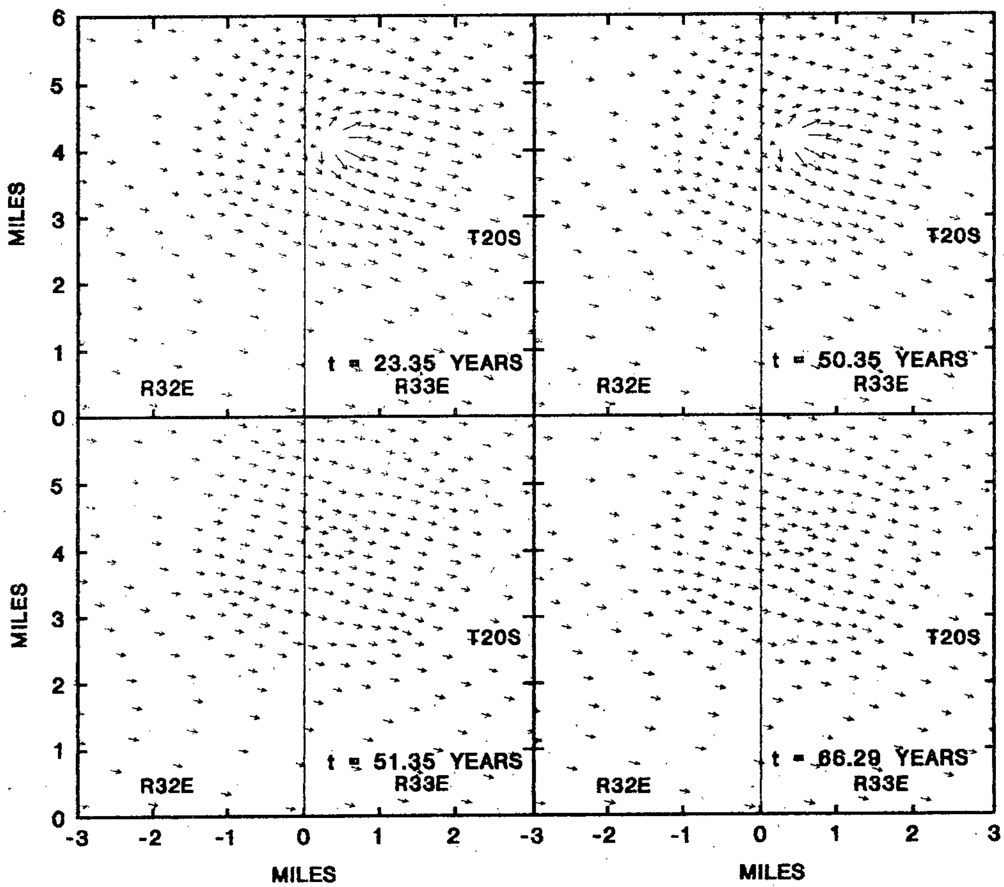
CAPITAN GROUNDWATER STUDIES



Prepared for:
Rhombus Corporation

RE/SPEC Inc.
RESEARCH / SPECIALISTS

March 1993

EXHIBIT 8
PRONGHORN SWD CASE NO.10693
Before Examiner Stogner
May 6, 1993

This report is the result of work performed by RE/SPEC Inc. for Rhombus Corp. over the first several months of 1993. It consists of four separate studies:

1. Ground-Water Quality of the Capitan Reef
2. Conceptual Model of Ground-Water Flow in the Capitan Reef
3. Modeling Assumptions, and
4. Capitan Numerical Model Implementation and Results

Although they can be read independantly of each other, they do roughly follow the above order, in terms of the development of the final numerical model.

Ground Water Quality of the Capitan Reef

Michael G. Wallace
Senior Hydrogeologist
RE/SPEC Inc.

Background

The State of New Mexico, in its efforts to protect underground sources of water, has made a distinction concerning natural ground-water quality. All ground waters in the State containing Total Dissolved Solids (TDS) less than or equal to 10,000 parts per million (ppm) fall under the protection of a number of laws and regulations, and are considered "fresh" waters. No such protection is provided to ground waters having TDS greater than 10,000 ppm, which are considered "saline" waters.

Apparently no state law or regulation has defined the approach to protection of saturated geologic units which contain both fresh and saline waters. Most such units in the state are basin fill deposits which contain fresh water near the land surface, and progressively more saline water with depth. This stratification generally is areally constant. The Capitan Reef also contains both fresh and saline waters. However its unique environment and arc-like shape have led to a condition in which ground water quality varies greatly with location both vertically and areally.

The purpose of this initial study was to define the limits of fresh and saline waters within the Capitan reef. This information will be integrated into a subsequent ground water flow and contaminant transport model to aid in predictions of the impact of brine injection on the water quality of the Capitan.

Data Development and Approach

Hiss (1973, 1975, 1980) conducted some of the most comprehensive surveys to date on Capitan reef hydrogeology. In those studies he postulated the overall flow regime, tabulated information on the stratigraphy, water levels, and water quality, and inferred future flow regimes due to (then) current conditions. It was desired in this study, due to the above mentioned regulatory issues, to map the distribution of TDS in an area of the Capitan Reef. Hiss had prepared a map of chloride ion distributions (1975) but not of TDS. He had, however, tabulated TDS for 10 Capitan observation wells and chloride (as well as all of the other major cations and anions) in a previous study (1973). The chloride map contained over 15 additional data points to the ten of the previous study. It was felt that a more reliable TDS map could be developed if these 15 chloride points could be taken into account.

For TDS to be backed out of chloride concentrations, a justifiable relationship would have to be determined. It is generally known that in most saline waters, chloride ions constitute roughly half of the total TDS. However, this relationship is dependant upon the relative concentrations of the other constituents, and these relative concentrations could vary widely from sample to sample. Therefore, the first step of this study was to determine how severely Capitan water samples varied chemically, within the region of concern. If the water samples did not vary greatly, the next step was to back calculate TDS from the chloride values. The final step was to map these values onto the Capitan and develop a contour plot of the distribution of TDS.

Table 2, "Chemical Quality of Water in Capitan Aquifer Observation Wells" in Hiss, 1973, and selected data from Richey et al., 1985, were used to develop a Piper Trilinear Diagram for the area. The Trilinear diagram is a useful tool for the comparison of different water samples due to their relative concentrations of major ions. The diagram is useful in this manner even if the TDS varies greatly, since it is only concerned with relative concentrations, in equivalents per million (epm). Once data points are mapped onto the diagram, patterns and/or clusters of water samples with similar chemistry can be discerned, and inferences can be made on the overall hydrogeological system.

Figure A1 is the resulting trilinear diagram for this exercise. The data development to obtain values in epm units from the original ppm is outlined in Attachment A. The locations of the points plotted on the trilinear diagram can be found in the Hiss papers.

Results and Interpretations

A number of preliminary results can be developed from Figure A1.

a. Water within the Capitan appears to be "well mixed". In other words, the ion ratios are consistently similar throughout the Capitan. This is especially interesting since water samples were not only taken at different locations, but also at different times and depths. This also supports the approach to back calculate TDS from chloride concentrations, since chloride has essentially the same proportion to TDS for all of the samples. The net result is that chlorides constitute an average 50% of the TDS for the Capitan waters. Therefore, all that is required is to double the chloride values from Hiss, 75 to obtain TDS. This has been done, and the TDS map for the Capitan is provided in this report as Figure A2.

This contour map has some features that, as far as the author is aware, have not been presented in the professional literature. Some of these features are also not apparent from either the data points or the contour plots of the Hiss chloride map. The primary features of the TDS map are tabulated below:

1. Most of the waters in the Capitan reef, from the Pecos River area arcing eastward to the Texas border, have a TDS concentration higher than 20,000 ppm.
2. A transition zone, from relatively fresh water (approx. 1000 to 2000 ppm) to relatively saline water (20,000 ppm), extends roughly six miles eastward/northeastward from the Pecos.
3. A zone of relatively high TDS waters (greater than 100,000 ppm) exists near the northernmost extension of the shelfward portion of the Capitan. This area covers parts of T19s R30e and T19s R31e.
4. A zone of waters having TDS concentrations below 10,000 ppm exists near the northeast "corner" of the Capitan. This area primarily covers T21s R35e, and T22s R35e.
5. Transition areas extend north and south from this 10,000 ppm zone, such that 50,000 ppm waters are encountered no more than roughly seven miles north of the zone and 6 miles south of it.
6. Waters south of the southern portion of this transition zone have TDS concentrations greater than 100,000 ppm.

All of these features, when considered in conjunction with other hydrogeological information, have helped to define a conceptual model of ground water flow in the Capitan that is consistent with the hypotheses of Hiss (1980). This conceptual model is detailed in a companion report.

In addition to this primary result, other information has become apparent as a result of this exercise:

b. Most water in the Capitan can be inferred to be relatively old, due to the low percentages of CO_3 and HCO_3. Capitan water does appear to be younger with proximity to the Pecos.

c. Several chloride values from Hiss's 1973 report were not included in his 1975 chloride map, even though they fall within the study's region and time frame. It is not clear why they were ignored.

d. Hiss's chloride contour map violates a large percentage of the map's data points. The reasons for this are not known, although it is suspected that the investigator tried to simplify the complicated chloride distribution pattern.

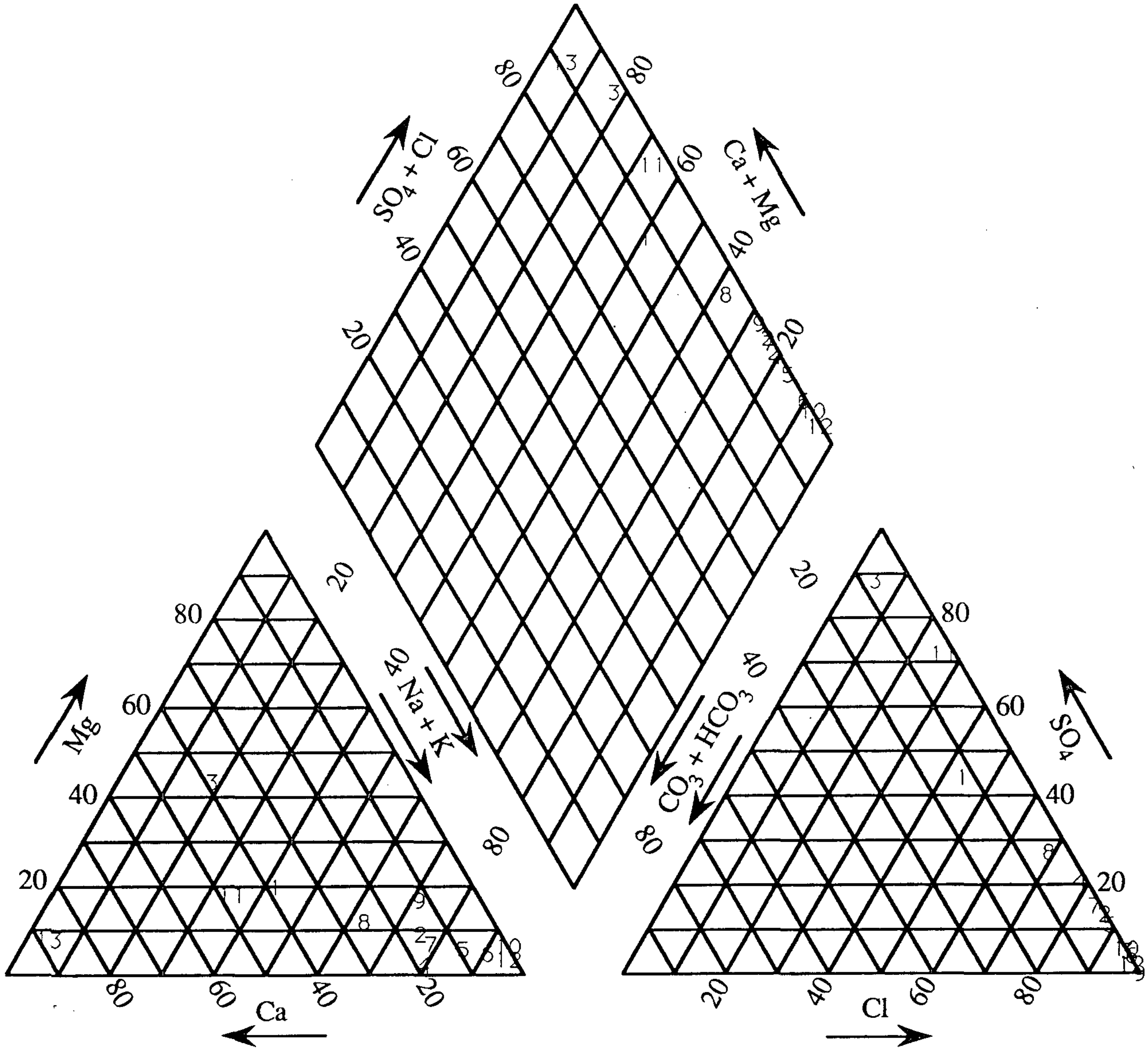
References

Hiss, W. L., 1973, "Capitan Aquifer Observation Well Network, Carlsbad to Jal, New Mexico", New Mexico State Engineer Report 38.

Hiss, W. L., 1975, "Chloride-Ion Concentration in Ground Water in Permian Guadalupian Rocks, Southeast New Mexico and West Texas", New Mexico Bureau of Mines and Mineral Resources, Resource Map 4.

Hiss, W. L., 1980, "Movement of Ground Water in Permian Guadalupian Aquifer Systems, Southeastern New Mexico and Western Texas", New Mexico Geological Society Guidebook, 31st Field Conference, Trans-Pecos Region pp. 289-294

Richey, S. F., J.G. Wells, and K.T. Stephens, 1985, "Geohydrology of the Delaware Basin and Vicinity, Texas and New Mexico", U.S. Geological Survey Water-Resources Investigations Report 84-4077.



Piper Trilinear Diagram
% reacting values

1. Carlsbad Well 13
2. North Cedar Hills Unit 1
3. Humble State 1
4. Carlsbad Test Well 3
5. Yates State 1
6. Hackberry Deep Unit 1
7. Middleton Federal B1
8. South Wilson Deep Unit 1
9. North Custer Mountain Unit 1
10. Federal Davison 1
11. USGS 574 (Rustler near WIPP)
12. USGS 556 (Rustler overlying Capitan, Winkler Co., TX)
13. USGS 1 (Alluvium overlying Capitan, Eddy Co., NM)

Figure A.1.

