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INFORMATION CIRCULAR 36

RADIUM IN THE MT. SIMON–HINCKLEY AQUIFER, EAST-CENTRAL AND SOUTHEASTERN MINNESOTA

UNIVERSITY OF MINNESOTA

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RADIUM IN THE MT. SIMON–HINCKLEY AQUIFER, EAST-CENTRAL AND SOUTHEASTERN MINNESOTA

By

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INTRODUCTION

Studies conducted in the 1960s showed that radium was a fairly common constituent in ground water throughout much of the Midwest. Concentrations of ^{226}Ra ranging from 1 to 80 pCi/L (picoCuries per liter) were found in northern Illinois, Iowa, and eastern Wisconsin (Rowland and others, 1977). The high radium values were associated with water from deep sandstone aquifers of Cambro-Ordovician age, but not with aquifers above or below. Additional studies and reports of radium in the Cambro-Ordovician aquifers by Gilkeson and Cowart (1982, 1987), Hahn (1984), and Weaver and Bahr (1991) further delineated distribution patterns and have suggested sources for the observed concentrations.

Radium is a naturally occurring radioactive element, formed by radioactive decay of uranium and thorium. The most abundant radium isotope, ^{226}Ra, has a half-life of 1600 years and is part of the ^{238}U decay series. Two other isotopes, ^{228}Ra (half-life = 5.76 years) and ^{224}Ra (half-life = 3.7 days), are part of the ^{232}Th decay series. In 1976, the U.S. Environmental Protection Agency published regulations that established contaminant levels for radioactivity and radioactive nuclides in public water systems. The maximum contaminant level (MCL) for gross alpha activity was not to exceed 15 pCi/L and the combined ^{226}Ra and ^{228}Ra activity in the water was not to exceed 5 pCi/L (Federal Register, 1976). The U.S. Environmental Protection Agency is reviewing the contaminant levels for radioactive nuclides in drinking water.

Testing of public water supplies by the Minnesota Department of Health showed that many communities in the southern half of Minnesota were not in compliance with the drinking water standards for radium. Sampling of some municipal wells indicated that high radium levels were chiefly associated with water from the Mt. Simon-Hinckley aquifer, a sandstone aquifer of Late Cambrian/Middle Proterozoic age. A few wells in the Jordan Sandstone of Late Cambrian age also showed elevated radium levels. Because these data were obtained from municipal wells in communities with known radium problems, it was difficult to detect a pattern or to isolate specific radium-producing horizons within the aquifer(s). Therefore, the Minnesota Geological Survey sampled water from sole-source Mt. Simon-Hinckley wells to identify the distribution of radium within the regional geologic framework. Base-level data were also acquired on other radionuclides, the age of the water, and the water chemistry. Sole-source Mt. Simon-Hinckley wells were selected for sampling based on existing water-well information, and included wells previously monitored by the Minnesota Department of Health. The study area extended north to south from the town of Hinckley to the Root River basin, and west to east from the Mankato area to the Mississippi River. Complete coverage could not be obtained because of a lack of sole-source Mt. Simon-Hinckley wells in the south-central part of the aquifer. Several Jordan aquifer wells were also selected for sampling. The data accumulated in this study provide a starting point for selecting mitigation strategies or for choosing appropriate sites for future wells.

GEOLOGIC SETTING

The study area for this project (Fig. 1) extends to the western and northern limits of the Mt. Simon Sandstone of Late Cambrian age and locally includes part of the Middle Proterozoic Hinckley Sandstone subcrop area. In the subsurface, the Mt. Simon Sandstone extends east into Wisconsin and south into Iowa.

The Precambrian structural map (Fig. 2) shows a complex series of faults, horst and graben structures, and basins. These structural features have influenced sedimentation patterns during the Paleozoic, particularly in the Twin Cities basin, where sediments have accumulated to as much as 1000 feet thick. The Paleozoic strata have been structurally modified by a number of folds and faults whose

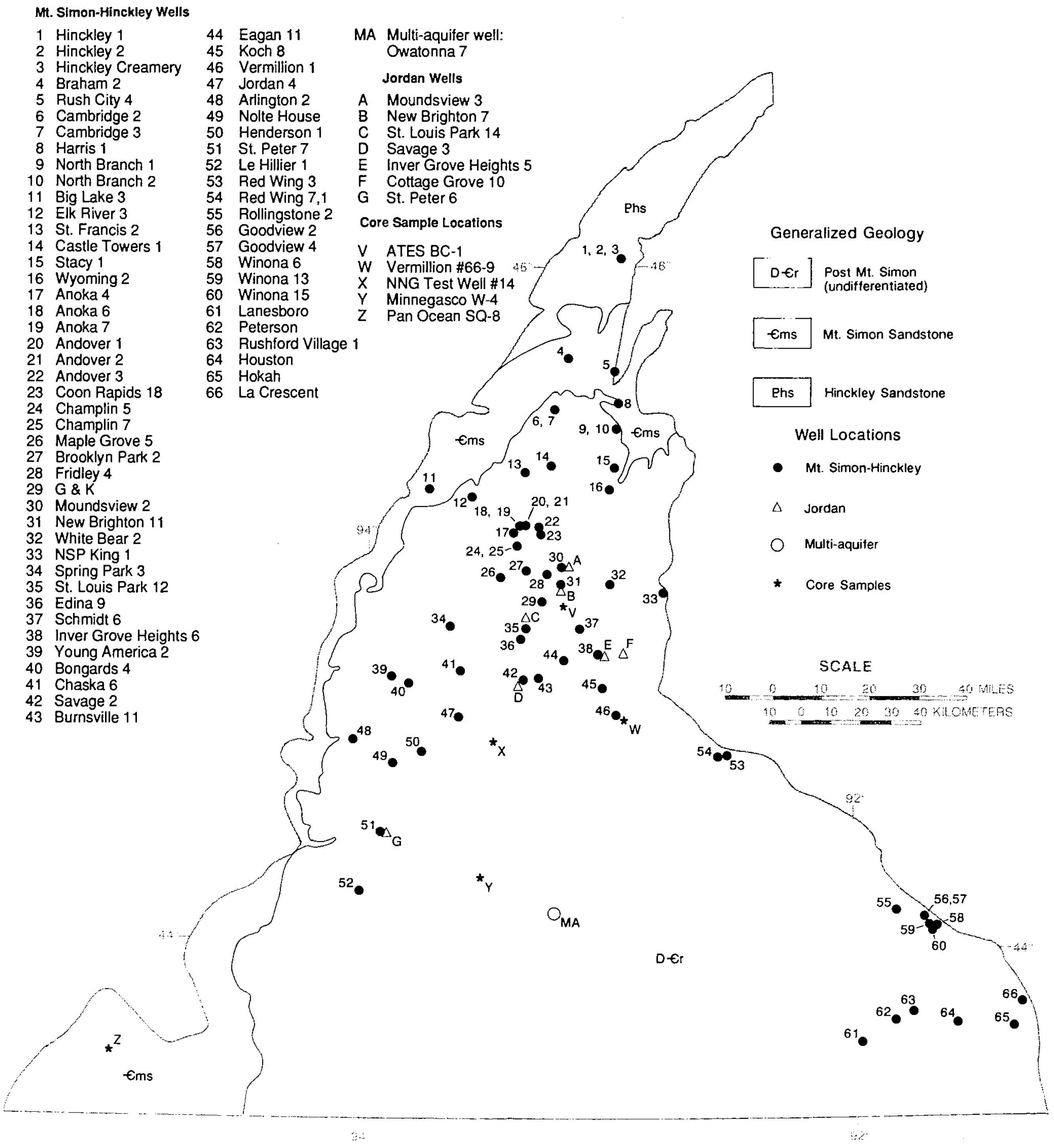

Figure 1. The Mt. Simon-Hinckley aquifer, the area where it is overlain by younger Cambrian to Devonian formations, and sample locations.

locations (Fig. 3) generally coincide with major structural breaks in the Precambrian basement (Sims, 1990). The coincidence of Precambrian faults and Paleozoic structures implies that the latter developed by reactivation of the former (Morey and Rensink, 1969). The extent and trend of these structural attributes as shown on Figures 2 and 3 are based primarily on geophysical data and therefore are only approximate.

On the flanks of the Hollandale embayment, the Mt. Simon Sandstone unconformably overlies the Middle Proterozoic Hinckley and Fond du Lac formations. Along local structural highs and near the center of the basin, the Mt. Simon Sandstone overlies the Middle Proterozoic Chengwatana Volcanic Group or sedimentary strata of the slightly younger Solor Church Formation (Morey, 1977). At the northern end of the study area, and on the edges of the basin, the Mt. Simon thins and the sampled wells most likely produce water from the Hinckley or Fond du Lac formations. Where the Hinckley is directly beneath the Mt. Simon, they function as a single aquifer. Furthermore, the contact between the two formations is difficult to identify without good cuttings samples or core. For the purposes of this study, therefore, no attempt was made to differentiate geologic or hydrologic contacts between these Cambrian and Proterozoic sandstones. None of the wells sampled are known to penetrate basaltic rocks of the Chengwatana Volcanic Group.

Within the Twin Cities basin proper, the Mt. Simon-Hinckley aquifer is overlain by younger sandstone, shale, and carbonate formations. Directly overlying the Mt. Simon Sandstone is shale of the Eau Claire Formation, which has a gradational contact with the Mt. Simon. Several of the overlying and younger sandstone and carbonate units are also important aquifers, and produce enough water that wells need not penetrate into the Mt. Simon-Hinckley aquifer. In the center of the Twin Cities basin, the Mt. Simon is more than 250 feet thick and as much as 1000 feet below the surface. At the edge of the basin on the west and on the north, the Mt. Simon thins to about 150 feet or less and is the first bedrock unit encountered beneath the glacial drift (Figs. 4 and 5).

The Hinckley Sandstone is medium to coarse grained and consists of 95% or more quartz. It was once considered possible to distinguish the Hinckley from the overlying Mt. Simon by the higher feldspar content of the Mt. Simon. However, localized feldspar-rich beds in the Hinckley prevent that from being diagnostic (Morey, 1972). The Hinckley contains some iron-bearing carbonate as a chemical cement, although the dominant cement is silica.

The Mt. Simon Sandstone is cross bedded, ranges from fine to coarse grained, and is poorly to well sorted with some interbedded green shale (Kiester, 1976). In Minnesota the Mt. Simon is subdivided into several facies representing a variety of energy conditions and source areas during deposition (Woodward, 1986; Mossler, 1992). Much of the Mt. Simon is classified as a quartz arenite (Driese and others, 1981; Mossler, 1992), because quartz is the dominant mineral phase, although feldspar makes up more than 25% of the detrital fraction in certain stratigraphic intervals (Tables 1-5). In the basal part of the Mt. Simon, where feldspar occurs, it is in the medium to coarse sand-size range. In the upper part feldspar occurs only in the silt-size to very fine sand-size range (Kiester, 1976; Mossler, 1992). Hematite, pyrite, siderite, zircon, and tourmaline have also been observed within the formation. Some of these minerals, such as siderite, have fairly restricted occurrences. The sandstone is cemented by dolomite, calcite, and some epitaxial quartz. Iron oxide staining and coatings occur around many grains, particularly in the upper part of the Mt. Simon and in the transition zone between it and the Eau Claire Formation. The clay minerals found in two Mt. Simon samples from the Vermillion 66-9 core (Table 2) are confined to reddish shaly beds. Representative sections of the Mt. Simon with lithologic descriptions are shown in Figures 6 and 7.

The Jordan Sandstone has a similar mineralogy to the Mt. Simon, being a quartz arenite with some dolomite and calcite and varying percentages of K-feldspar (Table 6). The X-ray diffraction analyses of this study did not identify any other minerals in the Jordan samples; however, the number of Jordan samples was small.

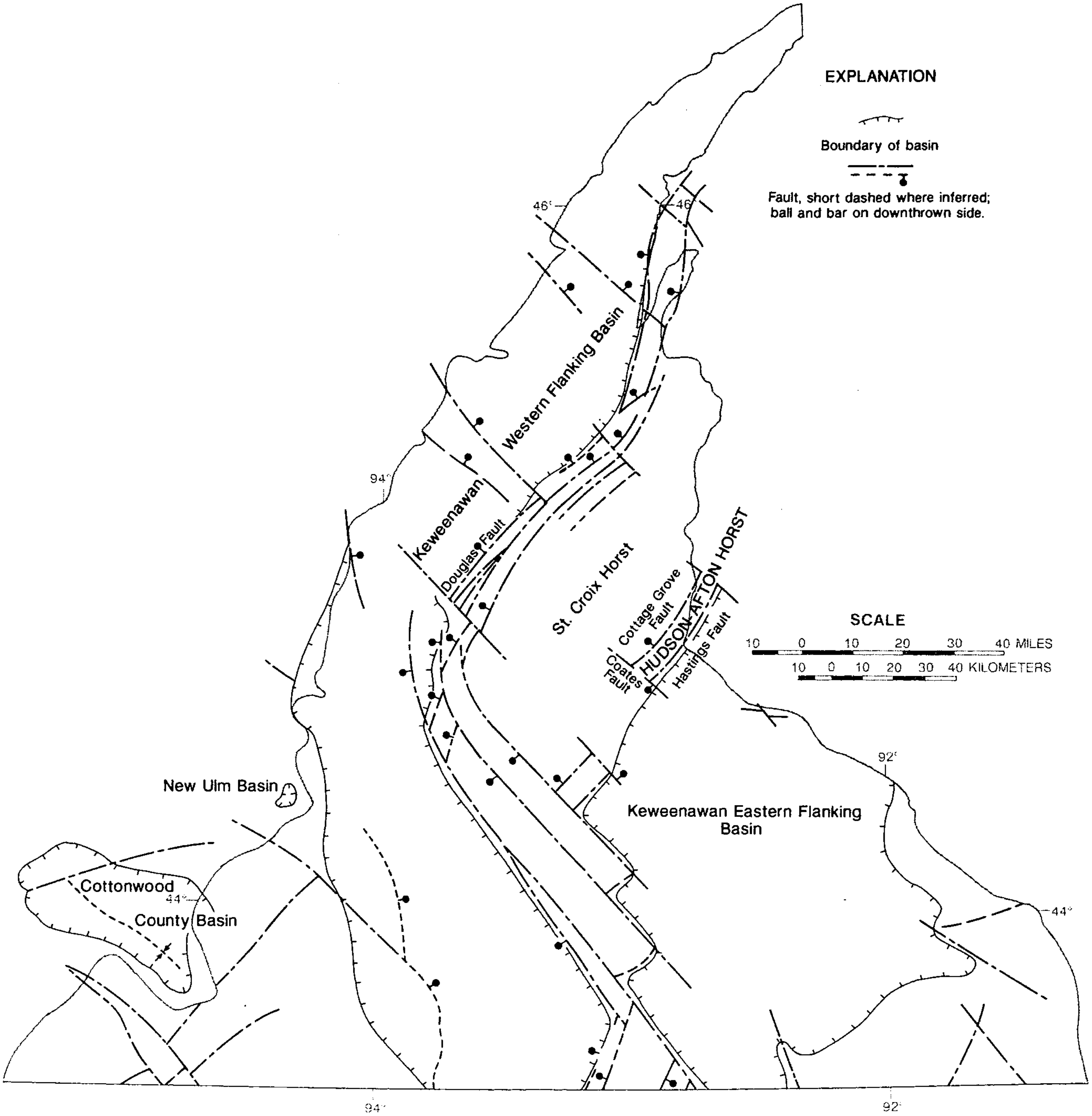

Figure 2. Basement tectonic and structure map. Modified from MGS data used by Sims (1990). The rocks in the Cottonwood County and New Ulm basins are Sioux Quartzite and were not part of this study.

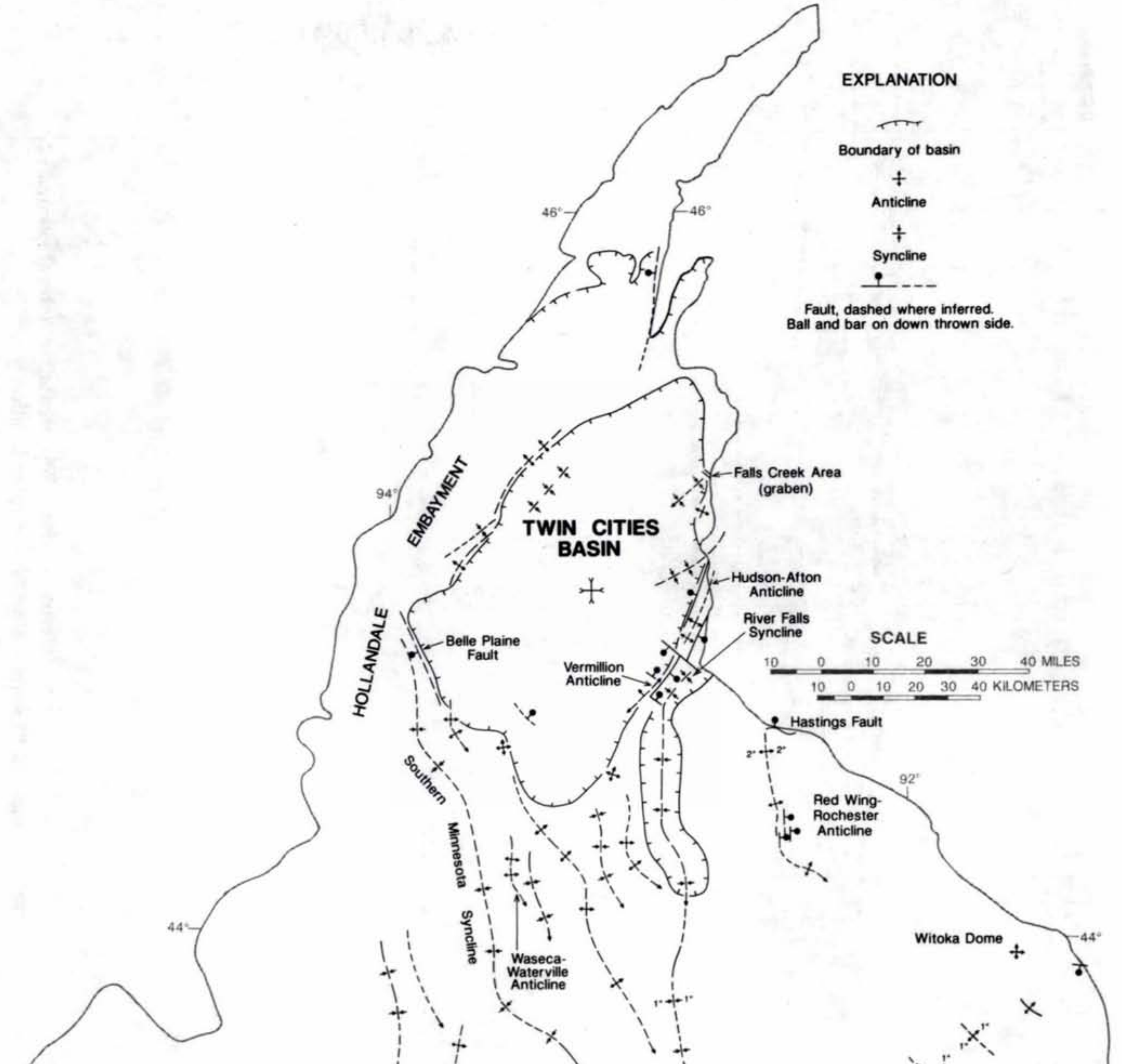

Figure 3. Paleozoic tectonic and structure map. Modified from MGS data used by Anderson (1988).

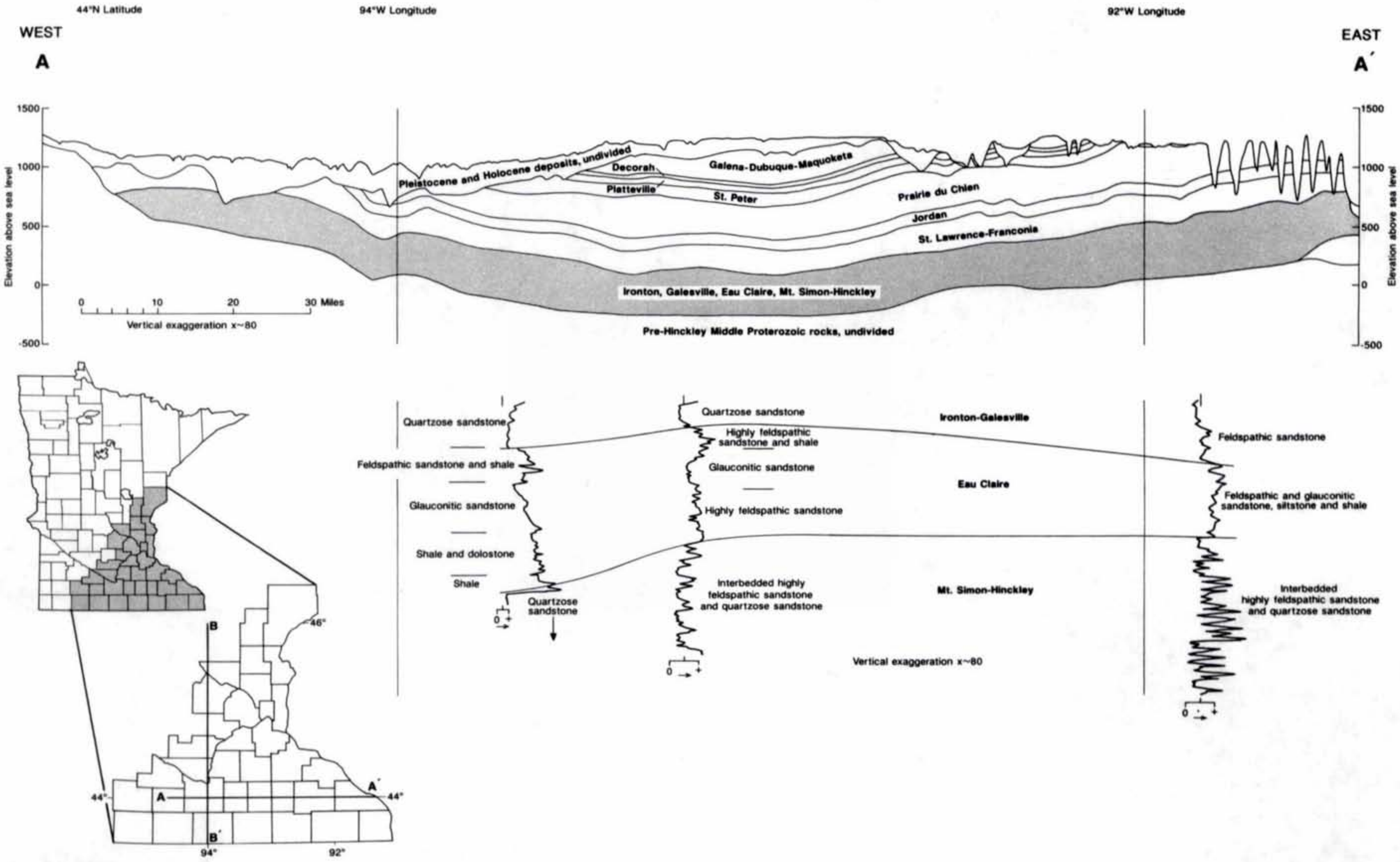

Figure 4. West-east Paleozoic basin cross section. Representative natural gamma-ray geophysical logs not to same scale or geographic location.

