} is the Sr concentration of the end-member water mixture, C_1 is the Sr concentration of the non-saline end-member water, V is the volume fraction of the Navajo aquifer end-member water, C_2 is the Sr concentration of the saline end-member water, $\delta^{87}Sr_{mix}$ is the Sr isotopic composition of the end-member water mixture, $\delta^{87}Sr_1$ is the Sr isotopic composition of the non-saline end-member water, and $\delta^{87}Sr_2$ is the Sr isotopic composition of the saline end-member water. Different values of $\delta^{87}Sr$ were used to represent the end-member composition of water from wells completed in the upper Paleozoic aquifer. Mixing lines for water from wells completed in the Navajo aquifer in flow area 1 used the mean value and the mean value plus one standard deviation. Mixing lines for water from wells completed in the Navajo aquifer in flow area 2 used the mean value and the mean value minus one standard deviation (Fig. 6).

The $\delta^{87}Sr$ value and Sr concentration of 48 water samples from the Navajo aquifer and 5 samples of oil-field brine were compared with the 8 constructed mixing lines (Fig. 6). The mixing lines generally match the observed trends in flow areas 1 and 2, with water from the upper Paleozoic aquifer as the source of salinity. The four mixing lines constructed with water from wells in flow area 1 (N13 and N1) fit the observed trend of decreasing $\delta^{87}Sr$ with increasing Sr concentration (Fig. 6). The four mixing lines constructed with water from wells in flow area 2 (N43 and N44) also match the observed trend of

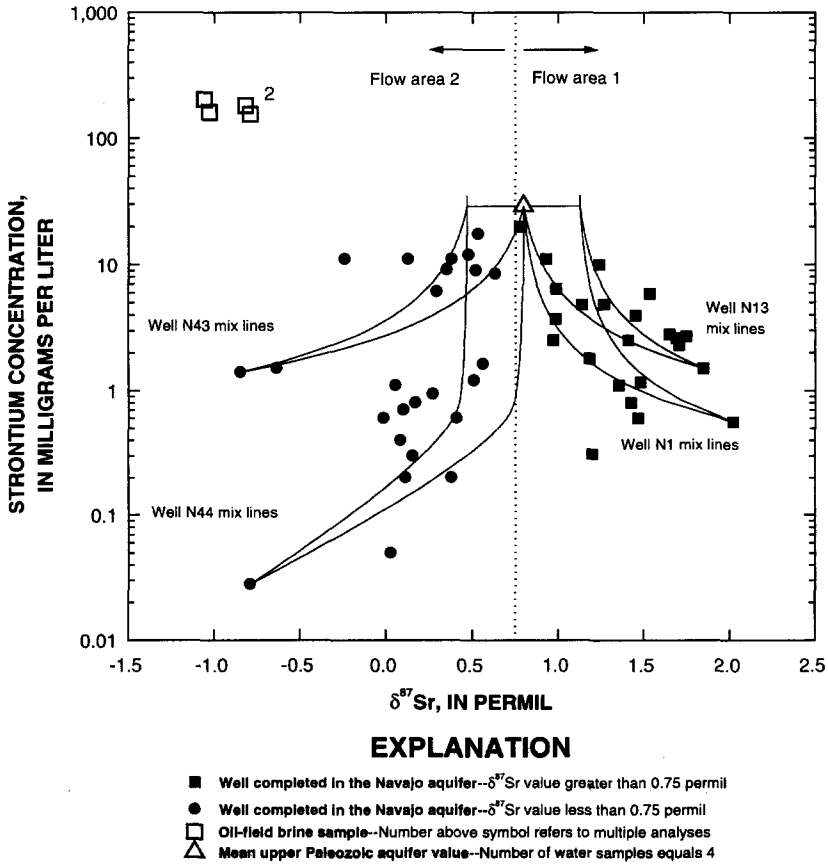


Fig. 6. Variation of strontium concentration and $\delta^{87}Sr$ value compared with eight mixing lines constructed with data collected from selected wells completed in the Navajo and upper Paleozoic aquifers.