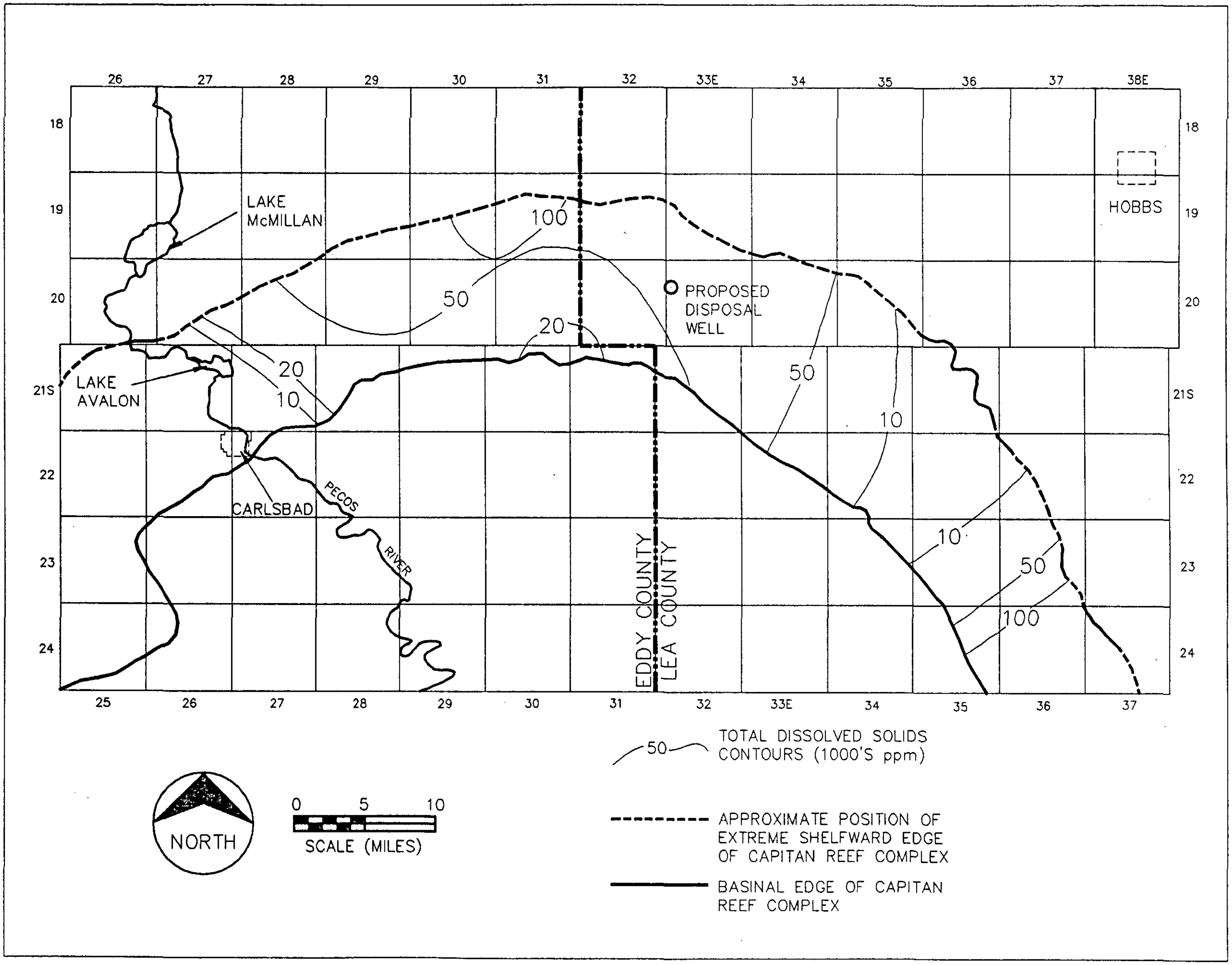


Figure A2. Contours of Total Dissolved Solids for an Area of the Capitan Reef, Southeastern New Mexico.

Valences of ions	
Ca	2
Mg	2
Na + K	1
HCO3	1
CO3	2
SO4	2
Cl	1

WELL NAME Carlsbad well 13

	SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	30	12/6/63	27	14		16	2	80	284
1	100		26	12	173	14	3	77	282
1	170		220	71		240	0	611	270
1	250		224	71		240	0	619	278
1	300		236	70	193	232	0	659	290
Averages:			146.6	47.6	183	148.4	1	409.2	280.8

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
7.31536926	3.91688953	7.95652174	2.43210908	0.03333333	8.51988807	7.92034525

sum cations (epm):	19.1887805	% cations:	50.37
sum anions (epm):	18.9056757	% anions:	49.63

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
38.12	20.41	41.46	12.86	0.18	45.07	41.89

sum cation %: 100 sum anion %: 100

WELL NAME North Cedar Hills Unit 1

	SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	1007-1170	12/11/68	1400	576	8260	626	0	3690	13800
Averages:			1400	576	8260	626	0	3690	13800

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
69.8602794	47.3976548	359.130435	10.2594359	0	76.8289027	389.247736

sum cations (epm):	476.388369	% cations:	50.00
sum anions (epm):	476.336075	% anions:	50.00

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
14.66	9.95	75.39	2.15	0.00	16.13	81.72

sum cation %: 100 sum anion %: 100

WELL NAME Humble State 1

	SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	1538-1916	11/3/67	7080	4580	3810	650	0	1570	30200
Averages:			7080	4580	3810	650	0	1570	30200

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
353.293413	376.877186	165.652174	10.6527689	0	32.6887201	851.832003

sum cations (epm):	895.822773	% cations:	50.02
sum anions (epm):	895.173492	% anions:	49.98

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
39.44	42.07	18.49	1.19	0.00	3.65	95.16

sum cation %: 100 sum anion %: 100

WELL NAME Carlsbad Test Well 3

SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm

	SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	640-1060	8/11/61	1120	388	6400	312	0	3430	10300
1	100	10/5/61	1060	342	5760	6	0	3340	9300
1	350	10/5/61	1050	352	5600	4	0	3360	9050
1	675	"	1120	356	5150	143	0	3440	8300
1	750	"	1060	342	5780	370	0	3350	9500
1	900	"	1240	416	6560	784	0	3410	10600
Averages:			1108.33333	121.666667	5875	269.833333	0	3388.33333	9508.33333

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
55.3060546	10.0116574	255.434783	4.42226483	0	70.547949	268.195451

sum cations (epm):	320.752495	% cations:	48.31
sum anions (epm):	343.165665	% anions:	51.69

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
17.24	3.12	79.64	1.29	0.00	20.56	78.15

sum cation %: 100 sum anion %: 100

WELL NAME Yates State 1

	SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	2239-2515	9/2/67	1490	480	11900	460	0	4190	18400
1	2275	10/22/71	744	350	7708	15	0	2450	12428
1	2475	"	590	243	6101	32	0	1820	9801
1	2500	12/29/71	946	482	10348	134	0	3080	16689
1	2500	10/22/71	968	457	9930	98	0	3150	15979
Averages:			947.6	402.4	9197.4	147.8	0	2938	14659.4

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
47.2854291	33.1125283	399.886957	2.42227576	0	61.1716304	413.48828

sum cations (epm):	480.284914	% cations:	50.17
sum anions (epm):	477.082186	% anions:	49.83

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
9.85	6.89	83.26	0.51	0.00	12.82	86.67

sum cation %: 100 sum anion %: 100

WELL NAME Hackberry Deep Unit 1

	SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	3770	10/21/71	1980	1883	66796	649	0	4970	107949
Averages:			1980	1883	66796	649	0	4970	107949

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
98.8023952	154.947542	2904.17391	10.63638	0	103.479579	3044.84811

sum cations (epm):	3157.92385	% cations:	49.99
sum anions (epm):	3158.96407	% anions:	50.01

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
3.13	4.91	91.96	0.34	0.00	3.28	96.39

sum cation %: 100 sum anion %: 100

WELL NAME Middleton Federal B 1

	SAMPLE DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	2923-2957	9/26/63	1032	537	8530	357	0	3430	13210
1	2923-2957	10/26/66	1200	446	7810	460	0	3650	12500
Averages:			1116	491.5	8170	408.5	0	3540	12855

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
55.6886228	40.444353	355.217391	6.69485553	0	73.7057765	362.592728

sum cations (epm):	451.350367	% cations:	50.47
sum anions (epm):	442.99336	% anions:	49.53

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
12.34	8.96	78.70	1.51	0.00	16.64	81.85

sum cation %: 100 sum anion %: 100

WELL NAME South Wilson Deep Unit 1

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	4169-4187	10/25/66	1040	302	3190	480	0	2820	5250
Averages:			1040	302	3190	480	0	2820	5250

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
51.8962076	24.8508537	138.695652	7.86666011	0	58.7147711	148.083378

sum cations (epm):	215.442713	% cations:	50.09
sum anions (epm):	214.664809	% anions:	49.91

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
24.09	11.53	64.38	3.66	0.00	27.35	68.98

sum cation %: 100 sum anion %: 100

WELL NAME North Custer Mountain Unit 1

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	4470-4507	10/12/66	1500	1270	11370	488	0	465	23900
Averages:			1500	1270	11370	488	0	465	23900

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
74.8502994	104.505246	494.347826	7.99777111	0	9.68169099	674.131949

sum cations (epm):	673.703371	% cations:	49.34
sum anions (epm):	691.811411	% anions:	50.66

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
11.11	15.51	73.38	1.16	0.00	1.40	97.44

sum cation %: 100 sum anion %: 100

WELL NAME Federal Davison 1

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	1500	11/15/72	820	1592	66389	288	14	6215	103688
Averages:			820	1592	66389	288	14	6215	103688

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
40.9181637	131.001851	2886.47826	4.71999607	0.46666667	129.401526	2924.66082

sum cations (epm):	3058.39828	% cations:	49.99
sum anions (epm):	3059.24901	% anions:	50.01

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
1.34	4.28	94.38	0.15	0.02	4.23	95.60

sum cation %: 100 sum anion %: 100

WELL NAME usgs 574 (Rustler, near WIPP)

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	315	9/20/72	580	130	453	111	0	2100	510
Averages:			580	130	453	111	0	2100	510

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
28.9421158	10.6973874	19.6956522	1.81916515	0	43.7237657	14.3852424

sum cations (epm):	59.3351553	% cations:	49.75
sum anions (epm):	59.9281733	% anions:	50.25

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
48.78	18.03	33.19	3.04	0.00	72.96	24.00

sum cation %: 100 sum anion %: 100

WELL NAME *usgs556 (Rustler overlying Capitan, Winkler County, TX)*

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1	1234	9/25/56	1380	1400	57400	56	0	7140	89700
Averages:			1380	1400	57400	56	0	7140	89700

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
68.8622754	115.202633	2495.65217	0.91777701	0	148.660804	2530.11029

sum cations (epm):	2679.71708	% cations:	50.00
sum anions (epm):	2679.68887	% anions:	50.00

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
2.57	4.30	93.13	0.03	0.00	5.55	94.42

sum cation %: 100 sum anion %: 100

WELL NAME usgs1 (alluvium overlying Capitan, Eddy County)

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1		5/1/50	632	39	24	174	0	1540	29
Averages:			632	39	24	174	0	1540	29

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
31.5369261	3.20921621	1.04347826	2.85166429	0	32.0640949	0.81798437

sum cations (epm):	35.7896206	% cations:	50.04
sum anions (epm):	35.7337435	% anions:	49.96

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
88.12	8.97	2.92	7.98	0.00	89.73	2.29

sum cation %: 100 sum anion %: 100

WELL NAME

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1									
1									
1									
1									
Averages:			0	0	0	0	0	0	0

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
0	0	0	0	0	0	0

sum cations (epm):	0	% cations:	#DIV/0!
sum anions (epm):	0	% anions:	#DIV/0!

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

sum cation %: #DIV/0! sum anion %: #DIV/0!

WELL NAME

SAMPLE	DEPTH	DATE	Ca ppm	Mg ppm	Na, K ppm	HCO3 ppm	CO3 ppm	SO4 ppm	Cl ppm
1									
1									
1									
1									
Averages:			0	0	0	0	0	0	0

Ca epm	Mg epm	Na, K epm	HCO3 epm	CO3 epm	SO4 epm	Cl epm
0	0	0	0	0	0	0

sum cations (epm):	0	% cations:	#DIV/0!
sum anions (epm):	0	% anions:	#DIV/0!

Percent reacting values:

Ca %	Mg %	Na, K%	HCO3 %	CO3 %	SO4 %	Cl %
#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

sum cation %: #DIV/0!

sum anion %: #DIV/0!

Conceptual Model of Ground Water Flow in the Capitan Reef

Michael G. Wallace
Senior Hydrogeologist
RE/SPEC Inc.

Background

The Capitan Reef is an immense, arcuate, buried Permian aged reef of significant complexity that extends through a large portion of Southeastern New Mexico and West Texas. A host of factors over an extended period of time have led to the current flow regime and water quality pattern of the Reef. The general purpose of this study is to develop a conceptualization of the flow regime that is consistent with current knowledge. This conceptualization will be integrated into a subsequent ground water flow and contaminant transport model to aid in predictions of the impact of brine injection on the water quality of the Capitan.

Numerous investigations and surveys have covered aspects of ground water flow in the Capitan Reef. These include Hendrickson and Jones, 1952; Nicholson and Clebsh, 1961; Hiss, 1973, 1975, 1976, and 1980; and Richey et al., 1985. Of these reports, the ones by Hiss (particularly Hiss, 1980) have been the most focused on determining the salient aspects of Capitan ground water flow. However, some issues that are important to the upcoming modeling effort are not extensively addressed in these reports. One factor of particular interest has been the water quality distribution throughout the Reef and its relationship to ground water flow.

A companion report to this one (Ground-Water Quality of the Capitan Reef) develops the existing water quality information about the Capitan and, among other results, presents a contour map of the Total Dissolved Solids (TDS) in parts per million (ppm) for an area of the Reef. A specific focus of this report is the development of an understanding of ground water flow patterns that is consistent with and expands upon that water quality information.

Hydrogeologic Setting

It is assumed that the reader already has basic knowledge about the Capitan. Nonetheless a brief review (without references) should be helpful to the discussion. This review is mainly confined to the portion of the Capitan between the Guadalupe Mountains and Jal, New Mexico.

The Capitan Reef's crescent shape, arching northeastward from Carlsbad, then continuing southeastward towards Jal, and on into Texas, delineates a boundary between the Delaware Basin (which it encloses) and several other major structural features, including the Northwestern Shelf, the Hobbs Channel, and the Central Basin Platform. The reef outcrops at the Guadalupe Mountains west of Carlsbad and at the Davis Mountains in west Texas. Its width ranges from 6 to 12 miles on average, and its thickness generally varies from 1000 to 2,200 feet. The reef dips to the east from Carlsbad, to such an extent that it's top lies over 2,000 feet below the land surface near the Hobbs area.

The basinal edge of the Capitan is relatively abrupt, with the reef bounded by the Castile Formation. The shelfward edge of the Capitan, however, is difficult to define, as it transitions gradually to the interbedded limestones, dolomites, sandstones, and anhydrites of the Artesia Group and the San Andres Limestone. A similar formation to the Reef, the

Goat Seep Limestone, underlies the Capitan, and is generally considered to be part of the Reef. Underneath that, lies the Delaware Mountain Group. Immediately overlying the Reef is the Artesia Group, followed by nearly 1,000 feet of the Salado Halite.

Numerous submarine canyons incise the Reef. These canyons are oriented along lines perpendicular to the arc of the Capitan (Figure B1). Many of these canyons cut as much as a thousand feet deep into the Capitan, and some of them have incised across the entire width of the Reef. They are filled with fine grained clastics and other material, and, as a result are several orders of magnitude lower in hydraulic conductivity than the Capitan itself. Hiss has maintained that these canyons now function as significant barriers to the horizontal movement of water through the Capitan. This claim is supported by hydrograph data, which show, among other things, that Capitan water levels west of the Eddy county line (or perhaps more precisely, west of the West Laguna Submarine Canyon) were largely unaffected by pumping from the Capitan further to the southeast.

Another feature that may act as a barrier to flow through the Capitan is an igneous dike that appears to have intruded through the Reef's entire width (Figure B1). According to Hiss, this feature is nearly vertical, and varies in thickness from under 4 feet to 15 feet.

The Reef is a Permian Guadalupian age limestone/dolomite unit which is of relatively uniform composition. It is generally thickest on the basin side, and thinnest along the shelf margin. Most of the Capitan is a saturated, confined formation, with water quality that varies greatly throughout its extent. Evidence suggests that the units which envelope the Capitan are 2 to 3 times less permeable than the Reef, and therefore have poor hydraulic connectivity. One exception to this rule is along the shelfward side of the Reef at the confluence of the Central Basin Platform and the Hobbs Channel. At this location the San Andres Limestone and the Artesia Group appear to have significantly enhanced hydraulic conductivities, equivalent to those of the Capitan in that area.

The hydraulic conductivity of the Capitan averages 5 ft. per day. The conductivity of the Capitan is even greater west of the Pecos, where significant dissolution appears to have occurred. Values of hydraulic conductivity for that region range from 1 to 25 ft. per day. That area of the Capitan is also the area of highest water quality.

The Pecos River is believed to be in hydraulic contact with the Capitan, even though they are separated by 500 ft of the Artesia Unit. It has been suggested that Lake Avalon, a reservoir along the river, recharges 10,000 to 20,000 acre-feet of water per year to the Capitan. Additional recharge likely occurrs in the Guadalupe Mountains from precipitation. These speculations are supported by, among other things, water quality data from the area, which shows relatively high proportions of CO3 and HCO3.

Significant amounts of water are withdrawn from the Capitan, primarily west of the Pecos, for domestic, municipal, industrial, and irrigation uses. Current withdrawals are not expected to vary significantly from a 1959 estimate of 16,000 acre-feet per year.