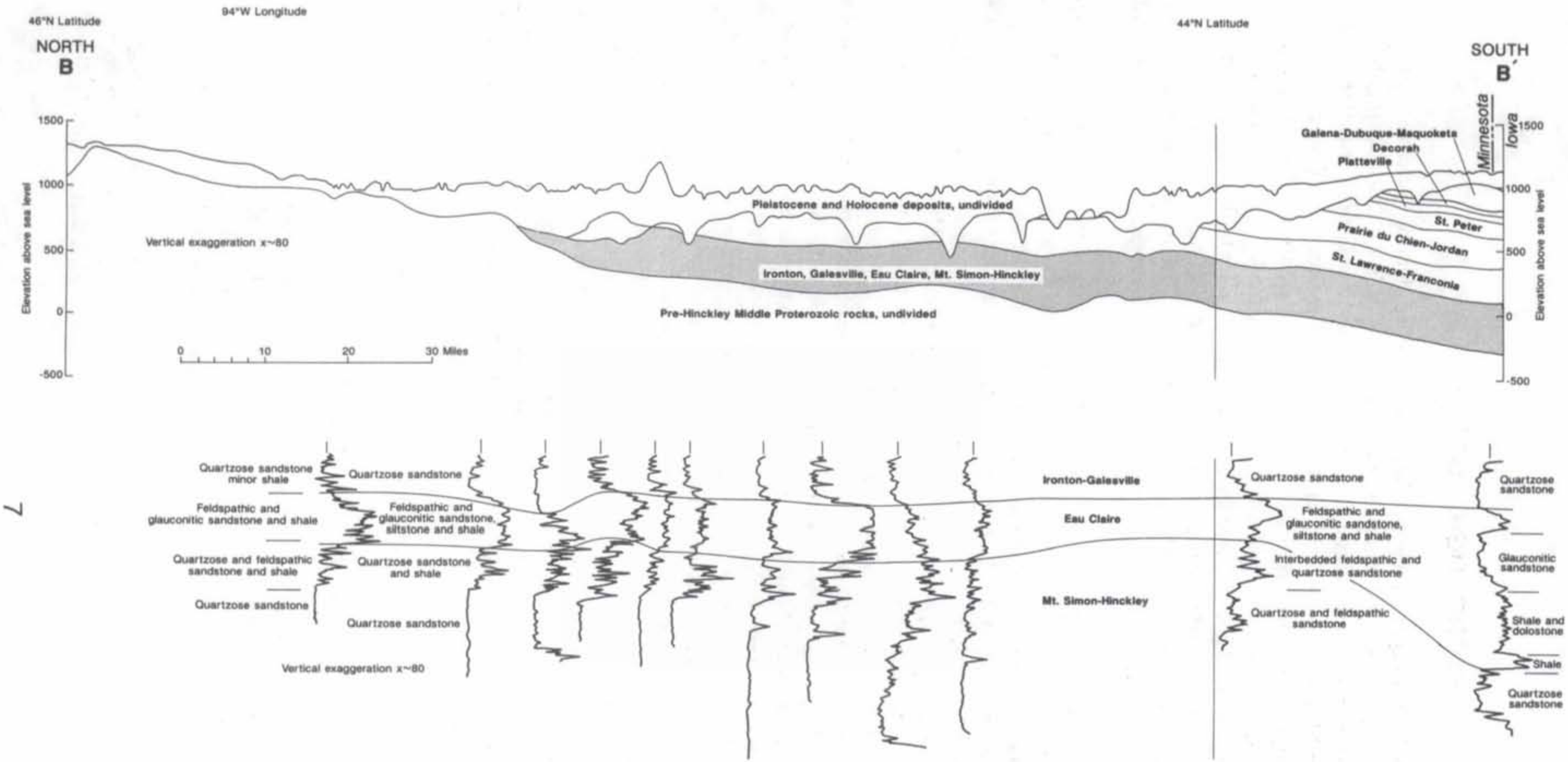

Figure 5. North-south Paleozoic basin cross section. Representative natural gamma-ray geophysical logs not to same scale or geographic location.

HYDROLOGIC SETTING

The Mt. Simon-Hinckley is the deepest of the four bedrock aquifers providing water to southern Minnesota and accounts for at least 10% of the pumped ground water in the Twin Cities Metropolitan Area (Schoenberg, 1989). It is overlain by the regional confining unit, the Eau Claire Formation. The margin of the Mt. Simon-Hinckley outside the limits of the Eau Claire Formation and younger Paleozoic strata (Fig. 1) is a significant source of ground-water recharge into the aquifer. Where the Mt. Simon-Hinckley is deepest, vertical recharge from the land surface is relatively unimportant, except where infiltration occurs around poorly cased wells. If the aquifer were undisturbed, water movement would primarily be lateral within the confines of the aquifer. To enter the aquifer vertically, water would have to pass through confining beds of the Eau Claire Formation; however, the greater hydraulic head in the Mt. Simon-Hinckley implies that vertical leakage, if it occurred, would most likely be upward.

Recently established ground-water ages based on carbon-14 and tritium dating indicate that water near the recharge areas of the Mt. Simon-Hinckley is fairly young (entered the ground since about 1953). Ages gradually become older toward the interior and deeper parts of the basin where some exceed 30,000 years (Alexander and others, 1987). However, there are a number of zones throughout the aquifer where the ages do not fit this simple time-depth relationship. Young surface water mixing with the older aquifer water reduces its age and changes the water chemistry (Alexander and Alexander, 1989; Schoenberg, 1989). Some anomalous situations probably result from older water entering the aquifer, possibly from below the Mt. Simon-Hinckley.

A simple model of uniformly horizontal flow is unlikely to represent real conditions in the aquifer, given the number of high-capacity wells pumping water from the formation, the presence of buried valleys in the bedrock, and the presence of faults and other geologic structures in the Paleozoic rocks. Measurements of water levels in the Twin Cities area over the past 100 years show substantial changes because pumping has affected both the rates and direction of water movement in the aquifer (Schoenberg, 1989). Valleys deeply entrenched into the bedrock surface in the Twin Cities and surrounding area, which now are filled with glacial sediments, provide routes for surface water to penetrate the deeper bedrock aquifers. It is also probable that there are valleys as yet unidentified in the subsurface, which further influence the chemical and recharge conditions in the bedrock aquifers. An even less well understood factor affecting the bedrock aquifers is the presence of faults and structural highs and lows in both the basement and Paleozoic rocks. Local structural highs and lows will influence the directions of ground-water movement. Faults can allow water to move vertically through multiple rock units and through confining layers. In the case of the Mt. Simon-Hinckley, the chemistry of water from still deeper sources is virtually unknown, and it is unclear in what direction water in a fault system is moving. Given the present lack of knowledge about the locations of faults and other structural features, it is also difficult to locate a given well relative to a tectonic feature.

METHODOLOGY

At the time this study was initiated, the Minnesota Department of Health had identified 14 municipal water-supply systems with radium levels above the limit of 5 pCi/L allowed under the 1976 U.S. EPA Drinking Water Regulations. Most of these communities were obtaining all or a major part of their water from the Mt. Simon-Hinckley, although in western Minnesota, some high radium concentrations were found in water produced from the Sioux Quartzite.

For this study, water samples were collected primarily from sole-source Mt. Simon-Hinckley wells. Sole-source wells are cased and grouted to the top of the aquifer used, to prevent water from aquifers higher in the section from entering the well. One multi-aquifer well that penetrated the Mt.

Simon-Hinckley was sampled in southern Minnesota where no sole-source well was available. Several Jordan wells near high-radium Mt. Simon-Hinckley wells were also sampled. The distribution of municipal wells sampled was intended to be representative of current water usage patterns and to allow extrapolation into areas where Mt. Simon wells are currently scarce.

A total of 66 wells (Fig. 1) were sampled from the Mt. Simon-Hinckley and 7 from the Jordan. Duplicate water samples were collected from several wells, and four were later resampled to check for temporal variation. One of these latter wells had been partially filled to try to reduce existing radium levels. The sampling extends as far north as Hinckley, west to Mankato, and southeast to the Root River and LaCrescent, resulting in a distribution pattern that includes recharge areas, the center of the basin, and the southeastern part of the aquifer. Some wells used in this study were part of a previous study to establish the age of water in the Mt. Simon (Alexander and Alexander, 1989). When possible, these wells were resampled to observe if changes in water chemistry have occurred. Other Mt. Simon wells were selected to expand the range of ground-water age information, as well as to investigate the distribution of radium. The study covers most of the aquifer where sampling by the Minnesota Department of Health showed high radium levels in community water supplies. Sampling density was dependent upon the distance between communities with suitable Mt. Simon wells, the number of these wells in use, and the degree to which additional sampling might be used to test for localized variations. It should also be noted that in a large area across southern Minnesota municipal wells do not penetrate to the Mt. Simon, but are producing water from overlying aquifers. In this area, the Mt. Simon was accessible for sampling only at one multi-aquifer well, and thus we know very little about the chemistry or radium levels.

The samples collected for this project were ground waters from municipal and selected industrial wells, and one private residential well. Unfortunately, we could not obtain rock samples from the same wells. Mt. Simon rock samples from the MGS core and cuttings library, together with representative samples of Jordan Sandstone, were analyzed for trace elements including uranium and thorium at X-Ray Assay Laboratories in Ontario. The mineralogical composition of the powdered rock samples was determined by X-ray diffraction analysis at the Department of Geology and Geophysics at the University of Minnesota. Many of the wells also had geophysical logs, where the combined gamma activity from the radioactive decay of uranium, thorium, and potassium within the rock was measured as a function of depth. Some of these logs were used to prepare the lithologic cross sections of the study area (Figs. 4 and 5). The available equipment could not differentiate between the radiation from the three decay series, and by themselves, total gamma activity logs cannot unequivocally identify zones of enhanced radium in the water.

Water sampling consisted of two parts, (1) measurements made in the field and (2) collection of water for laboratory analyses. A summary of the procedures is given in the appendix. Duplicate samples were collected at the beginning of the sampling and at random intervals throughout the study. Water chemistry was analyzed at the Department of Geology and Geophysics at the University of Minnesota; uranium and polonium were measured at the Minnesota Geological Survey laboratory, and radon at St. John's University. Radiocarbon (^{14}C and δ^{13}C) analyses were obtained from Beta Analytic, Inc., and tritium (^{3}H) analyses from the Isotope Laboratory at the University of Waterloo, Ontario. The radium isotopes and the gross alpha and beta activities were measured at the Wisconsin State Laboratory of Hygiene, which is a U.S. EPA-certified laboratory for radium analyses.

RESULTS

Tables 1-6 present the results of the X-ray mineralogy and the trace-element analyses of the rock samples. Figures 6 and 7 show the stratigraphic distribution of uranium and thorium in core from two locations. It is apparent from the data that some stratigraphic horizons are more enriched than others.

Table 1. Analyses of Mt. Simon Sandstone core from the ATES BC-1 well in St. Paul
[See Figure 1 for location; EC = sample from Eau Claire Formation]

Sample number	1-EC	2	3	4	5	6	7
Depth (ft)	860	865	883	895	904	914	920
			X-ray diffraction analyses [Results in weight percent; "-" = not detected]				
Quartz	90	90	75	95	95	90	50
K-Spar	10	-	25	5	5	10	50
Dolomite	-	-	-	-	-	-	-
Calcite	-	-	-	-	-	-	-
Apatite	-	-	-	-	-	-	-
Siderite	-	10	-	-	-	-	-
Mica	-	-	-	-	-	-	-
Mixed-layer clay	-	-	-	-	-	-	-
Phlogopite	-	-	-	-	-	-	-
			Trace-element analyses [Results in parts per million]				
Li	8	2	12	4	17	5	29
Be	3.7	1	2.9	1.4	3.7	1.4	8.2
B	16	1	35	3	11	14	132
Sc	3.9	0.9	3.8	1	6.4	1.8	9.4
V	31.6	25.1	27.4	4.3	50.6	12	104
Cr	432	539	248	399	270	308	144
Co	12	19	4	2	11	2	28
Ni	11	16	0.5	7	18	7	55
Cu	97.9	66.3	104	10	21.3	10.2	59.8
Zn	23.2	30.4	13.7	5	28.1	6.5	59.6
As	4	2	2	2	8	2	12
Se	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sr	95.4	89.1	90.4	37.6	92.8	42.9	92.4
Y	20	20.9	13.7	5.7	15.9	4.8	15.5
Zr	87.8	19.1	223	108	263	84.8	166
Mo	27	27	15	32	17	23	4
Ag	0.1	0.1	0.9	0.1	1.2	0.2	0.8
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Ba	233	80	863	194	885	244	574
W	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Pb	1	9	< 2	< 2	< 2	< 2	9
Th	7.2	3.6	6.3	2.2	5.8	3.5	16
U	1.6	1.7	1.9	0.7	1.4	0.8	3.2

Table 2. Analyses of Mt. Simon Sandstone core from the Vermillion 66-9 well

[See Figure 1 for location; sh = shale layer]

Sample number	1	2	3	4	5	6-sh	7	8-sh	9	10-sh	11
Depth (ft)	627	638	674	690	706	754	777.5	834	910	917	926
X-ray diffraction analyses [Results in weight percent; "-" = not detected]											
Quartz	15	97.5	97.5	90	100	95	85	-	100	20	-
K-Spar	15	2.5	2.5	10	-	2.5	15	-	-	15	-
Dolomite	70	-	-	-	-	-	-	-	-	-	-
Calcite	-	-	-	-	-	2.5	-	-	-	-	-
Apatite	-	-	-	-	-	-	-	-	-	-	-
Siderite	-	-	-	-	-	-	-	-	-	-	-
Mica	-	-	-	-	-	-	-	-	-	25	-
Mixed-layer clay	-	-	-	-	-	-	-	50	-	40	-
Phlogopite	-	-	-	-	-	-	-	50	-	-	-
Trace-element analyses [Results in parts per million]											
Li	16	2	5	8	2	3	14	78	6	78	3
Be	4.1	0.7	0.25	1	0.25	0.25	1.7	11.5	1	11.3	0.25
B	69	5	17	21	2	13	53	15	5	161	6
Sc	6.2	1.9	1.6	1.5	0.7	0.3	4.7	10.7	0.7	7.9	0.7
V	24.8	23.2	18.4	12.5	5.6	5.8	43	110	10.9	158	14.2
Cr	123	347	462	383	453	352	326	168	576	134	303
Co	8	8	4	3	2	2	5	27	2	29	3
Ni	9	15	5	3	8	8	2	50	7	68	8
Cu	8.1	33.3	16.6	14.6	10.6	10.6	38.5	27.1	16	17.4	25
Zn	24	22.6	8.9	8.9	7.4	7.4	18.8	85.9	7.7	87.2	22.8
As	11	7	2	5	4	2	< 3	9	2	2	2
Se	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sr	90.6	206	84	79.2	48	29.4	96.7	118	10.1	57.1	16.5
Y	16.7	46.1	7.1	4.7	3.4	1.2	5	6.1	4.3	5.4	2.8
Zr	108	26.4	84.9	84.4	65.6	23.4	121	117	83.2	109	23.1
Mo	6	26	33	25	34	25	21	21	39	0.5	21
Ag	0.6	0.05	0.05	0.05	0.2	0.05	0.05	0.05	0.05	0.05	0.1
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	12	12
Ba	401	68	280	655	106	111	882	370	23	212	19
W	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Pb	6	15	7	3	7	3	9	6	1	1	1
Th	9.4	6.5	2.3	2.1	1.7	1.2	3.9	14	2.3	10	1
U	1.9	2.1	1.1	0.8	0.9	0.25	1.5	1.8	0.7	2.4	0.6

Table 3. Analyses of Mt. Simon Sandstone core from the Northern Natural Gas test well 14 (NNG-337)
[See Figure 1 for location; EC = sample from Eau Claire Formation]

Sample number	1-EC	2	3	4	5	6	7
Depth (ft)	470	484	487	498	519	524	623
X-ray diffraction analyses [Results in weight percent; "-" = not detected]							
Quartz	75	85	60	85	90	90	90
K-Spar	25	-	-	15	10	10	10
Dolomite	-	5	-	-	-	-	-
Calcite	-	-	-	-	-	-	-
Apatite	-	-	-	-	-	-	-
Siderite	-	5	40	-	-	-	-
Mica	-	-	-	-	-	-	-
Mixed-layer clay	-	-	-	-	-	-	-
Phlogopite	-	-	-	-	-	-	-
Trace-element analyses [Results in parts per million]							
Li	15	2	5	9	6	10	9
Be	3	2.3	4.8	2.8	0.8	2.6	2.9
B	16	4	1	72	8	28	21
Sc	3.4	3	2.9	2.3	0.9	3.4	2.8
V	9.8	79.5	214	32.2	3.8	54.7	25.8
Cr	252	221	142	245	311	364	243
Co	5	18	18	8	2	23	5
Ni	1	9	19	8	3	19	5
Cu	28.3	20	14.5	21.2	23	24	30.1
Zn	13.1	23.8	54.3	16.4	28.3	33	23.9
As	7	9	21	2	2	5	2
Se	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sr	254	344	300	56	53.8	70	59
Y	12.2	64	80.6	13.8	5.9	12.4	8.1
Zr	157	16.3	69.3	257	81	176	125
Mo	17	16	6	17	24	25	18
Ag	0.3	0.1	0.1	1	0.2	0.7	0.3
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Ba	766	46	58	464	405	383	548
W	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Pb	1	18	27	4	< 2	2	< 2
Th	5.9	7.9	10	5.5	2.1	3.8	3.1
U	1.1	5.5	4.4	1.8	0.5	2.1	1.1

Table 4. Analyses of Mt. Simon Sandstone core from Minnegasco well W-4
[See Figure 1 for core location]

Sample number	1	2	3	4	5	6	7
Depth (ft)	875	886	898.5	918	925.5	937	950
X-ray diffraction analyses [Results in weight percent; "-" = not detected]							
Quartz	85	97.5	95	85	97.5	85	100
K-Spar	-	2.5	5	15	-	7.5	-
Dolomite	10	-	-	-	2.5	7.5	-
Calcite	-	-	-	-	-	-	-
Apatite	5	-	-	-	-	-	-
Siderite	-	-	-	-	-	-	-
Mica	-	-	-	-	-	-	-
Mixed-layer clay	-	-	-	-	-	-	-
Phlogopite	-	-	-	-	-	-	-
Trace-element analyses [Results in parts per million]							
Li	5	3	4	20	4	9	2
Be	2.9	1.3	1.7	5.3	1.8	3.5	0.9
B	31	12	11	30	8	23	4
Sc	15.5	1	2	5.4	4.4	4.9	0.4
V	17.6	4.3	1.2	45.5	12.4	17.9	4.6
Cr	79	380	317	139	233	183	330
Co	6	2	2	12	5	7	1
Ni	2	0.5	0.5	11	2	6	0.5
Cu	13.3	11	11.3	14.8	10	21.7	6.9
Zn	11.3	6	4.7	20.7	5.8	13.7	3.2
As	14	2	4	2	7	2	2
Se	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sr	360	73.2	107	168	129	193	53.8
Y	139	35	36	13.8	40.3	15	5.2
Zr	32.4	54.6	71.3	176	23.5	180	23
Mo	6	30	23	7	16	12	24
Ag	0.1	0.1	0.2	0.6	0.1	0.3	0.1
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Ba	315	929	551	599	468	360	426
W	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Pb	1	1	4	1	1	2	3
Th	10	9.5	11	7.9	5.1	7.4	3.1
U	4.6	0.9	1.3	1.5	1.6	1.3	0.8

Table 5. Analyses of Mt. Simon Sandstone core from Pan Ocean SQ-8

[See Figure 1 for core location. R = regolith]

Sample number	1	2	3	4	5-R
Depth (ft)	320	356	385	420	429
X-ray diffraction analyses [Results in weight percent; "-" = not detected]					
Quartz	100	90	75	97.5	75
K-Spar	-	-	25	2.5	25
Dolomite	-	-	-	-	-
Calcite	-	10	-	-	-
Apatite	-	-	-	-	-
Siderite	-	-	-	-	-
Mica	-	-	-	-	-
Mixed-layer clay	-	-	-	-	-
Phlogopite	-	-	-	-	-
Trace-element analyses [Results in parts per million]					
Li	3	3	9	4	30
Be	0.1	0.1	2.5	0.7	2.9
B	5	4	27	6	100
Sc	0.5	0.7	4.5	0.9	2.7
V	4.4	6.2	42.7	6.4	29.7
Cr	272	361	235	453	126
Co	0.5	1	5	2	3
Ni	6	6	2	4	< 1
Cu	8.5	8.5	7.9	7.5	3.2
Zn	6.8	6.8	15.6	8.5	15.9
As	2	5	2	2	< 3
Se	< 20	< 20	< 20	< 20	< 20
Sr	22.4	34.2	60.7	25.2	37.1
Y	2	3.3	8.1	3.3	2
Zr	29.5	29.4	179	60.2	87.5
Mo	21	27	16	30	7
Ag	0.4	0.1	0.05	0.05	< 0.1
Cd	< 1	< 1	< 1	< 1	< 1
Sn	< 10	< 10	< 10	< 10	< 10
Sb	< 5	< 5	6	< 5	< 5
Ba	33	50	618	139	528
W	< 10	< 10	< 10	< 10	< 10
Pb	6	1	4	3	< 2
Th	1.3	2.6	7.4	5.1	2.5
U	0.5	1.1	1.6	1.6	0.5

Table 6. Analyses of representative Jordan Sandstone rock samples

[Locations are not shown on Figure 1]

Twp, Rge, Sec.	30-20-14					112-14-18	112-13-27	111-11-36	103-24-28
Sample	B	F	G	J	L	O	R	S	T
X-Ray diffraction analyses [Results in weight percent. "-" = not detected]									
Quartz	100	82.5	95	80	82.5	35	100	35	82.5
K-Spar	-	7.5	5	20	7.5	10	-	10	17.5
Dolomite	-	7.5	-	-	7.5	55	-	55	-
Calcite	-	2.5	-	-	2.5	-	-	-	-
Trace-element analyses [Results in parts per million]									
Li	6	6	4	14	4	7	2	7	3
Be	0.25	1	0.25	1.1	1.4	2.6	0.25	1.9	1
B	2	1	1	1	6	1	1	1	1
Sc	0.3	3.8	0.2	0.9	3.1	2.4	0.3	2.6	0.2
V	0.25	8.9	0.25	3.5	7.5	15.9	2.9	7.6	0.25
Cr	2	12	2	9	9	16	3	8	2
Co	0.5	3	0.5	0.5	2	3	0.5	2	0.5
Ni	2	0.5	0.5	0.5	0.5	3	2	3	4
Cu	1.5	15.6	1.8	3	7.8	6.9	0.7	6.3	3
Zn	15.5	16.4	2.6	3.4	12.9	25.4	3.3	3.7	3.4
As	4	2	2	7	13	5	3	6	8
Se	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sr	25.3	119	39.2	92.8	58.5	58.5	8.7	72.8	26.4
Y	3.7	6	1.1	4.4	5.3	5.3	1.3	7.1	3.5
Zr	17.9	71.2	17.8	78	81.7	81.7	14.3	27.6	7.4
Mo	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ag	0.2	0.2	0.2	0.05	0.05	0.3	0.2	0.2	0.2
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Ba	64	600	320	929	541	301	23	405	13
W	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Pb	6	21	1	10	8	5	4	14	1
Th	< 2	3	< 2	2	< 2	5	< 2	3	< 2
U	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2