Table 2
Proportion of saline and freshwater mixtures determined from selected $\delta^{87}Sr$ isotopic mixing models compared with calculated and measured chloride concentrations in water from wells completed in the Navajo aquifer

Sample site	% Saline water from upper Paleozoic aquifer	% Freshw. from Navajo aquifer wells N13, N1, or N43	Calc. chloride conc. from $\delta^{87}Sr$ mixing model (mg/ml)	Meas. chloride conc. (mg/ml)
Well N13 mix line				
N50	4	96	240	520
N49	11	89	640	360
N54	18	82	1000	1300
N18	35	65	2000	4900
N19	71	29	4100	4700
Well N1 mix line				
N8	2	98	170	180
N15	4	96	290	160
N10	8	92	520	460
N30	11	89	690	610
Well N43 mix line				
N45	1	99	62	360
N46	21	79	1200	1100
N42	29	71	1700	890
N36	37	63	2200	4200

increasing $\delta^{87}Sr$ with increasing Sr concentration (Fig. 6).

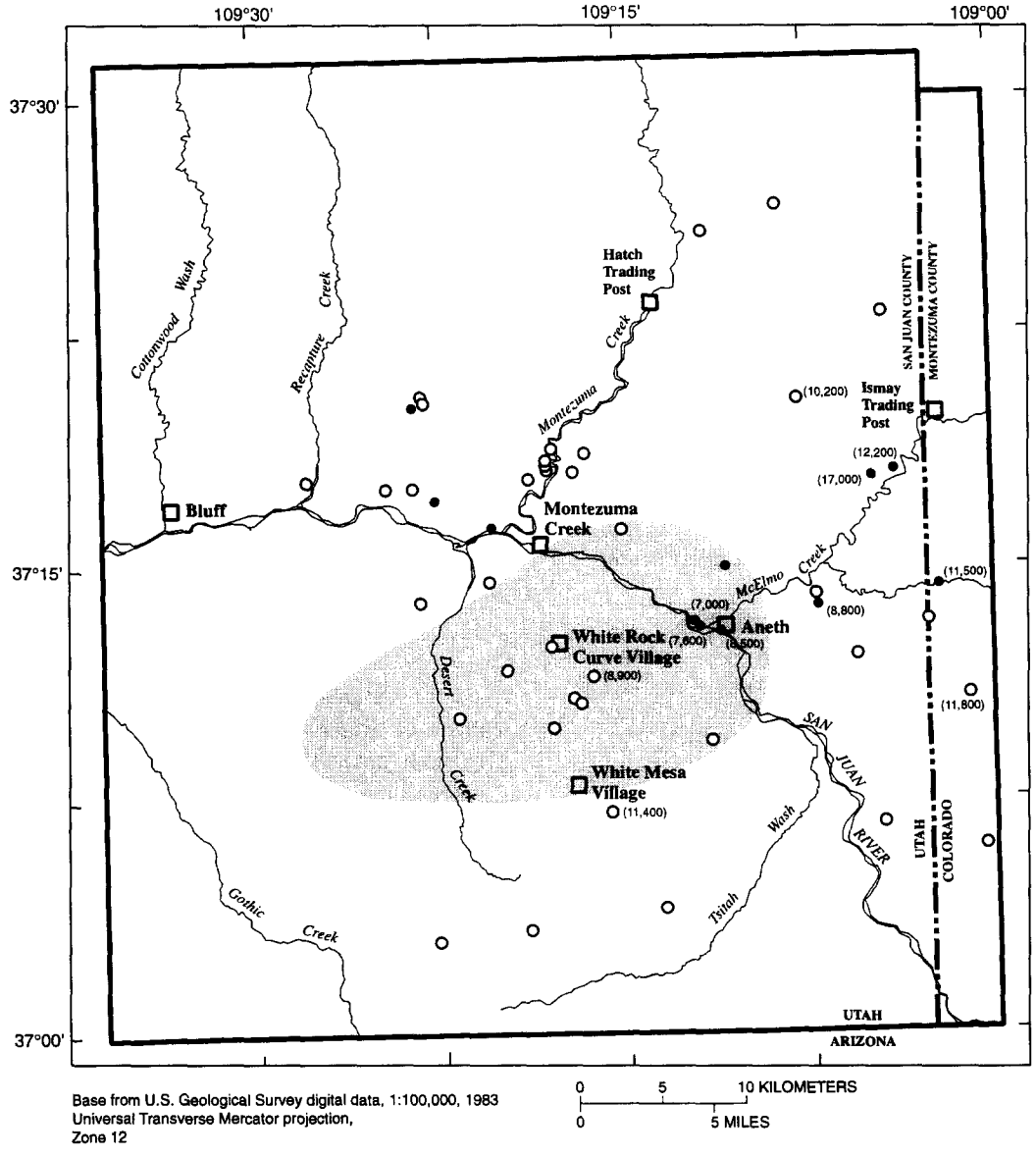
The N13, N1, and N43 mixing lines were used to estimate mixing proportions between the Navajo aquifer end-member and upper Paleozoic aquifer end-member waters in potentially affected wells completed in the Navajo aquifer (Table 2). Mixing proportions estimated from the $\delta^{87}Sr$ models were then used to calculate the chloride concentration expected in the affected wells. Because of the wide variation in chloride concentration in water from the four wells completed in the upper Paleozoic aquifer (1000 to 15,000 mg/l), the mean chloride concentration was used. The calculated and measured chloride concentrations in water from the affected wells along the selected mixing lines are generally in close agreement, considering the size of the study area and the limited data set for the upper Paleozoic aquifer (Table 2).