Over the past 60 years, significant quantities of water have also been withdrawn from the eastern arc of the Reef near the New Mexico / Texas border. These withdrawals, which were due to oil recovery enhancement projects, appear to have had a significant impact on water levels throughout much of the Capitan. This created sufficient concern to the State of New Mexico that it sponsored Hiss's original work in 1973. The primary goal of that project was to determine if the Texas withdrawals of brine from the Reef would lower the flows of the Pecos. It appears that no official determination was ever made by Hiss or the State regarding this question. However, well hydrograph information in figure 6 of Hiss's 1973 report indicate that significant water level declines (exceeding 100 feet over 5 years)

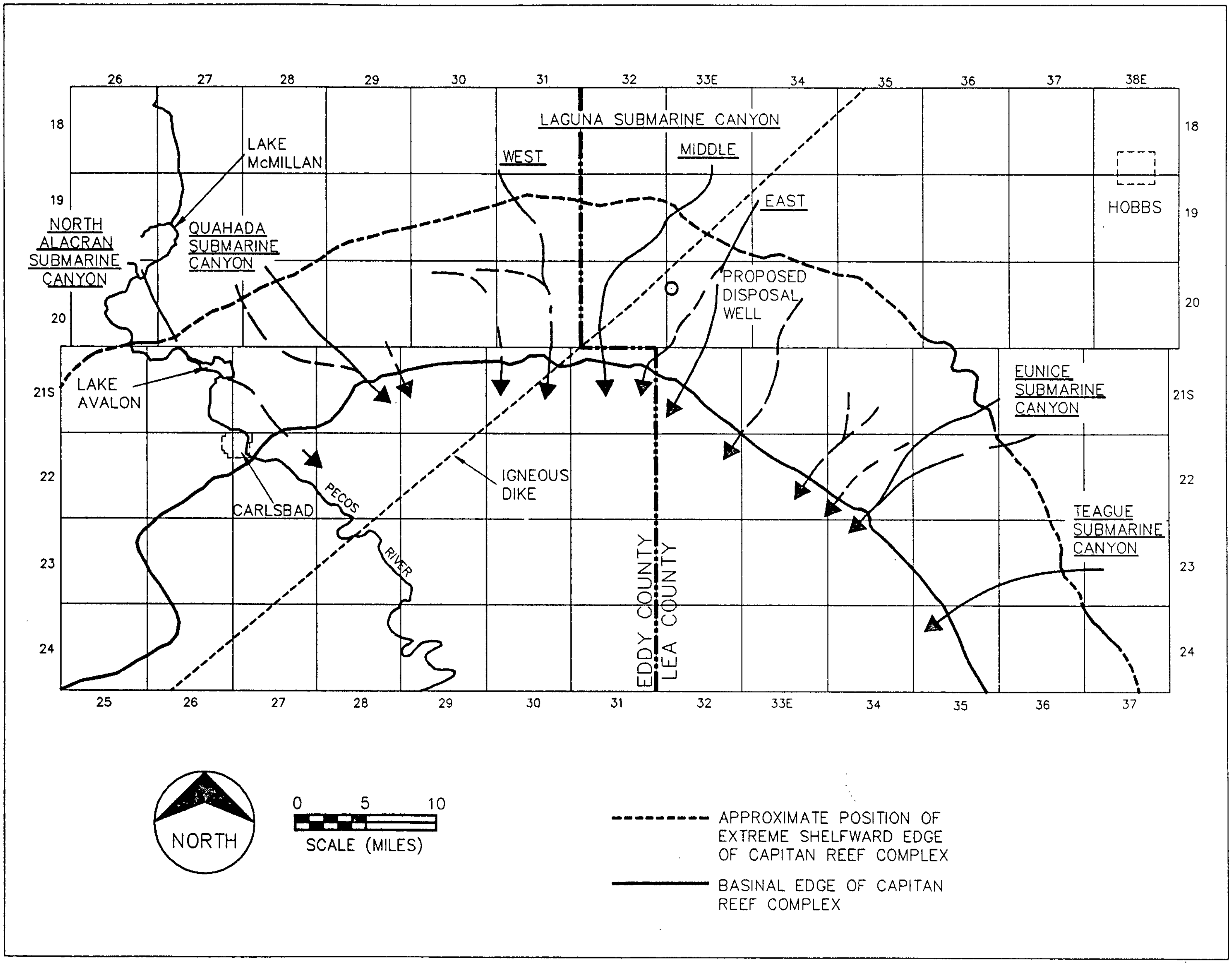


Figure B1. Submarine Canyons and Dikes of the Capitan Reef, Southeastern New Mexico.

occurred only in Lea County. Water levels in some wells in Eddy County actually increased over the recorded period.

Interpretation of Ground Water Movement

Hiss followed his 1973 study with a significant data gathering and interpretation effort, apparently culminating in his dissertation in 1976, and the 1980 paper. In these publications, he developed a theme of three major episodes in the latter Cenozoic history of ground water movement through the Capitan: regional tectonics, development of the Pecos River, and modern day exploitation of ground water and petroleum resources. His key points are summarized here.

Regional Tectonics:

> This flow regime is diagrammed in Figure 4a of Hiss's 1980 report. According to Hiss, the Capitan, shelf, and basin aquifers were all recharged by precipitation at their outcrop areas. The Pecos River did not exist yet. Flow within the Capitan was eastward / northeastward from the Guadalupes, and northward / northwestward from the Glass Mountains. Both flow streams exited into the San Andres Limestone / Artesia Group units near the previously mentioned confluence of the Hobbs Channel and the Central Basin Platform.

Erosion of the Pecos River at Carlsbad:

> This flow regime is diagrammed in Figure 4b of Hiss's report. According to Hiss, the development of the Pecos River, and its erosion into hydraulic contact with the Capitan created a ground water divide, wherein ground water drained from the Capitan from both east and west into the Pecos. Beyond some (probably moving) boundary to the east, water continued to flow towards the original San Andres / Artesia exit region. Northward flow of water in the Capitan from the Glass Mountains towards the exit region continued unaffected by the Pecos.

Exploitation of Ground Water and Petroleum Resources:

> This flow regime is diagrammed in Figure 4c of Hiss's report. As described by Hiss, the aforementioned Capitan water withdrawals just south of the New Mexico border have reversed flow gradiants so that once again water generally moves from west to east, in spite of the Pecos connection. Discharge into the San Andres / Artesia exit region has all but stopped, as all of the Capitan waters are now being funneled down towards the Texas pumping area. Hiss indicated that at some future point, ground water from the San Andres / Artesia exit region might actually enter the Capitan due to these pumping activities.

These theories of ground water movement within the Capitan seem plausible. However, some concerns exist with these interpretations. One concern is that Hiss generated equipotential lines based on the concept of equivalent fresh water head. These lines were then used to infer flow directions. Unfortunately the concept of equivalent fresh water head has been shown to be of questionable value in determining flow directions in dipping aquifers having extreme water density variations (Hubbert, 1940). (In all fairness to Hiss, there were few or no alternatives to this approach at the time of his investigation.)

Needless to say, the Capitan is such an aquifer, which leads to the next concern. This is the fact that ground water seldom naturally becomes lower in TDS as it moves though an aquifer, unless it is being mixed with fresher waters. Hiss appears never to have developed maps of TDS to compare with his determinations of ground water movement.

Such a map has been developed in the companion report to this study, and is included here as Figure A2. Examination of this map and consideration of the flow regime history as proposed by Hiss has led to some additional conclusions that are generally consistent with Hiss's interpretations. These conclusions are developed in the following paragraphs.

Inspection of Figure A2 will show that:

1. Most of the waters in the Capitan reef, from the Pecos River area arcing eastward to the Texas border, have a TDS concentration higher than 20,000 ppm.

2. A transition zone, from relatively fresh water (approx. 1000 to 2000 ppm) to relatively saline water (20,000 ppm), extends roughly six miles eastward / northeastward from the Pecos.

3. A zone of relatively high TDS waters (greater than 100,000 ppm) exists near the northernmost extension of the shelfward portion of the Capitan. This area covers parts of T19s R30e and T19s R31e.

4. A zone of waters having TDS concentrations below 10,000 ppm exists near the northeast "corner" of the Capitan. This area primarily covers T21s R35e, and T22s R35e.

5. Transition areas extend northwest and southeast from this 10,000 ppm zone, such that 50,000 ppm waters are encountered no more than roughly seven miles north of the zone and 6 miles south of it.

6. Waters south of the southern portion of this transition zone have TDS concentrations greater than 100,000 ppm.

Examination of Hiss's Chloride Map (1975) show that much of the shelf aquifers north of the Capitan contain waters with TDS greater than 200,000 ppm (Cl conc. greater than 100,000 ppm). Examination of Figures 2, 3, 4b and 4c of Hiss's 1980 report show a strong component of flow gradient directed towards the Capitan from these shelf units. It is particularly interesting to note that, in figure 2 of Hiss 1980, the 3300 ft head contour that dips southward from the shelf aquifers into the Capitan covers the same region (in the Capitan) that is covered by the 100,000 ppm zone discussed above in item 3. These factors all lead to a conclusion that in that area, some enhanced hydraulic connection exists between the Capitan and the shelf, and that higher TDS waters have been migrating into the Capitan there.

Items 5 and 6 above indicate that fresher waters must be mixing with the Capitan waters. This is occuring in the same location as the San Andres / Artesia exit region. As mentioned earlier, Hiss suggested that at some point in time this region might become a recharge zone instead of a discharge zone. Apparently this was the case at the time he suggested it, and

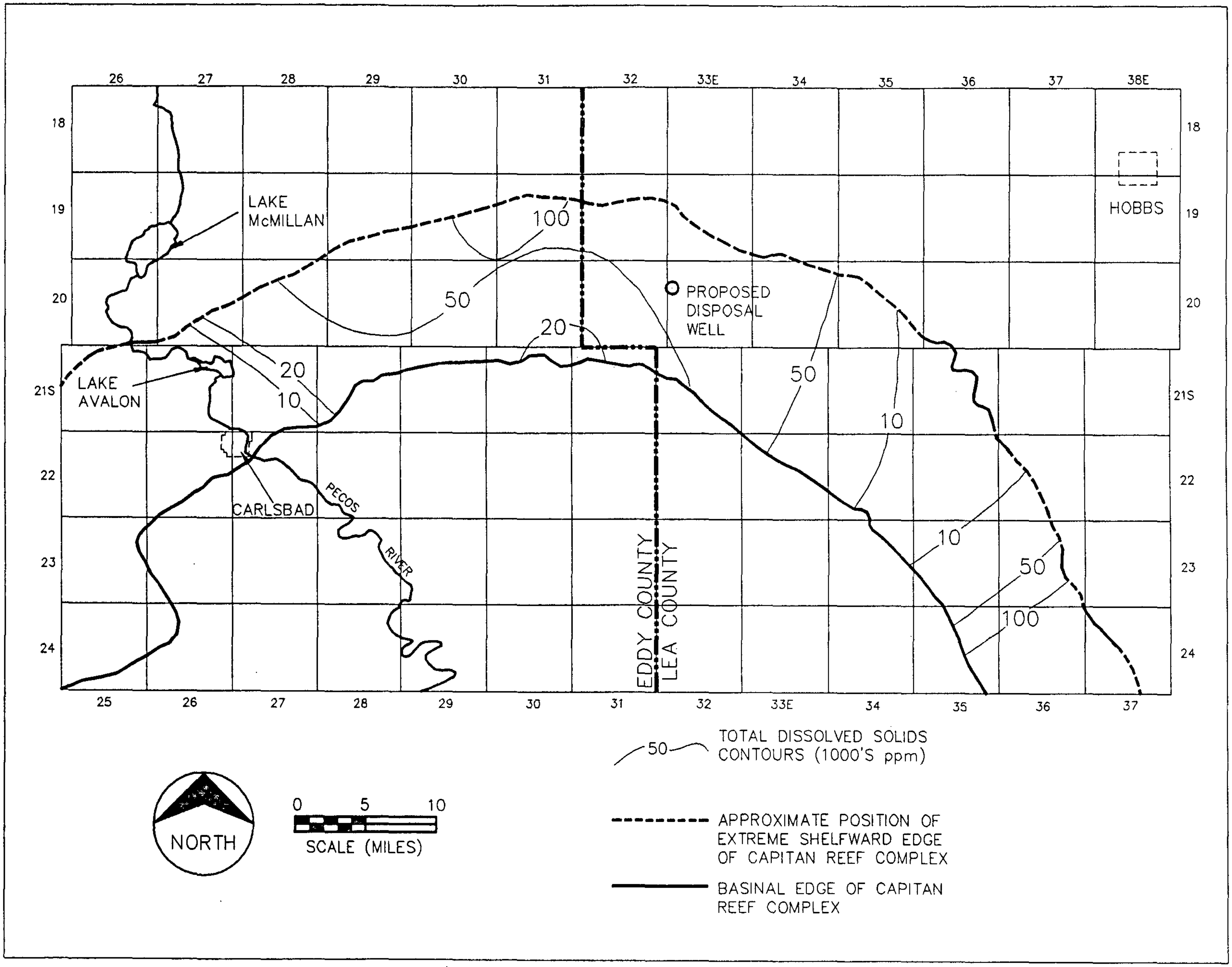


Figure A2. Contours of Total Dissolved Solids for an Area of the Capitan Reef, Southeastern New Mexico.

perhaps it still is. This interpretation is consistent with water quality data for the San Andres in that area.

It is important to note, that although the TDS concentrations at that location are below 10,000 ppm, the waters are nonpotable, having come from the San Andres, which contains major oil fields in that precise region.

One final point concerning the water quality pattern involves consideration of the perceived flow rates through the Capitan and outcrops of the Salado just east of the Pecos, over the Reef. As will be documented in the following section on "Modeling Assumptions", a case has been developed from Hiss and others that the average hydraulic gradient through the Capitan is directed eastward and has an approximate magnitude of 0.0016 ft./ft. The average hydraulic conductivity is 5 ft./day, and the average porosity is 0.18. Considering a travel path, for example, of 60 miles, the reader can readily calculate (using Darcy's Law) that the Capitan can be completely "flushed out" with low TDS Pecos River and mountain recharge water (from the Pecos to the Hobbs Channel area) in an approximate time of 20,000 years.

If that were the case, and the Capitan was truly isolated from its surrounding units (except directly below the Pecos), then it would be impossible for the high TDS zones to exist so far to the west. Now consider that the Salado halite unit (nearly 'pure' salt) outcrops just east of the Pecos, over the Capitan. This is likely another zone of recharge to the Capitan, as the Salado must be weathered in this location and surely would have experienced extensive dissolution. The author proposes that this area, and perhaps others, are sources of salinity that, superimposed over the regional flow regime, have helped to define the unique TDS pattern of the Capitan.

If this is so, then it is logical to conclude that it is the fate of the Pecos to be in close proximity (and perhaps contact) with very high TDS waters as long as it remains in its present location. This would hold true no matter what activities (such as brine injection) occurred elswhere in the Capitan.

This conceptual model description has only touched on the main points governing flow and water quality through the Capitan system. Development of these points has been expedited by previous extensive published research (primarily by Hiss) on many of these same issues. These previous investigations have led to fairly clear cut ideas on the nature of flow through the Capitan. The conceptual model contained here is consistent with and builds upon these previous studies. A numerical model is developed from this conceptual model in two companion sections of this report, "Modeling Assumptions", and "Capitan Numerical Model Implementation and Results".

References

Hendrickson, G. E. and R. S. Jones, 1952, "Geology and Ground-Water Resources of Eddy County, New Mexico", New Mexico Bureau of Mines and Mineral Resources, Ground Water Report 3.

Hiss, W. L., 1973, "Capitan Aquifer Observation Well Network, Carlsbad to Jal, New Mexico", New Mexico State Engineer Report 38.

Hiss, W. L., 1975, "Chloride-Ion Concentration in Ground Water in Permian Guadalupian Rocks, Southeast New Mexico and West Texas", New Mexico Bureau of Mines and Mineral Resources, Resource Map 4.

Hiss, W. L., 1976, "Stratigraphy and Ground-Water Hydrology of the Capitan Aquifer, Southeastern New Mexico and West Texas" University of Colorado at Boulder, Ph.D. dissertation, 396p.

Hiss, W. L., 1980, "Movement of Ground Water in Permian Guadalupian Aquifer Systems, Southeastern New Mexico and Western Texas", New Mexico Geological Society Guidebook, 31st Field Conference, Trans-Pecos Region pp. 289-294

Hubbert, M. K., 1940, "The Theory of Groundwater Motion", Journal of Geology, vol. 48, pp. 785-944.

Nicholson, A. and A. Clebsch, 1961, "Geology and Ground-Water Conditions in Southern Lea County, New Mexico", New Mexico Bureau of Mines and Mineral Resources, Ground Water Report 6.