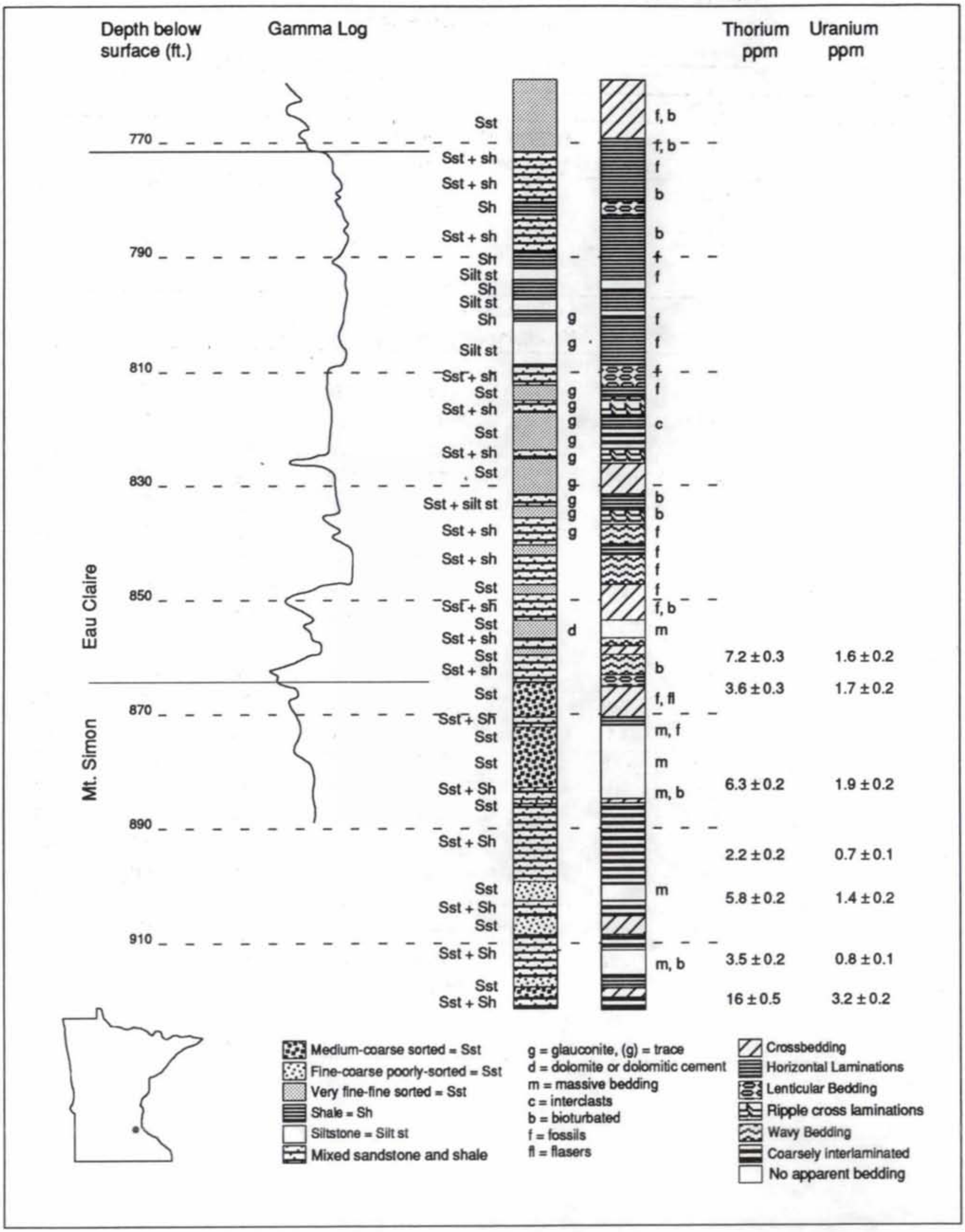

Figure 6. Graphic column (from Mossler, 1992) based on core from the ATES BC-1 well in St. Paul. Concentrations of uranium and thorium are shown at the depths corresponding to the core sample analyzed.

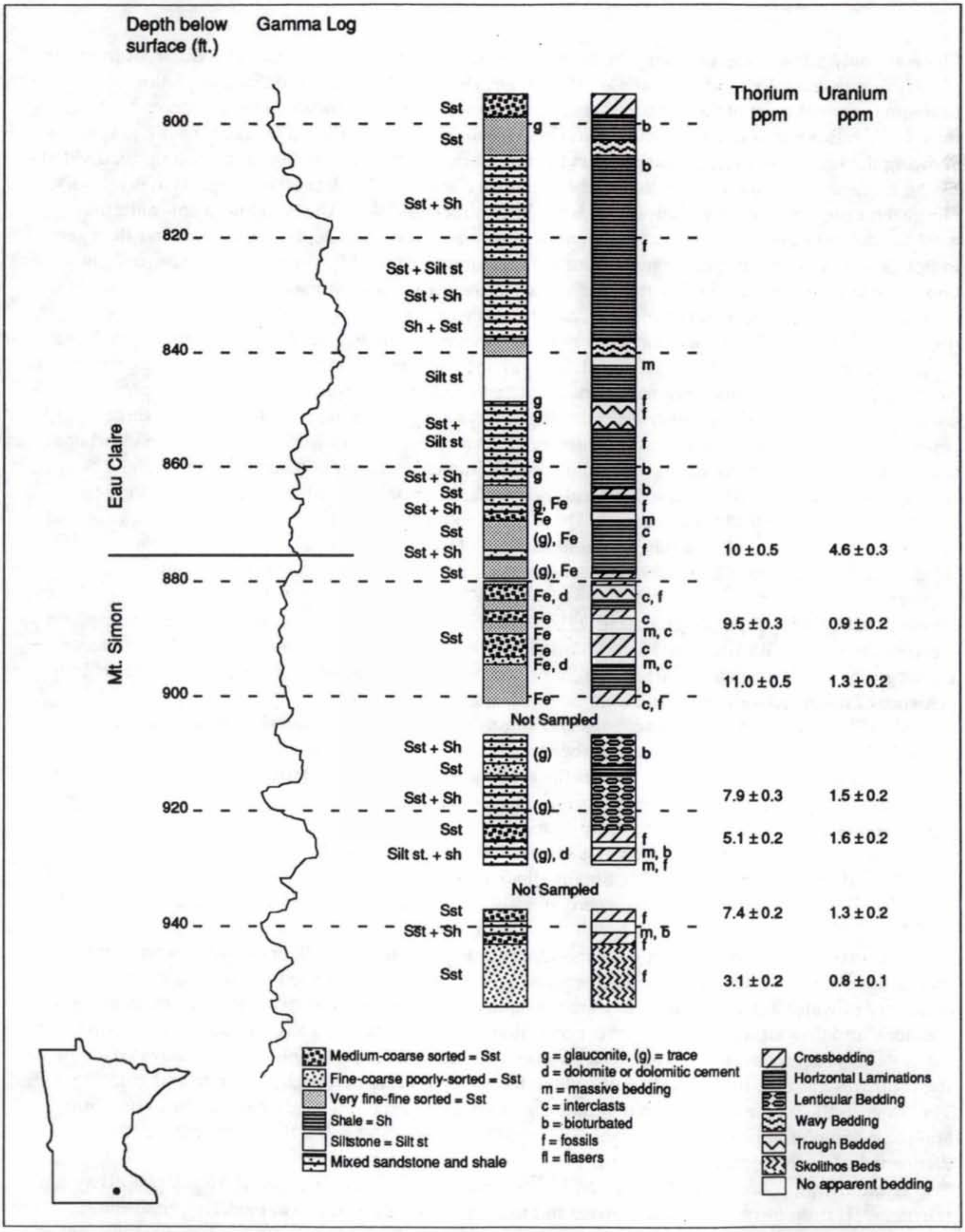

Figure 7. Graphic column (from Mossler, 1992) based on core from Minnegasco well W-4 in northern Waseca county. Concentrations of uranium and thorium are shown at the depths corresponding to the core sample analyzed.

There are only a few samples where the ratio of thorium to uranium is substantially different from that of the average crustal abundance ratio of 3.7 (Taylor, 1964). Higher ratios indicate depletion of uranium (or enrichment of thorium) and are from beds containing appreciable iron carbonate or shale. Low Th/U ratios are from zones with relatively low contents of both Th and U. Figure 8 is a graph showing the log of the average trace-element concentration in the five Mt. Simon core samples, divided by the average concentration reported in the literature (Faure, 1991). A similar comparison is shown in Figure 9 for the trace-element analyses from the Jordan rock samples. The zero line, a concentration ratio of one, indicates no relative enrichment; less than zero indicates depletion, and greater than zero indicates relative enrichment. Uranium and thorium in rock of the Mt. Simon Sandstone are slightly above the average and are higher than the values in the Jordan Sandstone.

Results of the chemical, radiological, and trace-element analyses of the water samples are presented in Tables 7-9. The water chemistry for the major cations and anions is summarized on the Piper diagrams of Figures 10 and 11. In Mt. Simon-Hinckley samples, cation compositions range from predominantly calcium- and magnesium-rich waters to sodium-rich waters. The trend appears continuous, with no obvious outliers or clustering. The anion plot is more complex, showing three separate trends. All three trends can be interpreted as modifications of calcium-magnesium bicarbonate waters. One trend corresponds to the addition of a sodium-chloride component. A second trend corresponds to the addition of a sodium-chloride-sulfate component with a distinctive chloride-to-sulfate ratio of about 60:40 (atomic units). These two trends correspond to the sodium-enrichment trend seen in the cation data and probably represent varying admixtures of brines from unknown sources. The third anion trend is one of increasing calcium-sulfate and presumably results from the solution of gypsum.

As shown in the Piper diagram (Fig. 11), the seven Jordan samples indicate a calcium-magnesium bicarbonate water with little sulfate or chloride. Given the limited distribution of wells sampled, these results cannot be extrapolated with confidence to the entire aquifer. Nonetheless, there is little evidence of major chloride or sulfate components in the Jordan aquifer.

The distributions of the major cations and anions in the Mt. Simon-Hinckley water are shown in Figures 12-16. Sulfate, chloride, and bicarbonate show a geographic pattern of predominantly bicarbonate waters in the northern part of the study area and sulfate-chloride-rich waters in the west-central, southwestern, and southeastern parts of the study area. Chloride distribution is more erratic than that of sulfate. Calcium is uniformly distributed over much of the study area, except for the southwestern group of samples, where it is somewhat more abundant.

The radiological analyses for Mt. Simon-Hinckley waters (Table 7) include uranium concentrations and $^{234}U/^{238}U$ activity ratios; ^{222}Rn where available; ^{210}Po; and the age of the water based on analysis of ^{14}C.

The areal distribution of uranium concentration (Fig. 17) in the Mt. Simon-Hinckley aquifer and that of the $^{234}U/^{238}U$ activity ratio for the same wells (Fig. 18) are affected by the age, depth, and chemistry of water in the aquifer. They are useful in delineating possible oxidation and reduction zones (Osmond and Cowart, 1976). Uranium concentrations in the aquifer tend to be greater in the north where the water is younger than 1953 and has a Ca-Mg-HCO_3 composition. Uranium is also elevated along the southwestern side of the study area, where the water is older and high in sulfate and chloride. The water in the center of the basin and in the southeastern part of the study area is low in uranium, and some samples approach levels where the uranium in the water could not be effectively distinguished from detector background.

Ground waters are typically enriched in ^{234}U relative to ^{238}U because recoil from alpha decay can transfer ^{234}U from the solid to liquid phase and make ^{234}U more accessible to oxidizing conditions, thereby increasing its geochemical mobility. In some waters the activity ratio can be very high, but generally it is between 1 and 3 (Hess and others, 1985; Osmond and Cowart, 1976). In the Mt. Simon-

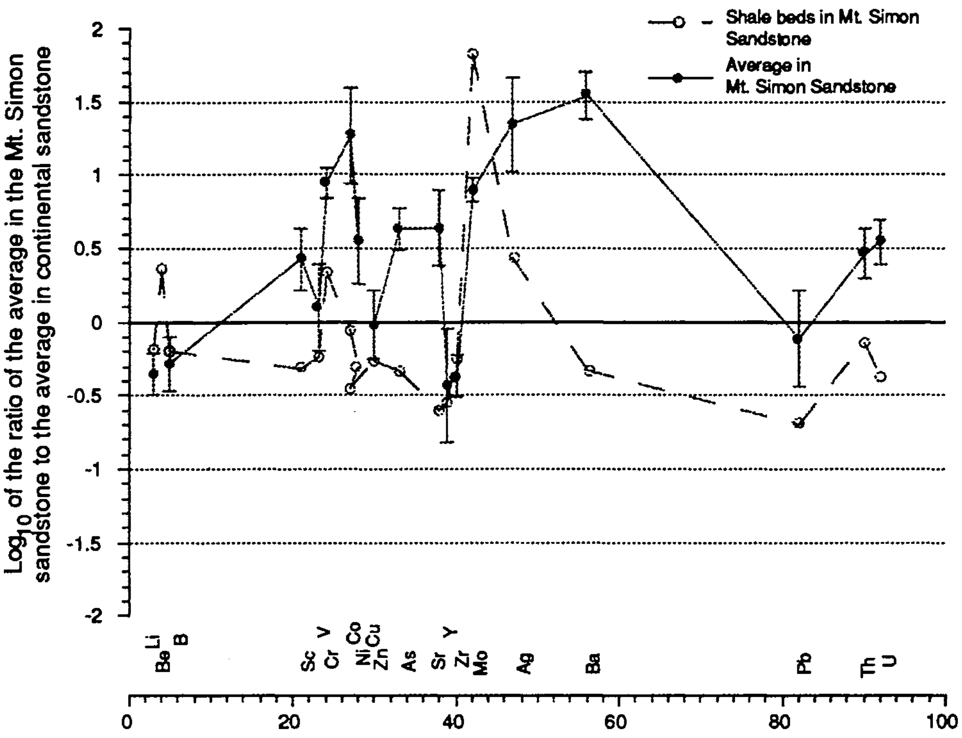

Figure 8. Enrichment diagram of selected trace elements in the Mt. Simon Sandstone. The plot is the log of the ratio of the average trace-element concentration relative to average sandstone values in the literature (Faure, 1991). Error bars, standard deviation of the analyses for each element.

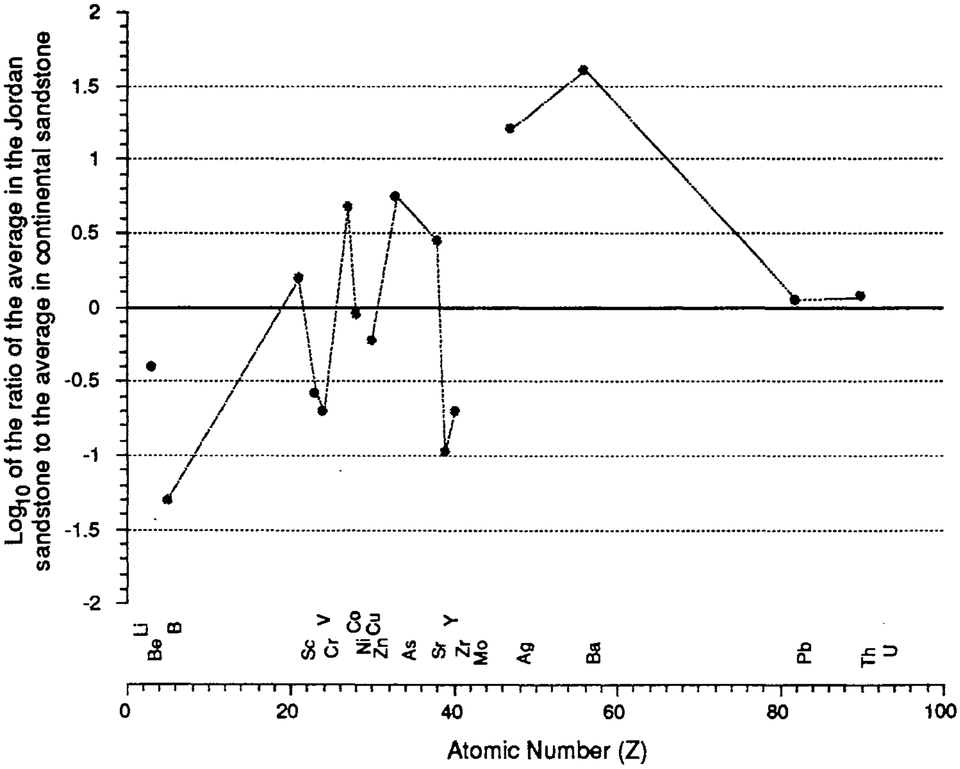

Figure 9. Enrichment diagram of selected trace elements in the Jordan Sandstone. The plot is the log of the ratio of the average trace-element concentration relative to average sandstone values in the literature (Faure, 1991).

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer

[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	1	2	3	4	5	6	7	8
Unique number	241991	232461	NA	217883	151559	219418	217868	217924
Well name and number	Hinckley 1	Hinckley 2	Hinckley Creamery	Braham 2	Rush City 4	Cambridge 2	Cambridge 3	Harris 1
Well depth (ft)	425	452	274	193	220	324	630	326
Field measurements and chemical analyses [Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]								
Date sampled	10/23/90	11/8/89	11/8/89	11/8/89	10/23/90	12/11/89	11/8/89	10/23/90
Temperature °C	9.0	8.0	8.9	8.5	9.7	9.3	9.4	8.8
pH	7.02	7.02	7.46	7.36	7.60	7.50	7.29	7.73
Conductivity	402	580	550	750	561	760	760	523
D. O.	1.70	0.40	3.68	0.41	1.40	0.13	0.28	2.85
Ca	44.0	43.8	44.6	66.4	65.4	65.0	63.8	49.9
Mg	17.0	17.4	15.5	23.1	34.3	23.0	22.4	24.6
Na	9.6	7.5	7.4	3.6	29.0	3.6	3.6	9.8
K	2.0	1.5	1.1	1.7	5.2	1.5	1.7	2.2
Fe	1.9	2.6	0.4	0.1	0.3	0.3	0.4	0.4
Mn	0.12	0.13	0.05	2.05	0.29	0.54	0.35	0.45
Sr	0.090	0.092	0.064	0.130	0.520	0.130	0.121	0.154
Ba	0.100	0.118	0.042	0.080	0.078	0.030	0.038	0.097
SiO2	13.1	12.1	21.8	22.2	15.9	22.2	20.3	13.5
HCO3	224	228	205	332	339	325	310	338
Cl	8.1	5.1	4.5	1.4	58.4	0.6	0.5	1.2
NO3-N	0.69	0.31	0.75	< 0.005	< 0.005	< 0.005	< 0.005	0.007
SO4	13.1	8.3	13.8	0.1	6.6	2.3	3.1	2.2
TDS	334	328	318	453	556	444	428	442
Radioactivity analyses [Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953; 1 part per billion (ppb) uranium = 0.333 pCi/L]								
U (ppb)	0.85	0.59	1.06	2.35	4.56	0.174	0.177	1.51
234U/238U activity ratio	2.4	2.76	2.07	2.7	1.39	6.3	6.4	1.81
226Ra (pCi/L)	5.2	5.7	2.6	1.4	9.4	4.7	8.8	2.3
228Ra (pCi/L)	8	8	4.4	2	4.5	4.8	9.3	6
Rn (pCi/L)	nm	1974	nm	448	nm	352	621	nm
Po (pCi/L)	0.18	0.19	0.10	0.18	0.94	0.07	0.07	0.06
Gross alpha (pCi/L)	13	20	5	7	18	18	25	10
14C (fraction of modern)	nm	0.266	0.647	0.679	nm	0.541	0.541	nm
δ13C (per mil)	nm	-15.4	-16.8	-9.79	nm	nm	-13.2	nm
Age	nm	5200	recent	recent	nm	recent	recent	nm

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	9	10	11	12	13	14	15	16
Unique number	217922	112244	163648	211176	184885	209223	217915	217901
Well name and number	N. Branch 1	N. Branch 2	Big Lake 3	Elk River 3	St. Francis 2	Castle Towei 1	Stacy 1	Wyoming 2
Well depth (ft)	762	733	300	315	421	505	495	701

Field measurements and chemical analyses
[Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]

Date sampled	12/11/89	12/11/89	12/18/89	12/18/89	11/8/89	10/26/89	12/11/89	12/11/89
Temperature °C	9.6	9.4	10.2	8.9	9.3	10.1	9.3	10.1
pH	7.56	7.88	7.71	7.60	7.10	7.60	8.01	7.85
Conductivity	780	790	910	510	790	560	740	500
D. O.	0.03	0.43	0.86	0.22	0.62	3.12	0.22	0.50
Ca	61.1	60.2	76.8	50.9	48.8	51.4	58.8	41.6
Mg	22.5	23.8	24.9	17.6	16.4	16.7	21.2	12.5
Na	9.9	10.0	7.4	2.6	27.3	4.7	12.1	5.2
K	2.6	2.3	1.8	1.3	2.4	2.0	1.9	1.5
Fe	1.0	0.6	0.1	0.7	1.1	0.5	0.2	0.6
Mn	0.11	0.20	0.19	0.11	0.03	0.40	0.27	0.11
Sr	0.205	0.201	0.137	0.086	0.149	0.107	0.136	0.096
Ba	0.049	0.060	0.081	0.056	0.116	0.038	0.052	0.041
SiO2	16.9	19.3	20.2	15.3	15.2	21.6	16.1	13.0
HCO3	324	335	310	252	225	253	306	207
Cl	4.6	2.7	29.9	0.6	45.6	1.5	2.7	0.7
NO3-N	< 0.005	< 0.005	0.970	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
SO4	2.0	1.7	21.1	5.6	6.7	2.0	5.2	3.1
TDS	445	456	496	347	389	354	425	286

Radioactivity analyses
[Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953;
1 part per billion (ppb) uranium = 0.333 pCi/L]

U (ppb)	0.174	nm	1.87	0.141	0.026	1.1	1.45	0.015
234U/238U activity ratio	4.5	nm	1.67	3.9	4.3	1.53	2.95	4.3
226Ra (pCi/L)	< 1.0	< 1.0	< 1.0	1.4	5.8	< 1.0	3.3	1.4
228Ra (pCi/L)	< 1.0	< 1.0	2.3	1.5	6.2	< 1.0	4.6	1.6
Rn (pCi/L)	2281	1477	459	150	165	405	183	323
Po (pCi/L)	nm	0.09	0.39	0.07	0.26	0.06	0.18	0.11
Gross alpha (pCi/L)	3	2	4	3	21	3.8	17	8
14C (fraction of modern)	0.548	nm	0.814	0.703	0.229	0.571	0.338	0.361
δ 13C (per mil)	-12.9	nm	-9.7	-12.8	-9.5	-11.4	-13.0	-9.4
Age	recent	nm	recent	recent	6500	recent	3200	2700

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	17	18	19	20	21	22	23	24
Unique number	201191	224625	453792	171011	415932	431683	110469	409524
Well name and number	Anoka 4	Anoka 6	Anoka 7	Andover 1	Andover 2	Andover 3	Coon Rapids 18	Champlin 5
Well depth (ft)	657	640	485	601	525	547	640	550

Field measurements and chemical analyses
[Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]