5.3. Probable areas influenced by mixing

The location of Navajo aquifer wells with water containing a $\delta^{87}Sr$ signature similar to that of water from the upper Paleozoic aquifer (mean value $\pm$ 1 standard deviation) was compared with the area identified by Freethey and Cordy (1991) where the hydraulic gradient is favorable for upward movement of water from the upper Paleozoic aquifer into the Navajo aquifer (Fig. 7). This area of upward potential was developed from regional-scale data and may be smaller or larger than that indicated by Freethey and Cordy (1991).

Four of the eleven Navajo aquifer wells containing water with $\delta^{87}Sr$ values most similar to water from the upper Paleozoic aquifer are within the area where the hydraulic gradient suggests a potential for upward water movement to the Navajo aquifer, and three additional wells are within 10 km of the boundary of this area (Fig. 7). An explanation(s) as to why four wells with $\delta^{87}Sr$ values characteristic of water from the upper Paleozoic aquifer and dissolved-solids concentration exceeding 6500 mg/l are located outside of the area where a potential for upward movement of water from the upper Paleozoic aquifer exists is unknown. Because the area of potential for upward movement is not well defined, it may be larger than the area shown in Fig. 7 and may include additional wells outside of the currently defined boundaries.

Water samples from wells in the Navajo aquifer with a $\delta^{87}Sr$ signature similar to water from the upper Paleozoic aquifer generally have the highest dissolved-solids concentrations relative to other Navajo aquifer well samples (Fig. 8). Seven of the eleven wells containing water with a dissolved-solids concentration greater than 6500 mg/l plot within the range of $\delta^{87}Sr$ values expected in water from the upper Paleozoic aquifer, and an eighth and ninth well plot close to the expected range. The $\delta^{87}Sr$ signature of water from these nine Navajo aquifer wells would indicate mixing with a substantial volume of water from the upper Paleozoic aquifer (dissolved-solids concentration ranging from 2540 to 25,500 mg/l). The remaining two wells (N25 and N40) have water with a substantially lower (0.67 and 1.04‰, respectively) $\delta^{87}Sr$ signature than water from the upper Paleozoic aquifer. These more negative values may



EXPLANATION

Area where hydraulic head determined from potentiometric contours in upper Paleozoic aquifer is higher than hydraulic head determined from potentiometric contours in Navajo aquifer—from Freethey and Cordy (1991)

Boundary of study area

(8,500) ● Well completed in Navajo aquifer—δ^{87}Sr value most similar to water from the upper Paleozoic aquifer (δ^{87}Sr greater than 0.47 or less than 1.13 permil). Number by symbol is dissolved-solids concentration, in milligrams per liter, if greater than 6,500 milligrams per liter

(11,400) ○ Well completed in Navajo aquifer—δ^{87}Sr value least similar to water from the upper Paleozoic aquifer (δ^{87}Sr less than 0.47 or greater than 1.13 permil). Number by symbol is dissolved-solids concentration, in milligrams per liter, if greater than 6,500 milligrams per liter

Fig. 7. Relation of area of possible upward water movement from the upper Paleozoic aquifer to location of wells completed in the Navajo aquifer that contain water with a δ^{87}Sr value similar to water from the upper Paleozoic aquifer.