Richey, S. F., J.G. Wells, and K.T. Stephens, 1985, "Geohydrology of the Delaware Basin and Vicinity, Texas and New Mexico", U.S. Geological Survey Water-Resources Investigations Report 84-4077.

Modeling Assumptions

Michael Wallace
Senior Hydrogeologist
RE/SPEC Inc.

In this section, the major assumptions utilized in the numerical simulation of brine injection into the Capitan are detailed. The conservative nature of each assumption is included in the description.

The guiding objectives for the development of this model were to make it as simple and conservative as possible while at same time, yielding useful information that is as relevant to the important issues as possible. This has necessitated the use of a numerical ground-water flow and solute transport code (described in another section). Apparently this will have been the first time that the Capitan has been so modeled. Although that may seem like a major departure from a simplified approach, the model is still relatively straightforward. In fact, far more complex models than this one could have been developed for the project, had there been sufficient justification.

Much of the following discussion draws upon companion sections to this report, including "Conceptual Model of Ground-Water Flow in the Capitan Reef" and "Ground-Water Quality of the Capitan Reef".

1. Two-Dimensional Horizontal Flow.

It is assumed that the Capitan, within the model domain, does not dip to the east but rather lays flat. It is also assumed that the Capitan has a constant vertical thickness of 1,000 feet and a constant width of 10.25 miles.

These simplifying assumptions are also very conservative. The most conservative aspect probably concerns the variable density flow issue. Since the injected brines have much higher TDS, (and thus higher density) than the ambient ground water, they will tend to sink. Therefore, they will tend to travel downdip, away from the Pecos and not toward it, even in the presence of a gradient towards the west. The horizontal model will not allow the injected brines to sink because all model cells are at the same elevation.

The use of a constant thickness and width are primarily for the sake of simplicity. The use of a constant thickness of 1,000 feet is also conservative. As can be seen from Hiss (1976, figure 11, 'Map showing the thickness of the Capitan Aquifer, Southeastern New Mexico and Western Texas'}, a major portion of the Capitan within the model domain, is greater than 1,500 feet thick, and much of the Capitan is greater than 2,000 feet thick. Limiting the thickness of the Capitan constrains the injected brines to move even further towards the Pecos than would realistically be expected.

2. Boundary Conditions.

It is assumed that the Capitan is surrounded by impermeable boundaries both above and below and to the north and the south.

As discussed in the Conceptual Model section, the Capitan is surrounded by geologic strata that are generally 10 to 100 times less permeable than the Capitan itself. Some adjacent areas may actually have equivalent permeabilties. Setting the permeabilities of the surrounding strata to zero, through an impermeable boundary condition, is conservative, since no injected brine will be able to exit the model except at the west or east ends. The west end, notably, is represented by the Pecos River.

It is assumed that the Pecos River fully penetrates the Capitan at the west end of the model. It is also assumed that the Pecos is 'fresh', having a TDS concentration of 0.0 ppm.

Although it is reasonable to assume that a hydraulic connection exists between the Pecos River and the Capitan, they are actually separated by over 500 feet of Artesian Unit material. Assuming the Pecos fully penetrates the Capitan is both a simplifying and conservative assumption, to say the least, since, among other things, it reduces the distance that injected brine would have to travel in order to cause an impact.

It is well known that the Pecos has TDS concentrations greater than 0.0 ppm. Setting its TDS to 0.0 ppm helps to maximize the diffusion gradients from the brine areas of the Capitan towards it.

It is assumed that a constant pressure boundary delimits the eastern end of the model.

This is a simplifying and natural assumption made to allow a reduced model domain size. This eastern end of the model corresponds to the area southwest of Hobbs where waters of the Capitan discharge out into the San Andres and Artesian unit strata.

3. Aquifer Characteristics.

It is assumed that the Capitan is homogeneous and isotropic, that it has a constant hydraulic conductivity of 5 ft per day and a constant porosity of 0.18. A constant longitudinal dispersivity of 100 meters is also assumed, along with a constant transverse dispersivity of 10 meters. The coefficient of molecular diffusion is assumed to be $5 * 10^{-10}\ m^2$.

Hiss has estimated an average hydraulic conductivity for the Capitan in the region comprising the model domain of 5 ft. per day. But use of this value throughout the model region is not only reasonable, it is extremely conservative. That is because it means that all known potential barriers to flow are completely ignored. These barriers include at least 6 major submarine canyons (maintained by Hiss and demonstrated by data to be significant barriers to horizontal flow throughout the Reef) and an igneous dike that cuts through the Capitan's entire width. In addition, the assumption of homogeniety, at least in the vertical direction is supported by the fact that water quality is relatively constant with depth in the Capitan (see Hiss, 73, table 2).

Records of porosity of the Capitan are rare. The value used comes from a series of porosity values from a well log interpretation, and represents the lowest value given. The lower the porosity, the farther injected brine will move away from the injection source (and towards the Pecos), all other things being equal.

Dispersivity values are taken from the literature (Freeze and Cherry, 1979). 100 meters longitudinal dispersivity is one of the highest values recorded in the literature. The greater the longitudinal dispersivity, the farther injected brine will migrate away from the injection source, along the direction of ground-water flow. Therefore, this is a conservative assumption. 10 meters lateral dispersivity is a reasonable assumption, even mildly conservative. Higher numbers could have been justified, yet in this case, a higher number would extend the brine plume out further laterally, or perpendicular to the direction of ground-water flow. This would dilute the plume more than a 10m value would. A diffusion coefficient of $5 * 10^{-10}$ m^2 is an extremely high value for diffusion of solutes in liquids in porous media. Once again this is a conservative assumption, serving to push the outer contamination boundary even further away from the injection source.

4. Initial Conditions.

It is assumed that an initial distribution of brine exists in the model domain, patterned after the TDS contour map presented in the previous section of this report titled "Ground-Water Quality of the Capitan Reef". Because the model is 2-dimensional-areal, the brine concentrations assigned are constant throughout the model thickness, and only vary with horizontal location. No additional sources of brine throughout time are present in the model, except at the proposed injection position.

In addition to the obvious need to create an initial water quality distribution, this assumption has important subtle consequences to the model results. As discussed in the companion section "Conceptual Model of Ground-Water Flow in the Capitan Reef", water could not possibly flow through the Capitan at the rates and directions implied by previous investigators without flushing out the high TDS waters that have been observed. A likely reason for the extensive and persistent brine zones is that some recharge sources percolate through the Salado and/or other related units, providing a constant source of brine to the Capitan.

This is only one of probably many plausible explanations for brine occurrances. In lieu of more information, the modeling effort has proceeded without making any assumptions on the source of brine. By doing this, however, an implicit assumption is made, that the original source of brine in the Reef no longer exists. This implicit assumption has a visible effect on the modeling results, depending upon the scenario modeled. The models presented in this report consist of two scenarios. The first scenario proposes a regional gradient consistent with the literature. The second scenario proposes that no regional gradient exists.

For the first scenario, if the model were allowed to run out to 20,000 or 30,000 years, all of the brines would eventually be flushed out the east end. This is clearly not a likely outcome. An artifact of this implicit assumption is seen in the model results, as the overall brine pattern has 'drifted' a small distance to the east over the 1,000 year simulations. One would be hard put to determine whether or not this implies that the assumption of no continuing natural source of brine is conservative or not. On one hand, the brines all drift away, however slowly, from the Pecos. On the other hand, were a constant source of brine assigned in the model a small distance east of the Pecos, it would 'drown out' the impact of the proposed injection activity. Clearly, such a source would, and perhaps does pose a much greater threat to Pecos River Basin water quality than any down-gradient injection activity. Therefore, taking these possibilities into account, ignoring the source represents a conservative assumption. The reader is merely cautioned to take note of the 'drifting' artifact when reviewing the model results.

For the second scenario, there is no real inconsistency with this brine source assumption, since there is no regional gradient to carry the brines away from the Pecos. From that standpoint, the second scenario is more conservative than the first scenario, since the high TDS water is allowed to diffuse naturally, over time towards the low TDS zones. An ultimate consequence of this initial condition for the second scenario is that if the model were run long enough, even without any brine injection from the proposed position, the high TDS zones would completely invade the low TDS zones, eventually making the average brine concentration greater than 10,000 ppm throughout the entire model domain. Once again the reader is cautioned to take note of this artifact when reviewing the model results.

5. Source Terms.

A constant source at the injection point is assumed, with an injection rate of 12,500 bbls. per day of brine with a TDS concentration of 250,000 ppm, for a period of 50 years. The screened zone of the well is assumed to fully penetrate the Capitan.

12,500 barrels per day is actually the maximum injection rate that would ever be applied, not the average rate. Likewise 250,000 ppm is the maximum brine concentration expected to be present in the injection fluids. Given inevitable down times and lower than maximum (even lower than average) rates and concentrations, these represent conservative assumptions. It is planned that the injection well will be screened throughout the Capitan thickness.

References

Freeze, R. A., and J. A. Cherry, 1979, "Goundwater", Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Hiss, W. L., 1973, "Capitan Aquifer Observation Well Network, Carlsbad to Jal, New Mexico", New Mexico State Engineer Report 38.

Hiss, W. L., 1976, "Stratigraphy and Ground-Water Hydrology of the Capitan Aquifer, Southeastern New Mexico and West Texas" University of Colorado at Boulder, Ph.D. dissertation, 396p.

Capitan Numerical Model
Implementation and Results

by Michael G. Wallace and John D. Osnes
RE/SPEC Inc.

Background

This section builds upon the previous sections of this report, namely "Ground Water Quality of the Capitan Reef", "Conceptual Model of Ground Water Flow in the Capitan Reef", and "Modeling Assumptions". Those sections developed the conceptual background and simplifying and conservative assumptions that are incorporated into the numerical model of this section. The numerical model was used ultimately to address two scenarios. The first involved an approximation of the regional flow regime (through a steady state run) followed by prediction of the impact from injection upon water quality. The second scenario involved a more conservative assumption of no regional gradient, followed by prediction of the impact from injection upon water quality.

Simulator and Model Setup

The numerical simulator SUTRA (Saturated-Unsaturated TRAnsport) was utilized in this exercise (Voss, 1984). SUTRA is a two dimensional computer code, developed by the U.S. Geological Survey, that can simulate contaminant transport and water flow through aquifers. The solute that is modeled can be subject to equilibrium adsorption on to the porous matrix as well as to natural decay, including biodegradation. In addition, SUTRA has all of the other standard solute transport features, such as attenuation parameters, including dispersivity and molecular diffusion.

SUTRA is also capable of modeling flow due to bouyant forces, as would be the case when waters of different densities (due to different TDS values) mingle. For the proposed injection activity, injected fluids would sink somewhat, since the TDS value is so high. Yet, as discussed in item 1 of the "Modeling Assumptions" section, a horizontally flat grid has been employed as both a simplifying and conservative assumption.

SUTRA is a finite element code, as opposed to a finite difference code, and as such, is capable of more easily appoximating the types of irregular flow domains that are common in nature. The Capitan is such a domain, and the use of SUTRA has allowed the investigators to build a model very similar in areal shape (for the region considered) to that of the Reef. Figure D1 shows the model boundary overlain onto an outline of the Capitan.

The model grid consists of 1,036 nodes, which define 966 four-noded elements (Figures D2 a and b). Although most of the grid pattern is rectilinear, a radially oriented pattern envelopes the injection position in order to better capture the nuances of radial flow in the immediate region about the well.

The boundary condition assignments and other input variables have been discussed in the previous section, "Modeling Assumptions". More specific details are provided in the appropriate scenario descriptions. There is little to add here, save to mention that the investigators have elected to use the SUTRA option of directly entering hydraulic heads (actually, in this case, equivalent fresh water heads), hydraulic conductivities, and TDS (in units of ppm). Normally SUTRA requires input of fluid pressures and permeabilities.

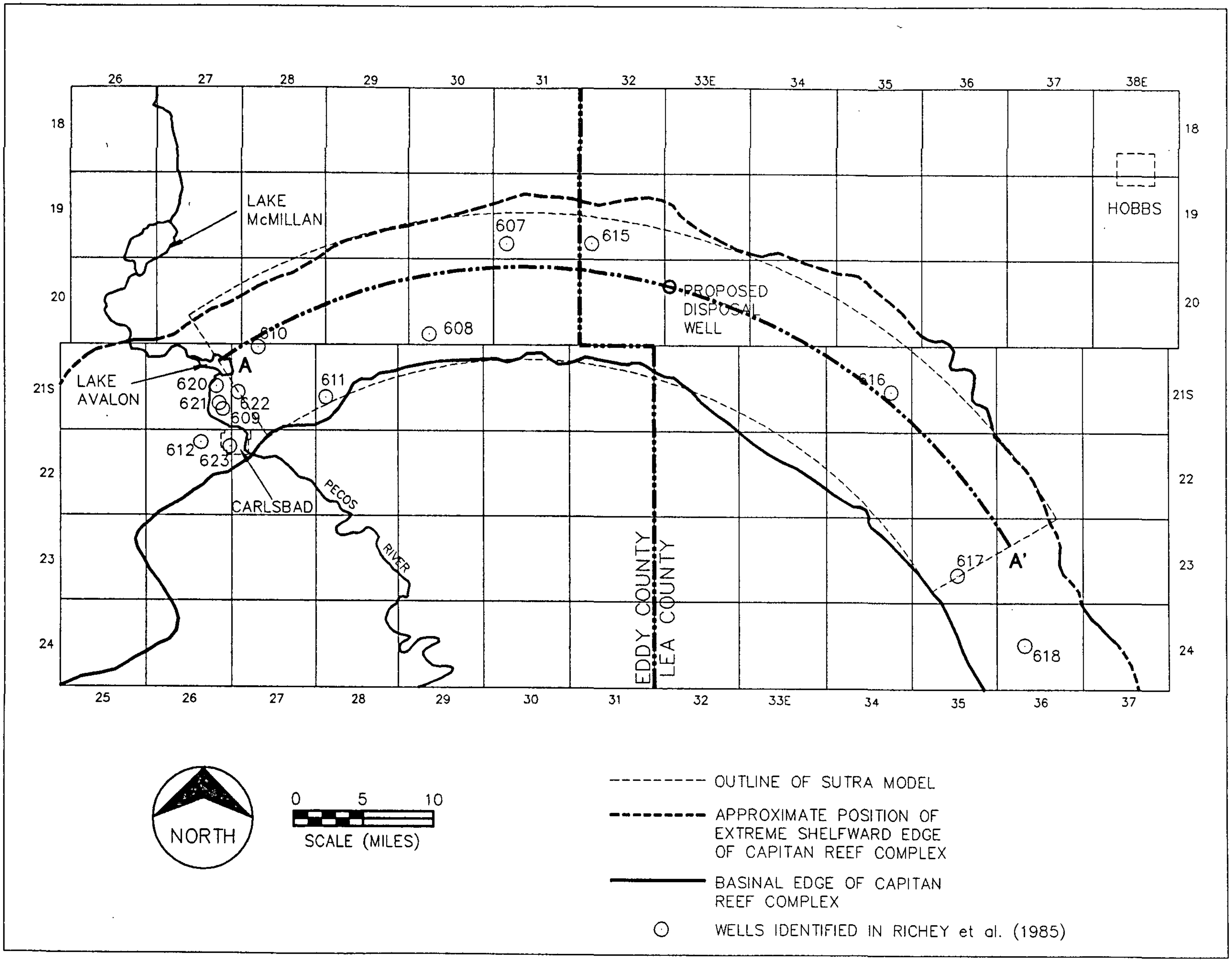


Figure D1. Model Domain.