Date sampled	10/12/89	10/12/89	1/22/90	10/6/89	10/6/89	10/6/89	10/12/89	10/26/89
Temperature °C	11.5	11.8	10.0	10.2	9.8	10.0	11.2	9.6
pH	7.43	7.27	7.60	7.52	7.46	7.40	7.60	7.45
Conductivity	730	730	600	1580	1360	680	650	810
D. O.	0.45	0.14	1.39	1.17	0.18	0.34	0.21	0.10
Ca	61.4	57.3	61.6	69.1	55.9	53.6	57.2	64.1
Mg	18.6	18.5	19.8	24.2	20.5	16.9	18.3	24.5
Na	14.8	19.5	30.4	117.7	74.9	6.4	11.8	24.1
K	3.2	3.7	4.5	7.3	5.2	2.5	3.1	3.9
Fe	0.8	1.1	1.2	1.2	1.1	0.9	0.9	1.0
Mn	0.04	0.03	0.03	0.03	0.03	0.17	0.09	0.03
Sr	0.248	0.258	0.325	0.612	0.299	0.172	0.236	0.327
Ba	0.371	0.228	0.303	0.222	0.199	0.133	0.127	0.140
SiO2	9.8	10.7	11.0	10.3	10.9	11.6	9.9	9.5
HCO3	269	249	260	261	277	277	296	324
Cl	32.1	38.6	67.9	247.0	120.0	1.4	6.6	14.4
NO3-N	0.010	0.006	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
SO4	3.9	5.6	6.3	12.9	10.0	0.4	0.9	37.0
TDS	414	405	464	753	577	371	405	504

Radioactivity analyses
[Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953;
1 part per billion (ppb) uranium = 0.333 pCi/L]

U (ppb)	0.051	0.023	0.018	0.023	0.03	0.013	0.005	0.1
234U/238U activity ratio	11.9	16	15.1	9	12.2	6.89	21.2	12.9
226Ra (pCi/L)	8	6.6	7.9	10.1	8.9	4.9	4	6.9
228Ra (pCi/L)	9.3	8.6	6.6	12.2	7.3	3.8	3.9	7.3
Rn (pCi/L)	400	216	115	212	218	214	110	175
Po (pCi/L)	0.66	0.04	0.07	0.07	nm	nm	0.04	0.09
Gross alpha (pCi/L)	30	21	22	38	24	16	15	22
14C (fraction of modern)	0.041	0.074	0.0027	0.024	0.147	0.303	0.292	0.287
δ13C (per mil)	-12.8	-13.0	-13.9	-11.7	-14.8	-10.5	-11.8	-11.8
Age	21000	16000	>35000	24000	10100	4100	4400	4600

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	25	26	27	28	29	30	31	32
Unique number	416093	122250	203022	201158	223722	206716	509083	222880
Well name and number	Champlin 7	Maple Grove 5	Brooklyn Park 2	Fridley 4	G & K Ind.	Mounds View 2	New Brighton 11	White Bear Lake 2
Well depth (ft)	513	715	617	831	930	835	857	970
Field measurements and chemical analyses [Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]								
Date sampled	10/26/89	9/11/90	9/11/90	1/22/90	3/20/90	10/11/90	1/22/90	2/2/90
Temperature °C	9.7	10.4	10.0	11.6	12.9	11.6	11.9	10.9
pH	7.40	7.50	7.20	7.56	7.51	7.62	7.62	7.46
Conductivity	960	1003	630	500	395	1210	430	505
D. O.	0.14	0.16	0.40	0.25	0.40	1.20	0.27	0.39
Ca	72.0	104.0	79.6	53.4	40.1	48.8	47.7	66.7
Mg	31.4	44.1	27.0	17.8	12.9	15.8	15.7	21.6
Na	29.8	35.6	9.5	17.7	17.8	12.2	11.4	5.1
K	5.0	6.1	5.7	5.5	6.1	3.6	4.4	5.2
Fe	1.3	0.1	1.0	0.9	1.3	0.7	0.9	0.5
Mn	0.02	0.03	0.02	0.02	0.02	0.06	0.03	0.04
Sr	4.630	0.640	0.410	0.334	0.305	0.138	0.210	0.217
Ba	0.065	0.030	0.067	0.113	0.114	0.097	0.112	0.072
SiO2	9.9	8.5	9.3	7.4	6.4	8.1	6.8	9.7
HCO3	382	442	332	278	196	258	250	341
Cl	3.2	16.8	2.2	21.8	23.8	7.5	8.3	0.6
NO3-N	< 0.005	< 0.005	< 0.005	< 0.005	0.013	< 0.005	< 0.005	0.009
SO4	66.3	135.3	53.7	3.5	4.4	0.4	2.9	1.5
TDS	602	794	520	407	310	356	349	453
Radioactivity analyses [Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953; 1 part per billion (ppb) uranium = 0.333 pCi/L]								
U (ppb)	0.11	0.168	0.086	0.012	0.013	0.001	0.009	0.081
234U/238U activity ratio	16.8	18.6	10.6	25.9	12.4	26	18.5	12.4
226Ra (pCi/L)	4	3.5	3	4.5	3.2	3.2	3.5	1.5
228Ra (pCi/L)	4.6	5.9	2.8	5.4	4.3	2.7	6.4	2.2
Rn (pCi/L)	195	29	156	124	108	nm	114	202
Po (pCi/L)	0.09	nm	0.53	nm	0.27	0.10	0.11	0.03
Gross alpha (pCi/L)	13	15	11	13	13	10	12	6
14C (fraction of modern)	0.323	0.253	0.143	0.266	0.038	0.213	0.152	0.293
δ13C (per mil)	-12.0	-12.0	-12.8	-12.2	-12.8	-12.5	-12.7	-12.4
Age	3600	5600	10300	5200	21000	7000	9200	4400

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	33	34	35	36	37	38	39	40
Unique number	231885	165595	206456	206588	231882	433259	132256	218993
Well name and number	NSP King 1	Spring Park 3	St. Louis Park 12	Edina 9	Schmidt 6	Inver Grove Hts. 6	Young America 2	Bongards 4
Well depth (ft)	664	790	1098	1130	1051	1044	943	705

Field measurements and chemical analyses
[Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]

Date sampled	2/2/90	3/22/90	2/14/90	2/14/90	2/14/90	3/20/90	5/3/90	5/3/90
Temperature °C	10.4	10.6	10.7	12.0	12.1	11.8	10.2	11.0
pH	7.62	7.35	7.65	7.73	7.56	7.49	7.47	7.50
Conductivity	335	940	570	575	640	420	930	900
D. O.	5.20	0.46	0.35	0.69	0.30	0.71	1.28	2.13
Ca	37.6	132.3	41.2	38.7	51.2	49.5	75.9	57.8
Mg	13.7	53.8	13.8	13.5	18.0	16.5	30.8	24.7
Na	8.6	21.1	26.3	29.1	16.0	15.2	26.6	42.5
K	3.5	5.1	6.9	6.9	6.1	6.4	5.7	5.6
Fe	0.5	3.4	0.6	0.3	1.3	0.8	1.3	0.2
Mn	0.12	0.08	0.02	0.02	0.02	0.02	0.05	0.05
Sr	0.164	0.761	0.434	0.517	0.311	0.343	0.711	0.574
Ba	0.036	0.030	0.324	0.124	0.089	0.066	0.129	0.194
SiO2	10.6	14.9	6.7	6.8	6.8	6.7	8.8	9.7
HCO3	199	521	208	221	230	267	407	324
Cl	12.1	2.0	26.5	20.8	34.8	11.6	2.4	43.4
NO3-N	0.015	0.024	< 0.005	0.019	0.014	0.020	0.010	0.361
SO4	3.0	175.0	12.6	6.5	5.7	4.1	58.5	23.4
TDS	288	930	344	345	371	379	618	533

Radioactivity analyses
[Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953;
1 part per billion (ppb) uranium = 0.333 pCi/L]

U (ppb)	0.006	0.19	0.026	0.012	0.013	0.076	0.066	2.04
234U/238U activity ratio	5.3	8.2	7.3	3.4	9	8.9	12.3	4.76
226Ra (pCi/L)	2	1.2	3.7	3.8	2.4	5.2	3.3	6
228Ra (pCi/L)	6.2	2.4	4.8	3.6	3.5	5.3	3.4	5.7
Rn (pCi/L)	144	157	179	219	282	553	423	773
Po (pCi/L)	0.03	0.22	0.60	0.34	0.31	0.11	0.30	1.01
Gross alpha (pCi/L)	5	6	13	9	7	20	10	18
14C (fraction of modern)	0.3	0.334	0.004	0.03	0.006	0.0019	0.12	0.02
δ13C (per mil)	-9.6	-10.9	-13.4	-13.5	-11.7	-13.8	-14.0	-14.2
Age	4200	3300	>35000	23000	>35000	>35000	12000	27000

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	41	42	43	44	45	46	47	48
Unique number	161435	208816	150359	433275	161421	502689	207994	217801
Well name and number	Chaska 6	Savage 2	Burnsville 11	Eagan 11	Koch Refinery 8	Vermillion 1	Jordan 4	Arlington 2
Well depth (ft)	817	846	984	1048	1004	815	560	732
Field measurements and chemical analyses [Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]								
Date sampled	3/22/90	3/22/90	10/9/90	10/9/90	3/20/90	3/20/90	5/3/90	5/8/90
Temperature °C	11.5	11.3	11.6	12.5	11.9	11.6	11.4	10.2
pH	7.35	7.68	7.77	7.35	8.06	7.56	7.34	7.42
Conductivity	1070	440	420	473	nm	1320	1350	1030
D. O.	0.65	1.36	0.68	0.80	nm	0.59	0.65	1.02
Ca	134.5	48.2	45.4	48.0	62.1	76.0	101.0	127.7
Mg	55.5	19.9	17.5	16.9	23.1	30.3	39.1	52.6
Na	36.8	21.5	26.1	17.3	97.2	201.0	58.0	38.8
K	5.4	9.1	8.4	7.3	10.3	10.8	5.2	3.3
Fe	2.5	0.6	0.7	0.8	0.8	0.8	1.2	0.8
Mn	0.10	0.02	0.02	0.02	0.02	0.03	0.09	0.12
Sr	0.749	0.948	0.746	0.515	1.240	2.830	0.561	0.564
Ba	0.424	0.124	0.109	0.143	0.113	0.023	0.046	0.040
SiO2	11.9	6.6	6.7	6.8	6.5	6.7	11.8	11.8
HCO3	521	285	263	250	338	368	505	566
Cl	34.1	11.4	13.3	15.6	81.0	208.0	12.0	2.0
NO3-N	0.026	0.016	< 0.005	< 0.005	0.016	0.021	0.021	< 0.005
SO4	178.0	14.0	11.4	5.4	92.0	156.0	136.0	150.0
TDS	981	418	394	369	713	1062	871	954
Radioactivity analyses [Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953; 1 part per billion (ppb) uranium = 0.333 pCi/L]								
U (ppb)	0.071	0.1	0.15	0.021	0.446	0.191	0.45	2.37
234U/238U activity ratio	25.3	7	5	7.5	10.9	7.8	6.2	4.4
226Ra (pCi/L)	2.5	4.5	5.8	4.2	9.1	4.4	4.3	4.5
228Ra (pCi/L)	2.4	9.4	7.1	6.5	7.6	9.2	11.6	14.3
Rn (pCi/L)	246	244	123	67	nm	nm	41	300
Po (pCi/L)	0.60	0.14	0.28	0.31	0.07	0.04	0.16	1.82
Gross alpha (pCi/L)	9	16	21	21	45	16	13	19
14C (fraction of modern)	0.029	0.0026	0.016	0.071	0.001	0.0029	0.251	0.272
δ13C (per mil)	-11.9	-13.3	-12.8	-10.8	-12.7	-14.8	-14.7	-12.7
Age	23000	>35000	28000	16000	>35000	>35000	5700	5000

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	49	50	51	52	53	54	55	56
Unique number	441516	132296	433254	191916	218623	216020	219201	112210
Well name and number	Nolte	Henderson 1	St. Peter 7	LeHillier 1	Red Wing 3	Red Wing 7	Rollingstone 2	Goodview 2
Well depth (ft)	500	900	798	560	635	630	410	455

Field measurements and chemical analyses
[Results in parts per million. Conductivity in μS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]

Date sampled	3/31/89	5/8/90	5/21/90	5/8/90	5/24/90	5/24/90	5/25/90	9/25/90
Temperature °C	11.5	11.2	11.2	11.4	11,3	11.4	10.7	12.1
pH	7.03	7.52	7.20	7.31	7.43	7.37	7.16	7.26
Conductivity	11300	780	2480	740	1100	450	510	1365
D. O.	nm	0.91	0.60	1.76	1.20	1.02	3.53	2.10
Ca	526.0	78.3	141.9	89.1	78.4	55.7	56.6	57.3
Mg	240.0	37.2	54.9	30.0	34.9	28.9	28.6	23.7
Na	1870.0	41.3	310.0	28.1	123.4	6.7	1.9	187.1
K	48.0	4.2	20.0	4.9	5.1	3.6	1.1	8.8
Fe	5.0	1.0	3.0	0.9	0.8	1.0	0.8	0.5
Mn	0.00	0.06	0.12	0.05	0.09	0.05	0.05	0.02
Sr	12.610	0.559	3.480	0.624	0.642	0.325	0.050	1.072
Ba	0.260	0.076	0.099	0.036	0.082	0.036	0.030	0.027
SiO2	9.3	6.9	6.8	7.9	9.4	9.2	12.0	7.9
HCO3	280	434	421	387	323	319	290	319
Cl	4120.0	6.1	440.4	4.9	258.0	7.1	1.7	185.0
NO3-N	3.19	0.02	< 0.005	< 0.005	< 0.005	< 0.005	0.09	< 0.005
SO4	331.0	87.0	328.0	93.0	26.4	17.3	14.2	135.7
TDS	7471	697	1728	647	862	449	407	928

Radioactivity analyses
[Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953;
1 part per billion (ppb) uranium = 0.333 pCi/L]

U (ppb)	25.7	2.3	2.33	0.113	0.055	0.074	0.346	0.64
234U/238U activity ratio	25.7	6.4	8.47	8.5	13.7	8.9	2.29	8.6
226Ra (pCi/L)	4.6	2.7	5.2	1.4	3.9	2.2	< 1.0	2.7
228Ra (pCi/L)	20	11.8	14.8	3.3	5.2	2.4	< 1.0	7.8
Rn (pCi/L)	nm	320	nm	200	193	232	125	100
Po (pCi/L)	nm	0.24	0.14	0.25	0.00	0.00	0.01	0.13
Gross alpha (pCi/L)	37	16	25.3	4	11	6	3	13
14C (fraction of modern)	0.038	0.079	0.041	0.041	0.283	0.414	0.734	0.097
δ13C (per mil)	-10.9	-14.8	-14.8	-14.4	-11.2	-8.9	-9.5	-10.7
Age	21000	15000	21000	21000	4700	1600	recent	14000

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	57	58	59	60	61	62	63	64
Unique number	449410	219184	219173	219194	110496	NA	409470	150341
Well name and number	Goodview 4	Winona 6	Winona 13	Winona 15	Lanesboro 3	Peterson Hatchery	Rushford Village 1	Houston 3
Well depth (ft)	515	484	516.5	1072	1070	633	366	408

Field measurements and chemical analyses
[Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]

Date sampled	9/25/90	6/14/90	6/14/90	6/14/90	6/13/90	1/16/90	6/13/90	6/13/90
Temperature °C	11.9	13.8	12.3	12.7	9.8	10.4	11.5	11.9
pH	7.60	7.47	7.56	7.42	7.63	7.68	7.31	7.47
Conductivity	1090	510	900	560	300	1140	450	970
D. O.	1.96	1.20	0.90	1.50	1.20	nm	1.40	1.60
Ca	52.7	55.5	60.0	64.1	53.5	76.9	60.9	86.3
Mg	22.1	21.4	24.4	34.5	18.9	25.0	19.2	28.6
Na	146.5	43.8	134.3	2.7	17.6	121.5	19.6	101.4
K	7.9	4.8	7.2	2.5	6.0	8.2	6.4	7.8
Fe	2.3	1.6	0.5	0.3	0.7	0.6	0.9	0.4
Mn	0.05	0.10	0.03	0.03	0.03	0.03	0.03	0.04
Sr	0.890	0.484	0.855	0.096	0.740	0.959	0.691	0.931
Ba	0.034	0.068	0.044	0.062	0.049	0.203	0.063	0.033
SiO2	8.0	10.7	8.4	9.5	6.8	7.1	7.0	7.3
HCO3	323	305	341	346	273	283	251	265
Cl	123.9	33.3	125.0	1.1	6.8	176.0	34.1	186.0
NO3-N	< 0.005	0.007	< 0.005	< 0.005	< 0.005	nm	0.009	< 0.005
SO4	94.5	42.9	101.0	33.2	33.2	97.0	29.7	102.0
TDS	783	515	804	495	418	798	431	787

Radioactivity analyses
[Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953;
1 part per billion (ppb) uranium = 0.333 pCi/L]

U (ppb)	0.252	0.149	0.25	0.046	0.054	0.264	0.064	0.077
234U/238U activity ratio	7.5	7.5	7.2	11.7	10.4	10.2	10.6	13.3
226Ra (pCi/L)	2.5	2.1	3.2	1.4	1.7	1.4	2.1	2.9
228Ra (pCi/L)	10.5	7.3	11.3	2	2.8	5.1	3.8	6.7
Rn (pCi/L)	84	nm	255	312	238	nm	181	258
Po (pCi/L)	0.00	0.03	0.01	0.02	0.02	nm	0.03	0.02
Gross alpha (pCi/L)	11	9	14	6	5	8.4	9	11
14C (fraction of modern)	0.078	0.301	0.121	0.189	0.008	0.0017	nm	0.022
δ13C (per mil)	-7.7	-12.7	-13.3	-12.5	-11.5	-13.6	nm	-11.9
Age	15000	4200	12000	8000	34000	>35000	nm	26000

Table 7. Analyses of water from the Mt. Simon-Hinckley aquifer (continued)
[See Figure 1 for locations. "NA" = not available; "nm" = not measured]

Map number	65	66	MA
Unique number	150345	219278	219022
Well name and	Hokah	LaCrescent	Owatonna
number	2	2	7
Well depth (ft)	648	591	1325

Field measurements and chemical analyses
[Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]

Date sampled	6/13/90	6/14/90	2/21/91
Temperature °C	12.4	12.8	10.4
pH	7.37	7.38	7.15
Conductivity	450	470	402
D. O.	0.80	1.10	1.92
Ca	72.7	70.8	61.9
Mg	29.2	30.2	19.29
Na	2.3	7.8	5.61
K	3.1	2.8	2.6
Fe	0.5	0.5	0.43
Mn	0.02	0.03	0.03
Sr	0.191	0.159	0.210
Ba	0.065	0.071	0.100
SiO2	9.2	9.6	7.7
HCO3	364	364	251
Cl	2.8	6.6	1.1
NO3-N	< 0.005	< 0.005	0.220
SO4	22.4	24.6	30.1
TDS	506	517	381

Radioactivity analyses
[Ages in radiocarbon years before present (1950) except for "recent" ages which are post-1953;
1 part per billion (ppb) uranium = 0.333 pCi/L]

U (ppb)	0.056	0.053	nm
234U/238U activity ratio	28	19	nm
226Ra (pCi/L)	1.1	2.6	1.9
228Ra (pCi/L)	1.9	6.6	< 1.3
Rn (pCi/L)	101	187	nm
Po (pCi/L)	0.01	0.01	nm
Gross alpha (pCi/L)	7	11	8.5
14C (fraction of modern)	0.205	0.171	nm
δ13C (per mil)	-12.5	-13.0	nm
Age	7400	8900	nm

Table 8. Analyses of water from the Jordan aquifer

[See Figure 1 for locations. "nm"=not measured]

Map symbol	A	B	C	D	E	F	G
Unique number	206720.0	206791.0	227965.0	151582.0	165640.0	191904.0	W06017
Well name and number	Mounds View 3	New Brighton 7	St. Louis Park 14	Savage 3	Inver Grove Hts 5	Cottage Grove 10	St. Peter 6
Well depth (ft)	317	437	485	393	452	284	130
Field measurements and chemical analyses [Results in parts per million. Conductivity in µS/cm; D.O. = dissolved oxygen; TDS = total dissolved solids]							
Date sampled	10/11/90	10/11/90	8/21/90	8/21/90	10/9/90	10/9/90	2/21/90
Temperature °C	10.1	10.0	10.0	9.9	9.8	9.5	11.2
pH	7.32	7.61	7.41	7.43	7.40	7.62	7.40
Conductivity	460	nm	624	503	465	499	607
D. O.	0.78	1.26	1.13	0.73	1.23	1.67	9.98
Ca	61.7	68.8	84.5	77.4	66.1	58.7	82.5
Mg	19.9	30.2	30.8	30.4	26.9	25.7	26.4
Na	13.2	5.6	10.3	4.8	3.9	3.0	8.9
K	2.2	2.0	1.2	1.9	1.7	1.7	1.5
Fe	1.6	0.2	0.7	0.7	0.2	0.1	0.0
Mn	0.96	0.20	0.08	0.10	0.27	0.02	0.02
Sr	0.258	0.176	0.178	0.220	0.119	0.072	0.145
Ba	0.162	0.114	0.157	0.620	0.247	0.022	0.066
SiO2	19.6	18.9	17.2	13.6	14.2	11.7	23.9
HCO3	377	360	380	412	329	257	323
Cl	1.7	6.7	13.6	1.1	1.2	5.2	17.5
NO3-N	< 0.005	< 0.005	< 0.005	0.009	0.120	0.090	8.8
SO4	0.8	14.7	41.8	9.0	10.0	37.7	35.6
TDS	431	507	581	545	454	401	529
Radioactivity analyses [1 ppb uranium=0.333 pCi/L. Radiocarbon ages were not obtained]							
Uranium (ppb)	1.5	1.55	0.3	0.9	0.91	16	1.3
U-234/U-238 ratio	1.78	1.83	2.4	2.2	1.95	1.31	1.3
226Radium (pCi/L)	< 1.0	1.9	3.5	6.6	6.8	2.2	< 1.0
228Radium (pCi/L)	< 1.0	1.6	1.3	2.7	1.8	< 1.0	< 1.0
Rn (pCi/L)	50	64	nm	nm	184	nm	nm
Po (pCi/L)	0.16	0.19	0.57	0.18	0.03	0.05	0.10
Gross alpha (pCi/L)	3	8	10.0	16.0	23	14	3.0

Table 9. Trace-element analyses of water from selected Mt. Simon-Hinckley wells
[See Figure 1 for well names and locations; see Table 2 for unique numbers. Samples collected in February 1991. Results in parts per billion; D = duplicate sample; Blank = distilled water]

Map number	18	20	21	25	26	27	28	30
Be	< 1	< 1	< 1	< 1	1	1	< 1	< 1
P	< 10	24	45	53	< 10	< 10	< 10	38
Ti	< 1	6	4	< 1	2	< 1	< 1	< 1
V	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Cr	< 1	< 1	2	< 1	1	< 1	< 1	< 1
Mn	2	33	26	27	24	6	20	57
Fe	4	1460	1250	1460	2150	1450	1050	702
Co	< 1	< 1	1	< 1	< 1	< 1	< 1	< 1
Ni	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cu	1	6	4	4	11	34	10	2
Zn	< 1	82	146	103	84	83	99	63
Sr	241	491	264	428	535	380	310	165
Zr	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Mo	< 1	< 1	< 1	1	2	< 1	< 1	< 1
Ag	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 5	< 5	< 5	6	< 5	< 5	< 5	< 5
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
W	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Bi	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Map number	38	39	40	40	41	42	45	46
Be	< 1	< 1	1	1	2	< 1	< 1	< 1
P	10	< 10	< 10	< 10	< 10	< 10	20	21
Ti	< 1	4	12	14	< 1	< 1	< 1	< 1
V	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Cr	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Mn	11	41	47	71	88	7	8	22
Fe	769	1180	518	696	2490	415	707	900
Co	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ni	< 1	< 1	< 1	< 1	< 1	1	< 1	< 1
Cu	2	4	3	3	8	4	2	4
Zn	9	98	90	89	92	89	7	6
Sr	289	603	521	506	603	868	1030	2690
Zr	< 2	< 2	< 2	< 2	< 2	< 2	< 2	3
Mo	< 1	< 1	2	1	2	< 1	< 1	< 1
Ag	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
W	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Bi	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Table 9. Trace-element analyses of water from selected Mt. Simon-Hinckley wells (continued)
[See Figure 1 for well names and locations; see Table 2 for unique numbers. Samples collected in February 1991. Results in parts per billion; D = duplicate sample; Blank = distilled water]