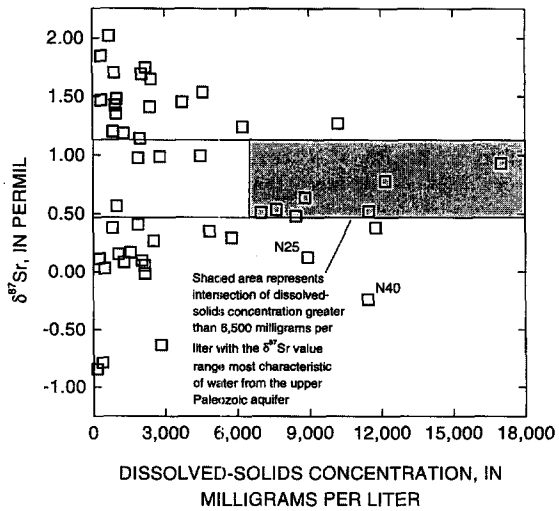


Fig. 8. Variation of δ^{87}Sr value and dissolved-solids concentration in water samples from wells completed in the Navajo aquifer.

indicate mixing with an unknown source(s) of salinity with a negative δ^{87}Sr signature. For example, the five oil-field brine samples from the study area have a median δ^{87}Sr value of -1.03‰ and a median dissolved-solids concentration of 78,800 mg/l.

Although the lower Mesozoic confining unit (Chinle–Moenkopi formations) that separates the upper Paleozoic and Navajo aquifers (Fig. 3) is more than 305 m thick in the study area (Freethey and Cordy, 1991), natural migration of saline water upward into the Navajo aquifer could take place over geologic time. Improperly abandoned drill holes in the Greater Aneth Oil Field also could have acted as potential vertical-flow conduits for water from the upper Paleozoic aquifer during the last 50 years. Upward migration of saline water containing highly variable concentrations of dissolved solids from the upper Paleozoic aquifer into the Navajo aquifer would help to explain why water from wells with significantly different δ^{87}Sr signatures may be in proximity to one another. Apparent increases in salinity of water from selected wells in the Navajo aquifer during the study (1989–1995) may be the result of pumping-induced movement of saline water into the well bore as relatively fresh water is removed.

Upward movement through partly open or poorly plugged bore holes of abandoned wells and test holes through corroded casings is a possible avenue through which water may move upward relatively rapidly, from the upper Paleozoic aquifer to the Navajo aquifer, particularly where large differences in hydraulic head between the aquifers exist. Investigations in progress by the Navajo Environmental Protection Agency (NEPA) indicate that many abandoned oil and injection wells in the study area may have insufficient surface casing to isolate the entire thickness of the Navajo aquifer and may have uncemented intervals behind the intermediate casing between the DeChelly and Navajo Sandstones. Almost 200 wells in the study area were identified as having the potential to provide conduits for upward water migration (James Walker, NEPA, oral commun., 1995). Further investigation of abandoned wells in and adjacent to the Greater Aneth Oil Field is underway by Navajo Nation and Federal regulatory agencies.

6. Conclusions

The δ^{87}Sr composition of ground-water samples from selected water wells in the vicinity of the Greater Aneth Oil Field has been useful in determining whether saline water from oil-field brine or the upper Paleozoic aquifer is a plausible source of salinity to the freshwater Navajo aquifer. In general, δ^{87}Sr values of the five oil-field brine samples are substantially more negative than the values of water samples from wells completed in the Navajo aquifer and confirm previous geochemical interpretations indicating that oil-field brine is not a likely source of salinity. The δ^{87}Sr values of water samples from the Navajo aquifer in flow area 1 are distinctly higher than values of water samples collected in flow area 2. With increasing Sr concentration, δ^{87}Sr values of water samples from wells in both flow areas 1 and 2 converge to the mean δ^{87}Sr value and mean Sr concentration of four water samples from the upper Paleozoic aquifer.

In general, mixing models using the δ^{87}Sr and Sr concentrations of non-saline water from the Navajo aquifer and saline water from the upper Paleozoic aquifer adequately represent the observed trends in δ^{87}Sr values with increasing Sr concentrations in water from the Navajo aquifer in flow areas 1 and 2.

Mixing proportions estimated from the $\delta^{87}Sr$ mixing models generally agree with measured chloride concentrations in the water samples from wells completed in the Navajo aquifer.

Most Navajo aquifer wells with water containing a $\delta^{87}Sr$ signature similar to that of water from the upper Paleozoic aquifer are located within or adjacent to an area where the hydraulic gradient is favorable for upward water movement from the upper Paleozoic aquifer into the Navajo aquifer. Most of the water samples from the Navajo aquifer with a high dissolved-solids concentration also have a $\delta^{87}Sr$ value characteristic of water from the upper Paleozoic aquifer. Salinization of the Navajo aquifer in some areas may result from upward movement of saline water from the upper Paleozoic aquifer through the bores of plugged and abandoned wells and test holes and (or) movement upward through the annuli between the well casings and bore-hole walls of poorly cemented or uncemented abandoned wells and test holes, into the Navajo aquifer.

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