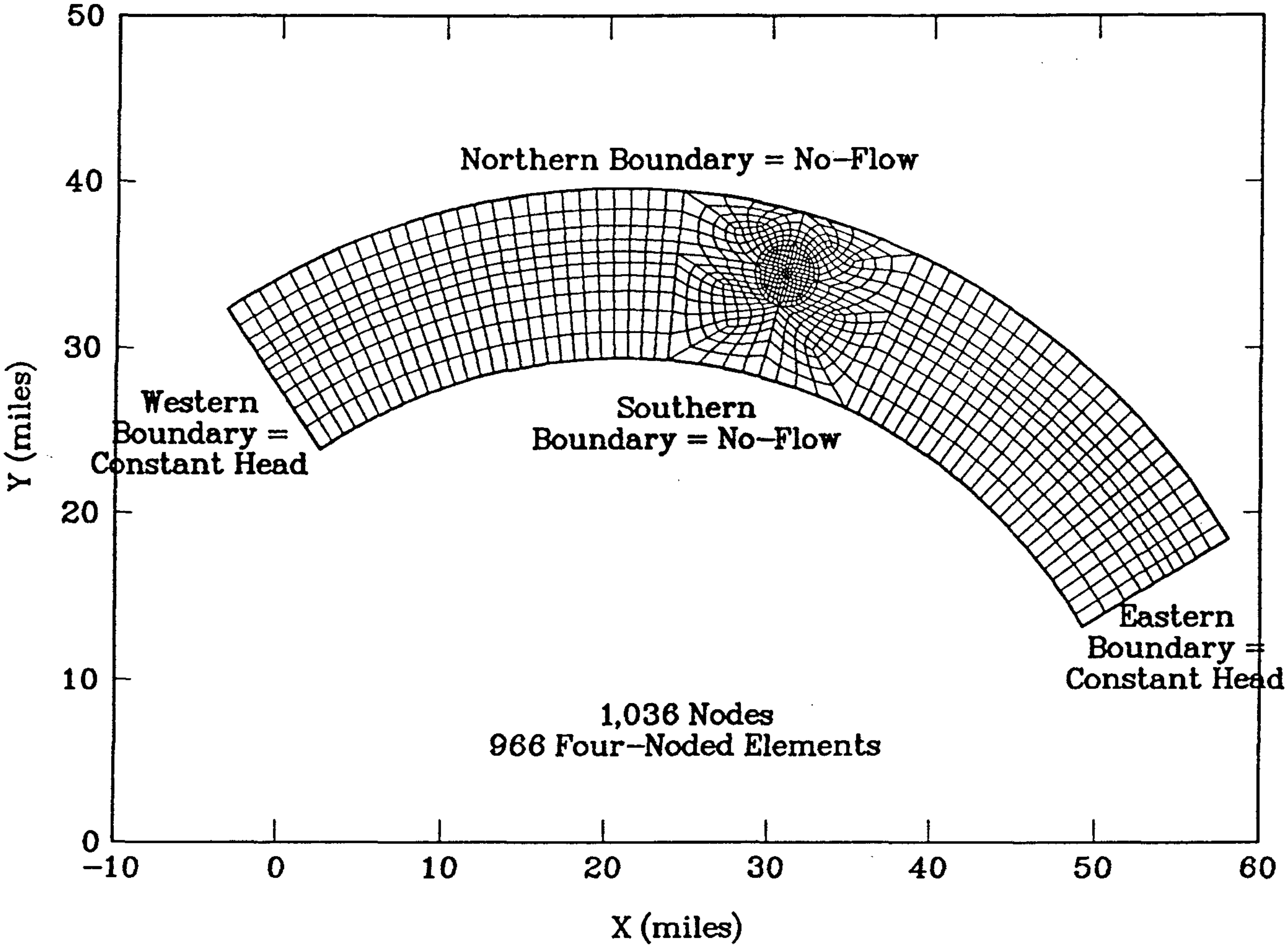


Figure D2(a). Model Grid.

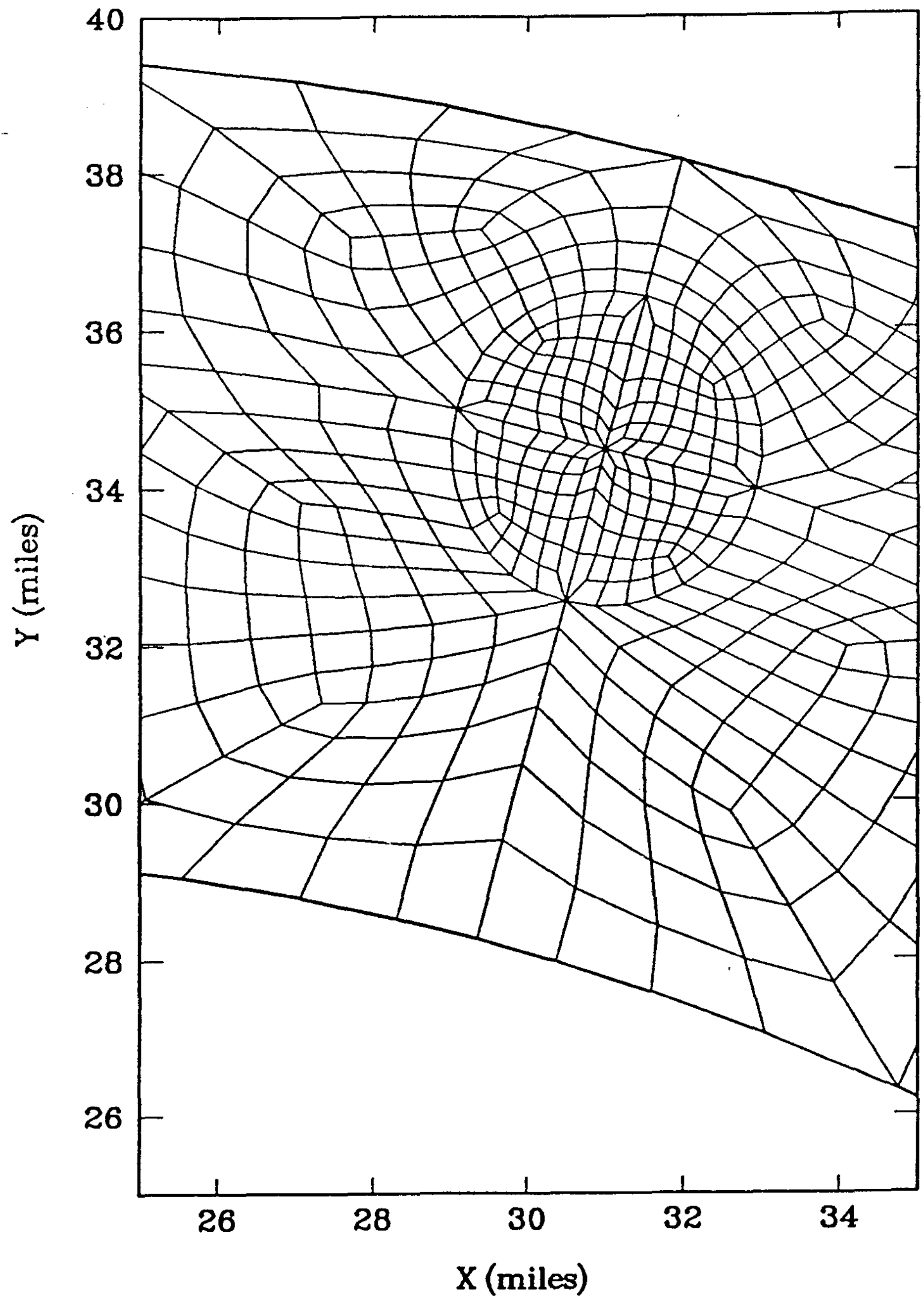


Figure D2(b). Closeup of Area About Injection Point.

Also, TDS is normally first converted to mass fraction before being input to the model. This option is discussed in example 6.4 of the SUTRA manual.

Hard- and soft-copies of the program, the input files, and the output files are provided with this report. In addition a complete copy of the SUTRA manual is provided. The diskettes are formatted for MS-DOS machines, but the information is compressed. A batch file, included with each diskette, must be run to download the files to a hard drive. Although the program is on an MS-DOS diskette, it will run on any standard UNIX platform with an F77 compiler.

Scenario #1

In Scenario 1, an injection activity is superimposed upon a regional flow regime. This was accomplished in two phases. First, the regional flow regime was approximated by a steady state simulation. The results from this simulation were then utilized as initial and boundary conditions for the subsequent simulation in which injection was included.

Phase 1: Constant-Head boundary condition assignments for the west and east ends of the model grid were taken from site specific data. The average elevation of Lake Avalon for the year 1989 was utilized for the west end (source: State Engineer District Office, Roswell, NM). The equivalent fresh-water head for North Custer Mountain Unit 1, taken from Hiss, 73, was utilized for the eastern end. These elevations were 3173 and 2606 feet above mean sea level, respectively. Given an appoximate length from the west end of the model to the east end of 67 miles, that represents a gradient of 567 feet over 67 miles, or 0.0016 ft./ft, directed eastward.

The resulting hydraulic head distribution is shown in Figure D3. This head distribution is compared to Hiss's equivalent fresh-water head diagram (1973) in Figure D4. The heads compare favorably over the region of interest. However, this does not necessarily imply that the model is calibrated, merely that it appears to be reasonable. As mentioned previously, data is relatively sparse for the Capitan, and because of this, any predictions must be based upon conservative data assignments and assumptions. It is not known what the recent equivalent fresh water head may be for the North Custer Mountain Unit 1 well and that is why the 1973 report was utilized (data from Richey, 1984, indicate that it is dropping). More recent data could easily be incoporated into the model for future simulations. However, as will become clear in the second scenario, any heads likely to be encountered will not noticably change the final predictions. In any event, if the heads at the east end are dropping, then the current assignments are conservative, since they minimize the gradient that is drawing water away from the Pecos.

Phase 2: Along with the initial head distribution from Phase 1, an initial brine distribution was now assigned to the model grid that closely mimics the TDS pattern presented in the section of this report titled "Ground Water Quality of the Capitan Reef". This initial distribution is shown in Figure D5. This second phase then simulated the injection of brine from the proposed injection site for a 50 year period, followed by a period of roughly 1,000 years in which the injection well was shut off, leaving the resulting contaminant plume to drift through the model domain in response to the regional flow gradient only. The injection rates and concentrations are outlined in the section titles "Modeling Assumptions".

The cross-section A-A' has been established for viewing some of the results (Figure D1). It parallels the north and south model boundaries throughout the model length and passes through the injection position. A number of figures are presented which show TDS, fresh-

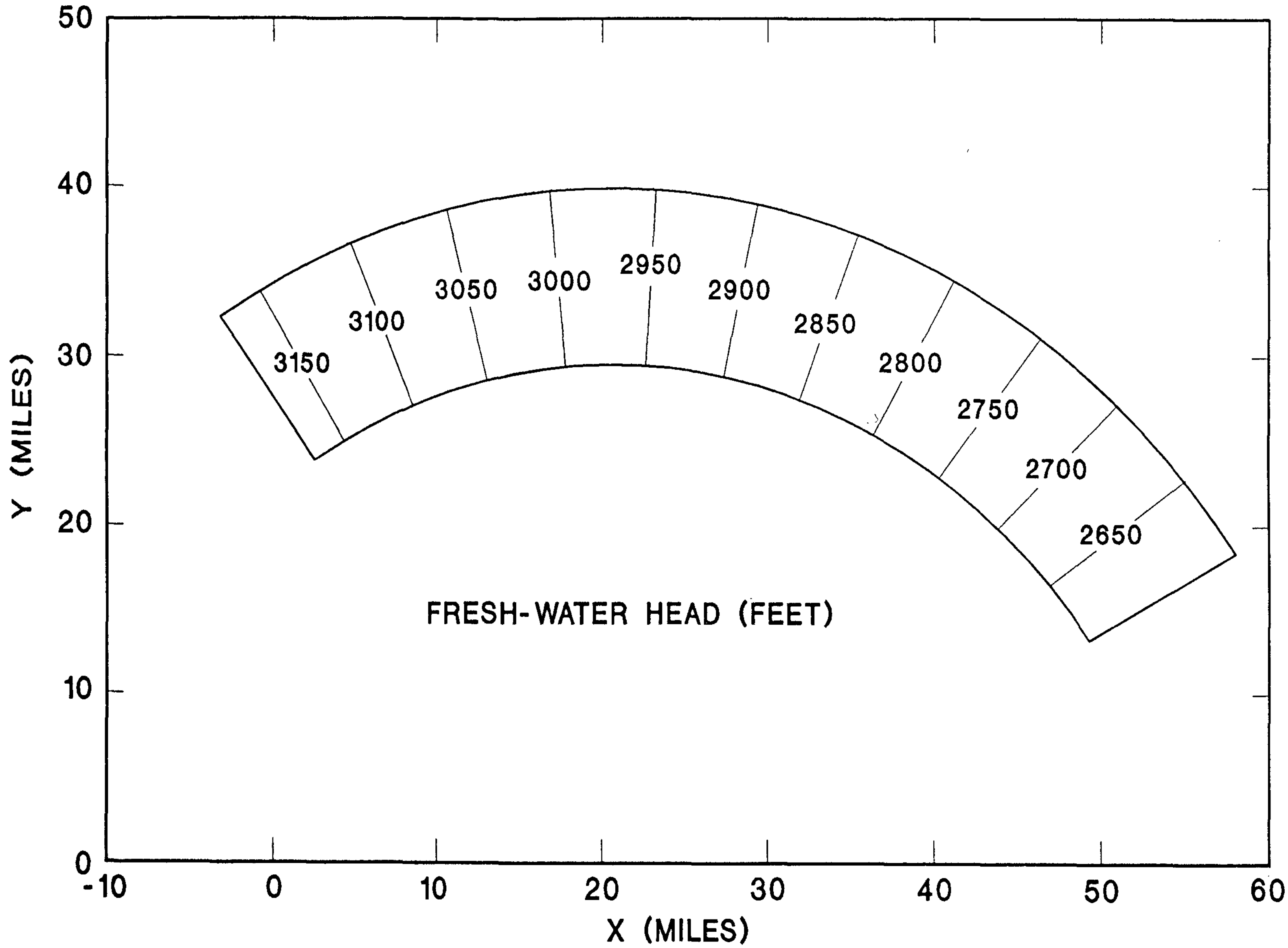
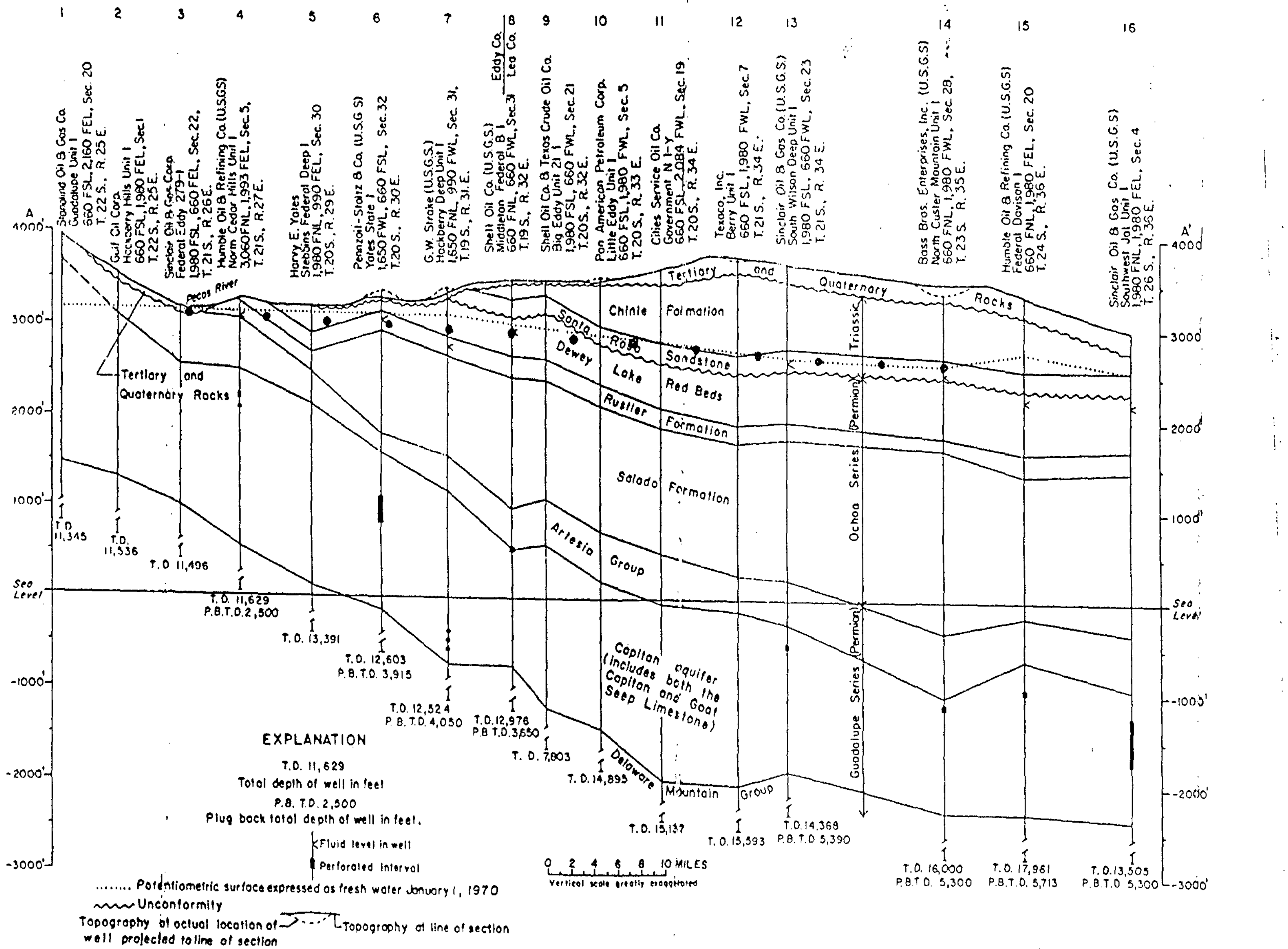


Figure D3. Steady State Head Distribution, Scenario 1.