Map number	46	47	48	50	Blank	51	51	52
Be	< 1	1	2	1	< 1	2	2	1
P	< 10	11	< 10	15	17	67	77	11
Ti	< 1	5	< 1	< 1	< 1	< 1	< 1	< 1
V	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Cr	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Mn	< 1	76	102	25	< 1	98	100	45
Fe	3	1090	757	1820	32	2930	2950	1020
Co	< 1	< 1	< 1	< 1	< 1	1	1	< 1
Ni	< 1	< 1	< 1	1	2	< 1	3	1
Cu	2	5	4	3	2	6	6	4
Zn	< 1	115	88	92	124	104	93	104
Sr	2750	485	452	495	2	3730	3770	517
Zr	< 2	< 2	< 2	< 2	< 2	4	3	< 2
Mo	< 1	1	< 1	< 1	< 1	< 1	< 1	< 1
Ag	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
W	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Bi	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Map number	53	56	57	57	59	60	60-D	Blank
Be	< 1	< 1	< 1	< 1	1	< 1	< 1	< 1
P	28	15	17	22	15	< 10	< 10	< 10
Ti	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
V	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Cr	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Mn	64	14	17	< 1	16	24	24	1
Fe	771	454	801	< 2	779	678	627	206
Co	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ni	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1
Cu	4	5	6	< 1	3	2	2	3
Zn	527	493	544	< 1	550	496	10	11
Sr	717	800	738	15	721	125	132	2
Zr	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Mo	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ag	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
W	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Bi	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Table 9. Trace-element analyses of water from selected Mt. Simon-Hinckley wells (continued)
[See Figure 1 for well names and locations; see Table 2 for unique numbers. Samples collected in February 1991. Results in parts per billion; D = duplicate sample; Blank = distilled water]

Map number	61	63	64	65	66	Blank	MA
Be	< 1	< 1	1	< 1	< 1	< 1	< 1
P	12	14	19	< 10	12	< 10	< 10
Ti	< 1	< 1	< 1	< 1	< 1	< 1	< 1
V	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Cr	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Mn	18	23	39	20	26	< 1	20
Fe	604	765	941	1170	749	155	474
Co	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ni	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cu	5	4	5	3	37	2	3
Zn	553	555	517	565	528	574	822
Sr	663	599	753	170	126	3	166
Zr	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Mo	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ag	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sn	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sb	< 5	< 5	< 5	< 5	< 5	< 5	< 5
W	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Bi	< 10	< 10	< 10	< 10	< 10	< 10	< 10

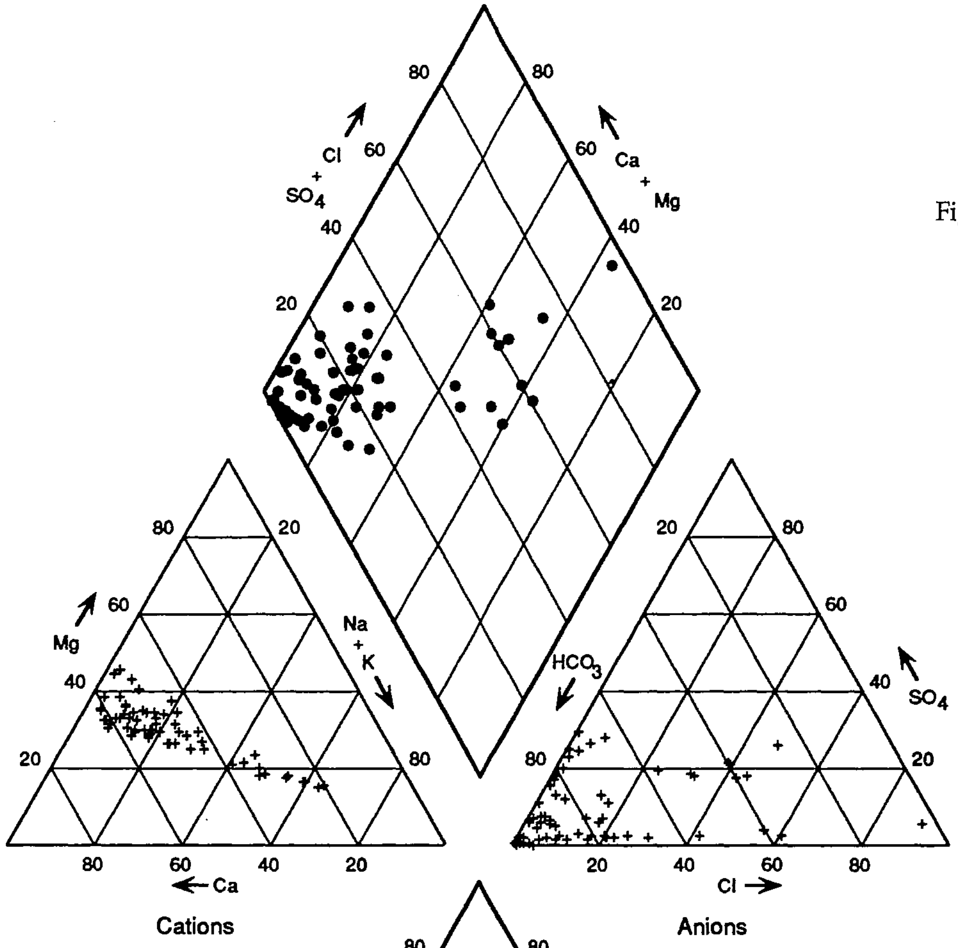

Figure 10. Piper diagram summarizing the major cation and anion chemistry for the Mt. Simon-Hinckley water samples. Note that the data are percent milli-equivalents per kilogram.

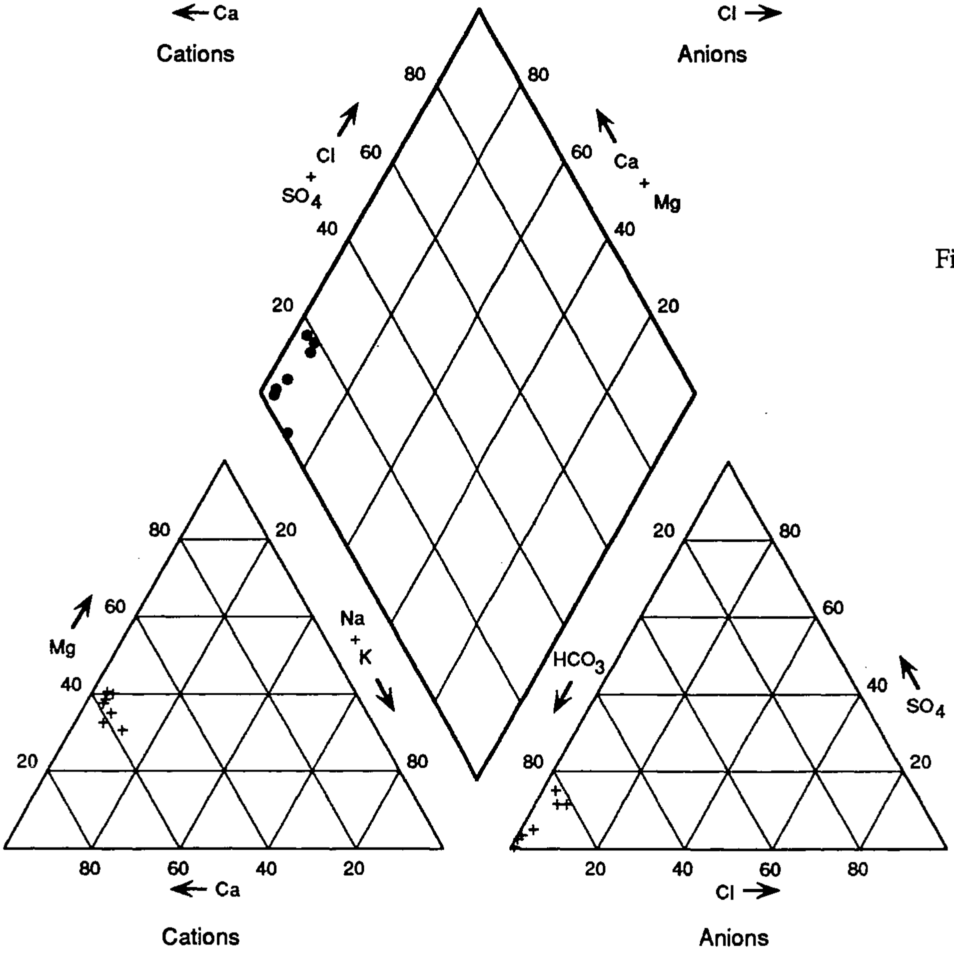

Figure 11. Piper diagram summarizing the major cation and anion chemistry for the Jordan water samples. Note that the data are percent milli-equivalents per kilogram.

Hinckley aquifer, the $^{234}U/^{238}U$ activity ratio ranges from 1 to 28, with a geometric mean of 0.82 ± 0.36. All but four of the samples having low activity ratios are in the northern part of the study area. In general, the uranium concentration and the U activity ratio is an inverse relationship — higher concentrations of uranium correspond to lower activity ratios.

Although ^{210}Po is not normally found in ground water because of its very low solubility and short half-life, it has been noted at high levels in some areas of the United States (Burnett and others, 1987). Our results in Table 7 are all under 2 pCi/L, at the low end of the range reported by Burnett and others (1987) and Hess and others (1985).

Low activities of ^{14}C indicate that the ground water has been isolated from the atmosphere for a long time, whereas high activities indicate that the water has entered the aquifer since 1953 (Alexander and Alexander, 1989). Calculated ages are based on the 5730-year half-life of ^{14}C. It should be noted that the ages given in Table 7 are very dependent upon the model used to calculate the value (Alexander and Alexander, 1989). The ages have been grouped on Figure 19 to emphasize underlying patterns. The map shows that as expected the youngest water in the Mt. Simon-Hinckley is in the north and west, closest to the subcrop and recharge zones. There appears to be anomalously old water on the northwestern edge of the Twin Cities basin, possibly associated with fault zones. The older water along the western margin of the study area implies that recharge from the edge of the Mt. Simon has not progressed far into the basin. In southeastern Minnesota along the Root River, ground water ages are greater than 25,000 years and become older toward the west. Younger ages near the Mississippi indicate some leakage into the Mt. Simon-Hinckley from the surface.

No Jordan samples were analyzed for ^{14}C and only three for radon. Except for one sample, the uranium concentrations and the U-activity ratios were low and uniform (Table 8). The data on trace elements in Mt. Simon-Hinckley well water (Table 9) have not been fully evaluated; they were not part of the original study, but have been included here for completeness.

RADIUM DISTRIBUTION

Although current regulations do not separate the activity of ^{228}Ra from that of ^{226}Ra, standards proposed in the EPA Environmental News Letter of June 1991 indicate that there will be a separate standard for each. Therefore both isotopes are shown in the tables and maps. The analyses represent the levels of the two radium isotopes ^{226}Ra and ^{228}Ra in the aquifer at the time of sampling. Temporal variability was less than 20% for individual wells. Temporal stability of radium in ground water was also noted by Hess and others (1985).

The areal distributions in the Mt. Simon-Hinckley of total radium and each of the isotopes are presented in Figures 20, 21, and 22. Duplicate samples showed consistent results, as did replicate analyses performed by the Wisconsin State Laboratory of Hygiene. Figure 20 demonstrates that most wells (75%) producing water from the Mt. Simon-Hinckley have total radium activity levels greater than 5 pCi/L. Individual wells had total radium concentrations that reached 25 pCi/L. The geometric mean for total radium activity of samples greater than the detection limit is 0.95 ± 0.23 pCi/L (N = 61; 5 out of 66 were below the detection limit). Total radium activity shows no distinctive distribution pattern. Ground water in the recharge areas is both high and low in radium. Intermediate concentrations are most prevalent in the central part of the basin and in the extreme southeast, whereas the highest levels occurred in the north-central and southwestern parts of the study area. Comparison of the total radium distribution with the structural maps of Figures 2 and 3 indicates a possible connection between radium in some of the wells and faults and structures in either the Paleozoic or basement rock. Near Anoka and Andover the ground water is anomalous in radiocarbon age, chloride, and radium when compared to the results from surrounding wells. The nearby Douglas fault may allow water to enter the Mt. Simon-Hinckley from below and either enhance transport of radionuclides or alter the water chemistry to allow more radium to remain in the aqueous phase. Similar situations may be responsible for anomalies in other areas.

The areal distribution of radium in the seven Jordan well samples is given in Figure 23. Little can be said about the distribution, given the limited sampling. However, it is evident that total radium levels are lower in Jordan water, due primarily to lower ^{228}Ra concentrations (geometric mean of 0.26 ± 0.11 in the Jordan vs. 0.72 ± 0.26 in the Mt. Simon-Hinckley) . The ^{226}Ra geometric mean of 0.56 ± 0.26 in Jordan water is similar to that of 0.54 ± 0.26 in the Mt. Simon-Hinckley.

DISCUSSION

In the Mt. Simon-Hinckley aquifer, ^{226}Ra activities are generally lower (geometric mean = 0.54 ± 0.26, N = 61; 5 below detection limit; range: <1–10 pCi/L) than those of ^{228}Ra (geometric mean = 0.72 ± 0.26, N = 61; 5 below detection limit; range: <1–20 pCi/L). The frequency distributions of the two radium isotopes are shown in Figure 24. The peaks at the extreme left of the histograms are artifacts of measurements of concentrations below the detection limit of about 1.5 pCi/L. Comparison of Figures 21 and 22 shows that in the southeastern and most of the southwestern samples, ^{228}Ra is the dominant isotope. In 85% of the water samples the activity of ^{228}Ra is greater than that of ^{226}Ra. The waters from the Anoka-Andover wells are the only group of samples where the ^{228}Ra/^{226}Ra activity ratio is at unity, or below.

The distribution of radium in ground water depends upon (1) the uranium and thorium contents of the aquifer rock, (2) the ability of radium to enter the water from the rock matrix (processes of dissolution and alpha recoil), (3) the half-life of the isotopes, and (4) the partitioning between the water and grain surfaces. Studies by King and others (1982) and Krishnaswami and others (1982) concluded that the adsorption of radium onto grain surfaces limits its transport in water to very short distances. Adsorption also varies with the geochemical reactivity of the aquifer material (Hess and others, 1985).

The mineral composition of the sandstone is a function of the depositional environment and source area(s) of the sediment entering the basin. Within a given stratigraphic interval the mineralogy can be relatively uniform over broad geographic areas. Uranium has two valence states and if oxidized is chemically more mobile than thorium. Both elements can be transported as adsorbed species on fine particulates. If uranium enrichment occurred as a result of chemical transport, the rock in that zone would show a relative depletion in thorium and the water in contact with the rock should have more ^{226}Ra than ^{228}Ra. The U and Th results from the Mt. Simon rock samples (Tables 1-5), however, indicate that most samples have a relative abundance similar to that in average crustal rocks. Because of the limited nature of the sampling, the rock data cannot be applied to the entire aquifer, although the results do support the assumption that U and Th are evenly distributed (within about a factor of 2) throughout the aquifer.

From the average U and Th concentrations in the rock, we were able to calculate the quantity of radium in the water that could be supported by radioactive decay, assuming all of the radium produced entered the water. Given these average concentrations, a porosity of 20%, a rock density of 2.7 g/cm^3, and a saturated aquifer, the Mt. Simon-Hinckley is capable of supporting several thousand pCi/L of each radium isotope. Because the measured concentrations in the water are only a fraction of the theoretical concentrations, most of the radium must stay with the solid phase. A similar calculation of the ability of the uranium dissolved in the water to support observed radium levels indicates that even the highest dissolved uranium levels can support no more than a few percent of the ^{226}Ra activity in solution and, because it is in a different decay series, none of the ^{228}Ra activity.

The detailed mechanisms controlling the transfer of radium between the solid and liquid phases cannot be determined from the existing data. The relatively uniform distribution of radium in the water is consistent with the rock radiochemical data, which show no major zones of anomalously high U or Th concentrations within the rock. Some fraction of radium may be derived from the dissolution of the aquifer solid and some from alpha recoil or chemical removal from adsorption sites. Those will be balanced by radioactive decay, (re)adsorption onto the aquifer solid, and chemical co-precipitation. Understanding these mechanisms` and their relative contribution to radium in solution is critical to developing an accurate model to explain the observed radium distribution. To do so, it will be necessary to measure isotopic characteristics from both water and rock at the same location and depth, something that was not possible with this study. The influence of geochemical changes on radium distribution in ground water has not been thoroughly investigated and much remains unknown (Gilkeson and Cowart, 1987; Hess and others, 1985; King and others, 1982; and Szabo and Zapecza, 1987). Comparisons of results from different parts of the country are questionable, because of variations in aquifer materials, wells screened in different aquifers or at different depths, and variations in hydrogeologic parameters. The results from the Mt. Simon-Hinckley aquifer in Minnesota indicate that even with good control on screened intervals, the interpretations can be complex.

The plot of ^{228}Ra versus ^{226}Ra in Figure 25 reveals two trends, both with positive slopes. As the total radium activity increases, both ^{228}Ra and ^{226}Ra increase; however there are several samples where the ^{228}Ra increases at a faster rate. Based on these trends, the data set was subdivided into samples with ^{228}Ra/^{226}Ra activity ratios greater than 2.0 (N = 18) and samples with ^{228}Ra/^{226}Ra activity ratios less than 2.0 (N = 48). Figure 26 is a map showing the areal distribution of the two data sets. The data were also compared with the major cation and anion concentrations in the waters, shown as scatter plots in Figures 27-29. Correlations are observed primarily in the data set with the radium activity ratios greater than 2.0. Bicarbonate (Figure 27) and sulfate (Figure 28) plotted against ^{228}Ra and ^{226}Ra show good correlations, with ^{228}Ra having a steeper slope than ^{226}Ra. The same anion data plotted against radium activity ratios less than 2.0 show more scatter and no significant trends. The chloride plots (Fig. 29) do not show significant trends.

The cation data plotted against radium isotope activities showed less correlation than did the anion data. Iron (Fig. 30) shows a correlation, particularly for the data set of radium activity ratios greater than 2.0. The trend for sodium vs. radium isotopes was identical to that for iron; however none of the other cations showed any correlation.

Although some correlations were observed between the radium and major-element chemistry of the ground water, their significance is not clear. The lack of correlation between radium and the radiocarbon age of the water implies that residence time, which does affect the chemical evolution of the water, is not a significant control on radium. The low absolute concentration, short half-life, and low solubility of radium would imply that equilibrium between the rock and aqueous phase is reached over a period that is short relative to the residence time of the water in the aquifer. Because the rocks have been shown to have sufficient U and Th to support the radium, the ground-water geochemistry will have the most effect on enhancing or limiting radium transport and accumulation in the aqueous phase. If waters high in total dissolved solids are introduced into the aquifer, they may carry radium or the parent nuclides into the rock matrix from outside, or may enhance the transfer of radium between the solid and aqueous phases. Without concurrent sampling for radioactive elements both in the water and the associated rock matrix, these questions cannot be answered with any certainty.

CONCLUSIONS

Sampling by the Minnesota Department of Health identified several communities where waters from the Mt. Simon-Hinckley aquifer exceed the current drinking water standard for radium. The aquifer underlies much of southeastern Minnesota and extends south into Iowa and east into Wisconsin. It is the second most important source of ground water in the Twin Cities Metropolitan Area. This study focused on the distribution of the isotopes ^{228}Ra and ^{226}Ra and total radium activity within Mt. Simon-Hinckley water and the relationship of radium to the regional geologic environment and to the major-element chemistry of the water.

Seventy-five percent of the Mt. Simon-Hinckley and two of the seven Jordan wells sampled exceeded the current 5-pCi/L standard for combined activity from ^{226}Ra and ^{228}Ra. In some water samples, the radium activity was as much as 5 times above the standard. The data establish that most water from the Mt. Simon-Hinckley aquifer could contain radium concentrations above 5 pCi/L. The areas of radium below 5 pCi/L are distributed throughout the study area and show no consistent pattern. Limited sampling of Jordan water indicates that the radium levels in Jordan water are significantly lower than in the Mt. Simon-Hinckley.

Individually, ^{228}Ra and ^{226}Ra have different patterns of distribution. ^{226}Ra occurs more or less uniformly throughout the aquifer, whereas ^{228}Ra appears to be more abundant in water from the southern half of the aquifer. Only 8 of the 61 water samples (13%) with detectable radium had a ^{228}Ra/^{226}Ra activity ratio that was less than unity, and these were all in the northern half of the study area. In wells where ^{228}Ra was elevated, there were also elevated concentrations of sulfate and chloride in the water. A positive correlation of elevated ^{228}Ra with chloride, sulfate and bicarbonate anions implies that ground water with high concentrations of these anions may also have elevated radium concentrations. However, an unambiguous prediction of radium activity applicable to the entire aquifer could not be made from analysis of water chemistry.

The only sources for radium in ground water are parent radionuclides within the minerals that compose the aquifer rock. Radium isotopes have short half-lives relative to the age of the aquifer and must be continuously replenished by the decay of the parent isotopes ^{238}U and ^{232}Th. Parent nuclides may be distributed evenly throughout the matrix or concentrated in specific zones or on grain surfaces by weathering and various depositional processes. Parent nuclides within the Mt. Simon-Hinckley were uniformly distributed with minor enrichment zones corresponding to original depositional environments. It was not possible to determine how much, if any, radium or parent nuclides resided on grain surfaces. The location of these nuclides may be less important than their concentration, because only a small fraction of the radium within the rock is needed to create the observed concentrations in the water.

Several of the wells with anomalous radium concentrations are in the vicinity of faults or structural features in the Precambrian rocks, such as the Douglas fault in the Anoka-Andover area. These wells also have older radiocarbon ages and more chlorides and sulfates than wells on either side. A probable explanation is that a fault allows older, more saline water to move into the Mt. Simon-Hinckley from the underlying Middle Proterozoic rocks. Although several other wells may be near faults, we lack precise fault locations and data on fault hydrology to do more than infer interaction between water in the Mt. Simon-Hinckley and deeper water. Although it is probable that parent nuclides in the aquifer matrix are responsible for the regional background of radium in ground water, faults may allow waters with different chemical and radiological compositions to mix and create local patterns that are independent of the regional picture.

It is probable that new wells drilled into the Mt. Simon-Hinckley aquifer will encounter similar levels of radium given the widespread distribution observed. However, the aquifers above the Mt. Simon appear to have lower total radium activities. One community was able to reduce the radium in its Mt. Simon-Hinckley well by closing off the part of the aquifer that showed elevated levels of gamma radiation in a downhole survey. We remeasured the radium in the well and found that the procedure had reduced ^{226}Ra activity from 2.7 to <1 pCi/L and ^{228}Ra from 11.8 to 1.6 pCi/L. We do not know if continued pumping of the well will eventually increase radium levels or if the reduction can be considered permanent for the life of the well. Given lithologic and hydrogeologic variability and a lack of significant gamma activity in major areas of the aquifer, similar mitigation strategies may not be warranted or successful in other wells.