● ● ● ● Steady state equivalent fresh water heads, from initial Capitan numerical model, March, 1993.

--Longitudinal stratigraphic section A-A' showing the position of the Capitan aquifer, Eddy and Lea Counties, New Mexico.

Adapted From Hiss, 1973

FIGURE D4 Fresh-water Heads Comparison

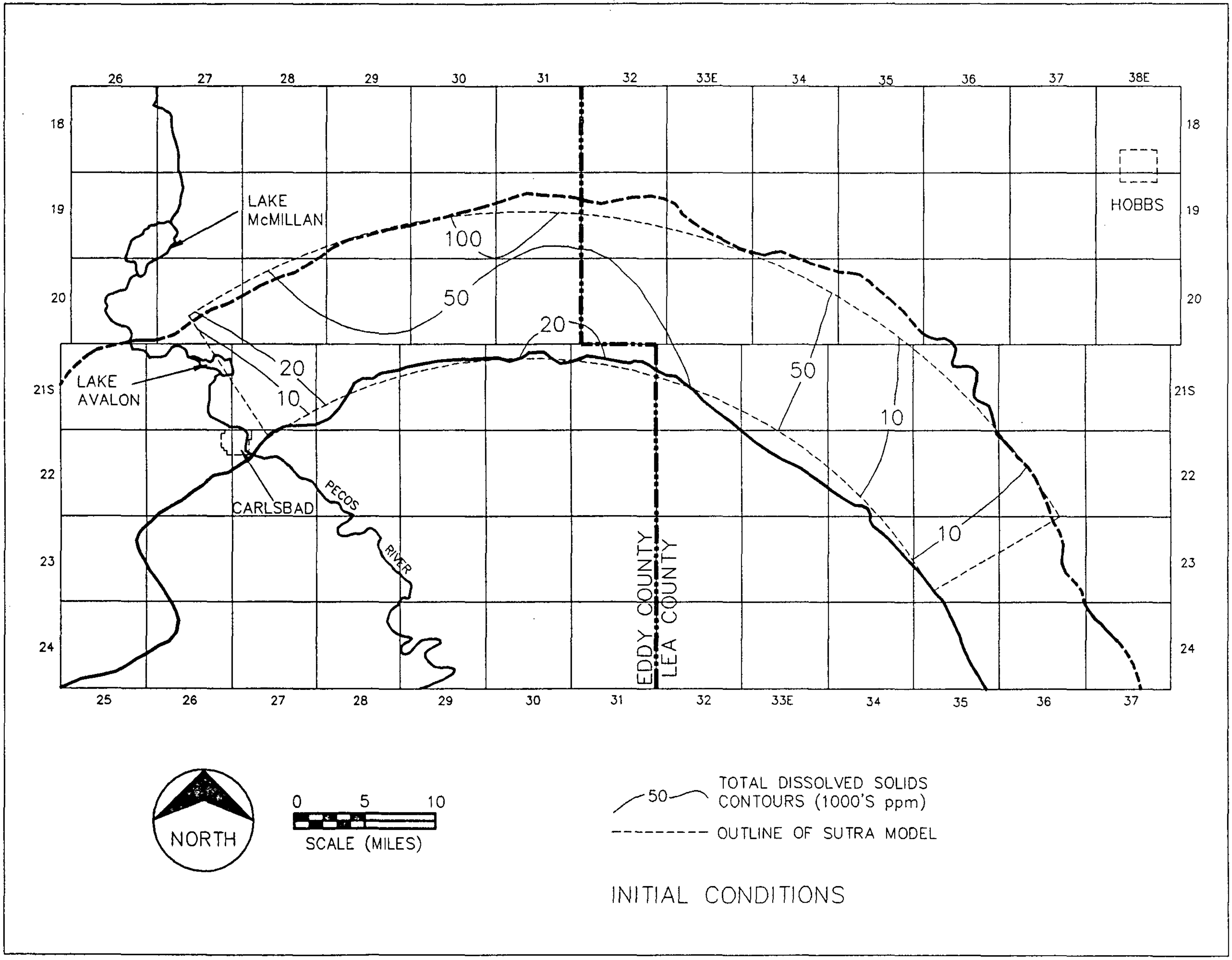


Figure D5. Initial TDS Distribution.

water head, and change in fresh-water head along the A-A' line at various times. In these figures the vertical scales are greatly exaggerated.

Figure D6 shows the development of a spike in TDS due to the injection activity over the 50-year pumping period, followed by its relaxation. It is evident, even in this highly exaggerated vertical scale, that the TDS changes are relatively small (perhaps infinitesimally so) over the entire area, except in the region immediately surrounding the injection well. This is also seen in the contour plots of FigureD7. Given the scale of these images, it is extremely difficult to detect any impact at all upon the Capitan due to the proposed injection activities. Close-up views of the area immediately surrounding the well are shown in Figure D8. Even at this magnified scale of only 6 miles by 6 miles, the plume from the injection activity appears minor, and has only a slight temporary effect upon the position of the 50,000 ppm contour line. Figure D9 shows close-up views of the velocity vector field around the injection well. The figure shows, in a relative sense, how rapidly brines that are injected towards the west are reversed in direction. Figure D10 shows the freshwater heads and the relative changes in freshwater heads with time over the A-A' line.

Scenario #2

A more conservative scenario could be addressed, in which there is no regional gradient which moves water (and therefore any injected brines) away from the Pecos. This has been simulated in Scenario 2. Essentially, this simulation is identical to the previous scenario in all aspects except the west and east boundary conditions. Equivalent fresh-water heads at both ends have been set to the same number, 2878 feet above mean sea level (note that any constant number would do). This removes any gradient to the east and also creates an initial head distribution that is perfectly flat.

The same initial brine concentration is assigned as previously. As before, the model simulates the injection of brine from the proposed injection site for a 50 year period, followed by a period of roughly 1,000 years in which the injection well is shut off. This time, however, the resulting contaminant plume does not drift through the model domain in response to the regional flow gradient, since there is none.

A number of figures are presented which show TDS, fresh-water head, and change in fresh-water head along the A-A' line at various times. In these figures, as before, the vertical scales are greatly exaggerated.

Figures D11 through D15 show essentially the same results as scenario1, namely that the impact of the proposed injection activity is negligible throughout the study area.

Figure D11 shows the development of a spike in fresh-water head due to the injection activity over the 50-year pumping period, followed by its relaxation. It is evident, even in this highly exaggerated vertical scale, that the head changes are relatively small over the entire area. Although these images only depict changes in head, they can be used to infer flow directions, since the initial water levels were the same everywhere.

A more descriptive result can be found from figures of the resulting TDS distribution. Figure D12 shows the development of a spike in TDS due to the injection activity over the 50-year pumping period, followed by its relaxation. It is evident, even in this highly exaggerated vertical scale, that the TDS changes are relatively small (perhaps infinitesimally so) over the entire area, except in the region immediately surrounding the injection well. This is also seen in the contour plots of Figure D13. Given the scale of these images, it is extremely difficult to detect any impact at all upon the Capitan due to the proposed injection

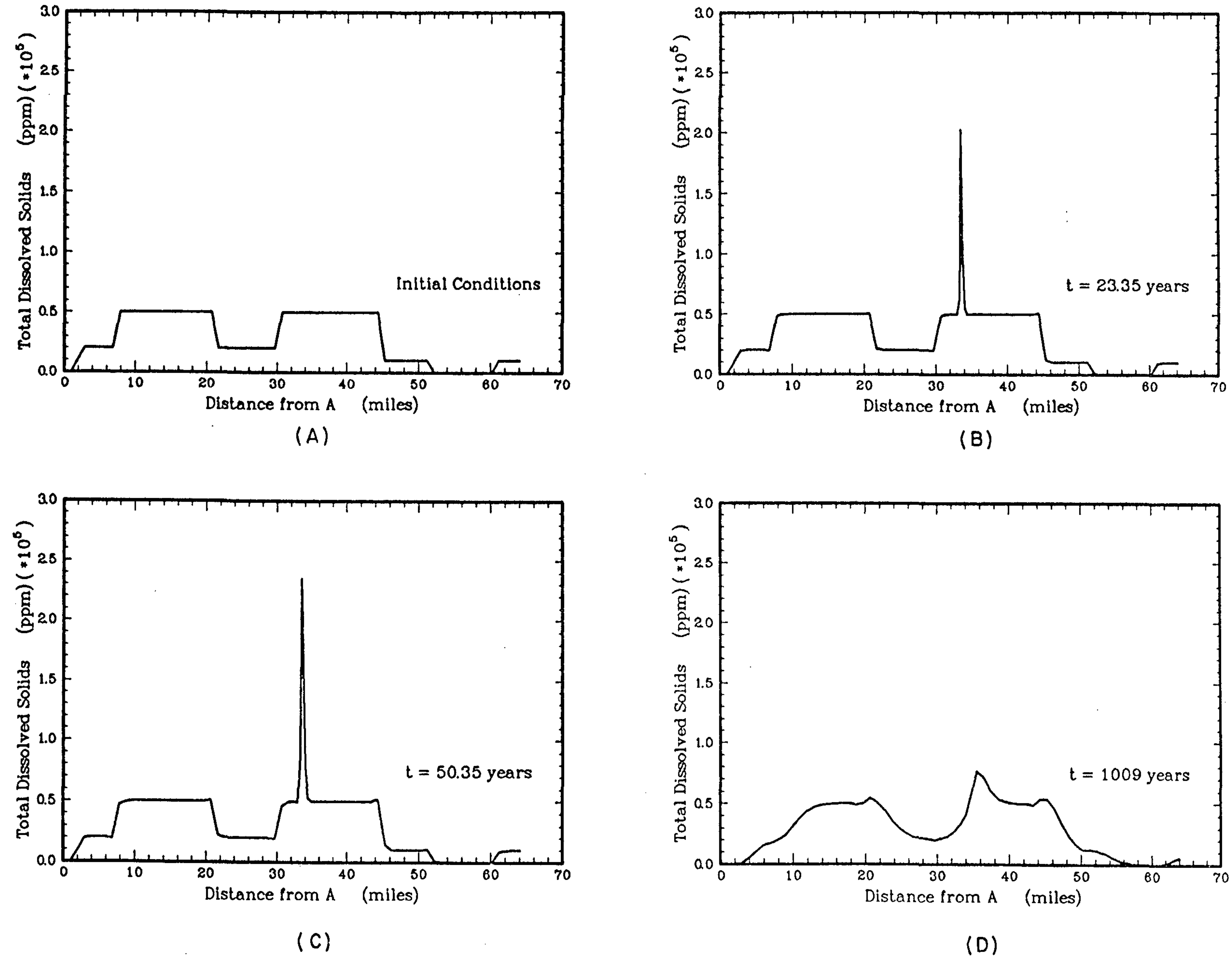


Figure D6. Total Dissolved Solids Distribution, Scenario 1.

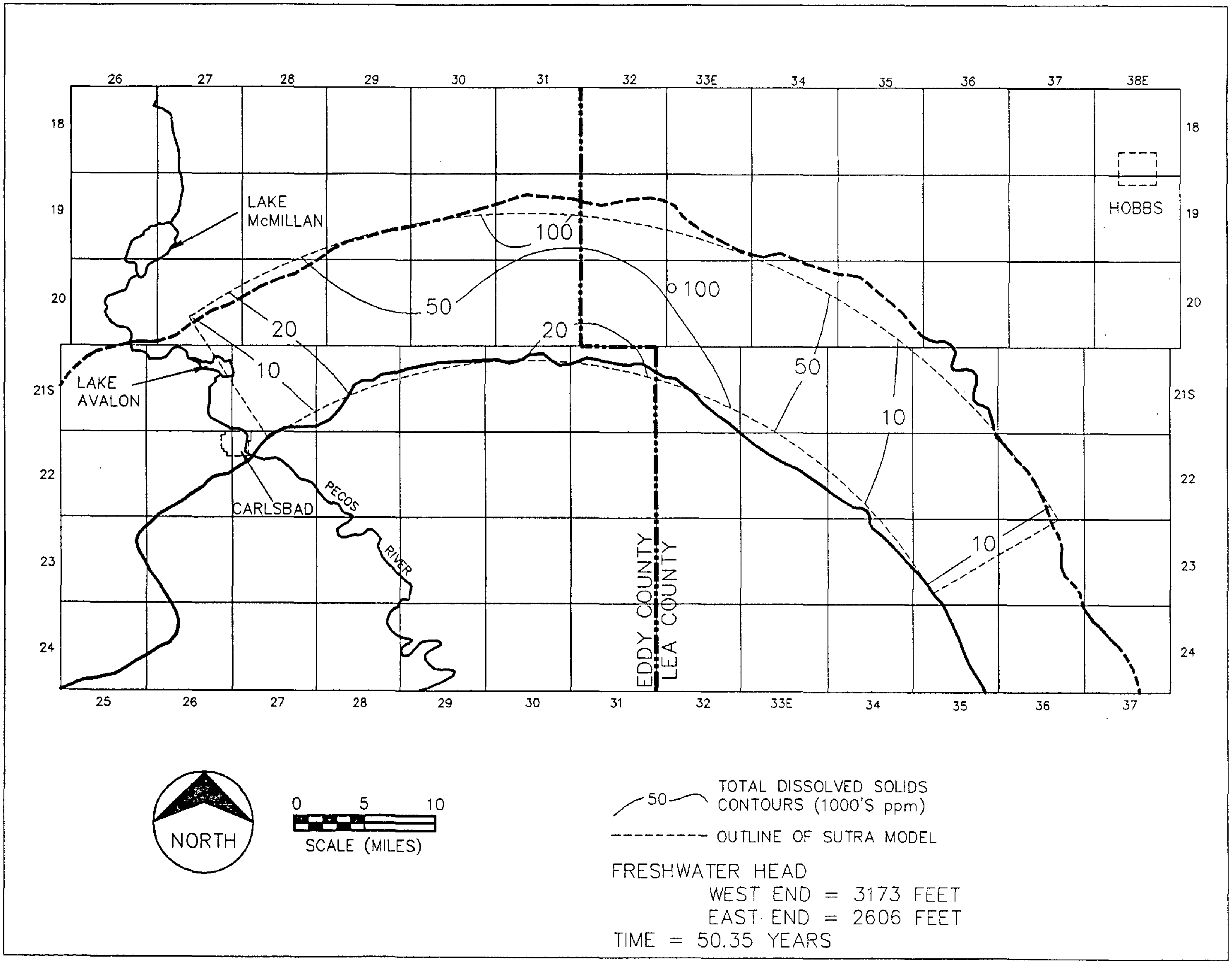


Figure D7. TDS Contours at 50.35 Years, Scenario 1.

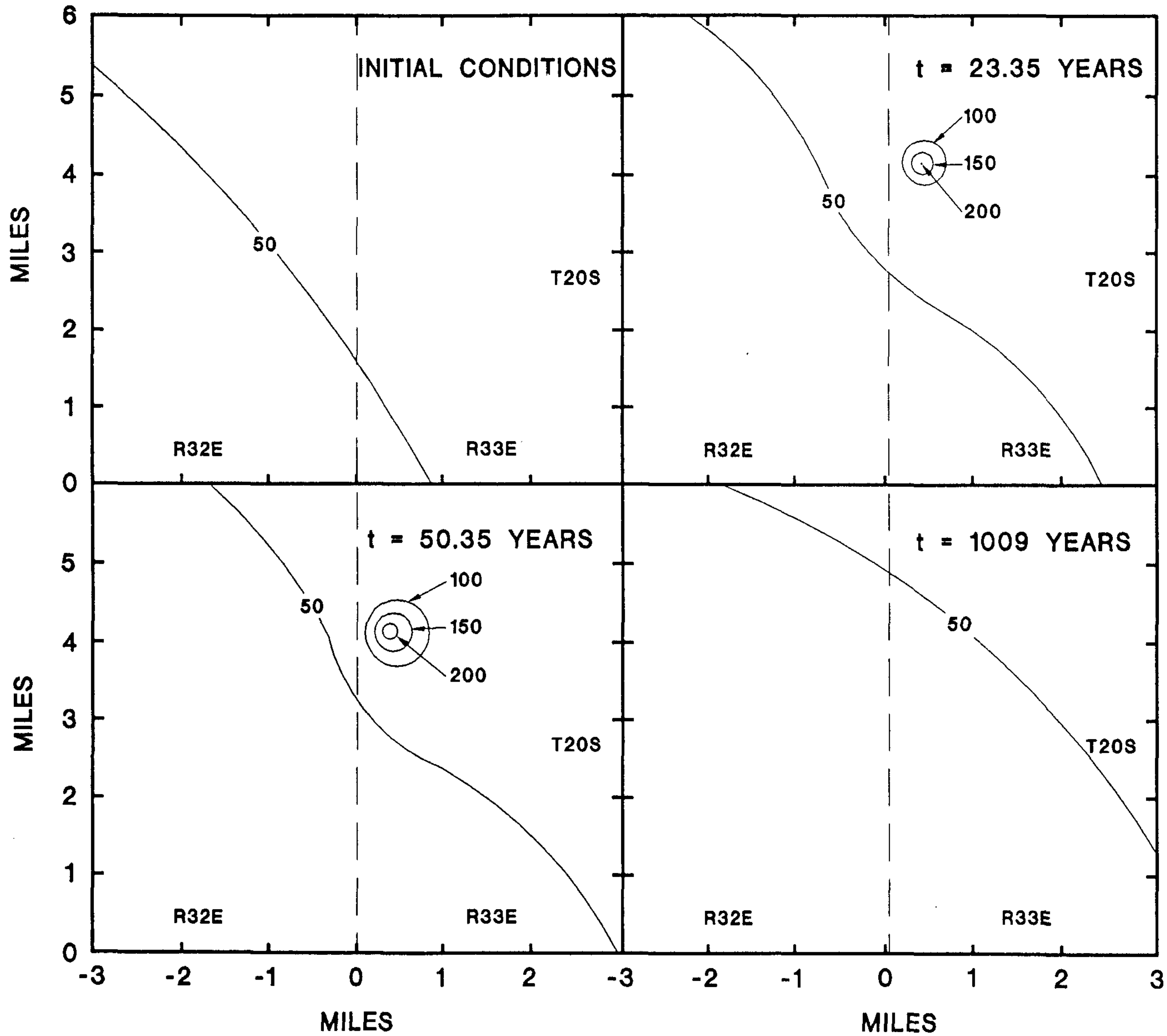


Figure D8. TDS Contours, Scenario 1, Expanded View.

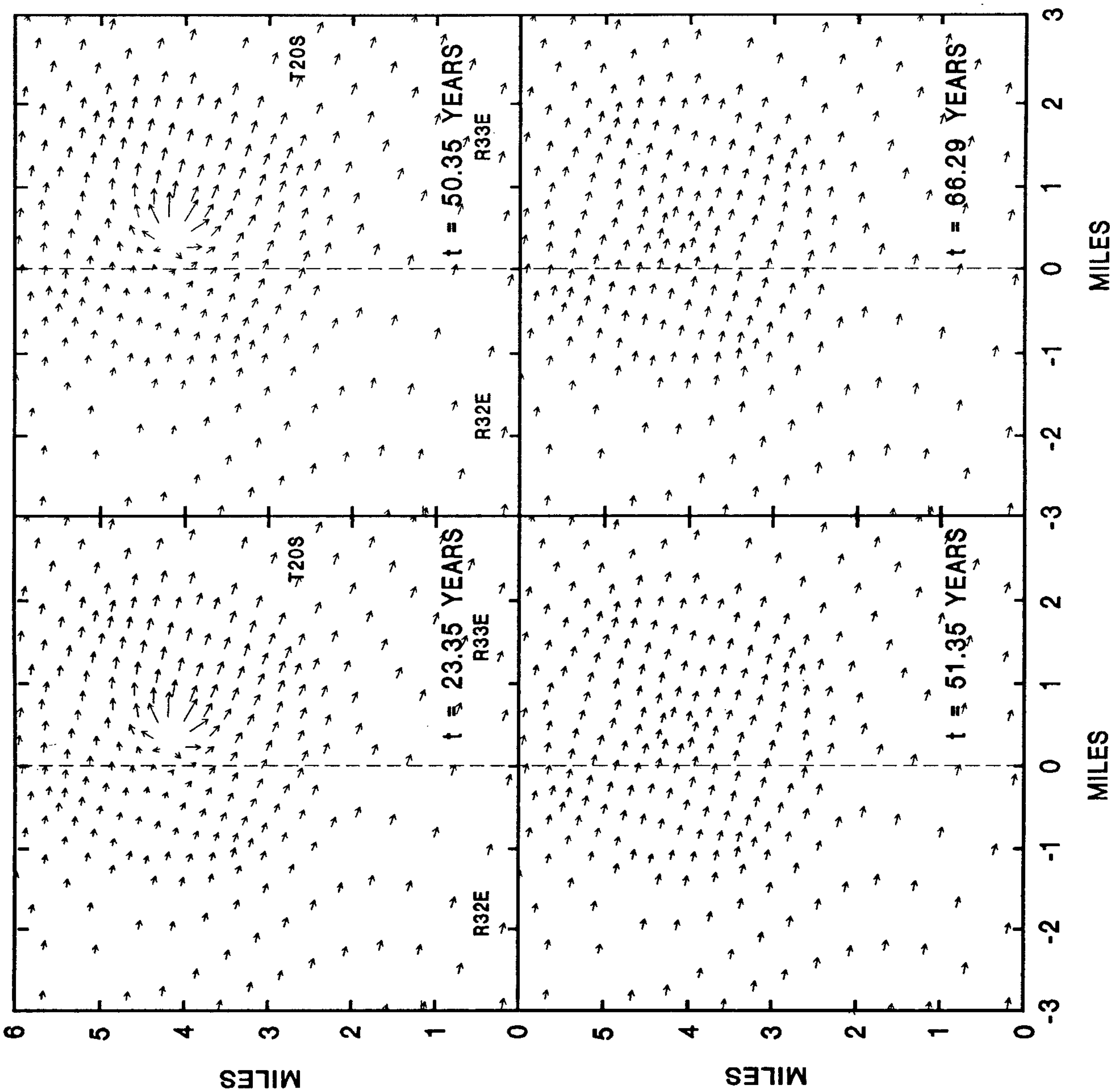


Figure D9. Velocity Vectors, Scenario 1.

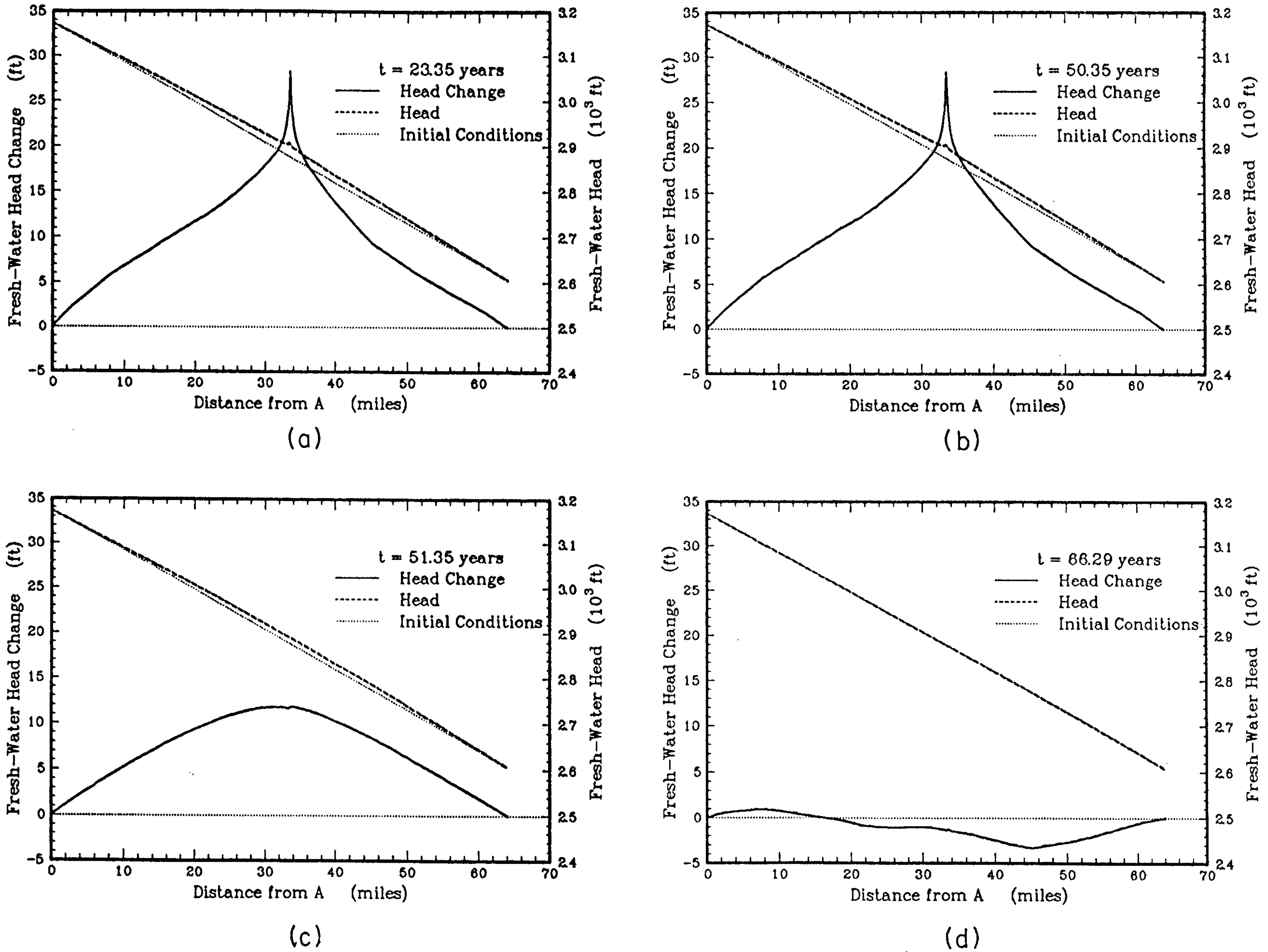


Figure D10. Heads Distributions for Capitan Reef Model, Scenario 1.

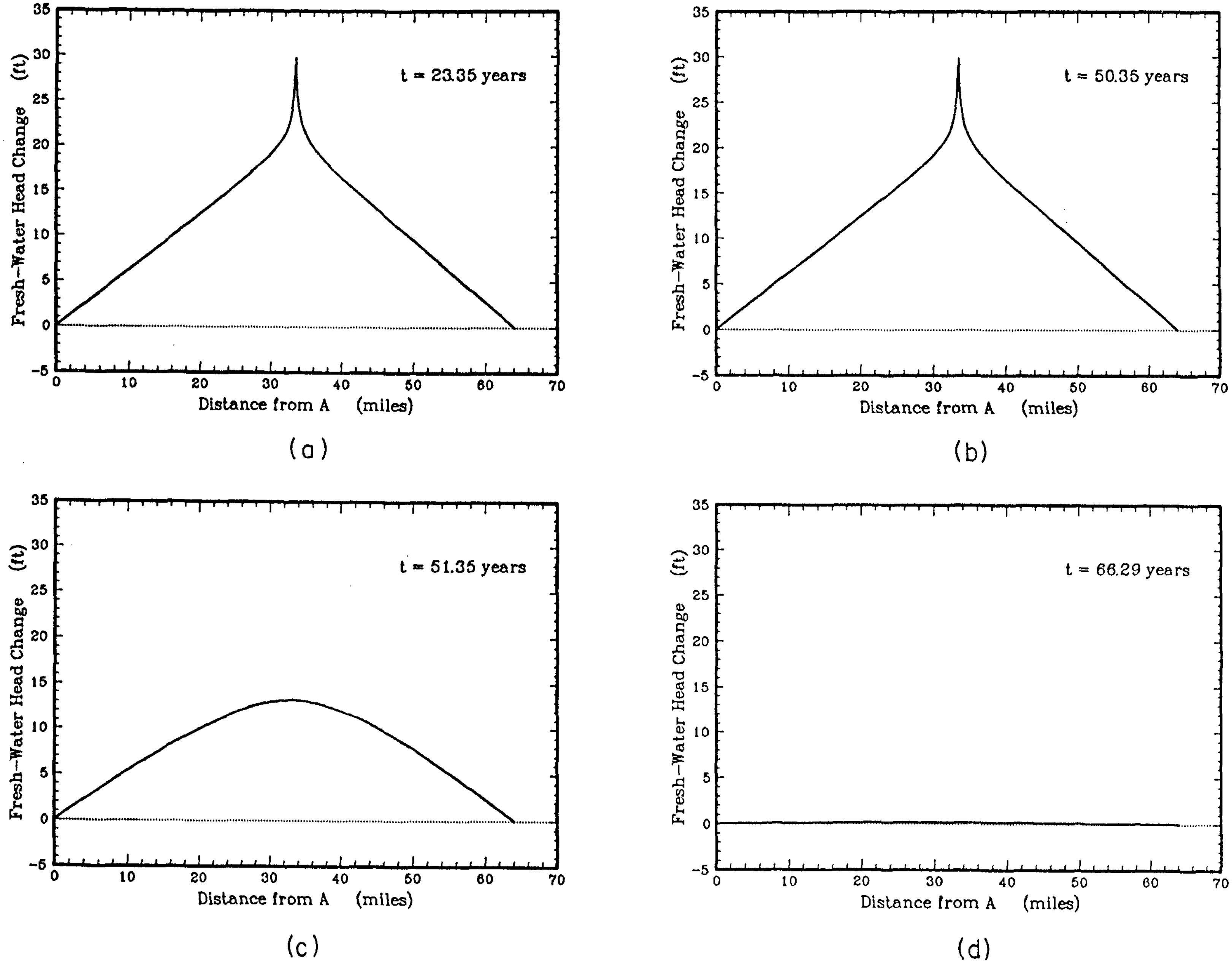


Figure D11. Change in Fresh-Water Head, Scenario 2.