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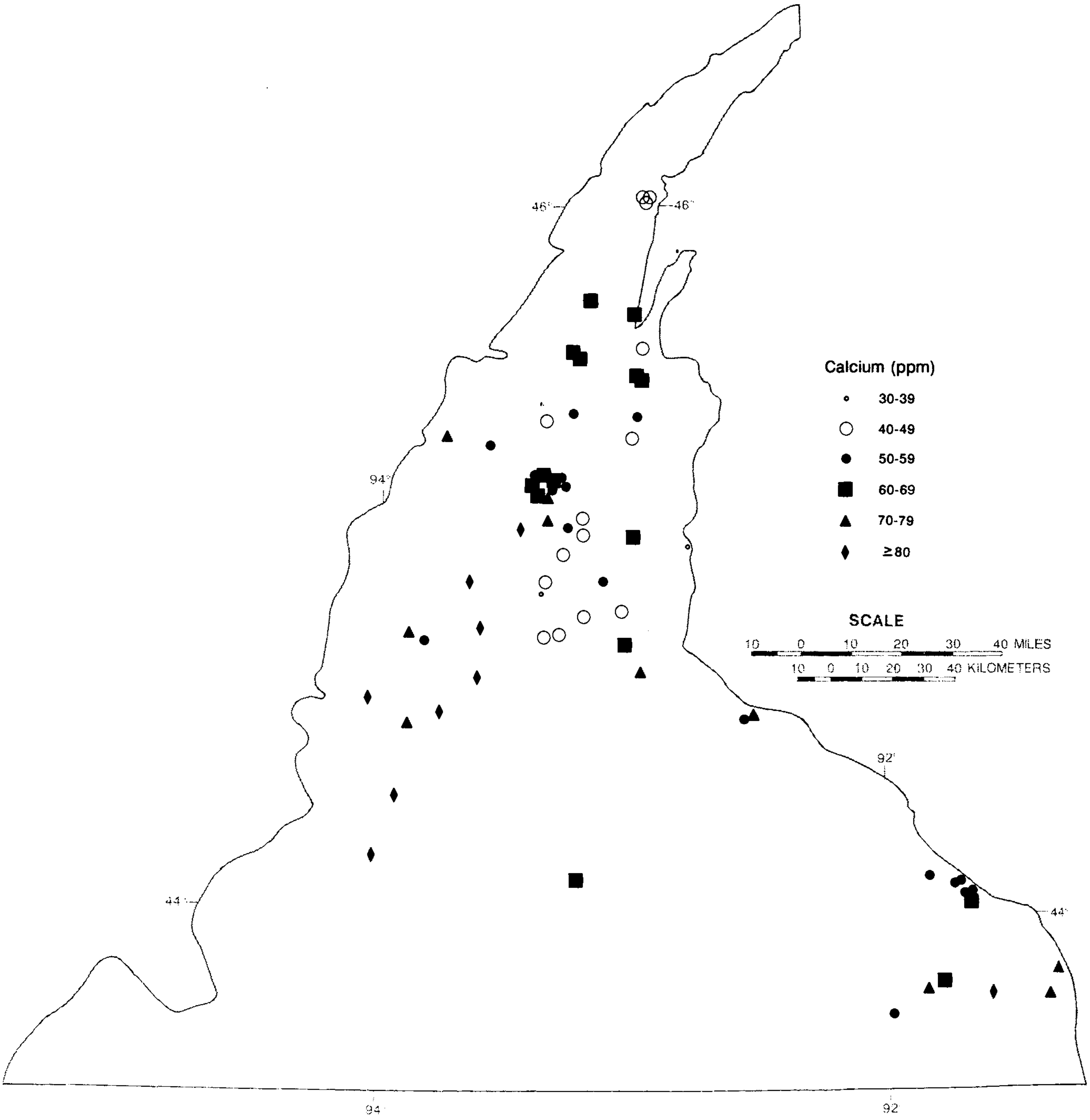

Figure 12. Areal distribution of calcium in the Mt. Simon-Hinckley well water.

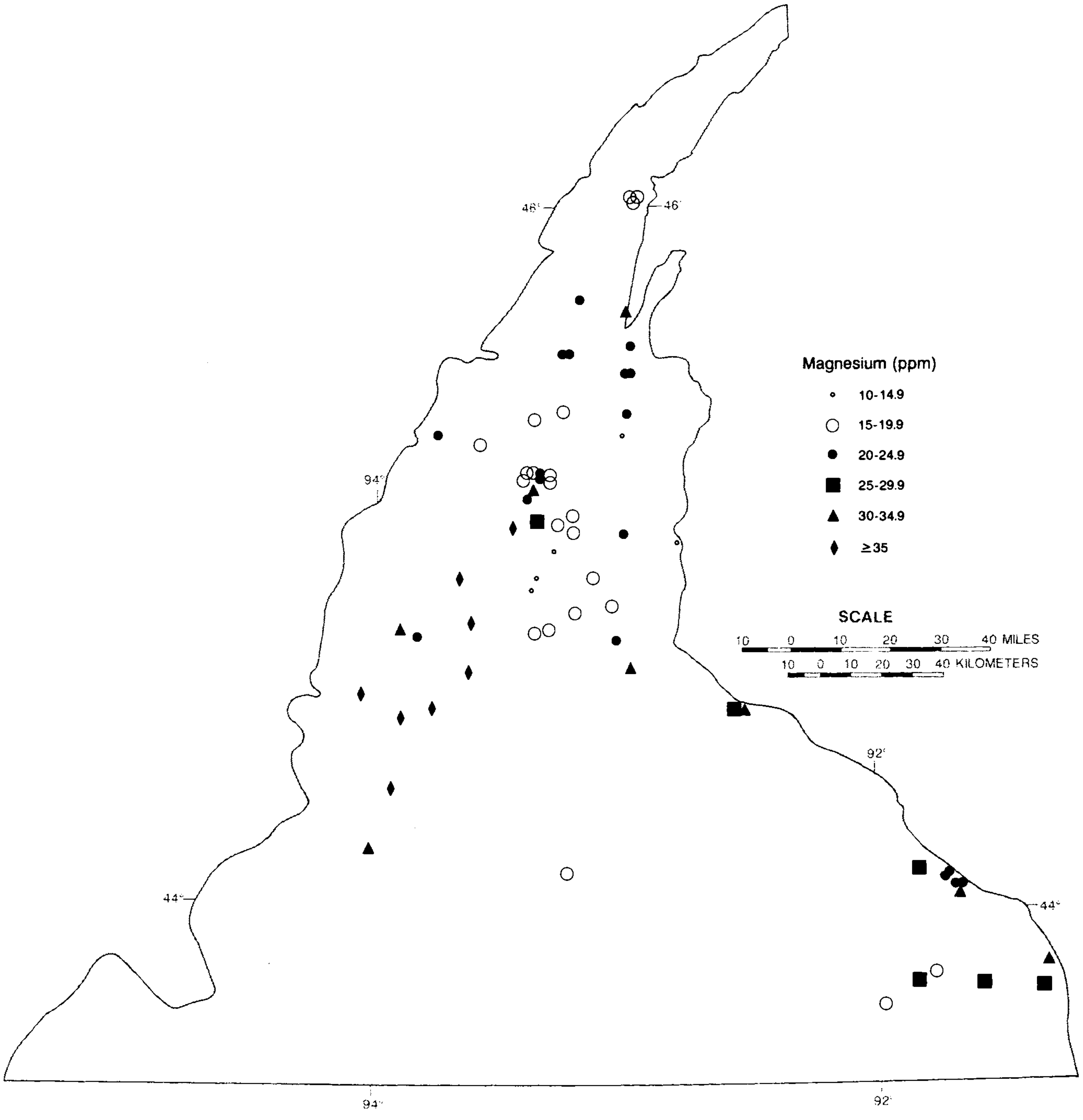

Figure 13. Areal distribution of magnesium in the Mt. Simon-Hinckley well water.

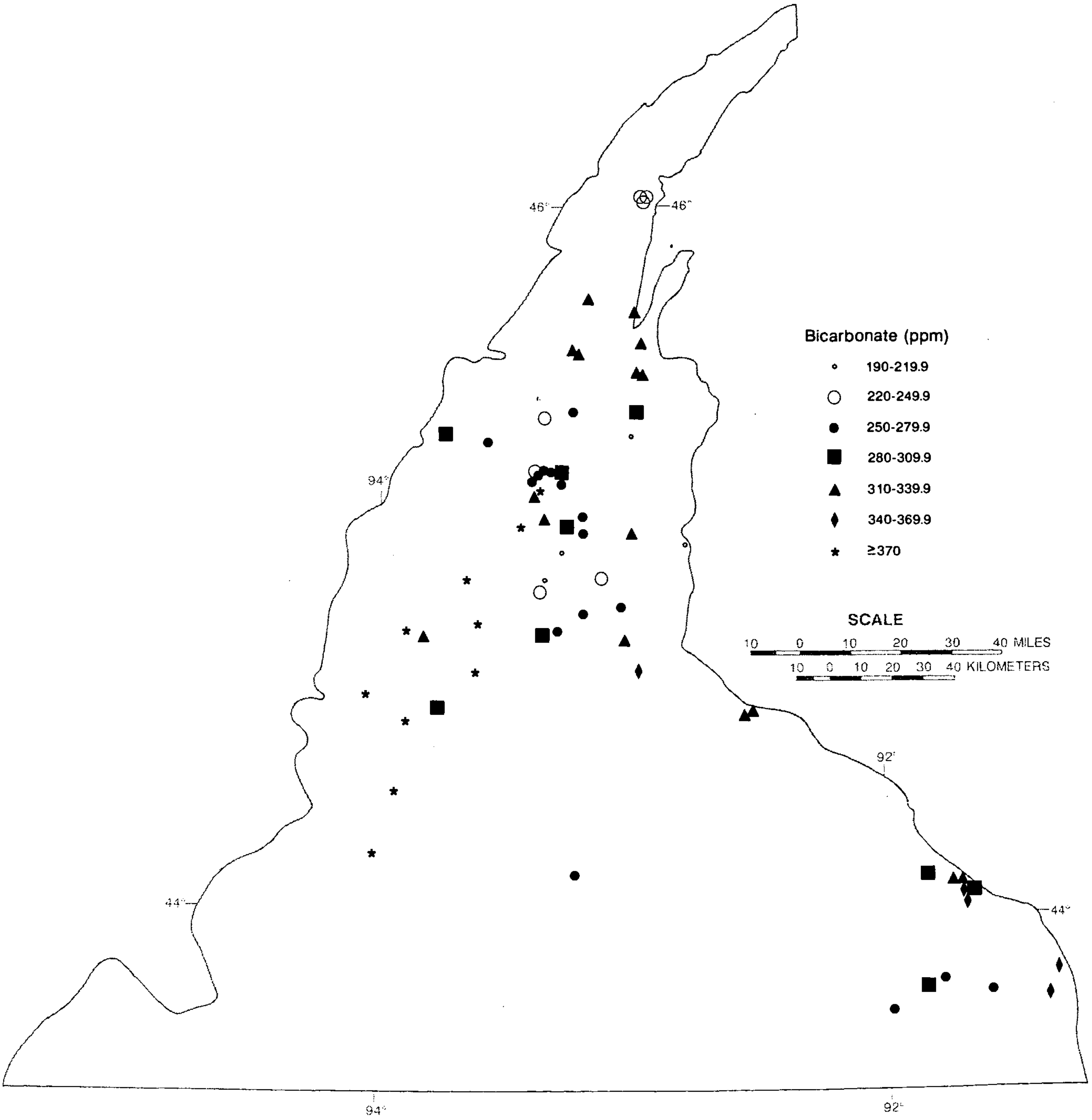

Figure 14. Areal distribution of bicarbonate in the Mt. Simon-Hinckley well water.

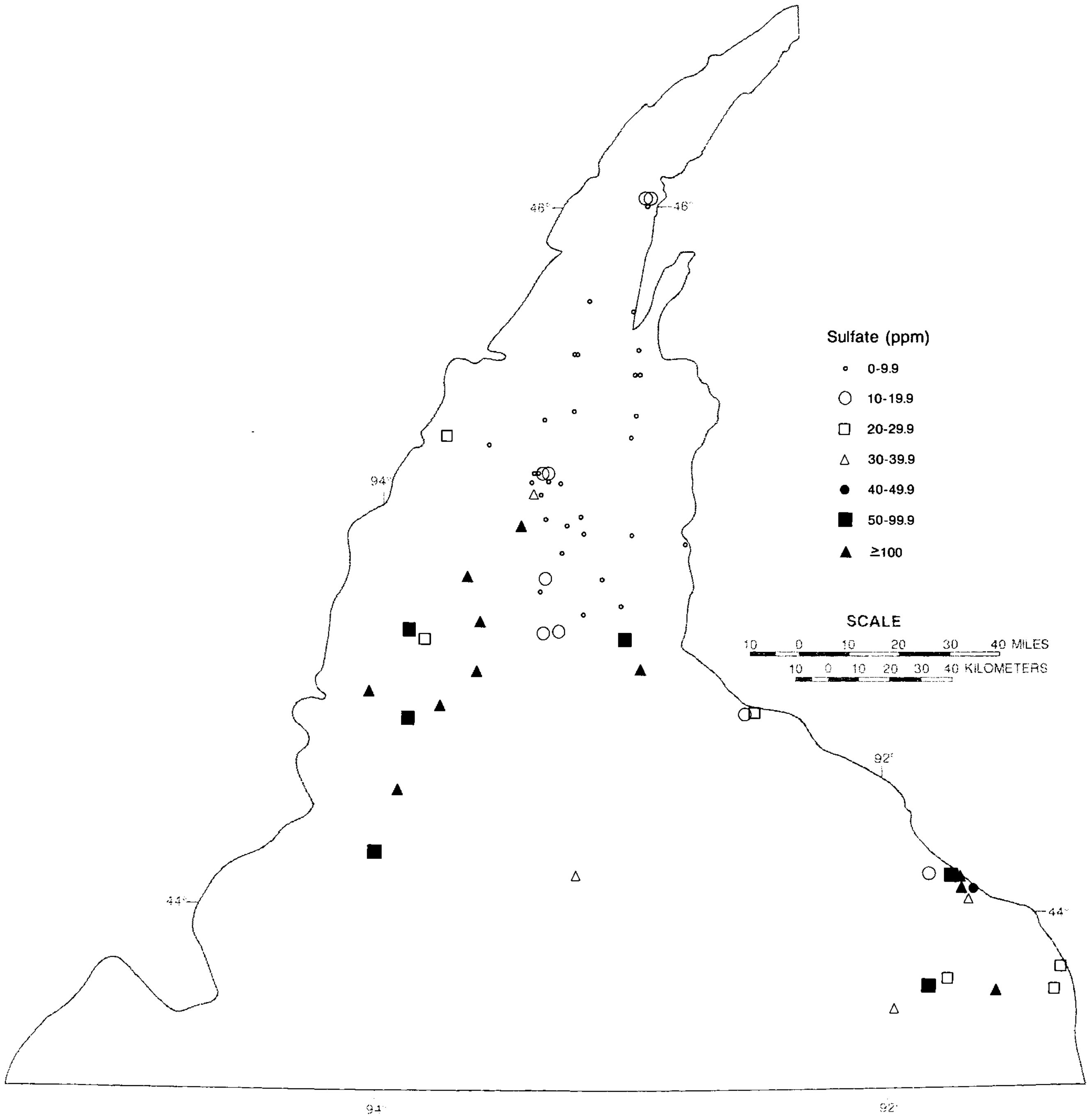

Figure 15. Areal distribution of sulfate in the Mt. Simon-Hinckley well water.

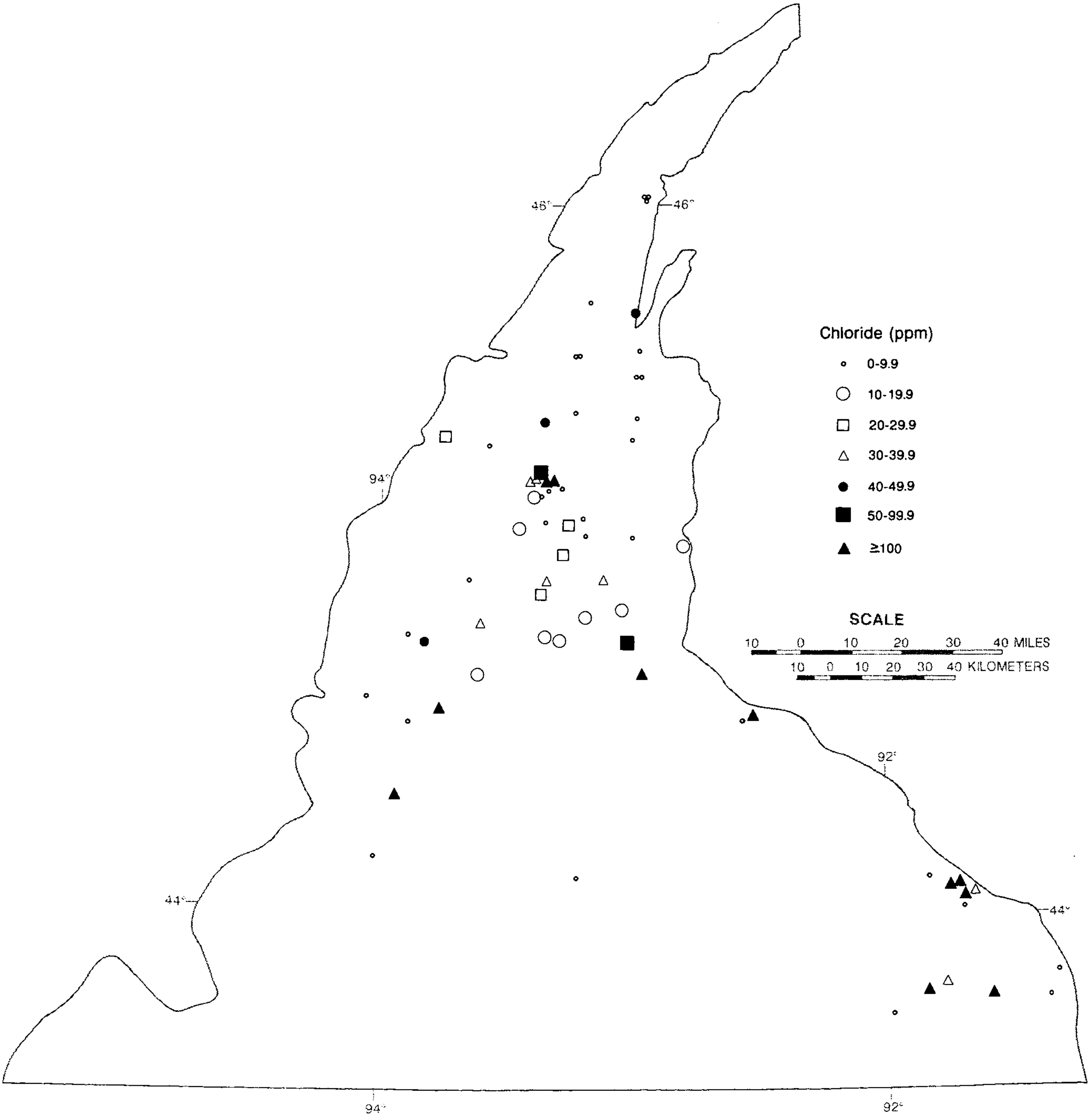

Figure 16. Areal distribution of chloride in the Mt. Simon-Hinckley well water.

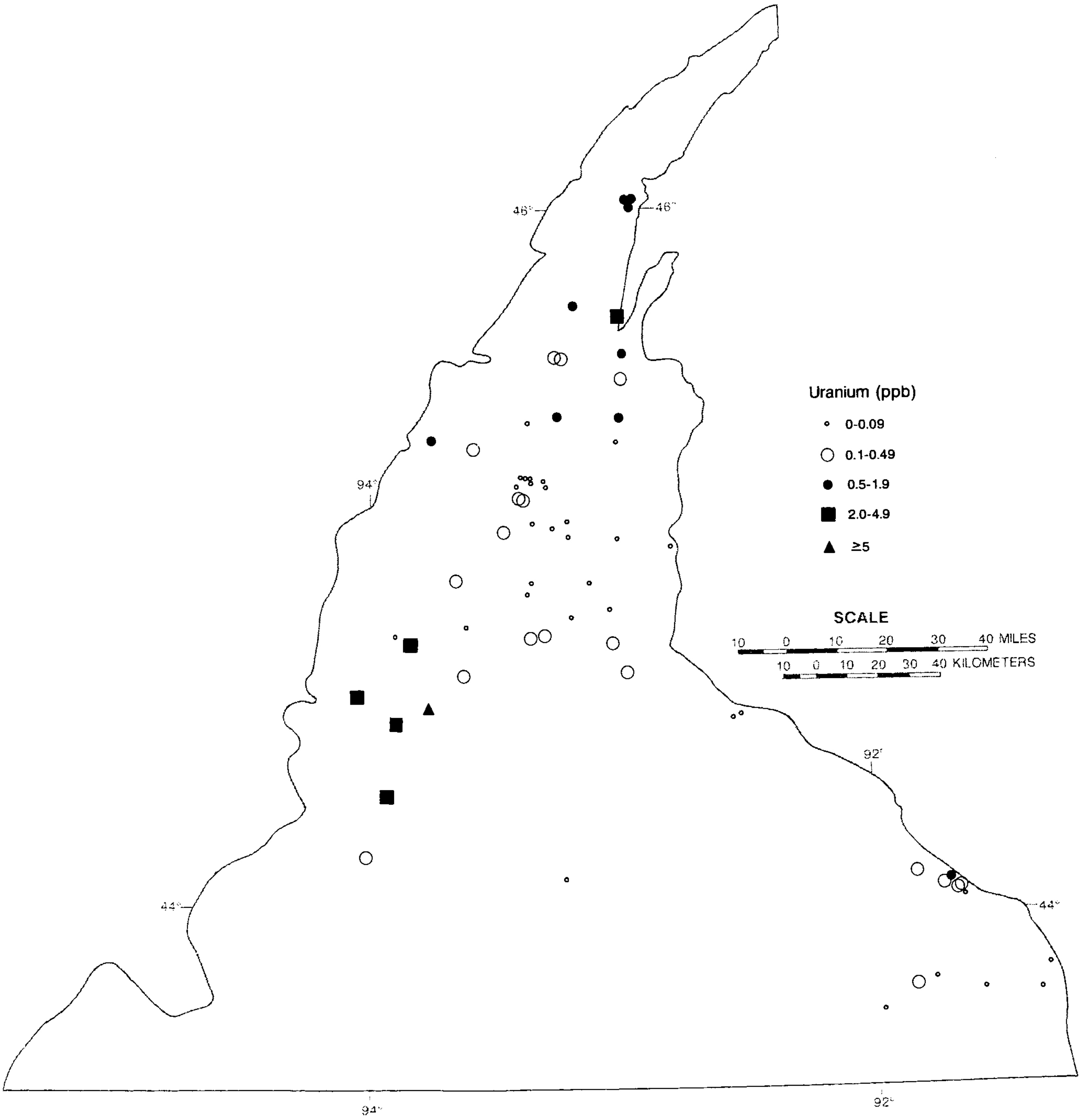

Figure 17. Areal distribution of uranium in the Mt. Simon-Hinckley well water.