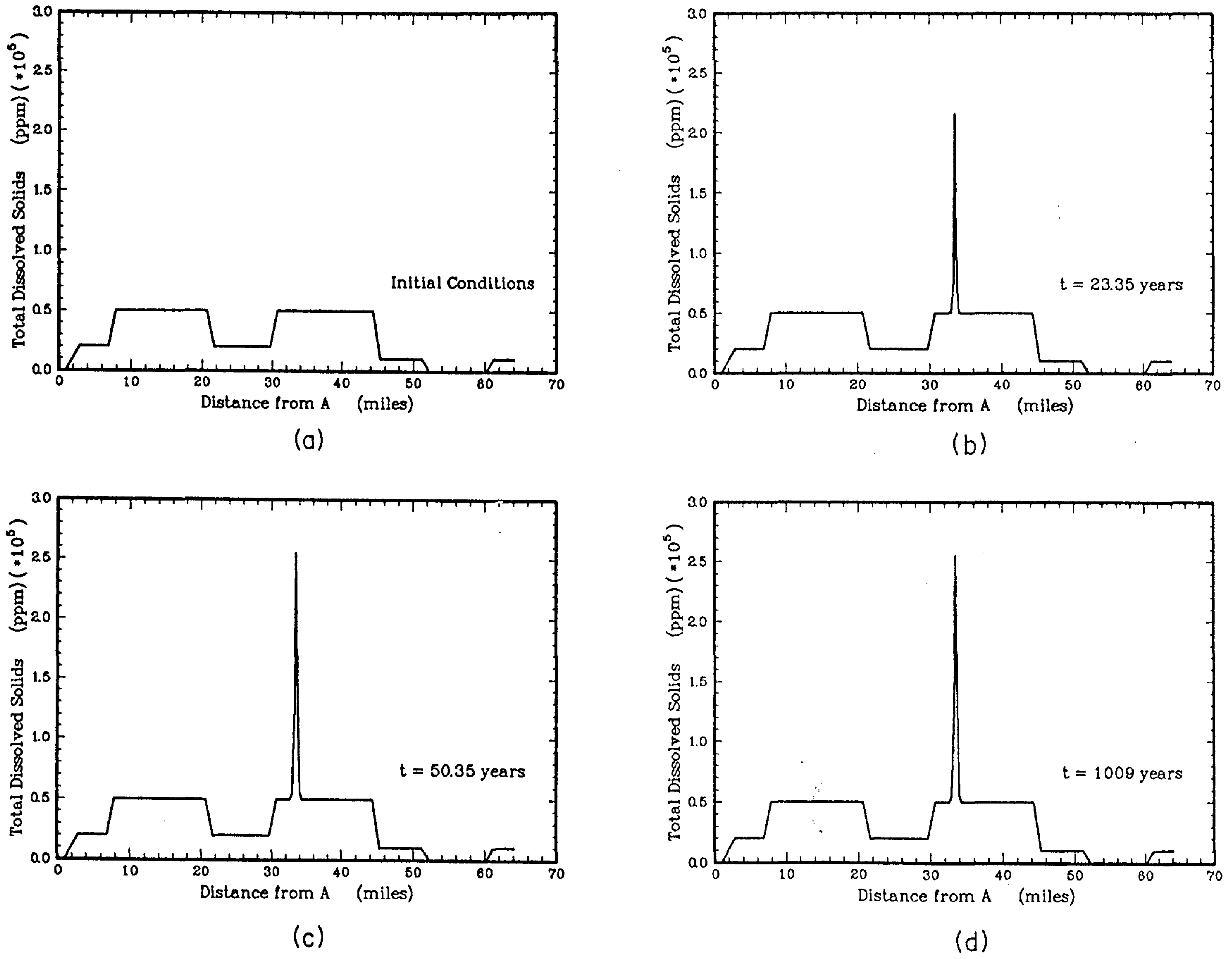


Figure D12. Total Dissolved Solids Distribution, Scenario 2.

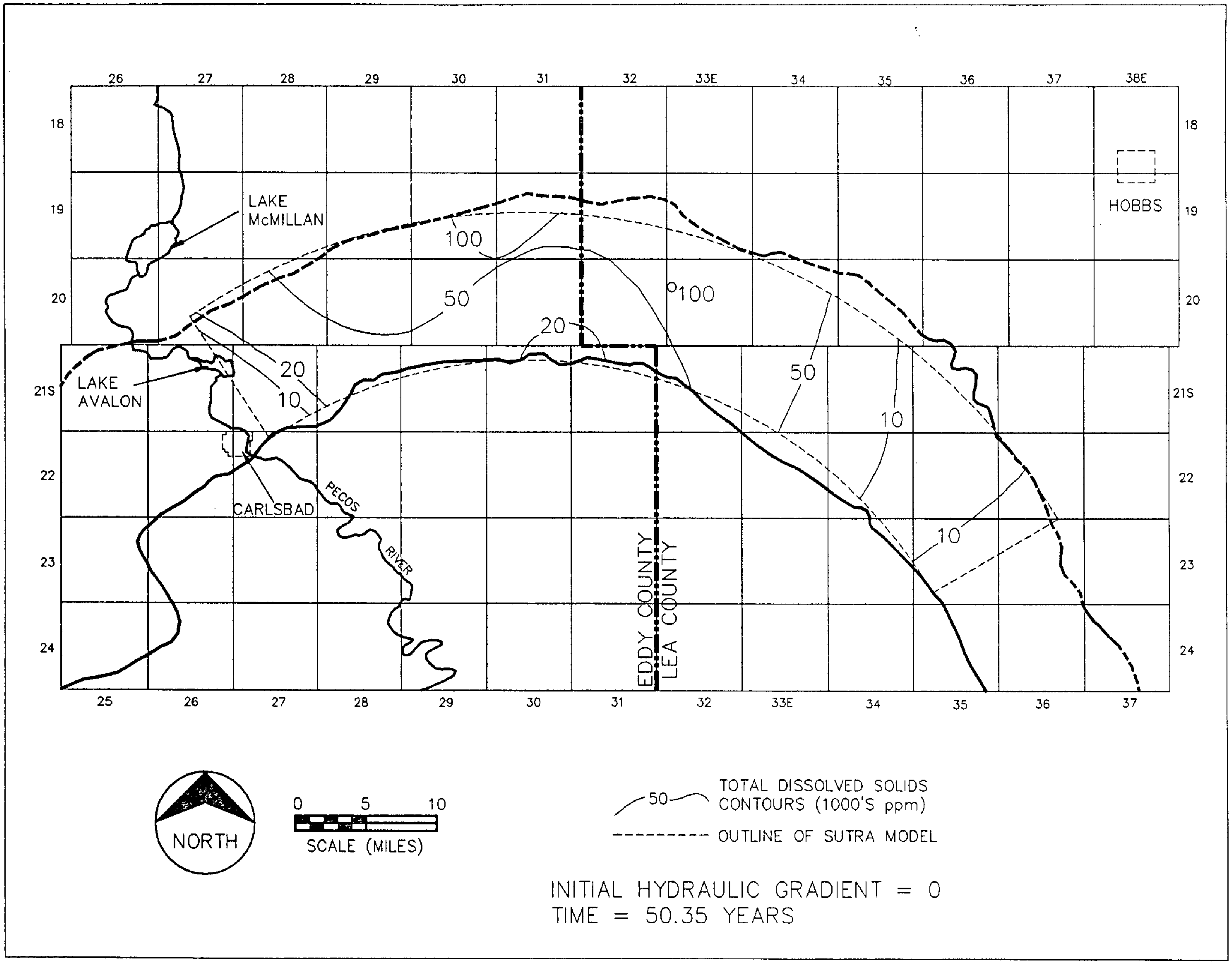


Figure D13. TDS Contour Map, Scenario 2.

activities. Close-up views of the area immediately surrounding the well are shown in Figure D14. Even at this magnified scale of only 4 miles by 3 miles, the plume from the injection activity is barely discernable, and it would still be difficult, if not impossible, to detect any westward movement of the 50,000 ppm contour line (not to mention the 10,000 ppm contour lines). Figure D15 is a vector plot of the area immediately about the well over the simulation time.

Verification and Mass Balance Considerations

The relative lack of data and the conservative assumptions employed preclude any rigorous verification of the predictive models at this time. However, steps were taken, including convergence analyses, grid refinement, independant error checking, and time step refinement to ensure that the model results were numerically valid. The excellent mass balance values, with a less than 1% discrepency in fluid and solute masses reported in the model outputs also help to confirm the validity of the solutions.

Summary and Conclusions

A study of the hydrogeology of the Capitan Reef was performed, having the goal of predicting the consequences of a proposed brine injection activity. The study began with the interpretation of the ambient water quality characteristics of the Reef, followed by an investigation into the dynamics of the regional flow regime. Water quality information was integrated with water flow information to develop a conceptual model of the Capitan Reef hydrogeology. This conceptual model, in conjunction with a host of simplifying and conservative assumptions, was utilized to build a numerical predictive model. The numerical model was then employed to predict the impact of the proposed injection activity upon water quality in the Capitan Reef throughout a 50 year injection period and for an additional thousand years.

In initial discussions concerning the potential impact of the injection activity, the situation was likened to an "ink dropper in a waterfall". In this analogy, the Capitan Reef east of the Pecos is the waterfall. The proposed injection well is the ink dropper and the high-TDS brine that it injects is the ink. The ink dropper is positioned half-way down the waterfall and is squeezing ink into the cascade of water at that level. It is obvious that the ink will never reach the top of the waterfall.

The study that was performed and the series of modeling simulations that followed have strongly supported this initial proposition. The plume of high TDS brines emanating from the injection postion would occupy a relatively inconsequential volume of the Capitan. Furthermore, the impact of this activity upon the current positions of the 10,000 ppm boundaries withing the Capitan (both east and west of the injection site) would be practically undetectable. This is because the Capitan Reef is so vast, and the zones within the Capitan having high TDS brines are so extensive, that the proposed injection volumes (which would be within these high TDS zones) are essentially insignificant. Put another way, the effects of this injection actvity would be virtually lost in the 'noise'.

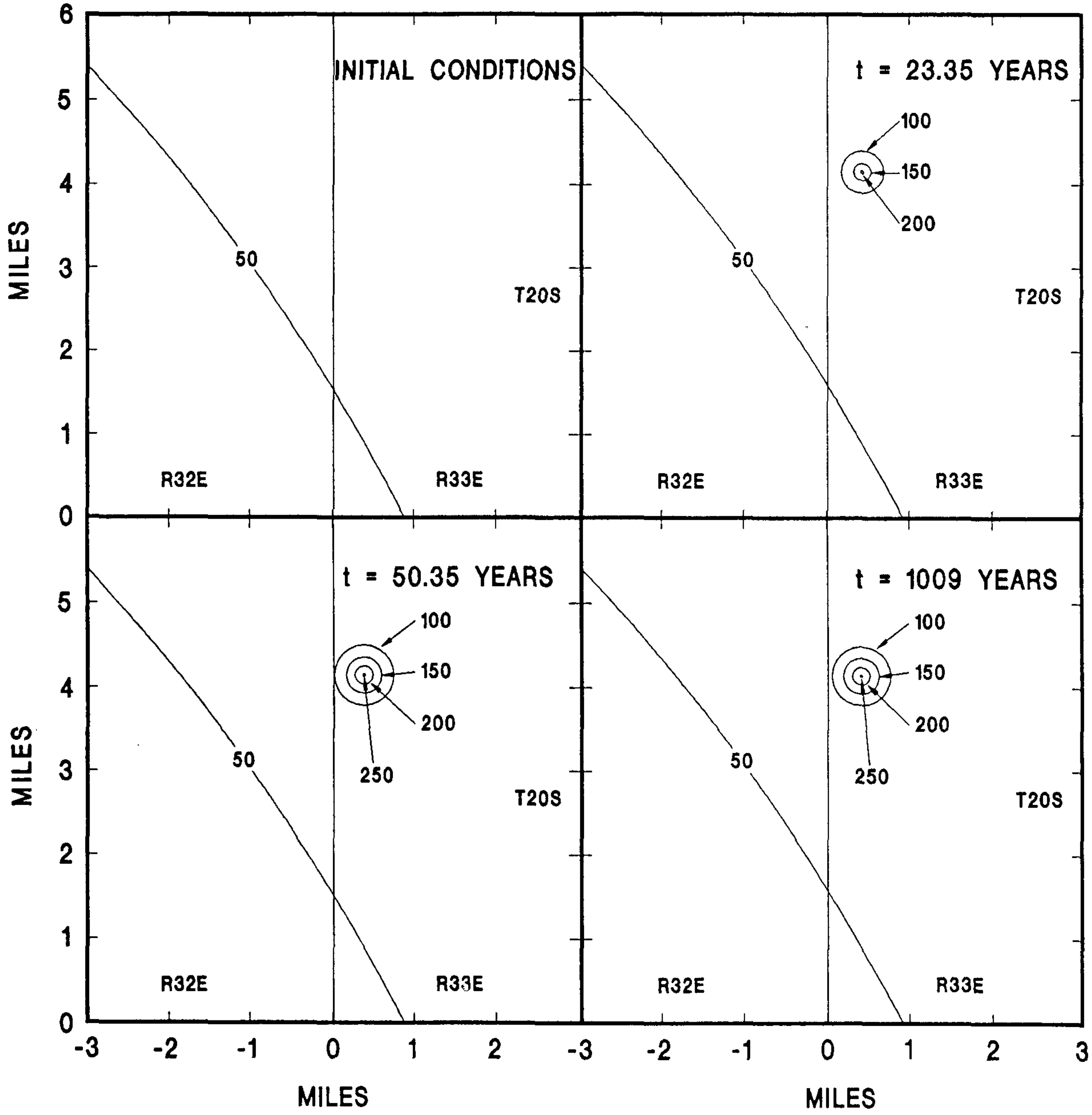


Figure D14. TDS Contour Map, Enlarged View, Scenario 2.

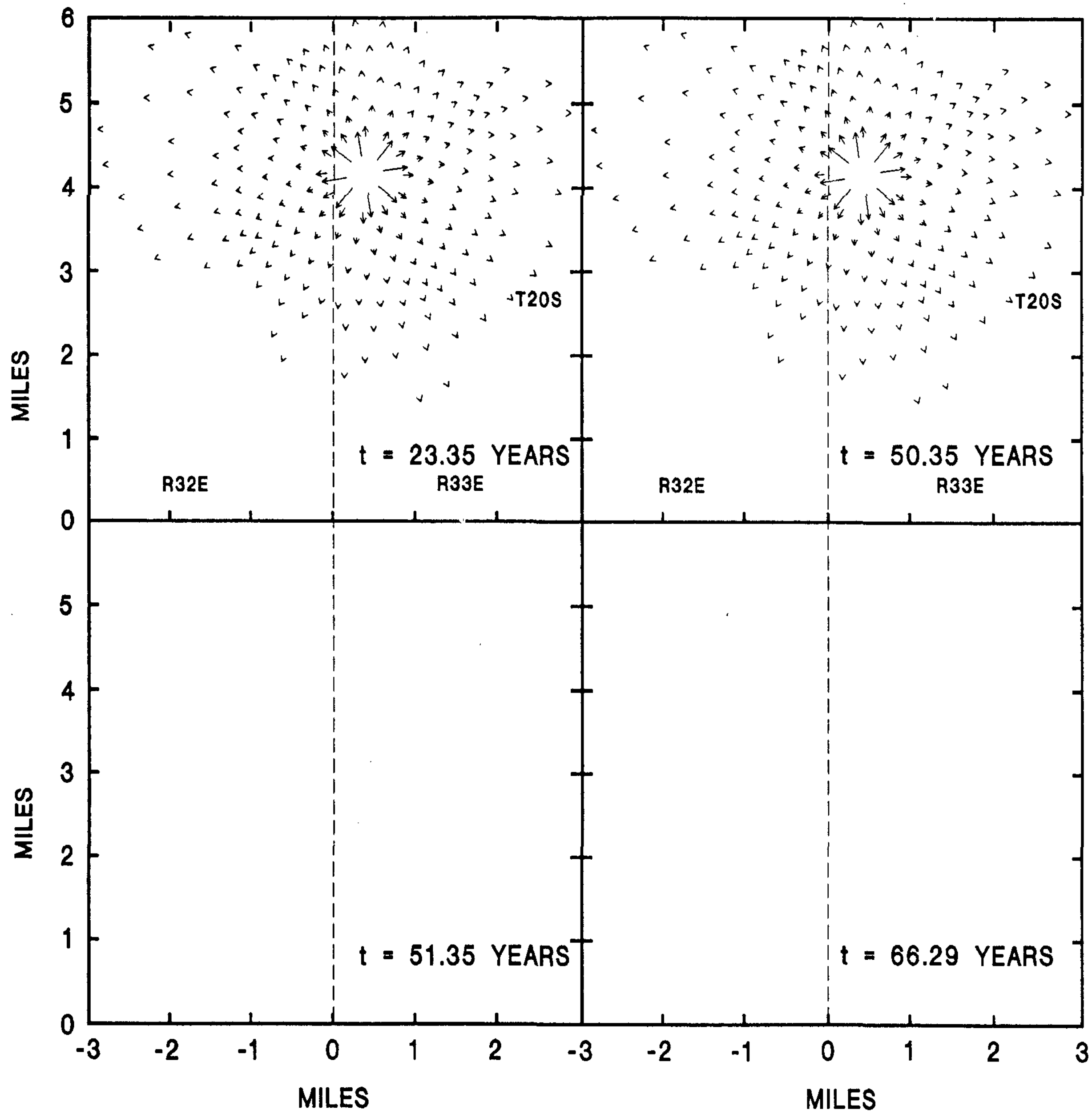


Figure D15. Velocity Vectors, Scenario 2.