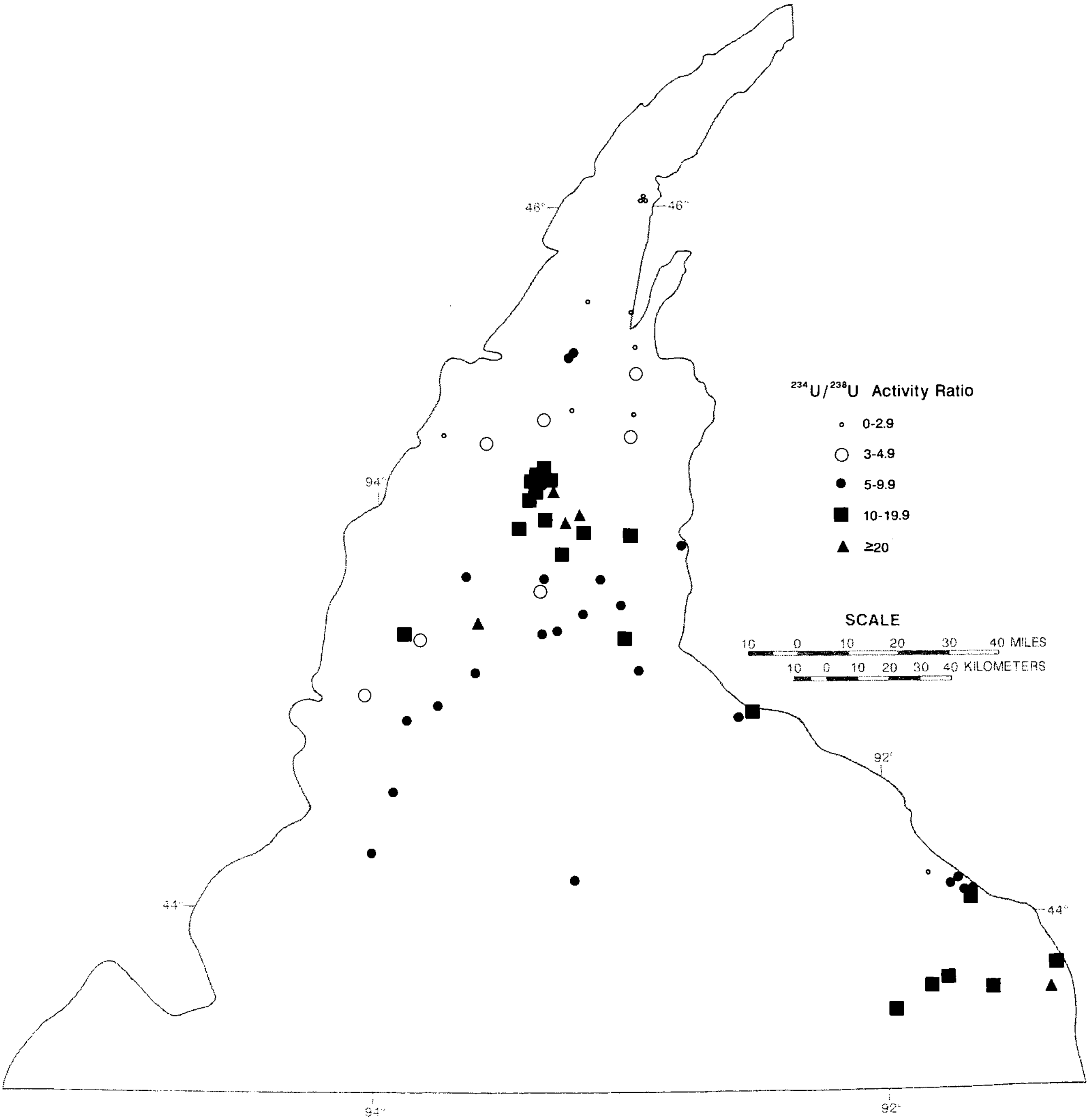

Figure 18. Areal distribution of $^{234}U/^{238}U$ activity ratios in the Mt. Simon-Hinckley well water.

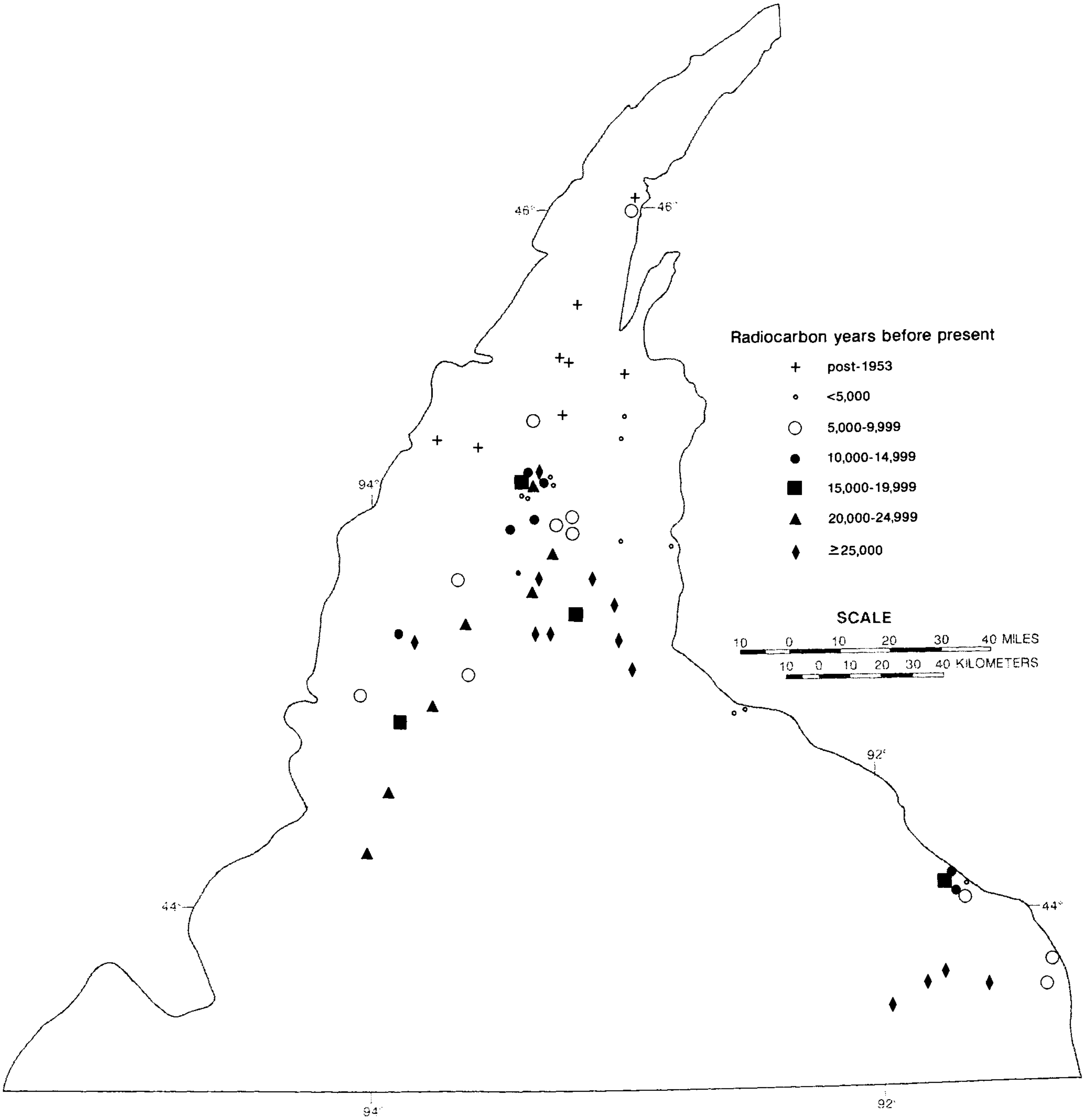

Figure 19. Areal distribution of radiocarbon age groups within the Mt. Simon-Hinckley well water.

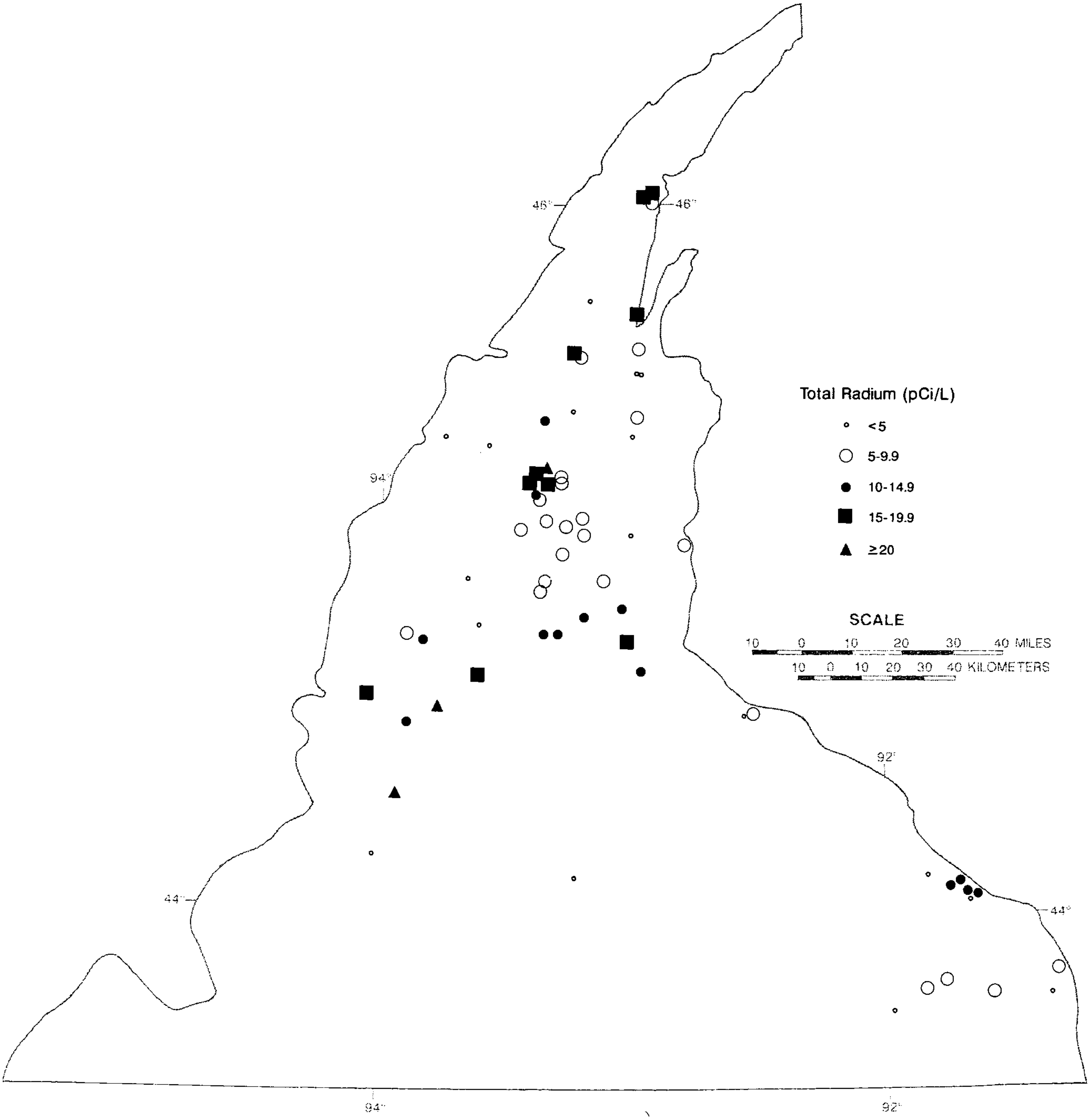

Figure 20. Areal distribution of total radium in the Mt. Simon-Hinckley well water.

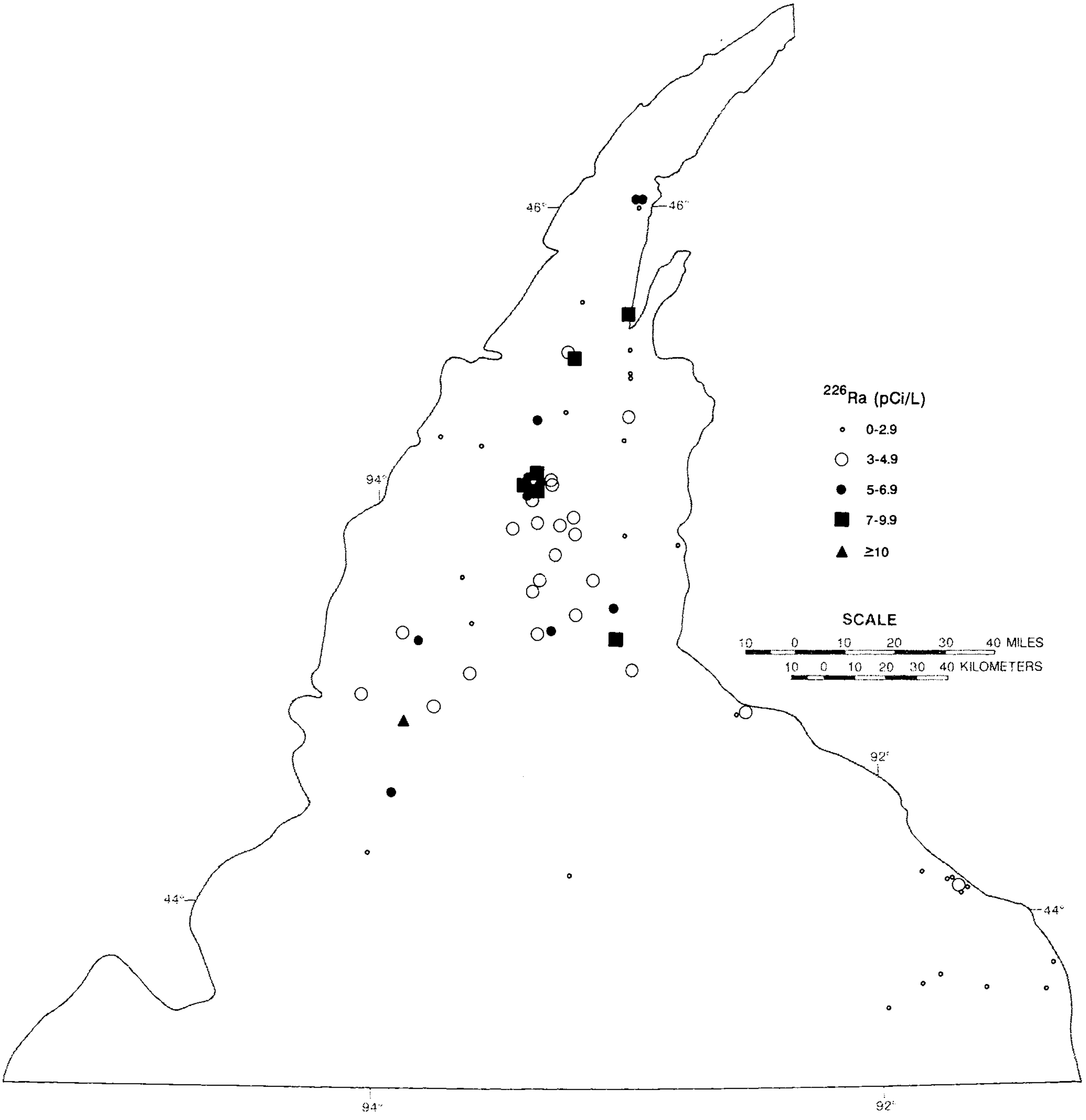

Figure 21. Areal distribution of ^{226}Ra in the Mt. Simon-Hinckley well water.

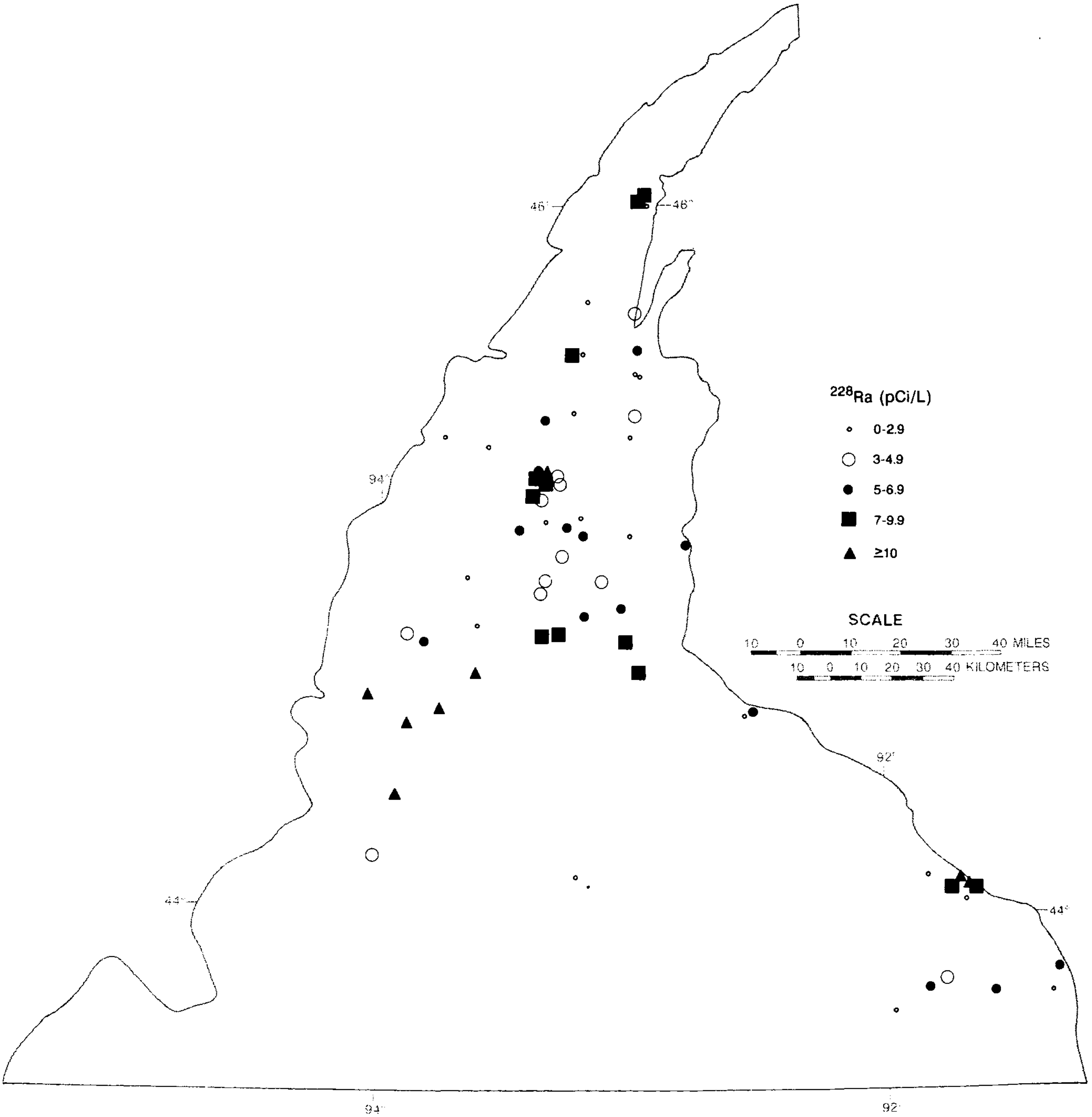

Figure 22. Areal distribution of ^{228}Ra in the Mt. Simon-Hinckley well water.

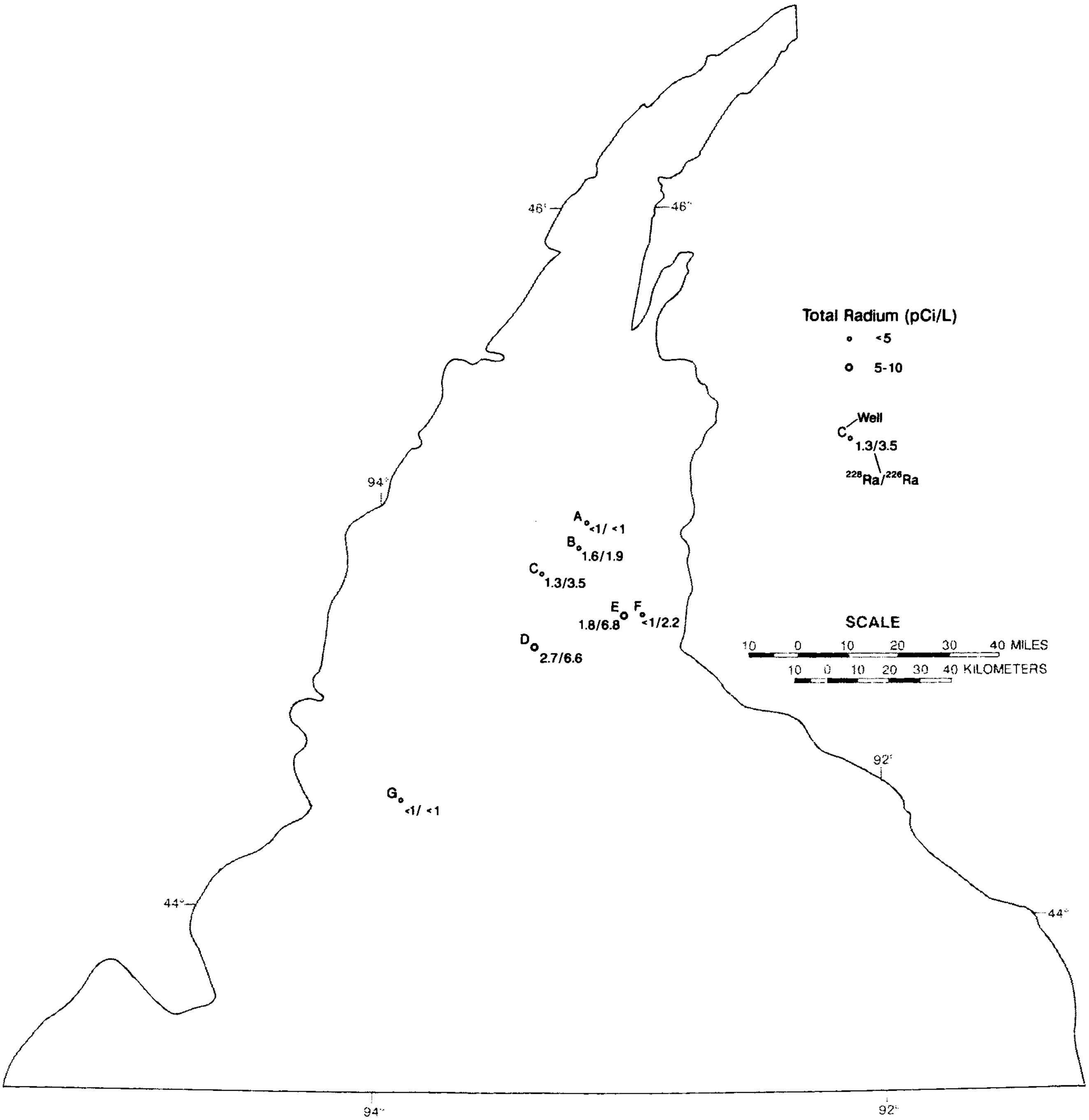

Figure 23. Areal distribution of total radium in the Jordan well water.

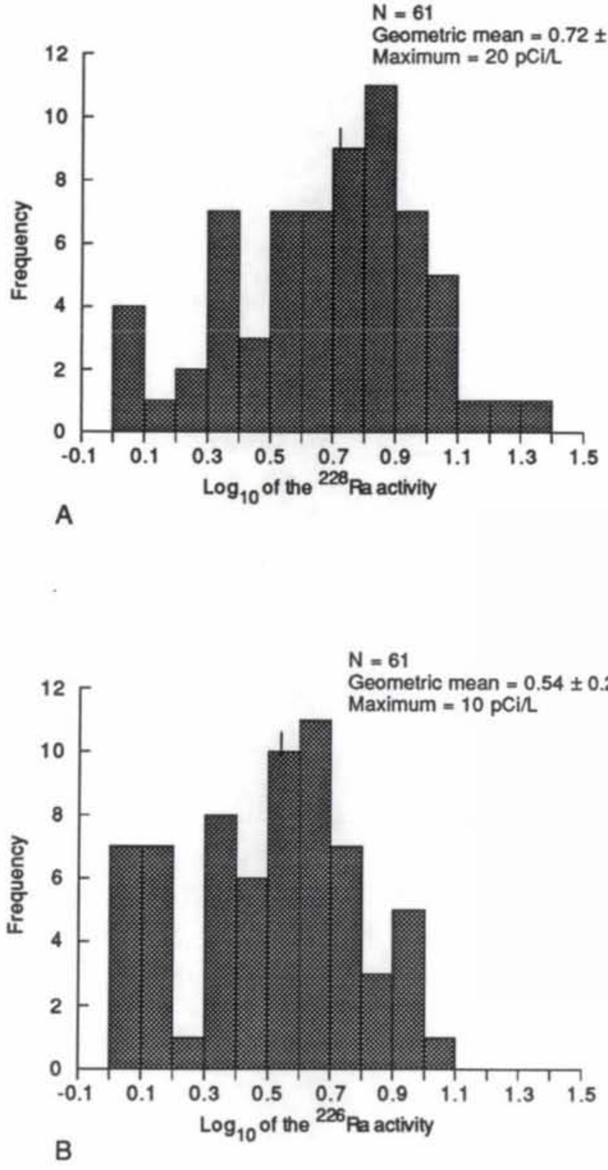

Figure 24. Histograms showing the frequency distribution of ^{228}Ra and ^{226}Ra in the Mt. Simon-Hinckley well water.

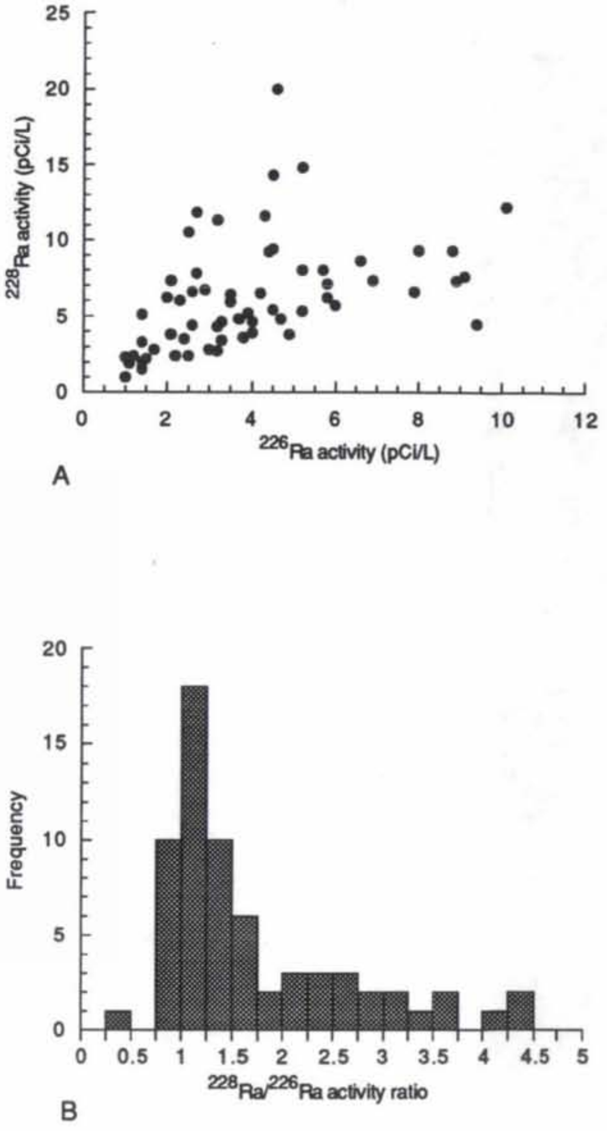

Figure 25. Scatter plot of the ^{228}Ra activity versus the ^{226}Ra activity and a histogram showing the frequency distribution of the ^{228}Ra/^{226}Ra activity ratio in the Mt. Simon-Hinckley water.

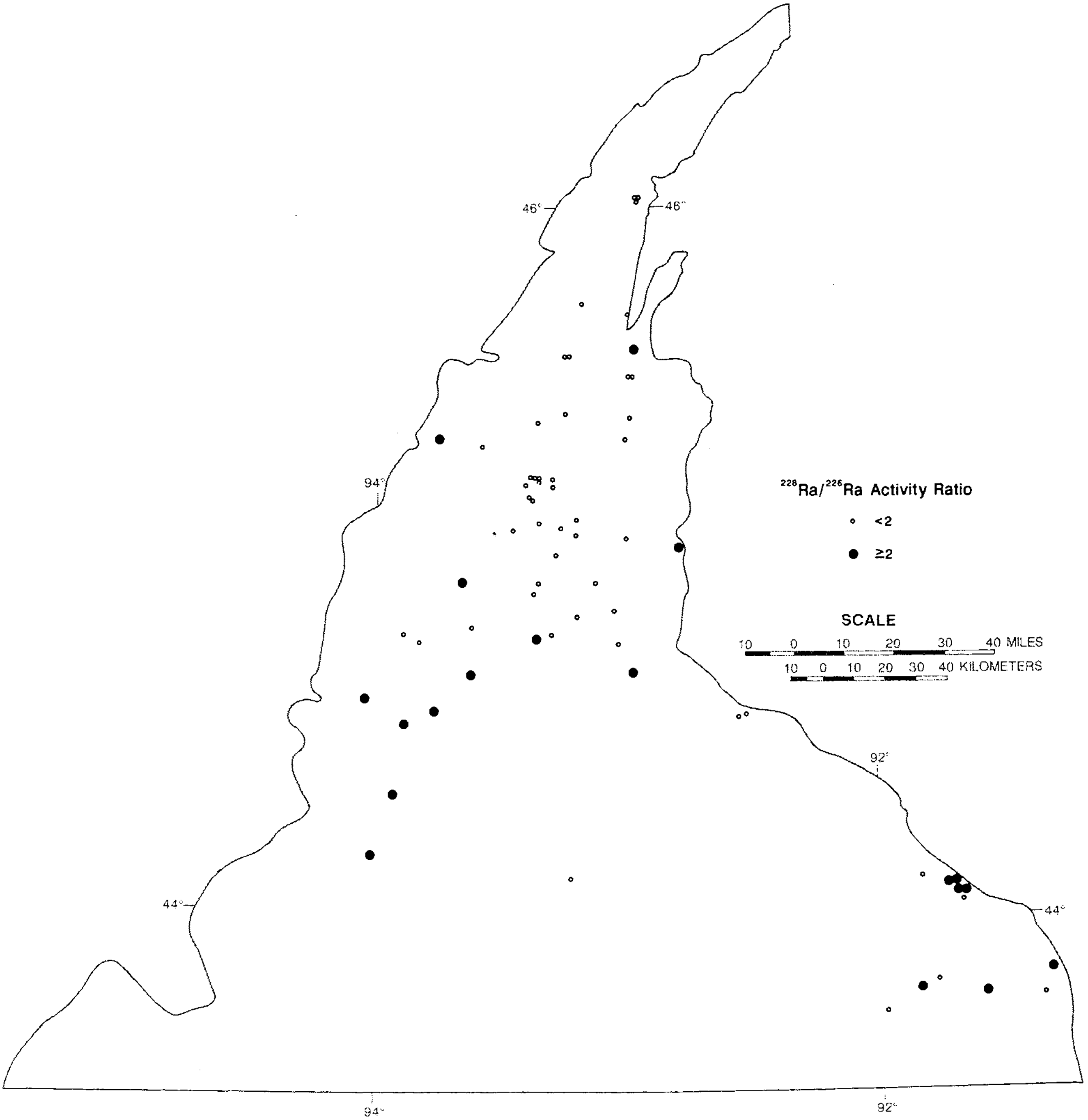

Figure 26. Areal distribution of the ^{228}Ra/^{226}Ra activity ratios subdivided into ratios <2.0 and >2.0. This division is based on the two trends in the scatter plot of Figure 25.

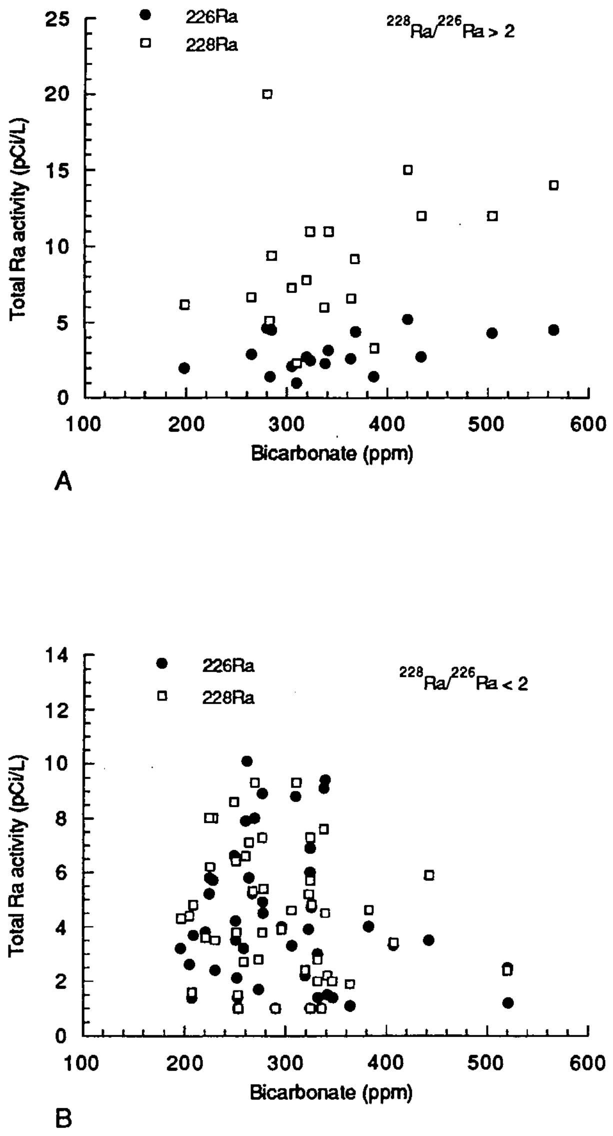

Figure 27. Scatter plots showing the relationship of ^{228}Ra and ^{226}Ra to bicarbonate concentrations in the Mt. Simon-Hinckley water. Graph A, activity ratios greater than 2; graph B, activity ratios less than 2. Squares, ^{228}Ra; closed circles, ^{226}Ra.

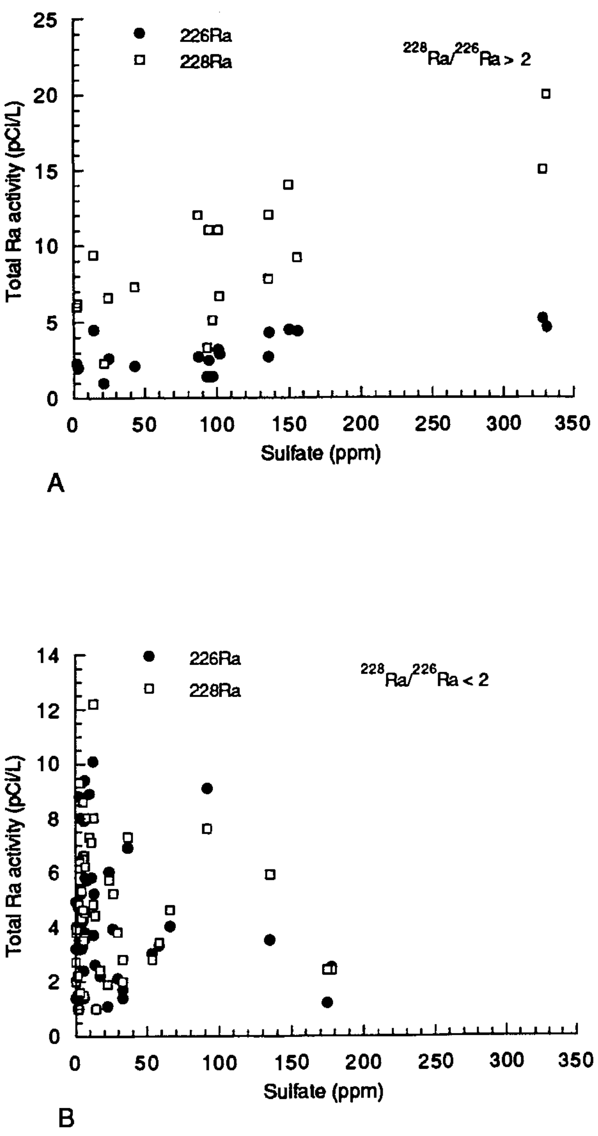

Figure 28. Scatter plots showing the relationship of ^{228}Ra and ^{226}Ra to sulfate concentrations in the Mt. Simon-Hinckley water. Graph A, activity ratios greater than 2; graph B, activity ratios less than 2. Squares, ^{228}Ra; closed circles, ^{226}Ra.

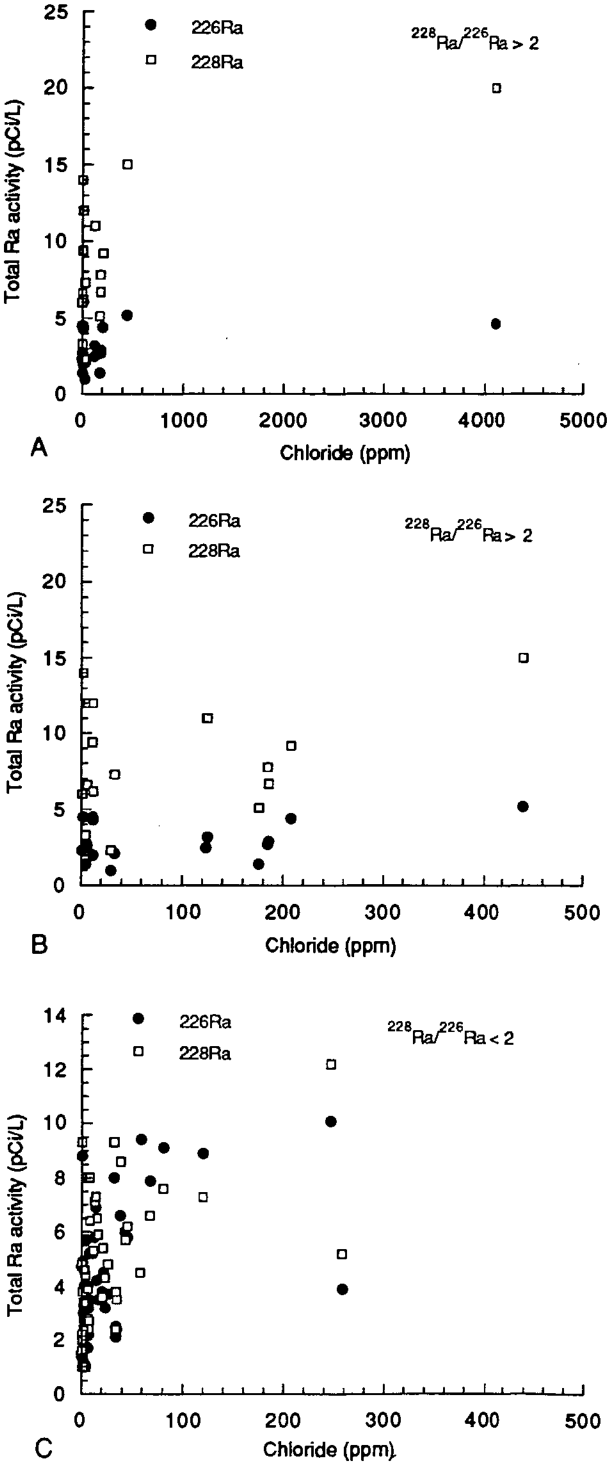

Figure 29. Scatter plots showing the relationship of ^{228}Ra and ^{226}Ra to chloride concentrations in the Mt. Simon-Hinckley water. Graph A, activity ratios greater than 2; graph B, same data as A at an expanded scale; graph C, activity ratios less than 2. Squares, ^{228}Ra; filled circles, ^{226}Ra.

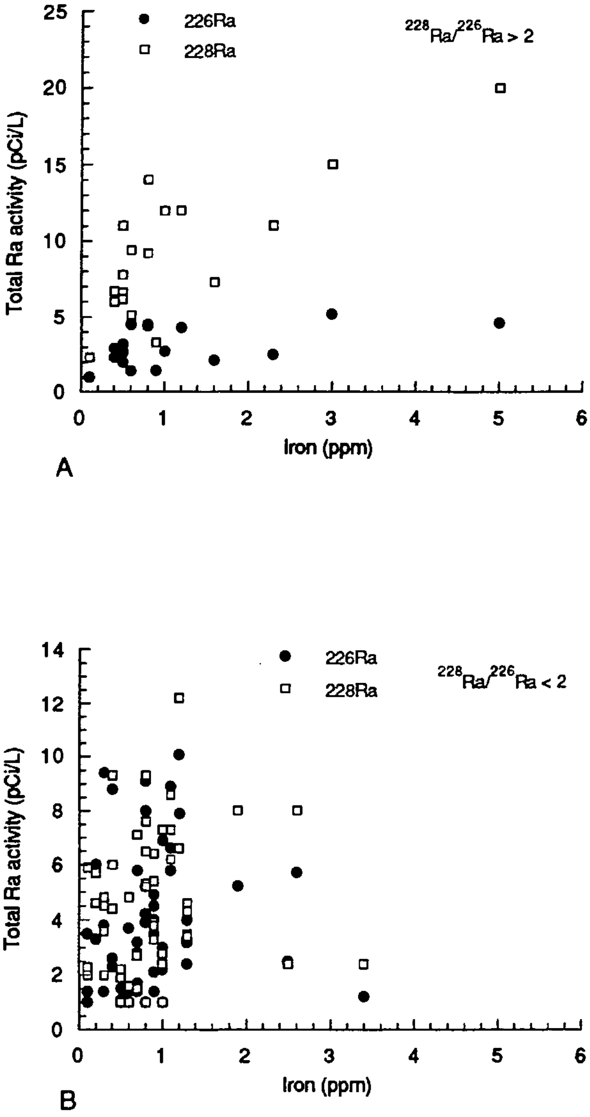

Figure 30. Scatter plots showing the relationship of ^{228}Ra and ^{226}Ra to iron concentrations in the Mt. Simon-Hinckley water. Graph A, activity ratios greater than 2; graph B, activity ratios less than 2. Squares, ^{228}Ra; filled circles, ^{226}Ra.

APPENDIX

SAMPLING AND ANALYTICAL PROCEDURES

The sample sites were municipal or commercial wells, with the exception of one private residential well. Samples were taken from as near the wellhead as possible, prior to any treatment or softening. During the sampling, wells were pumped at the nominal pumping rates set by the municipalities; rates varied from about 150 to 3000 gpm. Before sampling, the wells were pumped long enough to ensure collection of a fresh sample from the aquifer.

The dates shown in Tables 7 and 8 are when water samples for chemistry, radium, radon and polonium and gross alpha were collected. Some of the uranium, uranium activity ratio and carbon isotope (age) results in Tables 7 and 8 reflect sampling at earlier dates. Temperature, pH, conductivity, alkalinity, and dissolved oxygen were measured at the well. Temperature was measured to ± 0.1 °C with an ASTM 63C mercury thermometer immersed in water. The pH was determined to ± 0.01 pH units with Orion model SA 210 or SA 250 pH meters using Orion combination pH electrodes. The pH meter was calibrated before and after each measurement with pH 7 and pH 10 buffers equilibrated to the water temperature. Conductivity was measured with Cole Parmer model 1481-50 or 1481-40 conductivity meters calibrated with standard conductivity solutions ranging from 100 to 1200 μS/cm. A Hach digital titrator was used to determine the alkalinity. The samples were titrated with 1.6N H_2SO_4 to a pH end point using a bromcresol green/methyl red indicator. Alkalinity was titrated three times and the average of the measurements reported in Tables 7 and 8 as ppm HCO_3. Dissolved oxygen was measured once with a Hach digital titrator, using a modified Winkler titration with 2.0N sodium thiosulfate titrant in a 300-mL glass BOD bottle.

Samples for anion and cation analyses were collected in rinsed polyethylene bottles and cooled in an ice chest during transport to the laboratory. To retard precipitation, cation samples were acidified at the time of collection with 6N HCl. Cations were analyzed by direct-current plasma/atomic emission spectrometry, conforming to EPA Method 29. Anions were analyzed by Dionex Series 4000I ion chromatography, in accordance with EPA Method 300. Nominal detection limits (ppm) for cations are: Ca (0.01), Mg (0.01), Na (0.01), K (0.2), Al (0.02), Fe (0.01), Mn (0.02), Sr (0.002), Ba (0.002), and Si (0.05). Each analysis was replicated five times. Nominal detection limits (ppm) for anions are: Cl (0.03), NO_3-N (0.01), SO_4 (0.01), F (0.05), Br (0.02), PO_4 -P (0.03), NO_2-N (0.02). The results for F are subject to possible interferences, and NO_2-N values are easily masked if Cl is large. Each analysis was replicated twice.

Radium samples were collected in unrinsed, 1-liter polyethylene containers. No treatment of the water was done in the field, but the samples were acidified in the laboratory and allowed to sit for 24 hours prior to analysis. Analytical errors varied between 10% and 50%, with the highest errors associated with measurement of low levels of ^{228}Ra and the gross alpha activity.

For ^{222}Rn analysis, 17-mL samples of water were collected with a syringe from the bottom of a wide-mouth bottle in which the water was not aerated, and injected beneath a liquid-scintillation fluor in a glass bottle. The samples were counted within a few days of collection on a liquid scintillation counter. Activities were corrected for radioactive decay and counter background. The counter was calibrated with samples prepared from an NBS traceable solution of ^{226}RaCl.

Polonium-210 samples were collected in rinsed, 1-liter polyethylene bottles. The samples were acidified in the laboratory with 9N HCl. A ^{208}Po tracer was added to the water and the polonium plated onto silver planchettes. Polonium activities were measured by alpha spectrometry with an Ortec model 576 alpha spectrometer.

Uranium samples were collected in rinsed 20-liter polyethylene containers. The samples were acidified in the laboratory with 250 ml of 9N HNO_3. A ^{232}U tracer was added to the solution along with 3.6 g of $FeNO_3 \cdot 9H_2O$. After 24 hours, air was bubbled through the water to remove CO_2, and NH_4OH was added to precipitate the iron which carried along the uranium. Uranium was separated from the iron and other interfering elements by ion exchange and extraction into an organic liquid. The U isotopes were evaporated onto stainless steel disks and the activities measured by alpha spectrophotometry. The counting system was calibrated with NBS traceable solid-source standards. Analytical error varied between 5% and 100% with the largest errors associated with very low concentrations and counting rates.

Samples for carbon-14 analysis were collected by filling 120-liter or 200-liter barrels double lined with 2-mil polyethylene bags, with water. Initially, a minimum of 250 grams of $BaCl_2 \cdot 2H_2O$ was mixed with ammonia, that had been purified of CO_2, and about 4 liters of well water to form a slurry in the poly bag. The ammonia raised the pH of the water, causing the precipitation of $BaCO_3$, removing the dissolved carbonate from solution. After the bag was filled to nearly the top of the barrel, the inner bag was sealed to prevent contamination of the sample with atmospheric CO_2. The outer bag was also sealed, and the barrel capped. After 24 hours, the water-ammonia mixture was drained off and the precipitate was removed and shipped to Beta Analytic for measurement of the activity of ^{14}C and the concentration of ^{13}C.